AD-A127 937 PATOKA LAKE FOUNDATION REPORT BOOK 5 APPENDIX E SPECIAL GROUTING ANALYSIS REPORT(U) ARMY ENGINEER DISTRICT LOUISVILLE KY S BARTLETT ET AL. APR 83 1/2

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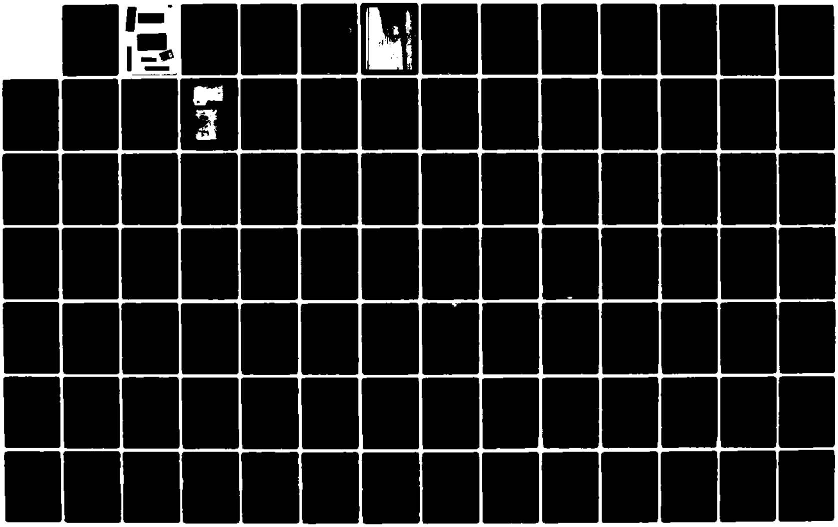

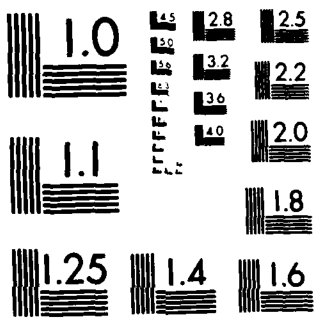
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BOOK 5 of 5

PATOKA LAKE FOUNDATION REPORT

APPENDIX E

SPECIAL GROUTING ANALYSIS REPORT

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report covers the construction of the Patoka Dam, Spillway and Dike. Patoka is a flood control structure on the Patoka River, a tributary of the Wabash River in Southwestern Indiana. It is in the flood control structures for the Ohio River Basin. The report contains narratives, charts, photos and construction logs.

APPENDIX E

SPECIAL GROUTING ANALYSIS REPORT
TO PATOKA LAKE FOUNDATION REPORT

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U. S. ARMY ENGINEER DISTRICT

LOUISVILLE

PATOKA LAKE, INDIANA

ANALYSIS OF GROUTING EFFECTIVENESS AND DISTRIBUTION AS OBSERVED DURING EXCAVATION

PATOKA RESIDENT OFFICE

PATOKA LAKE

GROUTING ANALYSIS

TABLE OF CONTENTS

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PART I - INTRODUCTION

1-01. Patoka Lake, when completed, will be a multipurpose earth and rock filled dam located on the Patoka River, a tributary of the Wabash River, in the south-central portion of Indiana. The damsite is located 118.3 river miles above the mouth of the Patoka River, and approximately 55 miles west of Louisville, Kentucky.

1-02. The Patoka Lake project was authorized as part of the flood control plan for the Wabash River Basin by the Flood Control Act, designated as Public Law 89-298, 89th Congress, approved on 27 October 1965.

1-03. Principal structural features consist of a cut and cover outlet works with two service gates, earth and rock filled dam and dike with crest elevations of 564 and an open cut uncontrolled spillway with a sill elevation of 548 located between the dam and dike structures. The crest of the dam structure is approximately 84 feet above the original stream level. The length of the dam structure is 1,550 feet between abutments. The dike structure is approximately 33 feet high and 1,550 feet long. The conservation pool at elevation 536 covers 8,800 acres, making this the second largest manmade lake in Indiana.

1-04. Construction of the control tower and outlet works was completed in 1974 and construction of the dam, dike and spillway was started in the spring of 1975. An early sequence of construction required grouting of the dike left abutment through overburden. Upon completion of this grouting program, a 10-foot deep inspection trench was planned with the remainder of the overburden to be left in place. Grouting in this area was started in May 1975 and continued until October 1976 without completion. Subsequent studies led to the decision to excavate the material within the partially grouted curtain down to shale and to make a positive tie into the left abutment with the dike embankment.

1-05. Observations of the grouted rock during subsequent excavation afforded a unique opportunity to evaluate the distribution and effectiveness of the grouting program in this area. The purposes of this report are to set forth the design criteria, to analyze the grouting program, to outline excavation procedures, to analyze grout distribution, and to evaluate the effectiveness of the grouting program. This report is further limited to discussion of the area between grout stations 100+00 and 104+20 (Dike Sta. 0+00 to 4+20). Grout stationing corresponds with dike stationing if 100 is added to each dike station. Discussion of other project features will be presented only to clarify and support details relevant to the dike left abutment.

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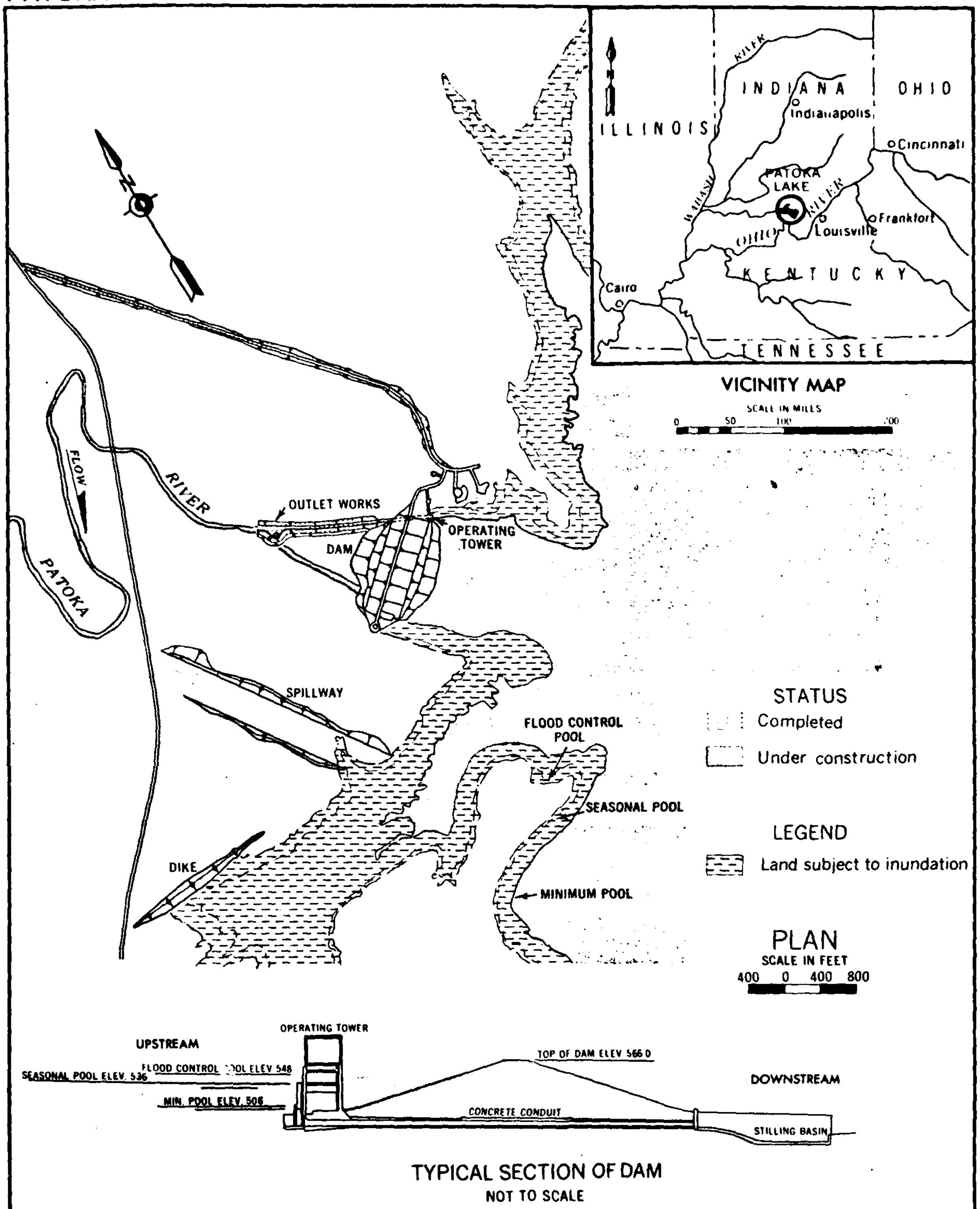


PATOKA RIVER, IND.

PATOKA LAKE

LOUISVILLE, KY. DISTRICT

SCALE AS SHOWN

REVISED 30 SEPTEMBER 1976

PART II - GEOLOGY

2-01. Geologically, the dike structure is founded on sedimentary rocks of the Mississippian and Pennsylvanian Systems. Regional dip is westerly at approximately 25 feet per mile. Overlying bedrock are formations of glacial lacustrine, colluvium, and recent alluvial deposits. Figure II-1, geologic column, is included for reference.

2-02. The oldest rock formation of concern is the limestone portion of the Mississippian Golconda Formation. This portion of the formation consists of a massive, gray, hard, fossiliferous, slightly shaley, crystalline limestone. The limestone averages 30 feet thick in the dike area. Though highly solutioned in other areas of the foundation, all available data indicates that this formation is unsolutioned below the dike. This limestone was not included in the grouting program for the left abutment of the dike.

2-03. Overlying the Golconda Limestone is the Hardensburg Shale formation. This formation consists of lenticular beds of mottled shale, calcareous sandstone, and soft slickensided indurated clay. The thickness ranges from 25 to 30 feet in the damsite area. This formation comprises the foundation for the major portion of the revised dike embankment.

2-04. The next younger formation in sequence is the Glen Dean Limestone. Normal thickness in the dike area is 30 feet. The thickness is less where the limestone has been subjected to extensive solutioning and erosion. The rock is a gray, hard, crystalline, fossiliferous, highly jointed, massive limestone. In the dike area, this limestone is highly solutioned along joints and bedding planes. In addition, this formation has been extensively eroded during a long interval of exposure between Mississippian and Pennsylvanian depositions. Normally there is a 30-foot section of alternating shales and limestones above the massive portion of this formation. However, in the general damsite area, this upper portion of the Glen Dean Formation is absent due to the pre-Pennsylvanian interval of erosion.

2-05. The three formations described above comprise the bulk of the Stephensport Group of the Chester Series. In the normal geologic column, another unnamed group of the Chester Series is present above the Stephensport formations. This unnamed group between the Stephensport Group and the Pennsylvanian System is totally absent in the damsite area. In this general area, the unnamed group of rocks was either not deposited or was removed during the long period of erosion between two major systems of deposition.

GENERALIZED GEOLOGIC SECTION FOR DIKE

Elev.	SYSTEM	SERIES	GROUP	FORMATION	DESCRIPTION
600				O B	CLAY & WEATHERED ROCK FRAGS
550	PENNSYLVANIAN	POTTSVILLE	MORROW	MANS-FIELD S S	SS BUFF-RUST BROWN; LAM - THICK Bd.; NUM SH LAM & BDS; PLANT FRAGS; POORLY CEM. MOD SOFT, V. POROUS
500	MISSISSIPPIAN	CHESTER	STEVENS PORT	GLEN DEAN L S	LS-LT GRAY MASS SHALEY in LOWER PORTION; SOL. ALONG JTS & SH Bd HD; XLYN; FOSS;
				HARDINS-BURG - SH	SH SS; GREENISH GRAY-MARROON; SOFT-MOD HD; LAM-THICK BD;
450				GOLCONDA L S	LS-LT GRAY, HD; SHALEY IN LOWER PORTION; XLYN; MASSIVE; FOSS; SOL ALONG JTS
					SH-DH GREY; THIN BD; FOS; MOD SOFT

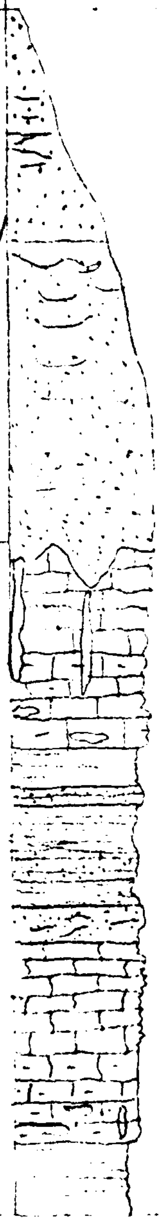


FIGURE II - 1

2-06. Consequently at the damsite, the Mansfield Formation, which is the basal member of the Pennsylvanian System, lies disconformably upon the Glen Dean Limestone. The Mansfield Sandstone consists of interbedded fine grained sandstones and shales. In the dike area, this formation is poorly cemented, leached and crossbedded in part. The beds are generally lenticular. The Mansfield Formation is the youngest rock unit found in the dike area.

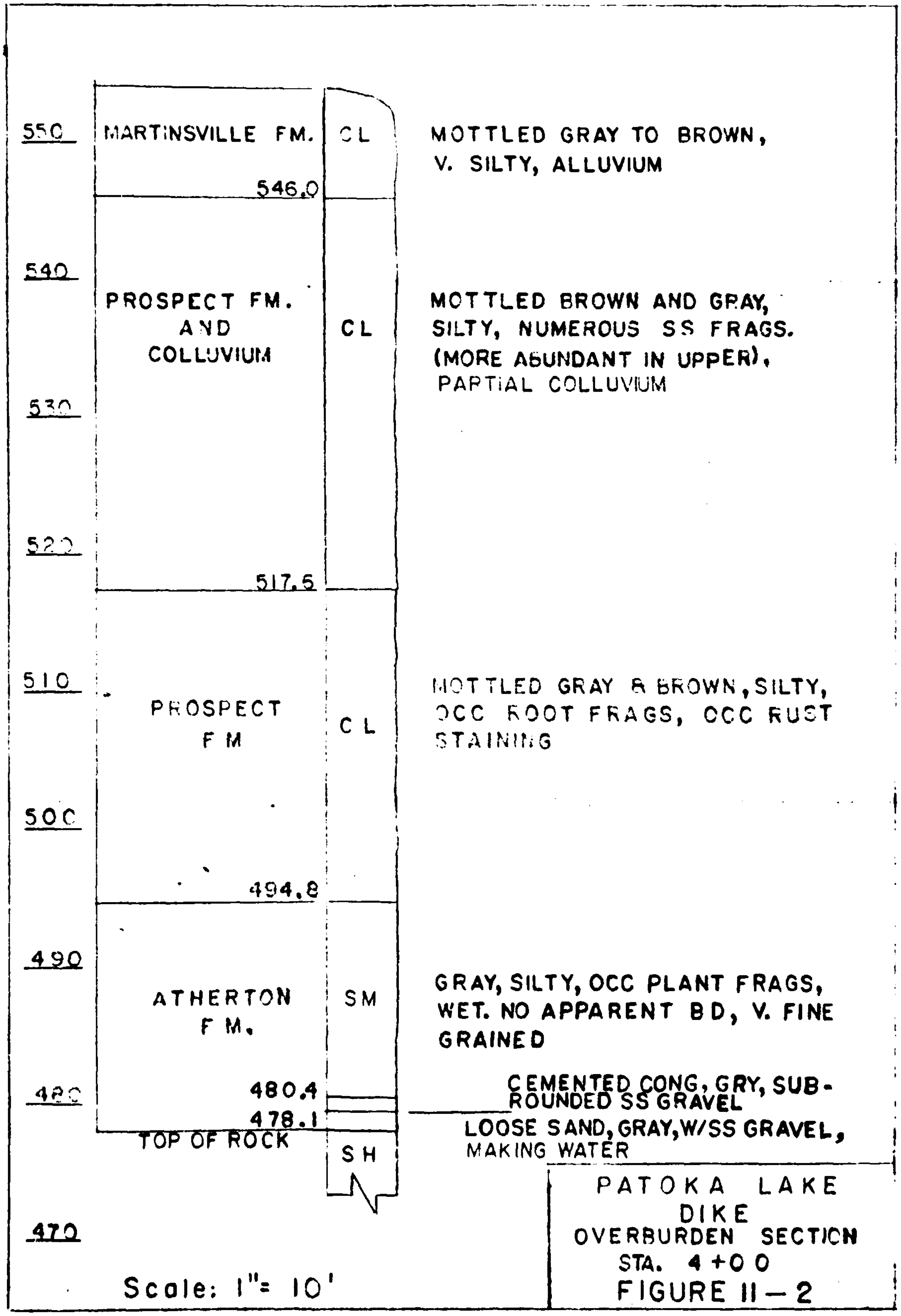
2-07. Subsequent to deposition and consolidation, the Mississippian rocks in this area have been raised and tilted slightly. Formations of this age generally dip S 65° W, with slight variations. The rate of dip is approximately 25 feet per mile, with lower Mississippian rocks dipping steeper than the higher beds. The Pennsylvanian rocks dip nearly westward at a slightly lower angle than the Mississippian rocks.

2-08. The Mississippian Limestones present well developed right angle patterns of nearly vertical joints. The joint patterns between the two limestones are nearly parallel and generally trend north-south and east-west. Variations are common that disrupt the general pattern. As mentioned earlier, large numbers of these joints have been extensively solutioned and subsequently filled with "Terra Rosa" clays.

2-09. The top of the natural water table in the left abutment of the dike generally conforms to the top of the presolutioned Glen Dean Limestone (elev. 522). Interestingly, the water table remains at elevation 522 in the areas where this limestone has been solutioned and eroded away.

2-10. Several large clay and rubble-filled relief joints were found in the Mansfield Sandstone at the dike left abutment during excavation. One of these joints contained a small 3-foot wide cave that most likely connected with another small cave at the county road 500 feet upstream of the dike. Portions of this cave have collapsed, but a small open section was uncovered during excavations at Sta. 0+60 above the top of the grout curtain. The clay and rubble-filled joints ranged from 0.2 to 3 ft. in width. All of these joints become narrower with depth and all stopped at or above the sandstone-limestone contact. From these characteristics, the joints apparently resulted from lateral relief of the sandstone during erosion of a deep river channel between Stas. 3+50 and 7+0. These joints have been plotted on Figure V-1.

2-11. Overburden in the study area was limited to weathered rock colluvium, "Terra Rosa" clays, and younger alluvial deposits. The alluvial deposits consisted of lacustrine sands and silts of the Atherton Formation overlain by alluvial, sandy clays of the Prospect and Martinsville Formations.



PATOKA LAKE DIKE
OVERBURDEN SECTION
STA. 4+00
FIGURE II – 2

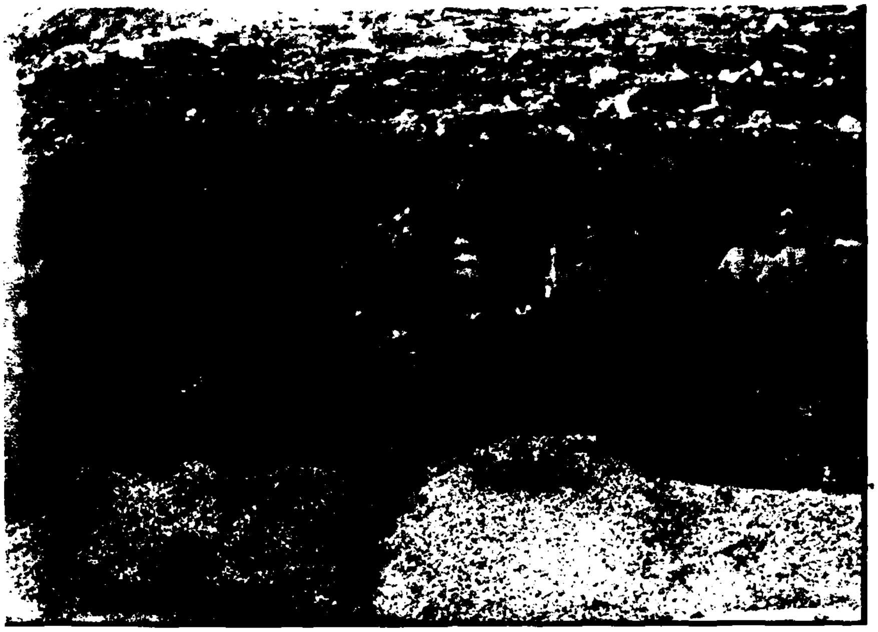
2-12. Of primary overburden interest were the "Terra Rosa" clays. These residual and transported clays were found within the highly weathered and solutioned areas of the Glen Dean Limestone. As described further in this report, a large portion of the right abutment portion of the dike foundation consisted of large isolated blocks (pinnacles) of limestone surrounded by the "Terra Rosa" clays. The "Terra Rosa" clays consisted of very wet, reddish brown, fat and lean clays. They also contained fossils, sandstone fragments, and thin sand lenses within the clay matrix.

2-13. Colluvial overburden material consisted of highly weathered sandstsone mixed with clay. These talus materials, derived from downslope movement of sandstone debris, were found covering the lower limestone and sandstone slopes. Above Station 3+0 this reddish brown colluvial material was found interbedded amid the younger alluvial formations with tongues of colluvial material extending out into the alluvial clays.

2-14. At the base of the ancient river channel between Station 3+50 and 7+50, a thin cemented gravel seam was found just above the lacustrine-shale contact. This seam varied from several tenths to one foot thick. This conglomeratic material was composed mainly of subrounded sandstone down to sand sized particles. Detrital material formed the matrix and cementation. Numerous very fine quartz grains could be observed. Occasional highly decomposed, soft, small limestone fragments were also observed within the matrix. In several places, lacustrine sands and silts could be seen between the conglomeratic seam and the rock. This cemented gravel seam was always overlain by lacustrine deposits.

2-15. The glacial lacustrine deposits of the Atherton Formation consisted of silt to sand sized particles with some gray lean clay lenses. Near the top of these deposits and just below the contact with the overlying alluvial deposits, considerable organic remains were found. Several pieces of wood were taken for radio-carbon dating, but were found to be too old (38+ thousand years) for dating by this method.

2-16. The youngest overburden material consisted of the alluvial Prospect and Martinsville Formations. Both these formations consisted of mottled gray and brown silty clay. The only differentiation between the two formations was the deeper weathering in the older Prospect Formation. See Figure II-2 for a section taken through the overburden at Sta. 4+0.



U.S. Wall. LS pinnacle overlain with SS.

Details of LS pinnacle at Sta. 2+20 on US wall

2-17. Seismically, the project lies in Algermission's risk area #2. Earthquakes with a surface wave of 6.25 magnitude at 0.46G can be expected in the project area. Faulting, however, is not evident in the dike formation. Geophysical considerations did not alter the dike foundation design.

PART III - DESIGN PHASE

3-01. Initial studies for Patoka Lake were undertaken by the Indiana Geological Survey in the late 1950's and early 1960's. Studies included exploratory drilling, seismic profiles, aerial photography and previous geologic and soil reports. The results of these studies were published in 1963 as Special Report #2. Conclusions reached in this report indicated that leakage through the two cavernous limestones was possible and would need further study. The damsite was selected as a result of these studies.

3-02. Foundations investigations by the Corps of Engineers were started in October 1962 and continued intermittently until the dam contract was awarded in January 1975. A total of eight exploratory holes, including state borings, were drilled in the left abutment area of the dike. During the design phase, extensive exploratory work was done on the right abutment of the dike including one 36-inch diameter auger hole drilled part-way into the Glen Dean Limestone.

A. General Design

3-03. The General Design Memorandum (DM #2) was published in September 1968. As set forth in this Design Memorandum, the dike was to be founded on alluvial material of the Prospect Formation, which had a maximum thickness of 70 feet at Sta. 5+0. A 10-foot deep inspection trench starting at Sta. 2+30 was intended to remove all surface obstructions. The right end of the dike embankment was planned to tie into the Mansfield Sandstone, but no rock tie-in was intended for the left end of the embankment. During exploratory drilling, excessive core losses were recorded in the Mansfield sandstone at the left abutment. Two exploratory holes, including one on the left abutment, were examined with a bore hole camera to check the reasons for excessive core losses. The results of these examinations indicated that the excessive core losses were due to poor cementation and not due to cavities. However, the exploratory hole in the left abutment area was not examined at the sandstone-limestone contact where problems with cavities ocurred during construction. The core hole in the right abutment area was indistinctly examined at the sandstone-limestone contact due to the very muddy sidewalls, indicating a clay-filled cavity.

3-04. Seepage below the dike was not considered a problem in DM #2 due to the great thickness of overburden and due to the planned normal pool near the ground surface. Grouting of the sandstone and upper limestone was considered adequate to prevent seepage beneath the left abutment of the dike. Many drill water losses were noted in core holes, but no pressure test data for the left abutment was presented in this Design Memorandum. Exploratory drilling also indicated a low water table in the left abutment of the dike. Consequently, the conclusion was reached that a positive grout curtain tied into a high water table was not possible. The grout curtain for the left abutment was therefore designed to insure the integrity of the embankment while allowing some end around seepage.

3-05. A triple line grout curtain was envisaged for the left abutment of the dike with the outside lines being grouted prior to the centerline. The top of the curtain was to coincide with the top of the dike (Elev. 564). The curtain was to be drilled from the ground surface with the overburden being cased off. In this General Design Memorandum, grouting was carried across the entire length of the dike. The proposed curtain on the left abutment terminated approximately 800 feet landward of dike Sta. 1+0. The lower (Golconda) limestone in the dike area was not mentioned in this D.M., but was inferred to be too deep to constitute a seepage problem. Exploratory core holes did not penetrate this deep limestone in the dike area.

3-06. Several review comments by ORD and OCE were published as addenda to this Design Memorandum. Grouting comments revolved around rim leakage, positive cutoff for the highly solutioned limestone on the right abutment of the dike and elimination of the grout curtain in the area where the Glen Dean Limestone was absent. These comments were answered by ORL with indications that the problems would be further studied for presentation in the Feature Design Memorandum.

B. Feature Design

3-07. Further groundwater studies and exploratory borings were made after publication of D.M. 2. The results of these studies and subsequent refinements to the grouting design were presented in the Feature Design Memorandum (D.M. 8). The Feature Design Memorandum was published in June 1970 with one appendix.

3-08. The general design for the dike foundation remained the same as presented in D.M. 2. The dike, again, was to be founded on alluvial material with a 10-foot deep inspection trench throughout its length. The embankment was again designed to tie into the Mansfield Sandstone at the right abutment, but not at the left abutment.

