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GEOPHYSICAL INVESTIGATION AT GATHRIGHT DAM

by

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Geotechnical Laboratory
U. S. Army Engineer Waterways Experiment Station
P. O. Box 631, Vicksburg, Miss. 39180

March 1982
Final Report

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Surface electrical geophysical surveys were used to detect and monitor seepage paths through the right (south) abutment at Gathright Dam. The merits of these geophysical surveys are documented as a case study. Spontaneous potential (SP) techniques determine the anomalies created in the ambient electrical field by water flowing through porous zones in the subsurface materials. Both static and injection-induced potential anomalies were investigated at this

(Continued)

20. ABSTRACT (Continued).

site. Wenner and Bristow-Bates resistivity surveys were performed in limited areas to verify SP results. The Norfolk District drilled several core borings which indicated success of the SP and resistivity tests. The results of dye and salt injection testing, as monitored by fixed SP electrode arrays, are presented in the report.

PREFACE

A geophysical investigation of seepage conditions at Gathright Dam was authorized by the U. S. Army Engineer District, Norfolk, Va., in Intra-Army Order CE-80-3024, Appropriation No. 96X4902.

The field investigation was performed during the periods 30-31 July 1980 by Messrs. Stafford S. Cooper and Joseph P. Koester, 2-10 September 1980 and 4-9 November 1980 by Messrs. Cooper, Koester, and Rodney N. Walters of the Earthquake Engineering and Geophysics Division (EE&GD), Geotechnical Laboratory (GL), U. S. Army Engineer Waterways Experiment Station (WES). Norfolk District geotechnical personnel, under the supervision of Mr. Carl S. Anderson, Jr., provided essential field implementation and assisted in all aspects of the operation. The sections describing the site geology were provided by Mr. Anderson.

The data analysis phase of the investigation was performed by Messrs. Cooper, Koester, and Dr. Arley G. Franklin, under the general supervision of Mr. Robert F. Ballard, Jr., Acting Chief, EE&GD, and Dr. Don C. Banks, Acting Chief, GL. This report was prepared by Messrs. Cooper, Koester, and Dr. Franklin, under the general supervision of Dr. William F. Marcuson III, Chief, GL, and Dr. Paul F. Hadala, Assistant Chief, GL, with review and technical assistance provided by Dr. Hadala and Mr. James B. Warriner, GL.

COL Nelson P. Conover, CE, and COL Tilford C. Creel, CE, were Commanders and Directors of WES. Mr. Fred R. Brown was Technical Director.

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
acres	4046.873	square metres
atmospheres (standard)	101.325	kilopascals
cubic feet per second	0.02831685	cubic metres per second
feet	0.3048	metres
gallons (U. S. liquid)	3.785412	cubic decimetres
gallons per hour	3.785412	cubic decimetres per second
gallons per minute	0.06309	cubic decimetres per second
inches	2.54	centimetres
miles (U. S. statute)	1.609347	kilometres
pounds (mass)	0.4535924	kilograms
square feet	0.09290304	square metres

GEOPHYSICAL INVESTIGATION AT GATHRIGHT DAM

PART I: INTRODUCTION

Background

1. The Norfolk District, U. S. Army Corps of Engineers, has recently completed the construction of Gathright Dam, located near Covington, Va. Filling of its reservoir, Lake Moomaw (Figure 1) commenced on 10 December 1979. As part of this effort, the U. S. Army Engineer Waterways Experiment Station (WES) was requested in August 1980 to participate in a study of groundwater migration paths in the right (south) abutment. Previous measurements made by the Norfolk District had shown that the reservoir, river, and groundwaters had moderately high resistivity (approximately 50 ohm-m) and WES representatives suggested that conditions could be favorable for using a special spontaneous potential (SP) technique and the principle of electrokinesis to locate or monitor seepage paths below the downstream toe of the dam. If this initial effort proved successful, the SP technique would be extended to monitoring others areas of interest, notably the reservoir flank of the right abutment. A limited series of resistivity measurements was also proposed by WES to augment and verify any SP results obtained. The field investigation was carried out 2-10 September 1980 and 4-9 November 1980 by members of the Earthquake Engineering and Geophysics Division, Geotechnical Laboratory, WES. In December 1980, the Norfolk District, in connection with other work, drilled four core borings along the SP and resistivity line. Results of these borings are also presented herein.

Purpose and Scope

2. This program was directed principally to locating and monitoring possible paths of seepage in the right abutment, immediately above

and below the dam. Secondary objectives were to make qualitative judgments of flow quantities, if possible, and to brief District personnel in application of SP and resistivity techniques.

PART II: PROJECT DESCRIPTION

3. The Gathright Dam-Lake Moomaw Project is located on the Jackson River in Allegheny County approximately 12 miles* north of Covington, Va. The lake, when completely filled, will extend 12 miles up the Jackson River from the dam site (Kincaid Gorge) impounding 2530 acres of water. The purpose of the project is threefold: flood control, water quality, and recreation. The dam was completed in May 1978, and the reservoir is presently being filled in three stages. At the time of this investigation, the filling was in the second stage with the reservoir level at 1538.5 ft mean sea level (msl). At this level, approximately 100 ft of water is impounded behind the dam, which has a crest elevation of 1684.5 ft msl. Full pool (1582) is planned for the winter of 1982.

4. The dam is a rolled rock-fill structure with a compacted, impervious earth core and is 257 ft high and 1180 ft in length. The outlet works are located in the right abutment and consist of a free-standing concrete intake tower, a diversion and outlet tunnel, and a stilling basin. The tower is a reinforced concrete structure having base dimensions of 45 by 80.5 ft and a height of 257 ft. The tunnel is concrete lined, approximately 1012 ft long, and has an inside diameter of 17.5 ft. The downstream stilling basin is a U-frame concrete structure 320 ft in length with a double row of baffles and an end sill.

5. The dam foundation and abutments are bedrock. Both required extensive treatment to consolidate the jointed and solutioned rock and to cut off potential seepage. Consolidation grouting, deep curtain line grouting, and local dental treatment were used. In addition, a 800-ft-long by 110-ft-high (maximum) concrete membrane cutoff wall was placed in the left abutment to cut off extensive solutioned rock (U. S. Army Engineer District, Norfolk 1978).

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* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 3.

General Site Geology

6. Gathright Dam and Lake Moomaw lie within the Appalachian Valley and Ridge Physiographic Province which is characterized by synclinal valleys and anticlinal ridges. The dam is located in a narrow gorge which the Jackson River has cut between Coles Mountain and Morris Hill, both anticlinal structures. The axis of dam traverses the gorge approximately 15 deg upstream of the Morris Hill anticline which strikes N35°E. Three Devonian Age and four Silurian Age formations are exposed in the gorge. The Devonian formations include the New Scotland Limestone, Healing Springs Sandstone, and Coeymans Limestone. The Silurian formations include the Upper and Lower Keyser Limestones, Clifton Forge Sandstone (calcareous), and the Tonoloway Limestone. Descriptions of these formations are given in Figure 2.

7. Along the dam alignment and upstream, the rock units dip to the northwest. The axis of the Morris Hill anticline traverses the stilling basin area where the rock units are flat lying or only slightly dipping. Jointing is extensive within all the rock units and occurs in four predominant orientations: a strike set, a dip set, and two oblique sets. Solutioning of the joints is fairly well developed in most of the limestones, especially the Coeymans in the left abutment, where the cutoff wall was placed. Extensive solutioning on Morris Hill is evidenced by several sinkholes occurring at various points along the top of the hill. Their location and configuration indicate that the sinkholes probably developed from solutioning of numerous and deep-seated strike joints which often occur at the axis of anticlines.

8. Several faults have been mapped in the dam area, most being high angle, normal faults along the axial joints of the anticlinal structures. The largest traverses the Jackson River approximately 1000 ft upstream of the dam. Because of their location and orientation, the faults do not affect the integrity of the dam.

Geological Conditions in Study Areas

9. The two study areas include the right bank and slope downstream of the stilling basin and the reservoir rim from the contact of the dam and right abutment to 2000 ft upstream. Phase I of the study investigated the downstream area below the stilling basin where seepage from springs in the area was traced from a sinkhole on Morris Hill using fluorescein dye. Phase II of the study investigated the reservoir rim upstream of the right abutment to locate potential seepage paths through the abutment.

10. As previously stated, the axis of the Morris Hill anticline traverses the Jackson River at the stilling basin; therefore, the rock units there are flat-lying. Downstream of the basin, the rocks dip to the southeast at progressively larger angles. At the downstream edge of the study area (approximately 1000 ft downstream of the basin), the rock units dip 15 deg to the southeast. A large rock cut above the stilling basin, excavated for the outlet works, exposes the stratigraphy of the right abutment from the Healing Springs Sandstone to the Tonoloway Limestone. The variable bedding thickness and extensive jointing are well defined. The detailed study area is along the right gorge slope downstream of the basin from elevation 1550 to the left riverbank. From 1550 to 1440 msl, the slope averages 1 vertical to 1 horizontal and then flattens along a 50- to 120-ft-wide bench above the river at 1430. Three formations are exposed in this area--the Clifton Forge, Lower Keyser, and Tonoloway. The Clifton Forge and Lower Keyser are medium-bedded and extensively cut with high-angle joints giving a blocky appearance to the sandstones and limestones. Many of the near-vertical joints have been enlarged by solutioning and a few small cavities are exposed in the Lower Keyser Limestone. The Tonoloway underlies the Lower Keyser and is exposed on the lower slope, riverbanks, and riverbed. The Tonoloway, although called a limestone, is actually a calcareous and dolomitic siltstone. The siltstone is thin-bedded and in areas almost fissile. The jointing of the Tonoloway in the study area is nearly vertical but not as extensive as the overlying formations. No enlarged

joints or solution structures are visible in outcrops, but exploratory borings and grout holes, drilled for the stilling basin construction, encountered open and interconnected zones to depths of 80 ft below the river elevation. The interconnections indicated bedding or horizontal joint-controlled conditions. There is some evidence of past or present solution activity in the Tonoloway (U. S. Army Engineer Division Laboratory, South Atlantic 1981). There are numerous thin calcite seams and stringers but of no great thickness. Many seeps are visible in the study area, but most are believed to be related to runoff. Several springs occur on the banks and in the riverbed with most being influenced by precipitation and some connected to at least one sinkhole on Morris Hill. Possibly some of the springs may be influenced by the reservoir pool, which is the primary purpose for this investigation.

11. The Phase II study area extends 2000 ft upstream of the dam along the right reservoir rim. Four formations are exposed on the slope: the Healing Springs Sandstone, Coeymans Limestone, Upper Keyser Limestone, and Clifton Forge Sandstone. Only the Upper Keyser and Clifton Forge outcrop below the normal pool level of 1582 msl, where the average slope is 1 vertical to 2 horizontal. Much of the Healing Springs and Coeymans formations on the upper flatter section of slope have been weathered to overburden at the surface. All the rock units strike northeast and dip 15 to 30 deg northwest, downslope. In addition to the thin to medium bedding, three joint orientations occur: one strike set, one dip set, and one oblique set. The blocky nature of the Upper Keyser and Clifton Forge is due to the moderately steep dipping and 1- to 5-ft spacing of the joints. Extensive solutioning and cavity development of the Coeymans on the upper slope caused collapse of the overlying Healing Springs and heterogeneous mixing of materials. Presently, no cavities or other large open-solutioned structures are present on the surface or were encountered by numerous borings along the slope. Leaching, pitting, clay seams, and moderate enlarging of joints do exist, however, in most of the bedrock. A relatively shallow groundwater table occurs in the Clifton Forge Sandstone and is perched on the lower limestone member. Several seeps occur on the lower slope along the Phase II study area.

During the driving of the outlet tunnel, a great deal of seepage was encountered in a bedding plane in the Clifton Forge Sandstone within the initial 130 ft from the portal. Drain holes within the tunnel in this area continue to flow at varying rates of 1 to 60 gpm. Some are dry.

PART III: APPROACH

12. The proposed SP study would be feasible only if SP levels at the site were of sufficient magnitude to make meaningful measurements (greater than, say, 25 mv) and if the SP readings were relatively free of influence from polarization effects and telluric currents. These undesirable SP phenomena are described in detail in the literature (Ogilvy, Ayed, and Bogoslovsky 1969, Corwin and Hoover 1979); however, a brief description of their effects is appropriate for this report. Electrode polarization may occur from chemical differences in the electrolyte (groundwater) in the vicinity of the electrode, temperature or moisture variations, or be induced by applying a few DC volts across the electrode pair. Polarization effects are usually seen as drift or spurious SP changes of up to 20-mv magnitude. Telluric currents can have much higher magnitudes, particularly in mountainous areas, and are generally seen as cyclical variations with 10- to 40-sec periods, although longer periods are possible (Corwin and Hoover 1979).

13. Both a precision voltage balancing device with 100-mv capacity and a digital multimeter having a high internal resistance (50 megaohms) were considered for use in this investigation. In limited field tests, these instruments typically agreed to within 1 mv. The digital multimeter was the instrument of choice because of its speed of measurement and greater voltage range. Its high internal resistance practically eliminated the effects of variations in contact resistance and induced polarization. (There is less than 0.01 microamp of current in the circuit when measuring a 500-mv DC potential.)

14. A pretest evaluation of SP phenomena at the site was made by WES personnel during a reconnaissance visit on 30-31 July 1980. Values of SP ranging from +85 to -125 mv were recorded during this visit using 3-ft-long copper-clad electrodes spaced up to 150 ft apart. Measurements were made at various elevations near the downstream toe and high on the right abutment, and stable readings were obtained over periods of several minutes even though the electrodes were hammer-driven only a short distance into the rocky soil. No stray AC,

polarization, or telluric current effects could be detected. These results were considered to be most encouraging, and to demonstrate the feasibility of making meaningful SP measurements at the site.

15. Both static and induced SP values were to be recorded in the SP investigation. The existing static SP levels would be recorded along two lines situated to intercept the suspected path of seepage between the injection sinkhole on Morris Hill and the area below the downstream toe of the dam. Earlier, dye injection tests performed by the Norfolk District had determined that flow time between dye injection at the Morris Hill sinkhole and dye appearance at the downstream springs was approximately 4 hr 10 min. This dye test confirmed a dye test by others in 1929 which had shown a relationship between the large sinkhole and a spring located on the right bank about 1200 ft downstream of the damsite. WES representatives proposed that a saline solution be injected with the dye for purposes of this investigation, with the expectation that increasing the salinity of the water flow would be reflected as a reduction in SP levels from the static measurements. A minimum spacing of 50 ft between most SP measurement locations was adopted as a reasonable balance of time, cost, and resolution, but the need to monitor SP changes with time after injection would require a preemplaced electrode array. Forty-two electrode stations were to be used in the downstream array and possibly in the upstream array as well, and time and terrain difficulties precluded the use of portable electrodes for repeated measurements at each station.

16. The electrode arrays finally adopted are shown in Figure 3. Copper-clad steel ground rods (5/8-in.-diam and 8-ft-long) were selected for use as electrodes. Electrodes in the lower downstream array were emplaced by drilling to the required depth (approximately 7 ft) with a pneumatic drill. Each electrode was then inserted and the hole was backfilled with sand. River water was used to dampen the sand during electrode emplacement to ensure electrical contact of the rod with the surrounding rock. Each lower electrode station was then hard-wired to a central recording station (Figure 3). The upper downstrem electrode array was emplaced by driving the electrodes 1 to 6 ft into the ground

with a sledgehammer, as the steeply sloping and rugged topography prevented use of the pneumatic drill. The above tasks were performed by personnel of the Norfolk District.

17. A single reference electrode was placed at a depth of 20 ft below the surface in a wet sand backfilled hole drilled near the injection sinkhole, as shown in Figure 3. All array measurements were referenced to this electrode by routing a shielded connecting wire (14 gage braided conductor) approximately 2500 ft downslope to the downstream central recording station (Figure 3). Figure 4 is a profile of the direct path from the injection sinkhole to the river spring developed from geologic and topographic maps made available by the Norfolk District.

PART IV: DATA ACQUISITION

18. Installation of the upper and lower downstream electrode arrays was completed the morning of 3 September 1980. The WES crew arrived onsite that afternoon, wired the electrodes to the central recording station, and made baseline reference readings for all electrode stations in the array. The initial readings were stable to within about ±3 mv and showed little or no drift from the initial readings during a 3-hr observation period. Results of the initial SP observations are tabulated in Table 1. Spatial SP variations for the upper and lower arrays are shown in Figures 5 and 6, respectively, for the measurement period of 3-7 September. These figures show that three very prominent negative SP zones occurred in both arrays, and that these zones also are situated at nearly the same position in each array. The negative SP anomalies typically had quite large magnitudes, reaching as much as -500 mv in the case of zones 1 and 2 in the lower array. The literature (Ogilvy, Ayed, and Bogoslovsky 1969, Corwin and Hoover 1979) suggests that negative anomalies may be associated with streaming (flow-related) conditions, so the existence of pronounced negative anomalies was judged to be significant. On the basis of the static data obtained on 3 September, it was decided to proceed with saline injections at the sinkhole shown in Figure 3.

19. The injection chronology of 4 September was as follows:

Time	Activity
0730	Reservoir water pumped into sinkhole at the rate of 96 gpm continuously until 0950 (13,440 gal)
1000	First injection of 2500 ppm NaCl saline solution, including 1/4 lb fluorescein dye for each of the first two 500 gal batches of solution
1400	Pumping suspended after approximately 10,000 gal of saline solution injected
1515	Resumed pumping of reservoir water at the rate of 96 gpm (12,960 gal)
1730	Stopped injection (36,400 gal total)

20. The SP array monitoring sequence began at 0930, 4 September, and was continued until 1930 hr the same date; these data are tabulated in Table 2 (upper array) and Table 3 (lower array). Concurrently, personnel of the Norfolk District monitored temperature, salinity, and conductivity in the river and at seepage spring locations along the bank. No evidence of a salinity increase or dye traces were detected by 1930 hr, so it was decided to follow with a second injection on 5 September. The injection procedure of 5 September was as follows:

Time	Activity
0815	Begin injection of 500 gal of 20,000 ppm saline solution (500 gal)
0840	Reservoir water pumped into sinkhole at rate of 96 gpm (50,880 gal)
0930	Injected 3 lb of fluorescein dye and continued pumping of reservoir water at rate of 96 gpm
1730	Stopped injection (51,380 gal total)

21. Monitoring of the electrode arrays began at 0945, 5 September, and was terminated at 1530 hr due to failure of the digital multimeter. Steps were taken to secure a substitute digital multimeter, but final readings could not be obtained until 7 September. All of the above data for the upper and lower arrays are tabulated in Tables 4 and 5, respectively.

22. Traces of the fluorescein dye were observed at one spring location (RB-2) near the stilling basin at 1350 hr on 5 September, confirming a travel time of approximately 4 hr 20 min from sinkhole to seepage exits below the electrode arrays. No traces of a salinity increase were ever detected, and it should be noted that the meters used were thoroughly checked during the 4 September injection and found to be operating properly.

23. A short section of Wenner resistivity sounding and Bristow-Bates resistivity line was begun 6 September in the vicinity of electrode station No. 5 in the lower array. The Bristow-Bates line encompassed electrodes 3-7 of the downstream lower SP array. This phase was interrupted by a relatively heavy rainfall the afternoon of 6 September. The

Bristow-Bates line was extended beyond the downstream lower array SP electrode 8 during the period 4-9 November 1980. Results of these lines are shown in Figures 7 (Wenner) and 8 (Bristow-Bates).

24. Personnel of the Norfolk District also installed a 42-electrode SP array with 50-ft spacing along the el 1550 line upstream of the dam on the right abutment. These 5/8-in.-by-8-ft copper-clad electrodes were driven by hand to depths ranging from 2 to 6 ft, governed by local conditions in the steep, rocky terrain. The installation was completed 6-7 September and SP readings were taken the morning of 8 September. Readings were made using the same reference electrode used in the downstream arrays. Results of the readings are tabulated in Table 6, and the array location is shown in Figure 3. A plot of SP levels versus location in the upstream array is shown in Figure 9.

PART V: INTERPRETATION

Spontaneous Potential

25. The concept for this SP study was novel in the sense that a fixed electrode array has to be used to record both the static SP and to monitor SP response to the flow of saline injections. The original premise was that comparatively large negative static SP anomalies might indicate paths of seepage (Ogilvy, Ayed, and Bogoslovsky 1969, Corwin and Hoover 1979) and that time-dependent changes of the SP in response to saline injections could verify the data interpretation and perhaps provide some insight as to flow quantities in the system. The expected effect of achieving a local high salinity condition in the groundwater would be a time-dependent reduction in magnitude of the SP anomaly, a condition analogous to shorting out a battery. As it turned out, no increase in salinity was measured in postinjection tests at any of the seepage outlets monitored, so the desired local high salinity condition was apparently never achieved.

