FEASIBILITY STUDY OF DEVELOPING VALLEY-FILL AQUIFERS

FOR

VILLAGE WATER SUPPLIES IN SOUTHERN GUAM

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Western Pacific

Technical Report No. 41

September, 1983

Project Completion Report

for

FEASIBILITY STUDY OF DEVELOPING ALLUVIUM AQUIFERS
FOR
VILLAGE WATER SUPPLIES IN SOUTHERN GUAM

Project No. A-027-Guam, Agreement No. 14-34-0001-2112

Principal Investigator: Jerry F. Ayers

Project Period: January 1, 1982 to September 30, 1983

The work on which this report is based was supported in part by funds provided by the United States Department of the Interior as authorized under the Water Research and Development Act of 1978.

ABSTRACT

Villages located in southern Guam occasionally experience domestic water supply shortages that affect both the home dweller and the farmer. Municipal water supplies are provided by the island-wide distribution system. Water is obtained from well fields which tap the complex Ghyben-Herzberg lens beneath the northern limestone plateau and is transported south at considerable cost. If alternative sources of freshwater can be located near the centers of high demand, the energy costs of pumping water long distances would be lowered, the reliability of the distribution system would be improved, the quantity of water extracted from the northern lens would be reduced, and lastly the village communities would become more self-sufficient in terms of water supply.

Potential sources of groundwater for domestic use have been identified near the outflow of the Inarajan River. Two water-bearing units of alluvium and shallow-water marine sediments overlie a partially weathered volcanic basement. From the results of the study it appears feasible to develop the groundwater resource, at least initially, on a limited scale. The quality of the product water is such that it could be used directly for agricultural purposes.

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INTRODUCTION

General

Villages located in southern Guam often experience domestic water-supply shortages that affect the home dweller, local businesses, and the farmer. Municipal water supplies are provided by the island-wide distribution system. Water is obtained from well fields which tap the complex Ghyben-Herzberg lens beneath the limestone plateau of northern Guam and is transported south at considerable cost. Because of mechanical failure, inadequate storage facilities, or (more recently) drought conditions, the village communities are sometimes subjected to the inconvenience of water hours or in extreme situations, water service discontinuation. These conditions may exist for days to weeks at a time. If alternative, more localized sources of freshwater could be found near the population centers of southern Guam, then (1) the energy costs of pumping water long distances would be lowered, (2) the overall reliability of the distribution system would be improved, (3) the quantity of water extracted from the northern lens would be reduced, and more importantly (4) the village communities would become more selfsufficient in terms of water supply.

Because of the geomorphological history of southern Guam, potential sources of fresh groundwater are the numerous sediment-filled valleys situated along the coastal borderland. Streams draining the dominant volcanic terrane of the south have eroded relatively deep valleys. Much of this erosion probably took place during glacial stages of the Pleistocene when sea level (i.e., base level) was considerably lower than at the present time. Subsequent rises in sea level tended to "drown" the eroded valleys near the river mouths. These valleys then became sites of sedimentation and consequently filled with material carried by the rivers in addition to waves and near shore currents. With the establishment of present-day conditions, meteoric water filled the interstices of the clastic fill displacing the saline groundwater thus providing a potential aquifer for freshwater.

Development of these valley-fill aquifers would depend on a number of factors. Of these, the water-bearing properties of the sediments, the size and extent of the valley fill, the characteristics of seasonal recharge to the flow system, and the interdependence of the stream and groundwater body are probably the most significant. The main theme addressed by this study then, is whether or not these potential resources will yield significant quantities of usable water to warrant the effort and expense of development.

Objectives and Scope of the Study

A suitable site, near Inarajan Village, was selected as the target area and a number of investigative activities were conducted. The primary objective was to determine the feasibility of developing the valley-fill aquifer for the purpose of augmenting the local water supply of the village.

To achieve this objective, a number of tasks were defined. Specifically, these tasks were:

1. to locate the boundaries of the valley-fill aquifers;

2. to describe the characteristics of the sediment fill in terms of its composition, structure, stratigraphy, and, if possible, water-bearing properties;

3. to determine the time-dependent behavior of the water table;

4. to determine the general quality of the groundwater; and

5. to evaluate the potential of the resource in terms of future development.

To accomplish these tasks, several field, laboratory, and analytical methods were employed. Among these methods were the installation of small-diameter observation wells, the utilization of geophysical techniques (seismic refraction and earth resistivity), the analysis of a number of water-quality standards, and the computer processing of relevant data. Of these methods, the most notable is the utilization of geophysical techniques. This study is the first to apply seismic-refraction profiling and earth-resistivity sounding in groundwater studies in southern Guam. These methods were particularly useful in view of the limited facilities at hand for sampling subsurface material.

Location and Description of the Study Area

The area selected for the feasibility study is located near the village of Inarajan along the southeastern coast of Guam (Figure 1). The study area encompasses the lower portion of the Inarajan River valley which is characterized by a relatively broad flat floor approximately ¼ to ½ mile wide. The valley is bounded on the north and south by hills developed on the volcanic terrane and on the east by Inarajan Bay. The photographs of Figure 2 show relevant features of the study area.

Access to the study area is via three roads; however, permission must be obtained from the land owners. During the wet season, the land surface becomes extremely boggy; thus, vehicle use is greatly limited.

The primary use of the land within the valley is agriculture, although there are a number of fish ponds along the southern bank of the stream. Cattle grazing and melon production are the two main agricultural activities.

The surficial geology of the study area is relatively simple. Except for near the shoreline, volcanic rocks of the Bolanos pyroclastic member of the Umatac formation (Tracey et al., 1964) surround the Inarajan River valley. This member consists of tuffaceous sandstone and shale interbedded with minor amounts of conglomerate. This material is usually deeply weathered near the surface; however, competent outcrops are found in a number of areas. Along

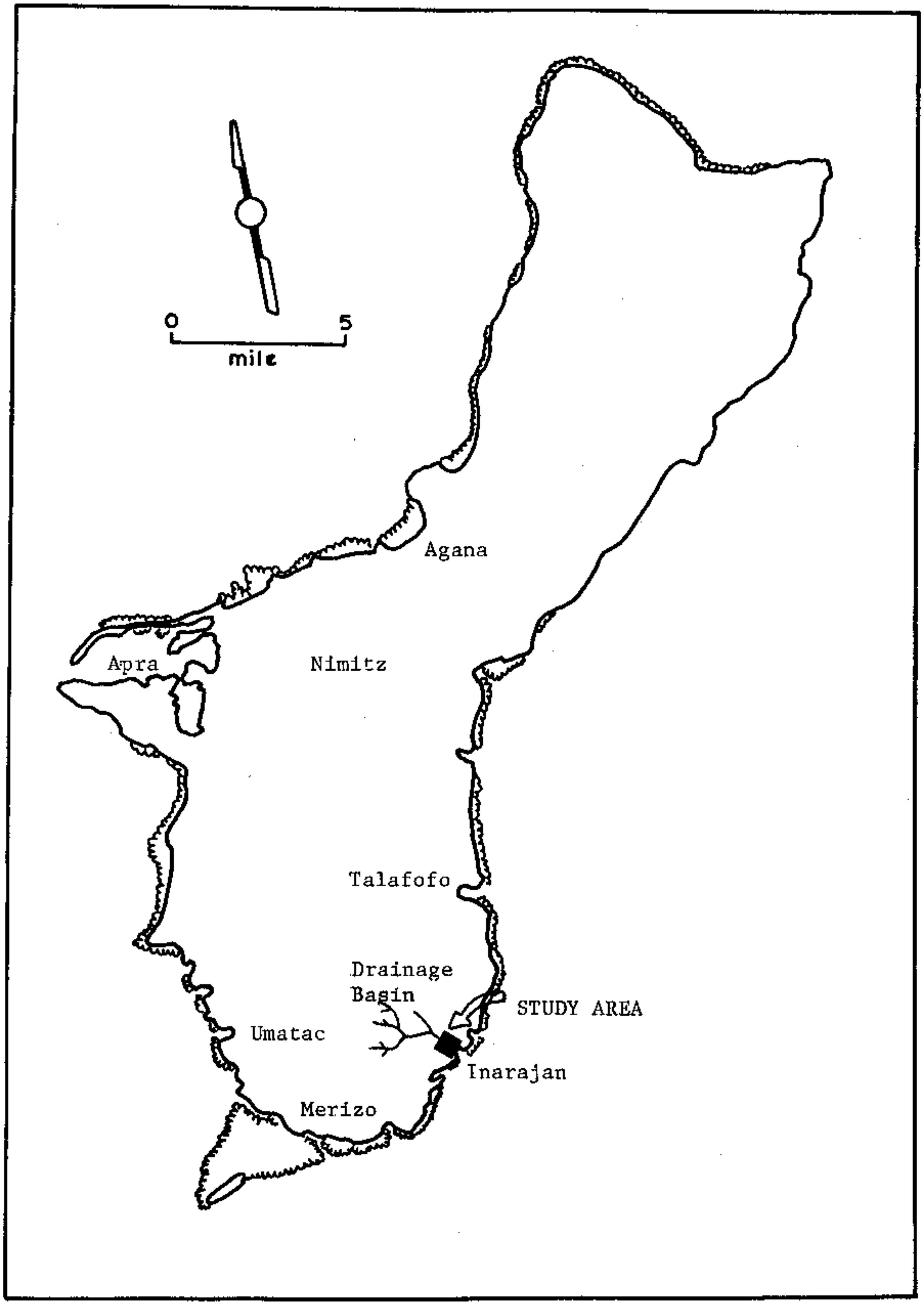

Figure 1. Map of Guam showing the location of the study area.

Figure 2. Overview of the study area.

the shoreline, the Agana argillaceous member of the Mariana limestone crops out (Tracey et al., 1964). This unit is distinguished from the volcanic rocks by its rugged appearance and support of vegetation which does not grow on the acidic soils produced from parent volcanics. The member is composed of a coarse- to fine-grained fossiliferous detrital limestone containing a significant amount of disseminated clay. Valley fill at the surface is composed of very fine-grained material supposedly derived from the volcanic terrane and deposited by fluvial processes. Although difficult to observe due to agricultural activities, it appears that the valley floor is a flood plain and that over-flow deposits have formed natural levees along the banks of the stream. In addition, alluvial fans have been deposited at the mouth of a number of tributary (intermittent) streams.

DESCRIPTION OF THE STUDY

The study was conducted between January and August, 1983. Most of this time period coincided with the annual dry season (which was extended due to drought conditions). During the course of the study, a variety of methods, both field and laboratory, were utilized in the effort of evaluating the groundwater conditions within the lower reaches at the Inarajan River valley. These methods included installing small-diameter observation wells, monitoring water levels, conducting geophysical surveys, collecting water samples, performing water-quality analyses, and computer processing of field data.

Installation of Observation Wells

A number of small-diameter observation wells were installed within the stream valley (Figure 3). These wells were used primarily as a means (1) to locate and monitor the position of the water table and (2) to collect samples of the subsurface sediments. Observation wells also allowed access to the subsurface for the purposes of collecting water samples and conducting a small-scale pumping test.

Observation wells were installed by first hand augering a 2 inch diameter hole then inserting a length of 2-inch PVC pipe. A total of eight holes were dug to depths ranging from 12 to 18 feet. The bottom 3 feet of the PVC casing was perforated and placed in the hole such that only the perforated section extended below the water table. Excess pipe above ground was removed and the casing secured in the hole.

The final step in the installation procedure was to obtain elevations to the top of the casing. This was achieved by running an elevation-control survey to all the necessary points. An arbitrary datum near sea level was selected because no established bench mark existed within a reasonable distance of the study area. All elevations, then, are relative to this arbitrary datum.

Geophysical Measurements

Two geophysical field methods were employed in the study. Specifically, these methods were (1) seismic-refraction profiling and (2) earth-resistivity soundings. These methods were used in an attempt to determine the subsurface structure and, to a certain extent, the quality of the groundwater. Several measurement stations were established within the study area; their locations are shown on the map of Figure 4.

Seismic-Refraction Profiling

Seismic-refraction methods have been used in a wide variety of investigations involving the determination of subsurface structure. Among these investigations are numerous applications of the method in groundwater-related studies. The object of refraction seismology is to obtain a time-distance graph from the first arrival of sound waves generated by an energy source. From time-distance graphs, seismic velocities can be calculated and depth determinations can be made.

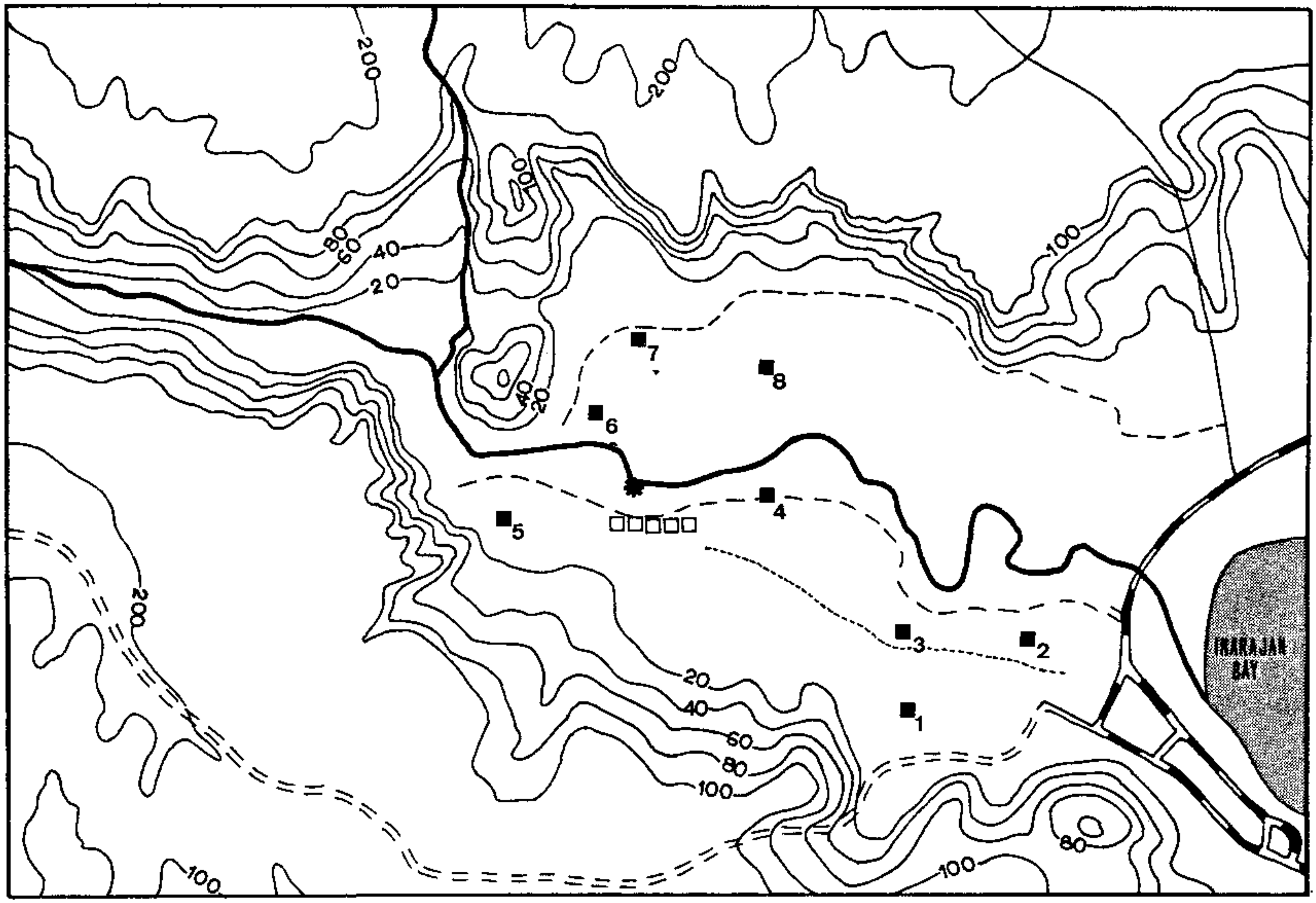

Figure 3. Map of the study area showing the locations of observation wells.

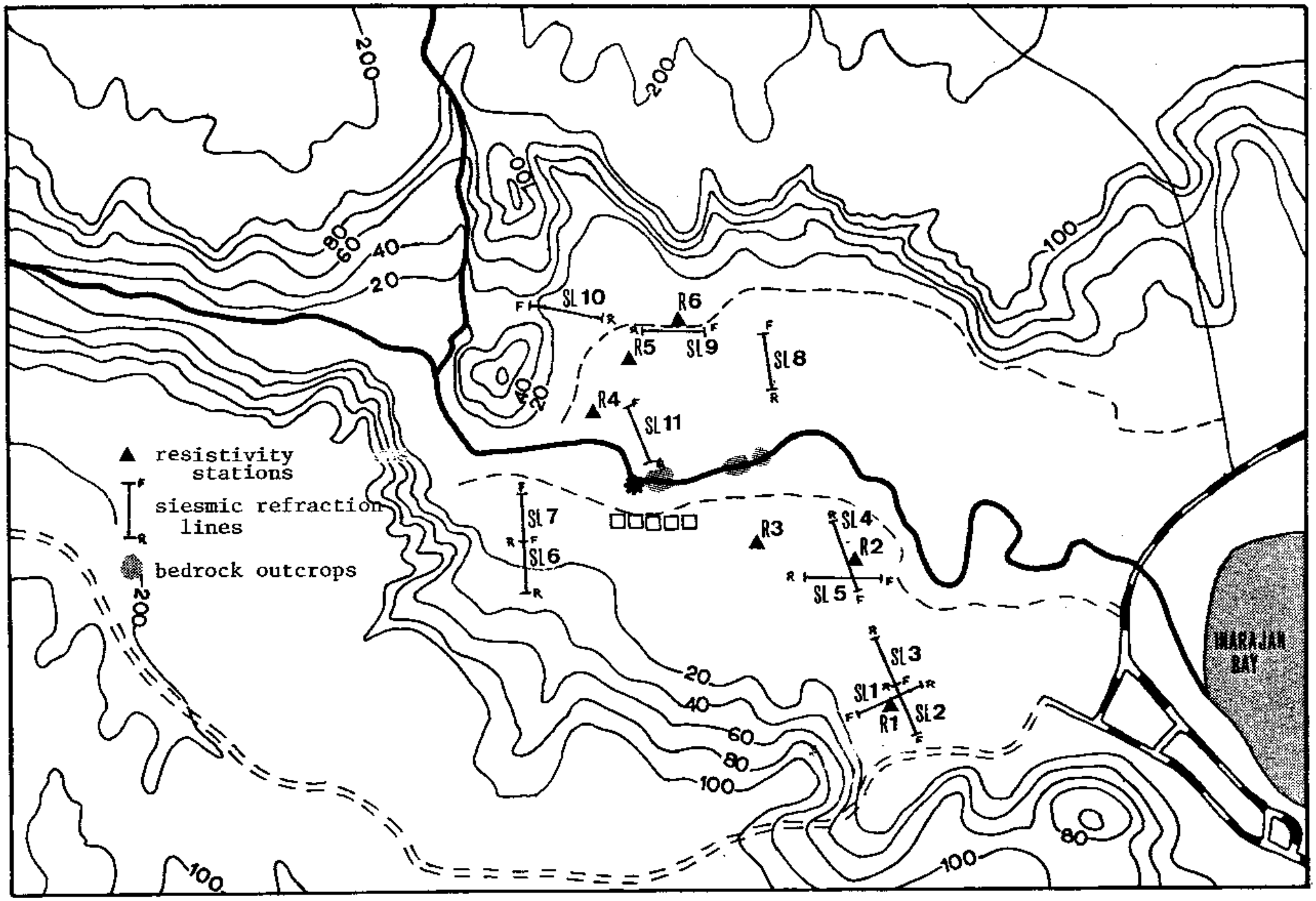

Figure 4. Map of the study area showing locations of geophysical stations and bedrock outcrops.

Detection of refracted sound waves generated by controlled energy sources (e.g., hammer striking a steel plate, weight drop, or explosion) usually produces a seismic record indicating one or more events that are caused by the change in velocity of the wave front. Seismic energy is transmitted through solid material as elastic waves. Abrupt changes in the elastic properties through which these waves are propagated will cause the waves to be refracted or bent. The degree to which the wave paths are refracted is related to Snell's Law, that is, the sine of the angle of incidence is equal to the sine of the angle of refraction. Another way of expressing this law is by the following equation:

$$\frac{\sin i}{\sin r} = \frac{V_1}{V_2}$$

where

i = angle of incidence,

r = angle of refraction,

V_1 = velocity of transmission of the elastic wave in the incidence medium, and

V_2 = velocity of transmission of the elastic wave in the refraction medium.

A primary concept in refraction work is that of the critical angle. Where r is equal to 90°, $\sin i$ is equal to V_1/V_2. Here, the incident wave path or ray strikes the interface at the critical angle and the refracted wave travels parallel to the interface. A refracted wave front acts as a first arrival when its travel time from the source through the refraction medium to the detector is equal to or greater than the time required for the direct wave to travel from the source to the same detector. The path that first-arrival waves take is dependent upon the depth to the reference interface and the distance between the first detector and the energy source (Telford et al., 1976; Zohdy et al., 1974).

When first-arrival times derived from seismograms are plotted on a time-distance graph, a break in slope of the curve will occur where the time taken for both direct and refracted waves to travel from the energy source to the detector are the same. Seismic velocities are obtained from the slope on the time-distance curve (i.e., velocity is the inverse of the slope).

The most widely used of all field techniques in refraction work is profile shooting. To obtain the necessary time-distance data, shot points and detectors or geophones are laid out on long lines and repeated shots are taken at various positions at the ends and middle of the geophone spread. If successive spreads are necessary, the lines are overlapped by at least one or two geophones.

During field operations, a total of 11 seismic-refraction lines were established within the study area. Each line was shot in both the forward and reverse order; several lines were shot at the midpoint of the spread. The energy source used in the refraction work was a sledge hammer striking a steel plate. The geophone spread consisted of 12 detectors spaced at 25-foot intervals connected to a McSeis-1300 (model 1191) Signal Enhancement Seismograph and display unit. A permanent record was produced on light-sensitive paper.

Although a number of analytical approaches are available (see, for example, Telford et al., 1976; Dobrin, 1976), the least time-consuming method utilizes computer processing of the time-distance data. The computer program used to process the Inarajan data was first published by the U.S. Bureau of Mines (Scott, 1972). The program generates a two-dimensional model representing a layered-earth depth interpretation. Travel times are picked from the seismogram by the user. These times, together with shot point and geophone locations and refraction layer control information, are used as program input. A first approximation delineation for each refraction interface is obtained by a computer adaptation of the delay-time method. The approximation is then tested and improved by the computer through the use of a ray-tracing procedure in which ray travel times computed for the model are compared to field data. The model is subsequently adjusted in an interative manner such that the discrepancy between computed and measured travel times is minimized. Seismic velocities and depths to refractor interfaces, among other information, are printed as the final step.

Earth-Resistivity Sounding

In addition to the application of seismic-refraction profiling in groundwater investigations, earth-resistivity measurements are widely used in the determination of subsurface characteristics. Essentially, the method involves measuring the electrical resistivity of earth materials by introducing an electrical current into the ground and monitoring the potential field developed by that current. In most earth materials, electricity is conducted electrolytically by the interstitial fluid, and resistivity is controlled more by porosity, water content, and water quality than by the resistivities of the matrix (Zohdy et al., 1974). Clay minerals, however, are capable of conducting a current electronically, and the electrical flow in a clay unit is both electronic and electrolytic.

In conducting earth-resistivity soundings, a commutated direct current or very low frequency (<1 Hz) current is introduced into the ground through two electrodes (Zohdy et al., 1974). The potential difference is measured between a second pair of electrodes; the current and potential measurements are used to calculate apparent resistivity.

The most commonly used electrode configuration for vertical electrical soundings, and the one used by this study, is the Schlumberger array. Four electrodes are placed along a straight line on the ground surface such that the outside current electrode distance ($\overline{AB}$) is equal to or greater than 5 times the inside potential electrode distance ($\overline{MN}$). For any linear, symmetric array $\overline{AMNB}$ of electrodes, the apparent resistivity is given by (Zohdy et al., 1974):

$$\rho_a = \pi \frac{(\overline{AB}/2)^2 - (\overline{MN}/2)^2}{\overline{MN}} - \frac{\Delta V}{I}$$

where

ΔV = measured potential difference, and
I = electrical current

A Soiltest R-60 resistivity unit was used to conduct the soundings. The unit utilizes dry-cell batteries as a power source with a maximum output of 810 volts and 1.0 amps. Electrode spacings for each of the 6 stations ranged from 3.0 to 200 feet for the $\overline{AB}/2$ distance.

Resultant data generated during the resistivity survey were analyzed by a trial-and-error procedure of curve matching. The first step was to plot the data on a graph of apparent resistivity versus electrode spacing ($\overline{AB}/2$) for each station and smooth the vertical electrical sounding (VES) curve to remove the discontinuities produced by the method of measurement (see, for example, Zohdy et al., 1974). Next, an appropriate layer model is selected as a first approximation to the field VES curve. Layer thickness or depth and resistivity values are used as input to a computer program (Zohdy, 1974) which calculates the model VES curve. This model VES curve is then compared to the field VES curve for goodness of fit (usually a qualitative comparison). If necessary, the input values are adjusted and the program rerun. This procedure is continued until a reasonable match is achieved between the model and field curves.