3-09. As in D.M. 2, seepage below the dike embankment was not considered a problem. Again, seepage at the disconformity would be controlled by grouting the Mansfield Sandstone and Glen Dean Limestone. On the left abutment and rim, seepage was not considered to be a problem since both soluble limestones (Glen Dean and Golconda) were deeply covered and were dipping into the hill. Seepage in the Mansfield Sandstone was not considered a serious problem and would be controlled by grouting. Seepage around the left end of the curtain was presented as a possibility and contingencies to extend the curtain at a later date were suggested.

3-10. Details of the grout curtain remained essentially the same except that grouting was eliminated where the Glen Dean Limestone was absent below the dike, Sta. 4+50 to 7+65. A more detailed grouting profile was included showing the curtain on the dike left abutment to be broken into two zones below elevation 564. The base of the curtain was defined as being 5 feet below the lower Glen Dean Limestone contact on the left abutment. The grout curtain was shortened 700 feet at the left abutment of the dike. There was no discussion as to why the grout curtain was shortened. Again, grouting through the overburden was planned. The grouting profile shown in this D.M. remained essentially the same a presented in the contract drawings.

3-11. The results of a groundwater study and better pressure test data were included in this D.M. Low water tables were noted on both reservoir rims. Seepage control for the left rim was not altered. Only one core hole on the left abutment of the dike (Sta. 1+20) was pressure tested. This hole indicated a tight limestone. However, water takes in the 15-foot interval at the contact between limestone and sandstone averaged 6 cu. ft. per minute. Water takes in the sandstone above this interval ranged from 1 to 5 cu. ft. per minute in 5-foot testing intervals. These takes were considerably less than takes observed during contract grouting. As in D.M. 2, drill water loss zones were presented. Of the eight exploratory holes drilled on the left abutment of the dike, four holes lost drill water in the sandstone, one hole lost drill water in the limestone, one hole lost drill water in both the sandstone and in the limestone, one hole encountered very little limestone, and one hole indicated no drill water loss.

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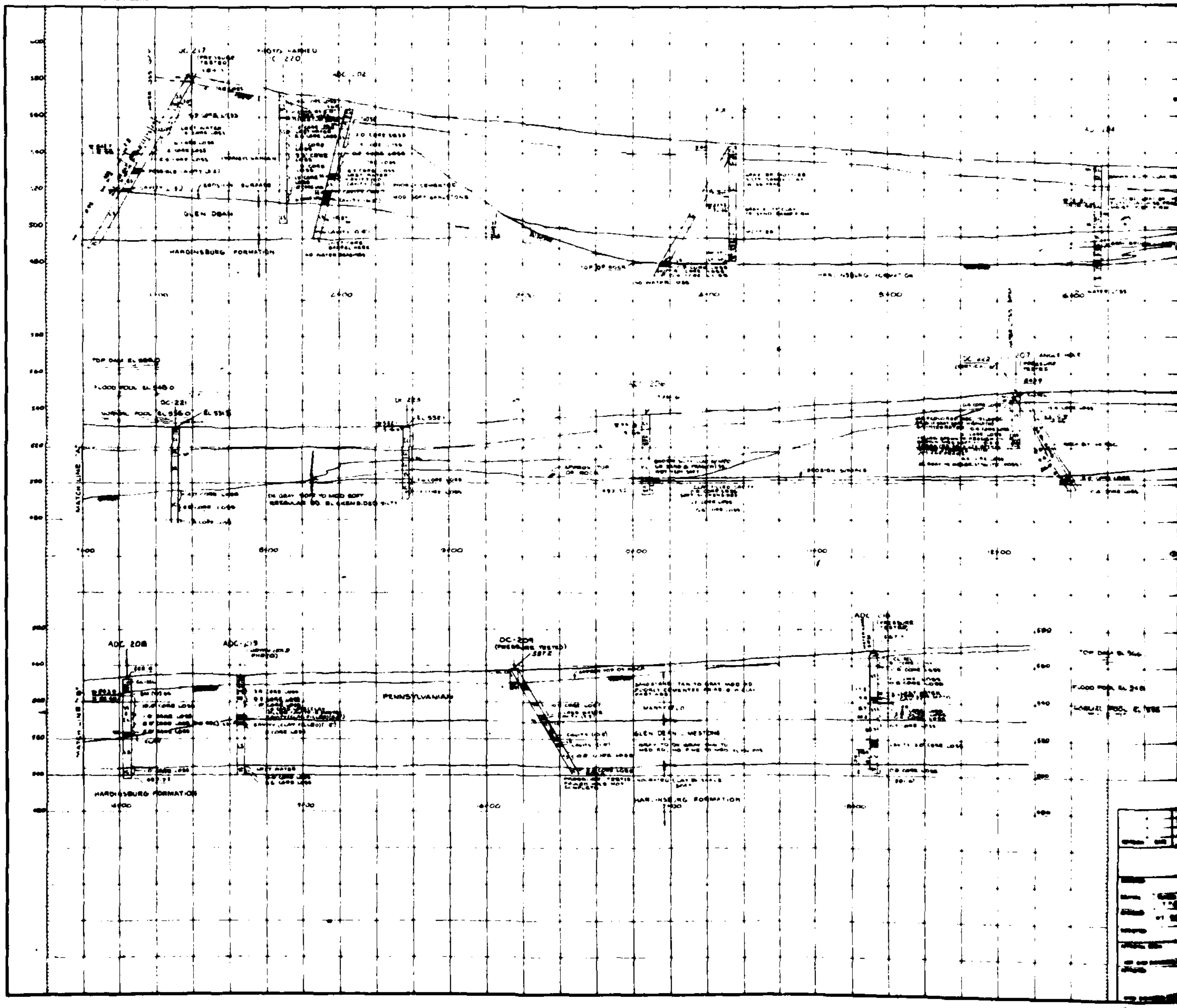
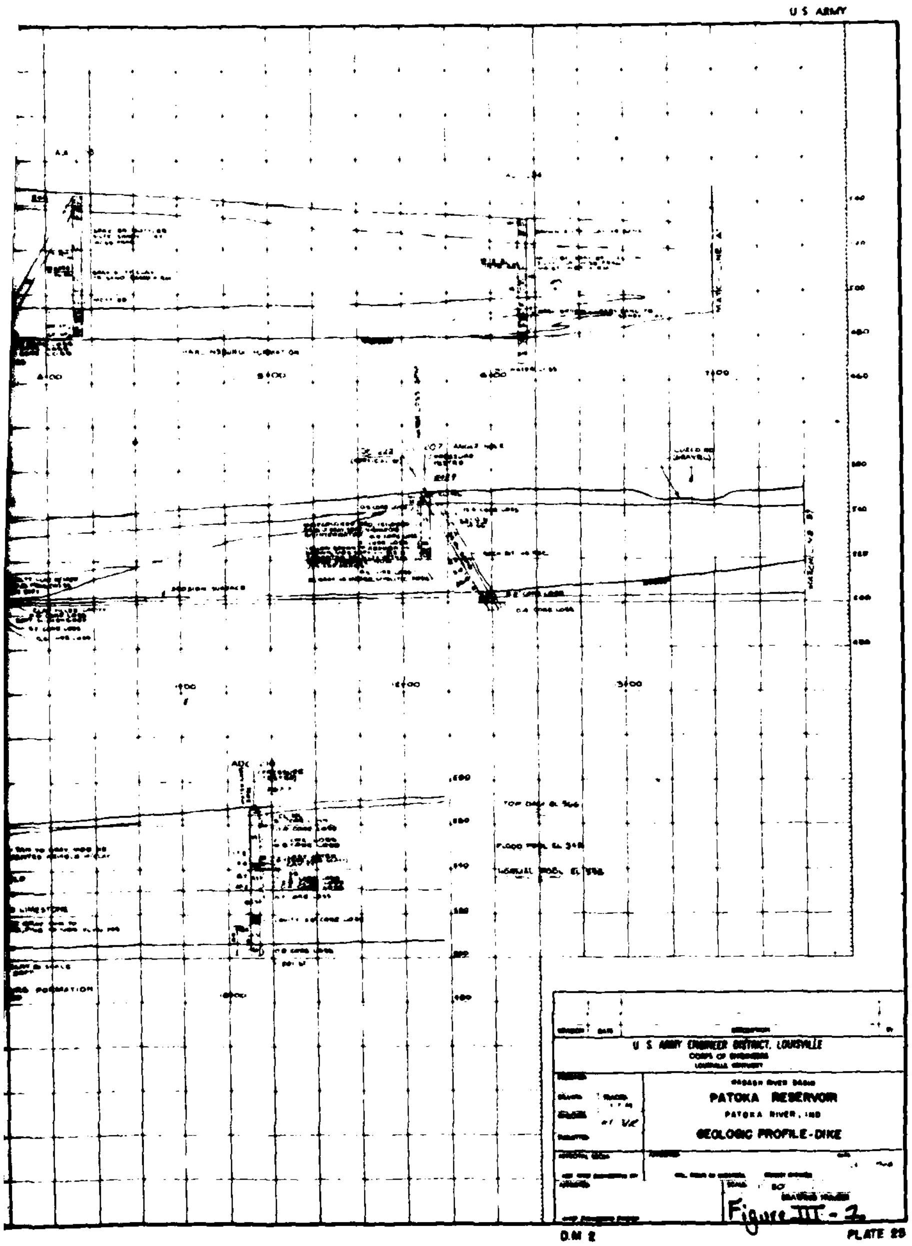


D.M 2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PATOKA RESERVOIR
PATOKA RIVER, IND
GEOLOGIC PROFILE-DIKE
Figure III-2
D.M 2
PLATE 23

2

3-12. After review, comments were made by ORD and OCE. These comments were inserted in the front of the Feature Design Memorandum. Several comments concerning grouting were pertinent to the problem encountered during construction. A lack of data to support rim grouting conclusions were noted. The presumption that the Mansfield Sandstone would not present a seepage problem was questioned. Further, the possibility of large cavities between the sandstone and the solutioned limestone was noted. A positive cutoff through the Glen Dean Limestone on the right abutment of the dike was strongly recommended to eliminate the piping potential in this area. The ineffectiveness of proposed grouting in the right abutment area was also noted. No comments were made about the left abutment. The left abutment seepage zone between sandstone and limestone was considered too far below the surface to be treated economically by an excavated cutoff. Further exploratory work was suggested for the dike area.

3-13. Further exploratory work including a 36-inch diameter auger hole on the right abutment was accomplished in the dike area. However, no further exploratory work was accomplished on the left abutment of the dike. The results of this additional exploratory drilling were presented in Supplement 1 to Design Memorandum 8.

3-14. In this supplement, the design was altered to excavate a positive cutoff trench through the Glen Dean Limestone on the right abutment of the dike. No changes were made to the left abutment foundation treatment.

3-15. Further comments by ORD and OCE with replies by ORL were included in this supplement. The only comment concerning the dike left abutment suggested placing a large waste material berm downstream of the dike. This berm would increase the length of the seepage path and prevent breaching of the dike in case of sink hole development above the solutioned limestone. The final contract plans included this added berm downstream of the dike.

C. Contract Specifications

3-16. The final grout curtain design was set forth in the contract plans and specifications. On the left abutment of the dike, the plans called for a triple line stage grouted curtain between Stations 1+0 and 4+20. The top of the curtain was set at Elevation 564 or at the top of rock, whichever was deeper. The grout curtain was divided into two zones. The bottom of the first zone was defined as being 20 feet below the top of the curtain. The bottom of the second zone was defined as being 5 feet below the base of the Glen Dean Limestone. The two outside lines were to be completed within a zone before completion of the centerline in the same zone. Original spacing was set at 20-foot centers with provisions for split spacing as necessary. Stages were defined as drill water loss or bottom of zone. The grouting operations were further reduced to 100-foot sections in which drilling and grouting could not be carried on simultaneously. Minimum diameter of holes was defined as 1-3/8 inches. All holes were battered on 20 degree angles into the abutment. The maximum depth for any one hole was 122 feet. Plans required this area to be completely grouted before excavation of the 10-foot deep dike inspection trench.

3-17. Casings were required through the overburden and sealed at least one foot into rock. Where rock overlaid the top of the grout curtain (Elev. 564), the rock above the curtain was not to be grouted. In this situation, a packer was required at Elevation 564 to prevent grout leakage. Upon completion of grouting operations, all casings were to be removed and the resulting voids backfilled.

3-18. After drilling any stage, the holes were to be washed and pressure tested immediately prior to grouting. If joint filling was encountered, washing under pressure would continue until all filling material was washed from the joints. Holes where no pressure could be built up were to be washed for a period of five minutes.

3-19. Specified water cement ratios for grouting varied from 3:1 to 0.6:1. Provisions were included for mortar grout if necessary. Allowable grouting pressures, as specified, ranged from 1 to 170 psi, static head. Specifications required air drive progressive cavity (non surge) or equal grout pumps. The grout pump could not be placed further than 100 feet from the hole being grouted. Grout supply lines of 1.5 inch diameter were specified between the grout pump and the hole being grouted.

PART IV - GROUTING PHASE

4-01. The contract for the Dam and Spillway was awarded in January 1975 and work began the same month. Grouting was started on May 22, 1975, at the dike left abutment. Work continued in this area almost continually until October 13, 1976, when grouting was abandoned.

4-02. This short area was divided into four 100-foot long sections and worked by sections thereafter. The problems encountered later coincided closely within the boundaries of these four sections. All the primary casings were installed before drilling and grouting were started.

4-03. Drilling and grouting equipment used in this area of the grout curtain was of standard design for the grouting industry. Casings were drilled with a Chicago Pneumatic air-trac drill converted to rotary operation using standard NW drill rods and rock bits. Grout hole drilling was performed with air-operated Chicago Pneumatic 55 post mounted drills utilizing EX rods and bits. The grout plant consisted of 2 each 17 cu. ft. mixing tubs and an air-operated Moyno progressive cavitating grout pump.

4-04. Mix designs and general grouting procedures were formulated early in the grouting process. Water cement ratios ranged from 3:1 to 0.6:1 in neat mixes. The sand mix designed for grouting contained 5 cu. ft. or mortar sand, 3 cu. ft. of water, 3 cu. ft. of cement, and 1 cu. ft. of flyash. The water content was low ered occasionally. However, inconsistent sand moisture contents and slightly inaccurate water meters resulted in varying mix consistencies when the water content was altered. The 3 cu. ft. of water was standardized to give a consistently pumpable mix. Grouting pressures of 10 and 15 psi were used for the first and second zones, respectively.

4-05. Grouting was usually started with a 2:1 mix depending upon water take. The mix was periodically thickened, usually in 30 cu. ft. increments, until a 0.6:1 mix was achieved. Where no pressure was recorded, pumping was continued until approximately 150 cu. ft. of solids were pumped into the hole. If no pressure was reached at this point, grouting was discontinued for one shift. The following shift, sanded grout, was pumped until a total of 500 cu. ft. of solids were pumped. Grouting was discontinued for another shift to allow a complete set. Pumping of sanded grout was continued in this manner until the hole refused. The grouting procedures described here represented a very general grouting procedure and were varied according to circumstances.

4-06. The 150 cu. ft. initial neat cement grouting was justified for two primary reasons. First, a large number of holes, especially in the sandstone, refused between 100 and 150 cu. ft. Secondly, this procedure allowed some smaller cracks to be filled while pumping into a larger void.

4-07. The sand used in the grout mixes posed one of the greatest supply problems. The contractor could not obtain sand to meet the contract specifications from his supplier. Other suppliers were contacted, but they could not meet the specifications either. One supplier would have been required to change his screen settings and to run a special batch to meet the specifications. Another supplier would have been required to add and blend material at different screen sizes to meet the specified gradations and fineness modulus. The relatively small quantities of sand involved did not economically justify these changes for the suppliers. The dispute over sand gradations caused some delay in grouting progress. After much discussion and testing, the specifications were changed to meet the sand available from the supplier. Table IV-I outlines changes made to sand specifications.

TABLE IV-I

Original Specifications: Sieve Size	% Passing	Changed Specifications Sieve Size	% Passing
8	100	8	100
16	85-100	16	85-100
30	50-85	30	50-92
50	10-40	50	10-40
100	0-20	100	0-20
200	0-5	200	0-5
F. M.: 1.5 to 2.0		F.M.: 1.5 to 2.15	

4-08 The section between Sta. 103+00 and 104+20 was designed for a single 20-foot zone since the top of rock contact coincided with the top of the Hardensburg Shale. This section was completed quickly with few grouting problems. The largest problem encountered in this section involved pulled casings during drilling and grouting operations. The casings penetrated up to 50 ft. of overburden and were sealed with grout 2 ft. into rock. The post mounted drills used for drilling were anchored to the same casings. A combination of thick overburden, poor sealing, and strain during drilling caused a large number of casings to unseat. Out of 24 holes drilled in this area, 12 casings pulled. Whenever a casing pulled, it was resealed with

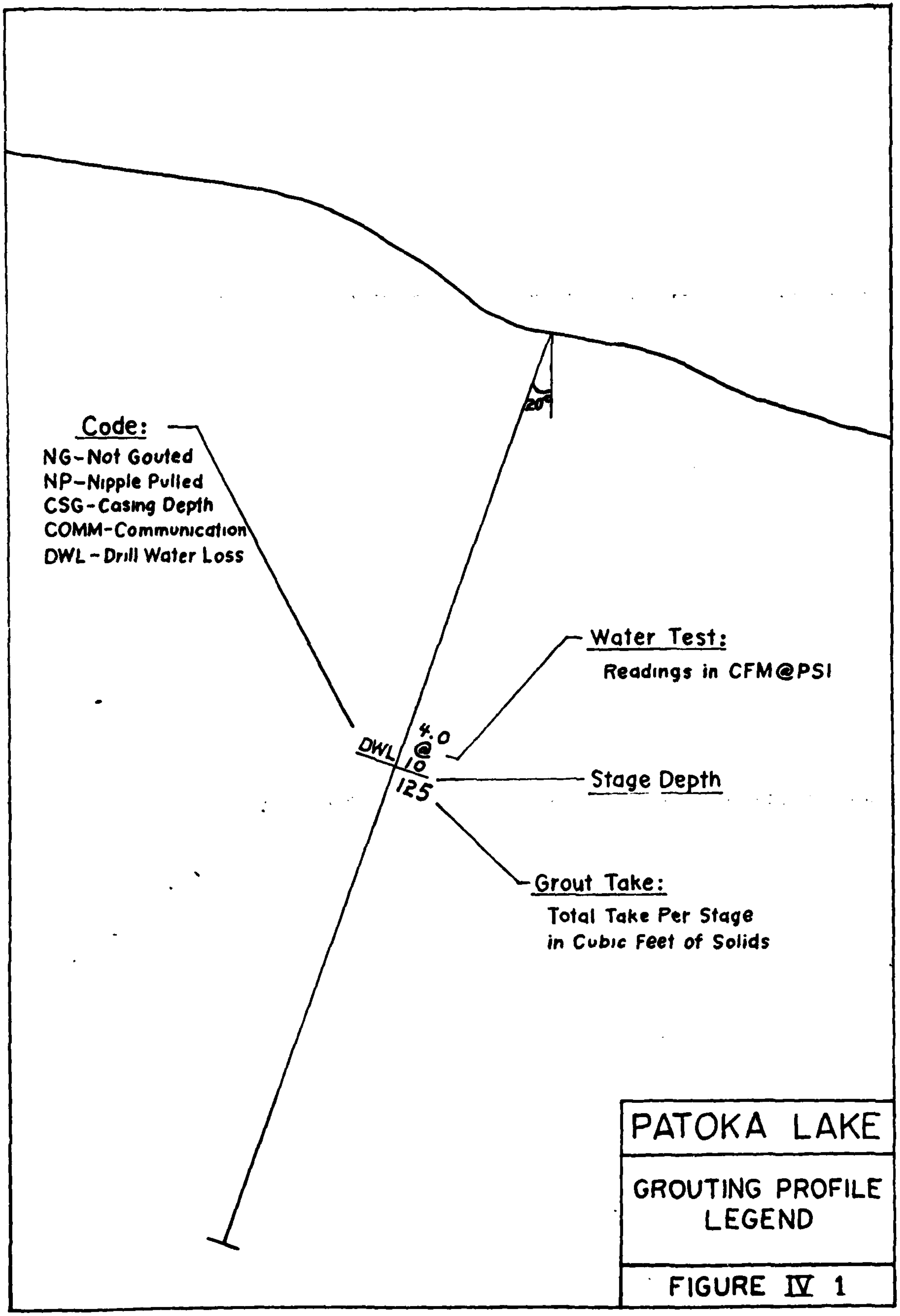
4-06. The 150 cu. ft. initial neat cement grouting was justified for two primary reasons. First, a large number of holes, especially in the sandstone, refused between 100 and 150 cu. ft. Secondly, this procedure allowed some smaller cracks to be filled while pumping into a larger void.

4-07. The sand used in the grout mixes posed one of the greatest supply problems. The contractor could not obtain sand to meet the contract specifications from his supplier. Other suppliers were contacted, but they could not meet the specifications either. One supplier would have been required to change his screen settings and to run a special batch to meet the specifications. Another supplier would have been required to add and blend material at different screen sizes to meet the specified gradations and fineness modulus. The relatively small quantities of sand involved did not economically justify these changes for the suppliers. The dispute over sand gradations caused some delay in grouting progress. After much discussion and testing, the specifications were changed to meet the sand available from the supplier. Table IV-I outlines changes made to sand specifications.

TABLE IV-I

Original Specifications: Sieve Size	% Passing	Changed Specifications Sieve Size	% Passing
8	100	8	100
16	85-100	16	85-100
30	50-85	30	50-92
50	10-40	50	10-40
100	0-20	100	0-20
200	0-5	200	0-5
F. M.:	1.5 to 2.0	F.M.:	1.5 to 2.15

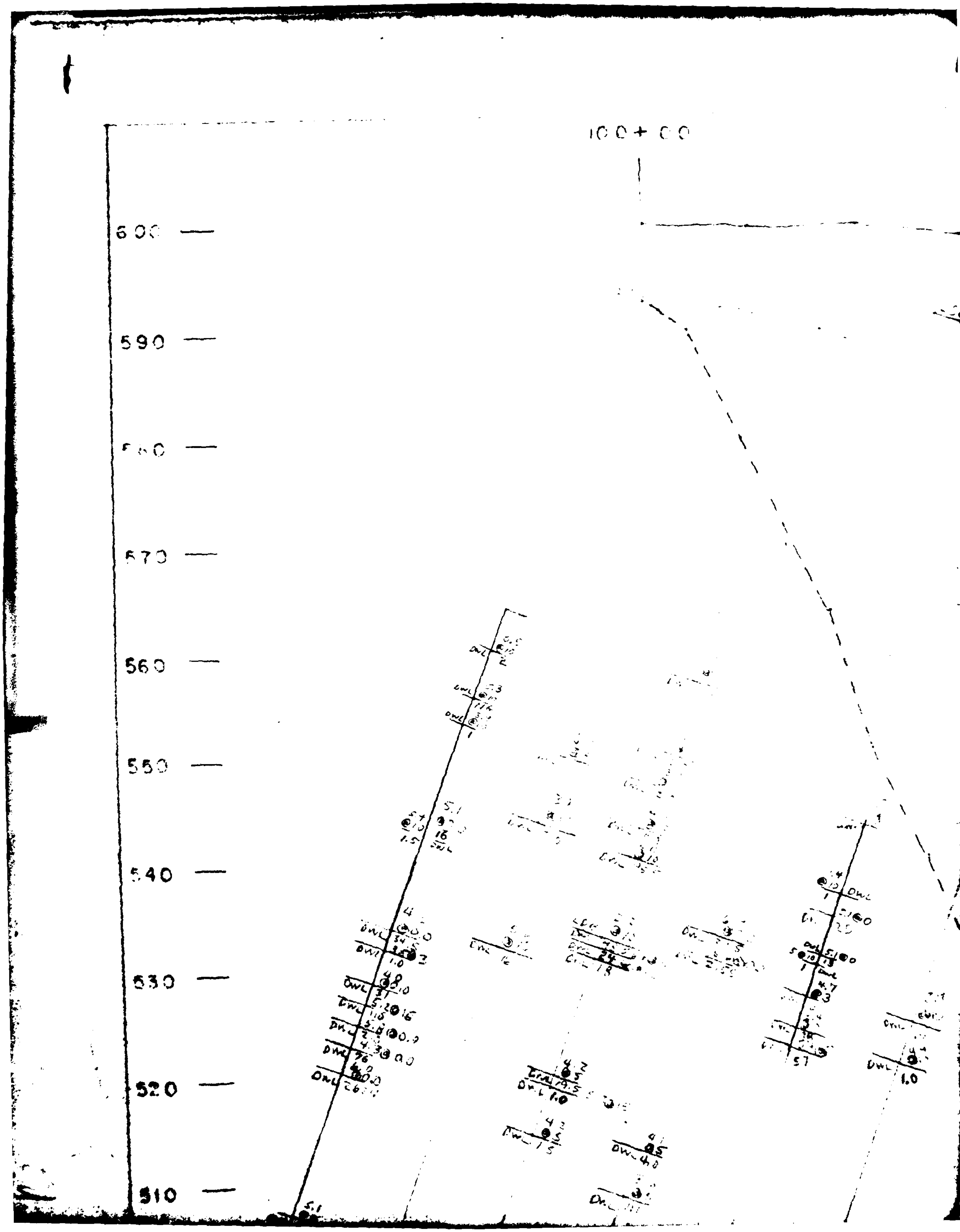
4-08 The section between Sta. 103+00 and 104+20 was designed for a single 20-foot zone since the top of rock contact coincided with the top of the Hardensburg Shale. This section was completed quickly with few grouting problems. The largest problem encountered in this section involved pulled casings during drilling and grouting operations. The casings penetrated up to 50 ft. of overburden and were sealed with grout 2 ft. into rock. The post mounted drills used for drilling were anchored to the same casings. A combination of thick overburden, poor sealing, and strain during drilling caused a large number of casings to unseat. Out of 24 holes drilled in this area, 12 casings pulled. Whenever a casing pulled, it was resealed with