26. On the other hand, since the investigation included measurements of changing SP during periods when the flow was incremented by a measured injection of water, there is an opportunity to attempt an estimate of flow quantity by comparing the SP changes with the flow increments. The succeeding paragraphs outline a proposed approach to such an analysis, using some simplifying assumptions and substituting plausible guesses for required information that is missing. The numerical results are therefore speculative and are intended for comparison with other indications of flow quantities rather than for any engineering purpose. This trial analysis is done with the additional expectation that it will be of help in planning future SP surveys.

27. Ignoring the relatively minor electrochemical and telluric contributions to SP, one may assume that values measured relative to a local reference situated in a similar geological condition are due to the electrokinetic contribution, or streaming potential. According to the Helmholtz equation (Corwin and Hoover 1979),

$$V = \frac{\rho \varepsilon \zeta}{4 \pi n} \Delta P \tag{1}$$

where

V = the measured streaming potential

ρ = fluid resistivity

ε = fluid dielectric constant

ζ = voltage across the Helmholtz double layer (laminar flow condition in a capillary tube)

n = viscosity of the pore fluid

ΔP = pressure drop along the flow path

28. For a given set of materials properties, the only variables in the above equation are V and ΔP ; i.e., V is directly proportional to ΔP and $V/\Delta P$ is a constant. For laminar flow through porous media, the quantities V and ΔP must also be related to permeability, hydraulic gradient, and flow through Darcy's law (Cedergren 1977):

$$Q = kia \tag{2}$$

where

Q = time rate of flow

k = coefficient of permeability

i = hydraulic gradient

a = cross-sectional area of flow

29. Limited data on streaming potential developed from laminar fluid flow through porous media has been published in the literature (Corwin and Hoover 1979), and these data were used to develop the plot of $V/\Delta P$ versus pore fluid salinity shown in Figure 10. In the plot, the upper and lower bounds to the data are indicated by straight lines. Entering the plot with the approximate local pore fluid resistivity of 50 ohm-m, one finds $V/\Delta P$ is in the range of 20 to 100 mv/atm for quartz sands and sandstones. Assuming a 150-ft waterhead in the right abutment (a head slightly greater than the total head in the reservoir) and an upper $V/\Delta P$ value of 100 mv/atm, the calculated value of V is

$$V = 100\Delta P = 100 \text{ mv/atm} \frac{150 \text{ ft}}{32 \text{ ft/atm}} = 470 \text{ mv} \tag{3}$$

This result is reasonably consistent with the recorded data, but is, of course, valid only for laminar flow conditions.

30. The question of whether laminar, transitional, or turbulent flow conditions predominate for seepage through rock fissures, which is of interest in the present case, cannot be accurately answered from the evidence at hand. A useful approximation to the answer may be found by using the Reynolds number equation (Cedergren 1977):

$$\mathrm{Re} = \frac{\gamma v d}{\mu} \tag{4}$$

where

Re = Reynolds number for flow through pipes; Re $\geq$ 2000 indicates turbulent flow

γ = density of the fluid = 1.0 g/cm^3

v = flow velocity

d = pipe diameter

μ = coefficient of absolute viscosity $\simeq$ 0.01 poises (dyne-sec/cm^2) for water

31. The length of the flow path, if in a straight line, would be about 2200 ft, but considering the probable tortuosity of the path, 3000 ft is probably a better estimate. Using an assumed flow length of 3000 ft and a travel time of 4 hr 20 min, the effective seepage velocity is calculated to be 2.31 in./sec or 5.86 cm/sec. Equating Re to 2000,

$$2000 = \frac{1.0\ \mathrm{g/cm^3}(5.86\ \mathrm{cm/sec})d}{0.01\ \mathrm{g/cm\text{-}sec}} \tag{5}$$

gives for a critical pipe diameter

$$d = 3.35\ \mathrm{cm,\ or}\ 1.32\ \mathrm{in.} \tag{6}$$

32. Although the above equation applies to circular pipes, turbulent flow conditions çan probably be expected if seepage channels are more than a few inches in maximum dimension. The seepage channels of interest at this site can safely be assumed to have irregular cross

sections with maximum dimensions greater than a few inches, so turbulent flow conditions probably dominate in major features. For this case, the relationship among Q , SP , and ΔP is nonlinear, and the laminar flow equations cited earlier cannot be directly applied. Nevertheless, the argument remains that the flow of water should generate measurable negative SP anomalies whose magnitude is in some manner related to the quantity of flow. In support of this argument, the postinjection response of electrode 6 in the downstream upper electrode array may be considered. Figure 11 shows the change from daily baseline spontaneous potential of electrode 6 plotted versus time after injection. It is apparent that on 4 and 5 September there was a pronounced negative shift in the SP at electrode 6, and that this phenomenon began about 3-1/2 hr after injection on both days. Also shown in Figure 11 is the known 4 hr 20 min time interval required for tracer dye to migrate from the injection sinkhole to seepage exits below the downstream toe of the dam, which are located farther away from the sinkhole than electrode 6 and can be expected to exhibit a longer travel time. Based on these data, the following statements may be made:

a. At this site, a pronounced negative SP anomaly probably indicates a zone of groundwater flow at some depth below the electrode.

b. The magnitude of the negative potential is apparently controlled by the quantity of flow through the zone.

c. On 4 September, the negative SP shift began 3-1/2 hr after injection reached a maximum value at 11 hr after injection, and then decreased. This time period conforms closely to the 4 September combined travel time and pumping time period indicated in Figure 11. On 5 September, a larger total volume of fluid was injected and no appreciable decrease in SP from the maximum negative magnitude which had been reached on 5 September had occurred by 7 September. There is no obvious explanation for this behavior, except for the occurrence of an internal change in the flow conditions (rainwater entering the system, etc.).

d. Electrode 6 in the upper array showed the only dramatic response to injection pulses. It seems clear that its response indicates a very localized phenomenon, perhaps a small seepage channel in the immediate vicinity. In fact, a small surface seepage area was noted between electrodes 6 and 7 in the upper array, but this seep is not known to be related to the sinkhole. No traces of increased salinity were recorded during injection for the water seeping from this area. Numerous other minor seeps can be found in the downstream rock face of the right abutment.

33. In order to make a very gross estimate of flow quantity Q through the three seepage zones identified in Figure 6, it is herein assumed that there is a linear relationship between Q and SP magnitude, which implies that

$$\frac{Q_o + Q_i}{Q_o} = \frac{SP_2}{SP_1} \tag{7}$$

where

Q_o = original quantity of flow in the system before injection

Q_i = quantity of injected water flowing in the system

SP_2 = average SP magnitude for the entire lower array during injection flow

SP_1 = average SP magnitude for the entire lower array prior to injection

34. The data for 4 and 5 September are compared with the preinjection data obtained 3 September in order to develop the necessary ratios. The time of 1500 hr was selected to sample computation data in order to be consistent with the environment of the baseline readings of 3 September. These data are tabulated in Tables 1, 3, and 5 and were used to compute the following mean SP values for the lower array:

Date	1500 hr Mean SP Value, mv
3 Sep	-218
4 Sep	-232
5 Sep	-240

The calculation for 3 versus 4 September is then:

$$\text{3 versus 4 September:} \quad \frac{Q_o + Q_i}{Q_o} = \frac{258}{242} = 1.06$$

$$\text{3 versus 5 September: } \frac{Q_o + Q_i}{Q_o} = 1.10$$

35. An injection rate of 3133 gph was computed from a plot of cumulative water injection at 1500 hr on 4 September (Figure 12) and can be assumed to be the quantity Q_i flowing entirely within the zone covered by the lower downstream SP array at that time. A similar computation yields 5480 gph for the same time on 5 September:

For 4 September:

$$Q_i = 3{,}133 \text{ gph}$$

$$Q_o = 52{,}200 \text{ gph}$$

$$Q_o + Q_i = 55{,}333 \text{ gph}$$

For 5 September:

$$Q_i = 5{,}480 \text{ gph}$$

$$Q_o = 54{,}800 \text{ gph}$$

$$Q_o + Q_i = 60{,}280 \text{ gph}$$

The computed Q_o quantities of 52,200 gph (4 September) and 54,800 gph (5 September) are in reasonably good agreement, but as noted earlier, these numbers must be regarded as speculative because of the gross assumptions made in their derivation. The SP data for 7 September, in fact, contradict the conclusions reached using the above approach, but have not been considered since the rainfall of 6 September may have resulted in an unknown increase in flow through the system on 7 September.

36. It is possible that the actual value of Q_o for the zones in question is even greater than the calculated values because no increase in salinity was ever measured at the downstream seepage outlets, so if dilution was the mechanism governing salinity, then much more than 55,000 gph would be required to dilute 2500 gph (10,000 gal in 4 hr) of 2500 ppm saline solution (4 September) to essentially zero salinity

as it migrated from sinkhole to seepage outlets.

37. The calculated total flow of about 55,000 gph (2.04 cfs) and estimated seepage velocity of 2.31 in./sec (0.19 ft/sec) can also be used to provide a very rough estimate of the required downstream total seepage flow area, from

$$Q = va$$

$$a = \frac{Q}{v} = \frac{2.04 \text{ cfs}}{0.19 \text{ ft/sec}} = 10.75 \text{ , say } 11 \text{ ft}^2$$

38. Recent comparison of flow in the river with gates shut and measurement of tunnel leakage under gates, as well as river flow at downstream gage stations, indicate combined spring and seep flows may be as high as 4 to 5 cfs.* The actual total flow area is presumed to be distributed among the three major flow zones indicated in Figures 3 and 4. The actual size of these features cannot be accurately predicted without additional information, but from Figures 3 and 4, it would appear that most of the flow is in zones 1 and 2, based solely on the large magnitude of the negative SP anomalies for these zones.

39. Finally, results from the upstream (reservoir) SP array, shown in Figure 9, indicate four seepage zones whose negative anomalies have lesser magnitude than the flow zones in the lower array, but in the absence of induced flow changes there is no way to provide even a gross estimate of flow quantity.

Resistivity

40. Wenner and Bristow-Bates resistivity surveys were conducted near electrode 4 in the lower array. Results of the Wenner vertical sounding are presented in Figure 7, and this plot indicates a pronounced low resistivity zone in the Tonoloway formation in a depth interval from

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* Personal communication, Carl Anderson, Jr., U. S. Army Engineer District, Norfolk, March 1981.

70 to 100 ft. Since the groundwater is known to have a resistivity of about 145 ohm-ft (44 ohm-m) and the surrounding rock has apparent resistivities ranging from 1000 to 1900 ohm-ft, the low resistivity interval from 70 to 100 ft in depth is taken to indicate a seepage zone. It should be noted that the resistivity surveys were conducted 6 and 7 September, and that there may have been some persistent groundwater effect from the saline injections of 4 and 5 September, although no measurable increases in groundwater salinity were ever recorded at any seepage outlet.

41. The Bristow-Bates resistivity survey results, shown in Figure 8, indicate the presence of several low resistivity zones at depths ranging from 45 to 87 ft. The Bristow-Bates interpretation technique is outlined by Cooper and Bieganousky (1978). The intermediate plots of apparent resistivity versus radial distance used to construct Figure 8 are included in Appendix A of this report. The largest zones indicated fall in the depth interval from 80 to 85 ft and on either side of electrode 5. The SP plot for the lower array (Figure 6) shows that electrode 5 registered a reasonably consistent -175 mv anomaly, but that the zones to either side consistently registered -500 mv or more. Unfortunately, space limitations prevented extending the Bristow-Bates survey line in the direction of the dam, which would have been desirable since better definition could have been obtained between SP electrodes 3 and 4 where two seepage outlets are located. In any case, the SP and resistivity results appear to be in reasonably good, although not exact, agreement. Also, the major zones of seepage near SP electrode 5 in the lower array appear to be located at a depth of about 60 to 90 ft below the ground surface, i.e., between el 1350 and el 1370. This range compares very favorably with a known cavity zone encountered during construction of the stilling basin in 1972.

Verification by Borings

42. In order to validate results of the geophysical investigation, the Norfolk District drilled four core borings in the downstream study

area in December 1980 and January 1981. Three of these core borings, designated RS-1 through RS-3, were located to penetrate probable seepage zones indicated by the SP and resistivity surveys. The fourth core boring, RS-4, was located to supplement other geologic information developed by the Norfolk District. Resistivity surveys conducted by WES personnel did not extend far enough to investigate the subsurface material penetrated by core boring RS-4. Locations of the core borings are shown in Figure 3 with respect to the Bristow-Bates resistivity survey line and downstream lower array of SP electrodes. Boring logs are presented in Appendix B. Also shown in Figure 3 are zones of weathered rock, clay, and water-filled cavities encountered in coring as well as the probable zones of seepage predicted from the resistivity survey. From Figure 8 it can be seen that the depth and position of the low resistivity zones correlates very well with the core boring cavity locations, serving to substantiate the geophysical interpretation.

43. The cavernous features anticipated by the geophysical investigation and indicated by borings RS-1 through RS-4 are rather complex in nature, as illustrated by the following summary, furnished by the Norfolk District:

a. When the cavity in core boring RS-1 was encountered, dye was injected and returned 3 hr later in Nelson Spring (indicated in Figure 2). No other known connected openings produced dye.

b. The cavity encountered in RS-2 at el 1380 produced muddy water flow at riverbank spring RB-2 only.

c. In RS-3, the fractured and clayey zone at el 1370 produced muddy flow in the river spring.

d. Core boring RS-4 caused muddy flow in both the river spring and the riverbank spring RB-2 when penetrating between el 1382 and 1362.

PART VI: CONCLUSIONS AND RECOMMENDATIONS

44. In this study, fixed arrays of SP measurement electrodes were successfully used to identify groundwater migration paths in the right abutment of Gathright Dam. The locations of seepage paths at this site were indicated by large negative SP potentials, which in some locales exceeded -500 mv DC at the ground surface. The SP results were found to be in good agreement with geologic and groundwater flow data furnished by the Norfolk District, and were supported by a limited amount of resistivity data obtained below the downstream toe of the dam. Borings performed by the Norfolk District verified the SP and resistivity data in locating several apparent seepage features. One phase of the study, the injection of high salinity water into a sinkhole high on the right abutment, did not produce the expected changes in static SP levels along the known groundwater migration path. In fact, no traces of increased salinity were ever detected in the monitoring of seepage outlets below the dam. However, changes in the static SP as a result of increased flow during injection were used to make gross estimates of flow quantities through the downstream seepage zones. The validity of these flow estimates remains to be established.

45. Using a fixed SP array, four seepage zones were also identified along the upstream (reservoir) flank of the right abutment. In the absence of injection-induced changes, no flow estimates were made for these zones, but their smaller negative anomaly values tend to indicate that less seepage occurs upstream than downstream.

46. Further study of the use of fixed-electrode SP measurement arrays in similar applications is highly recommended. If site and groundwater conditions are favorable, as at Gathright Dam, it is possible that a fixed SP array might prove to be a powerful method for monitoring seepage during construction, filling, and operation of a reservoir. The SP method has proven particularly attractive in terms of cost, time, and coverage.

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Table 1

Spontaneous Potential Measurements, Gathright Dam,

Array Electrode Potential Versus Reference Electrode,

3 September 1980

<table>
<tr><th colspan="21">Station</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th><th>13</th><th>14</th><th>15</th><th>16</th><th>17</th><th>18</th><th>19</th><th>20</th><th>21</th></tr>
<tr><td colspan="21">Upper Array, mv</td></tr>
<tr><td>-272</td><td>-060</td><td>-243</td><td>-376</td><td>-192</td><td>-235</td><td>-320</td><td>-346</td><td>-170</td><td>+067</td><td>+016</td><td>-119</td><td>-215</td><td>-430</td><td>-085</td><td>-355</td><td>-185</td><td>-275</td><td>+000</td><td>+112</td><td>-045</td></tr>
<tr><td colspan="21">Lower Array, mv</td></tr>
<tr><td>-255</td><td>-130</td><td>-324</td><td>-480</td><td>-198</td><td>-298</td><td>-455</td><td>-388</td><td>-073</td><td>-062</td><td>-196</td><td>-210</td><td>-178</td><td>-248</td><td>-145</td><td>-096</td><td>-225</td><td>-245</td><td>-367</td><td>+000</td><td>+000</td></tr>
</table>

Table 2

Spontaneous Potential Measurements, Gathright Dam,

Array Electrode Potential Versus Reference Electrode,

Upper Array (mv) - 4 September 1980

	Station																				
Hr	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
0930	-292	-056	-260	-420	-122	-277	-321	-355	-179	+070	+020	-132	-220	-460	-091	-280	-182	-280	+002	+110	-032
1130	-299	-055	-259	-423	-118	-282	-315	-350	-175	+070	+020	-135	-225	-460	-090	-280	-180	-270	+005	+115	-032
1230	-300	-053	-255	-422	-115	-295	-312	-345	-175	+070	+020	-135	-220	-460	-090	-280	-180	-272	+012	+120	-030
1330	-301	-054	-255	-422	-115	-295	-315	-348	-175	+075	+022	-135	-220	-460	-090	-280	-180	-275	+008	+120	-030
1400	-300	-054	-255	-425	-118	-300	-315	-348	-175	+075	+020	-130	-220	-462	-090	-280	-182	-280	+010	+118	-028
1430	-300	-054	-254	-424	-115	-300	-315	-347	-175	+075	+022	-129	-218	-458	-090	-279	-178	-275	+008	+120	-028
1500	-300	-053	-254	-425	-117	-298	-315	-343	-171	+075	+024	-128	-214	-456	-085	-275	-176	-272	+008	+120	-025
1530	-300	-053	-254	-424	-115	-304	-312	-344	-173	+075	+024	-132	-217	-454	-085	-279	-171	-270	+012	+124	-025
1600	-300	-053	-255	-426	-118	-315	-315	-346	-174	+074	+020	-130	-217	-455	-090	-282	-180	-274	+010	+120	-030
1630	-300	-054	-255	-425	-116	-321	-312	-343	-172	+075	+019	-124	-218	-453	-089	-280	-176	-272	+012	+122	-032
1700	-300	-053	-255	-427	-115	-331	-313	-344	-173	+076	+019	-127	-217	-457	-090	-280	-176	-271	+011	+122	-030
1730	-299	-053	-256	-428	-115	-350	-313	-345	-175	+074	+018	-127	-218	-458	-093	-284	-179	-275	+008	+118	-030
1800	-300	-053	-256	-428	-116	-358	-313	-345	-177	+074	+017	-126	-220	-460	-094	-284	-177	-275	+006	+118	-031
1830	-298	-054	-257	-430	-119	-364	-316	-347	-178	+073	+017	-126	-222	-461	-098	-288	-181	-279	+004	+114	-036
1900	-295	-053	-254	-429	-118	-345	-316	-346	-179	+074	+016	-127	-221	-460	-095	-287	-177	-277	+007	+120	-029
1930	-294	-052	-253	-426	-116	-321	-314	-342	-174	+077	+020	-122	-217	-459	-093	-285	-176	-275	+009	+120	-026

Table 3

Spontaneous Potential Measurements, Gathright Dam,

Array Electrode Potential Versus Reference Electrode,

Lower Array (mv) - 4 September 1980

Hr	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
0935	-282	-128	-444	-500	-190	-302	-478	-401	-076	-049	-206	-255	-210	-268	-162	-086	-237	-259	-412	+011	+008
1135	-280	-127	-445	-500	-187	-305	-480	-400	-075	-045	-210	-260	-210	-265	-160	-080	-235	-260	-410	+010	+010
1230	-282	-127	-445	-495	-185	-305	-475	-400	-072	-045	-205	-260	-210	-270	-160	-080	-235	-255	-410	+015	+015
1330	-284	-128	-444	-493	-185	-306	-476	-400	-072	-050	-205	-262	-212	-270	-162	-078	-235	-255	-410	+015	+010
1400	-286	-130	-445	-492	-185	-305	-472	-402	-072	-050	-205	-262	-212	-273	-165	-082	-238	-258	-412	+016	+014
1430	-288	-129	-445	-492	-184	-307	-475	-402	-070	-050	-202	-258	-210	-272	-159	-075	-232	-250	-403	+018	+016
1500	-292	-129	-447	-493	-184	-306	-477	-401	-069	-046	-202	-260	-206	-268	-159	-074	-232	-252	-405	+021	+017
1530	-294	-130	-440	-495	-183	-305	-470	-401	-069	-046	-203	-262	-210	-268	-160	-076	-230	-252	-405	+018	+018
1600	-297	-131	-437	-495	-185	-306	-475	-400	-072	-050	-206	-265	-210	-270	-165	-075	-240	-254	-410	+012	+010
1630	-300	-132	-438	-493	-183	-305	-478	-400	-070	-050	-202	-262	-210	-268	-160	-072	-235	-250	-405	+020	+020
1700	-300	-132	-439	-495	-184	-306	-479	-400	-070	-047	-202	-264	-211	-267	-162	-075	-233	-253	-405	+018	+017
1730	-302	-133	-440	-496	-185	-306	-485	-401	-072	-050	-206	-266	-213	-268	-164	-076	-237	-258	-411	+015	+014
1800	-301	-133	-440	-496	-184	-307	-487	-400	-071	-050	-205	-267	-213	-270	-164	-075	-236	-255	-408	+014	+014
1830	-302	-134	-441	-498	-185	-307	-487	-401	-073	-053	-207	-269	-216	-272	-167	-077	-239	-258	-412	+014	+012
1900	-303	-135	-443	-499	-184	-305	-487	-400	-072	-053	-206	-269	-217	-270	-165	-072	-239	-255	-411	+016	+014
1930	-304	-134	-444	-499	-183	-303	-484	-397	-069	-052	-204	-266	-215	-265	-163	-068	-236	-252	-410	+018	+017

