ROCK RIPPABILITY STUDY

FINAL REPORT

OCTOBER 1969

Prepared by

STATE DEPARTMENT OF HIGHWAYS
DIVISION OF HIGHWAYS - STATE OF COLORADO
MATERIALS DIVISION
ENGINEERING GEOLOGY UNIT

in cooperation with

U. S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION
BUREAU OF PUBLIC ROADS

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ABSTRACT

The purpose of this study was to determine the feasibility of predicting quantities of rippable and non-rippable rock on proposed construction projects, using seismic soundings supplemented by test borings and electrical resistivity measurements. Six projects scheduled for construction in different geologic settings were selected for investigation and field work has been completed on all six. To date, only three of the projects have been constructed.

Non-rippable material was encountered on only two of the projects constructed, and it was found that the distribution of this material was erratic due to the geologic conditions present. It also became apparent during the course of the study that the depth capability of the seismograph used, a Soiltest Terra-Scout, was too limited to permit adequate investigation of cuts as large as those encountered on the projects investigated. Under these circumstances, it was felt that the comparison of predicted and actual quantities of non-rippable material originally proposed would be less meaningful than a comparison of predicted and actual depths to non-rippable material, and the results of the study have therefore been evaluated on this basis.

RESEARCH IMPLEMENTATION

This research project pointed out the need for a more sensitive seismograph to investigate subsurface conditions. Results of this research have already been implemented to some extent by the purchase of a Dresser RS-4 multi-channel instrument by the Colorado Division of Highways to supplement work performed with drilling equipment.

Although the study did not make it possible to predict exact limits of rippable and non-rippable rock, it did result in an indication that the previously established upper limit for economical ripping of 6000 feet per second should be revised upward to 8500 feet per second. Actually, it was shown that material having a velocity up to 10,000 or 10,500 feet per second could be ripped.

Findings from this report should be used to assist in estimating excavation costs. While it may not be advisable to show on the plans for a project the rippable and non-rippable areas, it would certainly be advantageous to print known seismic velocities of layers to be encountered during excavation. This procedure would allow the contractors to draw their own conclusions regarding the rippability of these layers. Before additional research is scheduled with the multi-channel instrument, it would be well to try this approach on several mountainous projects to determine how further research should be directed.

TABLE OF CONTENTS

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SUMMARY

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ROCK RIPPABILITY STUDY

INTRODUCTION

Seismic classification of excavation has been in use for several years and has proven to be of considerable value in many areas outside of Colorado. Because of the large amounts of rock encountered on many highway construction projects in this State, and because the Department has no information concerning the use, if any, of the method on other types of construction within the state, it was felt that the present study should be undertaken.

Since the success of the method relies heavily upon interpretation of results rather than upon direct quantitative measurements, it is essential that trained personnel be used. Training is also required, although to a lesser extent, in the location, spacing and configuration of seismic traverses in the field to obtain adequate information for interpretation. It was recognized during planning of the project that the training and experience acquired by the personnel engaged in the study would be of considerable value to the Department in the event the method was adopted as a result of the project findings.

AREAS INVESTIGATED

Most of the investigative effort has been devoted to four projects along the proposed route of Interstate 70 between West Colfax Avenue and the Clear Creek County Line in Jefferson County. Short portions of two other projects along the same route near Vail in Eagle County have also been investigated, although in less detail. All areas were selected for investigation because they were scheduled for construction in the near future, thereby offering an opportunity to check results of the investigation within a fairly short time, and because they offered a variety of geologic situations in which to test the investigative methods. The three projects which have been constructed and which are described in this report are I 70-3(45), Colfax to Mt Vernon Canyon, I 70-3(54), Paradise Hills-East, and I 70-2(12), Vail-East and West.

METHOD OF INVESTIGATION

The principal technique used in the investigation was seismic sounding, supplemented in a few places with test borings and electrical resistivity measurements. Familiarity with the the principles and operation of the geophysical methods used will be assumed for the purposes of this report.

The seismograph used was the Soiltest Terra-Scout, a single-channel unit which utilizes a cathode ray tube display of the seismic wave with a digital time-delay readout, instead of the multiple-light timing system found on most single channel instruments. Toward the end of the study, a Dresser RS-4 multi-channel instrument became available, and four traverses were performed with this unit in the large hogback cut on Project I 70-3(45). All seismic traverses were of the reverse type, and most were performed normal or parallel to project centerlines at intervals generally not exceeding 100 feet. Traverses on Project I 70-3(45) were spaced at closer intervals than would normally be used in order to obtain a larger amount of data and maintain closer control over variations in the position of the boundaries between rippable and non-rippable material. Traverse lengths of 100 feet were usually sufficient to obtain the desired information, although longer or shorter traverses were occasionally used. Length of traverse was frequently limited by the inability of the equipment to time waves traveling distances greater than 100 feet through certain types of subsurface material. Field data was reduced by means of two computer programs, the first of which[7] utilizes a least squares solution to determine the best fit for the seismic velocity curves and the locations of the resulting time intercepts. The second program[8] uses the solution of Mota[10] to determine depths and marker velocities from the intercepts and velocities calculated by the first program.

Test borings to determine the nature of subsurface materials were performed where possible, using a Calweld bucket-auger type drill. The nature of the topography through the areas investigated limited the use of the drill to three cuts near the east end of Project I 70-3(45).

Preliminary experimentation with an electrical resistivity device constructed by the Colorado School of Mines indicated that the unit had a high rate of power consumption and only limited depth capability, and it was subsequently decided to use a Soiltest Strata-Scout unit for the project investigations. As the instrument was obtained on a loan basis from a supplier, it was possible to obtain only a limited number of resistivity soundings and all were performed on the hogback cut on Project I 70-3(45).

RESULTS

I 70-3(45), Colfax to Mt Vernon Canyon

Cut Section - Stations 302 to 317 (Plate 1)

This cut is approximately 1500 feet long with a maximum depth of

200 feet, and passes through a hogback ridge supported by sedimentary rocks which dip at an angle of approximately 60 degrees east. The stratigraphic sequence consists primarily of Dakota Sandstone and the underlying Morrison Formation, with small portions of the Benton Shale and Ralston Formation present at either end of the cut. Plan and profile views of the cut are shown on Plate 1.

The Dakota at this location consists of a thick sequence of tan to buff, fine grained, fairly hard sandstone which is cross bedded and contains abundant partings of weakly cemented material spaced at intervals from a fraction of an inch to as much as two feet. The spacing does not usually exceed four to six inches. The Morrison consists of green, red, and purple shales interbedded with layers of limestone, siltstone, and sandstone which seldom exceed 18 inches in thickness. The upper portion of the formation grades into the Dakota and contains abundant sandstone beds resembling those of the Dakota. The portion of the Ralston encountered consists of platy to massive, fine grained varicolored sandstones interbedded with shales and is similar to the upper Morrison. The Benton is a dark gray clayey shale which weathers light gray. Only a very small portion of this formation was encountered, on the east end of the cut.

Thirty-three seismic traverses carried out at this location indicated a configuration of velocity boundaries as shown on Plate 1. From this assumed boundary, using the most current velocity-rippability correlations available at the time, the seismic results were interpreted to indicate that less than 50 percent of the rock would be economically rippable. Since penetration to grade could not be obtained in the deeper parts of the cut with the seismograph used, it was necessary to assume that the velocities of the deepest boundaries encountered were continuous down to grade. However, using heavy duty tractors (D-9 or equivalent), the contractor was able to rip approximately 90 percent of the cut. The areas requiring blasting were irregular in shape and small in comparison to the entire rock mass involved, and showed little if any apparent relationship to the seismic results obtained.

The wide discrepancy between apparent and actual rippability characteristics is felt to have resulted either from the accuracy of the published information on which the predictions were based, or the influence of the attitude of the beds on the rippability characteristics. It also appears that the attitude of the beds may have influenced the seismic records of some of the traverses.

Reference velocities used for predictions were taken from an article by Church[5] which gave 6000 fps as the upper limit for economical ripping and 7000 fps as the limiting velocity for ripping. Information obtained since that time[11] indicates that these limits have been revised upward to 8500 fps for economical ripping and 10,000 to 10,500 fps for the limiting velocities for the rock types present and the equipment used. If the predictions had been based on the later figures, the degree of correlation would have been within five percent of the actual amount since the entire cut would have been classed as rippable. Again, it would have been necessary to assume that the velocities observed were constant down to grade. This assumption was later supported by the four traverses performed with the multi-channel seismograph in the base of the completed cut. Three of the four velocities obtained showed at least general agreement with the single channel unit, and all confirmed the rippable nature of the material at grade.

The attitude of the beds was favorable to ripping, which was conducted from west to east in the down dip direction of the beds. The upturned edges of the tilted strata provided firm points of engagement for the ripper teeth while the inclination of the relatively thin beds provided an angle of attack which took advantage of the low-strength direction of the rock. This probably enabled ripping of at least some materials which would not have been rippable if the beds had been horizontal.

The appearance of the completed cut suggests that some of the high velocities recorded in traverses performed normal to centerline may have resulted from refraction of waves along thin beds running alongside and parallel to the lines of traverse. The seismic record in such a case would resemble that for a high velocity boundary located below the traverse and would normally be interpreted as such. This situation would occur in formations such as the Morrison, where the section contains many thin, hard layers interbedded with softer shales. Visually, the cut slopes show little indication of a velocity boundary resembling that illustrated in Plate 1.

Electrical Resistivity

Most of the resistivity traverses were performed above the Morrison Formation. The resistivity depth interpretations showed some agreement with the corresponding seismic depth interpretations although the resistivity values were generally inconsistent with the velocity changes. Increases in seismic velocity were sometimes reflected as increases in resistivity and sometimes as decreases, as shown by the layer curves. Both the layer and cumulative curves frequently showed changes which were not reflected by velocity changes on the corresponding seismic record.

The nature of the formations was well indicated by the resistivity curves, the sandstones giving much higher values than the shales. The interbedded nature of the Morrison was shown by numerous breaks on both the layer and cumulative curves and the increasing sandstone content of the upper Morrison was indicated by higher resistivities.

It is probable that the resistivity results were also affected by the dip of the beads although there is nothing in the records obtained which can be definitely attributed to this. In a situation where interbedded layers of different rock types are steeply inclined, horizontal differences in resistivity would exist as well as the vertical differences normally encountered, and these would be recorded as the electrode array was expanded across the strike of beds, or along centerline in this particular case. In the absence of outcrops to correlate with, it would be difficult or impossible to differentiate the effects of the two variations on the resulting resistivity curves.