As discussed by Zohdy (1974), for a given earth model composed of horizontally stratified, laterally homogeneous, and isotropic layers, the computer program calculates the Schlumberger apparent resistivity in two parts. First, the total kernel function $T = f(h,e,\lambda)$ is calculated for an n-layer model using Sundi's recurrence formula which is given by

$$T_i = (h,\rho,\lambda) = [1-Q_i e^{-2\lambda h_i}]/[1+Q_i e^{-2\lambda h_i}]$$

$$Q_i=[\rho_i-\rho_{i+1}Q_{i+1}]/[\rho_i+\rho_{i+1}Q_{i+1}]$$

$$T_{n-1}(h,\rho,\lambda) = [1 - Q_{n-1}e^{-22h_{n-1}}]/[1 + Q_{n-1}e^{-2\lambda h_{n+1}}]$$

$$Q_{n-1} = [\rho_{n-1} - \rho_n]/[\rho_{n-1} + \rho_n]$$

where

ρ_i = Resistivity of the i $\underline{th}$ layer, and

h_i = thickness of the i $\underline{th}$ layer.

The second part in the calculation of Schlumberger apparent resistivity is based on convolving the inverse filter coefficients (Ghosh's coefficients) with the computed total kernel function curve. The convolution is made twice and six apparent resistivity values per logarithmic cycle are obtained. The abscissas of the computed points are logarithmically equally spaced, with

$$(\overline{AB}/2)_{i+1} / (\overline{AB}/2)_i = 1.468$$

where $\overline{AB}/2$ is the Schlumberger electrode spacing.

Small-Scale Pump Test

Aquifer or pump tests are usually included within the scope of work for hydrogeologic investigations and groundwater studies. However, because this is primarily a feasibility study more comprehensive aquifer tests are deferred to further work. Nonetheless, a simple test was performed utilizing a portable water sampling pump in order to roughly determine a value for the hydraulic conductivity of the valley fill. Unfortunately, only one test was completed that provided useful information. For much of the study duration, low water levels in observation wells due to the drought prevented the successful completion of all but one test.

The pump test was conducted on AH-4. Drawdown was measured over time until no appreciable decline was noted. Results of the test were then analyzed utilizing a steady-state flow equation derived for wells in unconfined aquifers. Solving for the hydraulic conductivity, the equation is expressed by (e.g., Davis and DeWiest, 1966):

$$K = \frac{Q}{\pi (H^2 - h^2)} \ln \frac{r_e}{r_w}$$

where

Q = discharge (pumping rate),
H = initial water-table elevation prior to pumping,
h = steady-state water-table elevation at the end of the test,
r_w = well radius,
r_e = effective radius.

Water-Quality Analyses

Determinations of water quality are important aspects of any groundwater investigation. The most obvious benefit of such studies is the assesssment of the resource in terms of its potability or fitness for human consumption and domestic use. However, water-quality data also can be used to evaluate natural processes within the subsurface hydrologic environment, such as the degree of mixing between fresh groundwater and seawater in the case of an insular setting or identifying sources of natural or artificial contamination in more general situation. Although no comprehensive program of water quality assessment was undertaken for this study, the methods outlined below were employed in order to obtain at least a general concept of water chemistry within the valley-fill aquifer.

Water samples were collected from two observation wells, AH-1 and AH-4. Two sets of analyses were performed on samples from AH-4; one set included a number of relevant water-quality standards and the other set included a number of dissolved metals. Because of low well yield to AH-1, sufficient sample quantity was obtained to perform only the analyses included in set one. All procedures used in the water-quality analyses were obtained from published standard methods. For non-metal constituents reference was made to Standard Methods for the Examination of Water and Wastewater (American Public Health Association, 1980) and for dissolved metals reference was made to Methods for Chemical Analysis of Water and Wastes (U.S. Environmental Protection Agency, 1979). Specific constituents are listed in Table 1.

Table 1. Constituents of the water-quality analyses.

Metals	Dissolved Metals
Temperature	Cadmium
Turbidity	Chromium
Specific Conductance	Copper
pH	Iron
Carbon Dioxide	Lead
Total Hardness	Manganese
Calcium Hardness	Mercury
Chloride	Nickel
Sulfate	Silver
Silica	Zinc
Nitrite-Nitrogen	
Nitrate-Nitrogen	
Total Kjedhal Nitrogen	
Total Nitrogen	
Ortho-Phosphorus	
Total Phosphorus	
Arsenic	
Selenium	

RESULTS OF THE STUDY

The following is a presentation of the study results. Included in the various categories are general observations, well logs, water-level measurements, geophysical survey results, and water-quality analyses. Field and laboratory data are presented in summarized form; more detailed information is listed in the appendices. The implication of these results will be discussed in the next section.

General Observations

A number of relevant observations were made during the field work that warrant consideration. Specifically, these observations are:

1. An area of active groundwater seepage is located in the south-central portion of the valley at the foot of the hills;

2. Alluvial fans characterize the land surface in the northwestern and southwestern portions of the river valley;

3. Natural levees have been formed along both banks of the river;

4. Volcanic bedrock is exposed in the stream bed in the vicinity of the U.S.G.S. gaging station (see Figure 4);

5. During the installation of the holes when groundwater was encountered, water would enter the hole rapidly and rise a few inches above the level where first struck;

6. Drought conditions prevailed from about January to about mid July; very little rain was received by the study area resulting in a river-stage decline to nearly dryness.

Well Logs

Installation of small-diameter observation wells provided important subsurface information related to the stratigraphy and composition of valley fill deposits. Essentially three units have been identified, a surface soil horizon, an underlying unit of alluvium, and a third lower unit of marine sediments (Table 2).

The surface unit consists of a dark brown soil horizon which ranges in depth from a few inches to about 1.5 feet. It is probable that the upper part of unit 2 beneath the top soil is the parent material.

The appearance of the material comprising unit 2 suggests an original composition of sand and fine gravel derived from the volcanic terrane. Although deeply weathered, individual grains can be observed in most cases. Where identifiable, these grains are subrounded to well rounded and exhibit compositions suggestive of a volcanic source area. Sorting and size

Table 2. Various units identified from auger holes.

Auger Hole	Unit 1 Thickness (ft)	Unit 2 Depth (ft)	Unit 2 Thickness (ft)	Unit 3 Depth (ft)
1	1.5	1.5	7.5	9.0
2	0.5	0.5	8.5	9.0
3	1.0	1.0	11.0	12.0
4	0.5	0.5	11.5	12.0
5	0.5	0.5	12.0	12.5
6	0.5	0.5	14.5	15.0
7	0.5	0.5	8.0	8.5
8	0.5	0.5	9.5	10.0
Average	0.7	0.7	10.3	11.0

Unit 1 - Soil Horizon
Unit 2 - Alluvium
Unit 3 - Marine Sediments

distributions, among other sedimentological parameters, could not be accurately accessed due to the degree of weathering; however, from the abundance and variety of relic grains, it can be concluded that the major transporting process was fluvial. Minor amounts of sediment may have entered the valley-fill deposits by slope wash from the surrounding hills; a number of small ravines with accompanying alluvial fans are present along the valley borders. In general, unit 2 thins toward the shoreline from a thickness of over 12 feet at the western end of the valley to about 7.5 feet near Inarajan Bay and the river outflow. Thicker portions of the unit appear to be associated with the buildup of natural levees and the deposition of alluvial fans.

Unit 3, underlying unit 2, consists of marine sediments composed of shallow-water carbonate skeletal material (including whole shells), carbonized plant fragments, and sand- and pebble-size clasts of volcanic rocks in a soft, black, very fine-grained (silt or clay) matrix. Most of the skeletal material consists of marine mollusc and gastropod shell fragments with numerous bivalves and whole individuals, soft coral spicules, foraminifera, and halimeda fragments. Little transport is evident from the lack of wear on much of the material. From this and the species type, the fossil assemblage seems to indicate a near-shore environment of deposit, possibly a protected embayment.

Non-skeletal clastics larger than silt size were derived from the volcanic terrane and transported to the site of deposition by fluvial processes. This sediment was then dispersed by wave and current action. Volcanic clasts, particularly the larger sizes, are usually subrounded to well rounded indicating greater distances of transport than the skeletal material.

Detailed geologic logs of the augered holes are presented in Appendix A.

Water-Level Measurements

In addition to providing a means of collecting subsurface sedimentological information, the observation wells provided a means of monitoring the water-table position. Measurements, taken at one- to three-week intervals, in general show a decline in water-table elevations from the beginning of the measurement period to two to three weeks after the drought ended; the remainder of the measurement period was a time of recovery (see Table 3). A number of the observation wells that initially contained water later became dry, indicating a water-table decline below the well bottom.

Geophysical Survey Results

Results from the application of seismic-refraction profiling and vertical electrical soundings are presented in summary below. A complete data set of the survey results is given in Appendix B.

Seismic-Refraction Profiles

From the computer analysis of time-distance data obtained from the field

Table 3. Water-level measurements at observation wells.

Date	Relative Elevation (ft)							
	AH-1	AH-2	AH-3	AH-4	AH-5	AH-6	AH-7	AH-8
3/22	4.48	1.25	3.89	6.33	12.32	---	---	---
4/13	3.95	1.11	3.29	6.38	dry	---	---	---
4/29	3.77	0.54	3.53	8.06	dry	---	---	---
5/5	3.63	0	3.54	8.13	10.73	---	---	---
5/11	3.54	0.02	3.53	9.08	dry	7.81	10.27	9.17
5/31	3.33	0.14	3.40	9.26	dry	7.81	9.56	8.40
6/11	3.14	0.12	3.28	6.13	dry	6.87	9.26	8.40
6/15	3.09	0.34	3.32	6.09	dry	6.95	9.25	dry
6/24	2.95	0.29	3.56	6.13	dry	6.69	8.22	dry
6/28	2.93	0.29	3.30	5.92	dry	6.49	8.88	dry
7/22	4.01	1.30	4.69	6.90	dry	dry	dry	dry
7/29	3.99	1.31	4.54	6.54	dry	6.59	dry	dry

NOTE: All elevations are relative to the lowest value measured in observation well AH-2. Spaces marked "dry" indicate water table position below bottom of the well while the dash indicates well not installed on that date.

survey, two types of information were obtained. These types were (1) seismic velocities for various subsurface layers and (2) depths to the top of the layers beneath each geophone. Velocities and average layer depths for each line are listed in Table 4. Data for two sets of overlapped spreads (numbers 2 and 3; numbers 6 and 7) are also given.

Analytical results for all but line 9 indicate three distinct velocity layers. Average velocities for layers 1, 2, and 3 are 1583 ft/s, 4454 ft/s, and 8690 ft/s, respectively. An average depth to the top of layer 2 is 16.0 feet and an average depth to the top of layer 3 is 66.4 feet. Results for line 9 indicate a 2-layer system with values of velocity and depth comparable to those for the other spreads.

A number of additional noteworthy points about the data in Table 4 and Appendix B are related to the velocity distribution and the surface configuration of layers 2 and 3. In general, layer 2 velocities are somewhat lower within the eastern sector relative to those of the western sector of the river valley. Although the difference is not great, a change in properties within layer 2 may be indicated. This change may be related to lithologic or structural (or both) differences in subsurface material. There appears to be no definite pattern evident in the velocity distribution of layer 3; however, layer 3 velocities for two spreads are significantly higher than the overall average. These velocities may indicate relatively fresh rock.

From the depth-distance plots (profiles) of Appendix B, the surface topography of both layers 2 and 3 is highly irregular compared to the ground surface. Values of depths to layer 2 range from 8.5 feet to 29.1 feet and depths to layer 3 range from 36.4 feet to 108.8 feet (Table 4). From the profile diagrams, the topography beneath individual spreads tends to range over a large scale of values. Topographic variability may be related to an original surface, to a weathering front, or to a facies change within the subsurface unit.

Vertical Electrical Sounding

The layer model that best fits field VES curves is composed of 5 units. Thickness values and corresponding bulk resistivities for each of the six stations are given in Table 5. It is assumed that layer 5 is of infinite depth; therefore, no thickness is given. Field VES curves and their calculated or matched counterparts are presented in Appendix B.

In general, the results from the resistivity work were relatively consistent in terms of thickness (and hence depth) determination. Notable exceptions are layer 4 thickness values for stations 1 and 4 which are high compared to other results. Bulk resistivities exhibit a wide range of values within individual layers. The greatest range of values is found within layer 5 with a spread from 19 ohm-ft to 140 ohm-ft; the surface layer runs a close second with values in the range of 13 ohm-ft to 112 ohm-ft; remaining layers show a somewhat more subdued set of ranges. The variability of layer 1 is probably related to moisture content at the time the sounding was taken

Table 4. Results from the analysis of seismic-refraction field data.

	Layer 1	Layer 2		Layer 3	
Spread	Velocity (ft/s)	Velocity (ft/s)	Depth (ft)	Velocity (ft/s)	Depth (ft)
1	1500	3954	8.5	7545	36.3
2	1500	3624	19.4	6697	64.2
3	2000	4414	10.6	8047	51.5
4	2083	4472	18.8	8995	108.8
5	1500	4205	13.0	8354	74.6
6	1500	4134	29.1	7109	73.6
7	1644	4910	17.0	*14718	59.8
8	1278	3708	8.9	8053	54.2
9	1509	5242	19.7	----	----
10	1143	5168	12.8	*10855	57.2
11	1275	5418	18.0	8264	83.1
2-3	2000	3980		7283	
6-7	1644	4671		8360	

Average Depth Layer 2 - 16.0 ft.
Layer 3 - 66.4 ft.

Average Velocity Layer 1 - 1583 ft/s
Layer 2 - 4454 ft/s
Layer 3 - 7871 ft/s
*With higher values
Layer 3 - 8690 ft/s

Table 5. Results from the analysis of vertical electrical sounding (VES) field curves.

Station	Layer 1 Thickness	ρ	Layer 2 Thickness	ρ	Layer 3 Thickness	ρ	Layer 4 Thickness	ρ	Layer 5 ρ
1	3	13	8	20	12	30	55	18	60
2	2	47	8	13	10	25	30	3	35
3	2	112	9	21	18	13	32	4	120
4	2	88	9	24	18	18	55	9	59
5	2	45	4	13	10	55	22	3	140
6	1	38	7	15	11	40	30	13	19
Average	2		7.5		13.2		37.3		
Average Depth Surface			2.0		9.5		22.7		60.0

(soundings were conducted over a several week period). Variability within the other layers is less definable and is probably attributable to a number of factors including degree of saturation, composition, texture, structure, and extent of weathering.

Bulk resistivities between units at any station seem to exhibit somewhat better consistency than within units for all stations. The general trend in bulk resistivity with depth is a thin surface layer of higher values overlying a second layer characterized by significantly lower values which in turn overlies a third unit of slightly higher resistivity. The fourth layer exhibits a bulk resistivity significantly lower than all overlying units but is in sharp contrast to the high resistivity values of layer 5. This rather consistent pattern is readily seen in the general configuration exhibited by the field VES curves.

Pump Test Results

Time-drawdown data obtained from the small-scale pump test are listed in Table 6. Utilizing the steady-state equation of flow to a well in an unconfined aquifer and the equilibrium data of Table 6, the computed hydraulic conductivity of the valley fill is about 16 ft/d. Of course this value is valid for that portion of the aquifer in the vicinity of AH-4 and probably is not representative of the general water bearing properties of the subsurface material.

Water Quality Analyses

Water-quality data obtained from the laboratory analysis of samples collected from AH-1 and AH-4 are presented here. Selected non-metal constituents determined from samples collected in AH-1 and AH-4 are listed in Table 7. Likewise, a number of relevant dissolved metal determinations from AH-4 are listed in Table 8. These chemical parameters were selected on the basis that they are good indicators of general groundwater quality . Therefore, if significant concentration of any of the selected constituents would lead to the inference of possible aquifer contamination by natural or artificial processes.

Table 6. Time-drawdown data from a small-scale pumping test. Test conducted on AH-4; discharge rate constant at 0.21 gal/min.

Time (Min.)	Depth to Water (ft)	Drawdown (ft)
0	6.72	0
1.0	6.90	0.18
2.0	6.92	0.20
3.0	6.93	0.21
4.0	6.93	0.21
7.0	6.97	0.25
8.0	6.97	0.25
9.0	6.98	0.26
10.0	6.98	0.26
11.0	6.99	0.27
12.0	6.99	0.27
13.0	6.99	0.27
15.0	6.99	0.27
17.0	6.99	0.27
20.0	6.99	0.27

Table 7. Non-metal constituents of groundwater samples from observation wells AH-1 and AH-4.

Constituent		AH-1	Observation Well AH-4a	*AH-4b[1]
Temperature	(°C)	32.0	30.4	30.3
Turbidity	(NTU)	34	24	4.8
Specific Conductance	(μmho/cm)	1300	825	875
pH		6.88	6.88	6.88
Carbon Dioxide	(mg/ℓ)	282	410	164
Total Hardness	(mg/ℓ)	329.3	167.7	
Calcium Hardness	(mg/ℓ)	248.5	84.5	
Chloride	(mg/ℓ)	105.0	41.5	40.5
Sulfate	(mg/ℓ)	31.0	10.0	10.0
Silica	(mg/ℓ)	3.0	3.6	3.6
Nitrite-Nitrogen	(mg/ℓ)	0.03	0.007	0.016
Nitrate-Nitrogen	(mg/ℓ)	16.87	<.01	<.01
Total Kjedhal Nitrogen	(mg/ℓ)	.875		<.10
Total Nitrogen	(mg/ℓ)	17.78		0.016
Ortho-Phosphorus	(mg/ℓ)	0.122	0.045	0.041
Total Phosphorus	(mg/ℓ)	0.182	0.073	0.055
Arsenic	(μg/ℓ)		0.2	0.1
Selenium	(μg/ℓ)		<0.1	<0.1

* Water sample collected after 30 minutes of pumping.

Table 8. Dissolved metal constituents in groundwater samples from observation well AH-4.

Dissolved Metal	Concentration (μg/ℓ) AH-4a	*AH-4b
Cadmium	0.3	0.4
Chromium	2.7	<0.2
Copper	55.3	<1.0
Iron	12363.0	81.8
Lead	7.5	<1.0
Manganese	2750.0	1.8
Mercury	1.8	0.3
Nickel	2.2	<1.0
Silver	< 0.1	0.1
Zinc	3229.0	2.0

* Water sample collected after 30 minutes of pumping

DISCUSSION

The following discussion of the study results is based on the interpretation of well logs, water-level measurements, water-quality analyses, and geophysical field data. Three main topics are addressed. Specifically, these topics are (1) geologic framework of the study area; (2) groundwater occurrence and water quality within the valley-fill aquifer; and (3) potential of developing the groundwater resource.

Geologic Framework

The stratigraphy within the study area can be deduced from well logs, geophysical data, and in part from general observations. In general, the geologic framework is characterized by three stratigraphic units of contrasting composition. Excluding the soil horizon, the three units consist of alluvium, marine sediments, and bedrock of the Umatac formation.

The near surface unit of alluvium is composed primarily of sand derived from the surrounding volcanic terrane and deposited by either the main stream or slope wash and tributary streams. Surface depositional features can be characterized by three categories: (1) overbank deposits (natural levees); (2) flood plain deposits; and (3) alluvial fan deposits. No doubt, these same features are present within the unit of alluvium but, because of the degree of weathering and the limited number of exploration auger holes, it is not possible to delineate depositional environments.

Assuming that the alluvium is the parent material of the soil horizon, the average thickness of the surface unit is about 11 feet. A comparison of resistivity results to well logs suggests that the geoelectric layers 1 and 2 are probably indicative of the alluvial sediments. From the analysis of field VES curves, an average thickness for both layer 1 and layer 2 is 9.5 feet. The geoelectrical properties of layers 1 and 2 (Table 4) appear to be dissimilar; however, this is probably due to differences in moisture content. Layer 1, which includes the soil horizon and the upper portion of the alluvial unit, was much drier at the time of measurement.

Underlying the alluvium is a unit composed primarily of marine sediments as indicated by the abundance of shell and other carbonate skeletal material. From the fossil assemblage, it appears that the environment of deposition was one of a protected shallow-water embayment, probably an inland extension of Inarajan Bay. Sediments comprising the unit were derived from organisms living within the back water area and, in part, from skeletal debris transported into the bay by wave action and surface currents. Inarajan River also contributed clastic sediments to the bay. These were probably reworked and transported by waves and currents. Apart from the shallow water marine organisms, an abundance of carbonized plant fragments and an organic-rich fine-grained matrix are evidence for a near-shore depositional environment.

From the results of the VES curve matching process, it appears that the geoelectric properties of layer 3 (Table 4) are dissimilar to those of layers 1 and 2 assigned to the alluvial unit. In addition, the electrical properties of layer 3 are in contrast to those of layer 4. Because of these differences between layers and because the top of the marine unit was identified in the well logs, the geoelectric layer 3 is assigned to the marine unit.

The thickness of the marine sediments was not measured by direct observation; however, resistivity results indicate an average thickness of approximately 13 feet.

Results from the seismic-refraction work do not indicate any significant difference in velocity between the alluvium and the underlying marine unit. Layer 1 velocities (Table 4) averaged 1583 ft/s and the average depth was 16.0 feet. Measured depths to layer 2 of the seismic model were consistently greater than those derived by direct observation and resistivity sounding. The implication is that there is no measurable contrast in density or internal structure within the alluvium and marine sediments.

As noted in the well logs of Appendix A, several pottery shurds of pre-Latte time (H. Kurashina, personal communication) were found within the marine unit while augering hole 7 (see Figure 3 for location). From the known minimum age of the shurds, an upper age limit for the marine units can be inferred. This upper limit is about 1500-1800 years B.P.

Bedrock of the volcanic terrane probably underlies the marine unit and is situated at relatively shallow depths. Weathered tuffaceous sandstone typical of the Umatac formation (Tracey et al., 1964) is exposed at several localities along the stream bed as well as along the valley walls.

As indicated by seismic-refraction profiles the surface, and hence the depth of layer 2 assigned to the bedrock unit, is very irregular (see Appendix B). This rough topography may be related to an original subareal erosion surface which developed prior to submergence and subsequent burial by marine sediment; however, until further information from drill holes can be obtained this view is mostly speculation.

Both seismic-refraction data and resistivity results indicate that the bedrock unit may consist of two sections. The upper part with a thickness of about 40 feet is characterized by low resistivity (layer 4 of Table 4) and by an average seismic velocity of 4454 ft/s. The lower section, at a depth of about 60 to 66 feet, is characterized by relatively high resistivities (Table 5) and by an average velocity of 8690 ft/s (layer 3 of Table 4). Several interpretation scan be made; however, to be consistent with other field data, it is suggested that the contrast in measurements represents deeply weathered bedrock overlying a fresh counterpart. Lower values of bulk resistivity and velocity tend to indicate a zone composed of material of high clay content and relatively low density. Non-weathered bedrock is represented by the higher values.

Groundwater Occurrence and Water Quality

From the available subsurface information, fresh groundwater within the lower reaches of the Inarajan River valley appears to occur as a continuous body under unconfined hydraulic conditions. In general, recharge to the system is by direct rainfall and infiltration over the land surface. Two other sources of recharge are (1) the Inarajan River and (2) the seepage area along the southern boundary of the valley. Recharge from the river is no doubt intermittent and dependent on seasonal fluctuations in river stage. Thus, most of the recharge water from the stream would probably enter the groundwater-flow system during the first one third or one half of the wet season. With a decline in rainfall during the dry season, the river stage would drop and groundwater would be contributed to the river flow. The second recharge source mentioned is an area of seepage. On field examination of this area, it was observed that this region of the valley did not become dry during the drought. The seepage area is located at an elevation somewhat higher than the valley floor. Groundwater appears to be associated with a flow system not related to the valley-fill aquifer. Water rises to the surface, moves down slope a short distance, then sinks into the alluvial unit of the valley fill.

Figure 5 shows a generalized water-table map of the study area. The map was constructed from observation well water-level data obtained in June and depicts subsurface conditions near the end of the drought. The June water-table configuration indicates that groundwater flow was directed primarily toward Inarajan Bay; however, some flow appears to have been directed toward the river, probably induced by the low river stage due to extremely dry conditions. (The U.S.G.S. gaging station is no longer in use. Therefore, no river-stage data was available to the study).

The time-dependent response of the water table to rainfall (recharge) is shown in Figure 6 by the graph of water levels and rainfall (rainfall obtained from the Nimitz Hill weather station). In general, there is a direct correspondence between rainfall events and response of the water table. During periods of little or no rainfall, water-table elevations decline rather rapidly. Likewise, during periods of significant rainfall, the water table recovers relatively quickly. An example is the recovery of the water table following the rainfall events in mid July that marked the end of the drought.

Water levels in AH-4 seem to be anomalous to other measurements. While the water table was dropping in other observation wells, water levels were rising in AH-4. This apparent anomally is attributed to a broken surface pipe which allowed water to flow across the area in the vicinity of the observation well. The water table rose in response to the artificial recharge created by the pipe break. Once the pipe was repaired and the rains decreased, the water table position began to decline in concert with that in other observation wells. The response of the water table to artificial recharge further demonstrates the ability of the groundwater-flow system to quickly recover from periods of reduced recharge.

Of the chemical constituents determined in the water quality analysis only nitrate-nitrogen concentration exceeds the recommended upper limit of 10 mg/ℓ (Guam Environmental Protection Agency, 1981). All other parameters appear to be within recommended limits. The high value for nitrate is no doubt related to (1) animal wastes from grazing cattle and horses, or (2) chemical fertilizer applied to the fields, or both. It should be noted however, that nitrate concentrations in samples collected from observation well AH-4, located very near the river, contained acceptable levels and in general the groundwater is of better quality relative to that in the vicinity of AH-1. Additional sampling is needed before a full assessment can be made of the potability of the groundwater within the valley-fill aquifer.