Table 4

Spontaneous Potential Measurements, Gathright Dam,

Array Electrode Potential Versus Reference Electrode,

Upper Array (mv) - 5 September 1980 (Second Injection)

	Station																				
Hr	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
0945	-301	-052	-260	-432	-125	-210	-320	-345	-180	+075	+028	-160	-218	-468	-090	-318	-180	-280	+010	+120	-020
1030	-305	-050	-258	-432	-125	-210	-318	-345	-180	+078	+020	-156	-210	-465	-090	-320	-180	-280	+000	+120	-028
1100	-305	-048	-258	-433	-124	-212	-314	-341	-180	+072	+018	-140	-220	-466	-092	-320	-178	-278	+003	+110	-024
1135	-307	-048	-257	-435	-125	-212	-312	-343	-180	+070	+018	-140	-220	-465	-090	-320	-180	-275	+005	+118	-018
1200	-312	-049	-256	-437	-128	-219	-312	-342	-182	+073	+020	-148	-220	-468	-095	-328	-180	-280	+005	+118	-022
1230	-312	-048	-256	-437	-123	-278	-312	-339	-180	+074	+018	-146	-218	-468	-095	-326	-180	-280	+006	+112	-010
1242	-312	-048	-256	-438	-125	-287	-313	-338	-180	+074	+018	-145	-218	-467	-094	-328	-180	-280	+007	+115	-010
1250	-312	-048	-257	-440	-124	-292	-312	-338	-180	+072	+016	-140	-220	-471	-095	-330	-185	-276	+005	+116	-010
1300	-312	-048	-257	-439	-125	-298	-314	-339	-182	+073	+016	-140	-220	-469	-096	-331	-179	-278	+005	+114	-010
1310	-312	-047	-256	-439	-124	-305	-314	-339	-182	+073	+014	-138	-219	-468	-093	-327	-179	-278	+004	+113	-008
1330	-312	-048	-257	-440	-125	-326	-316	-340	-182	+073	+014	-139	-220	-469	-097	-329	-180	-281	+001	+109	-025
1400	-314	-047	-254	-438	-121	-350	-314	-337	-180	+078	+021	-135	-218	-460	-095	-325	-174	-278	+008	+119	-020
1435	-312	-048	-256	-439	-120	-370	-319	-336	-180	+075	+016	-133	-218	-467	-096	-320	-180	-276	+006	+114	-021
1500	-311	-047	-255	-438	-118	-379	-319	-338	-180	+074	+014	-137	-220	-465	-099	-319	-178	-278	+007	+117	-022
1530																					
1200 (7 Sep)	-318	-027	-257	-441	-123	-373	-330	-331	-170	+084	+021	-130	-212	-469	-105	-312	-170	-274	+015	+122	-010

Table 5

Spontaneous Potential Measurements, Gathright Dam,

Array Electrode Potential Versus Reference Electrode,

Lower Array (mv) - 5 September 1980 (Second Injection)

	Station																				
Hr	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
0945	-309	-128	-452	-506	-180	-310	-490	-408	-060	-058	-205	-285	-235	-265	-168	-060	-250	-260	-415	+020	+022
1030	-308	-128	-450	-502	-180	-310	-495	-410	-068	-058	-210	-290	-230	-260	-175	-058	-255	-262	-418	+018	+015
1100	-306	-126	-450	-502	-178	-310	-491	-405	-065	-054	-208	-285	-230	-263	-174	-059	-250	-260	-412	+014	+017
1135	-309	-127	-450	-500	-178	-312	-491	-405	-065	-053	-210	-285	-230	-262	-175	-058	-250	-260	-410	+018	+020
1200	-311	-128	-452	-502	-180	-314	-488	-406	-066	-058	-208	-288	-235	-262	-178	-059	-258	-262	-415	+018	+018
1230	-313	-127	-452	-503	-179	-315	-488	-408	-066	-056	-210	-289	-232	-261	-178	-058	-255	-263	-411	+015	+018
1254	-313	-128	-451	-503	-178	-316	-488	-406	-063	-056	-209	-290	-233	-263	-178	-057	-253	-261	-413	+015	+015
1315	-314	-127	-452	-503	-178	-317	-488	-408	-065	-058	-210	-289	-232	-264	-179	-058	-256	-260	-414	+014	+016
1335	-315	-128	-453	-504	-181	-318	-491	-411	-067	-061	-212	-293	-235	-265	-180	-058	-253	-263	-413	+014	+016
1400	-316	-127	-452	-504	-177	-315	-487	-406	-062	-060	-207	-289	-232	-260	-175	-053	-252	-256	-408	+020	+024
1435	-317	-127	-452	-502	-178	-316	-490	-409	-068	-065	-210	-290	-232	-262	-178	-057	-256	-262	-413	+013	+017
1500	-319	-127	-452	-503	-178	-317	-488	-408	-064	-067	-210	-290	-233	-262	-176	-057	-256	-258	-410	+015	+021
1200 (7 Sep)	-376	-113	-418	-536	-187	-320	-499	-410	-055	-078	-199	-308	-246	-242	-164	-034	-273	-260	-408	+027	---

Table 6

Spontaneous Potential Measurements, Upstream Right Abutment Array

Electrode Station	SP mv	Electrode Station	SP mv
1	-210	30	+184
2	-004	30A	+129
3	+110	31	+107
4	-122	32	+170
5	-029	33	+168
6	+025	34	+078
7	+117	35	+130
8	-067	36	+171
9	+033	37	+161
10	-065	38	+053
11	-114	39	+146
12	+155	40	+153
13	+071	41	+072
14	+142	42	+125
15	+138		
16	+064		
17	+124		
18	+098		
19	+117		
20	+159		
21	+158		
22	+153		
23	+109		
24	+132		
25	+128		
26	+086		
27	+157		
28	+162		
29	+122		

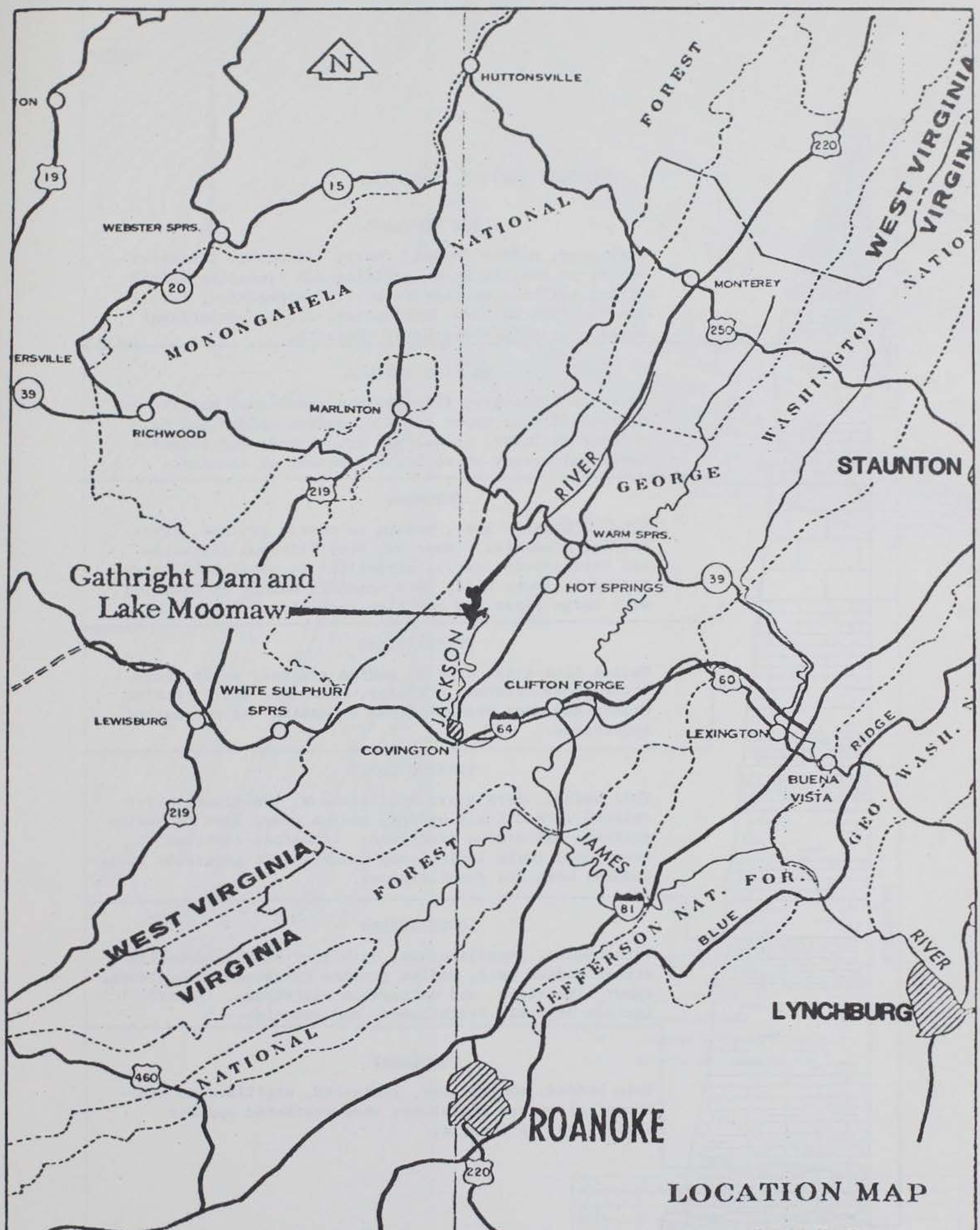
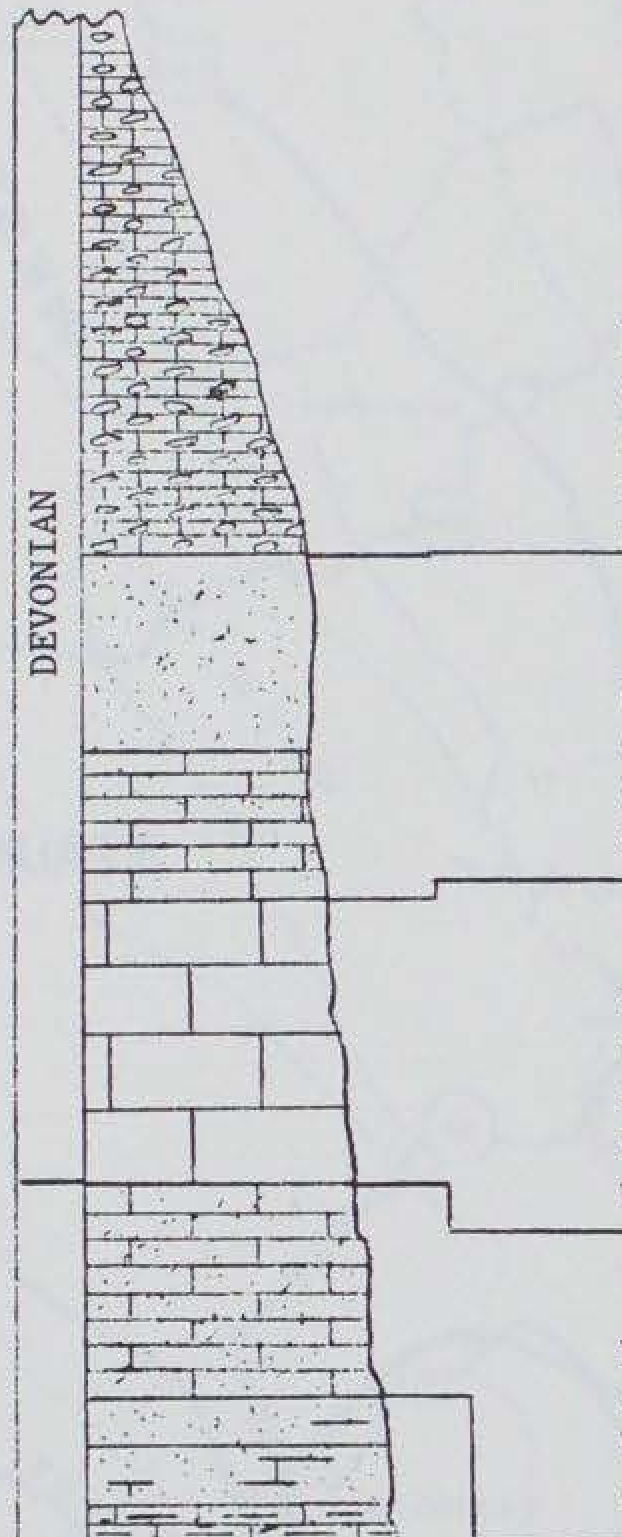


Figure 1. Location of site



GEOLOGIC SECTION, DAM SITE

NEW SCOTLAND

Dark gray, medium bedded, cherty limestone, the chert occurs as nodules in an argillaceous limestone matrix giving the beds a "ropy or knotty" appearance, fossiliferous (brachiopods, trilobites, etc.), gradational upper contacts, sharp basal contacts.

HEALING SPRINGS

White to light gray fine-grained sandstone, massive and cross-bedded in upper portion, medium bedded and calcareous in lower, occasional brachiopods and crinoids. Lower calcareous phase locally absent or changed.

COEYMANS

Blue to pinkish gray, medium to coarse grained, crystalline limestone. Massive, fossiliferous (crinoids and brachiopods, etc.), stylolitic in upper half, cross-bedded in lower half, rock weathers mainly by solution with large pipes and cavities resulting.

UPPER KEYSER

Medium blue-gray, fine to medium grained, sandy limestone, fossiliferous (bryozoa, crinoids, etc.), medium bedded and when weathered has a "nested" or pockmarked appearance.

CLIFTON FORGE

Thin bedded, dark gray, argillaceous, limestone, intercalated with thickly bedded, medium gray, fine to medium grained, calcareous sandstone. Limestone contains occasional shale laminae and sandstone is generally cross-bedded, both are fossiliferous.

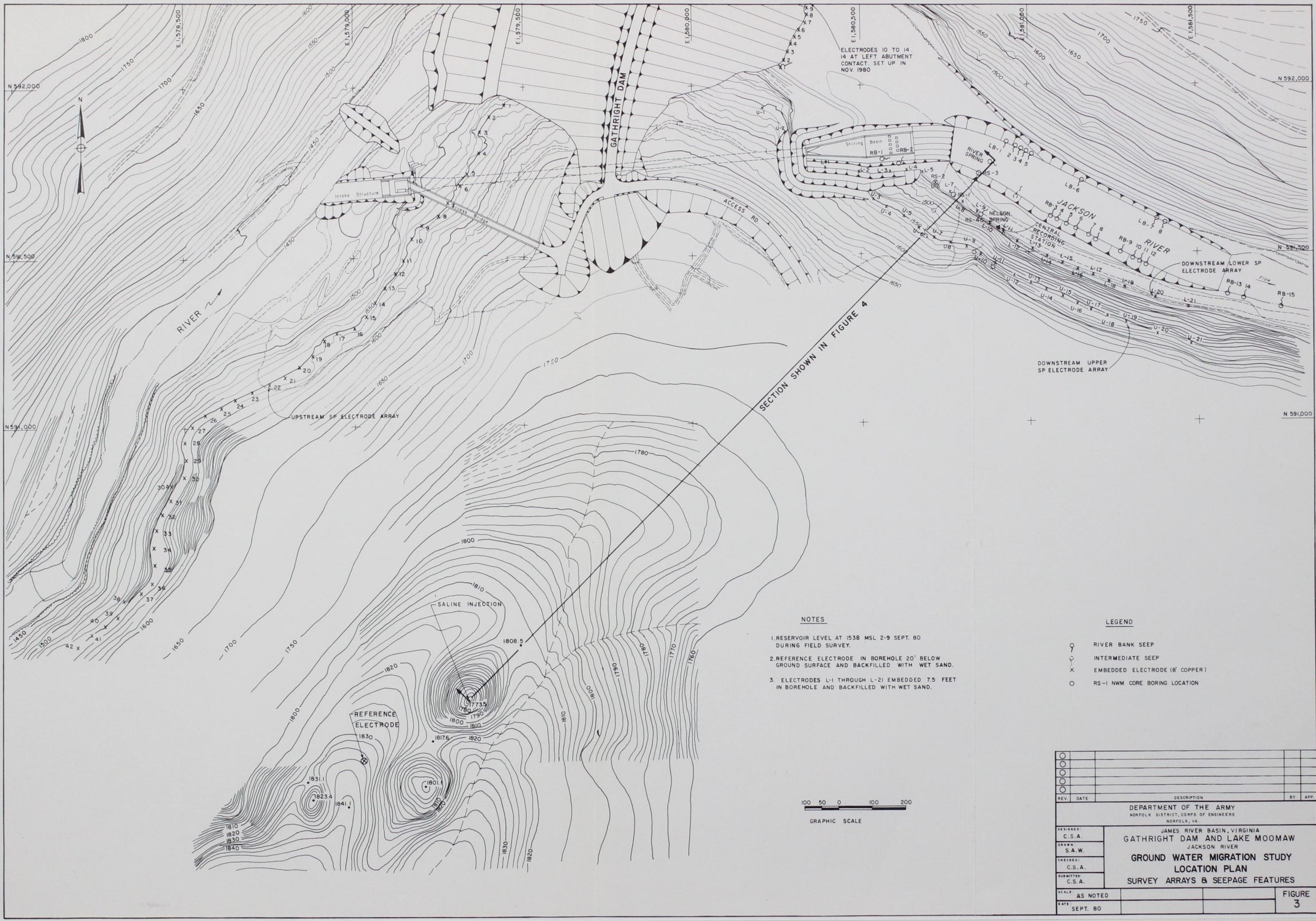
LOWER KEYSER

Interbedded, fossiliferous, dark gray argillaceous limestones medium gray, medium grained calcareous sandstones, sandy limestones, and calcareous siltstones. Fossils include bryozoi, brachiopods, and crinoids.

TONOLOWAY

Thin bedded, medium gray, laminated, argillaceous limestone/calcareous siltstone; when weathered appears shale-like, no fossils.

Figure 2. Typical geologic section



NOTES

1. RESERVOIR LEVEL AT 1538 MSL 2-9 SEPT. 80 DURING FIELD SURVEY.

2. REFERENCE ELECTRODE IN BOREHOLE 20' BELOW GROUND SURFACE AND BACKFILLED WITH WET SAND.

3. ELECTRODES L-1 THROUGH L-21 EMBEDDED 7.5 FEET IN BOREHOLE AND BACKFILLED WITH WET SAND.

LEGEND

⚲	RIVER BANK SEEP
⚲	INTERMEDIATE SEEP
×	EMBEDDED ELECTRODE (8' COPPER)
○	RS-I NWM CORE BORING LOCATION

REV.	DATE	DESCRIPTION	BY	APP.
○				
○				
○				
○				
○				

DEPARTMENT OF THE ARMY
NORFOLK DISTRICT, CORPS OF ENGINEERS
NORFOLK, VA.

DESIGNED: C.S.A.
DRAWN: S.A.W.
CHECKED: C.S.A.
SUBMITTED: C.S.A.