Cut Sections - Stations 345 to 351, 360 to 364, and 370 to 382

These cuts were relatively shallow and were located in an area underlain by steeply dipping clayey to silty shales, claystones, and friable sandstones of the Denver-Arapahoe Formation. The material is weathered to depths ranging from six to more than 20 feet and nineteen seismic traverses performed at these locations showed velocities ranging up to 4600 feet per second for material above grade, indicating that all material was rippable. These cuts have now been completed and were ripped without difficulty.

Three test holes, one at each cut section, confirmed the rippable nature of the material above grade and also correlated fairly well with higher velocity boundaries found at depth. A hard claystone was encountered at 21 feet in the hole at Station 362+44, ℄. The closest seismic traverse, between Stations 361+00, ℄ and 361+00, 100 ft. rt. showed a velocity of 4725 feet per second at a depth of 17.9 feet. The hole at Station 377+35, 75' rt. stopped in hard claystone at 12 feet. One hundred foot seismic traverses performed normal to centerline at Stations 377 and 378 showed velocities of 5225 and 4900 feet per second at depths of 16.8 feet and 15.4 feet respectively. The third hole, on centerline at Station 349+50 showed soft sandstone from 1.5 feet to the bottom of the hole at 30 feet. The seismic traverse between centerline Stations 347 and 348 detected a velocity of 3057 feet per second at 10.6 feet, but no higher velocities at greater depths. The test hole showed no indication of a change in the nature of the material near the ten foot depth. On the basis of the traverses noted above, a velocity of approximately 5000 feet per second was assumed for an undetected higher velocity layer located at the limit of seismic penetration at this location. Using this value to re-solve the traverse indicates that such a layer, if present, would lie below 31 feet, which is confirmed by the test hole.

I 70-3(54) Paradise Hills - East

The entire project is underlain by the Idaho Springs Formation, a thick sequence of highly contorted beds of alternating gneiss and schist, intruded in many places by pink granite. The beds are folded and faulted and show considerable variation in hardness due to weathering, degree of fracturing and changes in rock type. The situation is similar in some respects to that found in the hogback cut on the previous project, i.e. alternating hard and soft layers oriented at angles to the horizontal, although conditions here are somewhat more complex due to lack of preferred orientation of the beds. The bedrock is overlain in most places by mantle consisting of a thin residual soil overlying a zone of weathered highly fractured bedrock.

As on the previous project, the limited depth capability of the seismograph was evident on many of the traverses, although fairly consistent velocity relationships and well defined velocity boundaries were recorded at most locations. With few exceptions, the interpreted velocity boundaries showed good general agreement with the actual depths to non-rippable rock. However, the average velocities recorded below the boundaries fell in the 4000-6000 fps range, which is defined as rippable material. No satisfactory explanation for this discrepancy has been determined, but the consistency of agreement between the interpreted and observed boundaries in certain cuts indicates that the rock conditions here may constitute an exception to the published rippability criteria. An assumed maximum velocity of 5000 fps for rippable material would have provided much closer correlation with actual conditions than did the published information.

Several changes were made in the alignment of this project subsequent to the seismic investigations with the result that a portion of the data could not be used.

Cut Section - Station 616 to 627 (Plate 2)

The seismic traverses at this location indicated a well defined velocity boundary at a depth of approximately eight feet throughout the cut. Velocities for mantle material averaged 1300 fps while bedrock velocities ranged from 3081 to 5676 fps, averaging 4200 fps. During construction, non-rippable rock was encountered at approximately ten feet, which correlates well with the velocity boundary but not with the interpreted character of the rock.

Cut Section - Station 637 to 649 (Plate 3)

Velocities recorded at this location were slightly higher than those for the preceding section, averaging around 2500 fps for overburden and 4700 fps for bedrock. The maximum velocity recorded was 6741 fps. Between Stations 638 and 641, depths to the velocity boundary ranged from 13 to 21 feet but the rock was ripped to depths of 35 feet. In this case, it appears that higher velocity material may have been present at depths below the range of the instrument. Between Stations 645 and 649 the velocity boundary practically coincided with the actual boundary of rippability, which was located at a depth of about 20 feet.

Cut Section - Station 658 to 668 (Plate 4)

Bedrock velocities at this location were higher than those for either of the preceding sections, averaging around 5400 fps with a maximum of 7500 fps. Overburden velocities were in the same range as those previously recorded. Depth interpretations at this location showed general agreement with the rippability boundary exposed in the finished backslope, but due to subsequent alignment changes the traverses were not immediately adjacent to the area finally cut, and the correlation value of the data appears doubtful.

Cut Section - Station 680 to 687

Seismic data collected at this location showed velocity and depth configurations consistent with the data obtained elsewhere on the project, but the limited amount of data collected was felt to be insufficient for correlation purposes. The average bedrock velocity was 5500 fps, with overburden velocities in the range of those previously recorded. The maximum bedrock velocity recorded was 6650 fps.

Cut Section - Station 680 to 714 (Plate 5)

Depth correlations at this location were particularly good and the actual boundary between rippable and non-rippable material, shown in Figure 1, bears a close resemblance to the velocity boundary defined by the seismograph. Most of the velocities below the boundary were well within the defined range of rippability, averaging 5550 fps with a maximum of 7049 fps.

Figure 1. Boundary between rippable and non-rippable material in cut section between Stations 698 and 706. Compare with velocity boundary shown on Plate 5.

Cut Section - Stations 734 to 743

Seismic velocities and interpreted depths at this location were similar to those found elsewhere along the project with bedrock velocity averaging slightly more than 6000 fps and overburden velocity averaging almost 2100 fps. The data obtained could not be used for correlation due to the changes in alignment mentioned previously.

I 70-2(12) Vail East and West

Investigations on this project were limited to two large cuts at the east end of the project. Geology consisted of bouldery glacial till and colluvium overlying sedimentary bedrock. Eight traverses were performed. Overburden velocities ranged between 725 and 1670 feet per second for colluvium and between 2350 and 4450 for till.

Bedrock (?) velocities were detected in only four of the traverses and ranged from 5000 to 7700 feet per second. The material was interpreted to be limestone. Indicated depths to bedrock ranged from 20 to 37 feet.

No bedrock was encountered during construction of these cuts, although large limestone boulders were found at the horizons indicated as bedrock by the seismic records. Two possible explanations are suggested. The seismograph was working near the limit of its depth capability when the apparent bedrock velocities were detected, and nearly all of the records were received as secondary wave returns. If an instrument with greater depth capability had been used, the quality of the seismic record would have been better, and a different interpretation might have been indicated. Also, the traverses were carried out parallel to the roadway near the daylight point of the proposed cuts, and it is possible that bedrock was actually present beneath the seismic traverses but broke off at a point between the traverses and the finished cut slope.

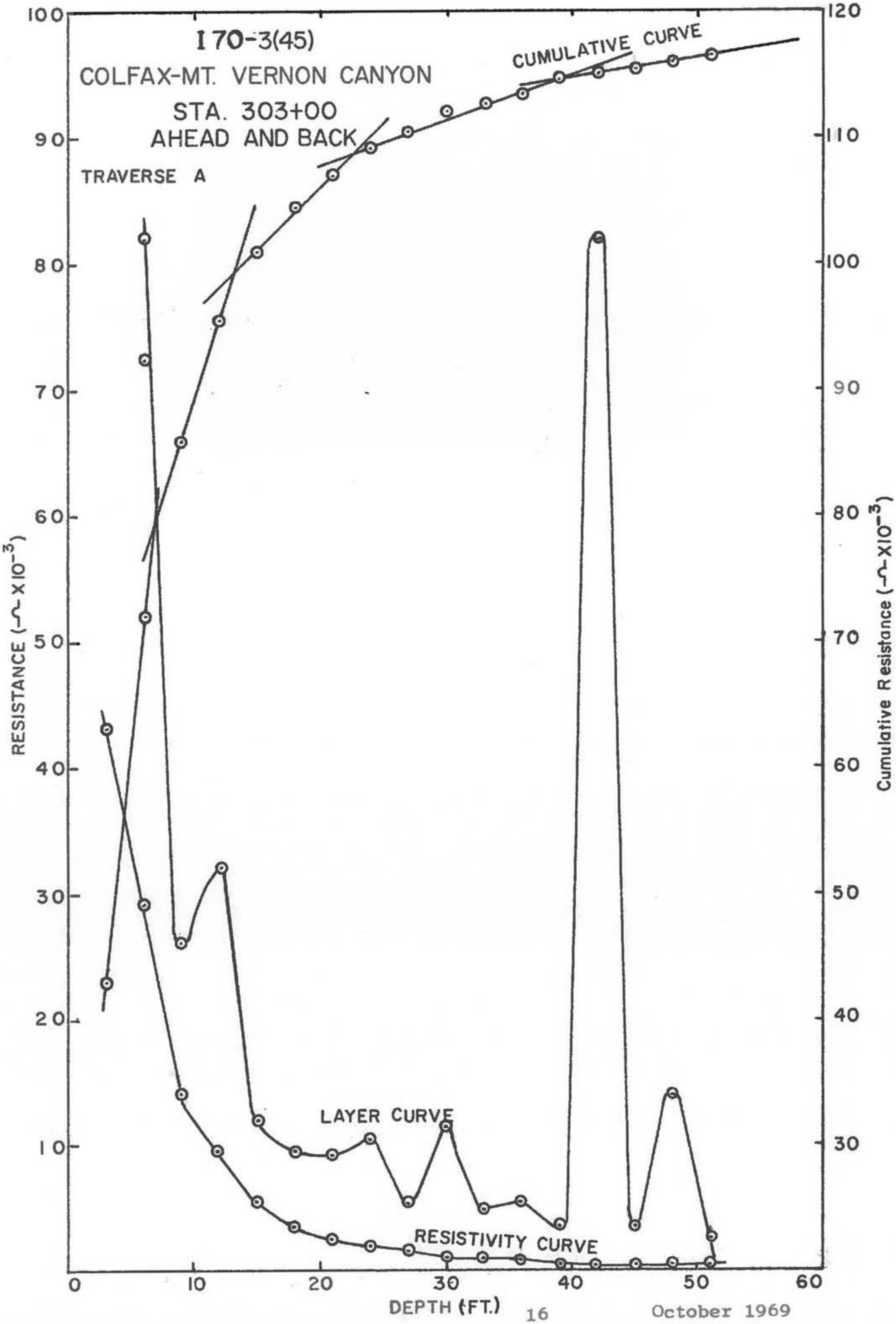
CONCLUSIONS

The first and perhaps most significant result of the study was the discovery that the seismograph used was inadequate for rippability studies in the type of terrain investigated. Depth of penetration was usually limited to depths of 40 feet or less and frequently did not exceed 25 feet. Since the proposed cuts at many of the locations tested exceeded this depth, it was often impossible to determine rock characteristics down to grade. In many cases, the interpretation of the seismic records was complicated by the uncertainty of the readings obtained at large hammer-geophone separations, and it frequently became necessary to base interpretations on second wave arrivals due to attenuation of the primary wave in certain types of materials. It appears that the principal cause of these difficulties lies in the method of initiating the shock wave. Although the hand operated tamper used with the Terra-Scout is more effective than the sledgehammer commonly used with single channel seismographs, the amplitude of the shock wave is definitely limited and the effectiveness of the system is thereby decreased. It is concluded that rippability surveys in areas where cuts deeper than 25 feet are anticipated should not be attempted with this instrument. It is the opinion of the study staff that explosive charges provide the most reliable means of obtaining the required penetration and that the most economical and efficient use of explosives implies the use of a multi-channel seismograph. This conclusion has resulted in the purchase of a Dresser RS-4 multi-channel unit by the Colorado Highway Materials Division for future work in subsurface investigations.