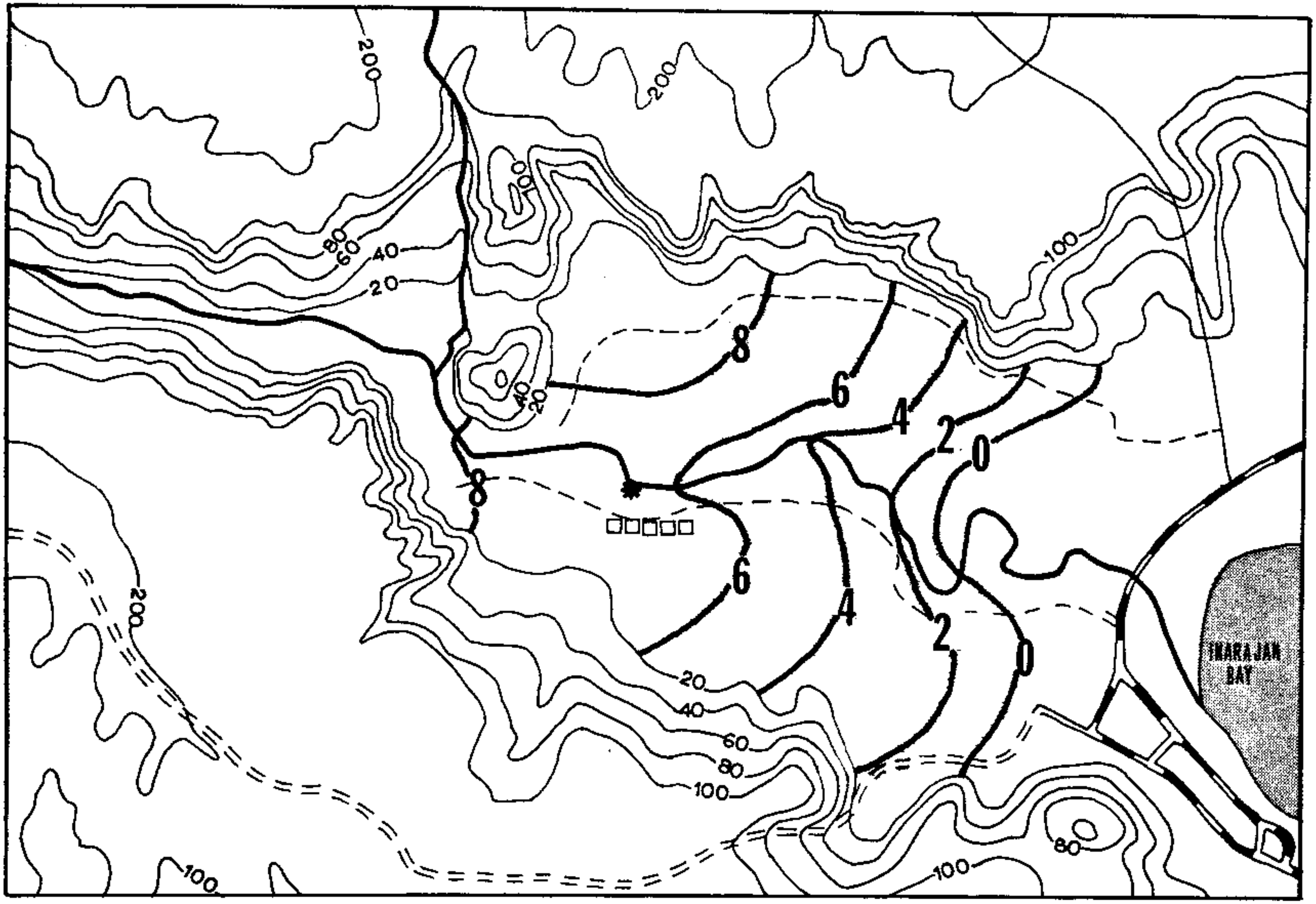

Figure 5. Generalized water-table map of the study area. Contour lines are relative to AH-2. Contour interval is 2.0 feet.

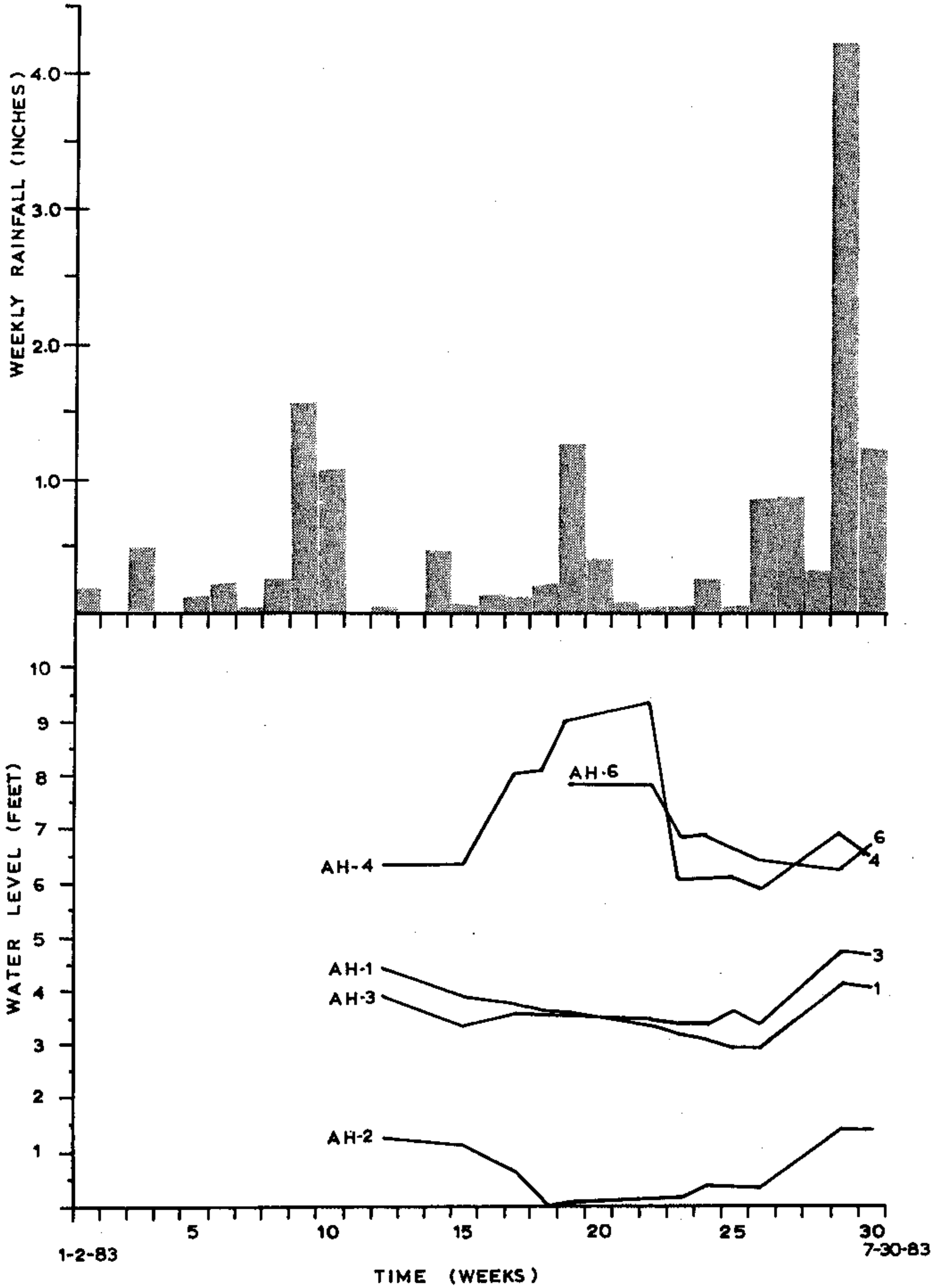

Figure 6. Comparison of rainfall and water-table fluctuations.

It should be noted that dissolved metal concentrations determined for the initial sample in AH-4 showed high values for copper, iron, manganese, and zinc but considerably lower concentrations in the sample collected after 30 minutes of pumping. These higher values are probably products of the interaction between borehole water and the surrounding sediments and do not reflect the true quality of the groundwater. However, these metals would be expected in water within a hydrogeologic environment composed of primarily volcanic-derived sediments.

One additional chemical constituent is worth noting. Chloride-ion concentrations in samples from the two observation wells differ by a significant amount. The relatively higher value found for AH-1 may indicate some degree of mixing between fresh groundwater and underlying seawater. Studies of the freshwater lens beneath northern Guam (Ayers, 1981) indicate that chloride-ion concentrations of about 70 mg/ℓ or less probably represent the non-mixed nucleus of the lens. Chloride is introduced to the lens flow system by infiltration of meteoric water in which the chloride-ion has been concentrated by evapotranspiration processes. If this logic can be extended to southern Guam then the higher value probably indicates mixing while the lower values represent the concentration products of evapotranspiration. If mixing is taking place in the vicinity of AH-1 then further work is needed to completely define the subsurface conditions in order to fully evaluate the prospects of development.

Potential for Groundwater Development

Groundwater development within the Inarajan River valley appears to be feasible on a limited-scale basis. Until further water quality work can be pursued, the extracted water should be used for agricultural purposes only.

Development could be initiated at two localities within the valley. Specifically, these localities are (1) the seepage area along the southern boundary and (2) near observation well AH-4. Other areas are probably suitable; however, additional field work is necessary before development proceeds past the initial stages discussed here.

Development of the seepage area would best be accomplished by installing an interception trench. This type of facility would be relatively simple to construct and would yield larger volumes of water compared to other extraction schemes. Installation procedures would consist of digging a trench a few feet deep and several feet long then placing a perforated pipe within the trench on an initial bed of coarse-grained sand; one end of the pipe is capped, the other leads to a lined sump or stand pipe. The remainder of the trench is filled with sand and back-filled with material originally removed. Once construction is completed, a pump is then placed such that the intake is below the water line in the sump (or in the stand pipe).

One advantage of this type of extraction facility is the length of the trench can be extended with little additional work and expense if an increase in yield is desired. Unlike wells, interception trenches do not normally induce widespread disruptions of the flow field and therefore, require less planning prior to installation. However, the facility described above is feasible only for shallow water-table depths.

The initial size of the trench should not exceed a length of about 30 feet and a depth of 2 to 3 feet below the static water level (about 4-5 feet below the ground surface at the Inarajan site). The width of the trench is not critical, however sufficient space should be allowed to accommodate a 4-6 inch pipe and sand pack. A sand cover over the pipe of about one foot should be adequate; the remainder of the trench can be back filled with other earth material. If a sump is used, it should be lined with an impermeable material. A stand pipe connected to the buried perforated collector would be the simplest and least expensive method.

With the specifications outlined above and observations at the site of installation, the yield of the interception trench may be relatively high, possibly in the range of 1500 to 3000 gal/day. However, it should be kept in mind that this is a very tentative estimate and that the extraction facility would be largely experimental.

Development of the resource in the vicinity of AH-4 can be accomplished by a different approach than the one for the seepage area. The hydraulic conductivity of the marine sediments appears to be great enough to warrant the use of well points. Like the trenching method, the installation and operation of well points is relatively inexpensive. Several well points driven into the ground to a depth of a few feet below the water table with a small pump attached would be an adequate development scheme.

If the measured hydraulic conductivity of AH-4 is representative of the aquifer material, the installation of say 4 well points could yield at least 3000 gal/day. With some minor additional field work, other sites could be located for well-point installation.

SUMMARY AND RECOMMENDATIONS

Summary

1. The study area is located in southern Guam and encompasses the lower reaches of the Inarajan River valley near the river outflow at Inarajan Bay.

2. The primary objective of the study was to evaluate the valley fill in terms of its potential as an aquifer.

3. Two water-bearing units appear to overlie a partially weathered volcanic basement. These units are composed of alluvium derived from the volcanic terrane and marine sediments deposited in a shallow-water protected embayment.

4. A hydraulic conductivity determination suggests a value of 16 ft/d for the marine unit, however, this is a very tentative estimate.

5. Although further work is needed, it appears feasible to develop the groundwater resource, at least initially on a limited scale. Two areas are sited as the best localities for development and the most appropriate type of extraction facilities are described.

Recommendations

The following recommendations are made based on the findings of this study.

1. Limited-scale development of groundwater is recommended for the two areas previously described; that is, the area of seepage along the southern boundary of the valley and in the vicinity of observation well AH-4.

2. The potential for groundwater development in the Inarajan valley warrants a more detailed study of the hydrogeologic environment and the subsurface hydraulic conditions.

3. The potential for future groundwater development in other river valleys in southern Guam should be investigated.

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APPENDIX A

Observation Well Logs

Log AH-1

Depth Interval	Symbol	Description
0-1.5		Top soil: dark brown
1.5-9.0		Alluvium: dark brown, deeply weathered sand in a clay matrix; well rounded to subrounded clasts; occasional pebble-size gravel of volcanic rocks.
9.0-12.0		Marine Sediments: Black; clay with abundant skeletal carbonate fragments including *Halimeda*, gastropod, and mollusk shells and shell fragments; numerous weathered sand- and pebble-size clasts of volcanic rock; well rounded.

Log AH-2

Depth Interval	Description
0.-0.5	Top soil: dark brown
0.5-4.0	Alluvium: dark brown; deeply weathered sand in a clay matrix; occasional weathered well-rounded pebble-size clasts of volcanic rock.
4.0-5.0	Alluvium: black to dark gray; plastic clay
5.0-9.0	Alluvium: dark brown; deeply weathered sand-size clasts to moderately weathered pebble-size clasts in a clay matrix; larger clasts are well rounded.
9.0-10.0	Mix Marine Sediments and Alluvium: black; sand- to pebble-size clasts in a clay matrix; clasts well rounded.
10.0-12.0	Marine Sediments: black; abundant carbonate skeletal fragments, sand to pebble-size clasts (volcanic) in a clay matrix; larger clasts less weathered and well rounded.

Log AH-3

Depth Interval	Symbol	Description
0-1.0		Top Soil: dark brown, very fine grained matrix (silt or clay).
1.0-3.5		Alluvium: dark yellowish brown, crumbly matrix with deeply weathered pebble-sized clasts of volcanic material. Volcanic clasts become less abundant and matrix becomes sticky (stiff) in texture near 3.5 feet depth.
3.5-5.5		Alluvium: dark yellowish brown, deeply weathered sand-sized clasts of probable volcanic origin in a stiff, plastic clay matrix.
5.5-10.0		Alluvium: dark grayish brown; deeply weathered medium to mostly fine-grained sand in a clay matrix. Carbonized wood and plant debris abundant. Sand grains probaly derived from the volcanic terrane.
10.0-12.0		Alluvium: mottled dark brown to very dark gray; weathered sand with minor pebble-sized clasts in a clay matrix; pebbles are well rounded; bedding apparent; minor carbonized plant debris. Minor amounts of shell fragments begin at 12.0 feet; larger volcanic clasts are angular to sub-rounded.
12.0-15.0		Mix Alluvium-Marine Sediments: medium brown to black; deeply weathered fine-grain sand in clay matrix with minor shell fragments (marine), carbonized plant debris abundant.

Log AH-4

Depth Interval	Symbol	Description
0-0.5		Top soil: dark brown
0.5-2.5		Alluvium: reddish brown, deeply weathered medium- to fine-grained sand probably derived from the volcanic terrane.
2.5-7.0		Alluvium: olive brown, dark yellowish brown to dark brown; very deeply weathered occasional pebble-size clasts in a clay matrix near the top. Original sandy texture becomes more apparent at 4 feet. Larger clasts become more abundant with depth; carbonized plant debris near bottom of section.
7.0-12.		Alluvium: dark brown to dark olive gray; deeply weathered sand and fine gravel in clay matrix; larger clasts are angular to sub-rounded. Larger clasts become more abundant with depth; abundant carbonized plant debris in lower part of the section.
12.0-Bo		Mix Marine Sediments and Alluvium: black, moderately weathered sand to fine gravel in a clay (soft) matrix; clasts well rounded; abundant shell fragments and other marine animal debris. Contains cerithed gastropods, shallow water spiraled gastropods, bivalves, soft coral spicules and foraminifera (*Marginopora*, *Baculogypsina*, *Calcarina*, *Homotrema*, and *Amphistegina*). Shell fragments show little wear, some non-articulated bivalves. Most volcanic derived clasts are subangular to well rounded. Abundant plant debris.

Log AH-5

Depth Interval	Symbol	Description
0-0.5		Top Soil: dark brown
0.5-4.0		Alluvium: dark yellowish brown to olive brown; deeply weathered sand and minor fine grained gravel (in zones) in a clay matrix.
4.0-5.0		abundant larger clasts; subrounded.
5.0-8.0		
8.0-9.0		abundant black very fine grained sand (magnetite?)
9.0-12.5		same material except the color is slightly reddish. Clasts are probably derived from the volcanic terrane.
12.5-15.0		Alluvium: very dark olive gray; deeply weathered sand-size clasts in a plastic clay matrix; abundant carbonized plant debris, becomes softer near bottom of hole.

Log AH-6

Depth Interval	Symbol	Description
0-0.5		Top soil: reddish brown
0.5-1.5		Alluvium: dark brown; deeply weathered medium to fine grained sand in a clay matrix. Clasts probably derived from the volcanic terrane.
1.5-4.5		Alluvium: olive brown; stiff, hard clay with deeply weathered pebble-size clasts (probably volcanic rock fragments).
4.5-10.5		Alluvium: light olive brown; deeply weathered sand in a clay matrix; occasional pebble-size clasts. Sediments derived from volcanic terrane.
10.5-15.0		Alluvium: dark olive gray to olive gray; clay with sand and fine-grained gravel clasts scattered through the matrix. Upper portion streaked with black clay laminae. Lower portion becomes darker and contains well-rounded pebble-size clasts of volcanic rock.
15.0-18.0		Marine Sediments: black, clay with abundant carbonate skeletal sand and minor sand- and pebble-size well-rounded clasts derived from the volcanic terrane; abundant organic debris.

Log AH-7

Depth Interval	Symbol	Description
0-0-.5		Top Soil: dark brown
0.5-2.5		Alluvium: dark grayish brown; deeply weathered sediments derived from the volcanic terrane; difficult distinguishing relic grains; abundant carbonized plant debris.
2.5-4.0		Alluvium: yellowiish brown; clay with occasional relic pebble-sized clasts; probably derived from the volcanic terrane.
4.0-6.0		Alluvium: yellowish brown gray and black streaks; clay with minor relic graines of sand and pebble-size gravel; dark gray to black laminae of clay, more abundant toward lower part of unit.
6.0-8.5		Alluvium: black; sticky clay with occasional deeply weathered pebble-size gravel; clasts are well rounded. Pre-Latte pottery sherds found at about 6-7 feet.
8.5-Bot		Marine Sediments: grayish brown to gray; primarily medium grained skeletal carbonate sand in a matrix of dark brown to black clay; grains are subrounded to well rounded.

Log AH-8

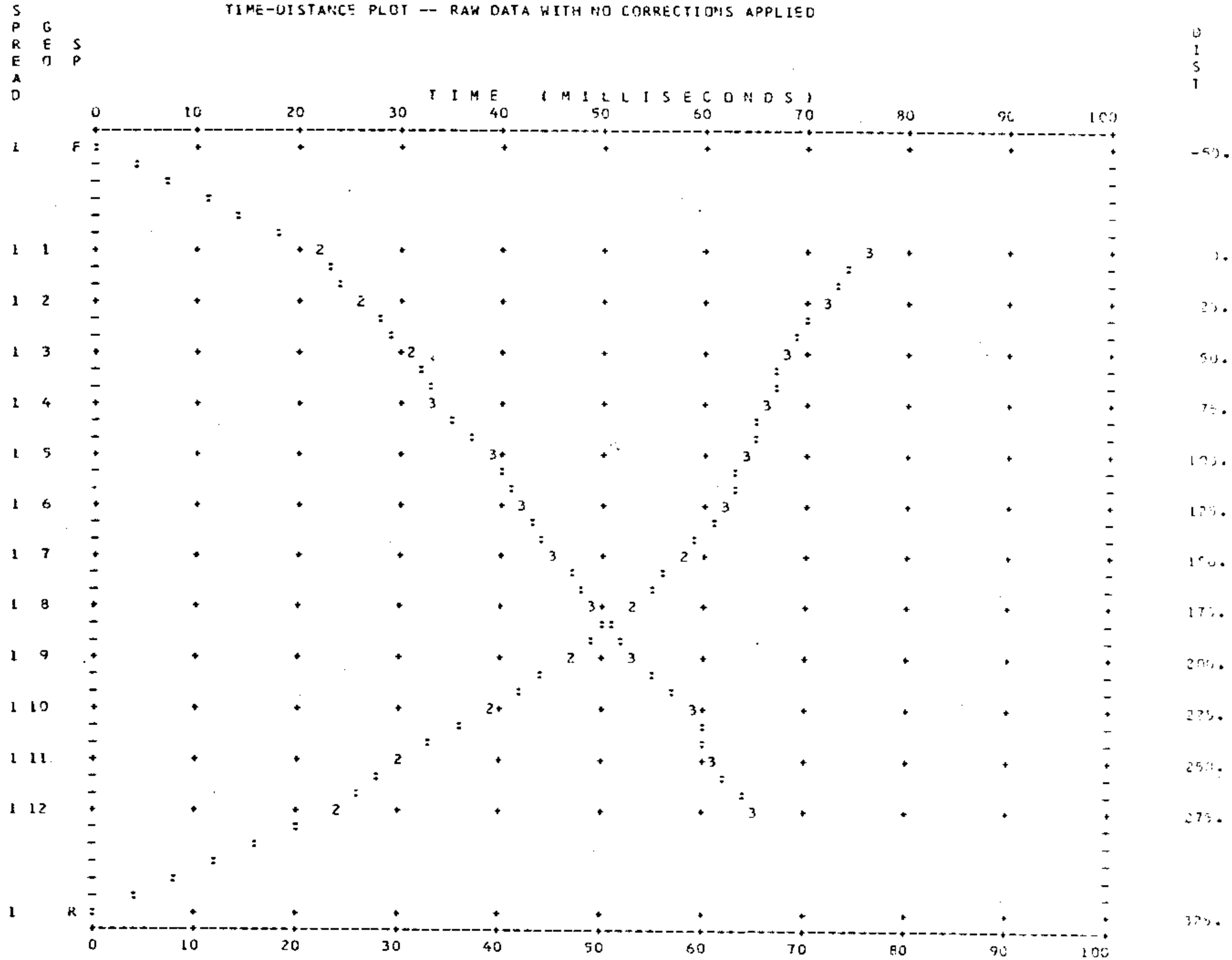
Depth Interval	Symbol	Description
0-0.5		Top Soil: dark brown
0.5-5.5		Alluvium: yellowish brown; clay with deeply weathered fine-grained sand. Clasts become more abundant and apparent in lower portion of section.
5.5-10.0		Alluvium: mottled light yellowish brown to dark bronw, clay matrix with scattered sand-size clasts (lighter color) and gray streaks; clasts deeply weathered and not well defined; carbonized plant debris; occasional pebble-size clasts.
10.0-11.5		Alluvium: (?) black; very fine-grained matrix with sand-size and small pebble-size clasts of volcanic rock. Material has oxidized to very dark brown; some clasts to a light yellowish bronw. Sediment may have been in a reducing marine environment prior to burial by alluvial deposits.

APPENDIX B

Geophysical Survey Results

INARAJAN PROJECT--SEISMIC REFRACTION LINE INJ-1.