JAMES RIVER BASIN, VIRGINIA
GATHRIGHT DAM AND LAKE MOOMAW
JACKSON RIVER
GROUND WATER MIGRATION STUDY
LOCATION PLAN
SURVEY ARRAYS & SEEPAGE FEATURES

SCALE: AS NOTED
DATE: SEPT. 80

FIGURE
3

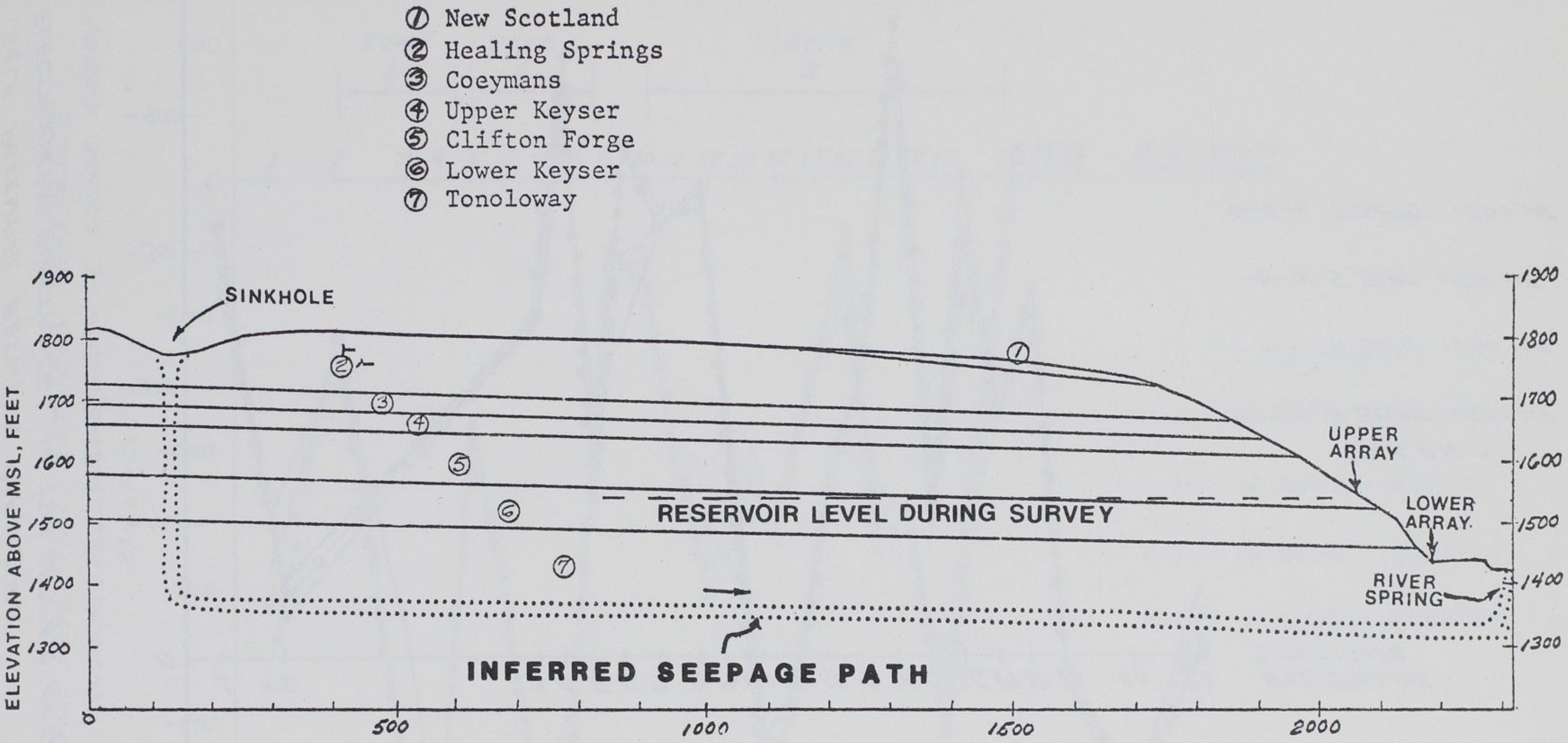


Figure 4. Cross section through right abutment showing assumed path of seepage

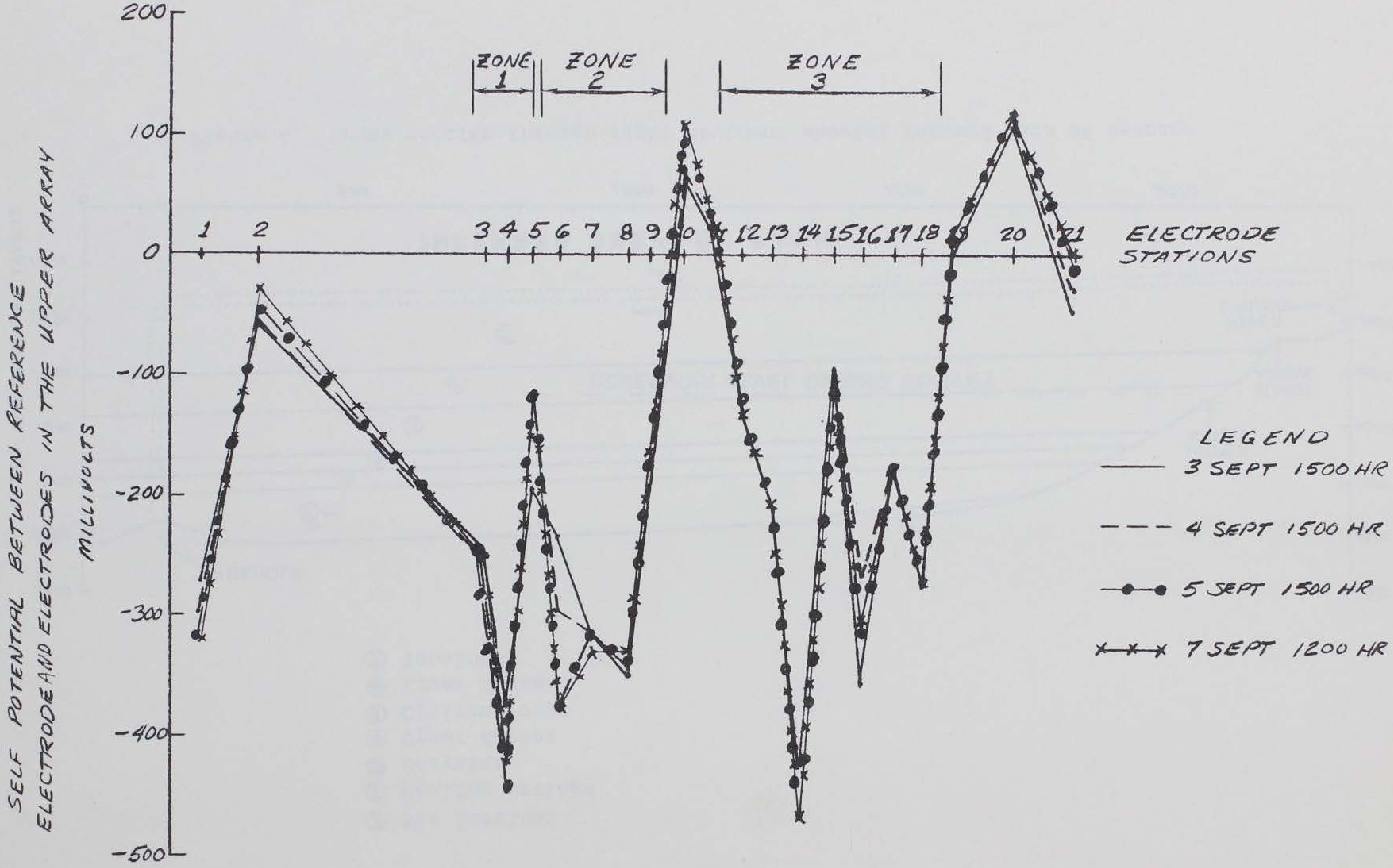


Figure 5. Measured SP values versus location in the downstream upper array (3-7 September)

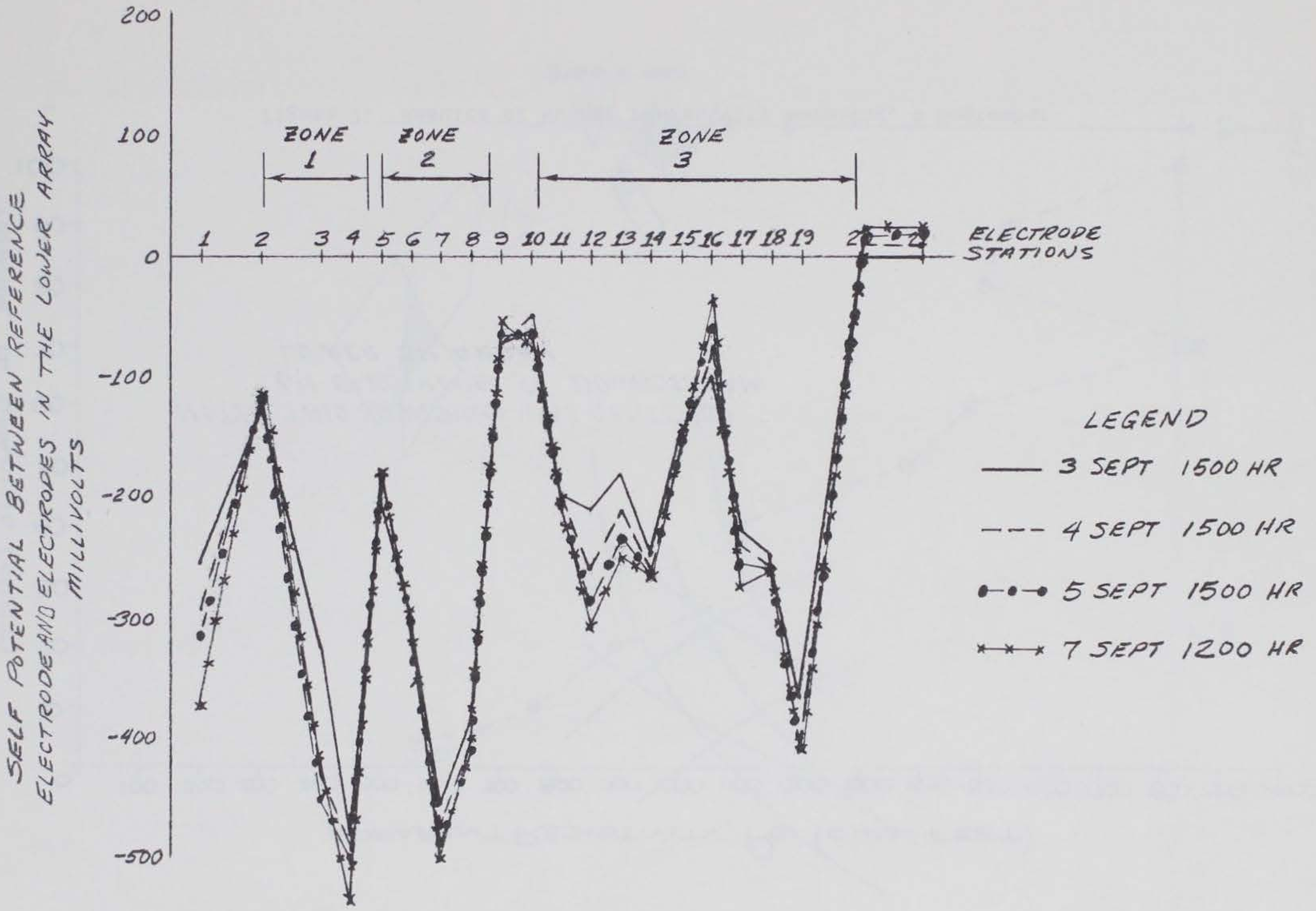
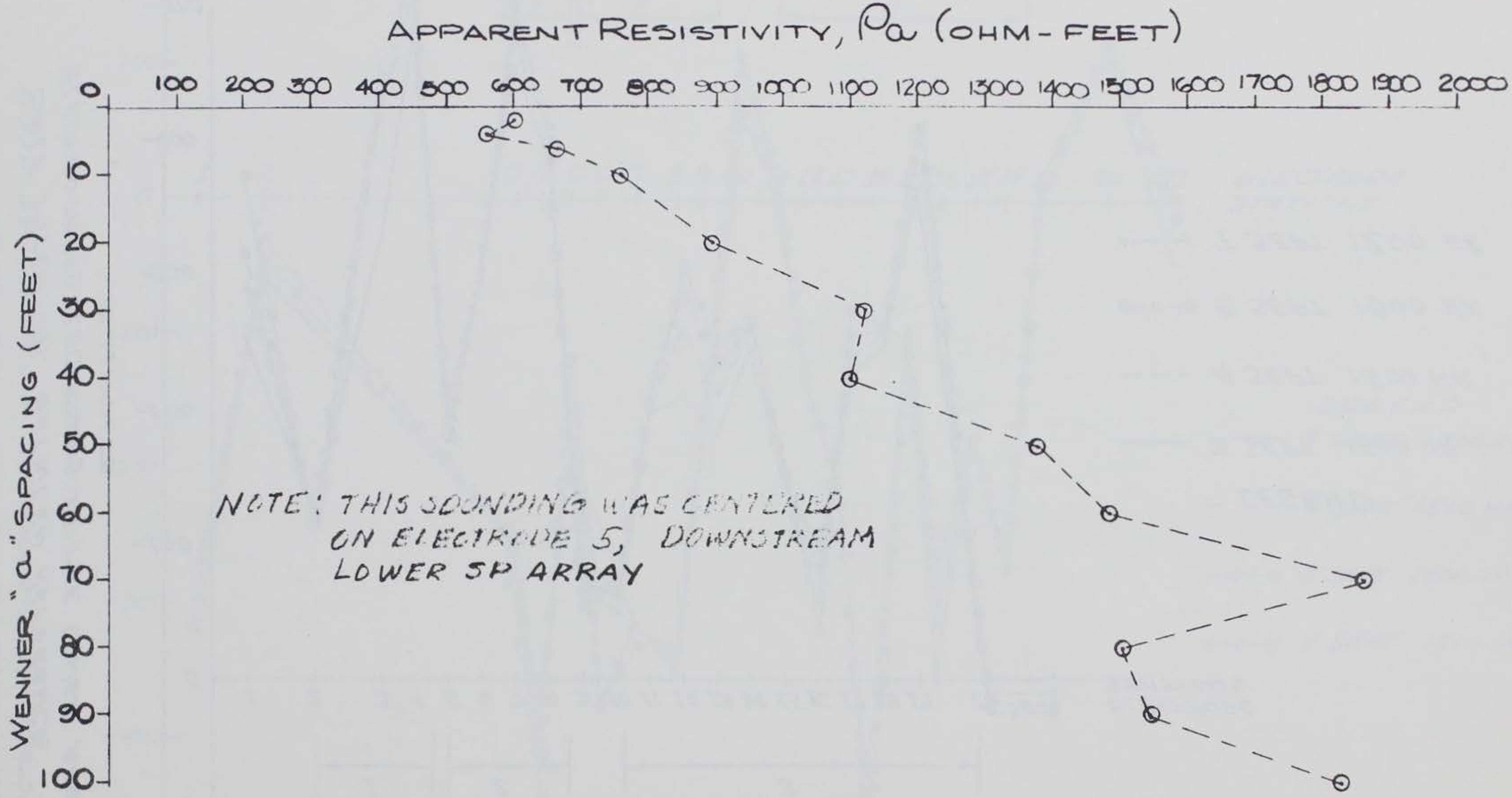


Figure 6. Measured SP values versus location in the downstream lower array (3-7 September)



NOTE: THIS SOUNDING WAS CENTERED
ON ELECTRODE 5, DOWNSTREAM
LOWER SP ARRAY

Figure 7. Results of Wenner resistivity sounding, 6 September

*Note-Borings are shown as their projection on the plane of the survey

Figure 8. Bristow-Bates resistivity survey results, low resistivity zones with core borings data superposed

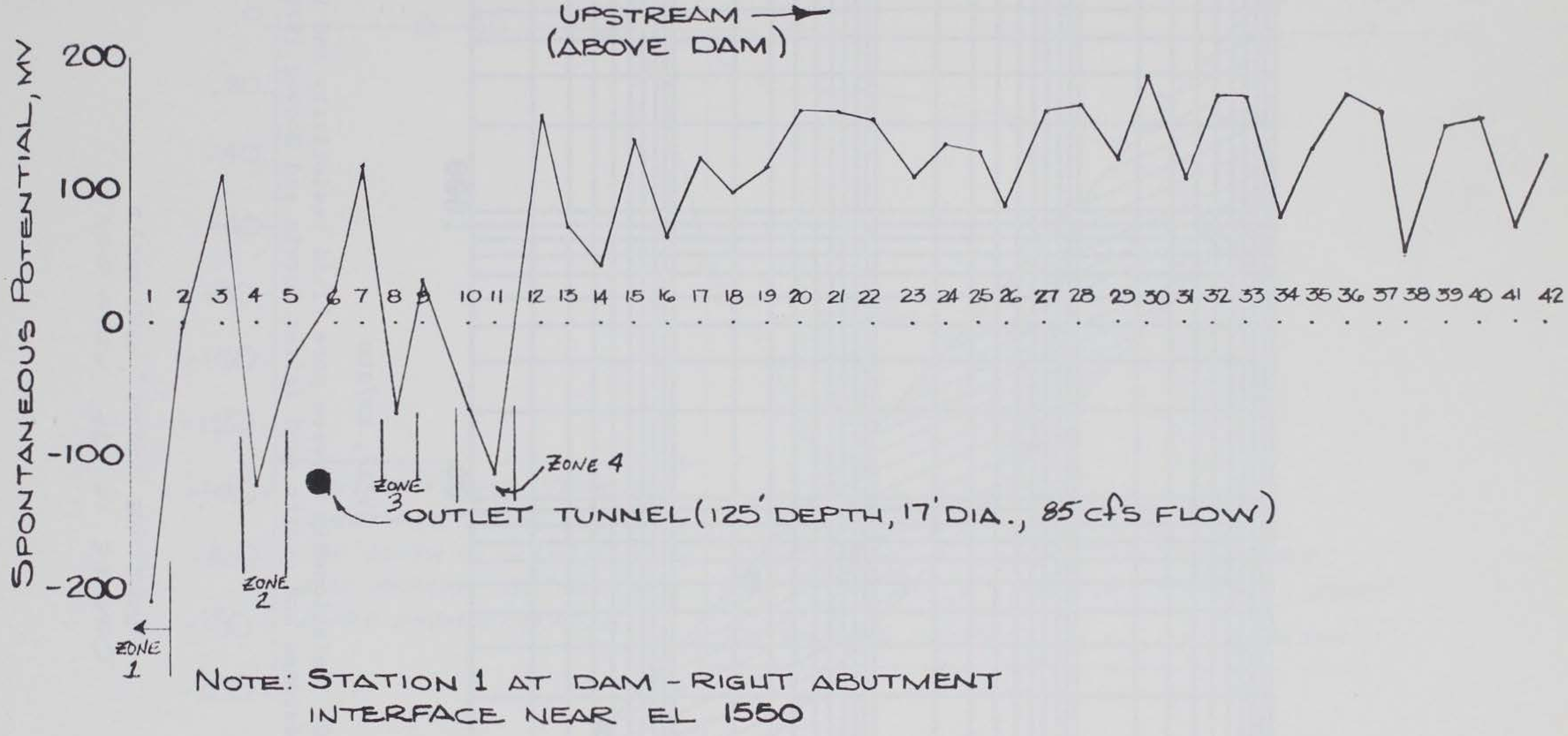


Figure 9. Measured SP values versus location in the upstream array (8 September)