Experience gained during this study have shown that accurate seismic interpretations are difficult in areas where geologic boundaries are inclined at steep angles. It appears that not only the seismic velocities but also the ripping characteristics of the rock may be affected when tilted bedded rocks are encountered. The results of the investigations on the Paradise Hills - East project indicate that exceptions to published velocity-rippability correlations may exist, but this conclusion is advanced only in the absence of any other reasonable explanation for the failure of the seismograph to detect high velocities where non-rippable material was present.

The resistivity records showed partial agreement with the seismic records but the results of this portion of the study were inconclusive due to the limited amount of data available. There was no indication that the method could be used for rippability determinations, except as a possible correlation tool in conjunction with seismic traverses.

The results of the study with regard to seismic depth interpretations were rated as good, which corresponds with previous experience of the study staff with this method. Results of the rippability determinations based on seismic velocities can only be rated as poor. However, the geologic conditions encountered during the study were found to be unusually difficult to analyze by the seismic method, and for this reason the results of the study are not felt to constitute an adequate basis for a fair and accurate assessment of the value of the method for rippability determinations. The study has demonstrated that three factors affecting optimum use of the method are a seismograph of adequate capability, rock units having distinct, uniform character, and geologic (velocity) boundaries having regular configurations. Where these conditions can be met, it is probable that the method can be used with a much higher degree of success than was experienced during this study.

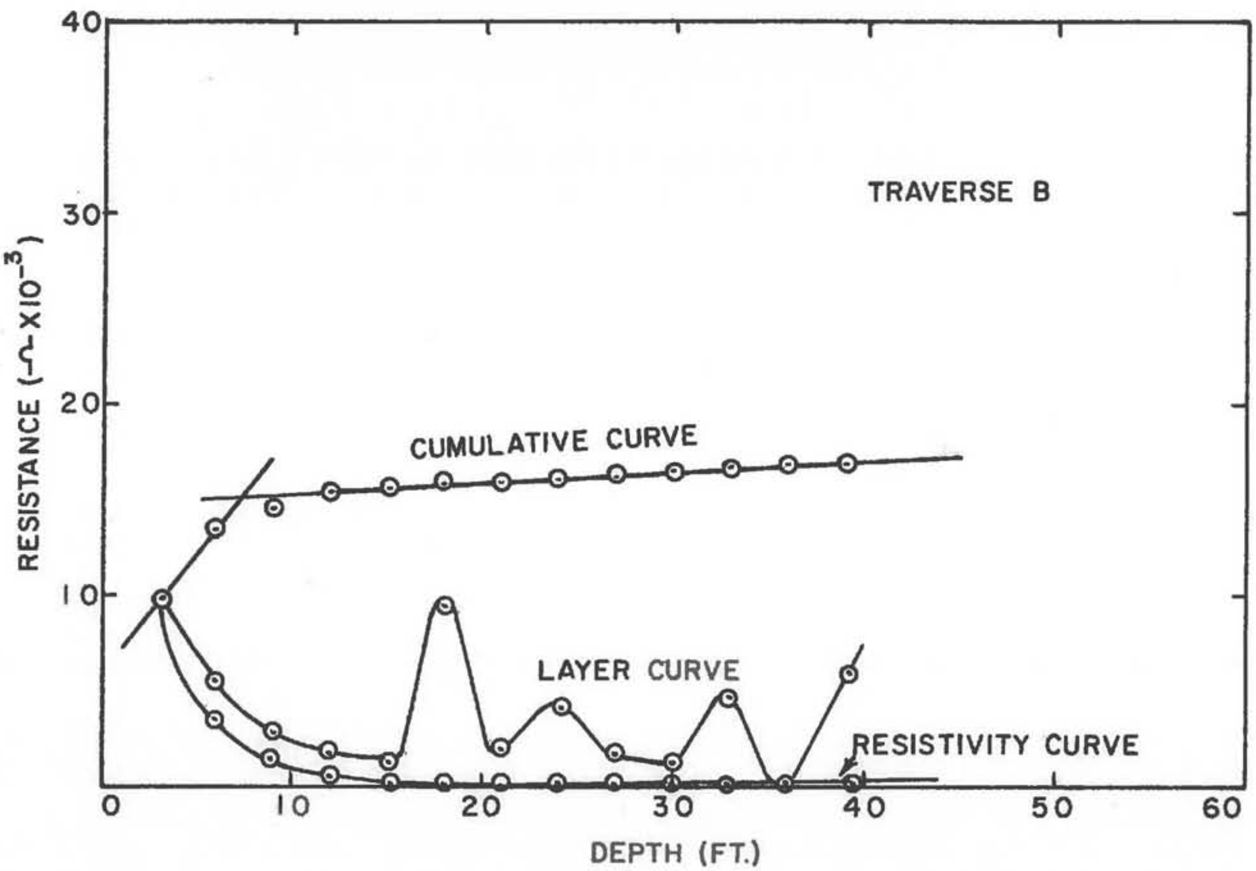

I 70-3(45)
COLFAX-MT. VERNON CANYON
STA. 303+00
AHEAD AND BACK
TRAVERSE A
CUMULATIVE CURVE
LAYER CURVE
RESISTIVITY CURVE
RESISTANCE (Ω X10⁻³)
Cumulative Resistance (Ω X10⁻³)
DEPTH (FT.)

I 70-3(45)

COLFAX-MT. VERNON CANYON

STA. 305+00

50 RT.

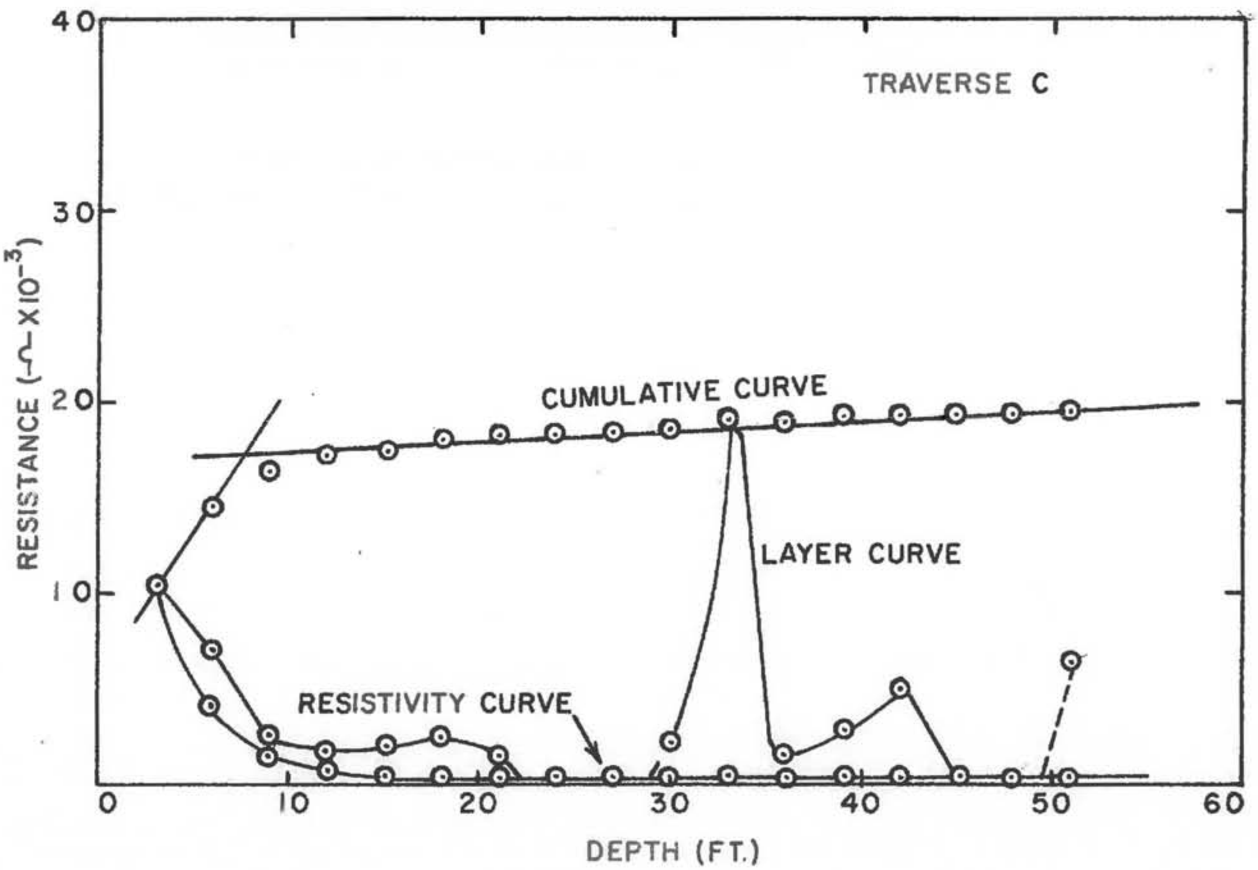


I 70-3(45)