TIME-DISTANCE PLOT -- RAW DATA WITH NO CORRECTIONS APPLIED

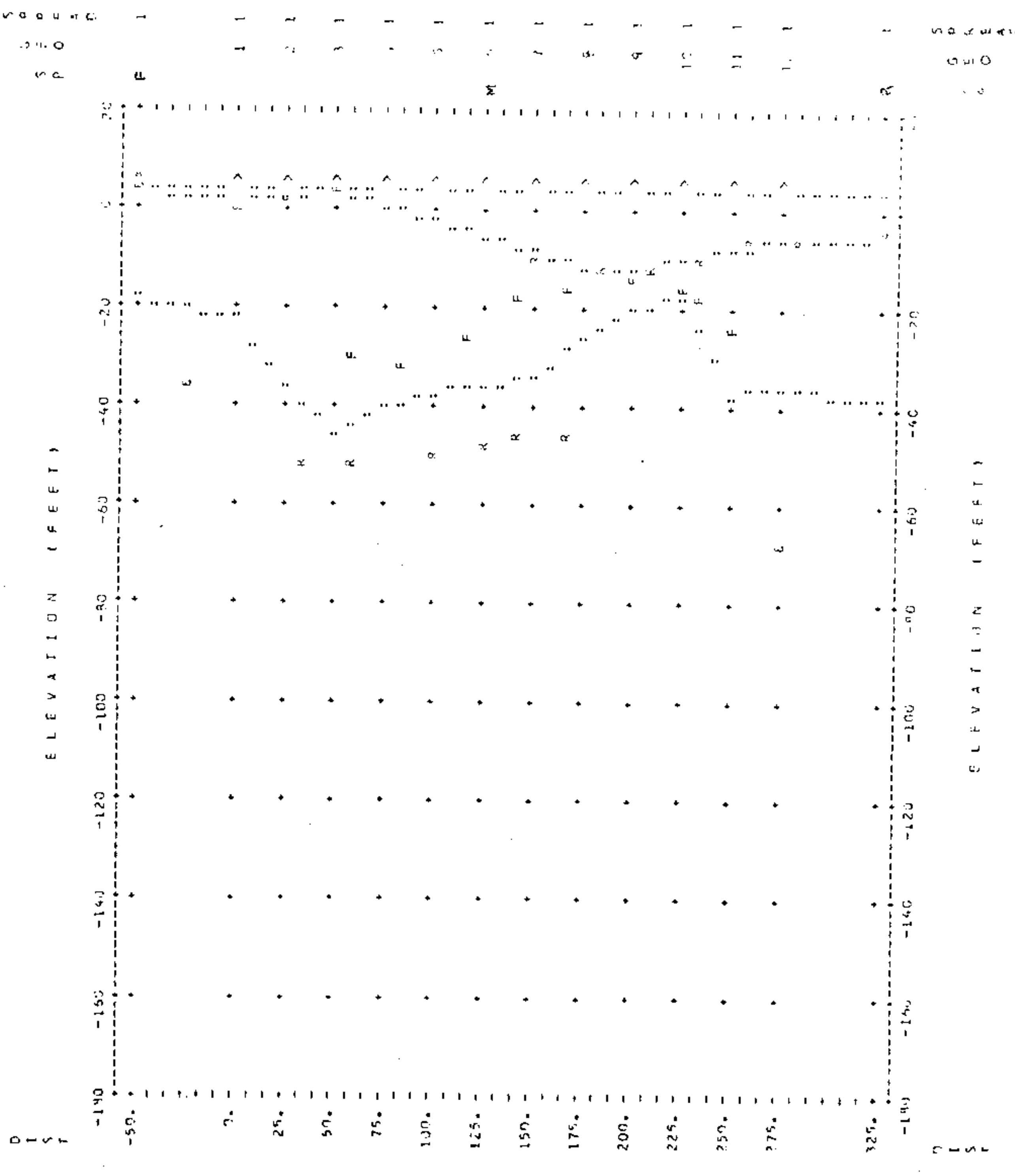


INARAJAN PROJECT - SEISMIC REFRACTION LINE INJ-1

Spread 1 Smoothed Position of Layers Beneath Shotpoints and Geophones

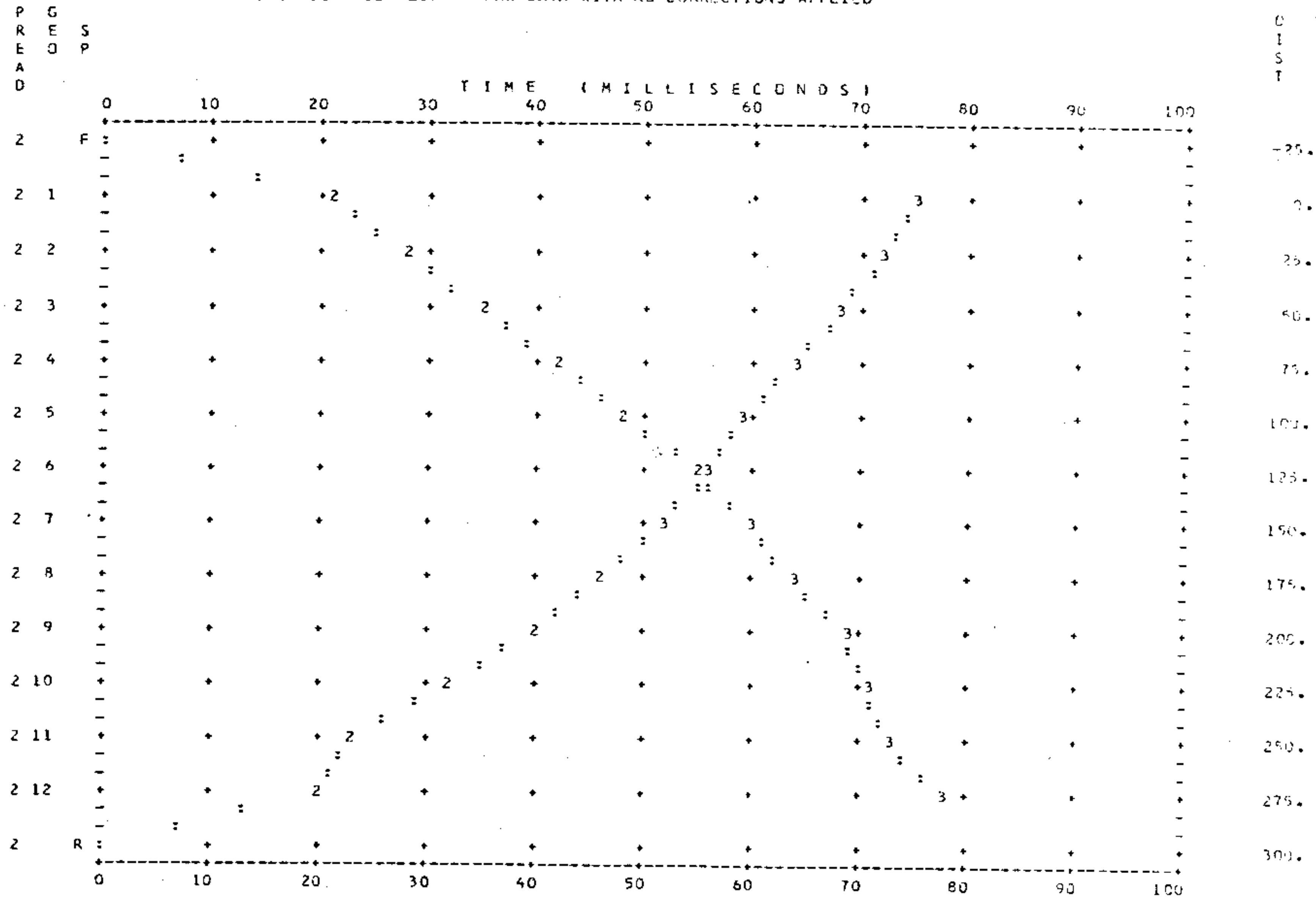
SP	Position	Surf Elev	Layer 2 Depth	Layer 2 Elev	Layer 3 Depth	Layer 3 Elev
GEO						
1	0.0	4.6	3.9	0.7	27.2	-22.6
2	25.0	4.3	1.6	2.7	40.9	-36.6
3	50.0	4.0	0.5	3.5	49.6	-45.6
4	75.0	3.6	3.2	0.4	44.3	-40.7
5	100.0	3.6	6.2	-2.6	40.9	-37.3
6	125.0	3.6	9.3	-5.7	39.7	-36.1
7	150.0	3.6	12.3	-8.7	37.9	-34.3
8	175.0	3.6	14.7	-11.1	29.7	-26.1
9	200.0	3.6	15.2	-11.6	23.8	-20.2
10	225.0	3.6	13.7	-10.1	21.7	-18.1
11	250.0	3.6	11.0	-7.4	40.9	-37.3
12	275.0	3.6	9.9	-6.3	39.5	-35.9
AVERAGE			8.5		36.3	

INARAJAN PROJECT--SEISMIC REFRACTION LINE INJ-1.



INARAJAN PROJECT--SEISMIC REFRACTION LINE INJ-2.

TIME-DISTANCE PLOT -- RAW DATA WITH NO CORRECTIONS APPLIED

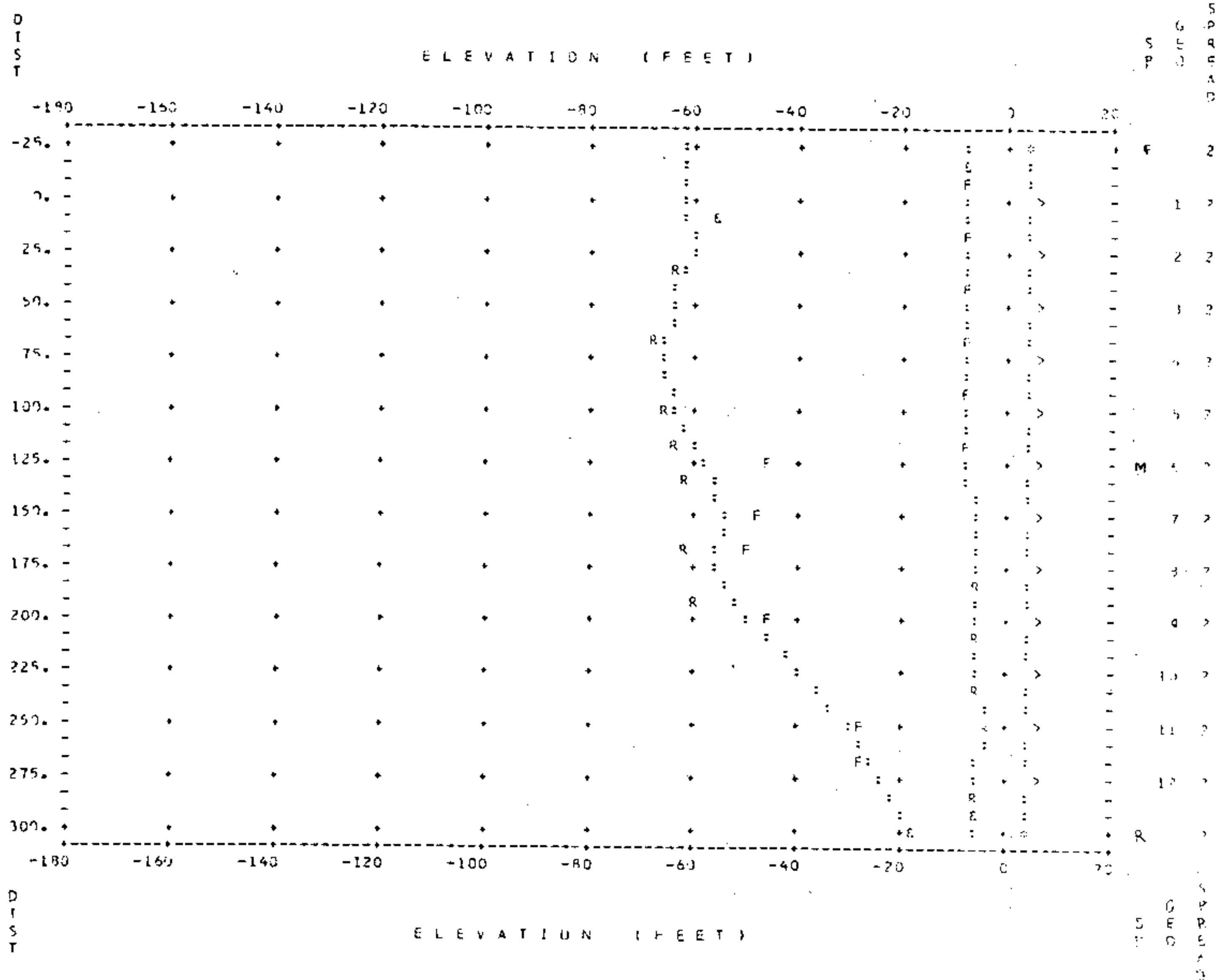


INARAJAN PROJECT - SEISMIC REFRACTION LINE INJ-2

Spread 2 Smoothed Position of Layers Beneath Shotpoints and Geophones

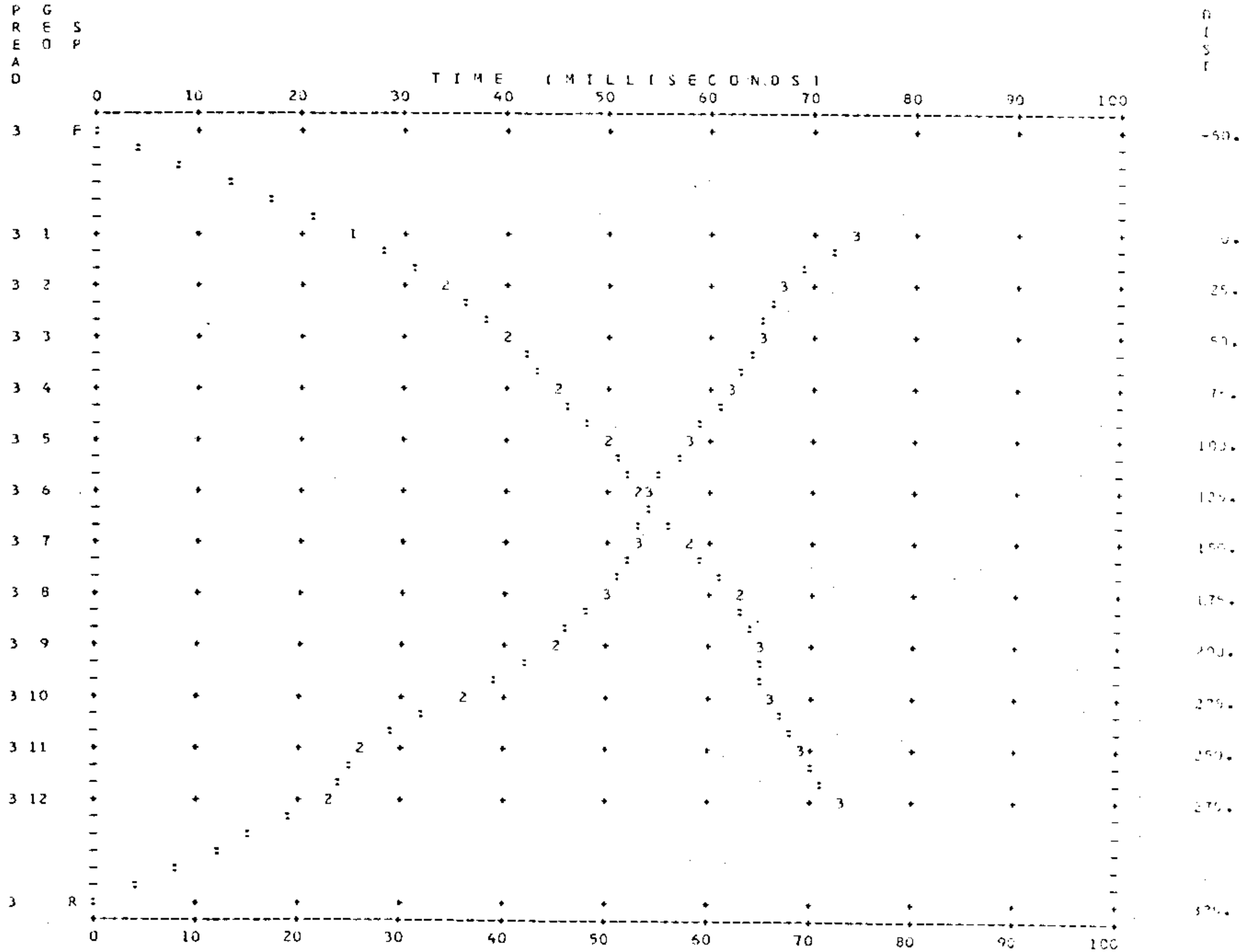
SP	Position	Surf Elev	Layer 2 Depth	Layer 2 Elev	Layer 3 Depth	Layer 3 Elev
GEO						
1	0.0	3.6	18.4	-14.8	56.3	-52.7
2	25.0	3.6	19.3	-15.7	62.6	-59.0
3	50.0	3.6	20.6	-17.0	66.6	-63.0
4	75.0	3.6	21.7	-18.1	69.2	-65.6
5	100.0	3.6	21.9	-18.3	67.4	-63.8
6	125.0	3.6	22.1	-18.5	66.9	-63.3
7	150.0	3.6	21.5	-17.9	67.2	-63.6
8	175.0	3.6	20.9	-17.3	67.0	-63.4
9	200.0	3.6	20.2	-16.6	66.4	-62.8
10	225.0	3.6	18.1	-14.5	63.9	-60.3
11	250.0	3.6	15.1	-11.5	60.1	-56.5
12	275.0	3.6	12.7	-9.1	56.2	-52.6
AVERAGE			19.4		64.2	

INARAJAN PROJECT--SEISMIC REFRACTION LINE INJ-2.



INARAJAN PROJECT--SEISMIC REFRACTION LINE INJ-3.

TIME-DISTANCE PLOT -- RAW DATA WITH NO CORRECTIONS APPLIED

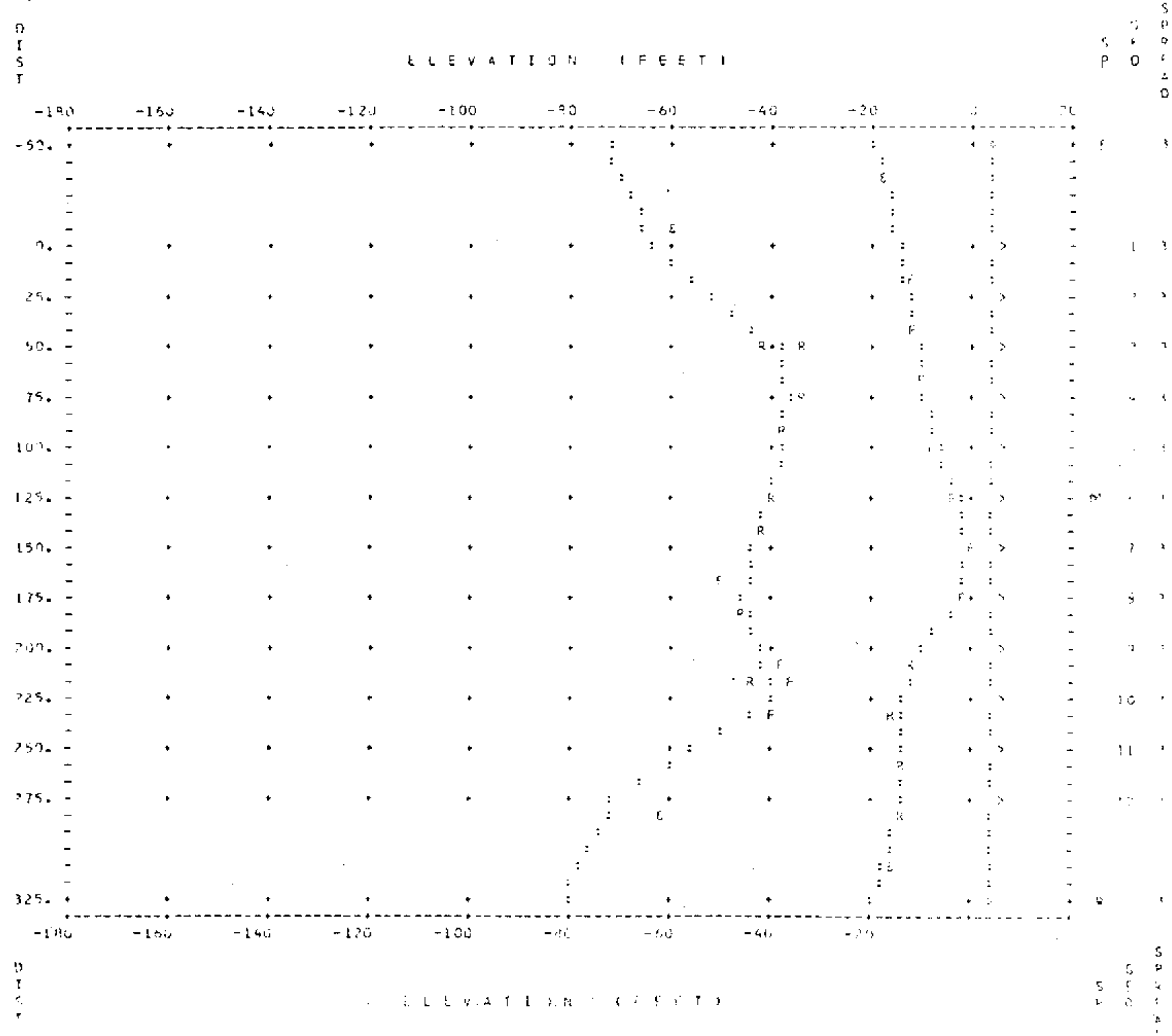


INARAJAN PROJECT - SEISMIC REFRACTION LINE INJ-3

Spread 3   Smoothed Position of Layers Beneath Shotpoints and Geophones

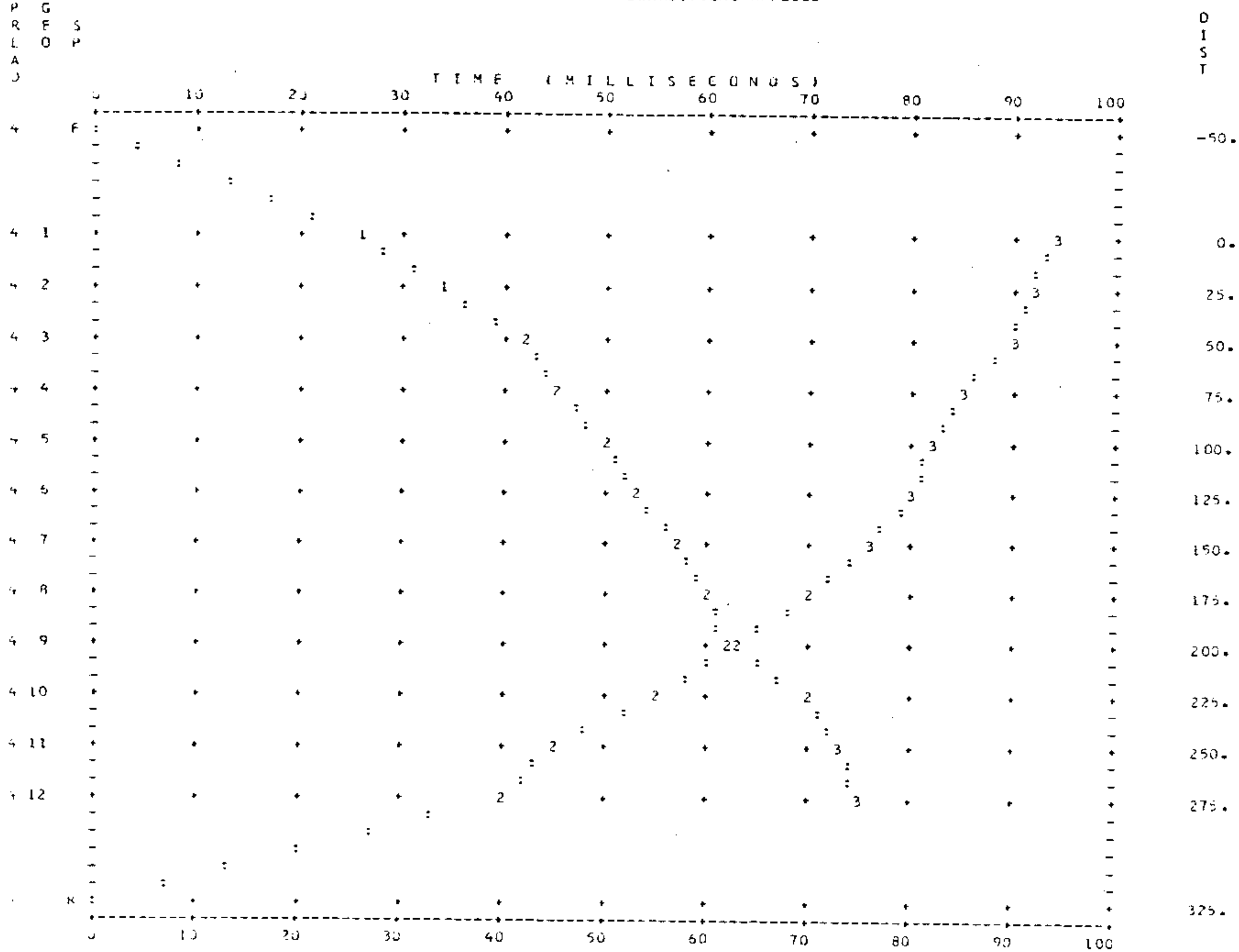
SP	Position	Surf Elev	Layer 2 Depth	Layer 2 Elev	Layer 3 Depth	Layer 3 Elev
GEO						
1	250.0	3.6	15.1	-11.5	60.1	-56.5
2	275.0	3.6	12.7	-9.1	56.2	-52.6
3	300.0	3.6	10.2	-6.6	55.1	-51.5
4	325.0	3.6	6.7	-3.1	58.3	-54.7
5	350.0	3.6	3.6	-0.0	61.1	-57.5
6	375.0	3.6	4.2	-0.6	63.2	-59.6
7	400.0	3.6	7.5	-3.9	60.0	-56.4
8	425.0	3.6	10.9	-7.3	53.1	-49.5
9	450.0	3.6	14.4	-10.8	47.2	-43.6
10	475.0	3.6	15.1	-11.5	42.1	-38.5
11	500.0	3.6	13.5	-9.9	33.6	-30.0
12	525.0	3.6	13.2	-9.6	27.7	-24.1
AVERAGE			10.6		51.5	

INARAJAN PROJECT--SEISMIC REFRACTION LINE INJ-3.



INARAJAN PROJECT--SEISMIC REFRACTION LINE INJ-4.