PATOKA LAKE

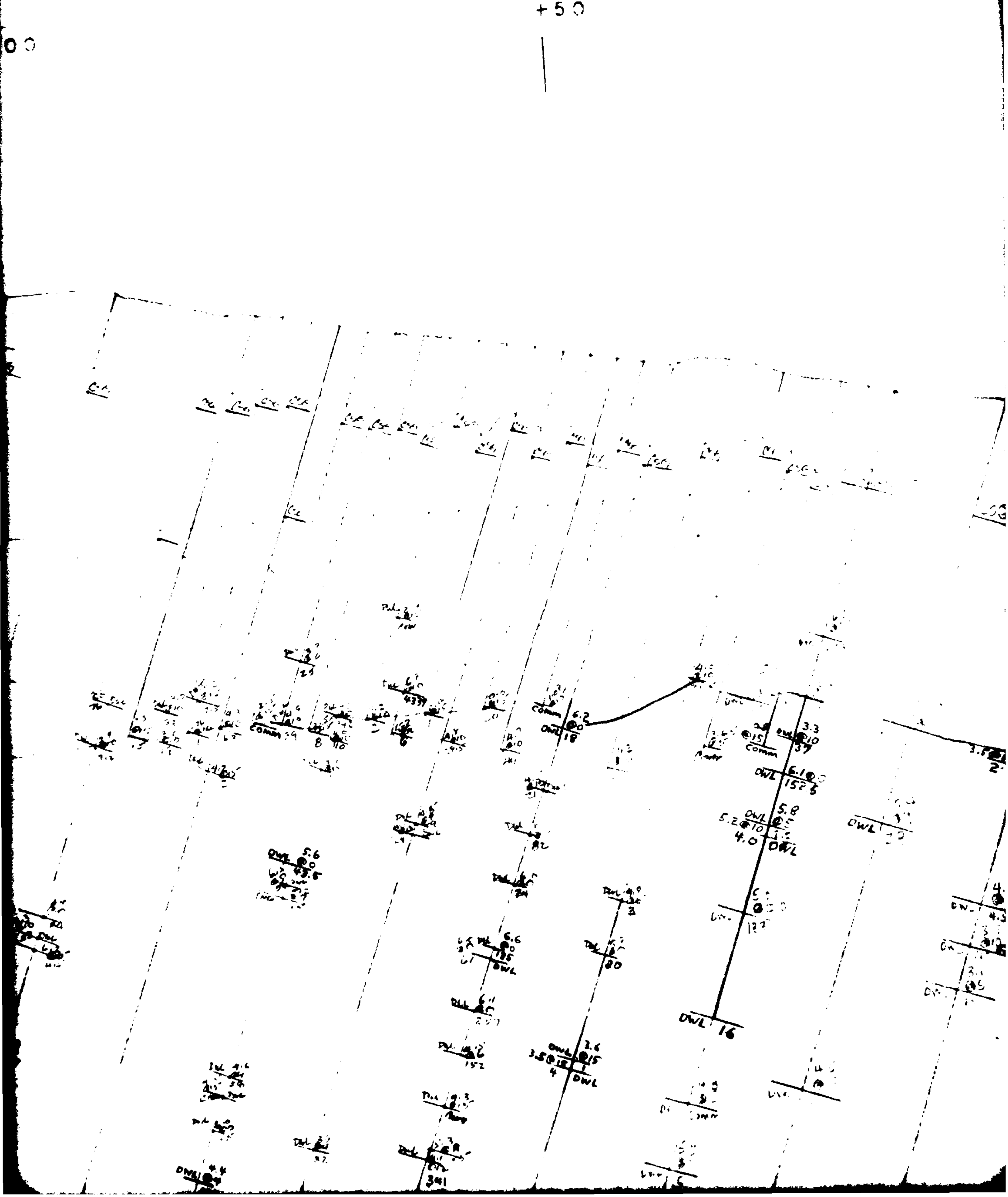
GROUTING PROFILE LEGEND

FIGURE IV 1


100+00
600
590
580
570
560
550
540
530
520
510

12

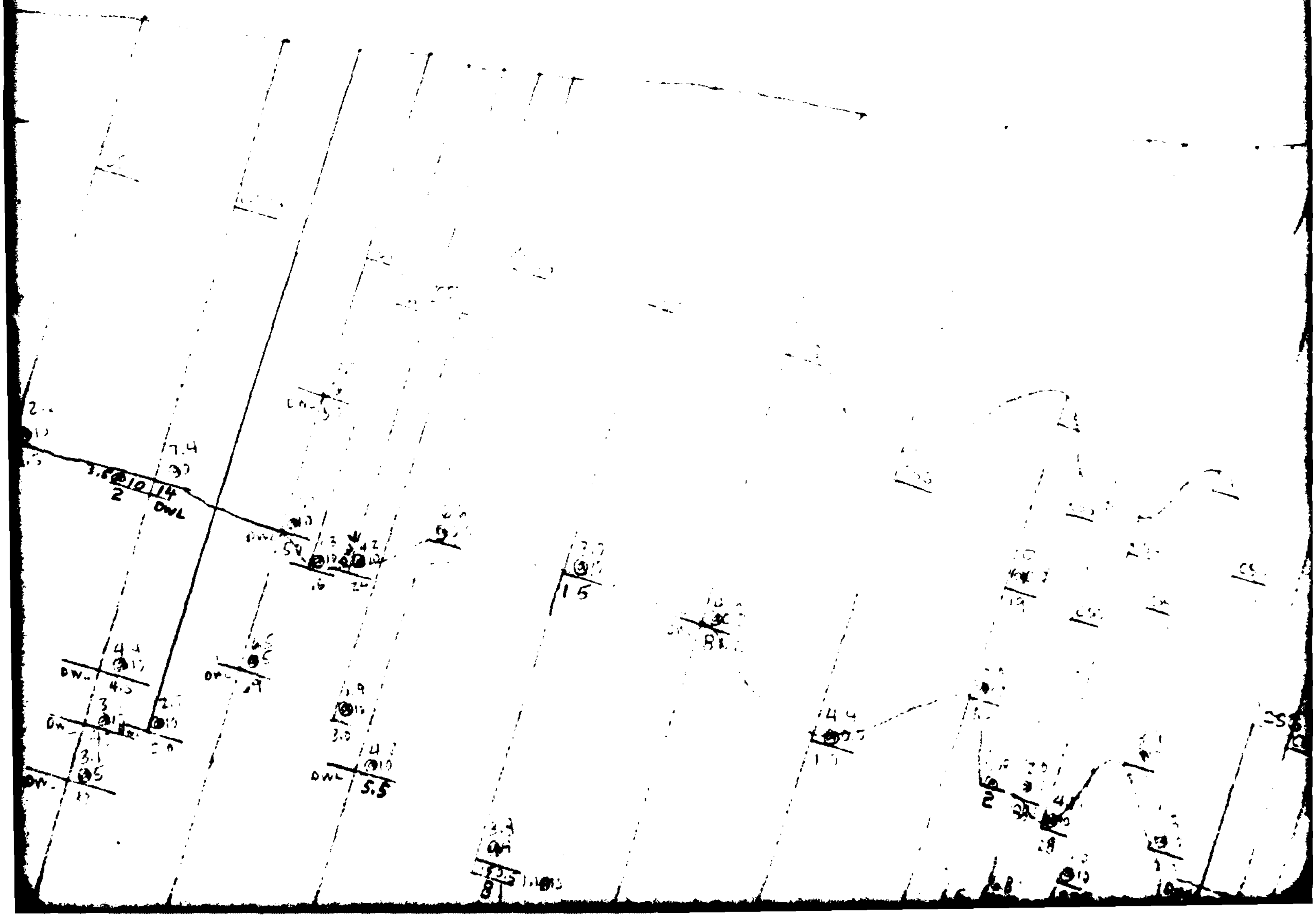
13


+50
00
OWL 16
6.2
@0
OWL 18
3.3
@10
37
6.1@0
152.5
5.8
5.2@10
4.0 OWL
5.6
@0
43.5
6.6
@0
185
OWL
3.6
3.5@15
4 OWL
341

4

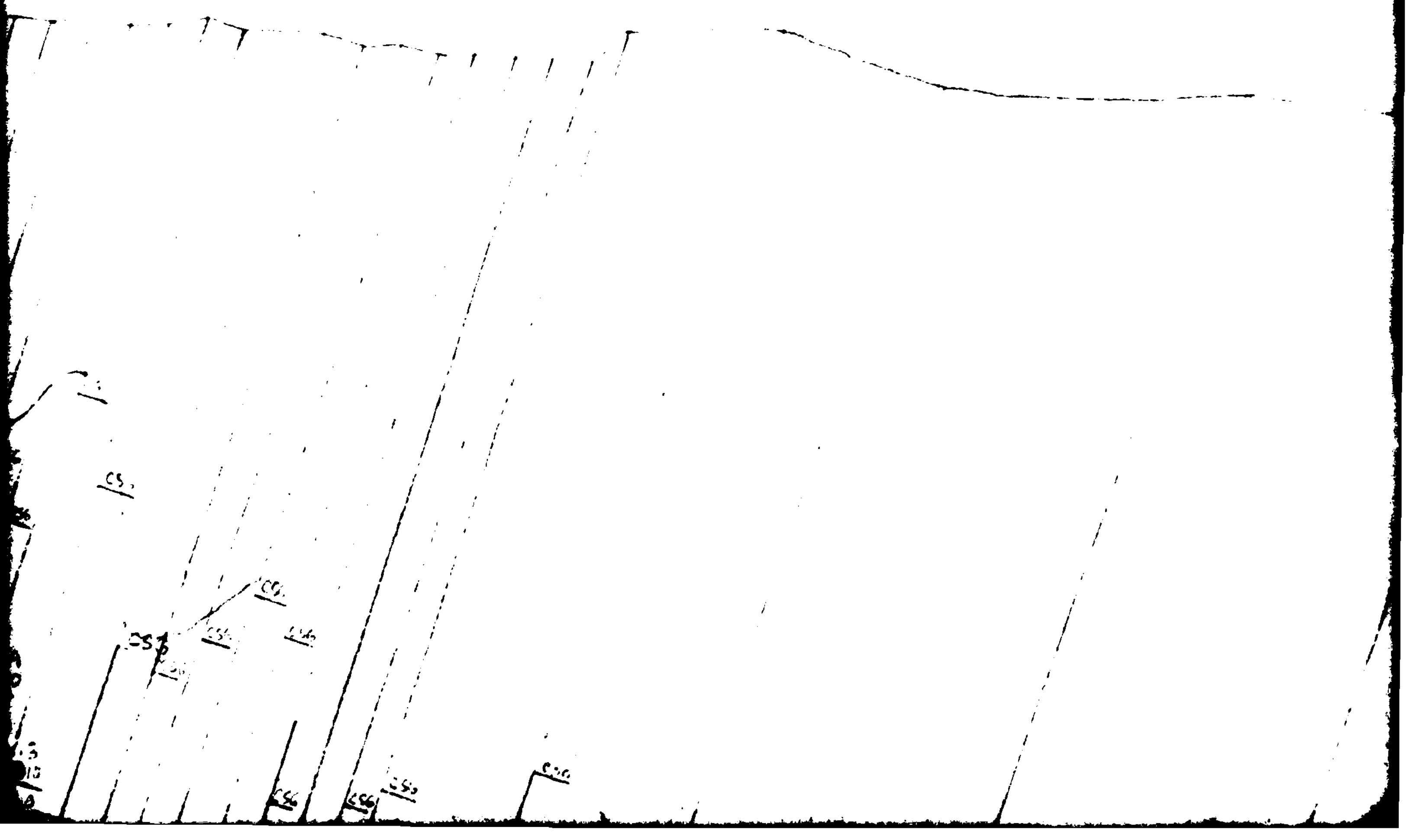
102+00

+50



15

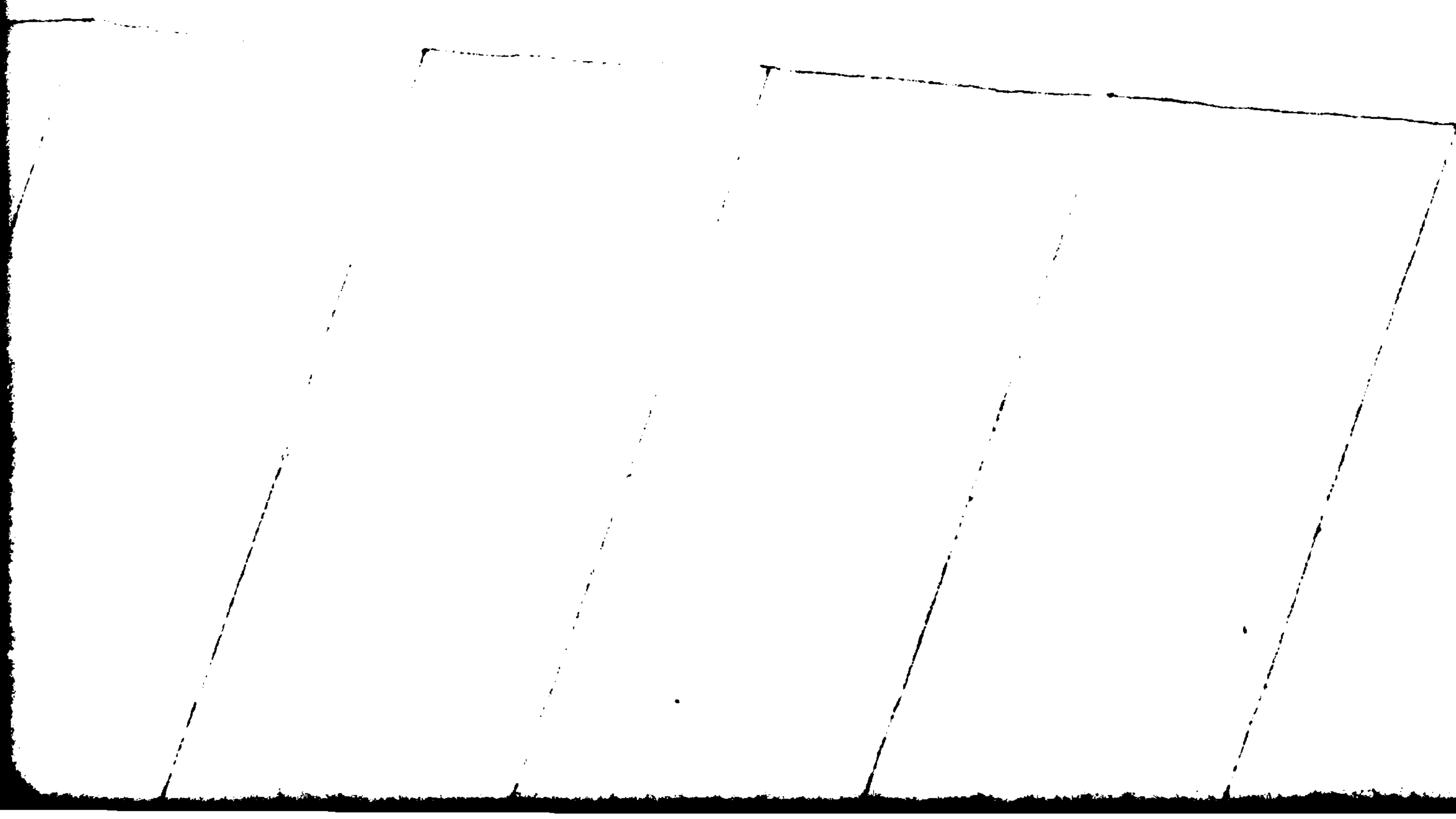
103+00



1 6

+50

104+00



17

— 600

— 590

— 580

— 570

— 560

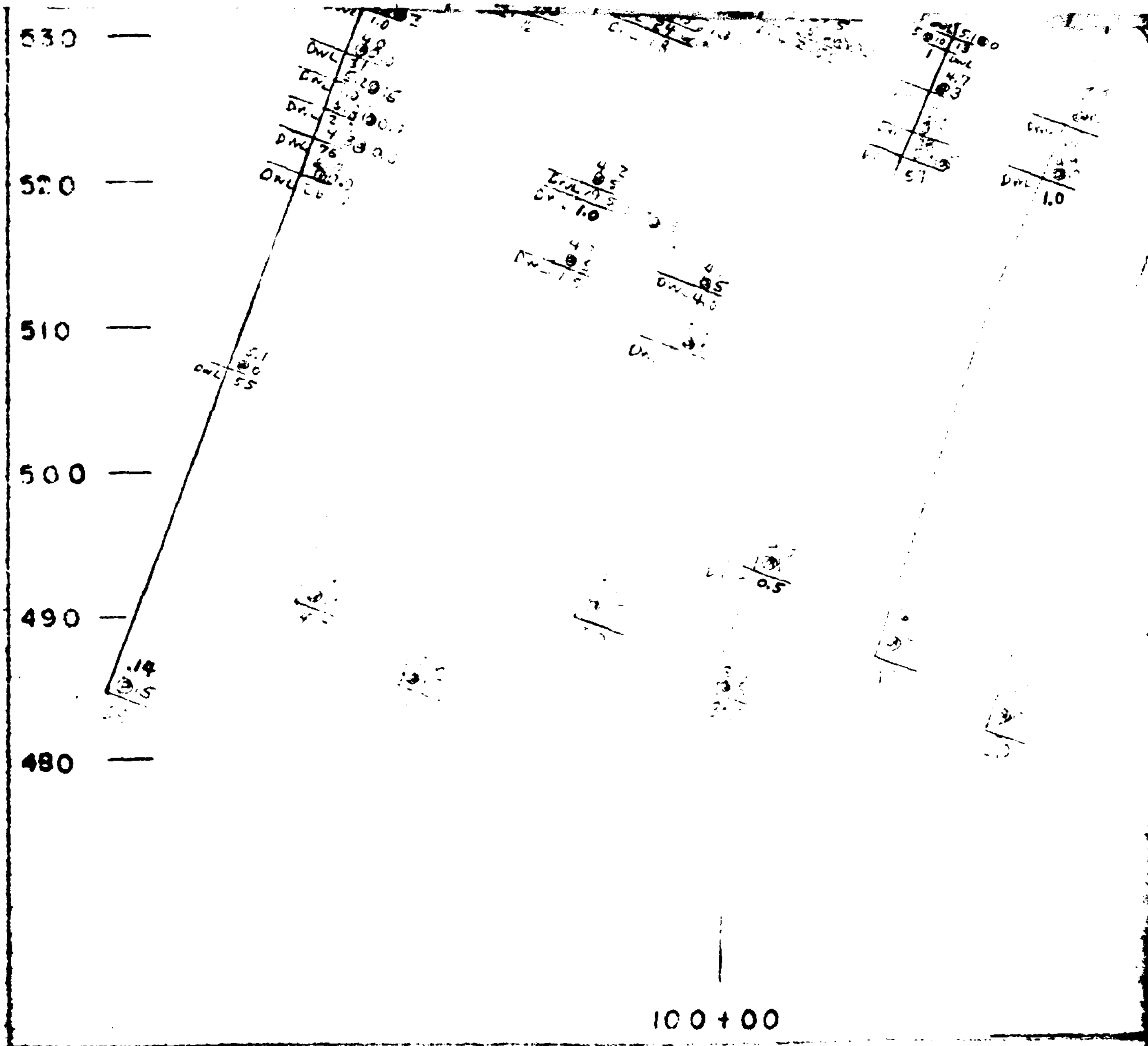
— 550

— 540

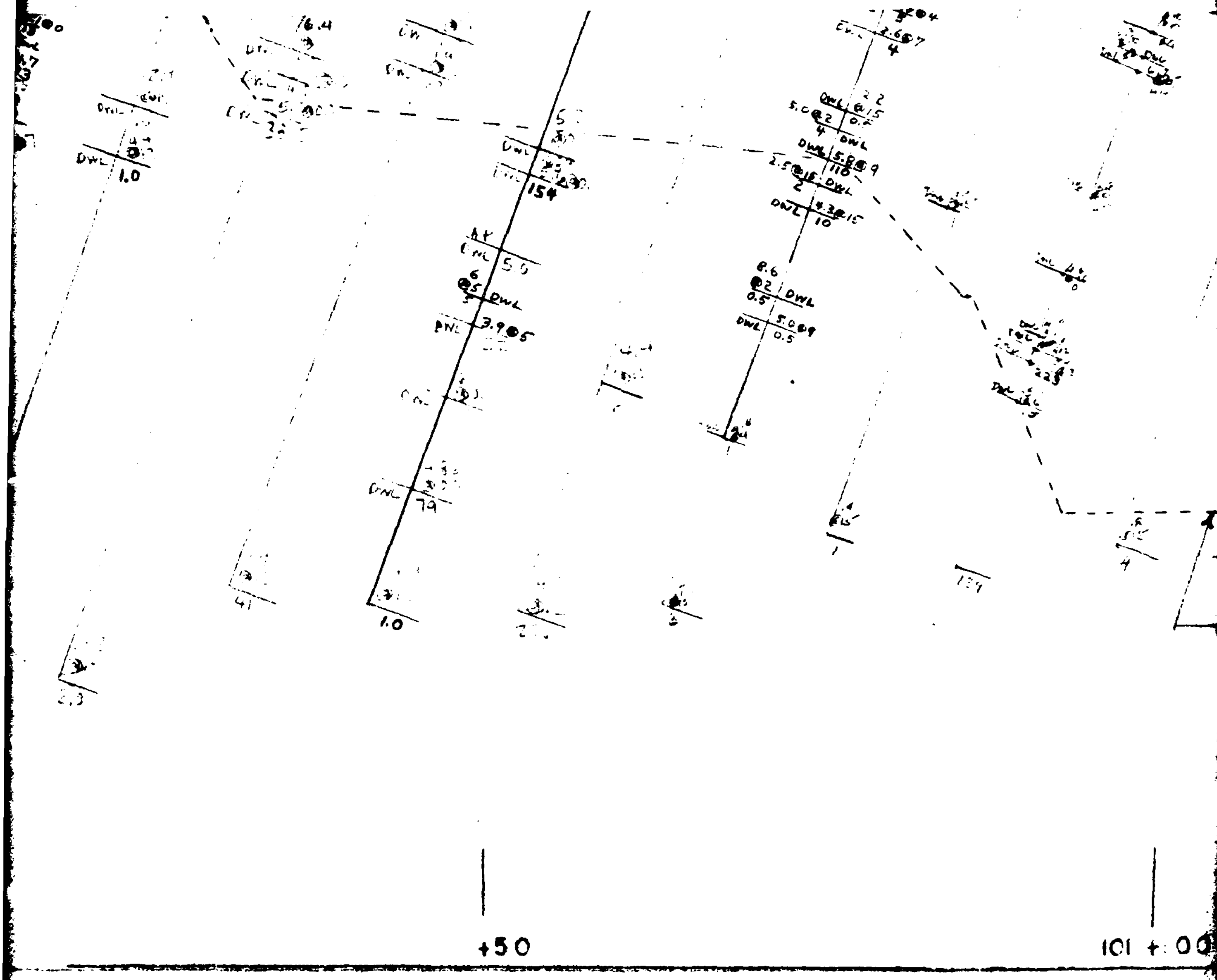
— 530