COLFAX-MT. VERNON CANYON

STA. 305+50

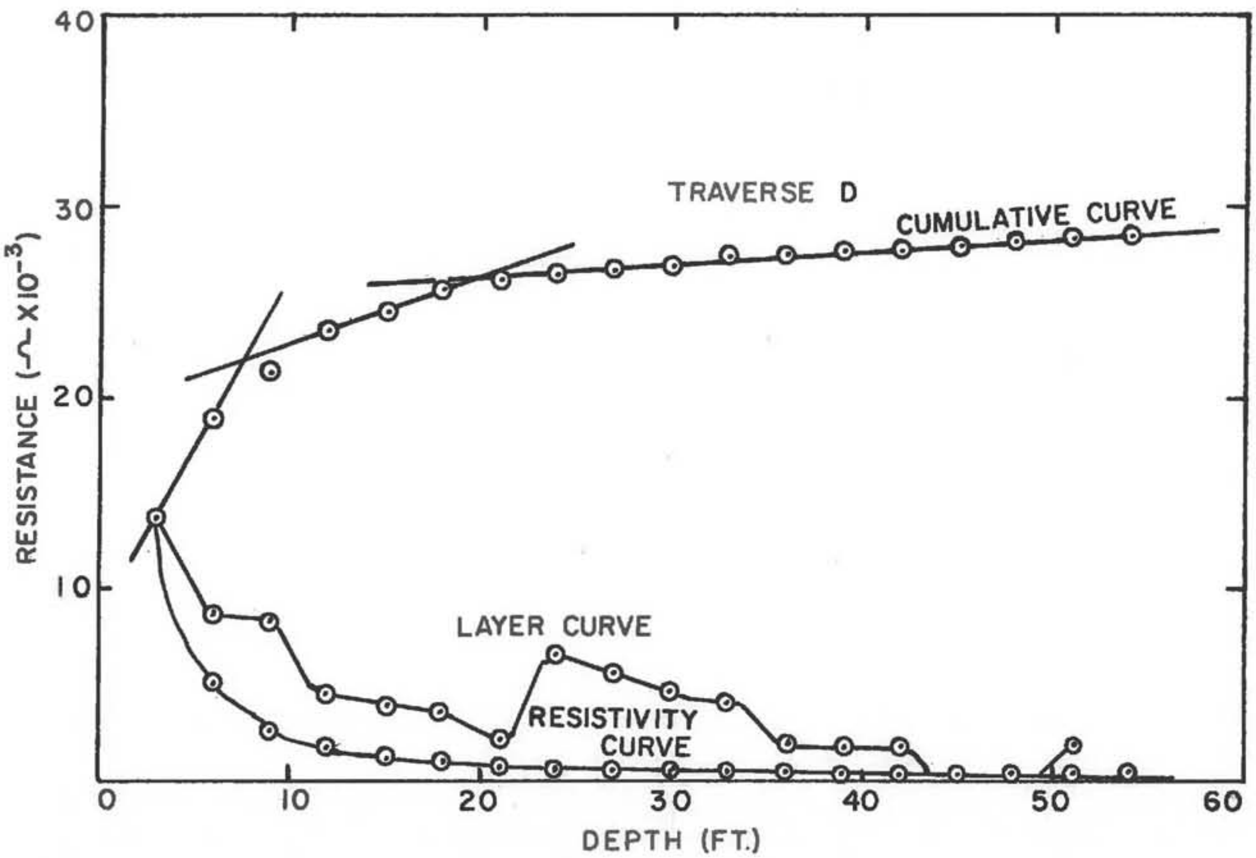
AHEAD AND BACK



I 70-3(45)

COLFAX-MT. VERNON CANYON

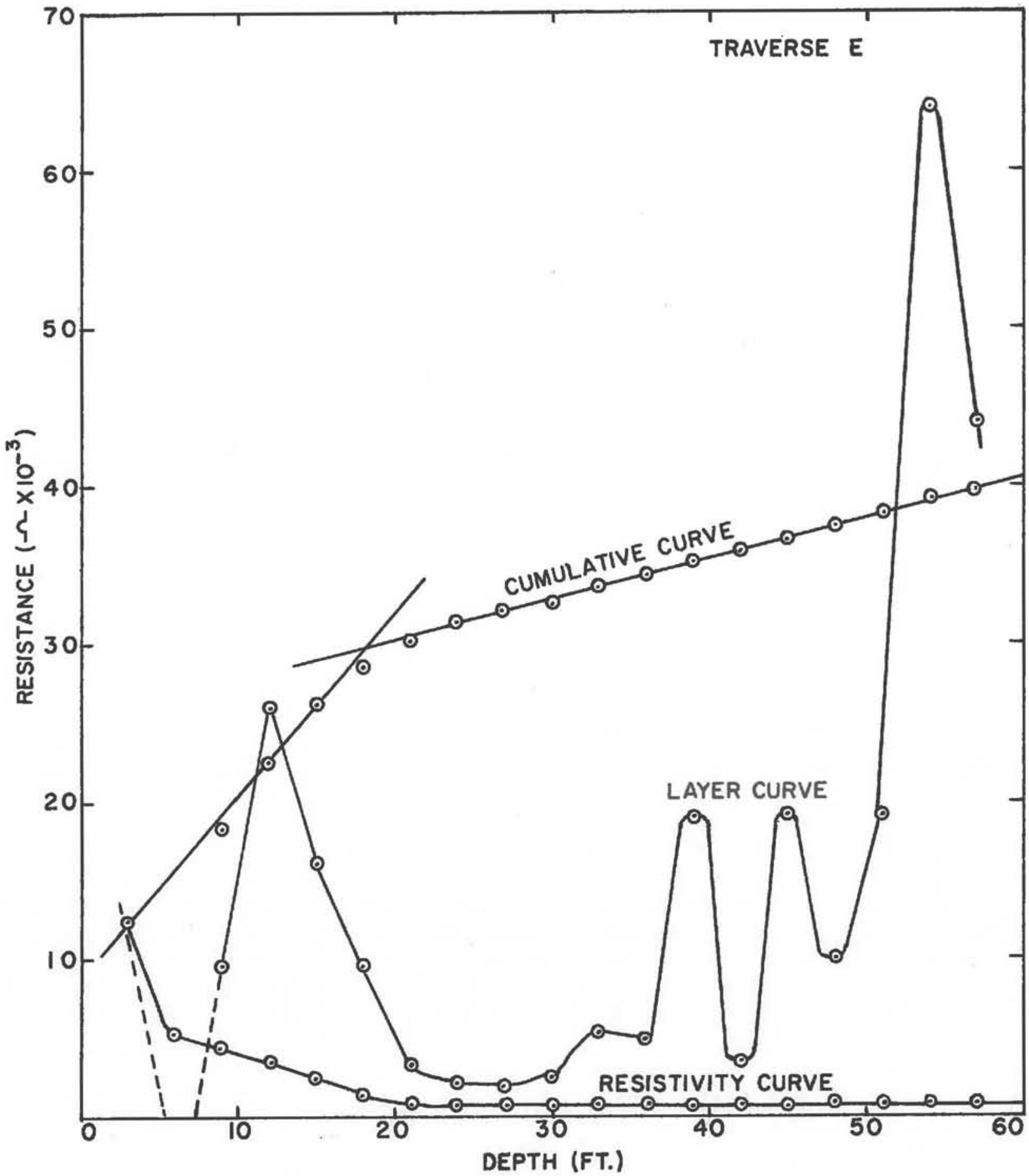
STA. 306+00
100' RT.



I 70-3(45)