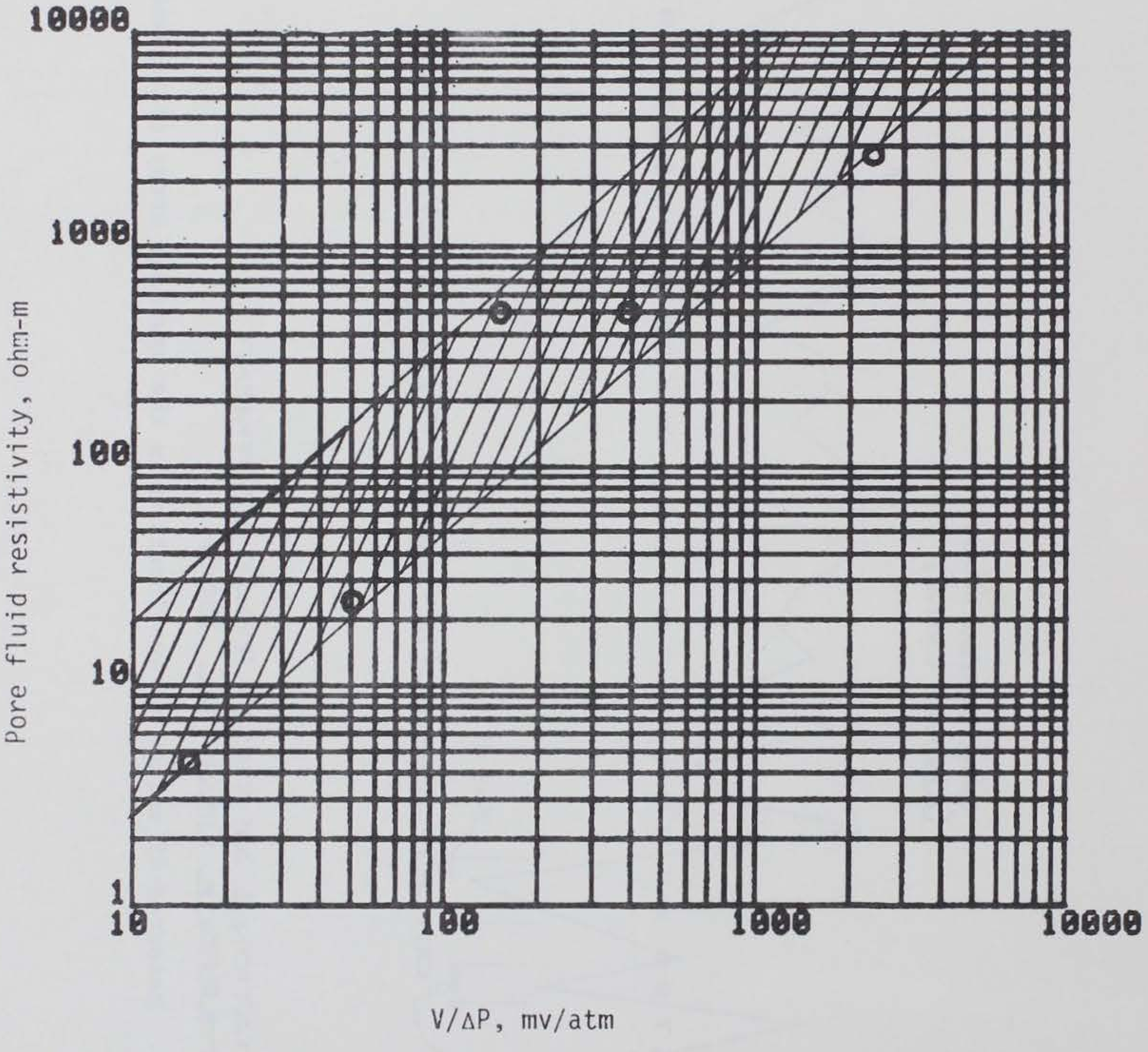


Figure 10. Relationship between pore fluid resistivity and V/ΔP for sandstones and quartz sand (after Corwin and Hoover 1979)

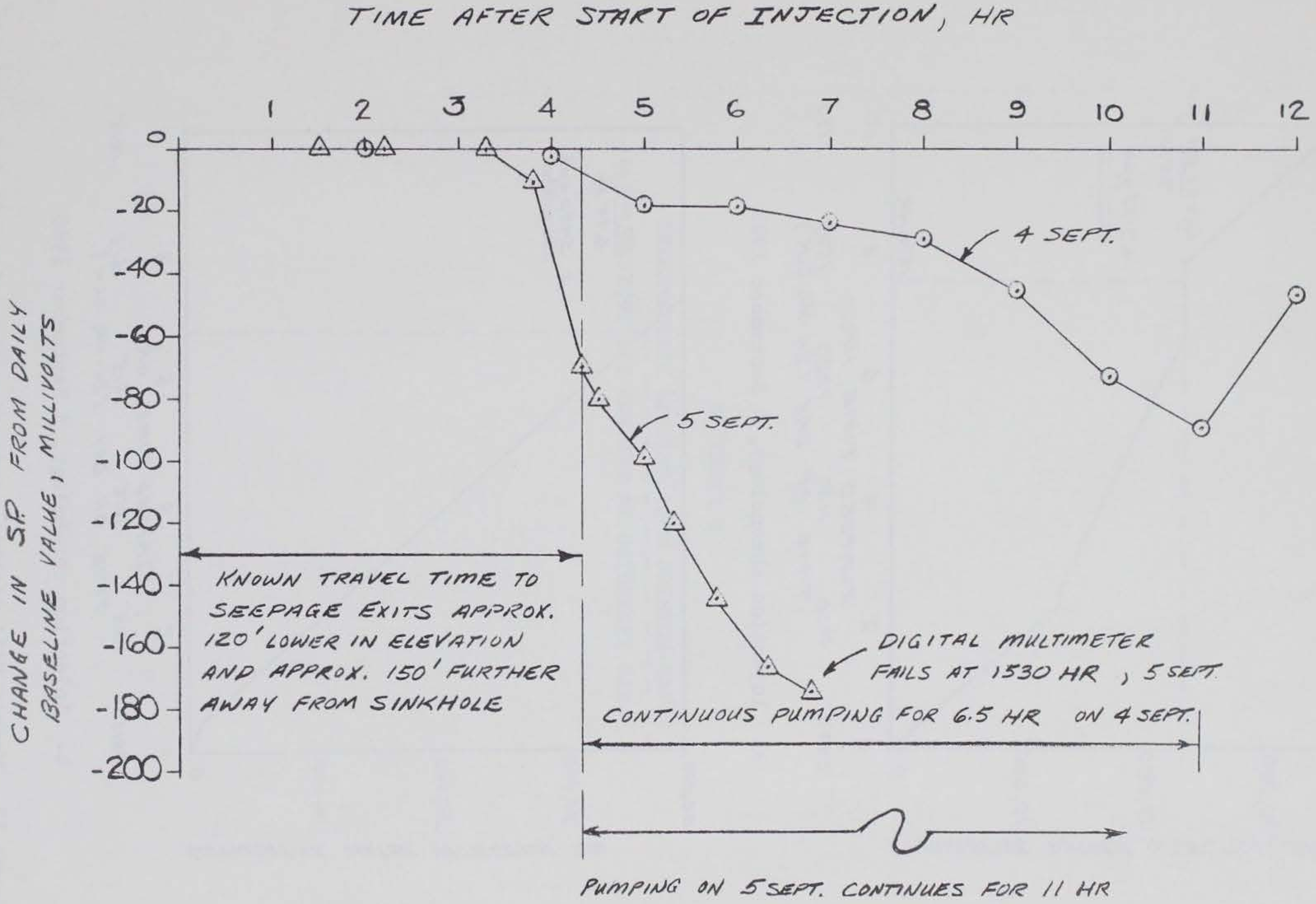
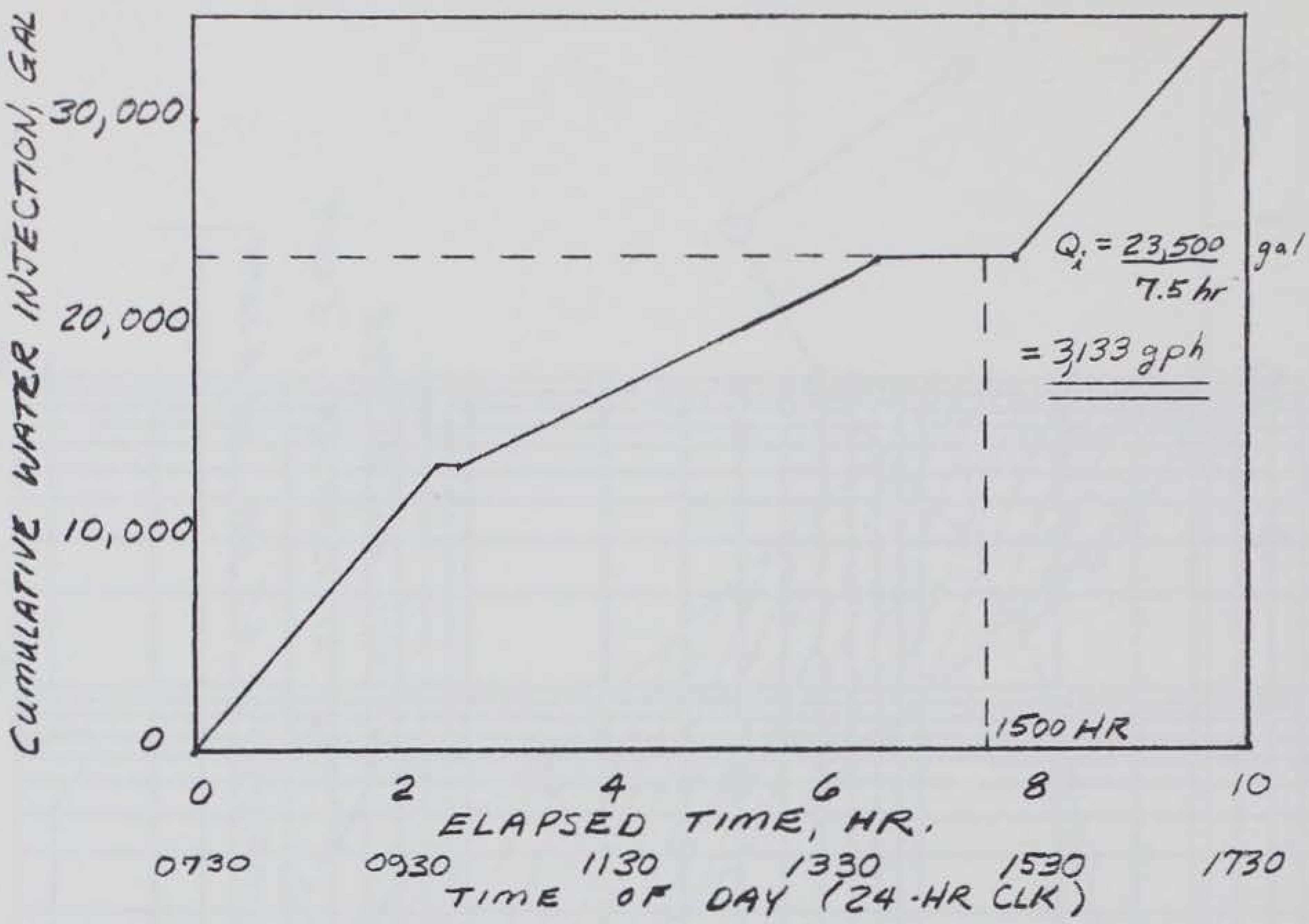
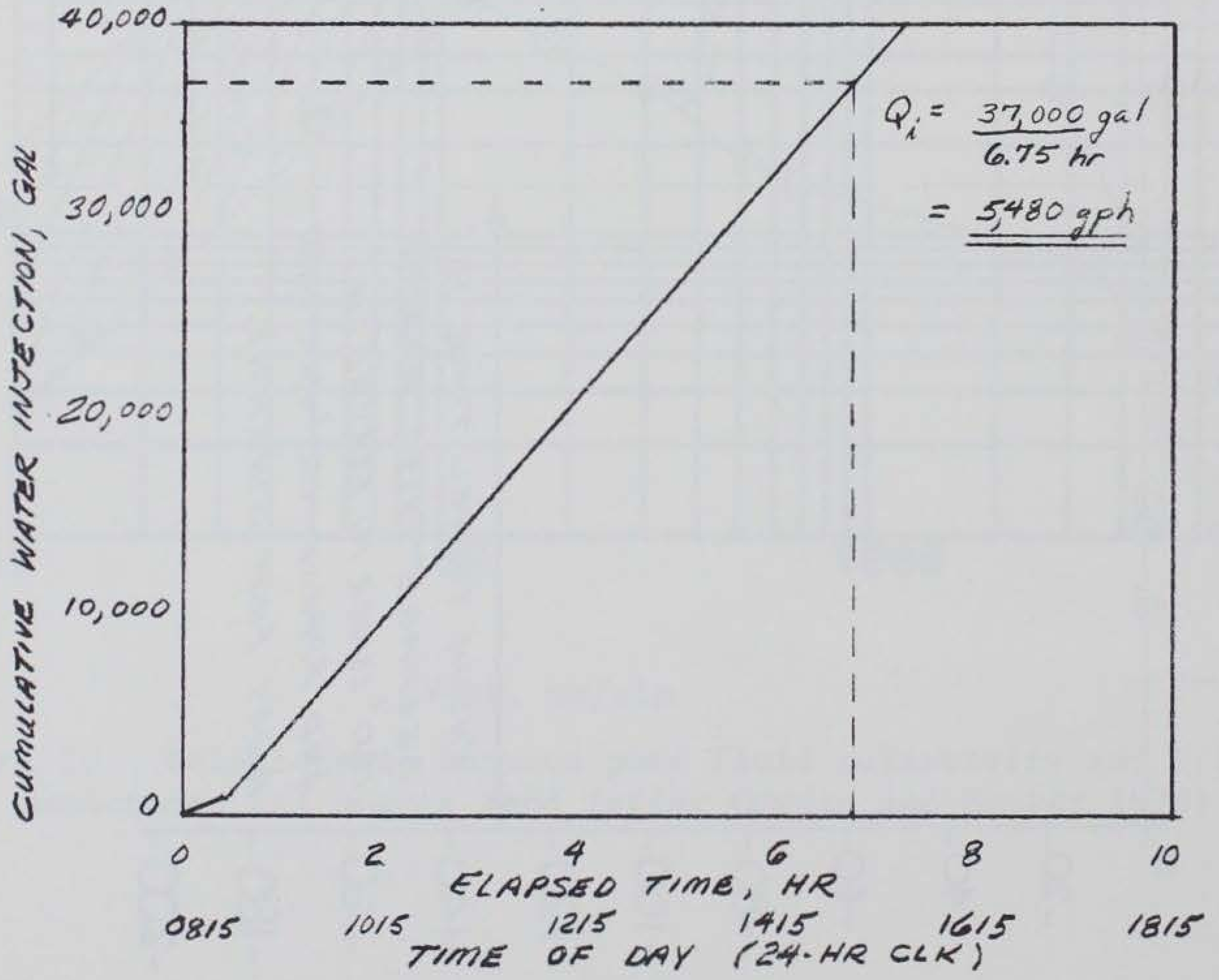


Figure 11. Postinjection SP response of electrode 6, downstream upper array (4-5 September)



a. Injection chronology, 4 September 1980

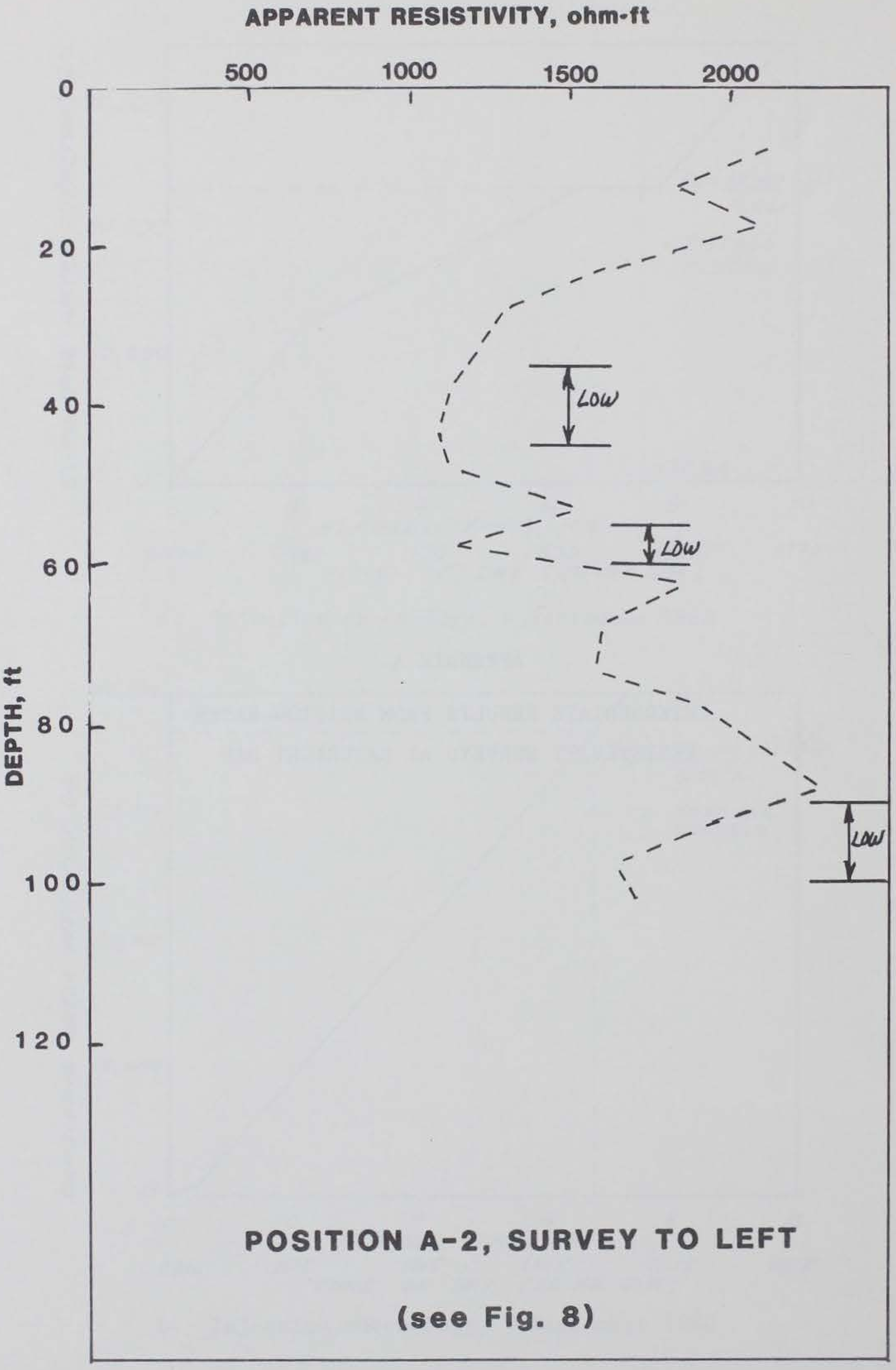


b. Injection chronology, 5 September 1980

Figure 12. Morris Hill sinkhole injection chronology (4-5 September)