TIME-DISTANCE PLOT -- RAW DATA WITH NO CORRECTIONS APPLIED

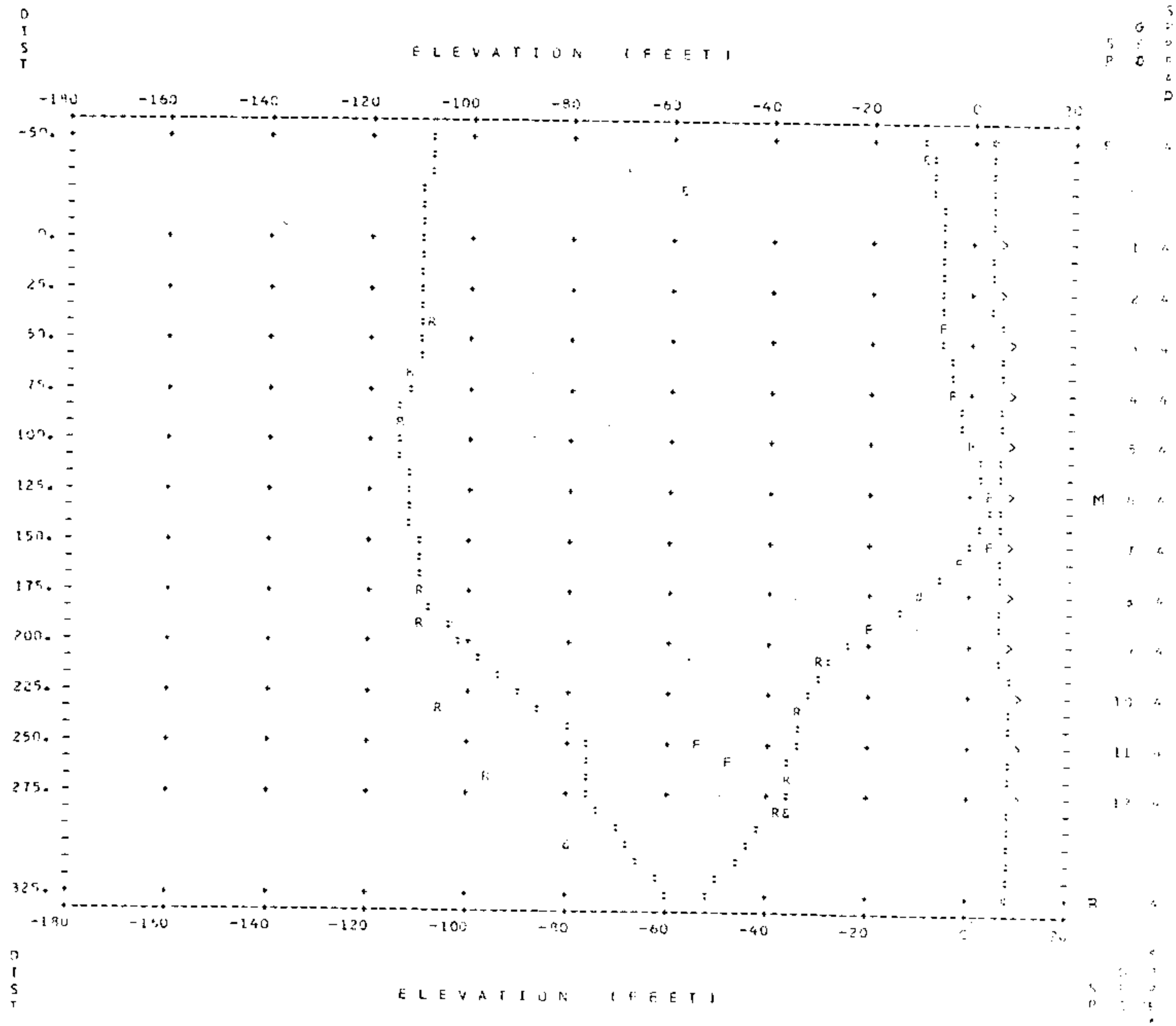


INARAJAN PROJECT - SEISMIC REFRACTION LINE INJ-4

Spread 4 Smoothed Position of Layers Beneath Shotpoints and Geophones

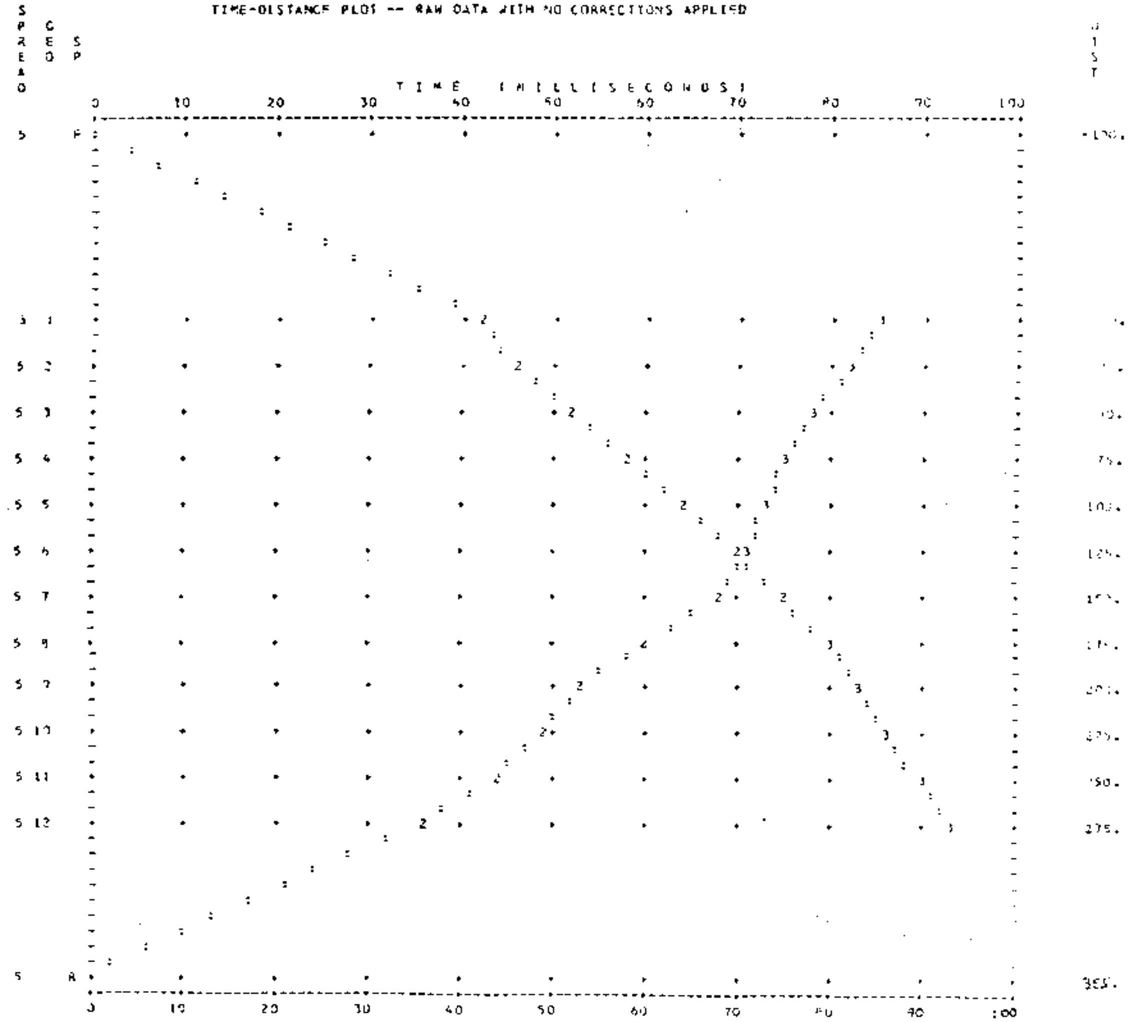
SP	Position	Surf Elev	Layer 2 Depth	Layer 2 Elev	Layer 3 Depth	Layer 3 Elev
GEO						
1	0.0	4.5	10.0	-5.5	114.3	-109.8
2	25.0	4.8	10.4	-5.6	114.4	-109.6
3	50.0	5.2	10.9	-5.7	114.6	-109.4
4	75.0	5.7	8.6	-3.2	118.3	-112.9
5	100.0	6.0	5.8	-0.1	119.2	-113.5
6	125.0	6.3	1.8	4.2	118.2	-112.2
7	150.0	6.6	5.5	0.8	117.2	-110.9
8	175.0	6.9	16.3	-9.7	116.1	-109.5
9	200.0	7.1	31.2	-24.3	109.5	-102.6
10	225.0	7.4	39.7	-32.6	96.3	-89.2
11	250.0	7.7	41.9	-34.5	84.1	-76.7
12	275.0	3.6	44.1	-36.4	83.8	-76.1
AVERAGE			18.8		108.8	

INARAJAN PROJECT--SEISMIC REFRACTION LINE INJ-4.



INAMAJAN PROJECT--SEISMIC REFRACTION LINE INJ-5.

TIME-DISTANCE PLOT -- RAW DATA WITH NO CORRECTIONS APPLIED

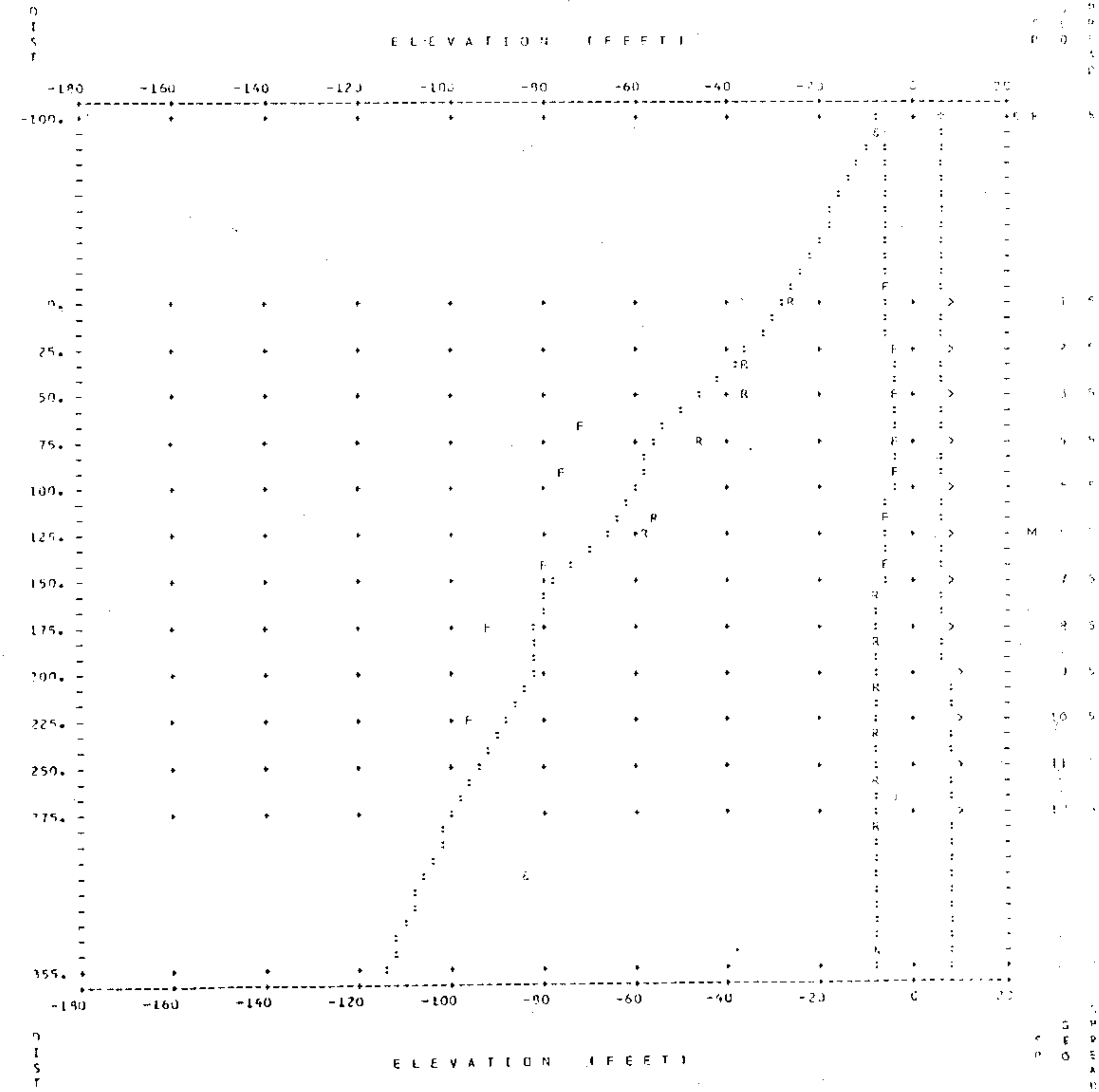


INARAJAN PROJECT - SEISMIC REFRACTION LINE INJ-5

Spread 5 Smoothed Position of Layers Beneath Shotpoints and Geophones

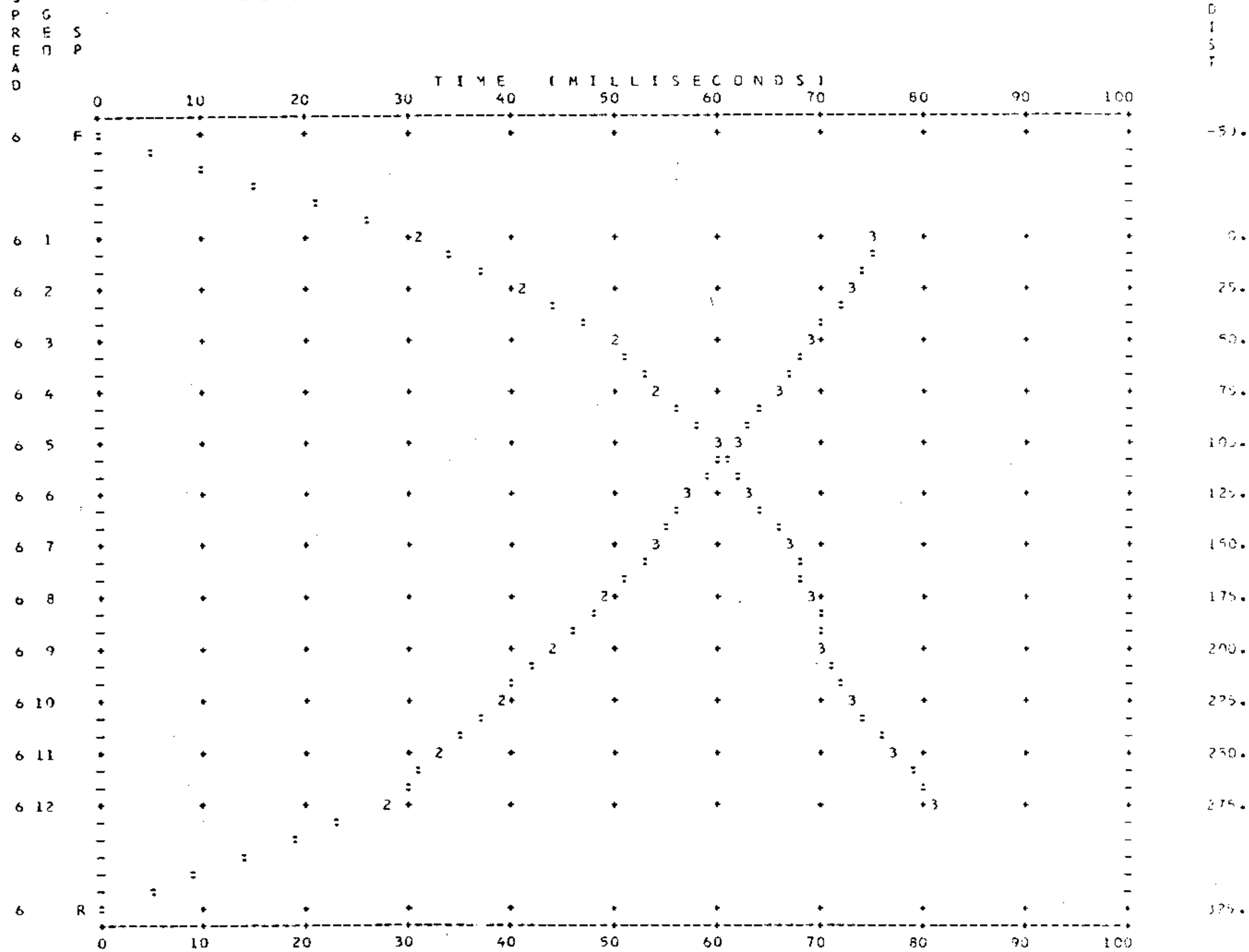
SP	Position	Surf Elev	Layer 2 Depth	Layer 2 Elev	Layer 3 Depth	Layer 3 Elev
GEO						
1	0.0	6.0	12.6	-6.6	33.1	-27.1
2	25.0	6.0	10.9	-4.9	41.0	-35.0
3	50.0	6.0	10.5	-4.5	52.9	-46.9
4	75.0	6.0	10.6	-4.6	62.3	-56.3
5	100.0	6.5	11.4	-4.9	66.8	-60.3
6	125.0	6.5	12.1	-5.6	72.9	-66.4
7	150.0	6.5	13.4	-6.9	84.8	-78.3
8	175.0	6.5	14.0	-7.5	87.8	-81.3
9	200.0	7.0	14.6	-7.6	89.3	-82.3
10	225.0	7.0	15.3	-8.3	95.1	-88.1
11	250.0	7.5	16.0	-8.5	101.5	-94.0
12	275.0	7.5	15.2	-7.7	107.4	-99.9
AVERAGE			13.0		74.6	

INARAJAN PROJECT--SEISMIC REFRACTION LINE INJ-5.



INARAJAN PROJECT—SEISMIC REFRACTION LINE INJ-6.

TIME-DISTANCE PLOT -- RAW DATA WITH NO CORRECTIONS APPLIED

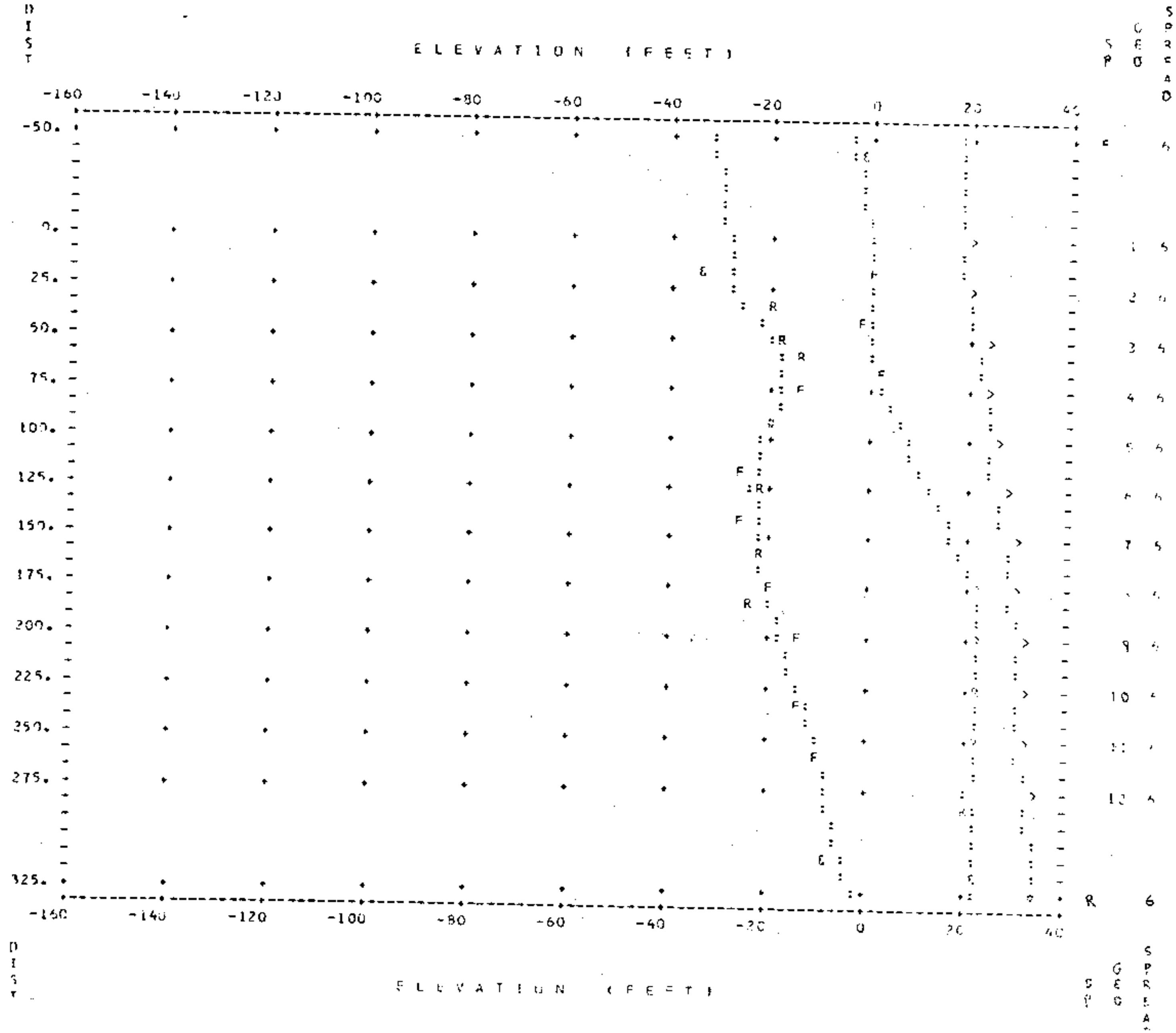


INARAJAN PROJECT - SEISMIC REFRACTION LINE INJ-6

Spread 6 Smoothed Position of Layers Beneath Shotpoints and Geophones

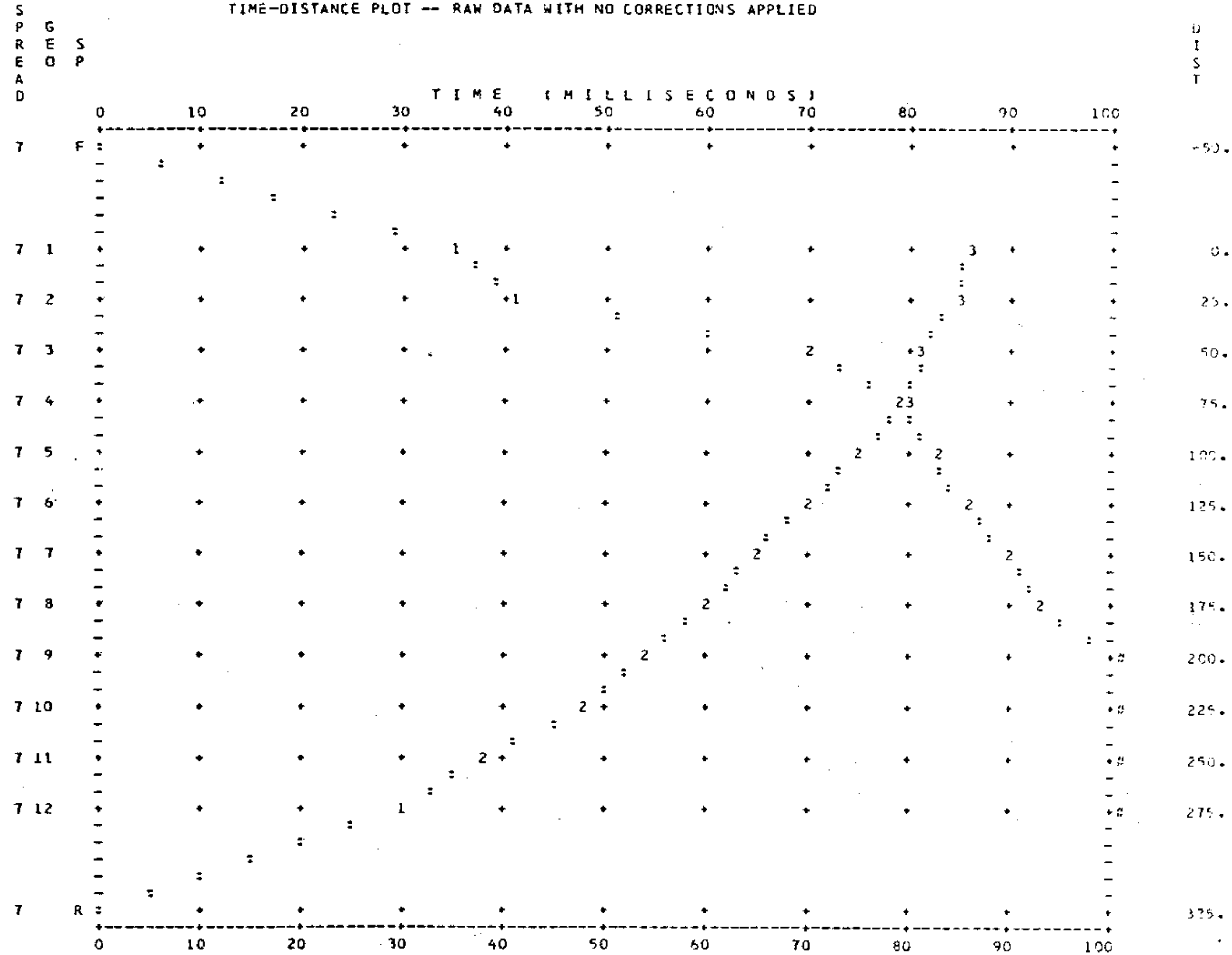
SP	Position	Surf Elev	Layer 2 Depth	Layer 2 Elev	Layer 3 Depth	Layer 3 Elev
GEO						
1	250.0	17.5	22.5	-5.0	86.4	-68.9
2	275.0	18.8	24.9	-6.1	80.4	-61.6
3	300.0	21.3	28.4	-7.1	72.3	-51.0
4	325.0	22.8	26.6	-3.8	63.3	-40.5
5						
6	375.0	25.1	19.9	5.2	59.4	-34.3
7	400.0	27.4	17.7	9.7	62.6	-35.2
8	425.0	28.7	14.5	14.2	63.6	-34.9
9	450.0	29.3	12.6	16.7	61.0	-31.7
10	475.0	30.0	12.4	17.6	58.1	-28.1
11	500.0	30.3	12.1	18.2	55.3	-25.0
12	525.0	31.8	12.7	19.1	54.8	-23.0
AVERAGE			17.0		59.8	

INARAJAN PROJECT--SEISMIC REFRACTION LINE INJ-6.