COLFAX-MT. VERNON CANYON

STA. 308+00
AHEAD AND BACK

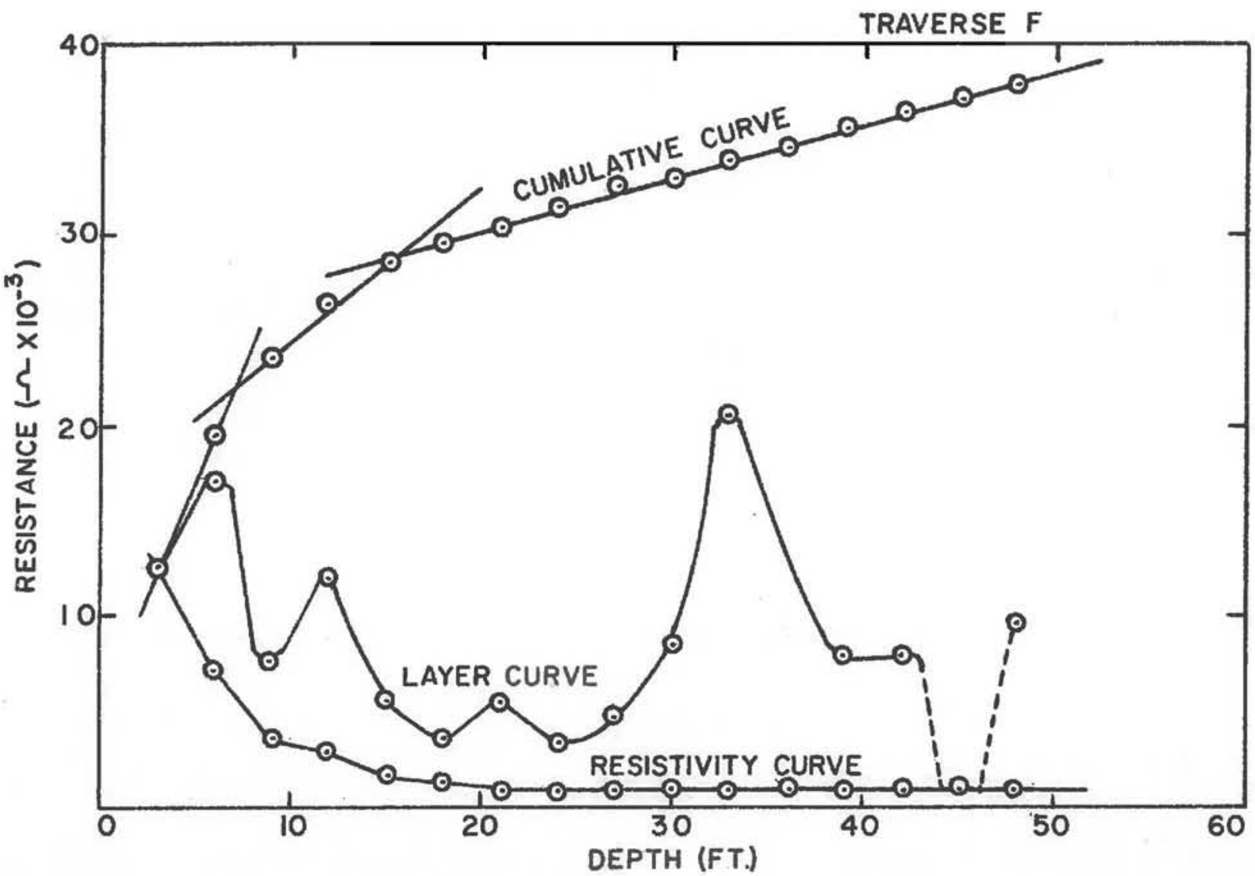


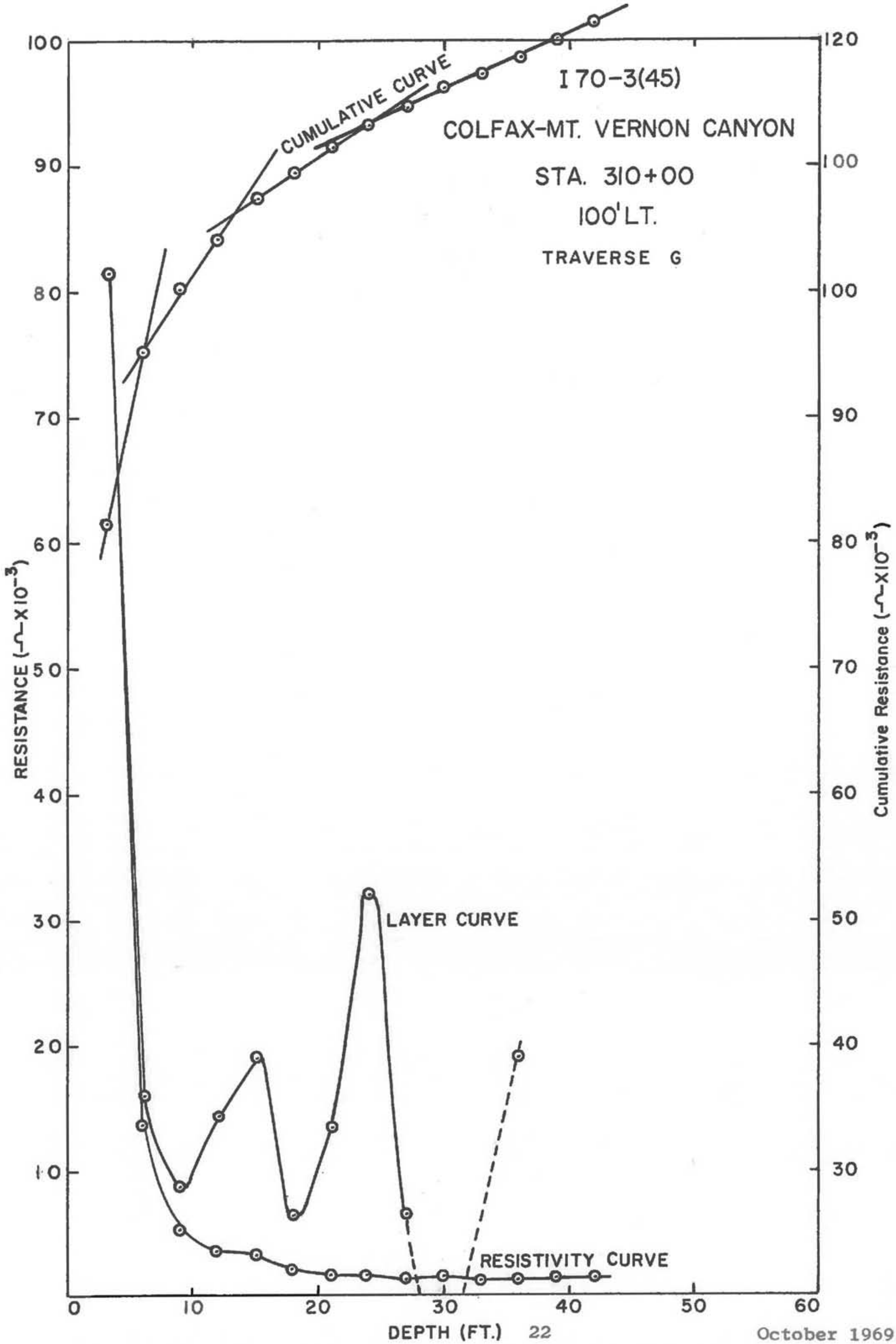
I 70-3(45)

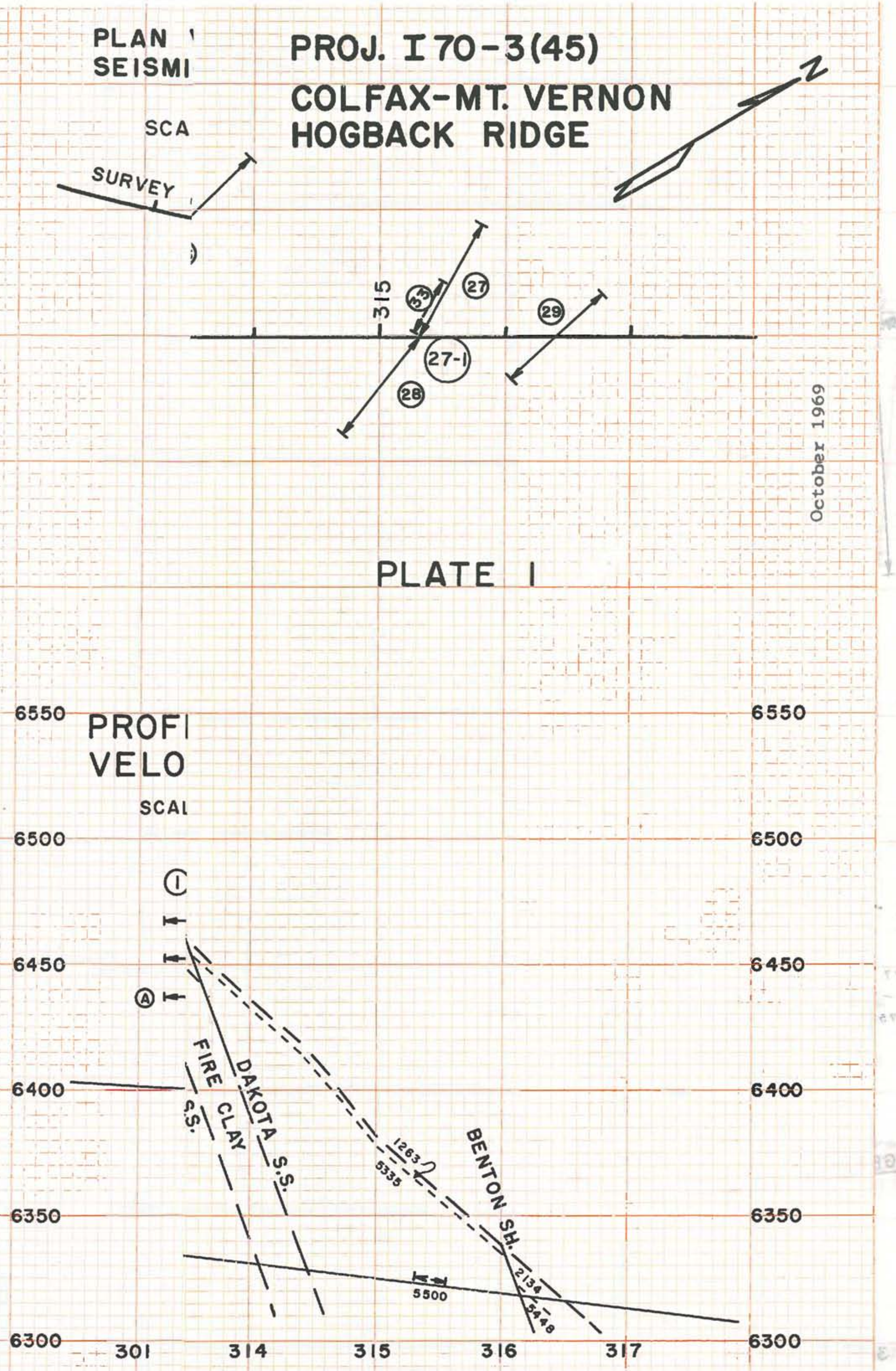
COLFAX-MT. VERNON CANYON

STA. 309+00

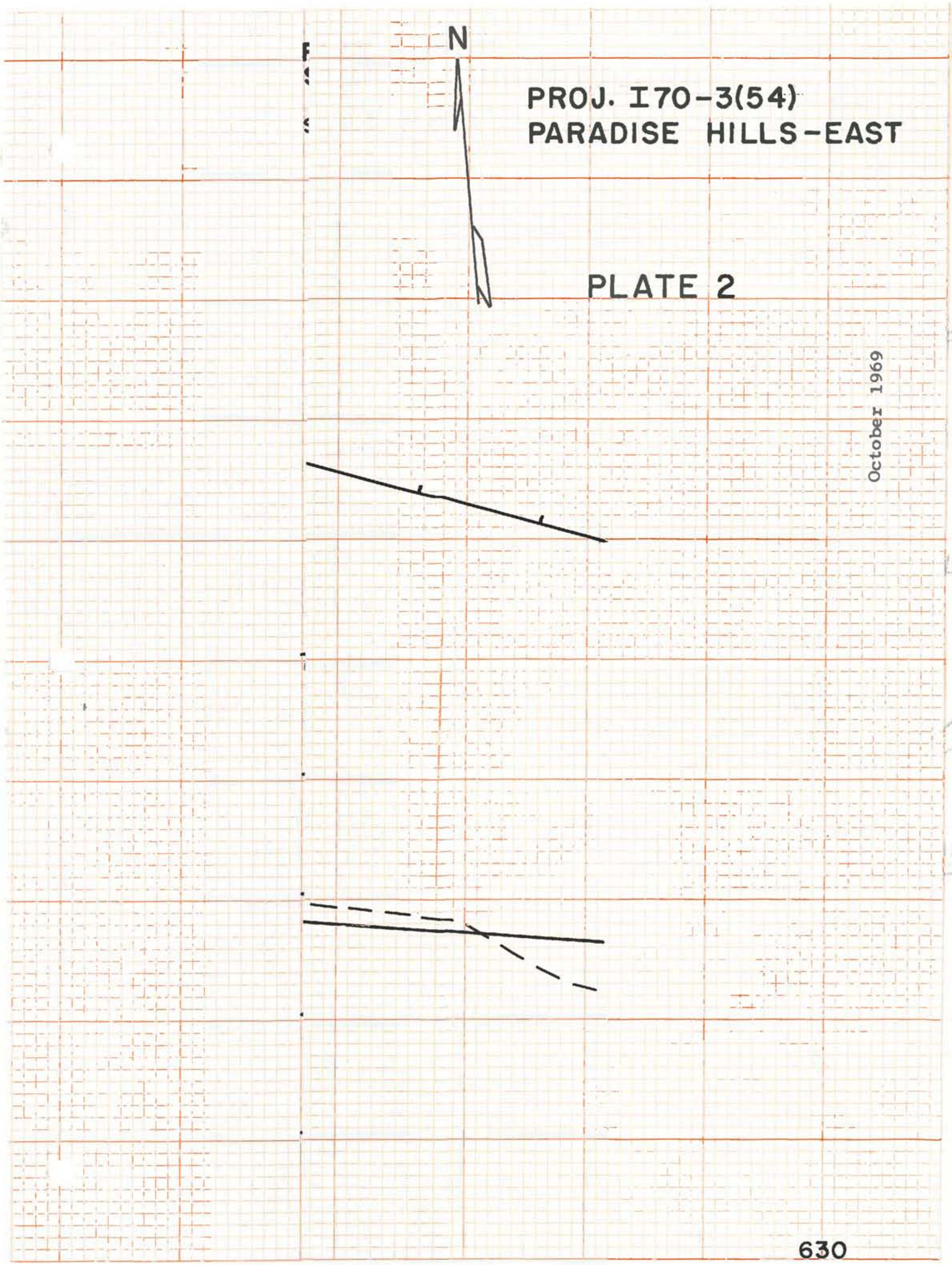
100' LT.