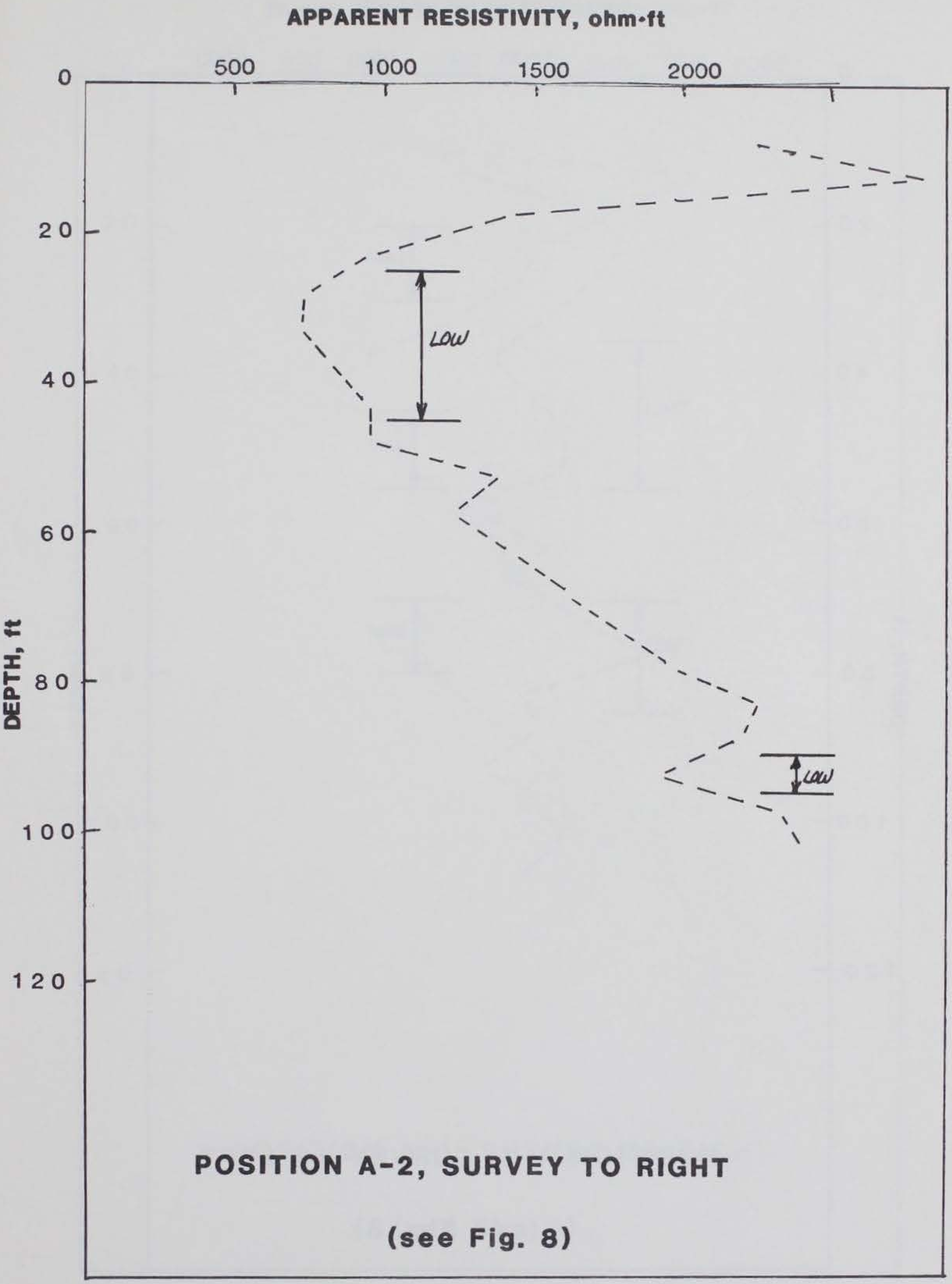
APPENDIX A

INTERMEDIATE RESULTS FROM BRISTOW-BATES RESISTIVITY SURVEYS AT GATHRIGHT DAM



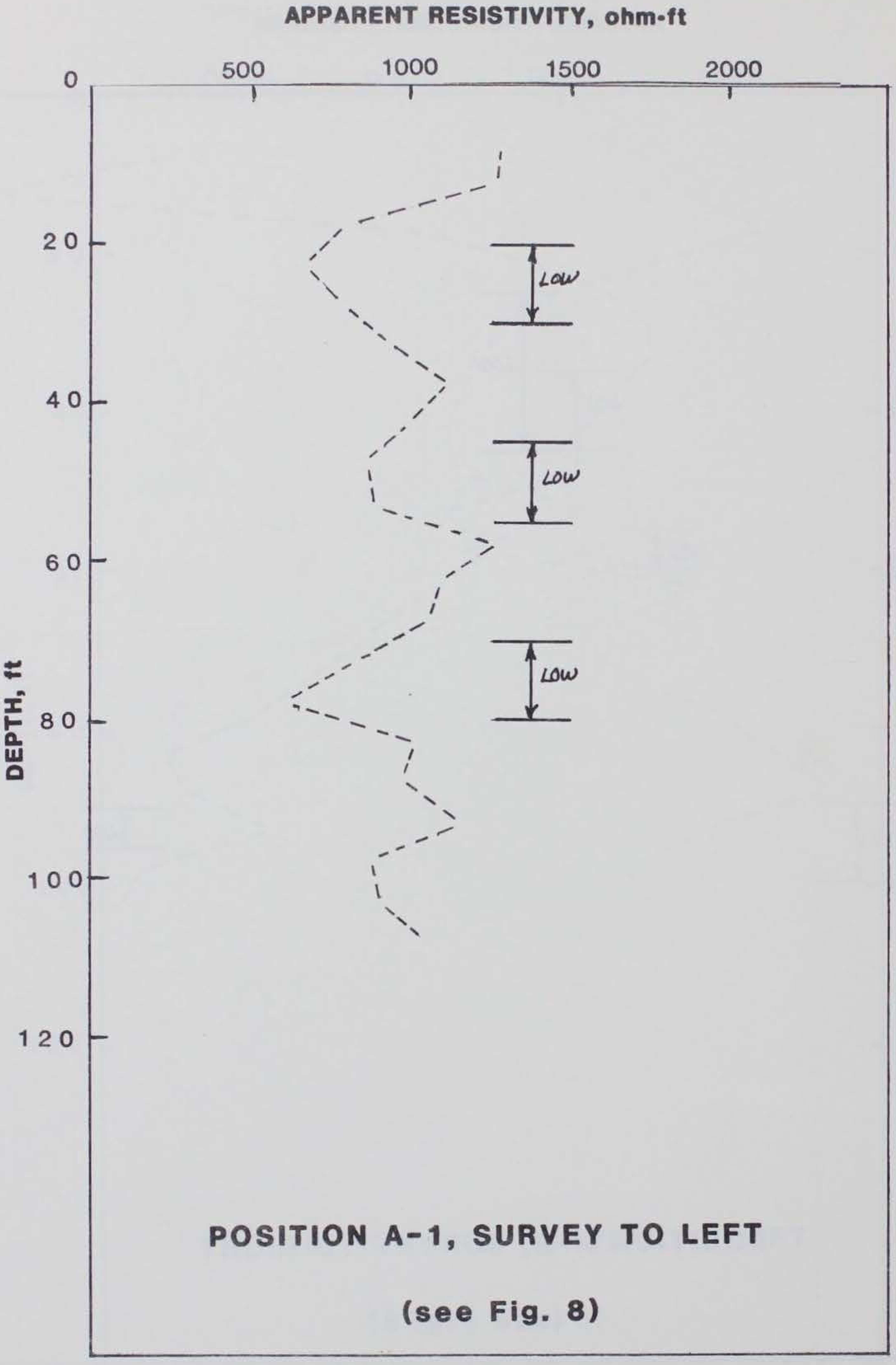
POSITION A-2, SURVEY TO LEFT

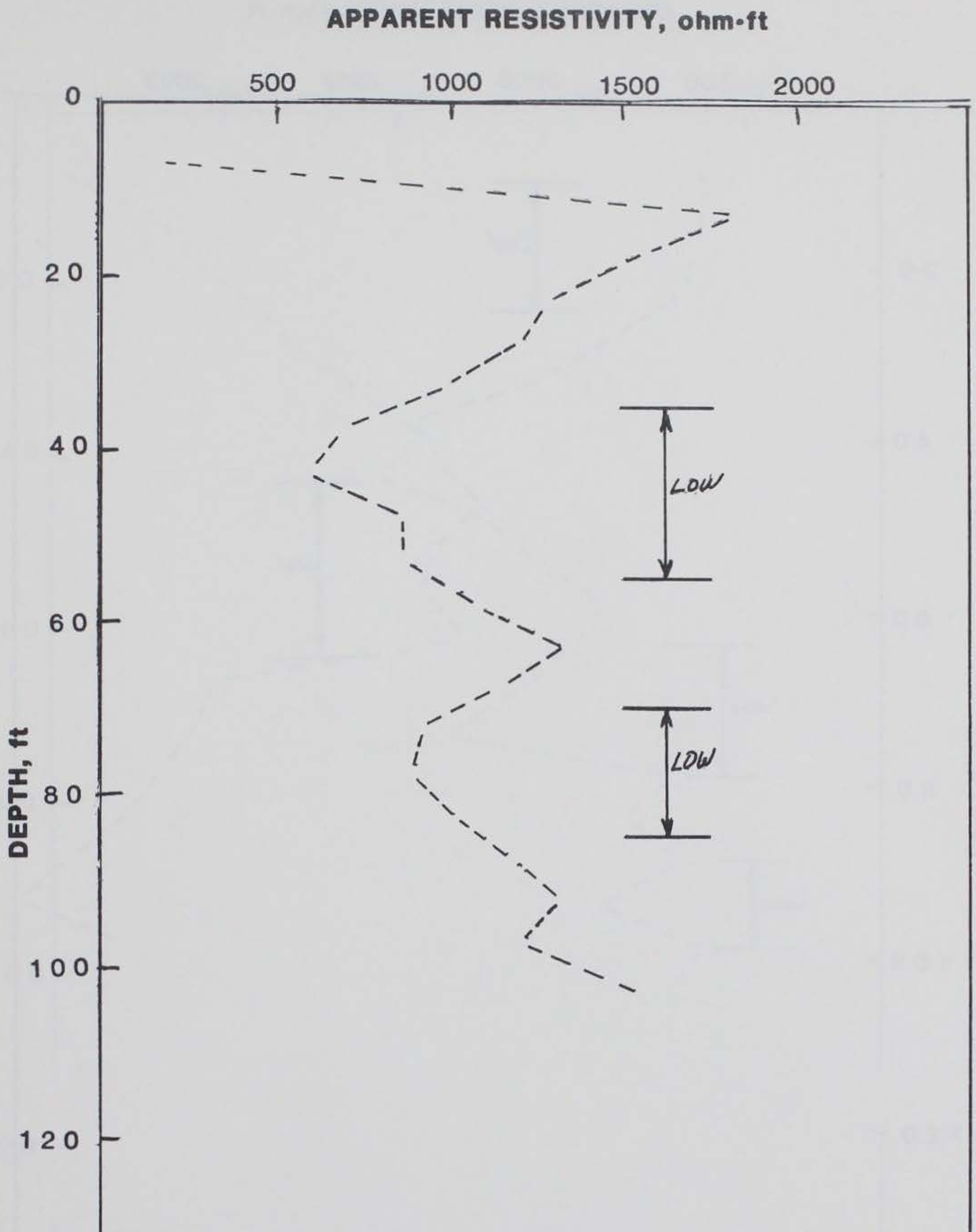
(see Fig. 8)



POSITION A-2, SURVEY TO RIGHT

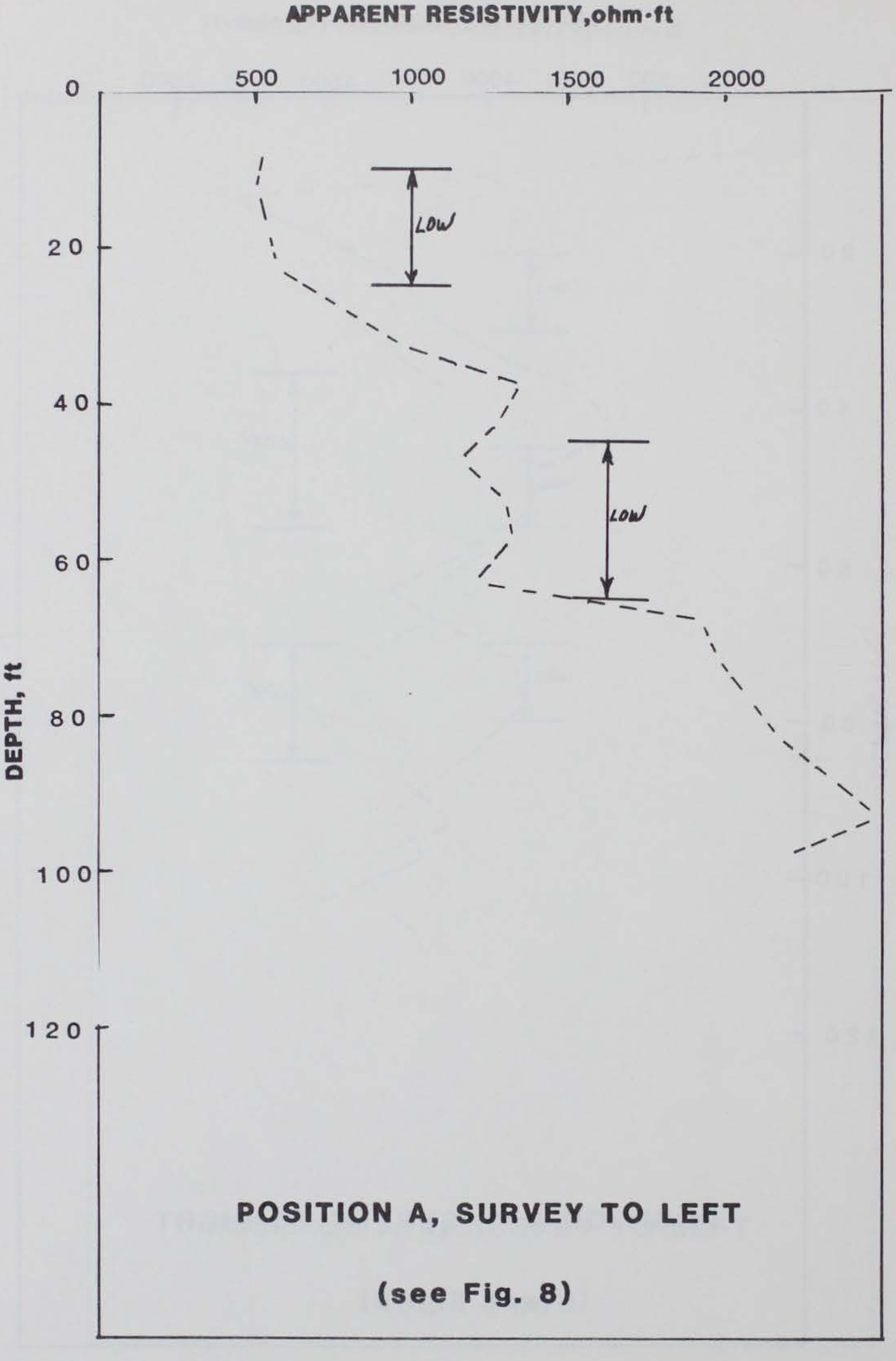
(see Fig. 8)


APPARENT RESISTIVITY, ohm-ft
0
500
1000
1500
2000
20
40
60
80
100
120
DEPTH, ft
LOW
LOW
LOW
POSITION A-1, SURVEY TO LEFT
(see Fig. 8)



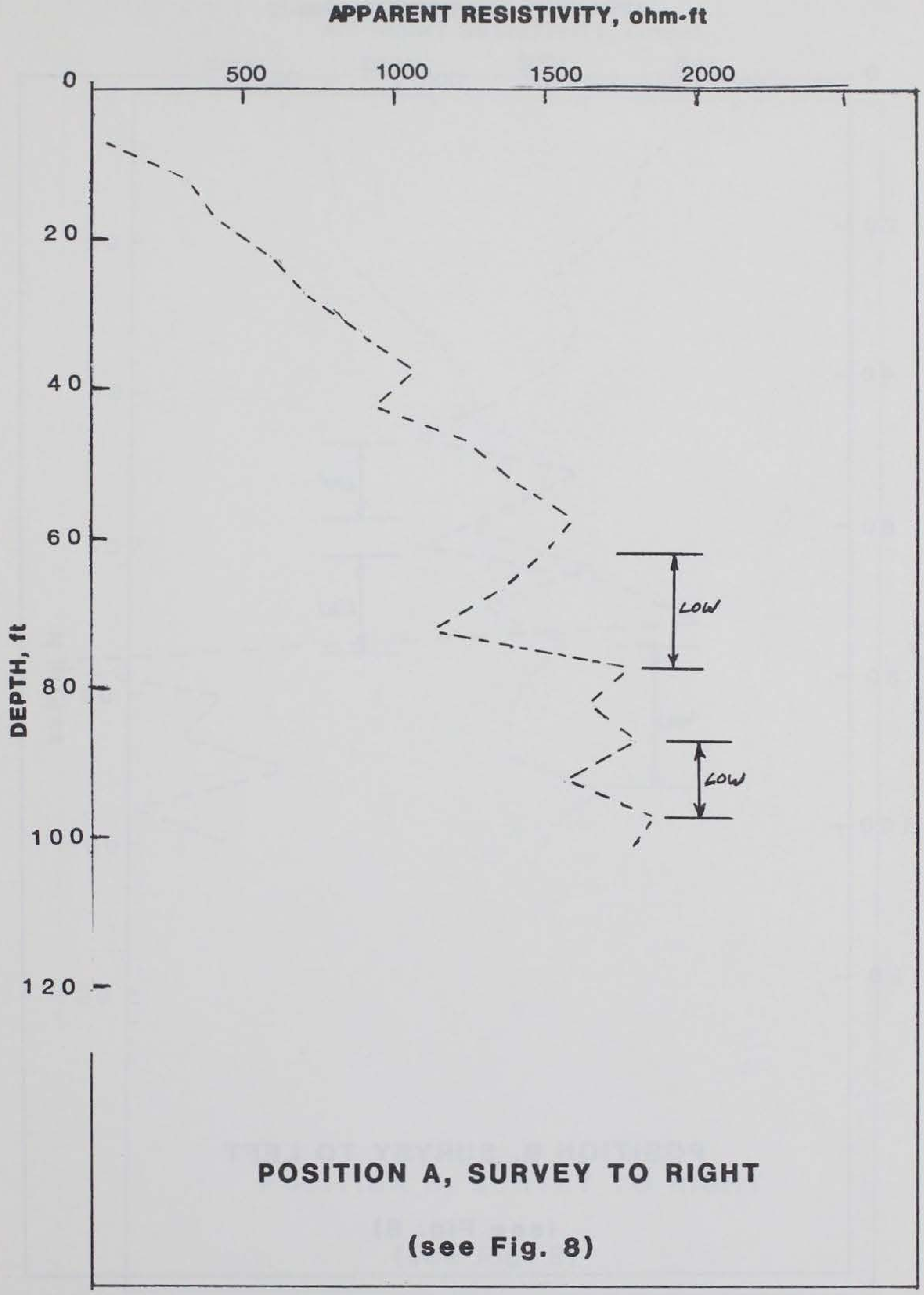
POSITION A-1, SURVEY TO RIGHT

(see Fig. 8)



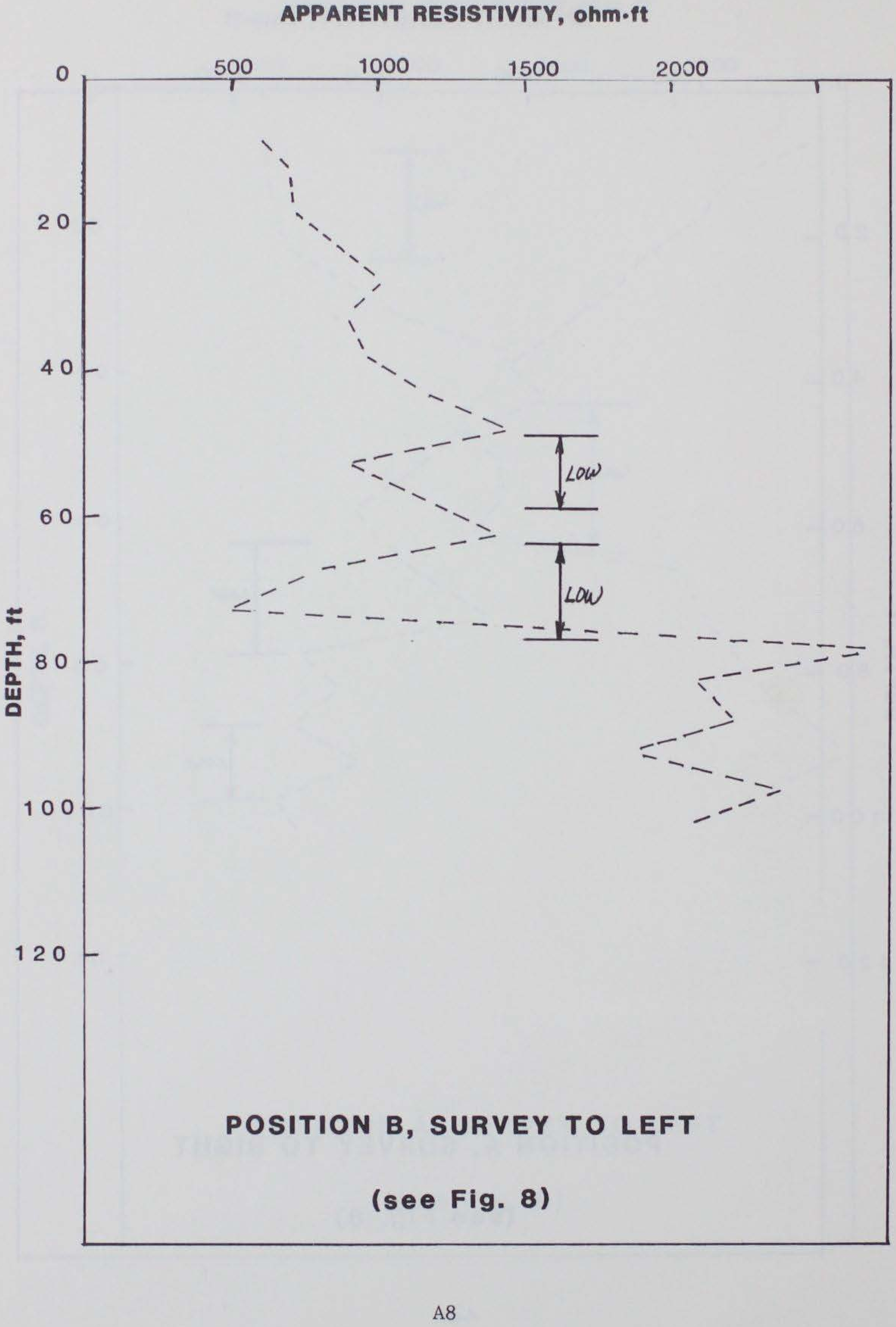
POSITION A, SURVEY TO LEFT

(see Fig. 8)