INARAJAN PROJECT--SEISMIC REFRACTION LINE INJ-7.

TIME-DISTANCE PLOT -- RAW DATA WITH NO CORRECTIONS APPLIED

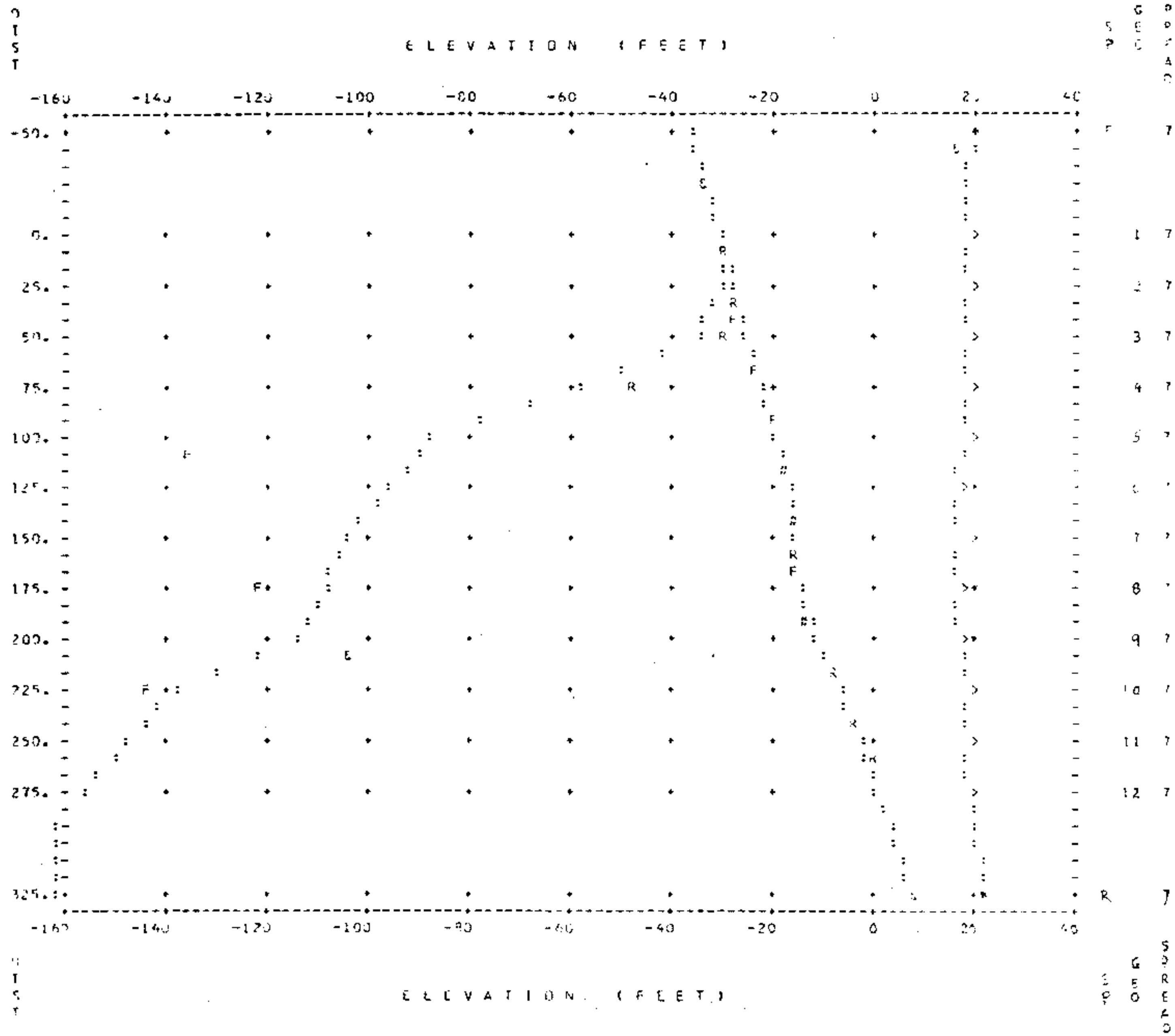


INARAJAN PROJECT - SEISMIC REFRACTION LINE INJ-7

Spread 7 Smoothed Position of Layers Beneath Shotpoints and Geophones

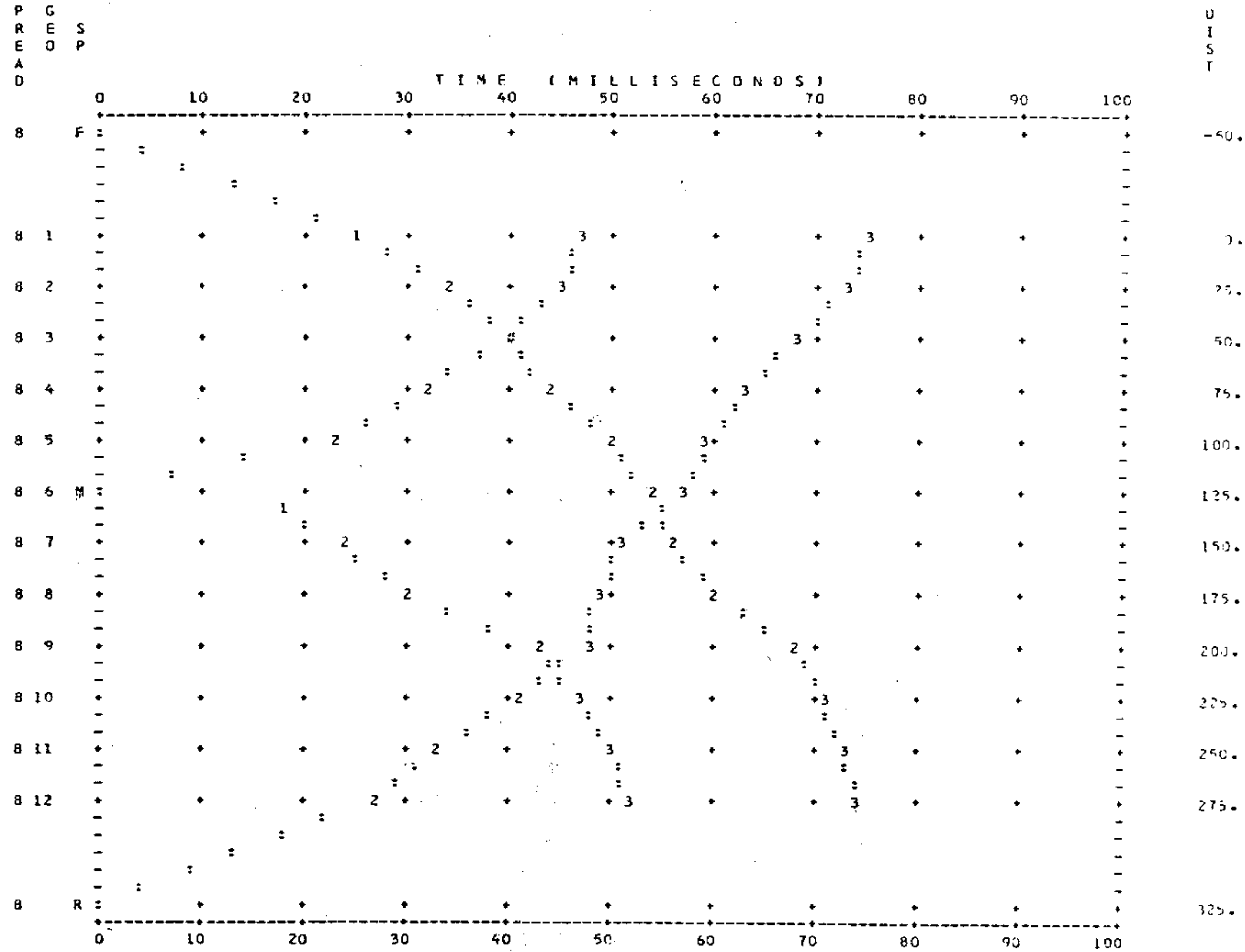
SP	Position	Surf Elev	Layer 2 Depth	Layer 2 Elev	Layer 3 Depth	Layer 3 Elev
GEO						
1	0.0	18.0	44.3	-26.3	73.3	-55.3
2	25.0	17.6	41.6	-24.0	51.7	-34.1
3	50.0	17.2	39.0	-21.8	48.8	-31.6
4	75.0	17.1	36.2	-19.1	63.3	-46.2
5	100.0	17.2	33.3	-16.1	85.2	-68.0
6	125.0	16.7	30.2	-13.5	106.3	-89.6
7						
8	175.0	16.8	27.6	-10.8	100.6	-83.8
9	200.0	16.8	25.6	-3.8	95.6	-78.8
10	225.0	17.8	24.2	-6.4	91.7	-73.9
11	250.0	17.5	22.6	-5.1	86.4	-68.9
12	275.0	18.8	24.9	-6.1	80.4	-61.6
AVERAGE			29.1		73.6	

INARAJAN PROJECT--SEISMIC REFRACTION LINE INJ-7.



INARAJAN PROJECT--SEISMIC REFRACTION LINE INJ-8.

TIME-DISTANCE PLOT — RAW DATA WITH NO CORRECTIONS APPLIED

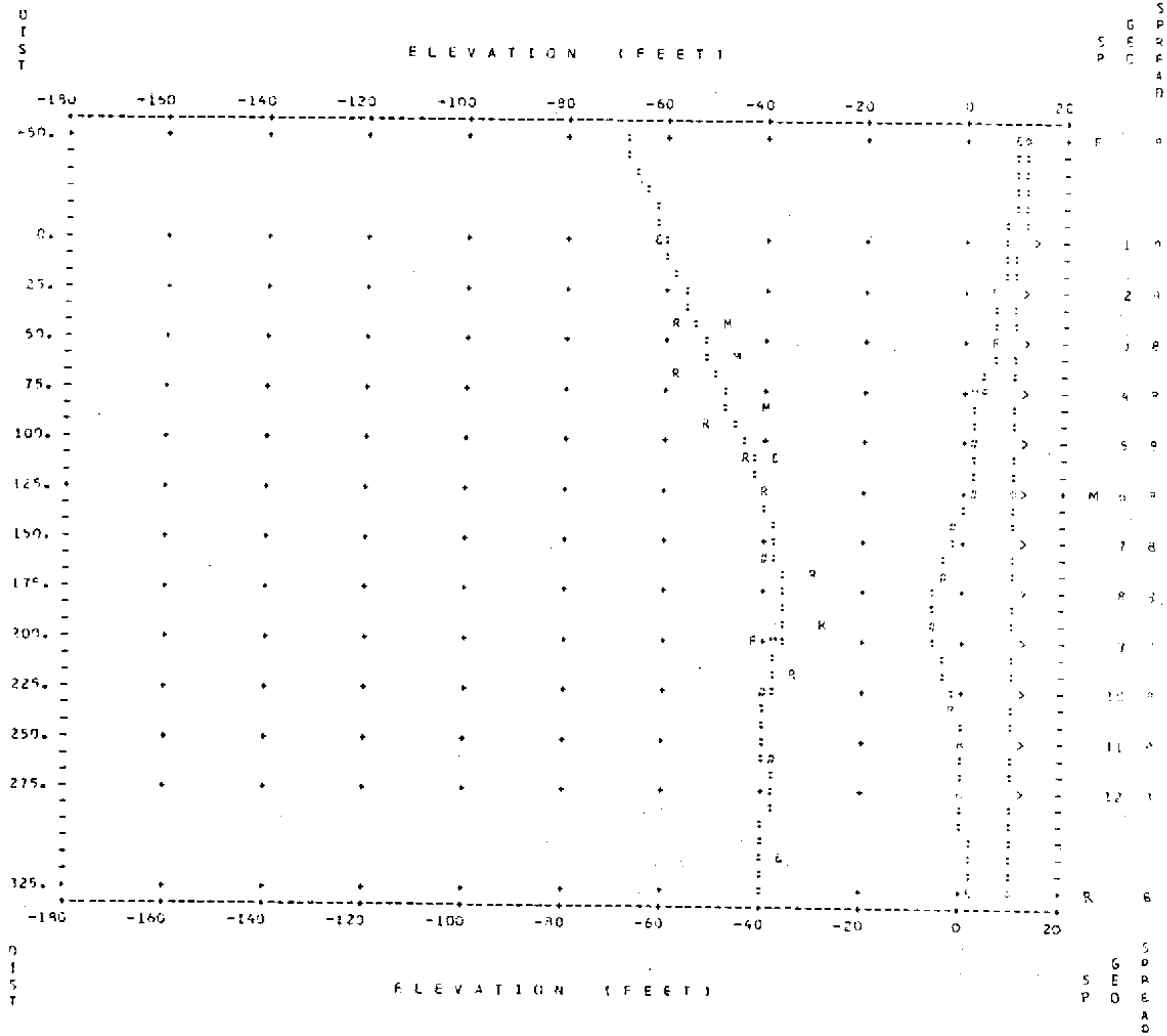


INARAJAN PROJECT - SEISMIC REFRACTION LINE INJ-8

Spread 8 Smoothed Position of Layers Beneath Shotpoints and Geophones

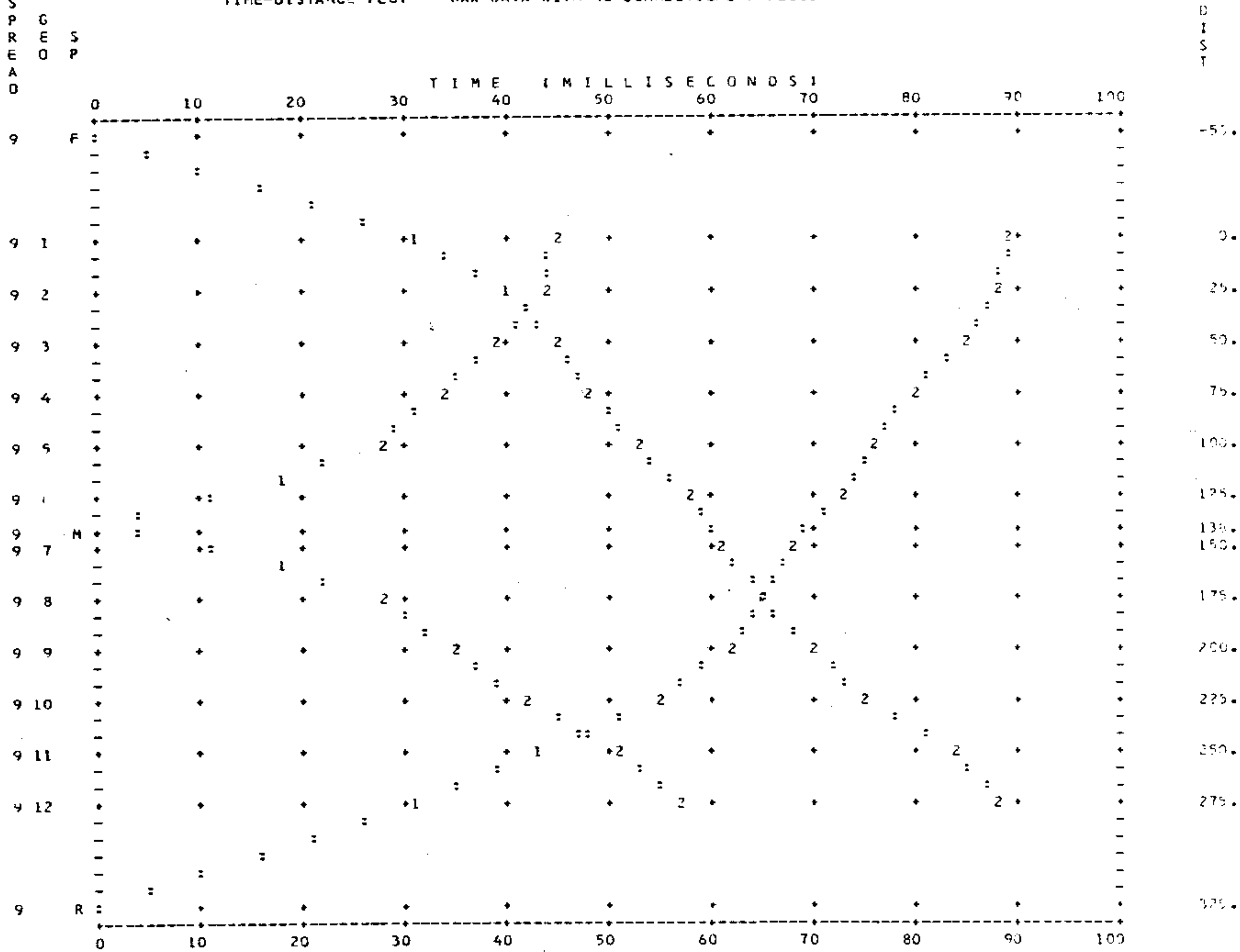
SP	Position	Surf Elev	Layer 2 Depth	Layer 2 Elev	Layer 3 Depth	Layer 3 Elev
GEO						
1	0.0	11.0	2.7	8.3	71.3	-60.3
2	25.0	10.8	4.2	6.6	67.3	-56.5
3	50.0	10.6	3.8	6.8	63.3	-52.7
4	75.0	10.4	7.4	3.0	59.2	-48.8
5	100.0	10.2	7.7	2.5	53.9	-43.7
6	125.0	10.0	8.4	1.6	50.5	-40.5
7	150.0	9.8	12.3	-2.5	47.8	-38.0
8	175.0	9.8	14.8	-5.0	45.6	-35.8
9	200.0	9.6	14.7	-5.1	46.2	-36.6
10	225.0	9.6	11.8	-2.2	48.5	-38.9
11	250.0	9.6	9.9	-0.3	48.9	-39.3
12	275.0	9.6	9.4	0.2	48.3	-38.7
AVERAGE			8.9		54.2	

INARAJAN PROJECT--SEISMIC REFRACTION LINE INJ-9.



INARAJAN PROJECT--SEISMIC REFREACTION LINE INJ-9.

TIME-DISTANCE PLOT -- RAW DATA WITH NO CORRECTIONS APPLIED

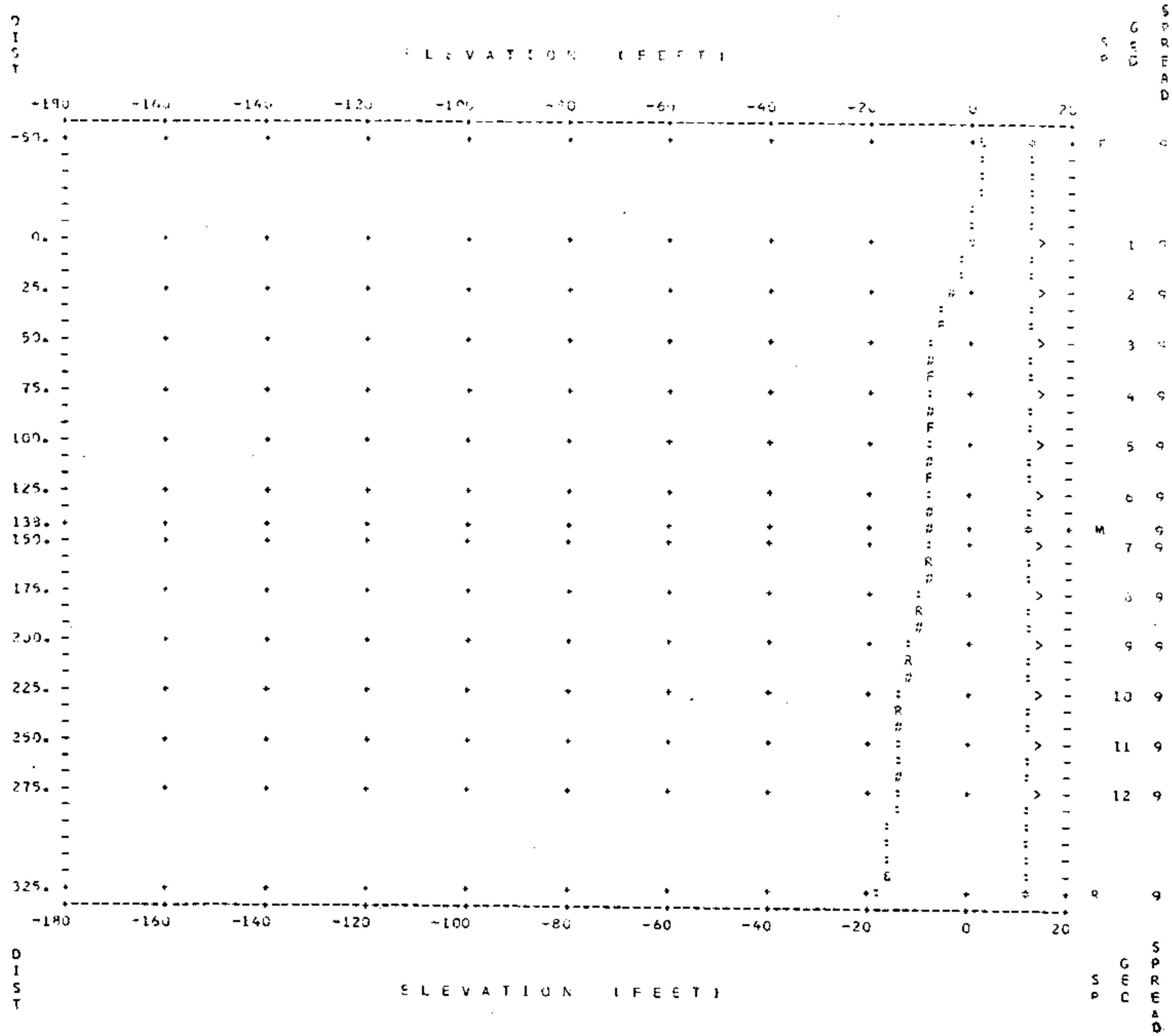


INARAJAN PROJECT - SEISMIC REFRACTION LINE INJ-9

Spread 9 Smoothed Position of Layers Beneath Shotpoints and Geophones

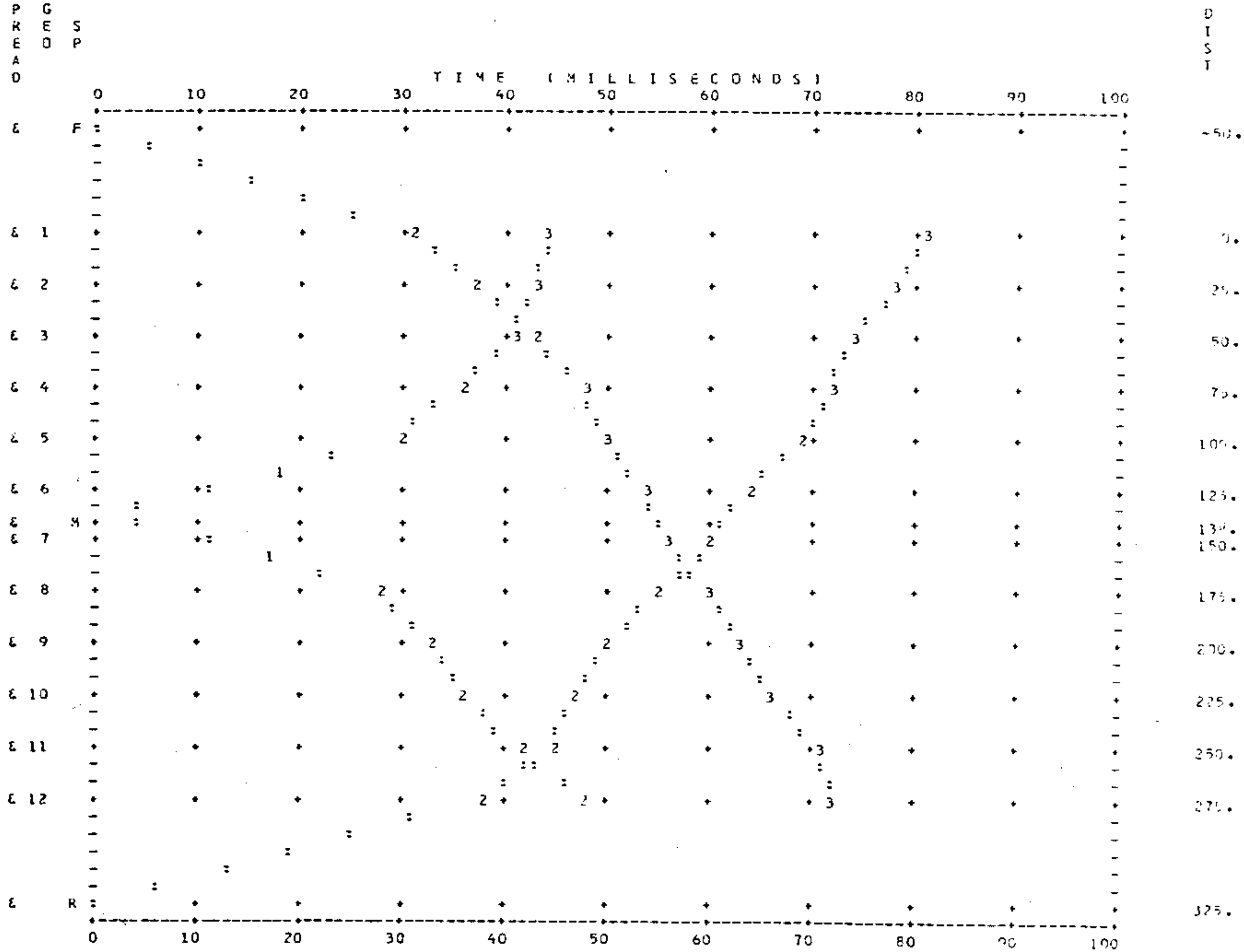
SP	Position	Surf Elev	Layer 2 Depth	Layer 2 Elev
GEO				
1	0.0	11.0	11.3	-0.3
2	25.0	11.0	15.3	-4.3
3	50.0	11.0	18.1	-7.1
4	75.0	11.0	18.2	-7.2
5	100.0	11.0	18.2	-7.2
6	125.0	11.0	18.7	-7.7
7	150.0	11.0	18.7	-7.7
8	175.0	11.0	20.1	-9.1
9	200.0	11.0	22.1	-11.1
10	225.0	11.0	24.4	-13.4
11	250.0	11.0	25.6	-14.6
12	275.0	11.0	25.4	-14.4
AVERAGE			19.7	

INARAJAN PROJECT--SEISMIC REFRACTION LINE INJ-9.