— 520

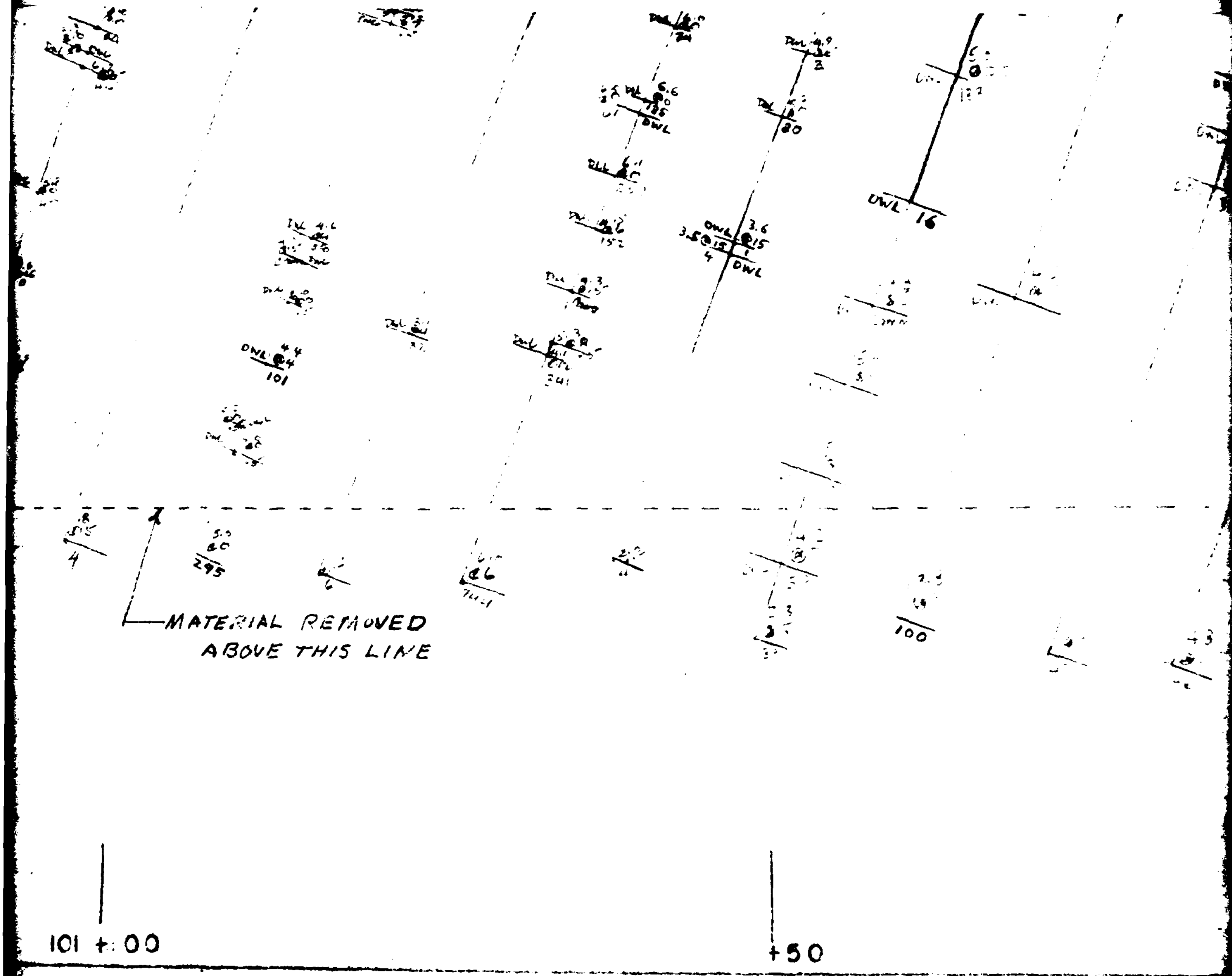
— 510



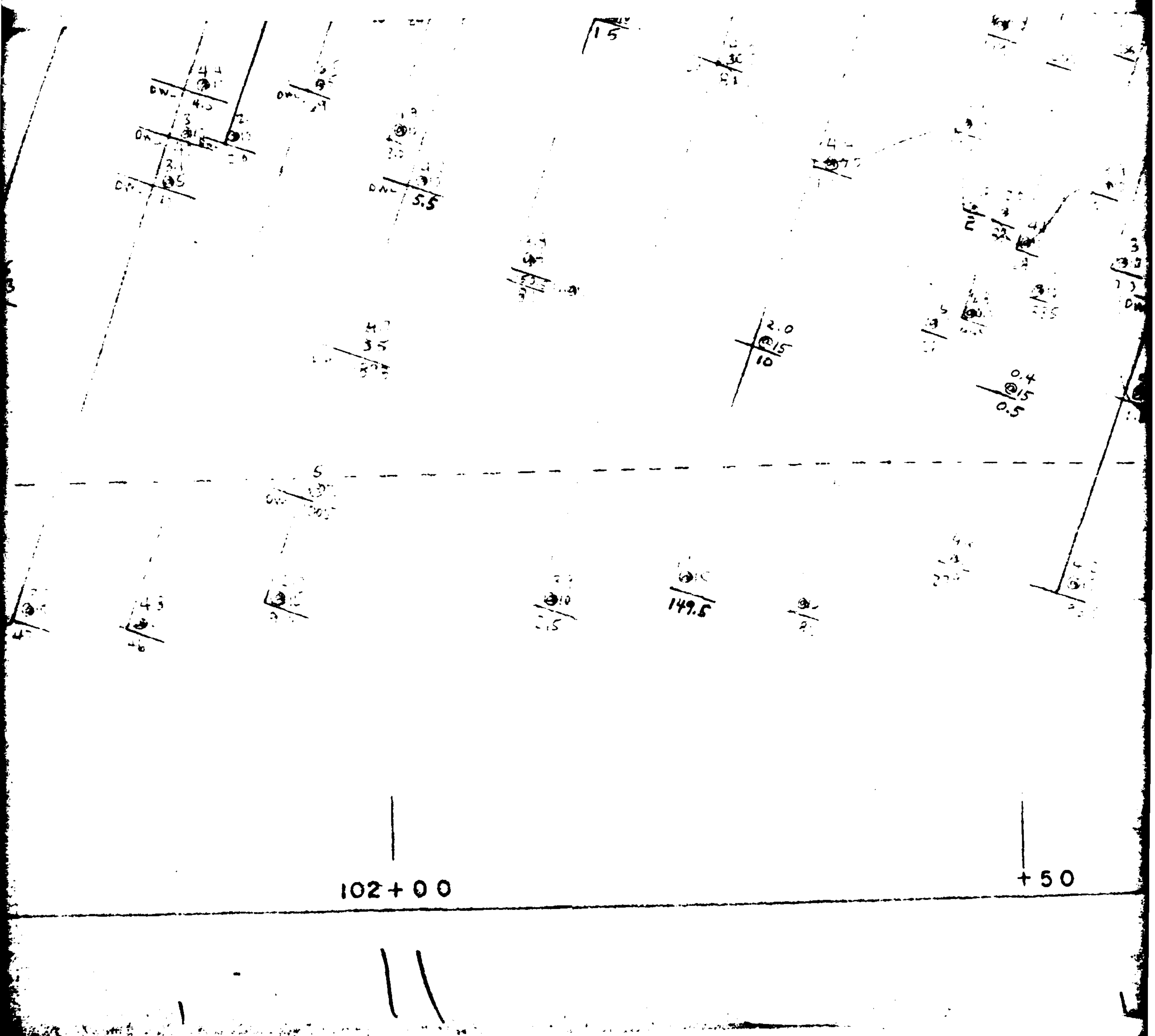
8



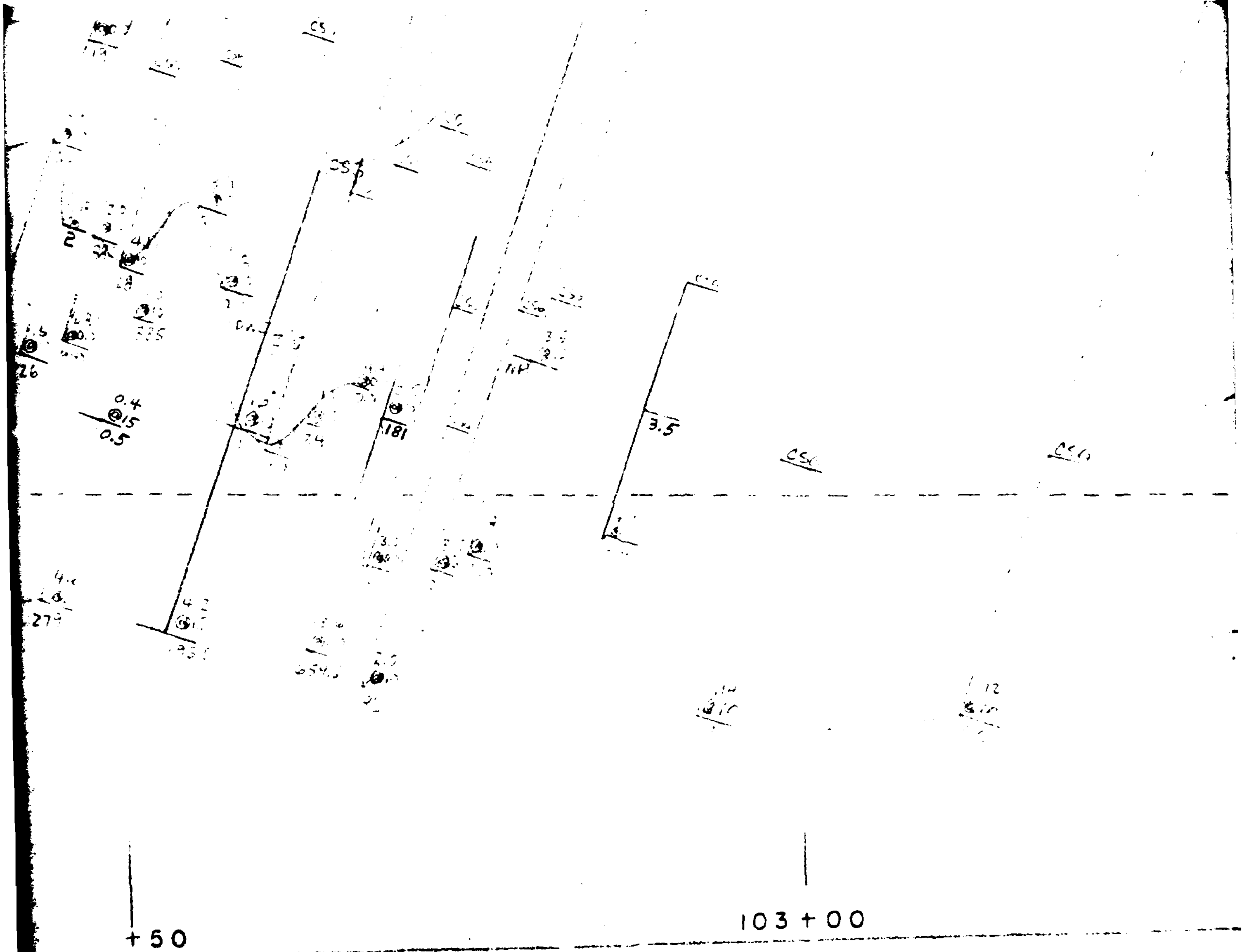
19



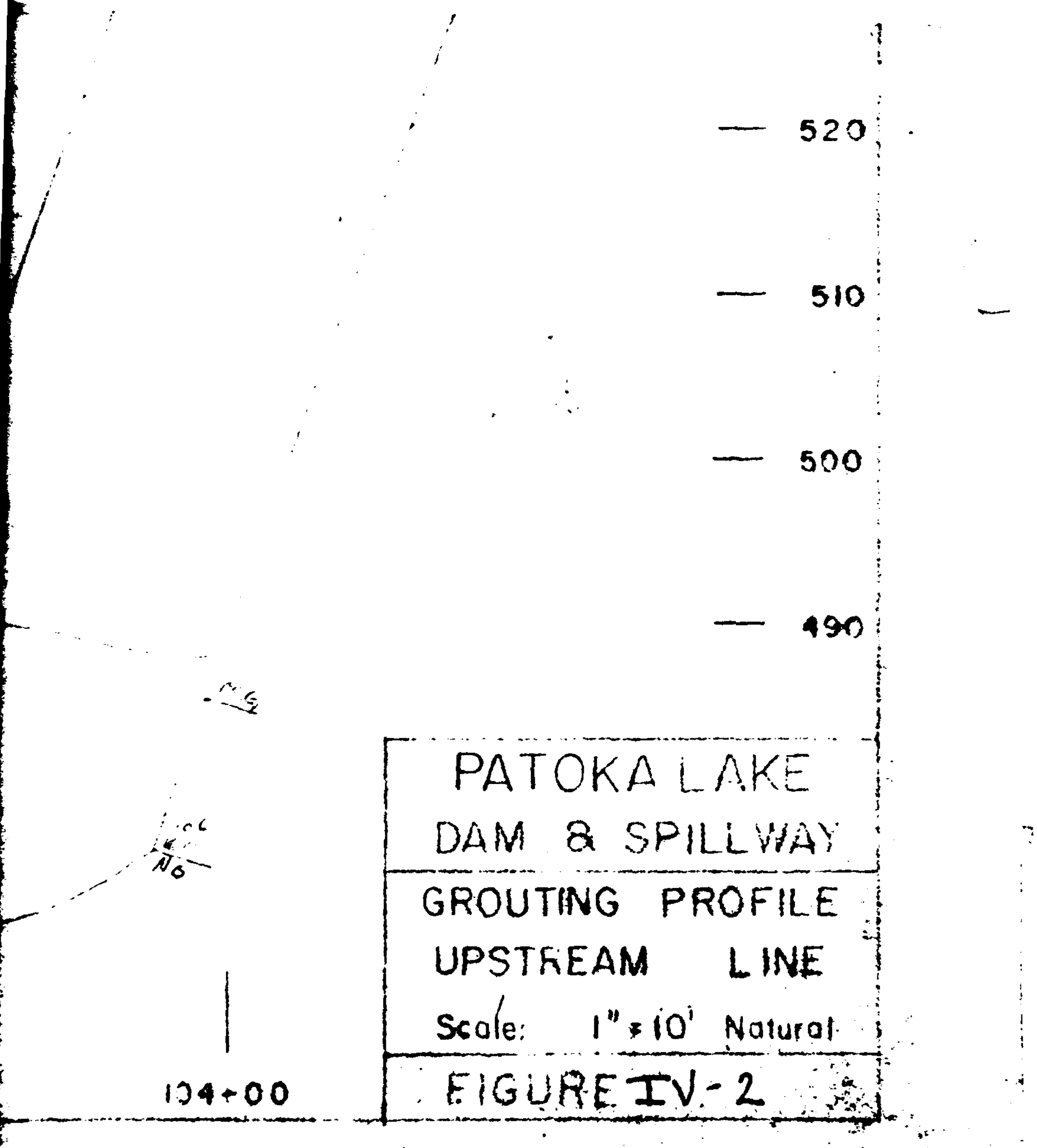
10



15
5.5
2.0
@15
10
0.4
@15
0.5
149.5
102+00
+50


0.4
@15
0.5
181
3.5
26
+50
103+00

1 13

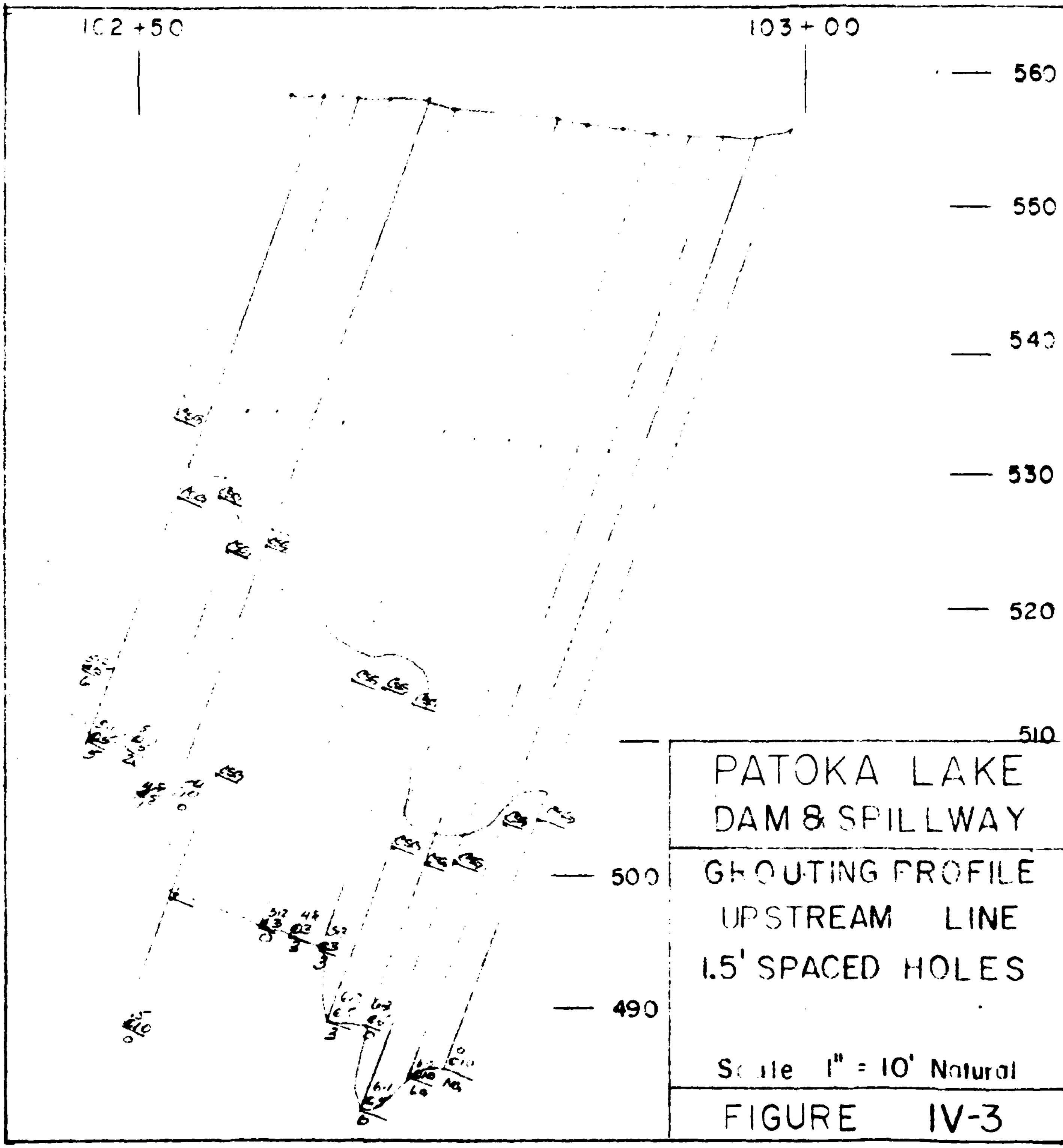


PATOKA LAKE
DAM & SPILLWAY

GROUTING PROFILE
UPSTREAM LINE

Scale: 1" = 10' Natural

FIGURE IV-2

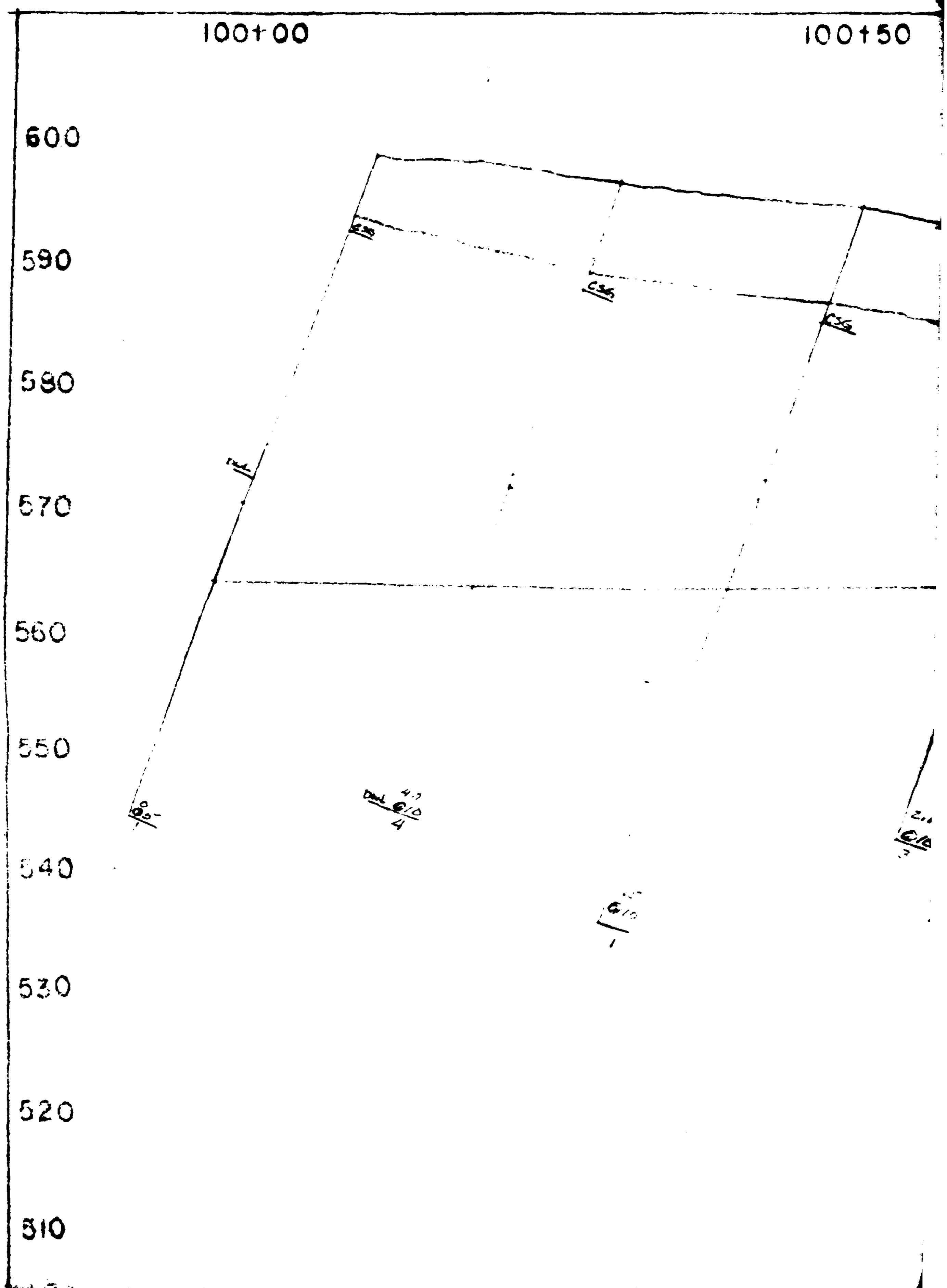


PATOKA LAKE
DAM & SPILLWAY

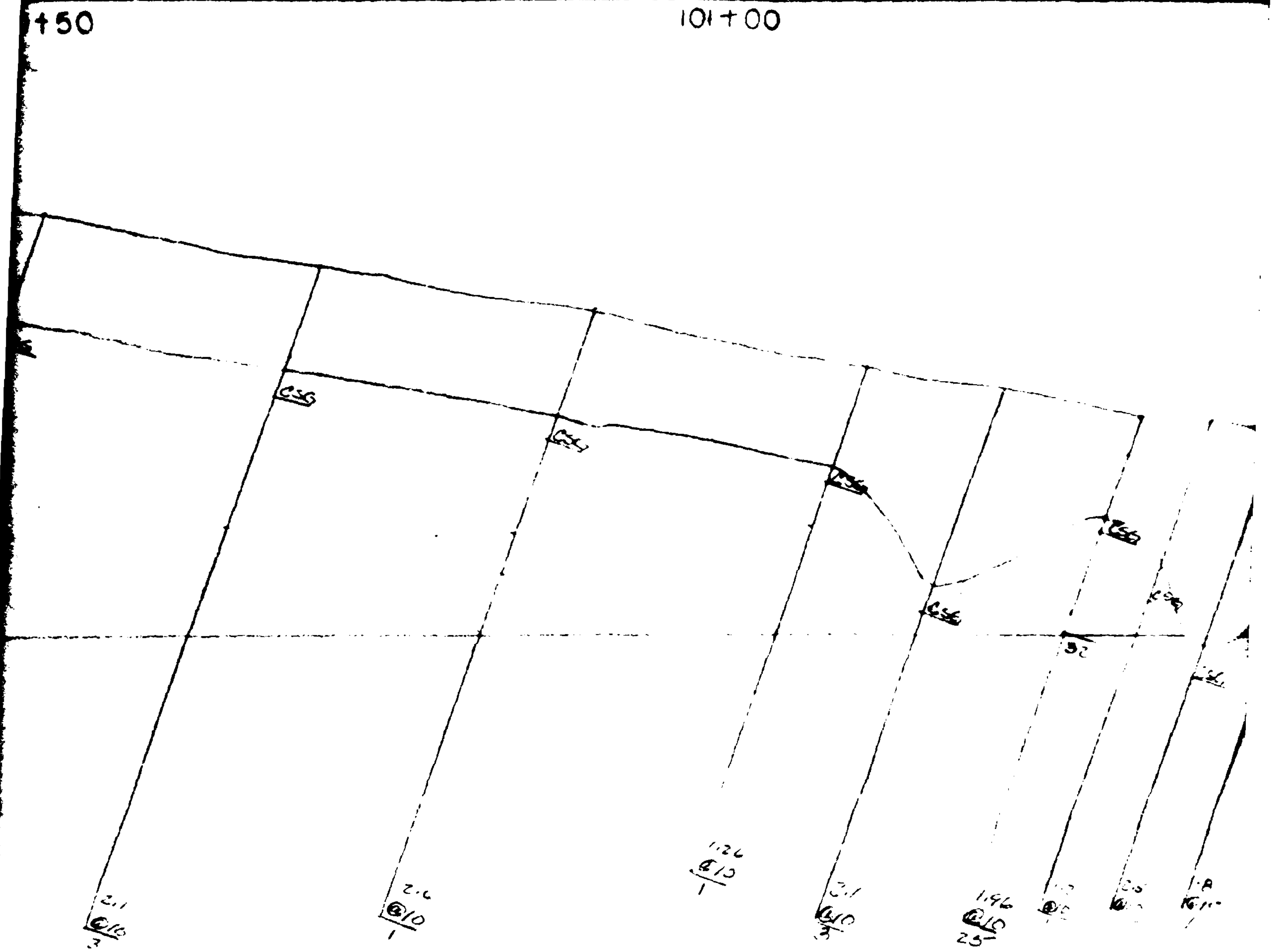
GROUTING PROFILE
UPSTREAM LINE
1.5' SPACED HOLES