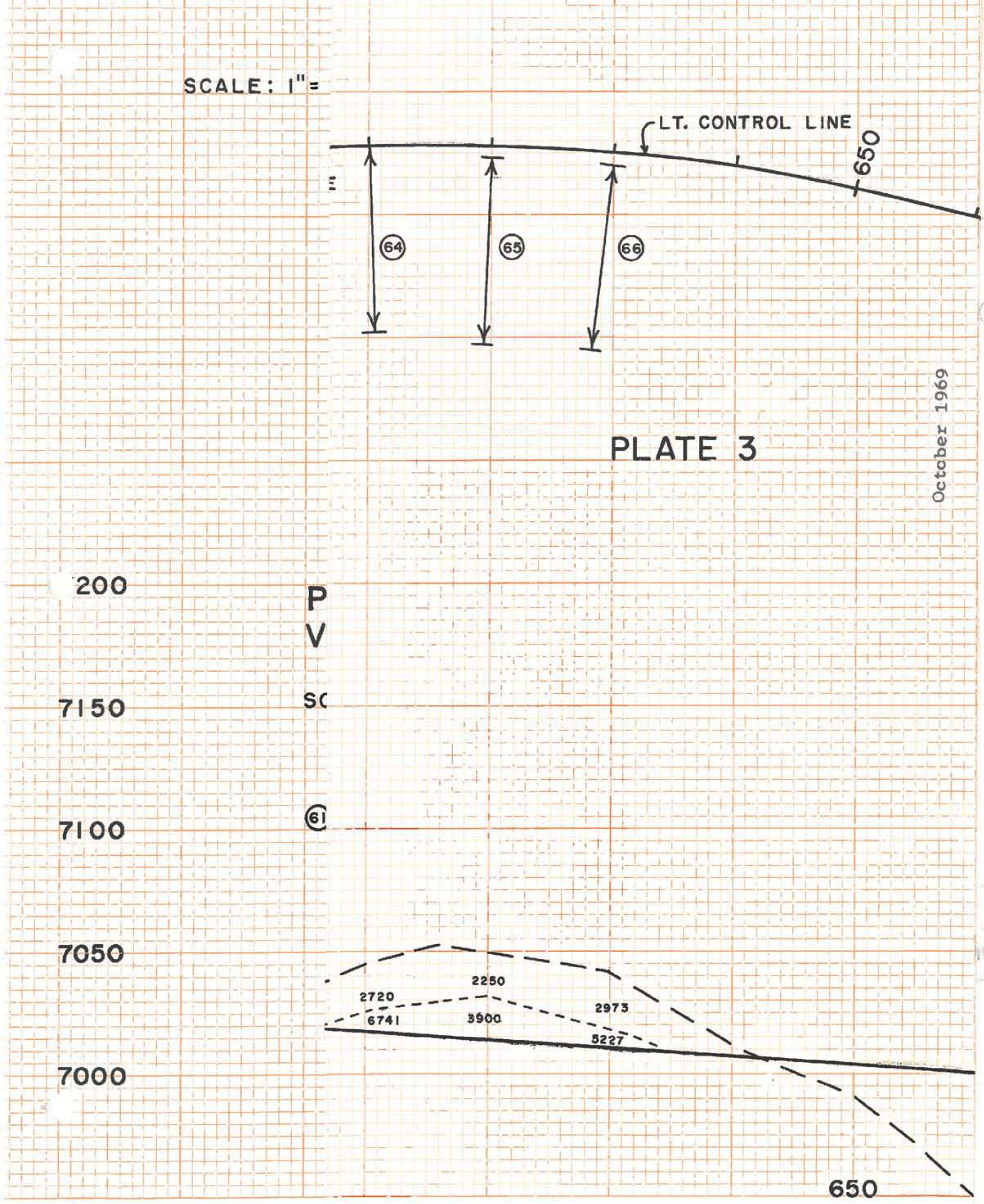

I 70-3(45)
COLFAX-MT. VERNON CANYON
STA. 310+00
100' LT.
TRAVERSE G
CUMULATIVE CURVE
LAYER CURVE
RESISTIVITY CURVE
RESISTANCE (Ω X 10⁻³)
Cumulative Resistance (Ω X 10⁻³)
DEPTH (FT.)