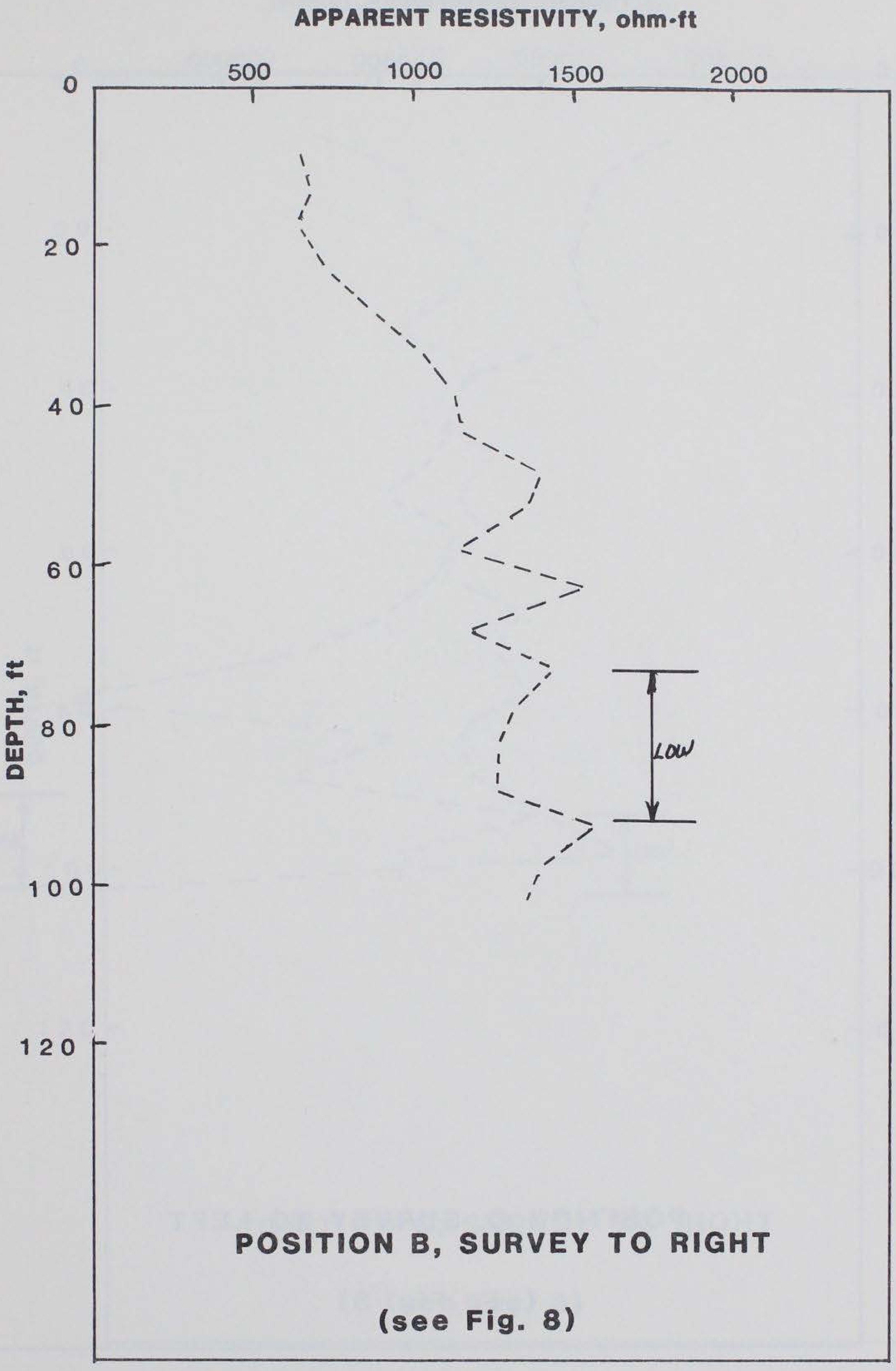
POSITION A, SURVEY TO RIGHT

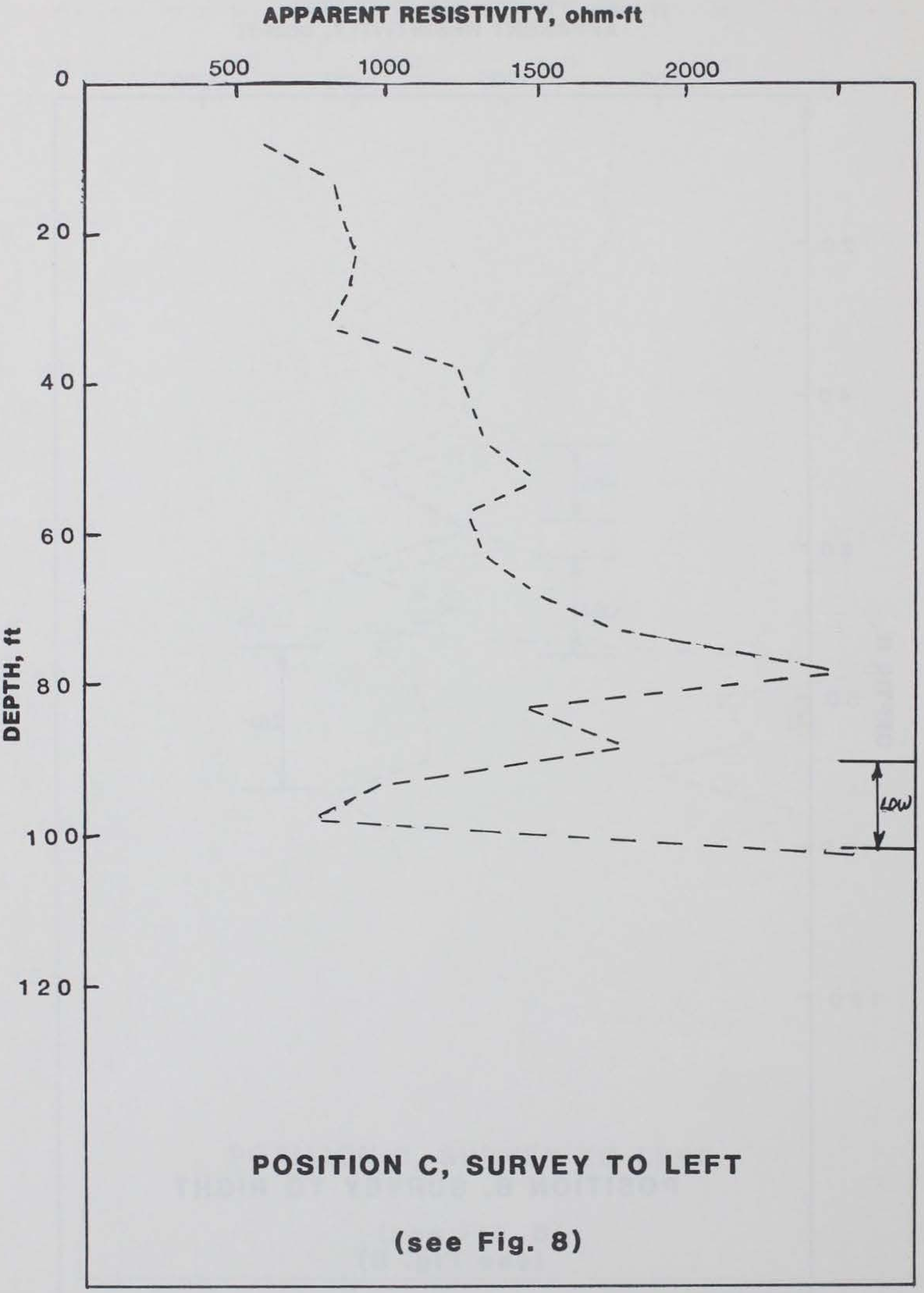
(see Fig. 8)



POSITION B, SURVEY TO LEFT

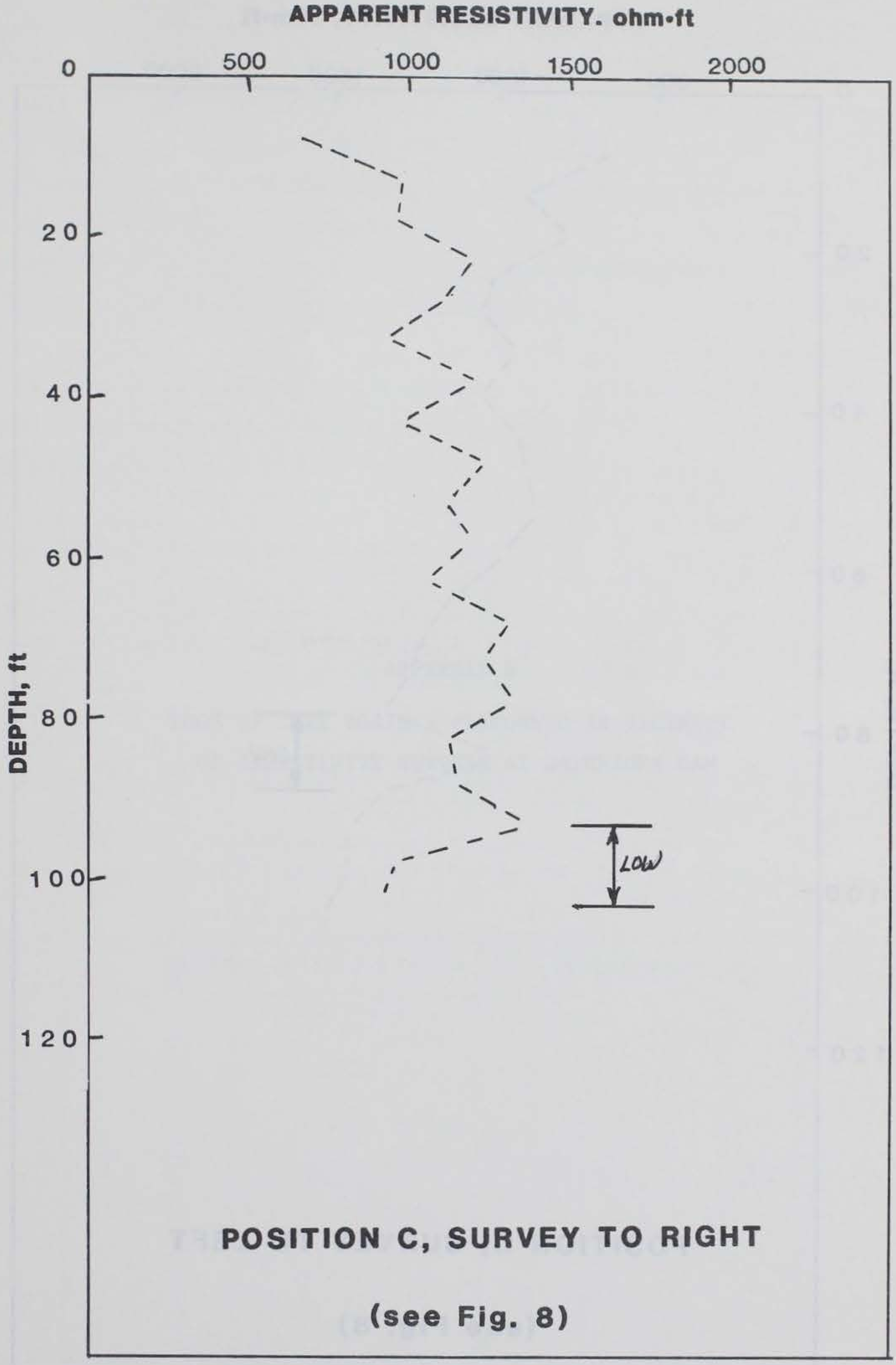
(see Fig. 8)


APPARENT RESISTIVITY, ohm-ft
500
1000
1500
2000
0
20
40
60
80
100
120
DEPTH, ft
LOW
POSITION B, SURVEY TO RIGHT
(see Fig. 8)



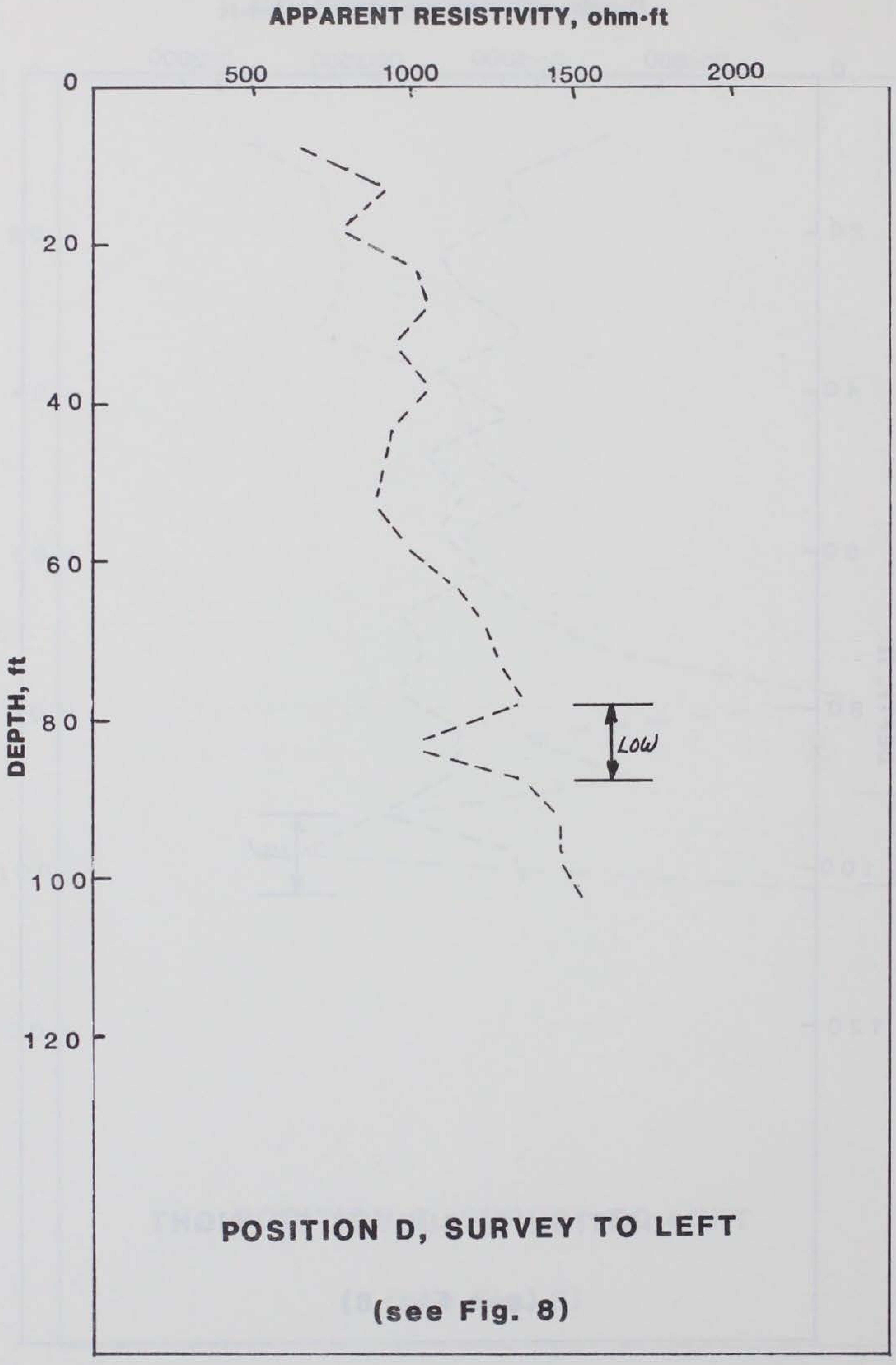
POSITION C, SURVEY TO LEFT

(see Fig. 8)



POSITION C, SURVEY TO RIGHT

(see Fig. 8)



POSITION D, SURVEY TO LEFT

(see Fig. 8)

APPENDIX B

LOGS OF CORE BORINGS PERFORMED IN VICINITY OF RESISTIVITY SURVEYS AT GATHRIGHT DAM

1. The four core borings, RS-1 through RS-4, located in Figure 3 (main text) were drilled to provide additional information about the underground aquifer and to complete the results of the resistivity study. To a certain degree, the core borings did indicate subsurface aquifers as predicted by the resistivity. Stick logs indicating core recovery, open cavities, and clay zones are presented with the probable seepage zones predicted by resistivity in Figure 8. The aquifer zones between el 1350 and 1380 msl are well documented by these core borings and stilling basin construction records.

2. Other observations made during this study prove the complex and indeterminant aquifer systems present in these limestone formations:

a. Dye testing in June 1980 confirmed connections between the large sinkhole on Morris Hill and seepage points RB-1, RB-2, River Spring, and LB-1 through LB-5. Nelson Spring was not exposed during this test; however, it was exposed by excavating a test trench in December 1980.

b. When the cavity in RS-1 was encountered, dye was injected, and returned about 3 hr later in Nelson Spring. No other known connected openings produced dye.

c. The cavity encountered in RS-2 at el 1380 produced muddy flow at RB-2 only.

d. In RS-3, the fractured and clayey zone at el 1370 produced muddy flow in the river spring.

e. Core boring RS-4 caused muddy flow in both the river spring and RB-2 when the cavity was encountered between el 1382 to 1362 msl.

f. No dye or muddy water was observed in LB-1 through LB-5 at any time during the core drilling operations.

Hole No. RS-1

DRILLING LOG

DIVISION: NAD

INSTALLATION: NAO

SHEET 1 OF 2 SHEETS

1. PROJECT: RIVER SPRING ISOLATION-GATHRIGHT DAM
2. LOCATION (Coordinates or Station): N-591 674 E-1,580,776
3. DRILLING AGENCY: CUNNINGHAM CORE DRILLING
4. HOLE NO. (As shown on drawing title and file number): RS-1
5. NAME OF DRILLER: MARVIN DEAN
6. DIRECTION OF HOLE: ☒ VERTICAL ☐ INCLINED ______ DEG. FROM VERT.
7. THICKNESS OF OVERBURDEN: 10.0'
8. DEPTH DRILLED INTO ROCK: 64.9'
9. TOTAL DEPTH OF HOLE: 74.9'
10. SIZE AND TYPE OF BIT: NXM
11. DATUM FOR ELEVATION SHOWN (TBM or MSL): MSL
12. MANUFACTURER'S DESIGNATION OF DRILL: SPRAGUE & HENWOOD 40A
13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN: DISTURBED 0 UNDISTURBED 0
14. TOTAL NUMBER CORE BOXES: 4
15. ELEVATION GROUND WATER: 1419.6 w/casing
16. DATE HOLE: STARTED 16 Dec 80 COMPLETED 17 Dec 80
17. ELEVATION TOP OF HOLE: 1429.6 w/casing
18. TOTAL CORE RECOVERY FOR BORING: 56.6 87.2 %
19. SIGNATURE OF INSPECTOR: DANIEL H. DAVIS

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g	
1429.6	0		OVER BURDEN - Rubble from construction, wood, boulders, steel, etc.			Advanced hole with NXBW single tube starter barrel ahead of NX casing. 10.0-10.5 CL-0.5'	
1419.6	10.0		Top of Rock			NX casing seated at 10.5'	10.5
			Calcareous Siltstone (Tonoloway) laminated horizontal bedding, moderately hard, gray & brown varved appearance, slightly weathered along laminations (10.5-14.5) scattered fractures along laminations	REC = 100% RQD= 80%	Run 1 Box 1 10.1'	10.5-20.6 CL-0.0 Core taken w/NXM double tube barrell dk gray below 14.5' 0.2' vuggy zones at 17.5' and 19.2'	20.6
				REC = 100%	Run 2 Box 1 & 2	20.6-30.6 CL-0.0	
1405.6	24.0		gray & brown varved appearance				
1402.1	27.5		hard, dk gray	RQD = 80%	10.0'		30.6
				REC = 100%	Run 3 Box 2	30.6-40.6 CL-0.0	
1397.6	32.0		brown				
1396.6	33.0		dk. grey	RQD = 87%	10.0'		40.6
1389.0	40.6		vuggy, zone	REC = 100%	Run 4 Box 3	40.6-50.6 CL-0.0	
1386.7	42.9		dk gray	RQD = 85%	10.0'	Pressure Tested 38.5 to 43.5 @ 21 psi for 10 minutes - No Water Taken	
1379.6	50.0						

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PROJECT: RIVER SPRING ISSOLATION GATHRIGHT DAM

HOLE NO. RS-1

Hole No. RS-1

DRILLING LOG	DIVISION NAD	INSTALLATION NAO	SHEET 2 OF 2 SHEETS

1. PROJECT RIVER SPRING ISOLATION-GATHRIGHT DAM
2. LOCATION (Coordinates or Station) N-591,674 E- 1,591,776
3. DRILLING AGENCY CUNNINGHAM CORE DRILLING
4. HOLE NO. (As shown on drawing title and file number) RS-1
5. NAME OF DRILLER MARVIN DEAN
6. DIRECTION OF HOLE ☒ VERTICAL ☐ INCLINED ______ DEG. FROM VERT.
7. THICKNESS OF OVERBURDEN 10.0'
8. DEPTH DRILLED INTO ROCK 64.9'
9. TOTAL DEPTH OF HOLE 74.9'
10. SIZE AND TYPE OF BIT NXM
11. DATUM FOR ELEVATION SHOWN (TBM or MSL) MSL
12. MANUFACTURER'S DESIGNATION OF DRILL SPRAGUE & HENWOOD 40A
13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN DISTURBED 0 UNDISTURBED 0
14. TOTAL NUMBER CORE BOXES 4
15. ELEVATION GROUND WATER 1419.6 w/casing
16. DATE HOLE STARTED 16 Dec 80 COMPLETED 17 Dec 80
17. ELEVATION TOP OF HOLE 1429.6
18. TOTAL CORE RECOVERY FOR BORING 56.6' 87.2%
19. SIGNATURE OF INSPECTOR DANIEL H. DAVIS

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g	
1379.6	50		Highly weathered 45° fracture at 53.9' some clay and calcite crystals, below that dk grey w/large irregular calcite stringers	REC = 47%	Run 5 Box 3 & 4	50.6-62.0 CL-6.0 Water Loss @ 55.4'	50.6
1374.2	55.4	■	WATER FILLED CAVITY	RQD = .06%	5.4'		
1368.2	61.4		Closly spaced 45° fractures w/clay and calcite crystals, gray & brown, apparrent contorted zone	REC = 69% RQD = 39%	Run 6 Box 4 2.9'	3 actual runs due to blocking 62.0-66.2 CL-1.3	62.0
1363.0	66.6		gray, laminated	REC = 100%	Run 7 Box 4	66.2-74.9 CL-0.0	66.2
1360.6	69.0		vuggy zones				
1357.1	72.5						
1354.7	74.9			RQD = 8.3%	8.7'		74.9
			BOH = 74.9' = 1354.7 WLOC (cased) = 10.0' = 1419.6				

ENG FORM 1836 MAR 71 PREVIOUS EDITIONS ARE OBSOLETE.