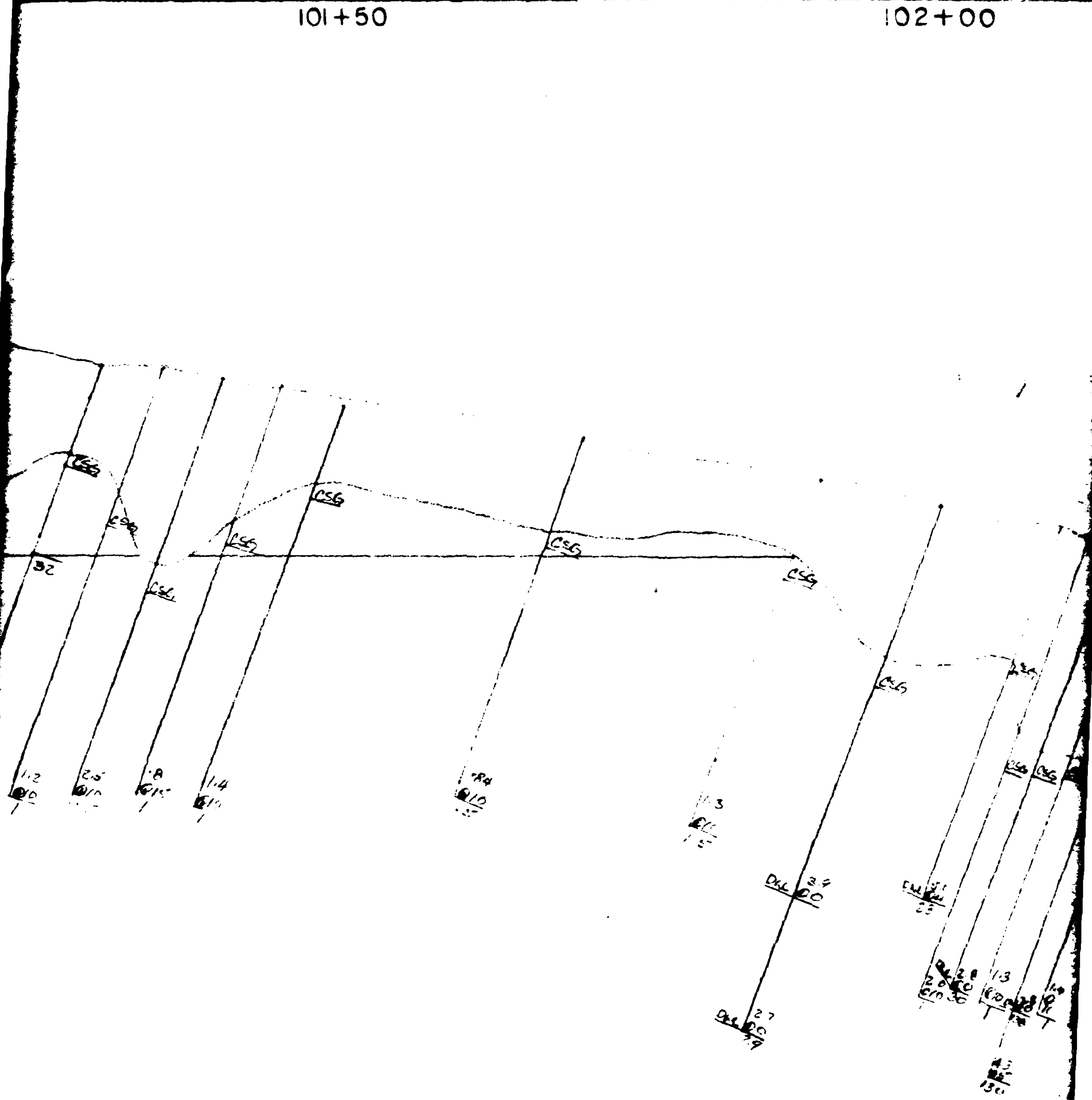
Scale 1" = 10' Natural

FIGURE IV-3


100+00
100+50
600
590
580
570
560
550
540
530
520
510

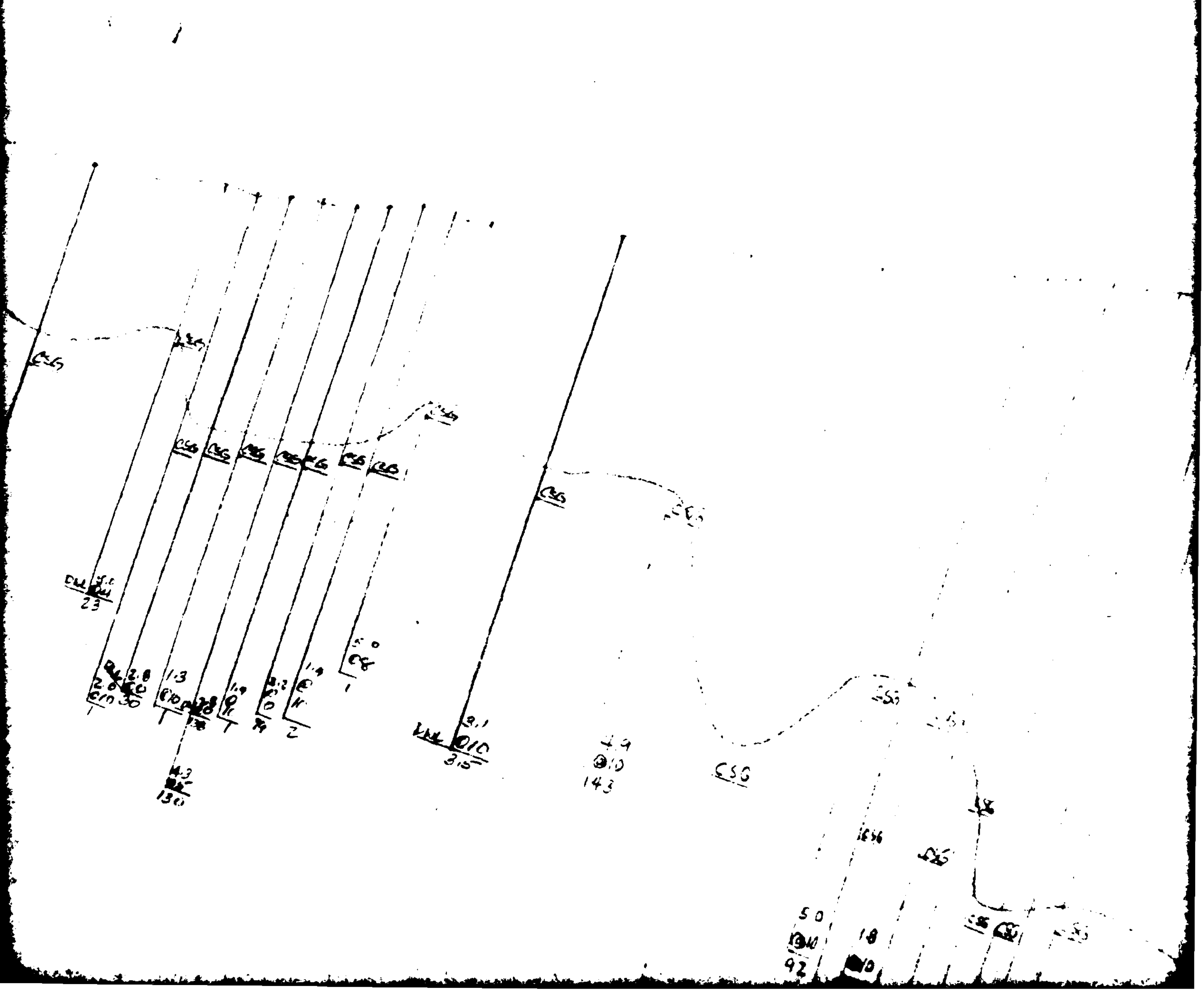
1 2




101+50
102+00
CSG
CSG
CSG
CSG
CSG
CSG
CSG

1 A 1

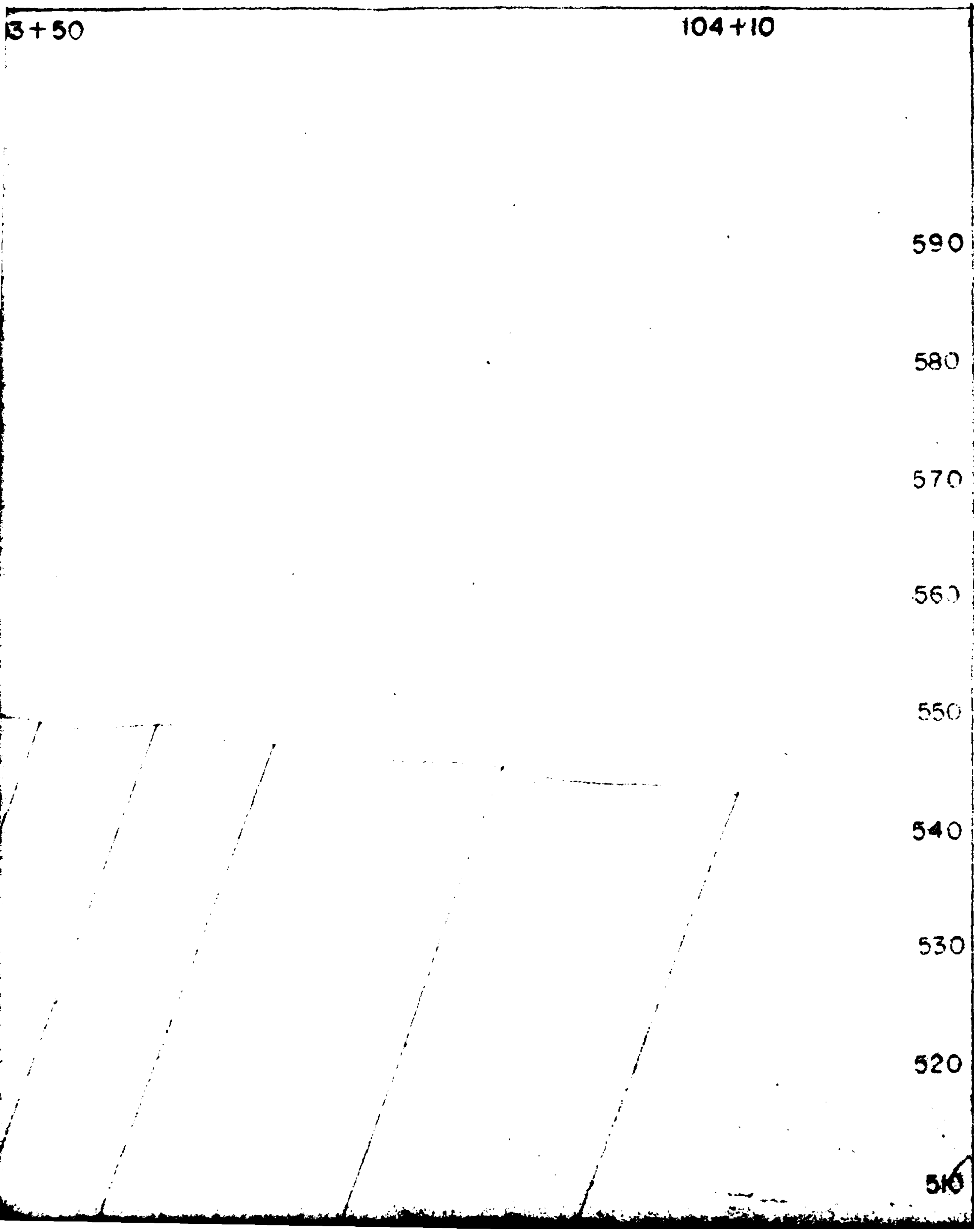
102+00 102+50

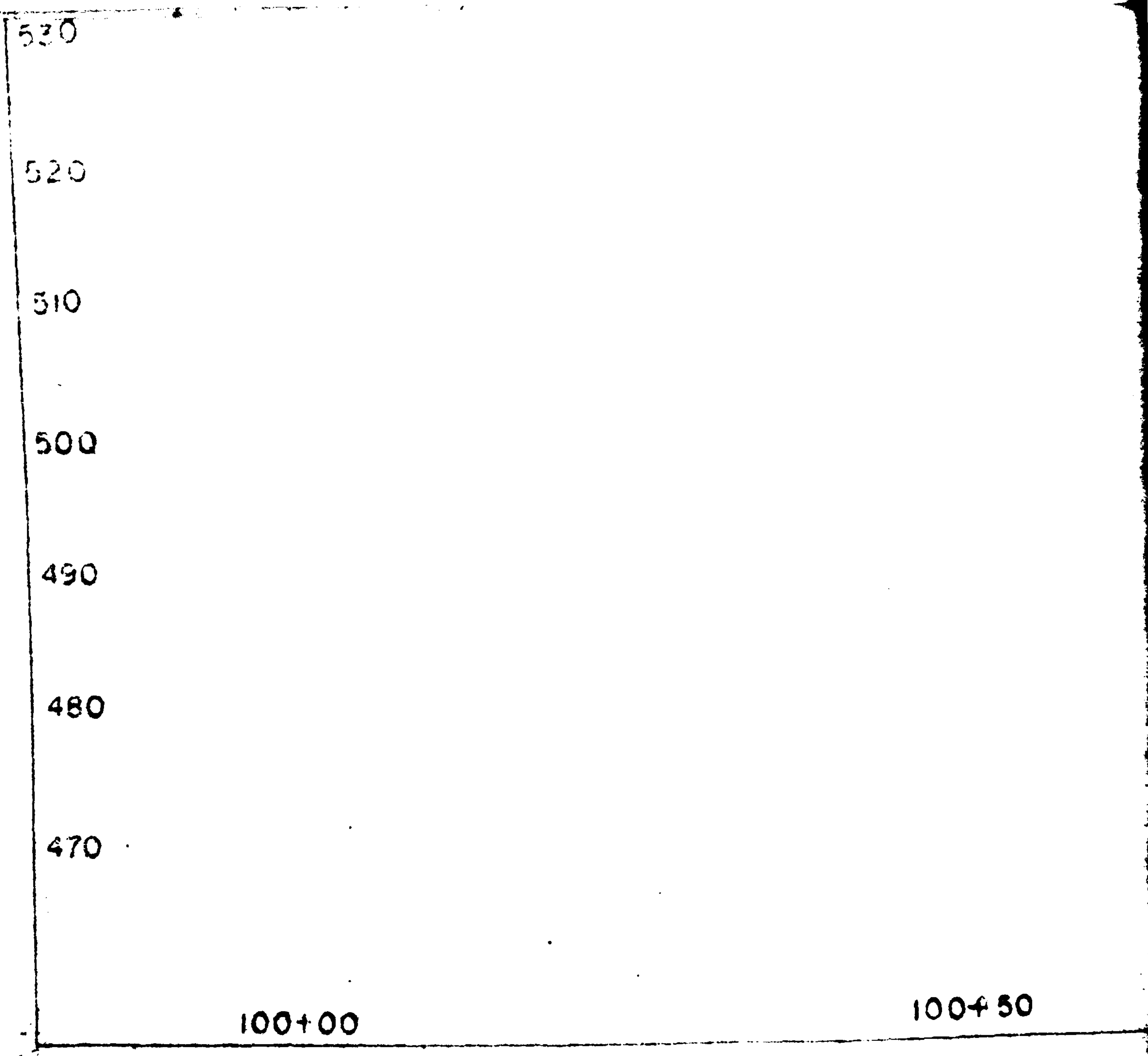


1 5 1

103+00 103+50

1 6

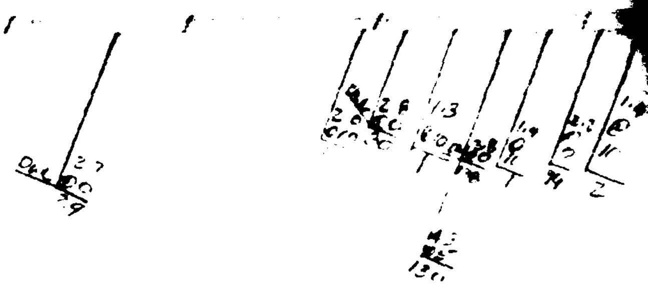




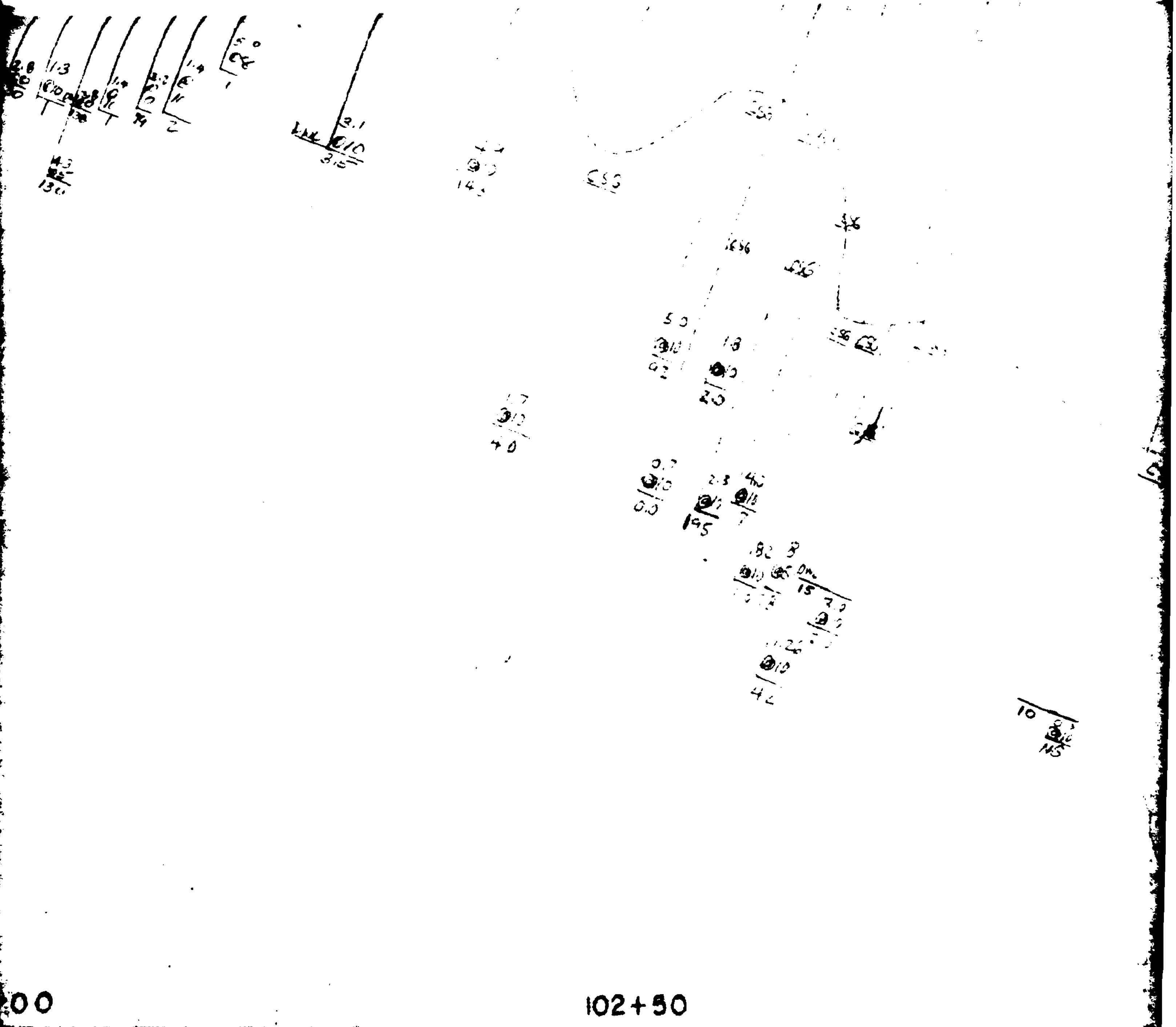
1 M

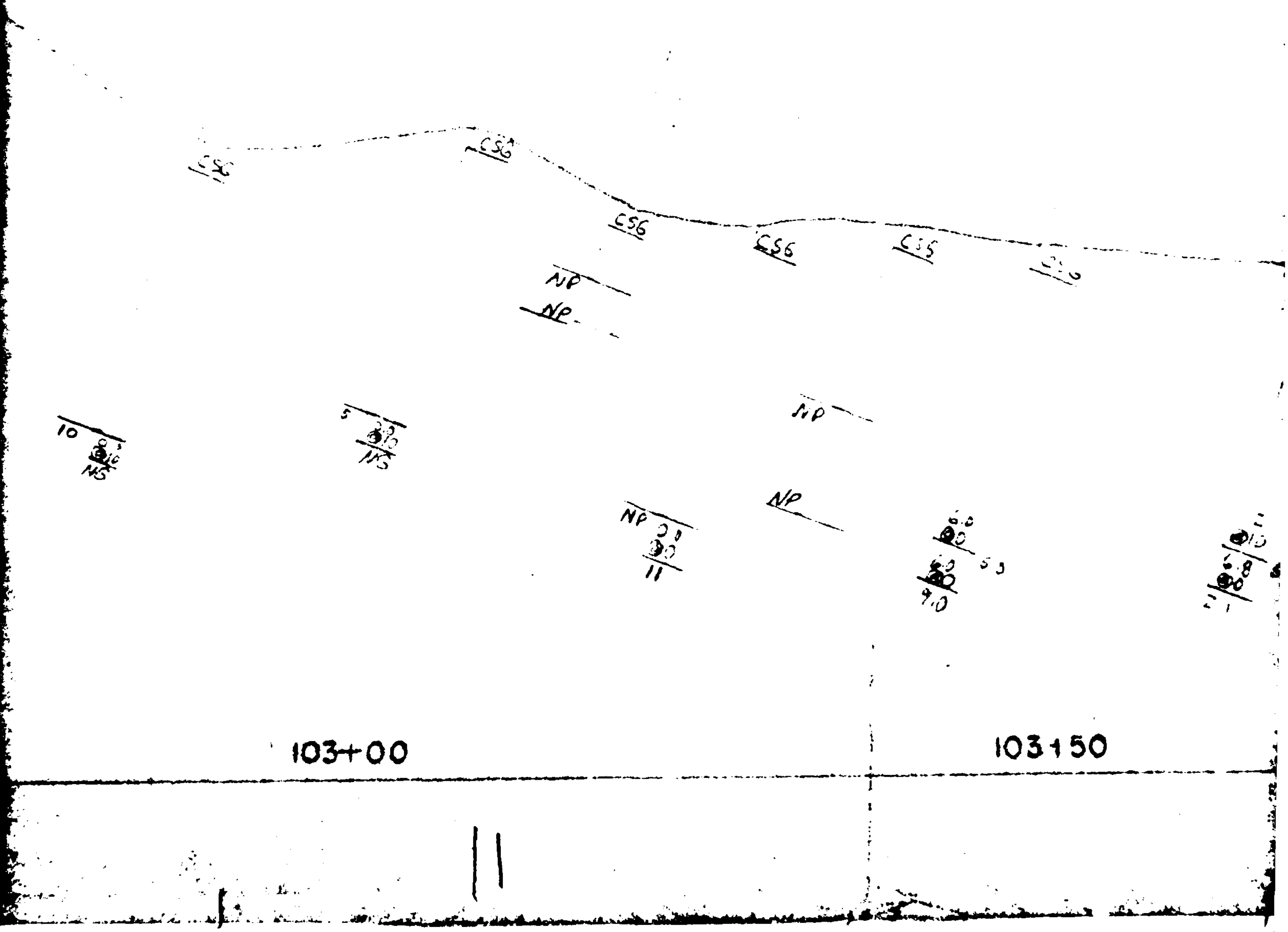
101+00

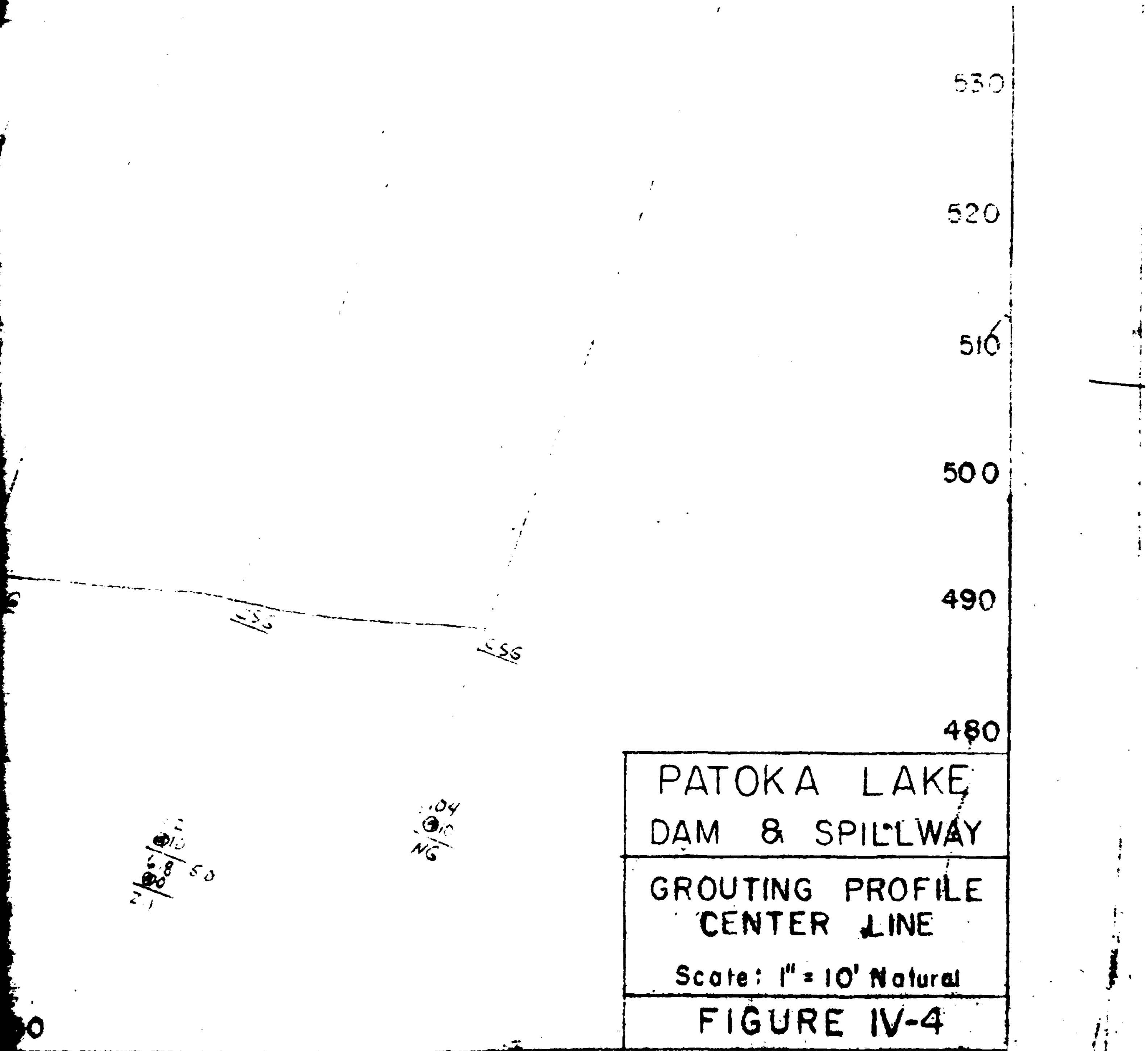
1 8



101+50 102+00


00
102+50


CS6
CS6
CS6
CS6
CS5
NP
NP
NP
NP
NP
10
NS
NS
11
9.0
103+00
103+50
11

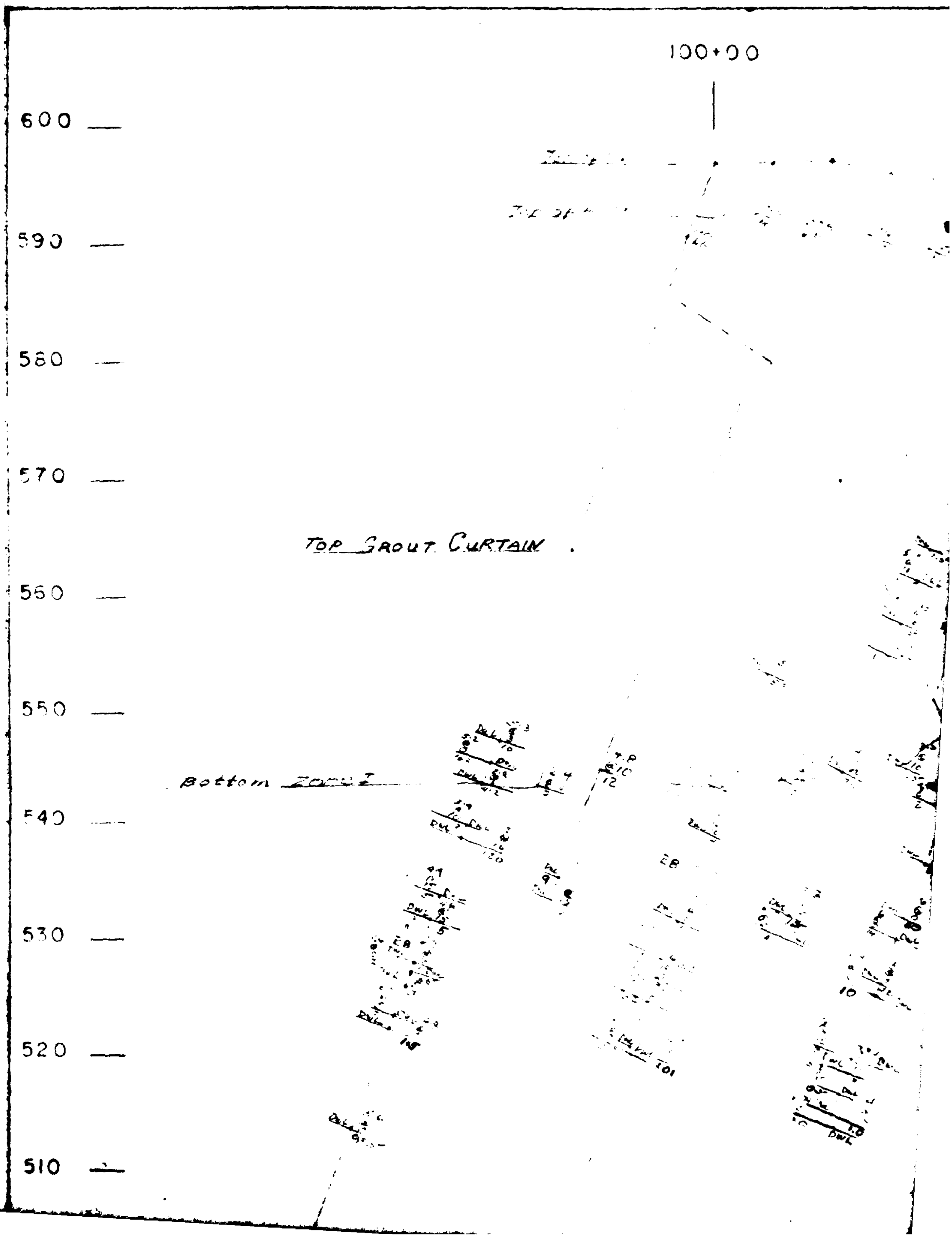


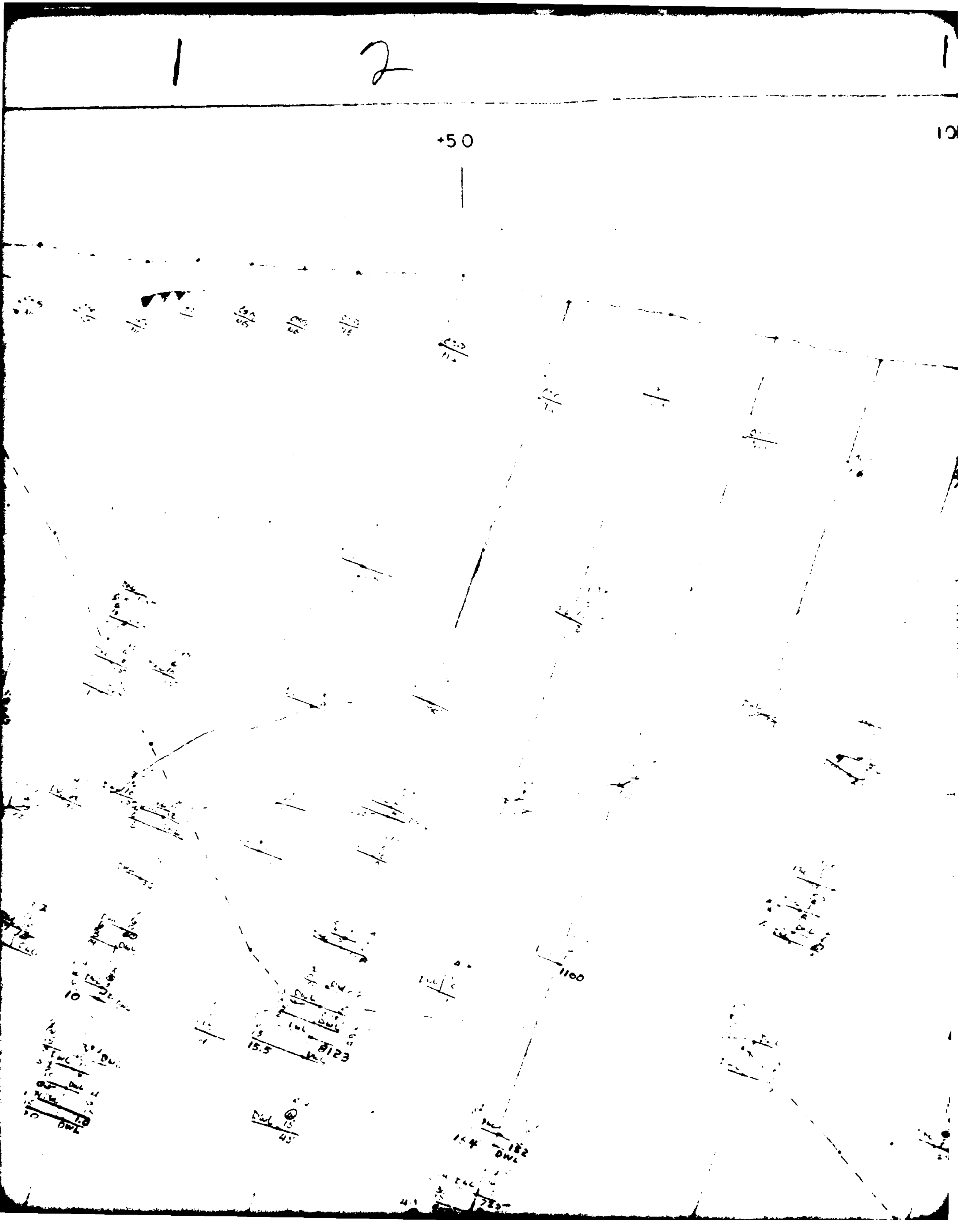
PATOKA LAKE
DAM & SPILLWAY

GROUTING PROFILE
CENTER LINE

Scale: 1" = 10' Natural

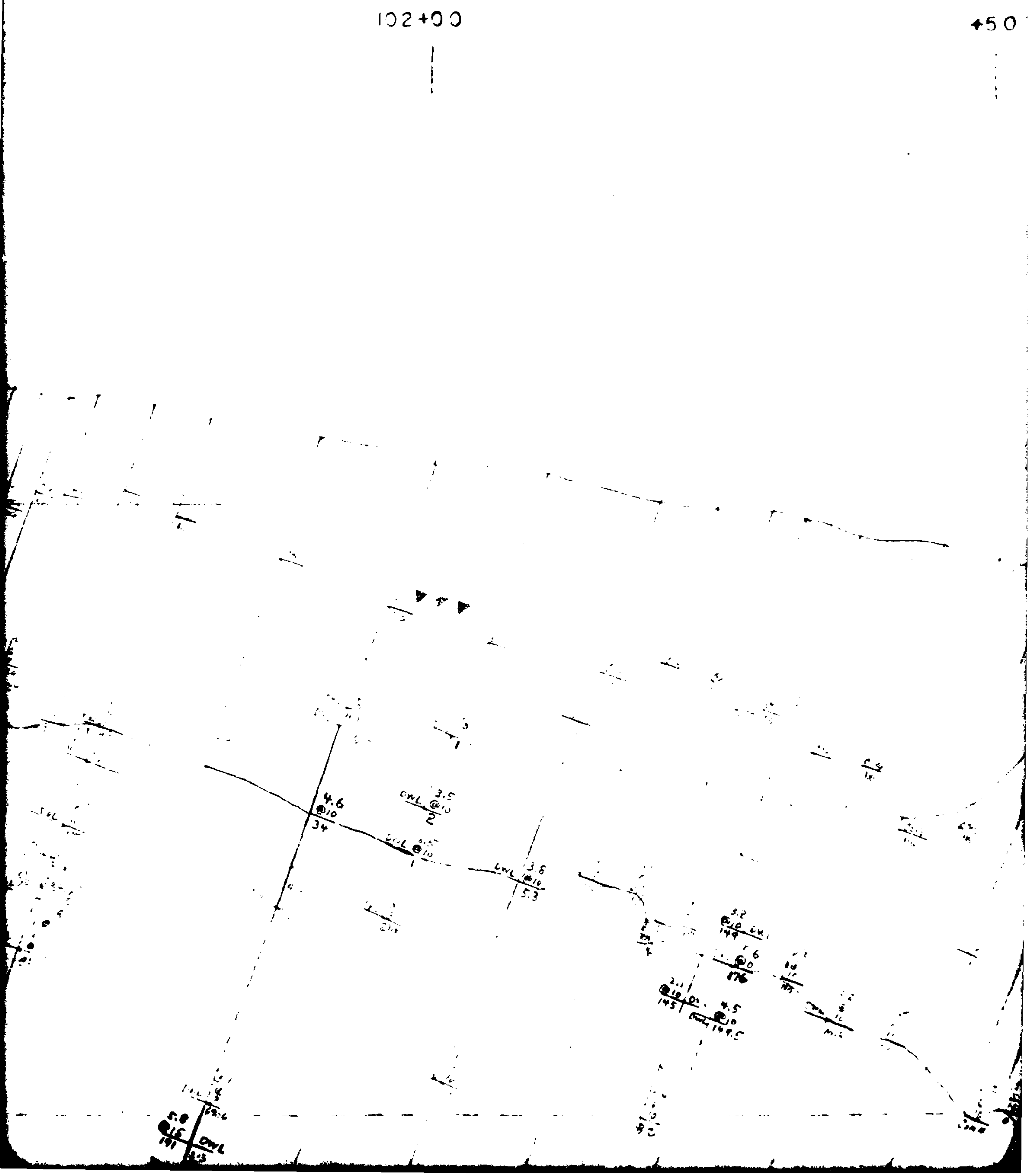
FIGURE IV-4


100+00
600
590
580
570
TOP GROUT CURTAIN
560
550
Bottom
540
530
520
510


1
2
1
+50
1100
10
15.5
8123
DWL
1.0
182

1 3

1 4 1

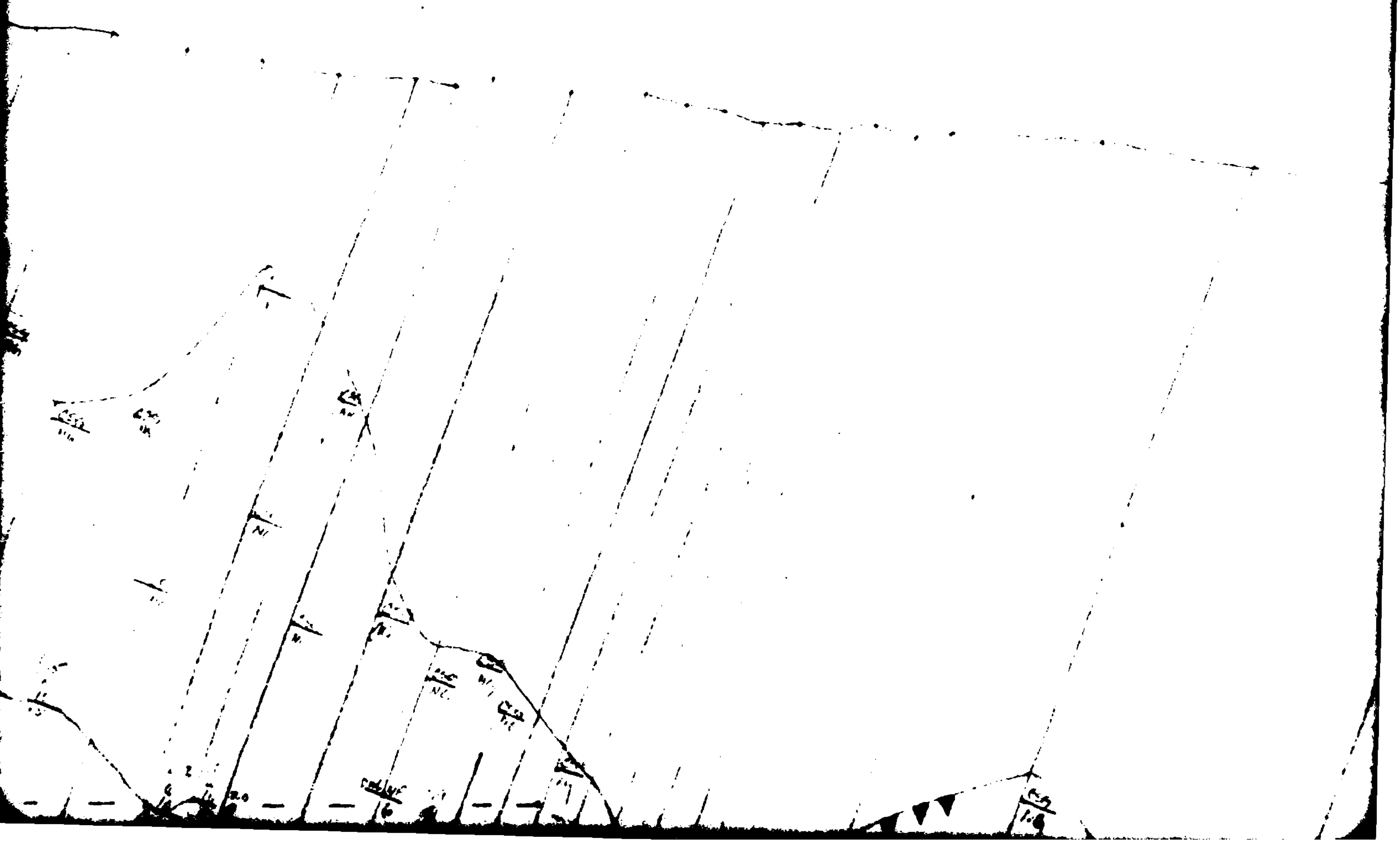


102+00
+50
4.6
@10
34
OWL @10
3.5
2
OWL @10
1
OWL
3.8
@10
5.3
5.8
@15
141
OWL
176
4.5
@10
149.5

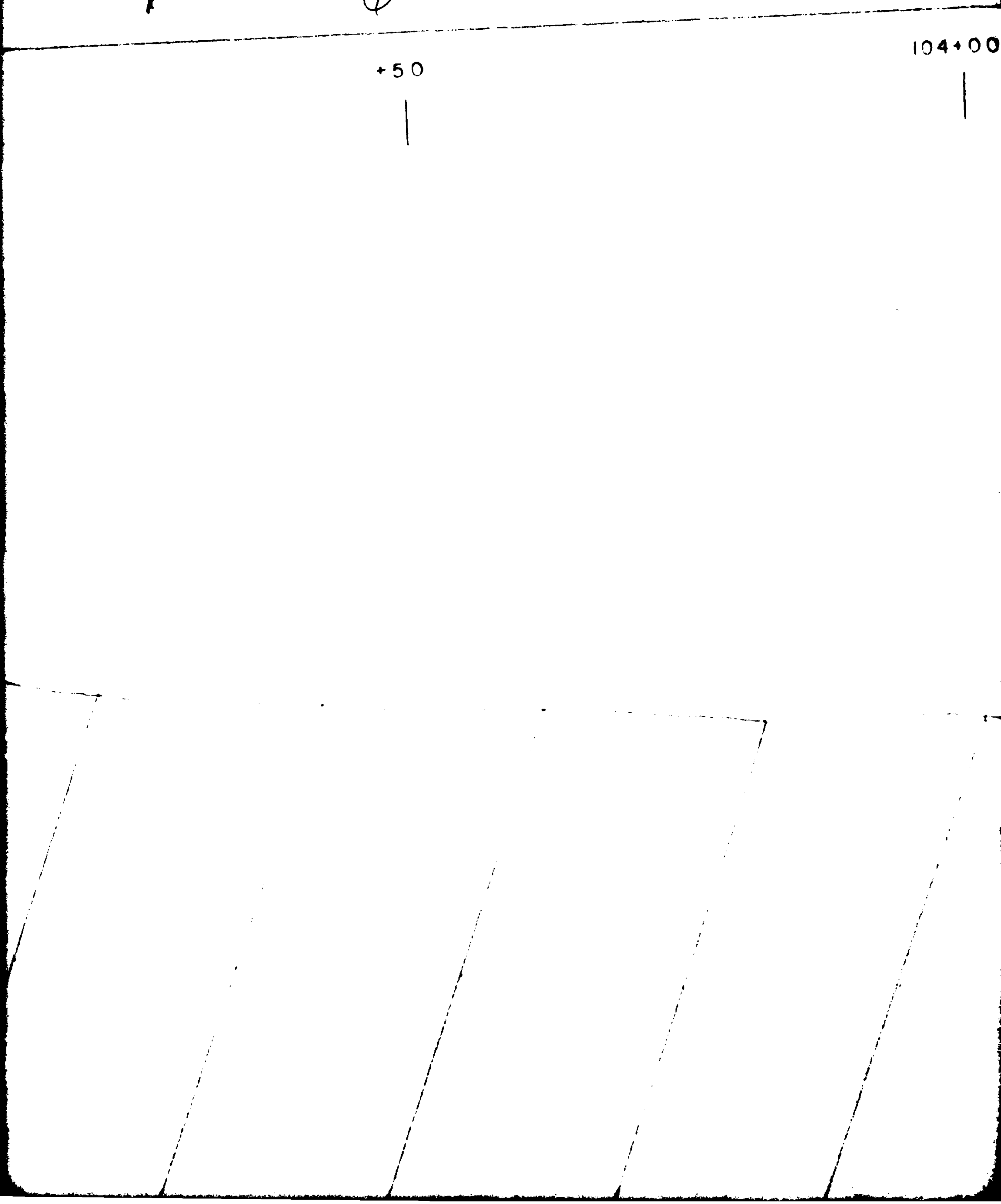
1 5

+50

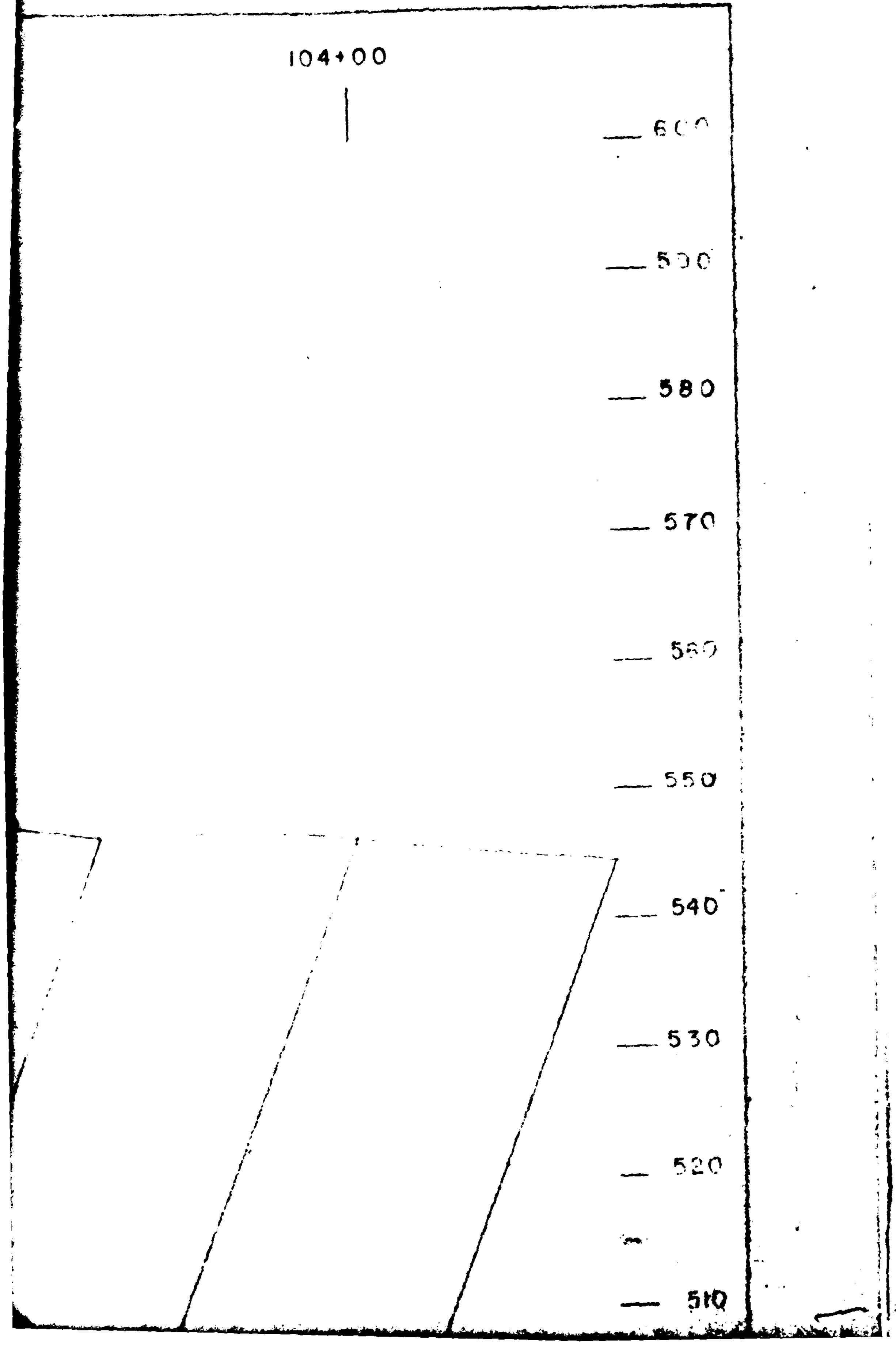
103+00

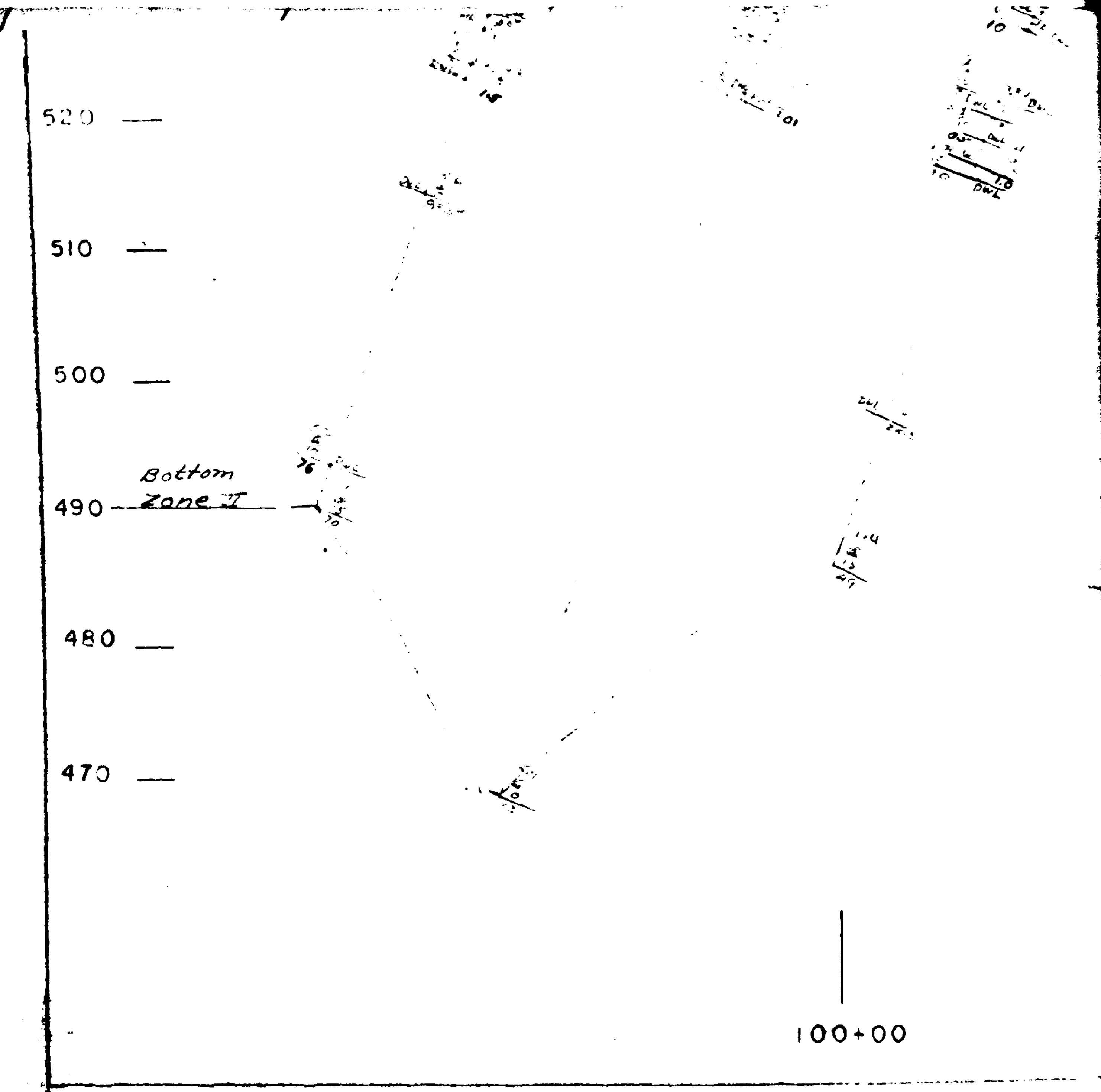


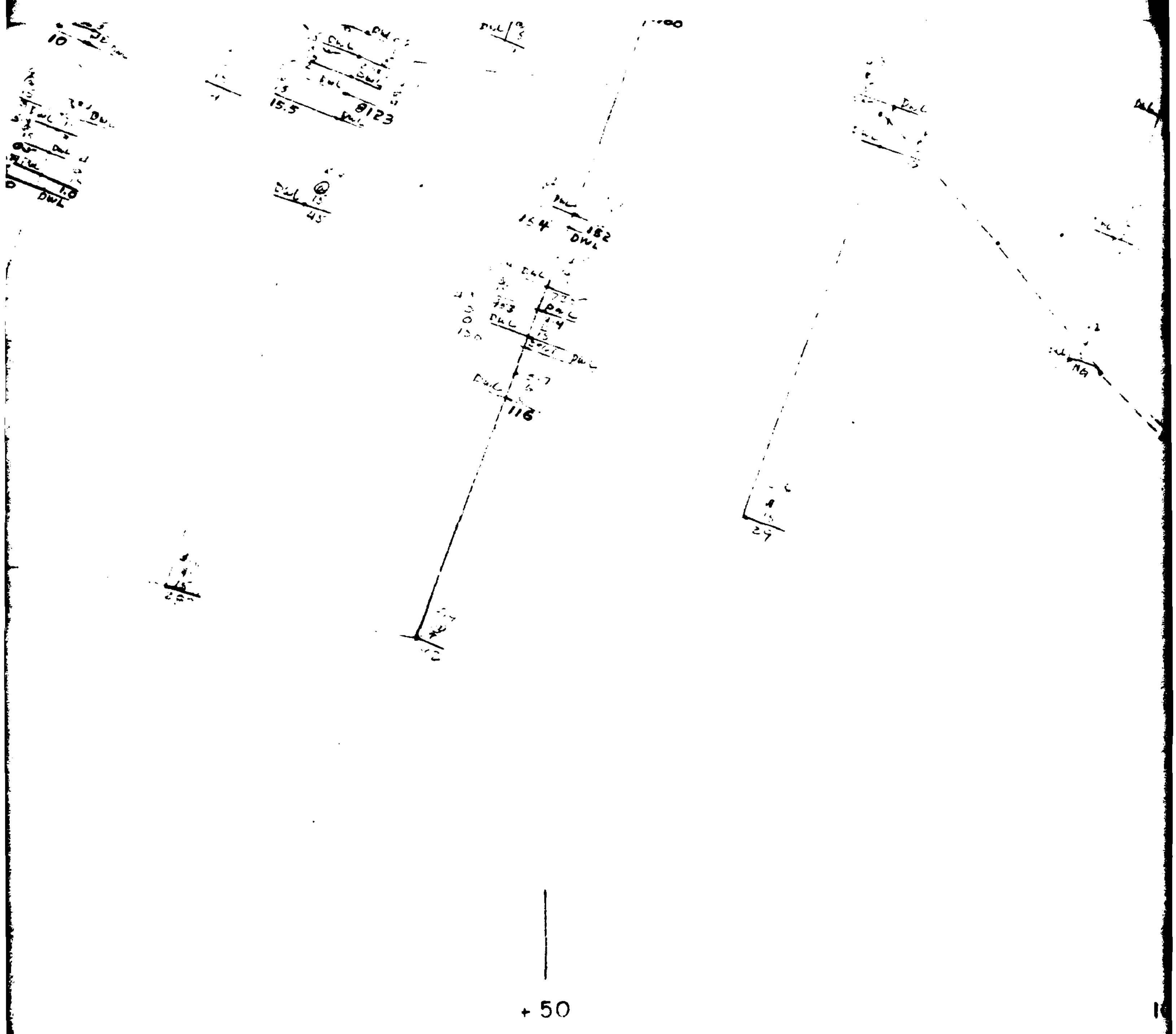
6



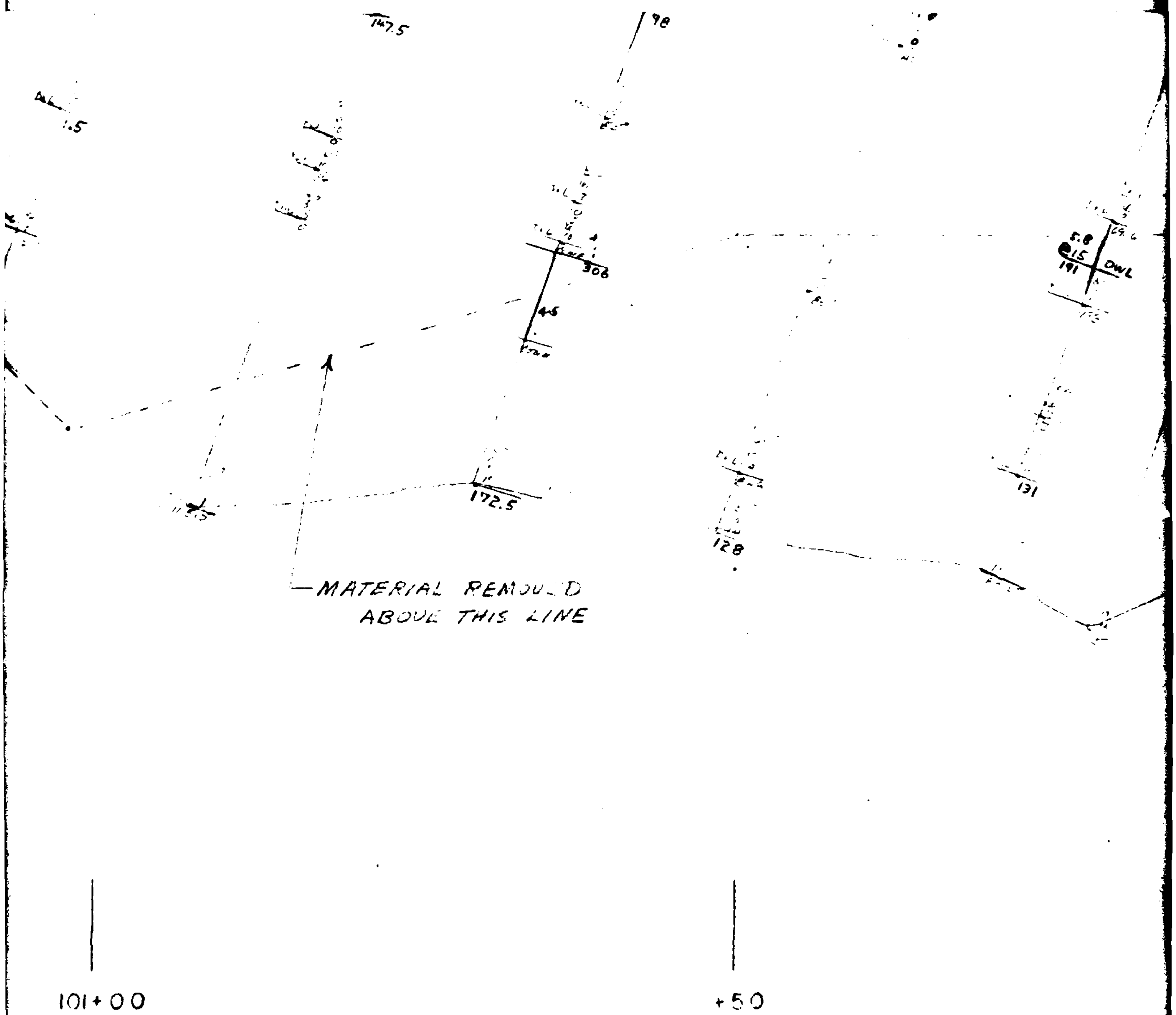
17



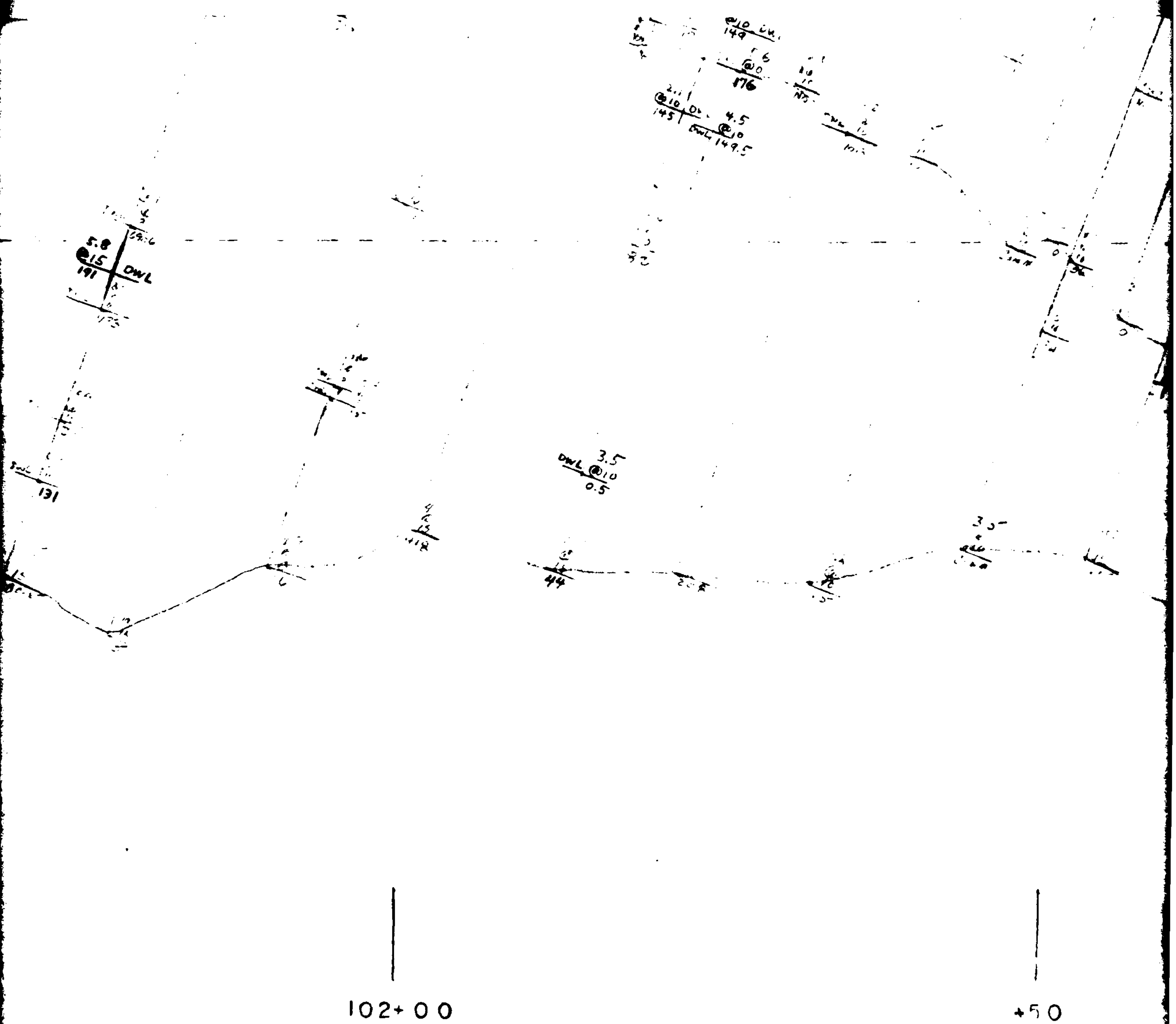

520
510
500
Bottom
Zone II
490
480
470
100+00



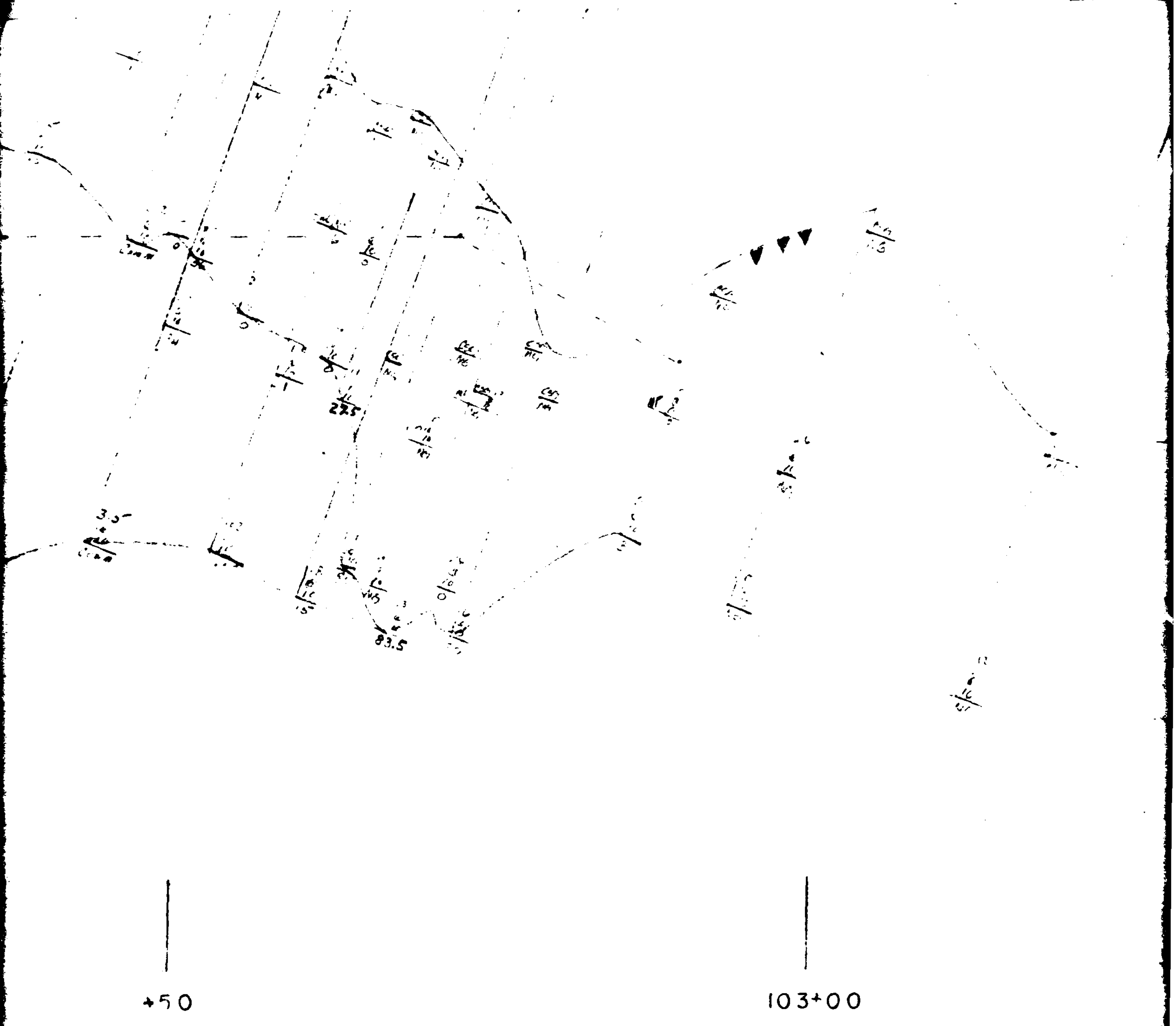
9


147.5
98
1.5
306
4.5
5.8
15
191
DWL
172.5
128
131
MATERIAL REMOVED
ABOVE THIS LINE
101+00
+50

1 10

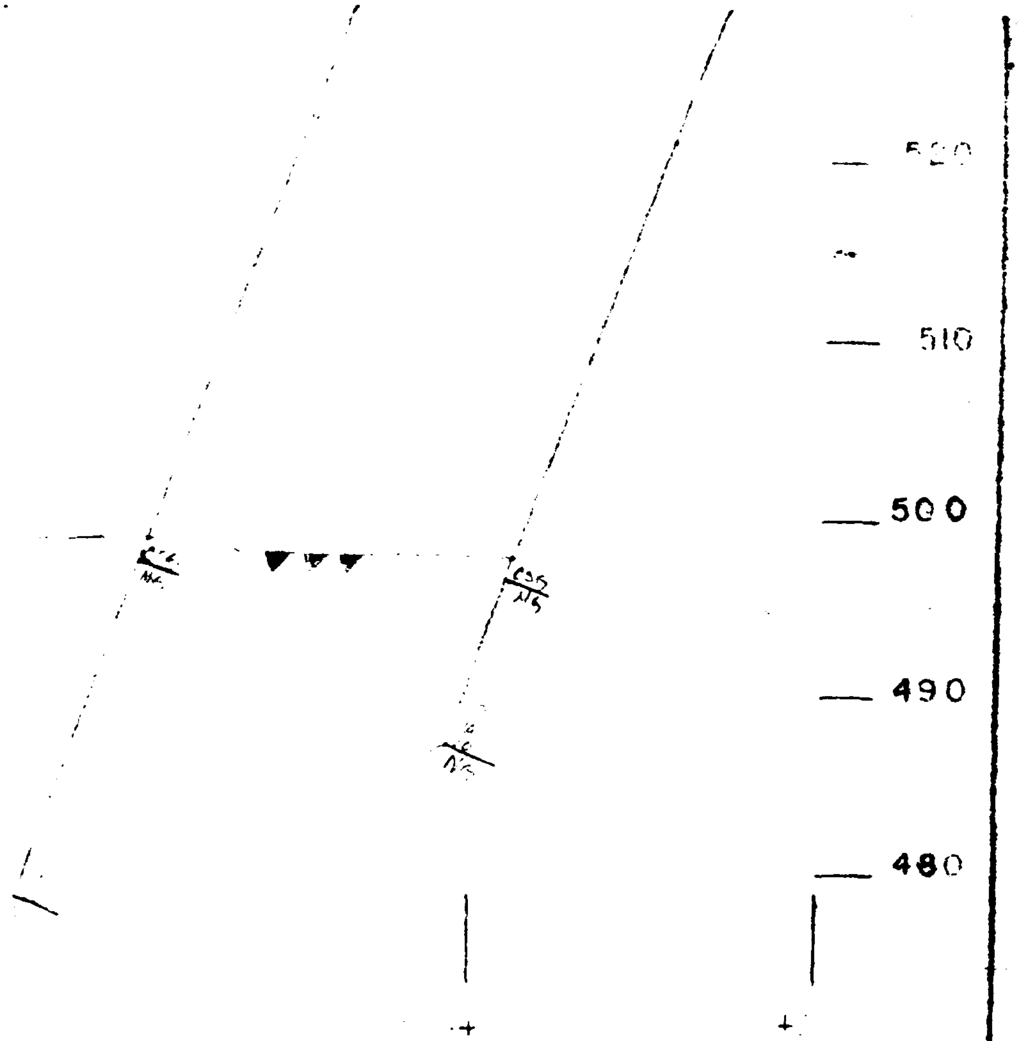


5.8
@15
191
OWL
131
3.5
OWL @10
0.5
@10
149
@10
176
4.5
@10
145
@10
149.5
44
102+00
+50



12

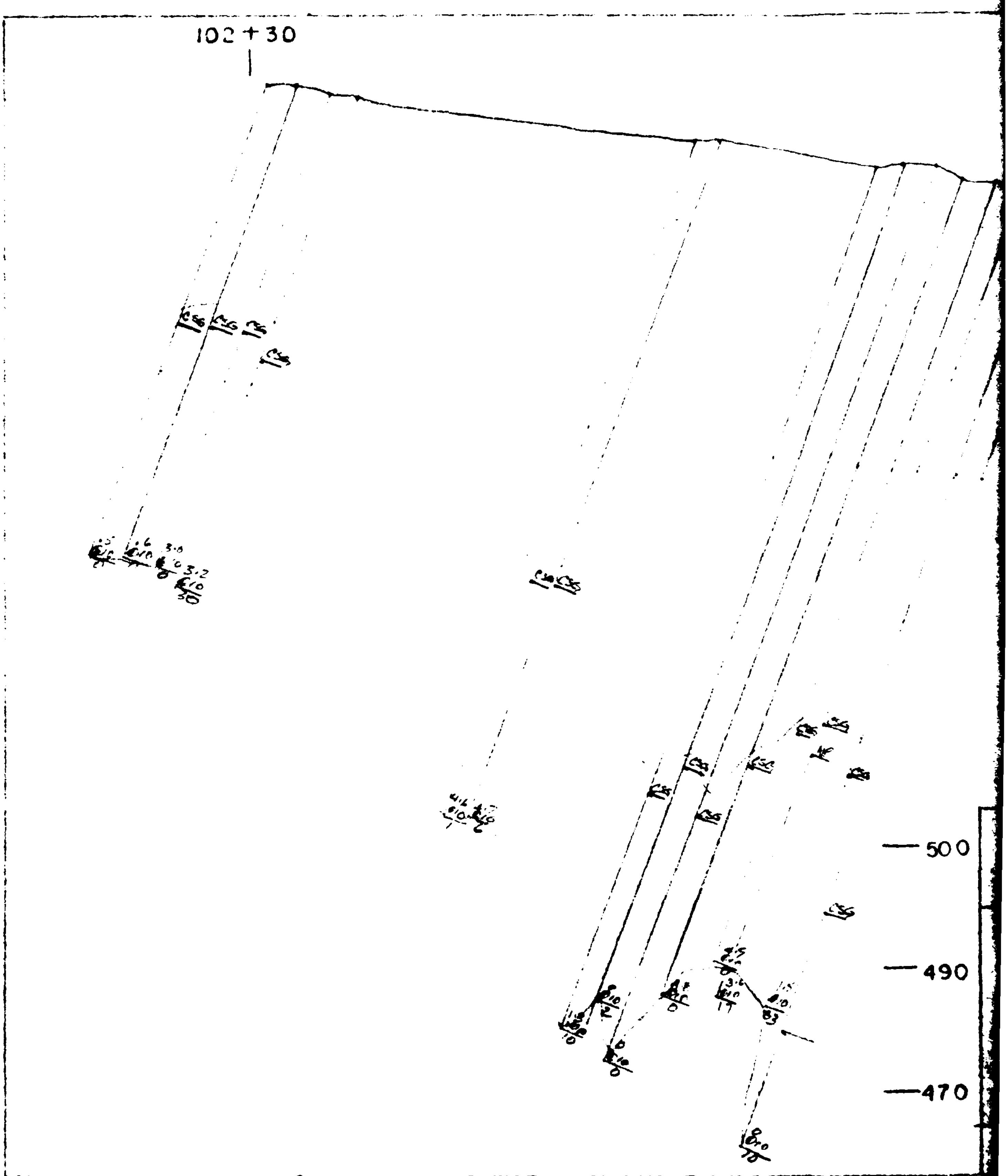
1 13

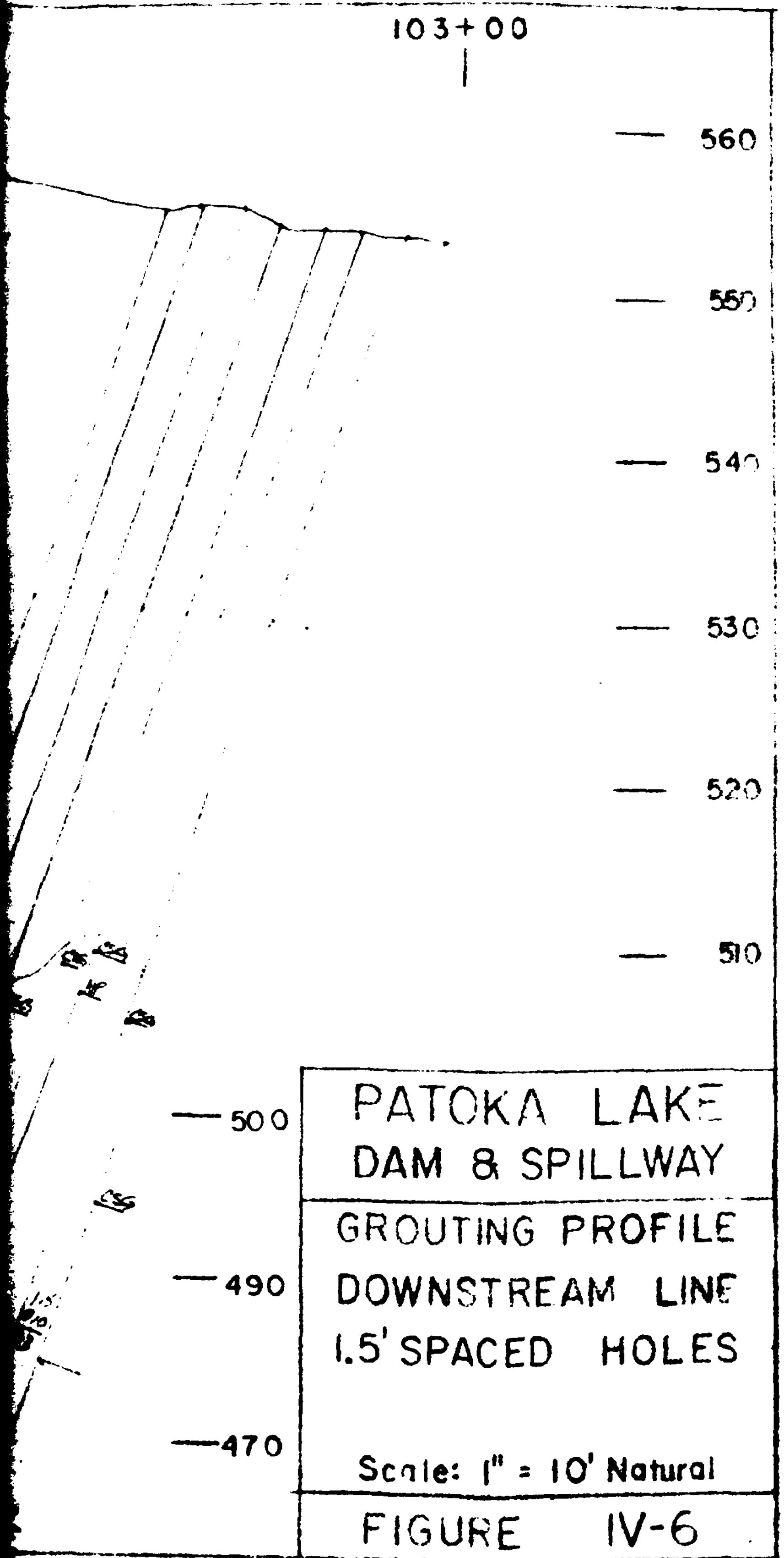


PATOKA LAKE
DAM & SPILLWAY

[illegible]TING PROFILE