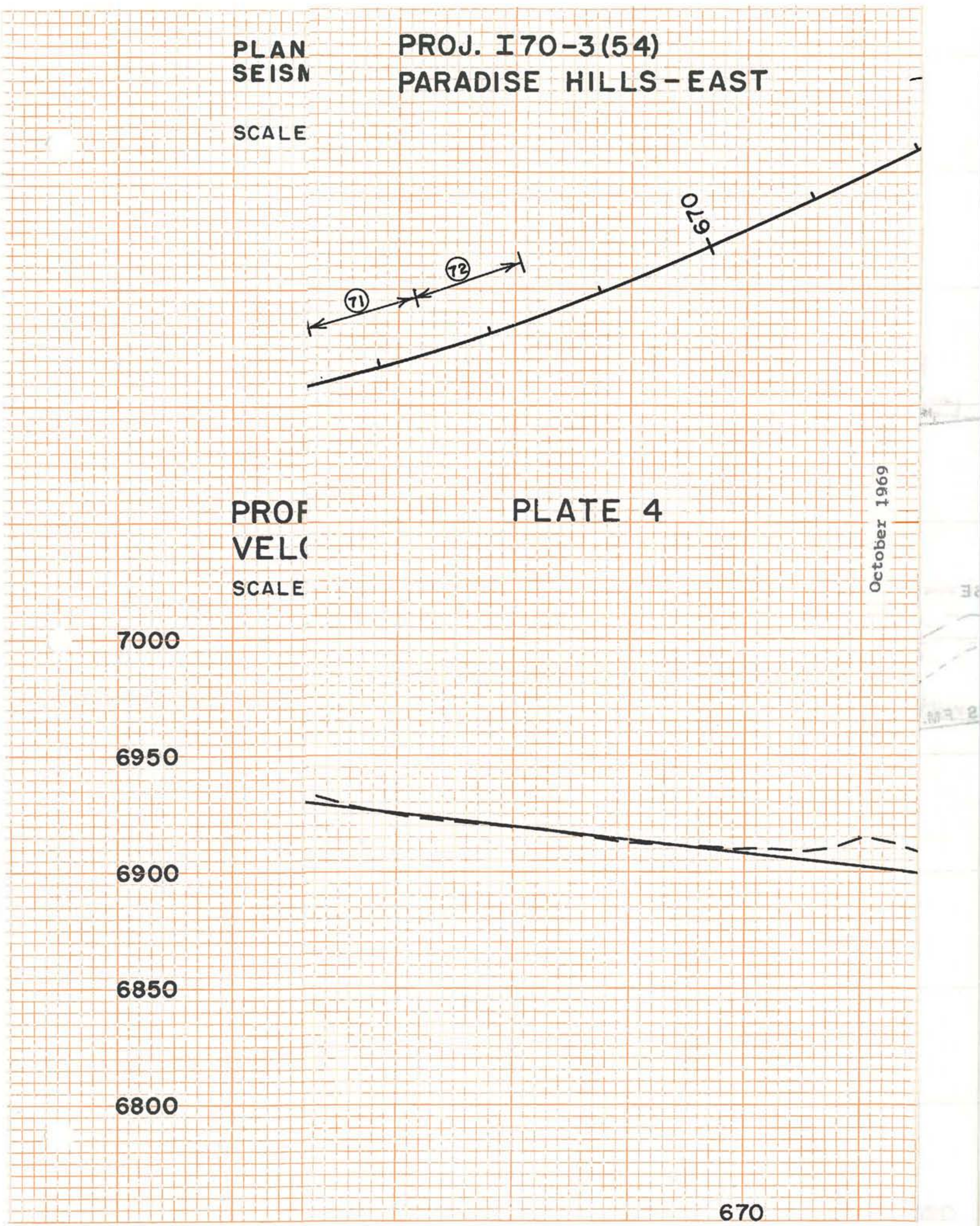


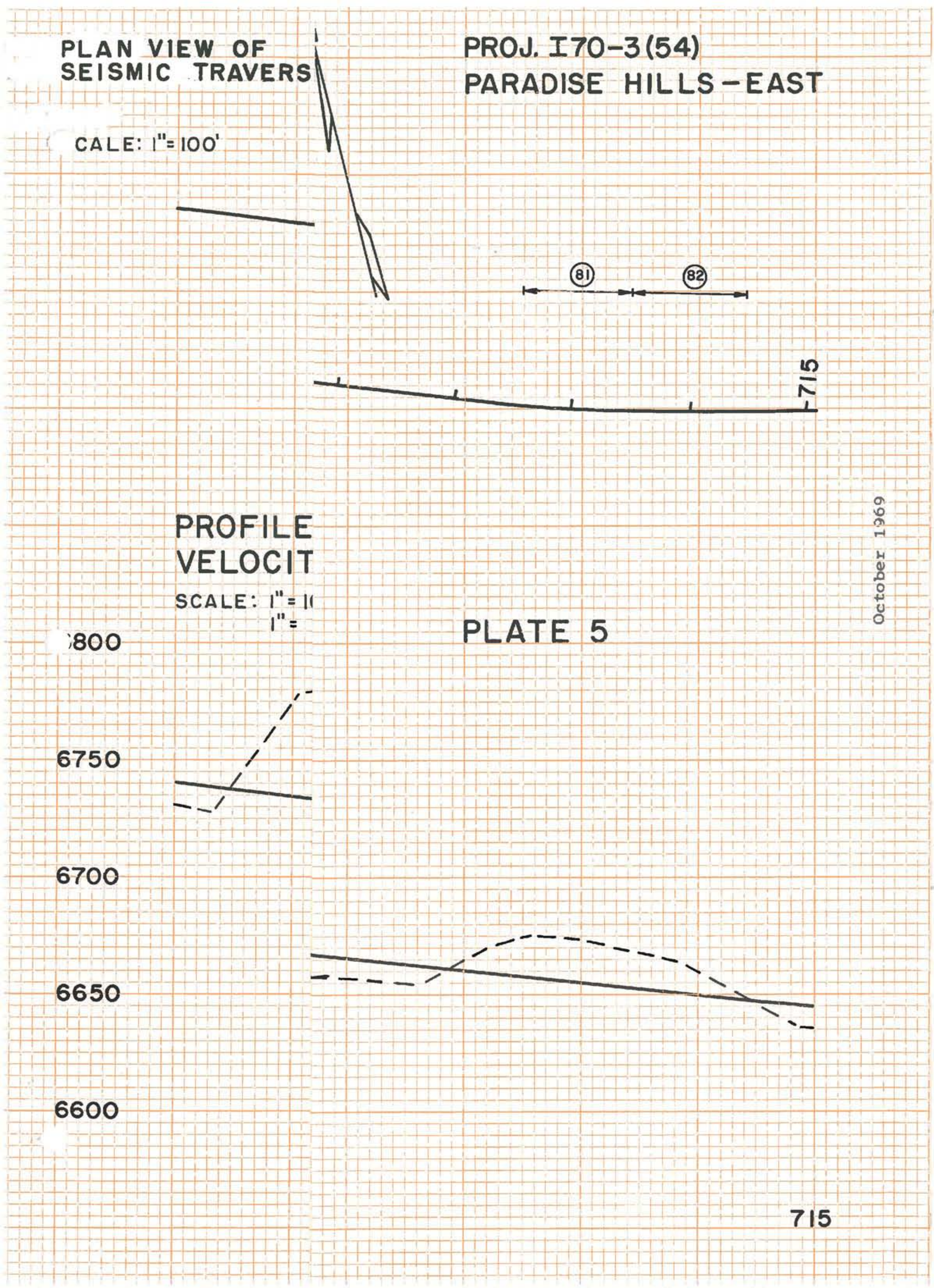
PLAN
SEISMI
SCA
PROJ. I 70-3(45)
COLFAX-MT. VERNON
HOGBACK RIDGE
N
SURVEY
315
33
27
29
27-1
28
October 1969
PLATE I
PROFI
VELO
SCAL
6550
6500
6450
6400
6350
6300
1
A
FIRE CLAY
S.S.
DAKOTA S.S.
BENTON SH.
1263
5335
2134
5448
5500
301
314
315
316
317


N
PROJ. I70-3(54)
PARADISE HILLS-EAST
PLATE 2
October 1969
630

PROJ. I70-3(54)
PARADISE HILLS-EAST




PLAN
SEISM
PROJ. I70-3(54)
PARADISE HILLS-EAST
SCALE
670
71
72
PROF
VEL
SCALE
PLATE 4
October 1969
7000
6950
6900
6850
6800
670



October 1969

BIBLIOGRAPHY

1. Church, Horace K. - "How Much is Rock", Roads and Streets, April, 1963.

2. - - - - - - - - - - "Geophysical Examination Can Make Earthmoving a Science in the Southwest", Southwest Builder and Contractor, March 13, 1964.

3. - - - - - - - - - - "Seismic Exploration Yields Data on Excavation Costs and Methods", Engineering News-Record, August 12, 1965.

4. - - - - - - - - - - "Exploring Excavation by Seismic Studies in the Southwest", Roads and Streets, October, 1966.

5. - - - - - - - - - - "1967 Ripping and Blasting Results in Southwestern U.S.A.", Roads and Streets, September, 1967.

6. Colorado Department of Highways - Intradepartmental memo from E. G. Swanson to T. C. Reseigh, "Evaluation of Seismic Refraction Equipment for Sand and Gravel Prospecting", August 23, 1965.

7. IBM Corporation, "Calculation of Intercepts and Velocities from Observed Seismic First Arrivals". Program 1620-MP-12X. IBM Data Processing Division Program Library.

8. - - - - - - - - - - "Refraction Interpretation and Velocity Determination". Program 1620-MP-13X (E-18). IBM Data Processing Division Program Library.

9. Jakosky, J. J. - "Exploration Geophysics", 1950.

10. Mota, Lindonor, "Determination of Dips and Depths of Geologic Layers by the Seismic Refraction Method". Geophysics, vol. XIX, No. 2, Society of Exploration Geophysicists.

11. Wylie, Kenneth M. - "The Big Breakthrough in Ripping Rock", The Testing World, No. 22, Winter 1968-1969.

LOGS OF TEST HOLES

I 70-3(45) Colfax - Mt Vernon Canyon

Sta. 349+50 ℄

0.0 - 1.5	Soil, sandy, dark brown, moist. Contains small amount of gravel.
1.5 -30.0	Sandstone, weathered, light brown, soft, friable
30.0 -	Stopped in same.

Sta. 362+44 ℄

0.0 - 1.0	Clay, silty, sandy, dark brown, moist.
1.0 - 3.0	Clay, dark brown, moist.
3.0 - 5.0	Silt, sandy, light tan, contains occasional gravels and cobbles.
5.0 -22.0	Claystone, light brown to brown, soft, slightly moist.
7.0 -	Becomes moderately hard.
21.0 -	Becomes very hard.
22.0 -	Stopped in same. Unable to penetrate further.

Sta. 377+35, 75' Rt.

0.0 - 2.0	Soil, slightly sandy, dark brown, moist. Contains scattered gravel.
2.0 - 4.0	Silt, sandy, light tan, slightly moist. Contains scattered cobbles.
4.0 -12.0	Claystone, brown, slightly sandy, soft. Contains occasional boulders or cobbles.
6.0 -	Becomes hard.
9.0 -	Contains pieces of very hard silicious rock.
11.0 -	Concentration of vesicular basalt boulders.
12.0 -	Stopped in claystone. Unable to penetrate further.

SEISMIC TRAVERSES

I 70-3(45) Colfax to Mt. Vernon Canyon

Cut Section - Stations 302 to 317 (Plate 1)

Traverse	Station	Depth	Velocity	Material
1	303+00, ℄ to 303+00, 150' lt	0.0	1350	Mantle
		6.8	3516	Weathered bedrock
		32.1	6617	Ralston sandstone
1-1	303+00, ℄	0.0	1226	Mantle
	Split traverse (1-A & 2-A)	7.5	3700	Weathered bedrock
		24.5	5425	Ralston sandstone
2	303+00, ℄ to 303+00, 120' rt	0.0	700	Mantle
		3.7	3400	Weathered bedrock
		16.8	4850	Ralston sandstone
3	303+00, 150' rt to 303+00,	0.0	580	Mantle
	300" rt	3.7	2500	Weathered bedrock
		21.1	5650	Morrison formation
4	303+12, 75' rt to 304+00, ℄	0.0	635	Mantle
		5.6	4275	Weathered bedrock
		23.6	8150	Ralston sandstone
5	304+00,℄ to 304+00, 120' rt	0.0	618	Mantle
		6.1	3650	Weathered bedrock
		25.7	6598	Morrison formation
6	304+00, ℄ to 304+90 ℄	0.0	560	Mantle
		6.5	5324	Morrison formation
7	305+00, ℄ to 305+00, 120' rt	0.0	1000	Mantle
		9.3	4500	Morrison formation
8	305+00, ℄ to 305+00, 100' lt	0.0	721	Mantle
		2.3	1298	Weathered bedrock
		13.0	5681	Morrison formation
9	305+00, 150' rt to 305+00,	0.0	1350	Mantle
	300' rt	8.0	5450	Morrison formation
10	306+00, ℄ to 308+00, ℄	0.0	900	Mantle
		5.3	3217	Weathered bedrock
		54.5	10,162	Morrison formation
11	306+00, ℄ to 306+00, 200' rt	0.0	850	Mantle
		7.3	2450	Weathered bedrock
		27.0	6000	Morrison formation
11-1	306+00, ℄			
	Split traverse (11-A & 12-A)	0.0	756	Mantle
		6.1	2625	Weathered bedrock
		25.8	5601	Morrison formation

12	306+00, ℄ to 306+00, 200' lt	0.0	718	Mantle
		5.2	3022	Weathered bedrock
		18.9	4213	" "
		34.7	9831	Morrison formation
13	307+00, ℄ to 307+00, 200' lt	0.0	1310	Mantle
		14.8	3050	Weathered bedrock
		44.8	8800	Morrison formation
14	307+00, ℄ to 307+00, 200' rt	0.0	1200	Mantle
		1.3	2240	Weathered bedrock
		22.3	8158	Morrison formation
15	308+00, ℄ to 308+00, 200' lt	0.0	1258	Mantle
		1.1	1855	Weathered bedrock
		8.0	2897	" "
		33.4	8411	Morrison formation
15-1	308+00, ℄	0.0	1157	Mantle
	Split traverse (15-A & 16-A)	6.7	3077	Weathered bedrock
		33.7	7529	Morrison formation
16	308+00, ℄ to 308+00, 200' rt	0.0	1270	Mantle
		7.0	2900	Weathered bedrock
		32.8	7900	Morrison formation
17	308+00, ℄ to 310+00, ℄	0.0	1379	Mantle
		1.6	2344	Weathered bedrock
		11.6	4594	" "
		41.0	9032	Morrison formation
18	309+00, ℄ to 309+00, 200' rt	0.0	1060	Mantle
		7.4	3351	Weathered bedrock
		25.5	6995	Dakota sandstone
19	309+00, ℄ to 309+00, 200' lt	0.0	833	Mantle
		4.3	1639	"
		18.7	5313	Weathered bedrock
		56.1	9382	Morrison formation
20	310+00, ℄ to 310+00, 200' lt	0.0	2300	Mantle
		14.3	4800	Weathered bedrock
		36.3	9700	Morrison formation
20-1	310+00, ℄			
	Split traverse (20-A & 21-A)	0.0	1539	Mantle
		12.0	6954	Dakota sandstone
21	310+00, ℄ to 310+00, 200' rt	0.0	1440	Mantle
		4.0	5400	Dakota sandstone
22	311+00, ℄ to 311+00, 200' lt	0.0	1350	Mantle
		6.8	3700	Dakota sandstone
23	311+50, ℄ to 313+12, 115' lt	0.0	1140	Mantle
		2.9	3280	Weathered bedrock
		13.0	6690	Dakota sandstone