INARAJAN PROJECT--SEISMIC REFRACTION LINE INJ-10.

TIME-DISTANCE PLOT -- RAW DATA WITH NO CORRECTIONS APPLIED

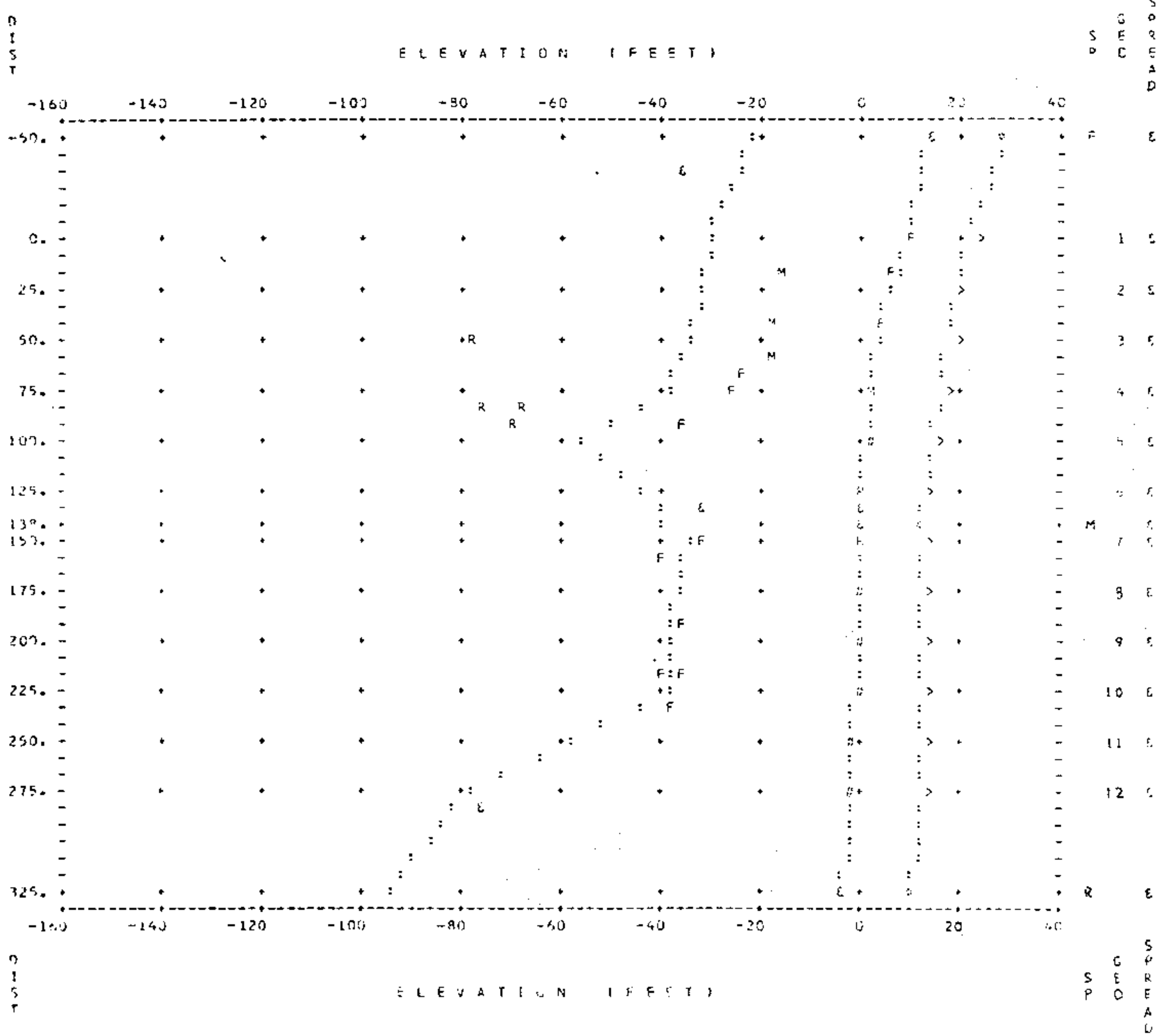


INARAJAN PROJECT - SEISMIC REFRACTION LINE INJ-10

Spread 10 Smoothed Position of Layers Beneath Shotpoints and Geophones

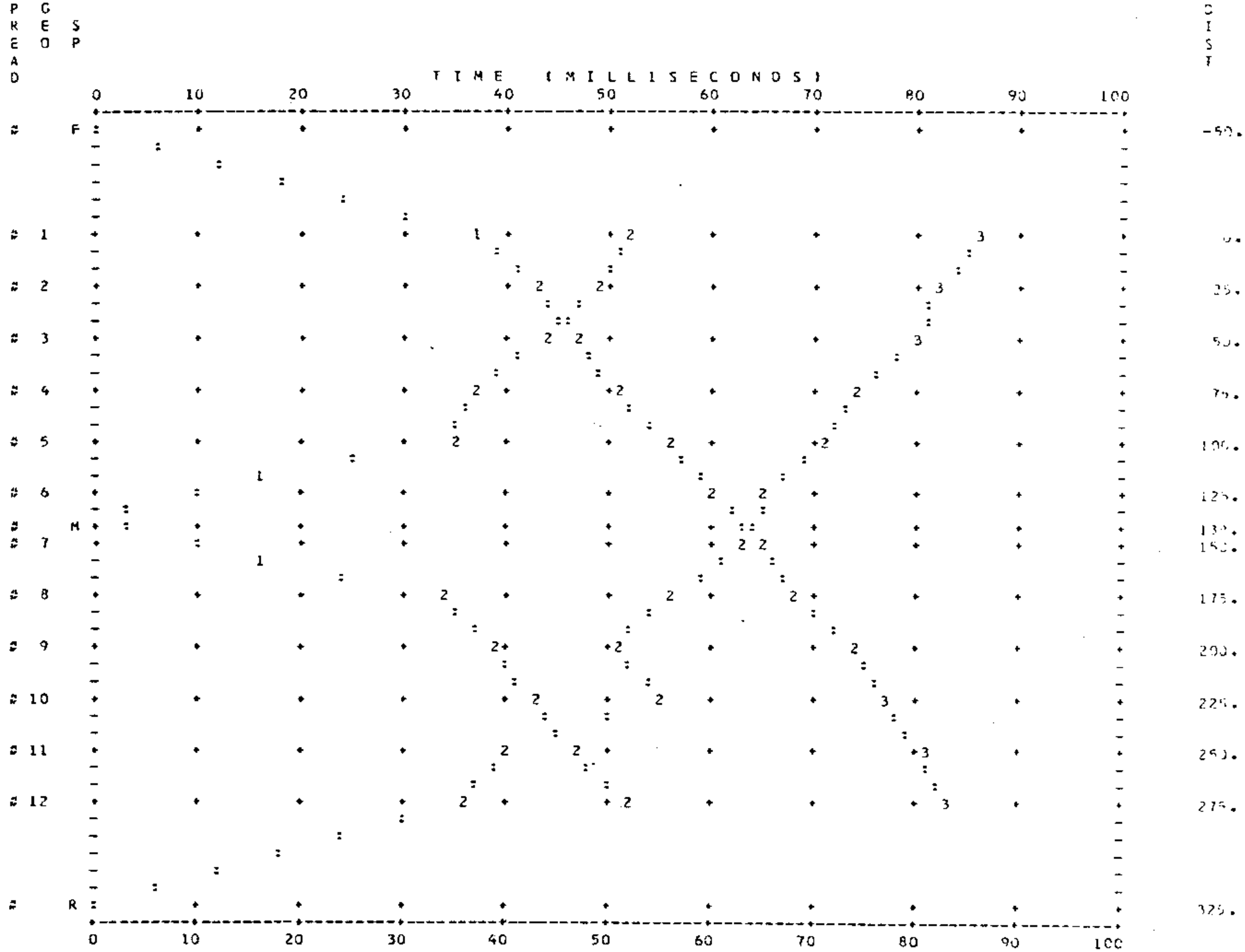
SP	Position	Surf Elev	Layer 2 Depth	Layer 2 Elev	Layer 3 Depth	Layer 3 Elev
GEO						
1	0.0	21.7	12.1	9.6	52.1	-30.4
2	25.0	18.6	12.8	5.8	50.7	-32.1
3	50.0	17.1	14.0	3.1	51.5	-34.4
4	75.0	15.8	14.4	1.4	54.7	-38.9
5	100.0	13.9	12.7	1.2	70.0	-56.1
6	125.0	12.8	12.1	0.7	56.7	-43.9
7	150.0	12.3	12.5	-0.2	46.7	-34.4
8	175.0	11.2	12.0	-0.8	48.2	-37.0
9	200.0	11.2	12.0	-0.8	49.3	-38.1
10	225.0	11.3	12.2	-0.9	49.2	-37.9
11	250.0	11.6	13.6	-2.0	69.8	-58.2
12	275.0	11.3	13.7	-2.4	89.7	-78.4
AVERAGE			12.8		57.4	

INARAJAN PROJECT--SEISMIC REFRACTION LINE INJ-10.



INARAJAN PROJECT--SEISMIC REFRACTION LINE INJ-11.

TIME-DISTANCE PLOT -- RAW DATA WITH NO CORRECTIONS APPLIED

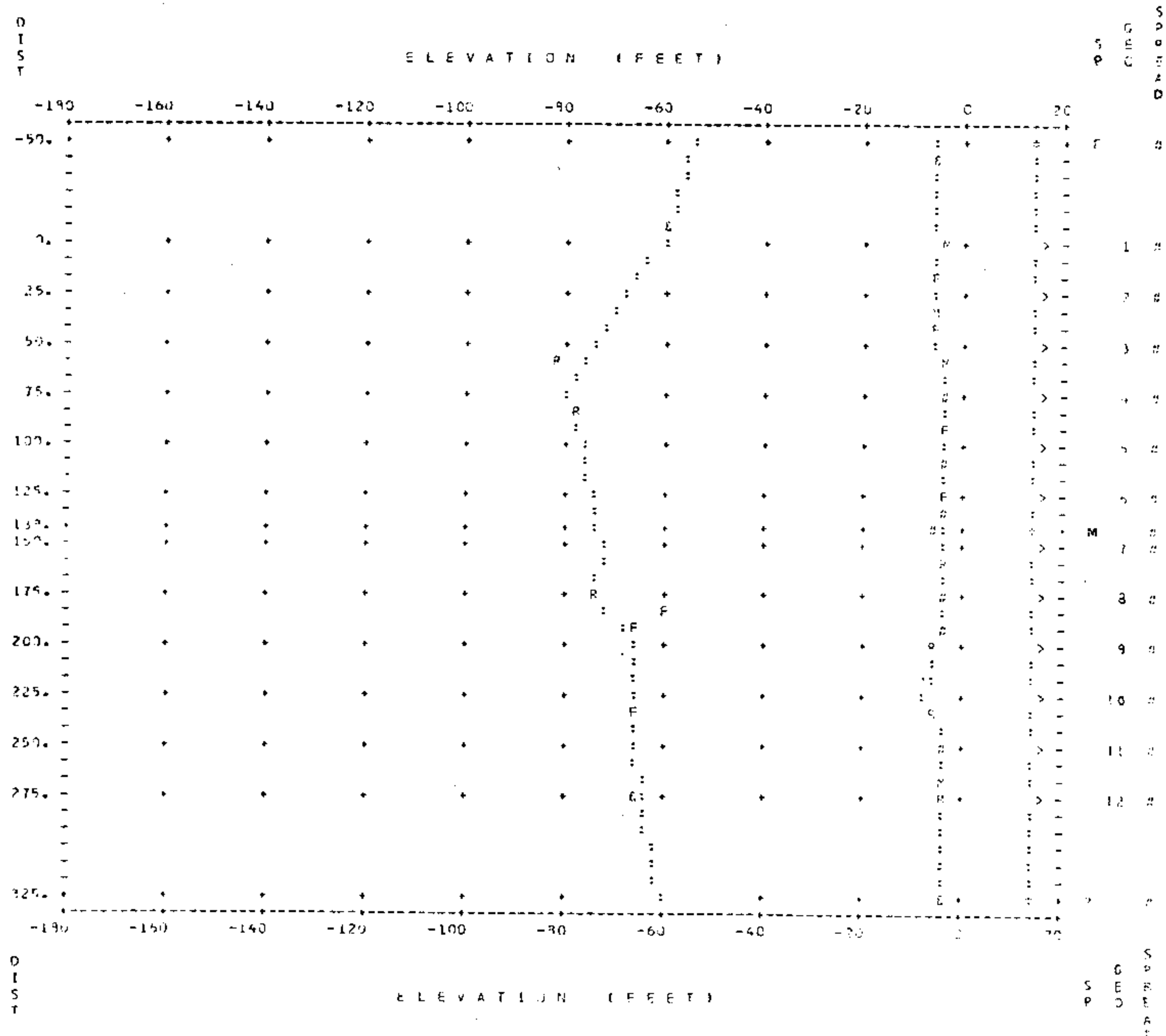


INARAJAN PROJECT - SEISMIC REFRACTION LINE INJ-11

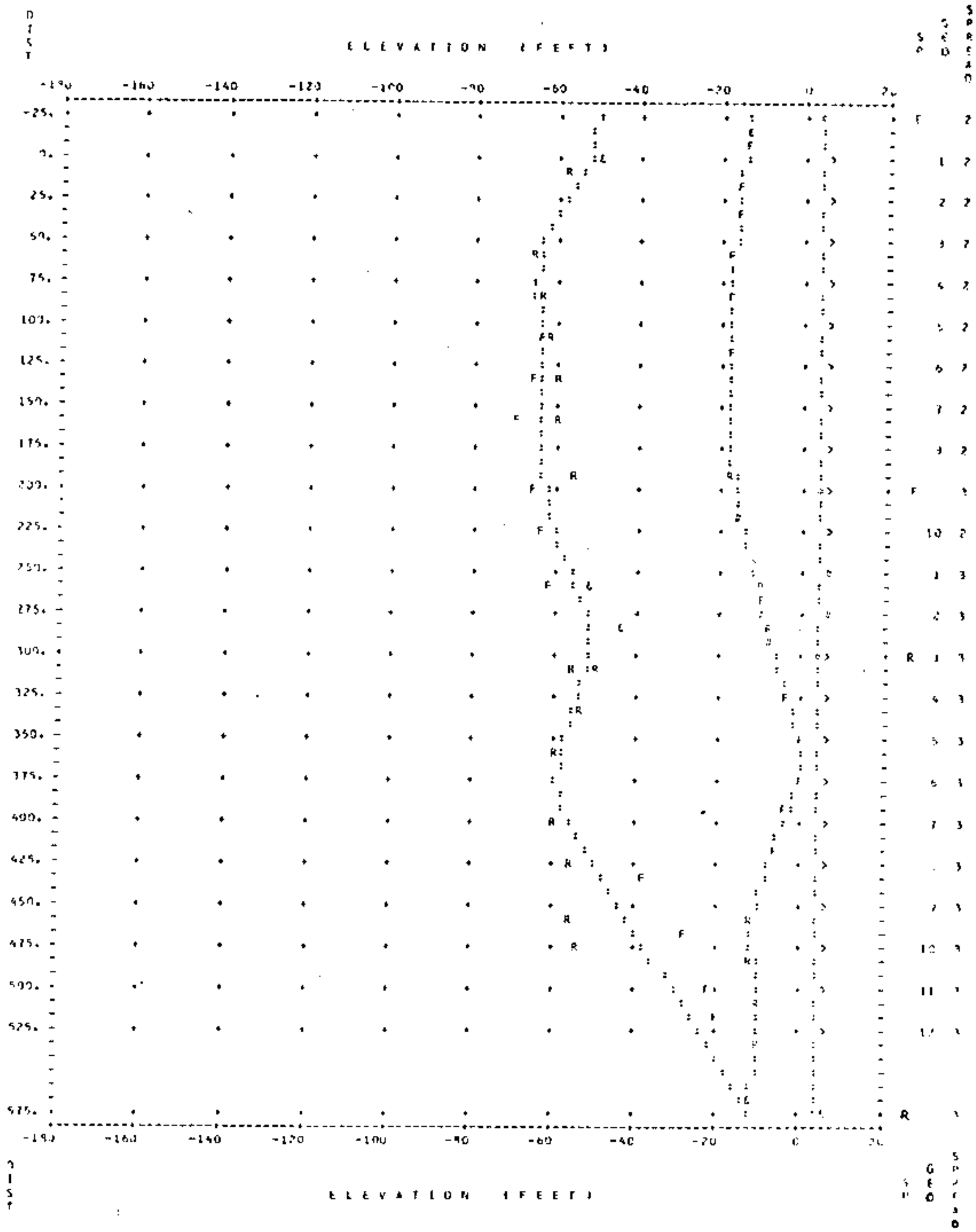
Spread 11 Smoothed Position of Layers Beneath Shotpoints and Geophones

SP	Position	Surf Elev	Layer 2 Depth	Layer 2 Elev	Layer 3 Depth	Layer 3 Elev
GEO						
1	0.0	13.0	18.0	-5.0	73.6	-60.6
2	25.0	13.0	18.7	-5.7	80.7	-67.7
3	50.0	13.0	18.2	-5.2	87.9	-74.9
4	75.0	13.0	17.4	-4.4	92.2	-79.2
5	100.0	13.0	17.9	-4.9	89.8	-76.8
6	125.0	13.0	17.9	-4.9	87.4	-74.4
7	150.0	13.0	18.0	-5.0	85.0	-72.0
8	175.0	13.0	17.3	-4.3	86.8	-73.8
9	200.0	13.0	18.3	-5.3	79.1	-66.1
10	225.0	13.0	20.1	-7.1	79.4	-66.4
11	250.0	13.0	16.9	-3.9	78.4	-65.4
12	275.0	13.0	16.7	-3.7	77.3	-64.3
AVERAGE			18.0		83.1	

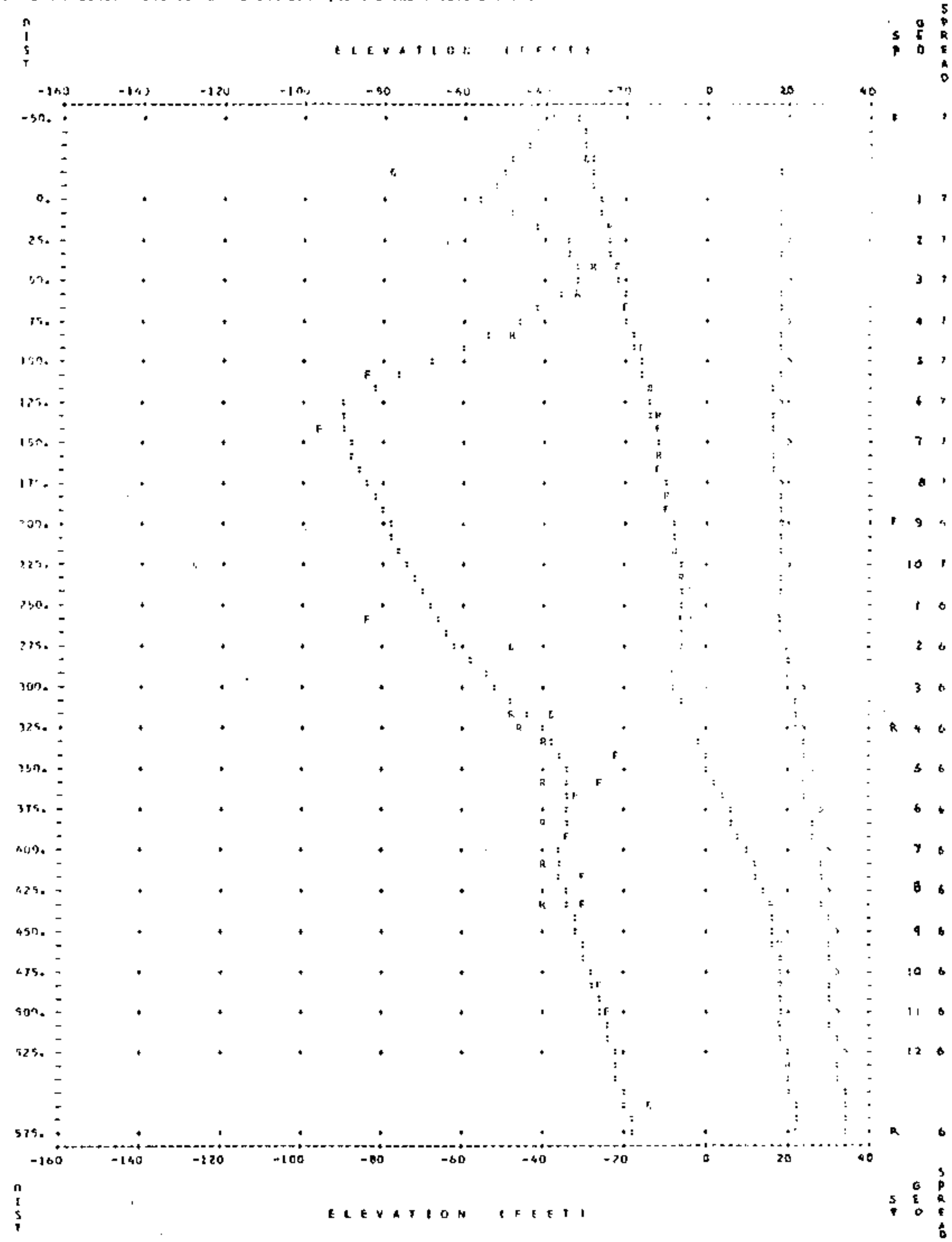
INARAJAN PROJECT--SEISMIC REFRACTION LINE INJ-11.