DOWNSTREAM LINE
[illegible]

FIGURE IV-5


102+30
500
490
470



PATOKA LAKE
DAM & SPILLWAY

GROUTING PROFILE
DOWNSTREAM LINE
1.5' SPACED HOLES

Scale: 1" = 10' Natural

FIGURE IV-6

2

grout, allowed to set, and was then redrilled with mixed results. This problem was never completely resolved, but low grout takes in this section indicated a tight zone. Consequently, this section was considered satisfactorily grouted.

4-09. As noted on the design geologic and grouting profiles, the top of rock contact between Sta. 102+0 and 103+0 was very irregular. In the plans, a thinning of limestone was shown for this section. The first problem involved setting casing in this section. The contractor was instructed to set casings 2 feet into solid rock and the driller's judgment was relied upon to determine the top of rock. After plotting the installed casings on a profile, a very erratic top of rock contact was noted between Sta. 102+30 and 103+0. During further split spacing, this erratic pattern persisted. The conclusion was reached that this erratic pattern was not an error on the drillers part, but represented the actual top of rock contact.

4-10. This section of grout line, Sta. 102+0 to 103+0, presented the greatest grouting problems with the limestone. As noted in the previous paragraph, the top of rock was very erratic. The first zone included sandstone and limestone and shale in different portions of this same section. Consequently, holes within the same stage were being grouted at widely varying depths and rock types. In addition, a second zone was required for a portion of this section of grout line. Few casings, however, became unseated as noted in the previous section.