23-1	311+50, ℄	0.0	1320	Mantle
	Split traverse (23-A & 24-A)	5.5	6761	Dakota sandstone
24	310+00, 125' rt to 311+50, ℄	0.0	1330	Mantle
		4.8	6400	Dakota sandstone
25	310+65, 65' rt to 312+52, ℄	0.0	1935	Mantle
		5.0	5369	Dakota sandstone
25-1	312+52, ℄	0.0	1945	Mantle
	Split traverse (25-B & 26-A)	7.2	5661	Dakota sandstone
26	312+52, ℄ to 313+95, 140' lt	0.0	2070	Mantle
		8.2	5510	Dakota sandstone
27	315+30, ℄ to 315+80, 90' lt	0.0	910	Mantle
		2.5	5600	Dakota sandstone
27-1	315+30, ℄	0.0	1263	Mantle
	Split traverse (27-A & 28-B)	4.7	5335	Dakota sandstone
28	314+40, 75' rt to 315+30, ℄	0.0	1330	Mantle
		4.0	6250	Dakota sandstone
29	316+05, 33' rt to 316+78, 33'lt	0.0	989	Mantle
		2.5	2134	Weathered bedrock
		14.2	5448	Benton formation
30	303+55, 65' rt to 304+00, ℄	0.0	4500	Morrison formation
31	306+75, ℄ to 307+25, ℄	0.0	4200	Morrison formation
32	311+75, 50' rt to 312+25, 50'rt	0.0	5600	Dakota sandstone
33	315+30, ℄ to 315+55, 40' lt	0.0	5500	Dakota sandstone

<u>Cut Section - Stations 345 - 351</u>

34	346+00, ℄ to 346+00, 100' rt	0.0	715	Mantle
		7.5	2262	Weathered bedrock
		28.7	5555	Denver-Arapahoe formation
35	346+00, ℄ to 347+00, ℄	0.0	801	Mantle
		10.0	2238	Weathered bedrock
		24.4	3768	Denver-Arapahoe formation
36	347+00, ℄ to 348+00, ℄	0.0	890	Mantle
		10.6	3057	Denver-Arapahoe formation

<u>Cut Section - Stations 360 - 364</u>

37	359+00, ℄ to 359+00, 100' rt	0.0	670	Mantle
		4.3	2900	Weathered bedrock
		14.7	4600	Denver-Arapahoe formation
38	360+00, ℄ to 360+00, 100' rt	0.0	815	Mantle
		2.5	1726	Weathered bedrock
		21.2	7021	Denver-Arapahoe formation

39	361+00, ℄ to 361+00, 100' rt	0.0	855	Mantle
		5.1	2580	Weathered bedrock
		17.9	4725	Denver-Arapahoe Fm.

Cut Section - Stations 370 to 382

40	370+00, ℄ to 370+00, 100' rt	0.0	691	Mantle
		4.8	3554	Weathered bedrock
41	371+00, ℄ to 371+00, 100' rt	0.0	668	Mantle
		4.9	3925	Weathered bedrock
42	372+00, ℄ to 372+00, 100' rt	0.0	940	Mantle
		4.8	2925	Weathered bedrock
		24.0	8600	Denver-Arapahoe Fm.
43	373+00, ℄ to 373+00, 100' rt	0.0	710	Mantle
		4.6	3200	Weathered bedrock
		21.8	7500	Denver-Arapahoe Fm.
44	374+00, ℄ to 374+00, 100' rt	0.0	704	Mantle
		5.7	3375	Weathered bedrock
		17.5	5234	Denver-Arapahoe Fm.
45	375+00, ℄ to 375+00, 100' rt	0.0	660	Mantle
		5.1	5377	Denver-Arapahoe Fm.
46	376+00, ℄ to 376+00, 100' rt	0.0	660	Mantle
		3.5	3100	Weathered bedrock
		14.3	5450	Denver-Arapahoe Fm.
47	377+00, ℄ to 377+00, 100' rt	0.0	925	Mantle
		4.3	3250	Weathered bedrock
		16.8	5225	Denver-Arapahoe Fm.
48	378+00, ℄ to 378+00, 100' rt	0.0	835	Mantle
		4.2	3200	Weathered bedrock
		15.4	4900	Denver-Arapahoe Fm.
49	379+00, ℄ to 379+00, 100' rt	0.0	580	Mantle
		3.3	3125	Weathered bedrock
		14.8	4675	Denver-Arapahoe Fm.
50	380+00, ℄ to 380+00, 100' rt	0.0	670	Mantle
		3.6	2710	Weathered bedrock
		15.4	4870	Denver-Arapahoe Fm.
51	381+00, ℄ to 381+00, 100' rt	0.0	712	Mantle
		3.4	3069	Weathered bedrock
		19.7	5566	Denver-Arapahoe Fm.
52	382+00, ℄ to 382+00, 100' rt	0.0	685	Mantle
		3.5	3220	Weathered bedrock
		13.3	4490	Denver-Arapahoe Fm.

I 70-3(54) Paradise Hills - East

Cut Section - Stations 616 to 627 (Plate 2)

Traverse	Station	Depth	Velocity	Material
53	615+50, ℄ to 617+50, ℄	0.0	1201	Mantle
		4.2	3217	Idaho Springs Fm.
53-1	617+50, ℄			
	Split traverse (53-B & 54-A)	0.0	1293	Mantle
		5.1	3081	Idaho Springs Fm.
54	617+50, ℄ to 619+50, ℄	0.0	1465	Mantle
		9.8	3225	Idaho Springs Fm.
54-1	619+50, ℄			
	Split traverse (54-B & 56-A)	0.0	952	Mantle
		8.7	3681	Idaho Springs Fm.
55	618+00, ℄ to 618+00, 200' rt	0.0	1244	Mantle
		3.2	1536	Weathered bedrock
		15.2	5676	Idaho Springs Fm.
56	619+50, ℄ to 619+50, 200' rt	0.0	820	Mantle
		6.2	2600	Weathered bedrock
		22.3	5300	Idaho Springs Fm.
57	620+00, ℄ to 622+00, ℄	0.0	1175	Mantle
		9.6	5550	Idaho Springs Fm.
57-1	622+00, ℄			
	Split traverse (57-B & 59-A)	0.0	1108	Mantle
		7.5	4371	Idaho Springs Fm.
58	621+00, ℄ to 621+00, 200' rt	0.0	1155	Mantle
		6.5	3500	Idaho Springs Fm.
59	622+00, ℄ to 624+00, ℄	0.0	1329	Weathered bedrock
		6.9	3707	Idaho Springs Fm.
59-1	624-00, ℄			
	Split traverse (59-B & 60-A)	0.0	1643	Weathered bedrock
		8.0	3514	Idaho Springs Fm.
60	624+00, ℄ to 625+50, ℄	0.0	1275	Weathered bedrock
		7.6	3550	Idaho Springs Fm.

Cut Section - Stations 637 to 649 (Plate 3)

Traverse	Station	Depth	Velocity	Material
61	639+00, ℄ to 639+00, 150' rt	0.0	870	Mantle
		4.1	2500	Weathered bedrock
		21.1	4450	Idaho Springs Fm.

62	640+00, ℄ to 640+00, 150' rt	0.0	975	Mantle
		1.6	2095	Weathered bedrock
		12.8	3191	Idaho Springs Fm.
63	641+00, ℄ to 641+00, 150' rt	0.0	2700	Weathered bedrock
		16.9	4600	Idaho Springs Fm.
64	646+00, ℄ to 646+00, 150' rt	0.0	854	Mantle
		2.7	2720	Weathered bedrock
		19.1	6741	Idaho Springs Fm.
65	647+00, 10' rt to 647+00, 160' rt	0.0	1210	Mantle
		6.0	2250	Weathered bedrock
		17.2	3900	Idaho Springs Fm.
66	648+00, 10' rt to 648+00, 160' rt	0.0	928	Mantle
		4.5	2973	Weathered bedrock
		23.0	5227	Idaho Springs Fm.

Cut Section - Stations 658 to 668 (Plate 4)

67	658+50, 50' lt to 659+50, 50' lt	0.0	1533	Weathered bedrock
		11.1	5913	Idaho Springs Fm.
68	659+40, 10'lt to 660+40, 10' lt	0.0	1575	Weathered bedrock
		7.4	7500	Idaho Springs Fm.
69	661+00, ℄ to 662+00, ℄	0.0	2120	Weathered bedrock
		22.9	4800	Idaho Springs Fm.
70	665+50, 50' lt to 666+50, 50' lt	0.0	880	Mantle
		3.8	2800	Weathered bedrock
		23.9	6200	Idaho Springs Fm.
71	666+50, 50' lt to 667+50, 50' lt	0.0	1650	Mantle
		9.7	4050	Idaho Springs Fm.
72	667+50, 50' lt to 668+50, 50' lt	0.0	1265	Mantle
		5.5	3125	Weathered bedrock
		11.6	4227	Idaho Springs Fm.

Cut Section - Stations 680 to 687

73	680+00, 200' lt to 681+00, 200' lt	0.0	736	Mantle
		4.1	2669	Weathered bedrock
		12.3	3735	" "
		23.9	5195	Idaho Springs Fm.
74	683+00, 100' rt to 684+00, 100' rt	0.0	1475	Mantle
		5.3	2650	Weathered bedrock
		26.9	6650	Idaho Springs Fm.
75	685+00, ℄ to 685+00, 50' rt	0.0	1500	Mantle
		1.6	2300	Weathered bedrock
		11.7	4800	Idaho Springs Fm.

Cut Section - Stations 698 to 714 (Plate 5)

76	700+00 ℄ to 701+00, ℄	0.0	2400	Weathered bedrock
		13.5	4800	Idaho Springs Fm.
77	701+00, ℄ to 702+00, ℄	0.0	1620	Mantle
		5.6	3121	Weathered bedrock
		26.6	6241	Idaho Springs Fm.
78	702+00, ℄ to 703+00, ℄	0.0	1115	Mantle
		2.0	2817	Weathered bedrock
		25.3	7049	Idaho Springs Fm.
79	703+00, ℄ to 704+00, ℄	0.0	1710	Mantle
		6.8	3850	Idaho Springs Fm.
80	704+00, ℄ to 705+00, ℄	0.0	1386	Mantle
		4.6	2272	Weathered bedrock
		13.0	5807	Idaho Springs Fm.
81	712+50, 100' lt to 713+50,	0.0	1540	Mantle
	100' lt	12.5	5300	Idaho Springs Fm.
82	713+50, 100' lt to 714+50,	0.0	2342	Weathered bedrock
	100' lt	9.4	5793	Idaho Springs Fm.

Cut Section - Stations 734 to 743

83	739+00, 80' lt to 740+00, 80'	0.0	1221	Mantle
	lt	5.6	5255	Idaho Springs Fm.
84	740+50, 75' lt to 740+50, 125'	0.0	943	Mantle
	lt	2.2	2083	Weathered bedrock
		7.4	6766	Idaho Springs Fm.