(TRANSLUCENT)

PROJECT RIVER SPRING ISSOLATION GATHRIGHT DAM

HOLE NO. RS-1

Hole No. RS-2

DRILLING LOG

DIVISION NAD

INSTALLATION NAO

SHEET 1 OF 2 SHEETS

1. PROJECT RIVER SPRING ISOLATION-GATHRIGHT DAM
2. LOCATION *(Coordinates or Station)* N-591, 710/E-1,580 725
3. DRILLING AGENCY CUNNINGHAM CORE DRILLING & GROUTING CORP
4. HOLE NO. *(As shown on drawing title and file number)* RS-2
5. NAME OF DRILLER MARVIN DEAN
6. DIRECTION OF HOLE ☒ VERTICAL ☐ INCLINED ______ DEG. FROM VERT.
7. THICKNESS OF OVERBURDEN 7.0
8. DEPTH DRILLED INTO ROCK 73.5
9. TOTAL DEPTH OF HOLE 80.5
10. SIZE AND TYPE OF BIT NXM
11. DATUM FOR ELEVATION SHOWN *(TBM or MSL)* MSL
12. MANUFACTURER'S DESIGNATION OF DRILL SPRAGUE & HENWOOD 40-A
13. TOTAL NO. OF OVERBURDEN SAMPLES TAKEN DISTURBED 0 UNDISTURBED 0
14. TOTAL NUMBER CORE BOXES 5
15. ELEVATION GROUND WATER
16. DATE HOLE STARTED 23 Dec 80 COMPLETED 24 Dec 80
17. ELEVATION TOP OF HOLE 1430.5
18. TOTAL CORE RECOVERY FOR BORING 68.6' 93.3 %
19. SIGNATURE OF INSPECTOR J. SWEAN

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS *(Description)* d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS *(Drilling time, water loss, depth of weathering, etc., if significant)* g	
1430.5	0		Overburden, fill, gobbles, gravel, sand, clay, wood				
1423.5	7.0		Top of Rock				7.0
			Siltstone, dk. gray, thin bedded, slightly calcareous, hard, fn. to dense texture, bedding slightly dipping, fractures along bedding, with fen fractures across bedding, slightly weathered, some pitting present. (TONOLOWAY)	Rec= RQD= 0	Run 1 Box 1	7.0-10.2 CL-1.5	
				REC= 100	Run 2	10.2-20.4 CL-0.0	10.
1414.9	15.6		Weathered zone, lt. gray		Box 1		
1413.7	16.8		Hard Rock, dk. gray				
				RQD= 77			20.4
1407.1	23.4		23.4-23.6 -zone of badly weathered rock, soft, lt. gray	REC= 100	Run 3	20.4-30.5 CL-0.0	
1404.7	25.8		25.8-26.2-laminations are micro folded.		Box 1 & 2	24.1-24.4-zone of calcite healing across bedding planes.	
				RQD= 78			30.5
			31.4-31.7 zone of weathered rock	REC 100	Run 4 Box 2	30.5-40.5 CL-0.0	
1393.4	37.1		Zone of badly weathered rock, heavy concentration of calcite healed seams				
1390.0			39.4-Cavity through core	RQD 75			40.5
	40.5		Hard rock, dk. gray 41.7-calcite healed zone	REC= 100	Run 5	40.5-50.5 CL-0.0	
			45.0-small 0.01' cavity		Box 3		
1380.5	50			RQD 79			

ENG FORM 1836 1 APR 63 PREVIOUS EDITIONS MAY BE USED *(EM 1110-1-1801)* GPO 1963 OF-712-878

PROJECT RIVER SPRING ISOLATION GATHRIGHT DAM

HOLE NO RS-2

Hole No. RS-2

DRILLING LOG

DIVISION: NAD

INSTALLATION: NAO

SHEET 2 OF 2 SHEETS

1. PROJECT: RIVER SPRING ISOLATION-GATHRIGHT DAM
2. LOCATION *(Coordinates or Station)*: N 591,710 E-1580,725
3. DRILLING AGENCY: CUNNINGHAM CORE DRILLING & GROUTING
4. HOLE NO. *(As shown on drawing title and file number)*: RS-2
5. NAME OF DRILLER: MARVIN DEAN
6. DIRECTION OF HOLE: ☒ VERTICAL ☐ INCLINED ______ DEG. FROM VERT.
7. THICKNESS OF OVERBURDEN: 7.0
8. DEPTH DRILLED INTO ROCK: 73.5
9. TOTAL DEPTH OF HOLE: 80.5
10. SIZE AND TYPE OF BIT: NXM
11. DATUM FOR ELEVATION SHOWN *(TBM or MSL)*: MSL
12. MANUFACTURER'S DESIGNATION OF DRILL: SPRAGUE & HENWOOD 40-A
13. TOTAL NO. OF OVERBURDEN SAMPLES TAKEN: DISTURBED 0 UNDISTURBED 0
14. TOTAL NUMBER CORE BOXES: 5
15. ELEVATION GROUND WATER:
16. DATE HOLE: STARTED 23 Dec 80 COMPLETED 24 Dec 80
17. ELEVATION TOP OF HOLE: 1430.5
18. TOTAL CORE RECOVERY FOR BORING: 68.6' 93.3 %
19. SIGNATURE OF INSPECTOR: J. SWEAN

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS *(Description)* d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS *(Drilling time, water loss, depth of weathering, etc., if significant)* g	
1380.5	50		Hard rock, dk. gray	REC 66	Run 6	50.5-60.5 CL-3.4	50.5
1377.2	53.3	■	Rock is badly weathered lt. tan, clay present in seams pitted, fractured along bedding planes		Box 3 & 4	Lost water 53.3' rod drop 53.3-54.3 alternate cut & drop 54.3-56.2 spring RB-2 muddy 30 minutes after water loss at 53.3'	
1374.3	56.2			RQD 38			
1370.0	60.5		Hard rock, dk. gray	REC 100	Run 7	60.5-70.5 CL-0.0	60.5
					Box 4		
				RQD 80			70.5
						70.5-80.5 CL-0.0	
1358.6	71.9		Rock is badly weathered lt. tan, pitted, vuggy.	REC 100	Run 8		
1357.1	73.4		Hard rock, dk. gray		Box 4 & 5		
				RQD 76			
1350.0	80.5						80.5
			BOH - 80.5' elev. 1350.0				

ENG FORM 1836
1 APR 63

PREVIOUS EDITIONS MAY BE USED (EM 1110-1-1801)
GPO 1963 : OF—713-575

PROJECT: RIVER SPRING ISOLATION GATHRIGHT DAM

HOLE NO. RS-2

Hole No. RS-3

DRILLING LOG

DIVISION NAD

INSTALLATION NAO

SHEET 1 OF 2 SHEETS

1. PROJECT RIVER SPRING ISOLATION~~-~~-GATHRIGHT DAM
2. LOCATION (Coordinates or Station) N-591,740 E-1,580,855
3. DRILLING AGENCY CUNNINGHAM CORE DRILLING & GROUTING CORP
4. HOLE NO. (As shown on drawing title and file number) RS-3
5. NAME OF DRILLER MARVIN DEAN
6. DIRECTION OF HOLE ☒ VERTICAL ☐ INCLINED ______ DEG. FROM VERT.
7. THICKNESS OF OVERBURDEN 1.3'
8. DEPTH DRILLED INTO ROCK 72.9
9. TOTAL DEPTH OF HOLE 74.2'
10. SIZE AND TYPE OF BIT NXM
11. DATUM FOR ELEVATION SHOWN (TBM or MSL) MSL
12. MANUFACTURER'S DESIGNATION OF DRILL SPRAGUE & HENWOOD 40-A
13. TOTAL NO. OF OVERBURDEN SAMPLES TAKEN DISTURBED 0 UNDISTURBED 0
14. TOTAL NUMBER CORE BOXES 5
15. ELEVATION GROUND WATER 1415.1 (River)
16. DATE HOLE STARTED 22 Dec 80 COMPLETED 22 Dec 80
17. ELEVATION TOP OF HOLE 1414.6
18. TOTAL CORE RECOVERY FOR BORING 71.1' 97.5%
19. SIGNATURE OF INSPECTOR J. SWEAN

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g	
1414.6 1413.3			Overburden-Alluvium deposit sand, gravel & cobbles				
			Top of Rock	REC=83 RQD=0	Run 1 Box 1	1.3-2.5 CL-0.2	1.3 2.5
			Siltstone, gray, thinly bedded, slightly calcareous, moderately hard, bedding v. gently dipping, slightly weathered, pitted, few calcite filled seams, fractures occur along bedding planes. (TONOLOWAY)	REC= 95 RQD= 63	Run 2 Box 1	2.5-8.1 CL-0.3	8.1
1404.5	10.1		10.1-13.1 alternating black and gray laminations.	REC= 100	Run 3 Box 1 & 2	8.1-18.3 CL-0.0 Solution zone @ 8.7' Calcite crystals in void	
1401.5	13.1						
1396.3	18.3		17.7-18.3-Zone of badly weathered rock.	RQD = 83			18.3
			Hard rock, dk. gray	REC= 100 RQD= 93	Run 4 Box 2	18.3-28.3 CL-0.0	28.3
			36.8' calcite seam	REC= 100 RQD= 100	Run 5 Box 2 & 3	28.3-38.3 CL-0.0	38.3
1369.2	45.4		Rock is broken up into gravel size fragments, color change to lt. tan	REC= 100 RQD 9.5	Run 6 Box 3	38.3-46.1 CL-0.0 Pressure tested 40.5 to 45.5 @ 20 psi for 5 minutes - water take 55 gallons. K=1011.2 feet/year	46.1
1365.2	49.4		46.1-49.4-badly weathered, clay present in fractures	REC = 88	Run 7 Box 4	46.1-56.1 CL-1.2 Pressure tested 45.0-500 @ 20 psi for 5 minutes-water take-105.0 gallon K=1847.6 feet/year	
			Hard rock, dk. gray				

ENG FORM 1 APR 63 1836 PREVIOUS EDITIONS MAY BE USED (EM 1110-1-1801) GPO 1963 OF-712-278

PROJECT RIVER SPRING ISOLATION GATHRIGHT DAM

HOLE NO. RS-3

Hole No. RS-3

DRILLING LOG
DIVISION NAD
INSTALLATION NAO
SHEET 2 OF 2 SHEETS

1. PROJECT RIVER SPRING ISOLATION—GATHRIGHT DAM
2. LOCATION *(Coordinates or Station)* N 591,740 E-1,580,855
3. DRILLING AGENCY CUNNINGHAM CORE DRILLING & GROUTING CORP
4. HOLE NO. *(As shown on drawing title and file number)* RS-3
5. NAME OF DRILLER MARVIN DEAN
6. DIRECTION OF HOLE ☒ VERTICAL ☐ INCLINED ____ DEG. FROM VERT.
7. THICKNESS OF OVERBURDEN 1.3
8. DEPTH DRILLED INTO ROCK 72.9
9. TOTAL DEPTH OF HOLE 74.2'
10. SIZE AND TYPE OF BIT NXM
11. DATUM FOR ELEVATION SHOWN *(TBM or MSL)* MSL
12. MANUFACTURER'S DESIGNATION OF DRILL SPRAGUE & HENWOOD 40-A
13. TOTAL NO. OF OVERBURDEN SAMPLES TAKEN DISTURBED 0 UNDISTURBED 0
14. TOTAL NUMBER CORE BOXES 5
15. ELEVATION GROUND WATER 1415.1 (River)
16. DATE HOLE STARTED 22 Dec 80 COMPLETED 22 Dec 80
17. ELEVATION TOP OF HOLE 1414.6
18. TOTAL CORE RECOVERY FOR BORING 71.1' 97.5 %
19. SIGNATURE OF INSPECTOR J. SWEAN

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS *(Description)* d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS *(Drilling time, water loss, depth of weathering, etc., if significant)* g	
1364.6	50		49.4-56.1 Hard, non weathered rock, dk. gray.	RQD= 76		Pressure test 49.0-54.0' @ 20 psi for 5 minutes- water take 35 gallons. K=587.5 feet/year While drilling between depths 50.0-51.0-river boil became muddy.	56.1
				REC= 99	Run 8 Box 4	56.1-66.1 CL-0.1	
1354.0	60.6		60.6-60.8 badly pitted zone.			Pressure test-54.0-74.2 @ 20 psi for 5 minutes water take 6 gallons K=28.9 feet/year	
			64.6-64.9 clay filled seam lt. tan color	RQD 93			66.1
				REC= 100	Run 9	66.1-74.2 CL-0.0	
1347.0	67.6		Hard, nonweathered rock, dk. gray		Box 4 & 5		
				RQD= 99			
1340.4	74.2'						74.2
			BOH - 74.2' elev. 1340.4				

ENG FORM 1836 1 APR 63 PREVIOUS EDITIONS MAY BE USED *(EM 1110-1-1801)*
GPO 1965 OF—712-279

PROJECT RIVER SPRING ISOLATION GATHRIGHT DAM
HOLE NO. RS-3

Hole No. RS-4C

DRILLING LOG

DIVISION NAD

INSTALLATION NAO

SHEET 1 OF 2 SHEETS

1. PROJECT RIVER SPRING ISOLATION-GATHRIGHT DAM
2. LOCATION (Coordinates or Station) N 591,615 E-1,580,860
3. DRILLING AGENCY CUNNINGHAM CORE DRILLING & GROUTING CORP
4. HOLE NO. (As shown on drawing title and file number) RS-4C
5. NAME OF DRILLER MARVIN DEAN
6. DIRECTION OF HOLE ☒ VERTICAL ☐ INCLINED ____ DEG. FROM VERT.
7. THICKNESS OF OVERBURDEN 0
8. DEPTH DRILLED INTO ROCK 81.7
9. TOTAL DEPTH OF HOLE 81.7
10. SIZE AND TYPE OF BIT NXM
11. DATUM FOR ELEVATION SHOWN (TBM or MSL) MSL
12. MANUFACTURER'S DESIGNATION OF DRILL SPRAGUE & HENWOOD 40-A
13. TOTAL NO. OF OVERBURDEN SAMPLES TAKEN DISTURBED 0 UNDISTURBED 0
14. TOTAL NUMBER CORE BOXES 5
15. ELEVATION GROUND WATER 1420.2 w/casing
16. DATE HOLE STARTED 07 Jan 81 COMPLETED 09 Jan 81
17. ELEVATION TOP OF HOLE 1418.4
18. TOTAL CORE RECOVERY FOR BORING 60' 73.4%
19. SIGNATURE OF INSPECTOR J. SWEAM

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g	
1418.4	0		Siltstone, lt. gray, thin bedded, calcareous, clayey, moderately hard, dense texture, flat bedding, badly weathered. (TONOLOWAY)	REC 90	Run 1 Box 1	0.0-1.0 CL-0.1	0
				REC= 63 RQD= 10	Run 2 Box 1	1.0-5.8 CL-1.8	
1412.6	5.8		Rock is moderately weathered lt. tan, clay present in fractures & voids.	REC= 83 RQD= 56	Run 3 Box 1	5.8-12.8 CL-1.2	5.8
1410.3	8.1		Hard rock, dk. gray				
1406.6	11.8		Rock is badly weathered pitted vuggy				
				REC= 100 RQD= 87	Run 4 Box 1 & 2	12.8-22.7 CL-0.0	12.8
1404.9	13.5		Hard rock, dk. gray				
1399.5	18.9		18.9-19.5 concentrated vuggy zone				
1398.9	19.5						
				REC= 99 RQD= 96	Run 5 Box 2	22.7-30.6 CL-0.1	22.
1392.1	26.3		Rock is badly weathered, cavities with calcite crystals, ~~pitted~~.				
1390.2	28.2		Hard rock, dk. gray				
				REC= 63 RQD= 54	Run 6 Box 3	30.6-45.5 CL-5.6 River spring and RB-2 muddied during drilling-flow cleared as hole advanced in depth.	30.
1379.9	38.5		Rock is badly weathered				
1378.8	39.6	■	Clay seam and void 2 foot rod drop in zone				
1376.8	41.6		Soft clay 41.6				
1373.7	44.7		Rock is badly weathered broken up into gravel size fragments, lt. gray & yellow, cavities, clay deposits in seams				
				REC= 53 RQD=0	Run 7 Box 3	45.5-47.8 CL-1.1	45.5
				REC= 19	Run 8 Box 4	47.8-58.6 CL-8.8	47.8
1368.4	50						

ENG FORM 1 APR 63 1836 PREVIOUS EDITIONS MAY BE USED (EM 1110-1-1801)
GPO 1963 : OF-715-279

PROJECT RIVER SPRING ISOLATION GATHRIGHT DAM

HOLE NO. RS-4C

Hole No. RS-4C

DRILLING LOG

DIVISION NAD

INSTALLATION NAO

SHEET 2 OF 2 SHEETS

1. PROJECT RIVER SPRING ISOLATION GATHRIGHT DAM
2. LOCATION *(Coordinates or Station)* N 591,615 E 1,580,860
3. DRILLING AGENCY CUNNINGHAM CORE DRILLING & GROUTING CORP.
4. HOLE NO. *(As shown on drawing title and file number)* RS-4C
5. NAME OF DRILLER MARVIN DEAN
6. DIRECTION OF HOLE ☒ VERTICAL ☐ INCLINED ______ DEG. FROM VERT.
7. THICKNESS OF OVERBURDEN 0
8. DEPTH DRILLED INTO ROCK 81.7
9. TOTAL DEPTH OF HOLE 81.7
10. SIZE AND TYPE OF BIT N x M
11. DATUM FOR ELEVATION SHOWN *(TBM or MSL)* MSL
12. MANUFACTURER'S DESIGNATION OF DRILL SPRAGUE & HENWOOD 40-A
13. TOTAL NO. OF OVERBURDEN SAMPLES TAKEN DISTURBED 0 UNDISTURBED 0
14. TOTAL NUMBER CORE BOXES 5
15. ELEVATION GROUND WATER 1423.4 w/casing
16. DATE HOLE STARTED 07 JAN 81 COMPLETED 09 JAN 81
17. ELEVATION TOP OF HOLE 1421.6
18. TOTAL CORE RECOVERY FOR BORING 60' 73.4 %
19. SIGNATURE OF INSPECTOR J. SWEAN

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS *(Description)* d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS *(Drilling time, water loss, depth of weathering, etc., if significant)* g	
1368.4	50		No core recovery from 50-59.2 zone is mostly clay, some rock fragments			47.8-58.6 CL-8.8	
				RQD = 8			58.6
1359.2	59.2		59.2-59.7 - Rock is moderately weathered	Rec.= 78	Run 9	58.6-71.7 CL-2.9	
			Hard rock, Dk gray		Box 4 & 5		
1352.4	66.0		Clay seam, probable core loss zone				
1349.4	69.0						
				RQD = 67			71.7
				REC = 99	Run 10	71.7-81.7 CL0.1	
					Box 5		
1336.7	81.7			RQD = 83			81.7
			BOH - 81.7'				

ENG FORM 1836 1 APR 63 PREVIOUS EDITIONS MAY BE USED (EM 1110-1-1801)
GPO 1963 : OF-718-878

PROJECT RIVER SPRING ISOLATION GATHRIGHT DAM

HOLE NO. RS-4C