4-11. During first zone drilling, large numbers of communications between holes and with the surface were encountered. As many as nine holes communicated at one time. Consequently, after drilling a series of stages in this section, extensive washing was required. The first hole in the series usually communicated with many more holes and large quantities of clay, fossils and rock fragments were washed from the adjacent holes. After this hole was washed clean, another hole in the communicating series was washed with further communictaions and removal of material. The longest washing time per series amounted to 16 hours with washing times averaging 3 hours.

4-12. After pressure testing and thorough washing, the communicating holes were grouted. Immediately, the holes again communicated producing clay mixed with grout. In addition, many surface leaks were observed, mostly around casings. As split spacing progressed, fewer surface leaks were observed, but the number of communications between holes generally increased. During grouting the communicating holes were capped after good grout return. Upon capping, communications with additional holes within the series were usually noted. After completion of grouting within a series of communicating holes, most holes were redrilled with the same results. After split spacing, the first zone of two outside lines in this section to 1.3 ft. centers, the decision was made to drill and grout the centerline to see if the grout line would tighten up.

4-13. The same problems occurred during drilling and grouting of the center (B) line and split spacing of this line (Station 102+0 to 103+0) was commenced. At this point the contractor was instructed to split space no further than 2.5 ft. centers. The center (B) line split spaced holes on 2.5 ft. centers still communicated and took sufficient grout to require further splitting. At this point, the decision was made to try the second zone outside line of holes in this section. The second zone holes will be discussed in a later paragraph.