INARAJAN PROJECT--SEISMIC REFRACTION LINE INJ-2 & INJ-3 (OVERLAPPED)



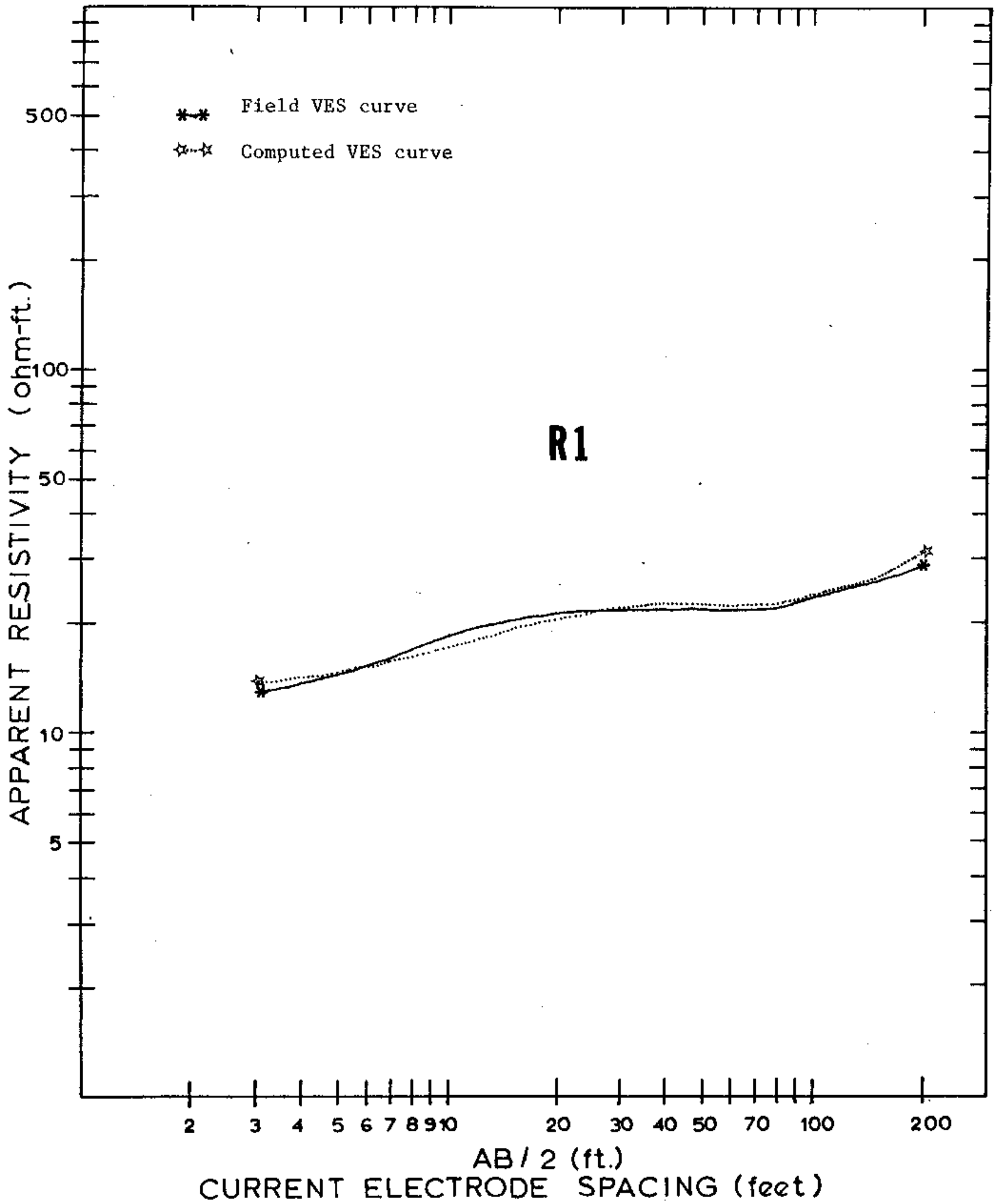
THAKAJSN PROJECT--SEISMIC REFRACTION LINE INJ-6 & INJ-7 (OVERLAPPED)



INARAJAN PROJECT: STATION R-1

THICKNESS	DEPTH	RESISTIVITY
3.00000	3.00000	13.00000
8.00000	11.00000	20.00000
12.00000	23.00000	30.00000
55.00000	78.00000	18.00000
---------	---------	60.00000

AB/2	VES
3.00000	13.51945
4.40340	14.23970
6.46330	15.46442
9.48683	17.02672
13.92476	18.72523
20.43875	20.44986
29.99997	21.89159
44.03392	22.58442
64.63295	22.67995
94.86819	23.41923
139.24745	26.20226
204.38730	31.20814

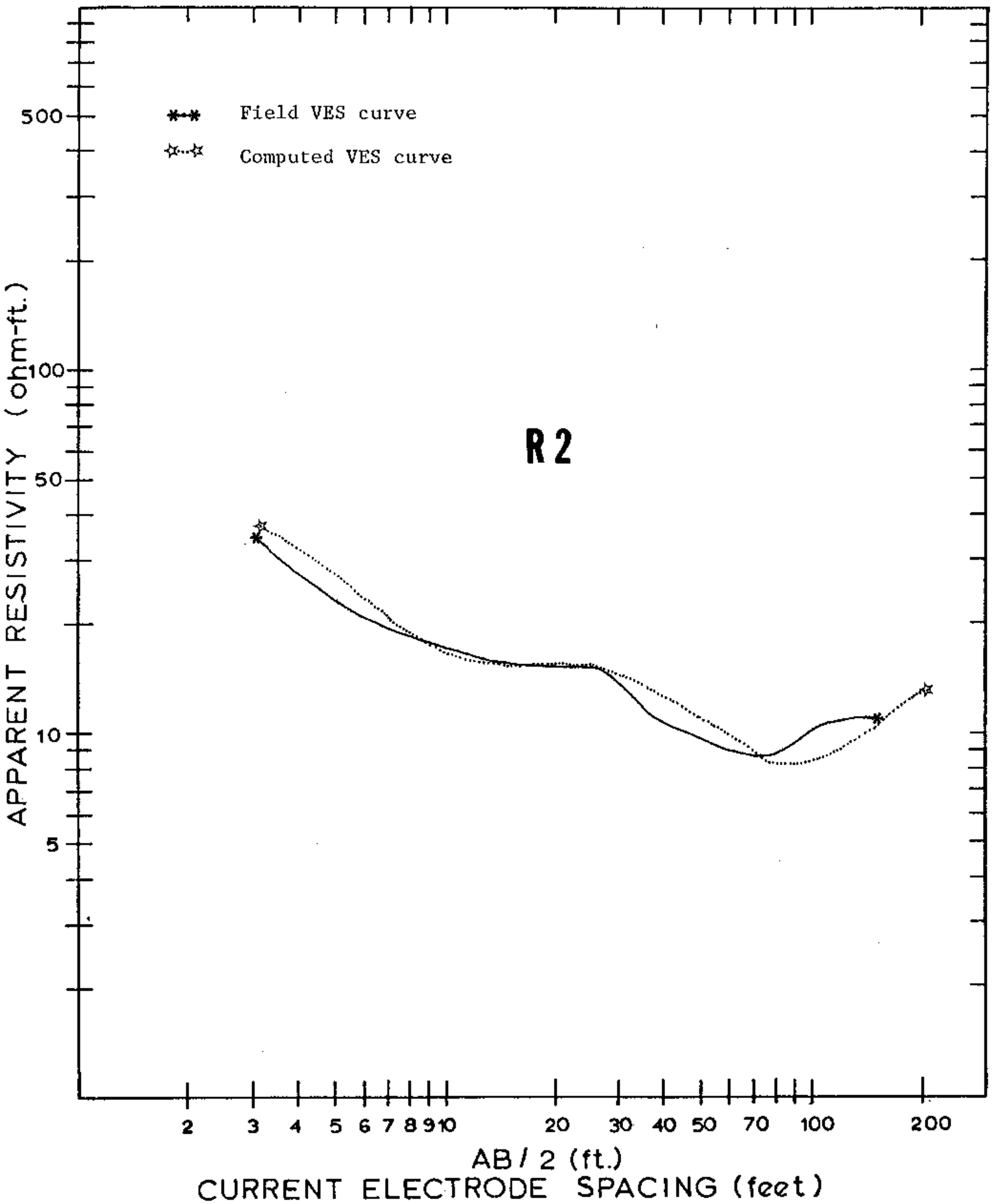


Field VES curve
Computed VES curve
R1
500
100
50
10
5
APPARENT RESISTIVITY (ohm-ft.)
2 3 4 5 6 7 8 9 10 20 30 40 50 70 100 200
AB / 2 (ft.)
CURRENT ELECTRODE SPACING (feet)

INARAJAN PROJECT: STATION R-2

THICKNESS	DEPTH	RESISTIVITY
2.00000	2.00000	47.00000
8.00000	10.00000	13.00000
10.00000	20.00000	25.00000
30.00000	50.00000	3.00000
--------	--------	35.00000

AB/2	VES
3.00000	36.56991
4.40340	28.26829
6.46330	20.62921
9.48683	16.32166
13.92476	15.16183
20.43875	15.08545
29.99997	13.99579
44.03392	11.33367
64.63295	8.72117
94.86819	8.14653
139.24745	9.85874
204.38730	12.88158

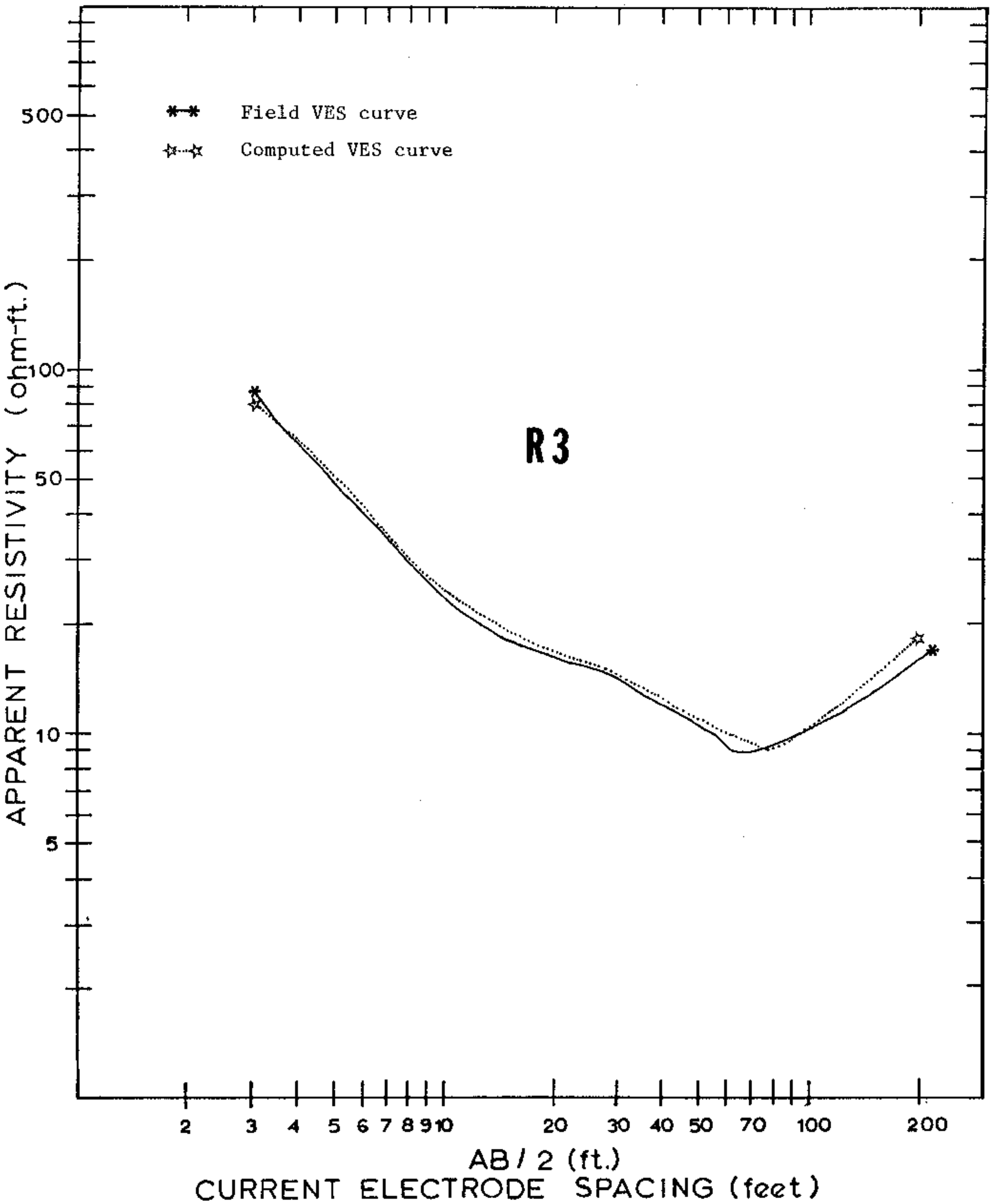


Field VES curve
Computed VES curve
R2
APPARENT RESISTIVITY (ohm-ft.)
500
100
50
10
5
2
3
4
5
6
7
8
9
10
20
30
40
50
70
100
200
AB / 2 (ft.)
CURRENT ELECTRODE SPACING (feet)

INARAJAN PROJECT: STATION R-3

THICKNESS	DEPTH	RESISTIVITY
2.00000	2.00000	112.00000
9.00000	11.00000	21.00000
18.00000	29.00000	13.00000
32.00000	61.00000	4.00000
--------	--------	120.00000

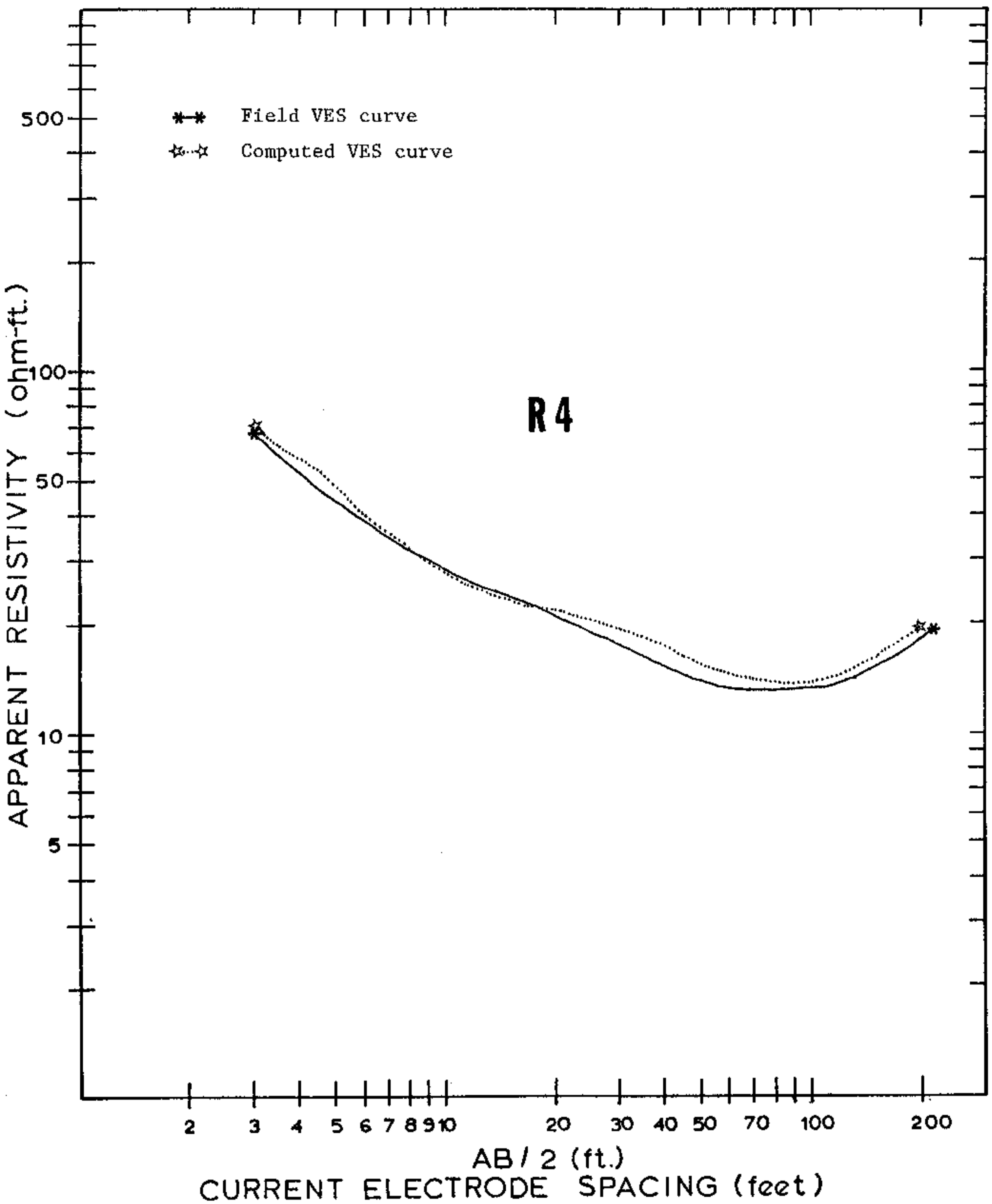
AB/2	VES
3.00000	82.50259
4.40340	59.11036
6.46330	37.91916
9.48683	25.69088
13.92476	20.56569
20.43875	17.62743
29.99997	14.62422
44.03392	11.68524
64.63295	9.85889
94.86819	10.28958
139.24745	13.25830
204.38730	18.30500


Field VES curve
Computed VES curve
R3
500
100
50
10
5
APPARENT RESISTIVITY (ohm-ft.)
2
3
4
5
6
7
8
9
10
20
30
40
50
70
100
200
AB / 2 (ft.)
CURRENT ELECTRODE SPACING (feet)

INARAJAN PROJECT: STATION R-4

THICKNESS	DEPTH	RESISTIVITY
2.00000	2.00000	88.00000
9.00000	11.00000	24.00000
18.00000	29.00000	18.00000
55.00000	84.00000	9.00000
--------	--------	59.00000

AB/2	VES
3.00000	68.28652
4.40340	52.41505
6.46330	37.58341
9.48683	28.49063
13.92476	24.29001
20.43875	21.80354
29.99997	19.32207
44.03392	16.68363
64.63295	14.51283
94.86819	13.97544
139.24745	15.92508
204.38730	20.14482

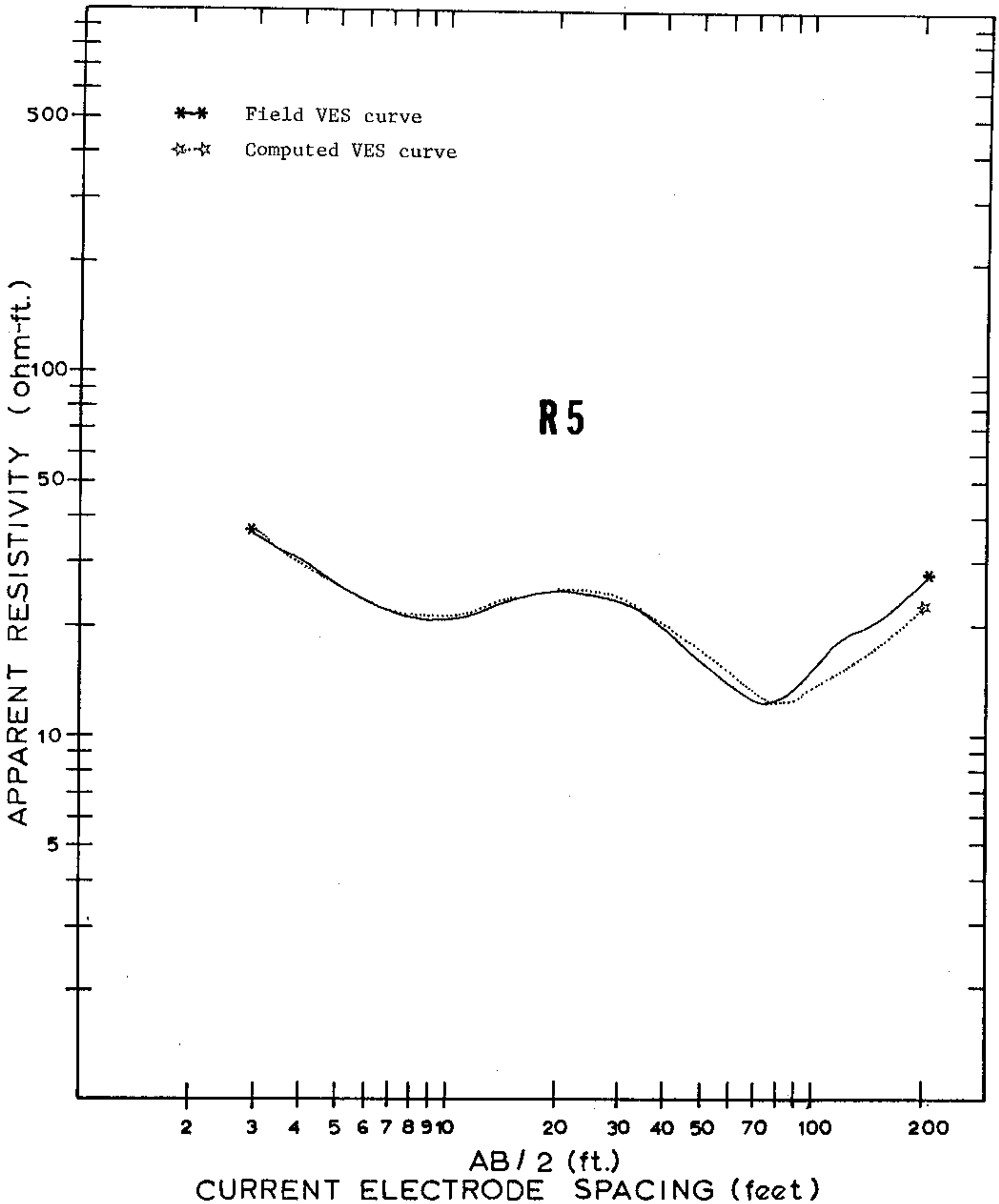


Field VES curve
Computed VES curve
R4
APPARENT RESISTIVITY (ohm-ft.)
500
100
50
10
5
2
3
4
5
6
7
8
9
10
20
30
40
50
70
100
200
AB / 2 (ft.)
CURRENT ELECTRODE SPACING (feet)

INARAJAN PROJECT: STATION R-5

THICKNESS	DEPTH	RESISTIVITY
2.00000	2.00000	45.00000
4.00000	6.00000	13.00000
10.00000	16.00000	55.00000
22.00000	38.00000	3.00000
--------	--------	140.00000

AB/2	VES
3.00000	35.58892
4.40340	28.46276
6.46330	22.81794
9.48683	21.47827
13.92476	23.58361
20.43875	25.62527
29.99997	24.32733
44.03392	19.34744
64.63295	14.24158
94.86819	13.00114
139.24745	16.26816
204.38730	22.53172

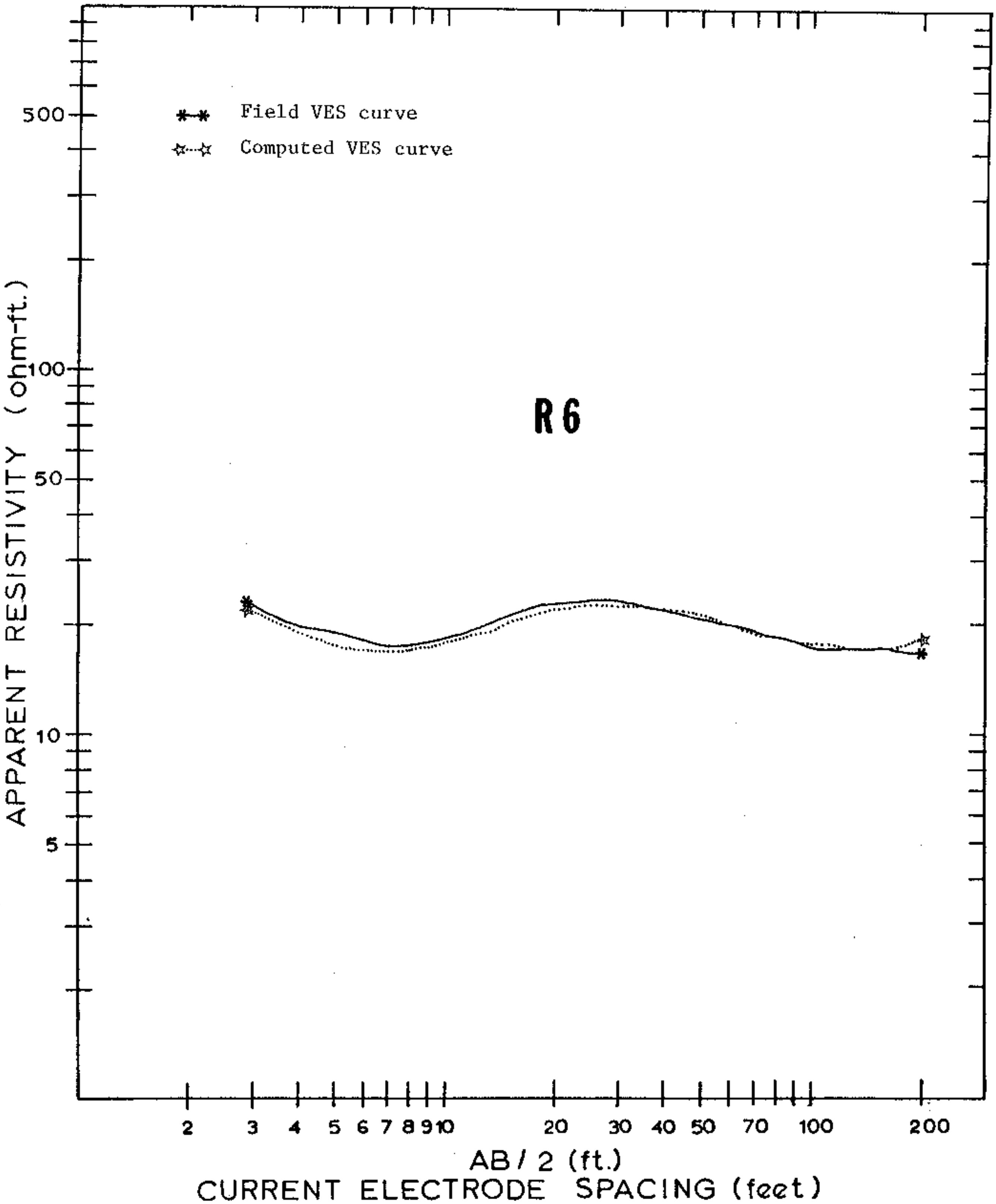


Field VES curve
Computed VES curve
R5
APPARENT RESISTIVITY (ohm-ft.)
500
100
50
10
5
2
3
4
5
6
7
8
9
10
20
30
40
50
70
100
200
AB / 2 (ft.)
CURRENT ELECTRODE SPACING (feet)

INARAJAN PROJECT: STATION R-6

THICKNESS	DEPTH	RESISTIVITY
1.00000	1.00000	38.00000
7.00000	8.00000	15.00000
11.00000	19.00000	40.00000
30.00000	49.00000	13.00000
--------	--------	19.00000

AB/2	VES
3.00000	21.73907
4.40340	18.17652
6.46330	16.93990
9.48683	17.50606
13.92476	19.34823
20.43875	21.62379
29.99997	22.88227
44.03392	22.10199
64.63295	19.95047
94.86819	18.17339
139.24745	17.66806
204.38730	17.98381


Field VES curve
Computed VES curve
R6
500
100
50
10
5
APPARENT RESISTIVITY (ohm-ft.)
2
3
4
5
6
7
8
9
10
20
30
40
50
70
100
200
AB / 2 (ft.)
CURRENT ELECTRODE SPACING (feet)