4-14. From the erratic communicating behavior in this section, several conclusions were reached. The large numbers of communications between holes were believed to be the result of the clay-filled solutioned cavities and joints within the limestone. The communications through the overburden were believed to be related to the highly weathered, irregular top of rock contact and possible poor seating of casings. The high static head pressures, coupled with 10 psi pressure at the header, would be sufficient to cause the grout to force its way through the clay in the solutioned cavities. Further evidence to support this conclusion was found in the varying pressures noted at the header. Pressure would build to 10 psi, hold for a short period of time, diminish to 5 psi or less, and rebuild to 10 psi. This cyclic pressure fluctuation continued throughout the grouting process in this section.

4-15. Only sandstone was encountered in the first zone of the section from Sta. 101+0 to 102+0. Occasional losses of drill tools occurred in this area due to caving holes. General progress was slow in this section due to grouting difficulties incurred in the adjacent sections. High grout takes were concentrated in the area around Sta. 101+40. The remainder of the first zone in this section had few takes over 60 cu. ft. Generally, few problem areas were encountered in this section until the tertiary (5 ft. center) holes on the outside lines were drilled. On tertiary split spacing, one hole (101+45) would not refuse. After placing over 3,000 cu. ft. of solids in this hole, grouting was stopped until an alternate method of sealing this hole could be found.

4-16. To seal the hole at Sta. 101+45 and two other large taking second zone holes between Sta. 100+0 and 101+0, 6-inch diameter vertical roller rock bit holes were drilled. The contract was modified to drill three holes to the base of the grout curtain and backfill each hole with ready mix mortar. The three vertical holes were picked to intersect the three angled grout holes at the point where the largest takes were being recorded. Drill water was lost high in the curtain and was never regained. In addition, nuumerous tool drops and soft zones were encountered. Consequently, the contractor would not drill the entire depth of the hole at one time for fear of losing the drill tools. After drilling the first hole (Sta. 101+34) to elevation 510, a bore hole camera from the Waterways Experiment Station was used for in-situ observations of the rock. A large number of fractures and very small cavities were observed, but no large cavities were noted. However, the camera could not be lowered to the bottom of the hole due to caving. Consequently, the sandstone-limestone contact could not be observed. At this point, the two remaining 6-inch holes were drilled to an intermediate depth.

4-17. Upon completion of intermediate drilling, all three holes were backfilled with ready mix, 6-inch slump, mortar. Two of the three holes (101+34A, 100+55A) took less than one cubic yard of mortar each. However, the third hole (100+58C) took 24.5 cu. yards. Coincidentally, this hole was not photographed so the exact loss zone could not be pinpointed. After backfilling, the three holes were drilled to completion. At this point, the ready mix mortar was considered too expensive and consequently the three vertical holes were backfiled with sanded grout. Sanded grout takes for backfilling ranged from 730 to 1,192 cu. ft. These high grout takes indicated open conditions below previously drilled depths.

4-18. Several advantages were seen for using large diameter holes to seal loss areas in the grout curtain. This method allowed thick mortar grout mixes to be placed directly into the grout loss zone. Also, mixes too thick to be pumped could be utilized to minimize grout travel. When first envisaged, the air-trac method of drilling was desired which would further reduce drilling costs. However, due to poor rock conditions and depth of holes, air-trac drilling could not be utilized. Consequently, the high drilling costs and sporadic mortar takes made this method of grouting unfeasible and this method was abandoned after completion of these three large diameter holes.

4-19. Grouting was again continued in the hole at Sta. 101+45. Another 950 cu, ft. of grout was pumped before this hole finally refused. This hole (101+45A) was further split spaced and neither of the first zone split holes took over 2 cu. ft. of grout. The remainder of the first zone in this section was grouted without further problems. The other two grout holes intersected by large diameter vertical holes were further grouted also. Both of these holes sealed rapidly and were staged further. Both holes took large quantities of grout during subsequent staging.

4-20. The first zone of the section between Sta. 100+0 and 101+0 was drilled entirely in sandstone below elevation 564. To reach the top of the curtain (Elev. 564), casings were set to the top of rock and all holes were drilled to this elevation regardless of drill water losses. If a water loss occurred between the top of rock and elevation 564, a very thick mix was pumped into the hole to seal the leaks and the hole was redrilled. This procedure eliminated the specified packer at the top of the curtain and proved satisfactory for this limited application. Grout holes were then staged below the top of the curtain as specified. Frequent drill water losses occurred in the first zone requiring excessive staging in this section. Also, large water takes (in excess of 4 cu. ft. per minute) occurred that would not take grout. In addition, a larger number of negative stages were encountered; i.e., drill water losses occurring at shallower depths than previously drilled. Generally, the first zone in this section was completed without large grout takes. The primary centerline holes in this section were completed through the first zone without split spacing. In general, except for the area between Sta. 102+50 and 103+00, centerline first zone holes took little grout.

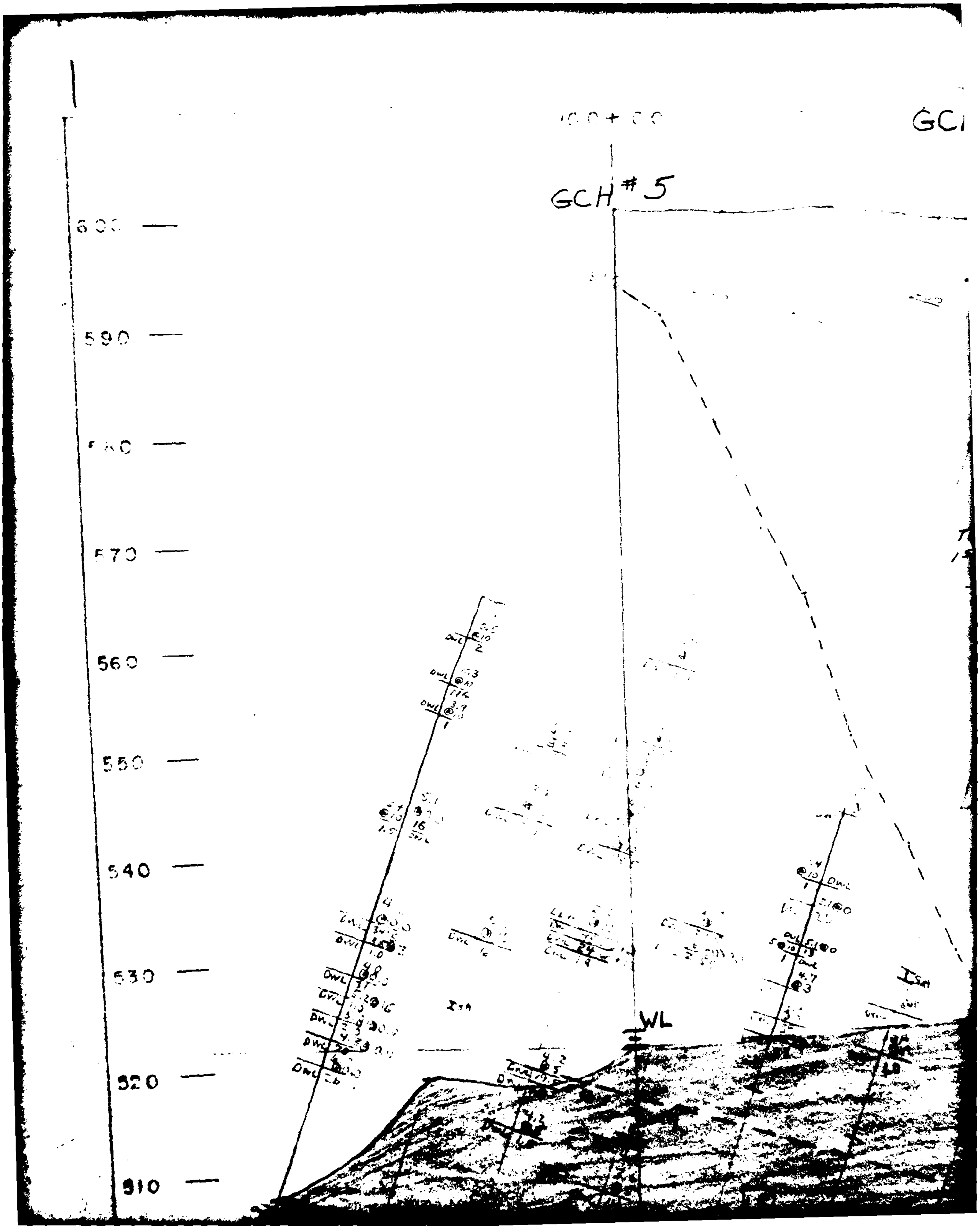
4-21. Upon completion of the three large diameter (6-inch) holes, the magnitude of the grouting problem in the dike became evident and other solutions to the problems were considered. Stop grouting with 3-inch diameter holes was chosen as a possible grouting solution. The contractor was asked to submit a proposal utilizing the stop grouting method in the left abutment dike area and in the area between the dike and the dam. The contractor's proposal was so expensive that this consideration was abandoned and normal contract grouting was continued.

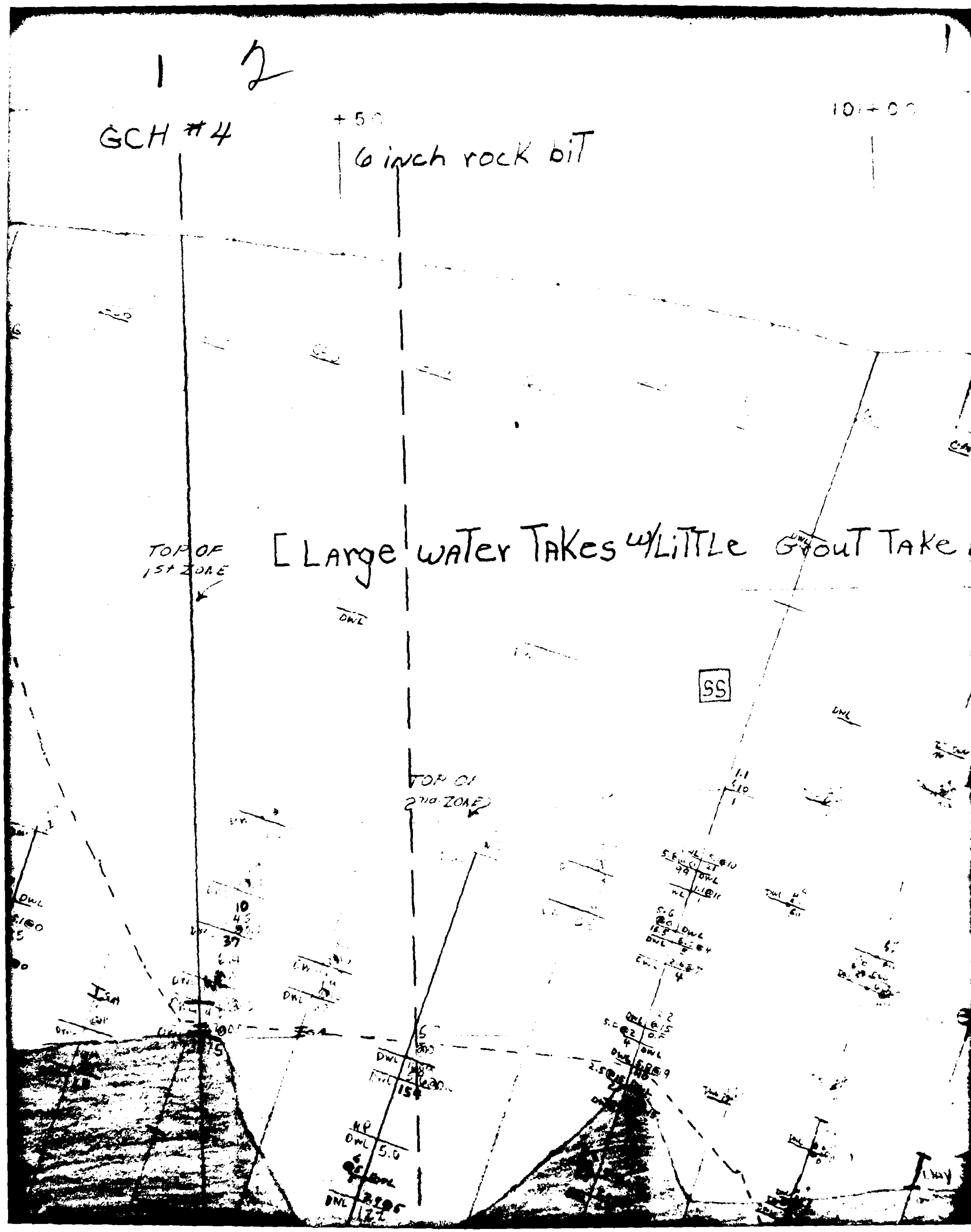
4-22. Upon completion of the first zone centerline holes, the second zone portion of the curtain was started. In some instances, second and first zone holes were being drilled simultaneously in adjacent sections. However, for the purpose of this report, grouting has been analyzed by zones, not by chronology. Generally, the second zone presented more problems than the first zone. In addition to the excessive staging in sandstone mentioned earlier, excessively large takes and loose sand at the limestone contact proved to be the most difficult problem encountered in second zone grouting.

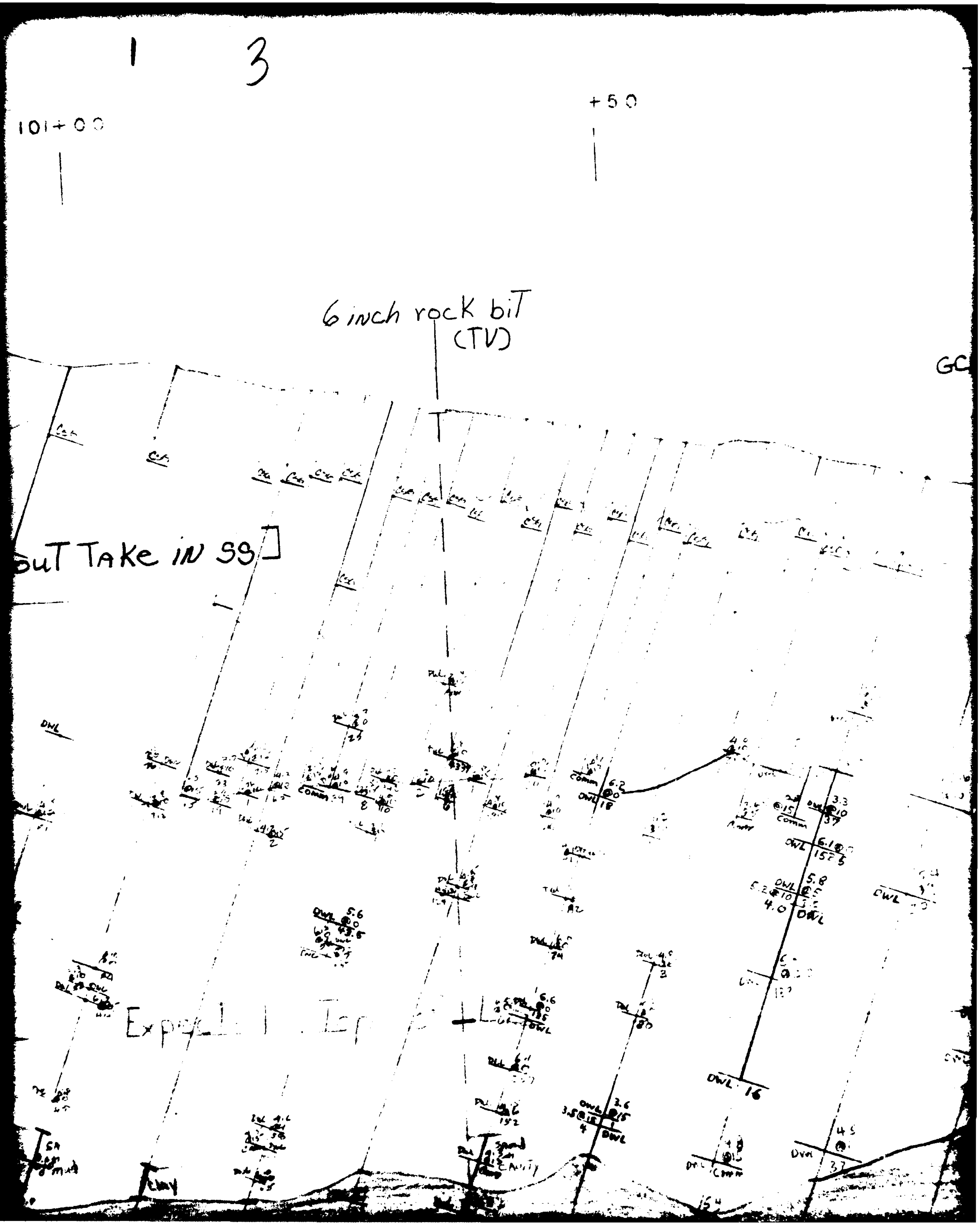
4-23. Grout takes in excess of 29 cu. ft. per linear foot of drilled hole occurred in second zone primary holes between Stas. 100+0 and 101+0. High grout takes occurred in other sections of the curtain, but were not of this magnitude. These excessively high takes indicated a very open condition within the curtain and also indicated that the grout was not being confined within the limits of the curtain. The take decreased to 8.8 cu. ft. per linear foot in the secondary holes of this section, but remained high. Only the upstream secondary holes were completed; consequently, this figure is not representative of a completed section. High takes also occurred in the remaining second zone portions of the left abutment curtain, but other problems precluded judgment on a take per linear foot basis.

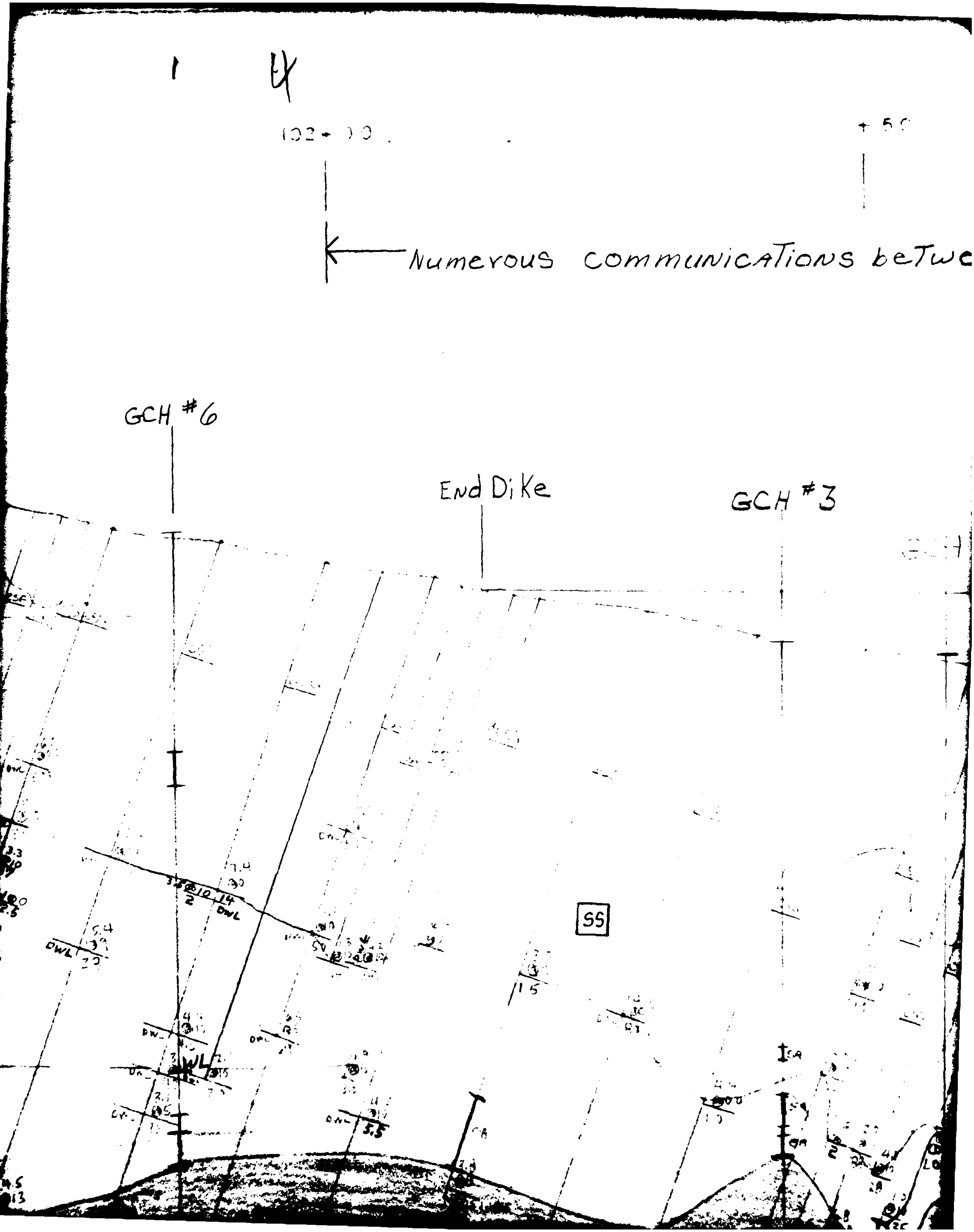
4-24. Between Sta. 101+00 and 103+00, loose sand and mud constituted the major problem in the second zone holes. As the limestone contact was drilled, a large number of tool drops were noted and large quantities of sand were washed from the grout holes. These holes, with suspected sand zones, were water tested with resulting high water takes. Utilizing the header to grout, these holes would take no grout. After allowing the grout to gain an initial set, the holes were washed, but could not be washed below the suspected caving horizon. The holes were then redrilled with the same results.

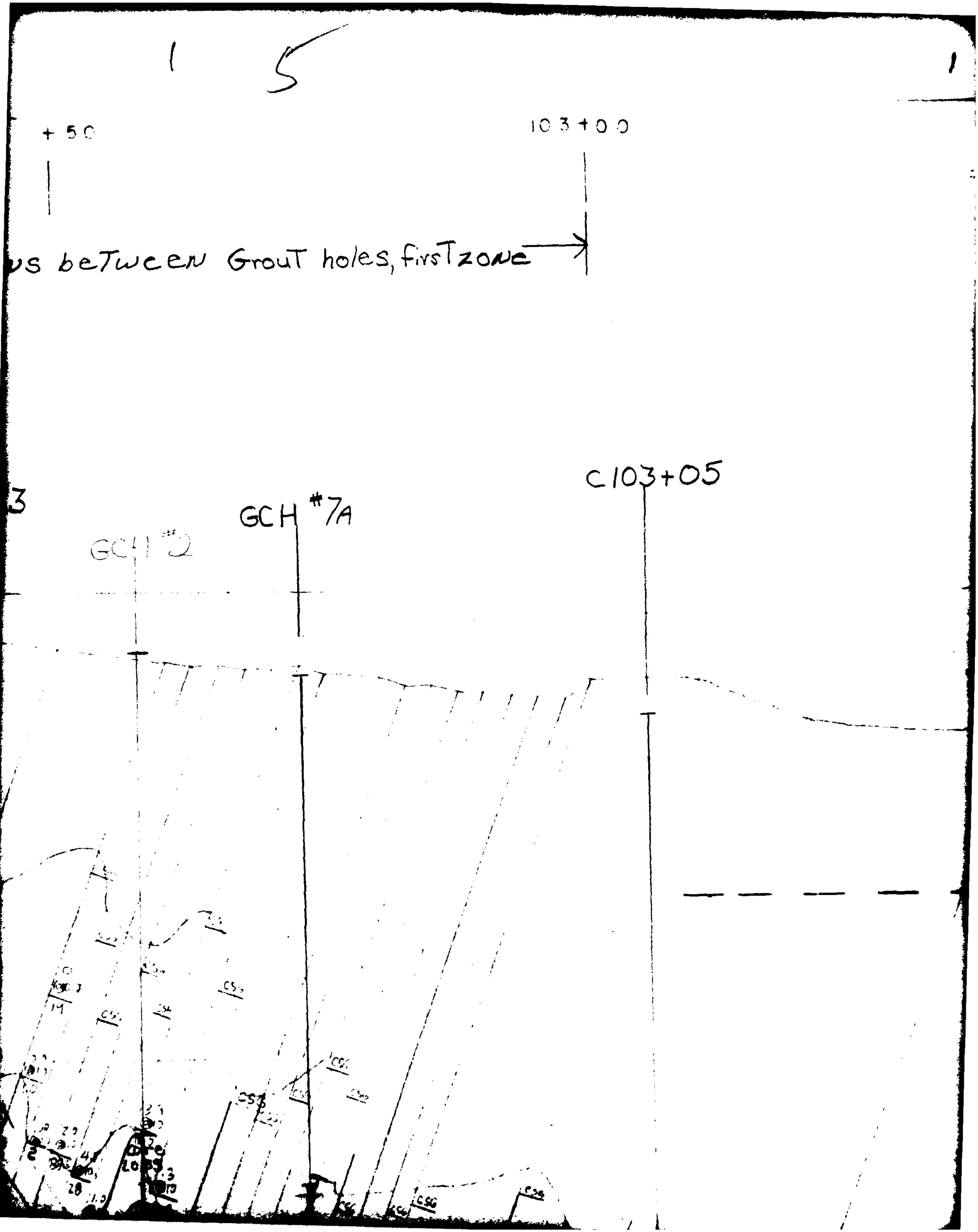
4-25. Circuit grouting was tried as a means of circumventing this caving sand problem. A one-inch (inside diameter) packer pipe was washed down below the caving sand zone and grouting was started. Excessive pressure due to the confined space between the sides of the hole and the inserted grout pipe caused a pressure build-up which necessitated moving the packer pipe progressively up the hole. When the end of the packer pipe was moved up to the base of the caving sand and mud zones, a dramatic increase in takes would occur. However, due to the inability to pump grouter thicker than 1:1 cement-water ratio through the packer pipe, the holes could not be grouted to refusal. When a mix thicker than 1:1 was needed, the packer pipe was removed from the hole and the header was used. At this point the hole refused and could not be grouted further. When these holes were redrilled, the same results were observed. All the holes in this area did not encounter caving sand and mud, but enough holes of this type were found to constitute a major grouting problem. Further, the above description represents a very general pattern for those holes that encountered caving sand conditions.


100+00
GCH #5
600
590
580
570
560
550
540
530
520
510
WL
DWL


1 2
1
GCH #4
+50
10+00
6 inch rock bit
TOP OF 1st ZONE
[Large water Takes w/Little Grout Take
55
TOP OF 2nd ZONE


1
3
101+00
+50
6 inch rock biT
(TV)
uT TAke IN SS
DWL 16


102+00
+50
Numerous communications betwe
GCH #6
End Dike
GCH #3
SS
DWL
5.5


1
5
1
+50
103+00
us between Grout holes, first zone
C103+05
3
GCH #7A
GCH #2

1 6

+50

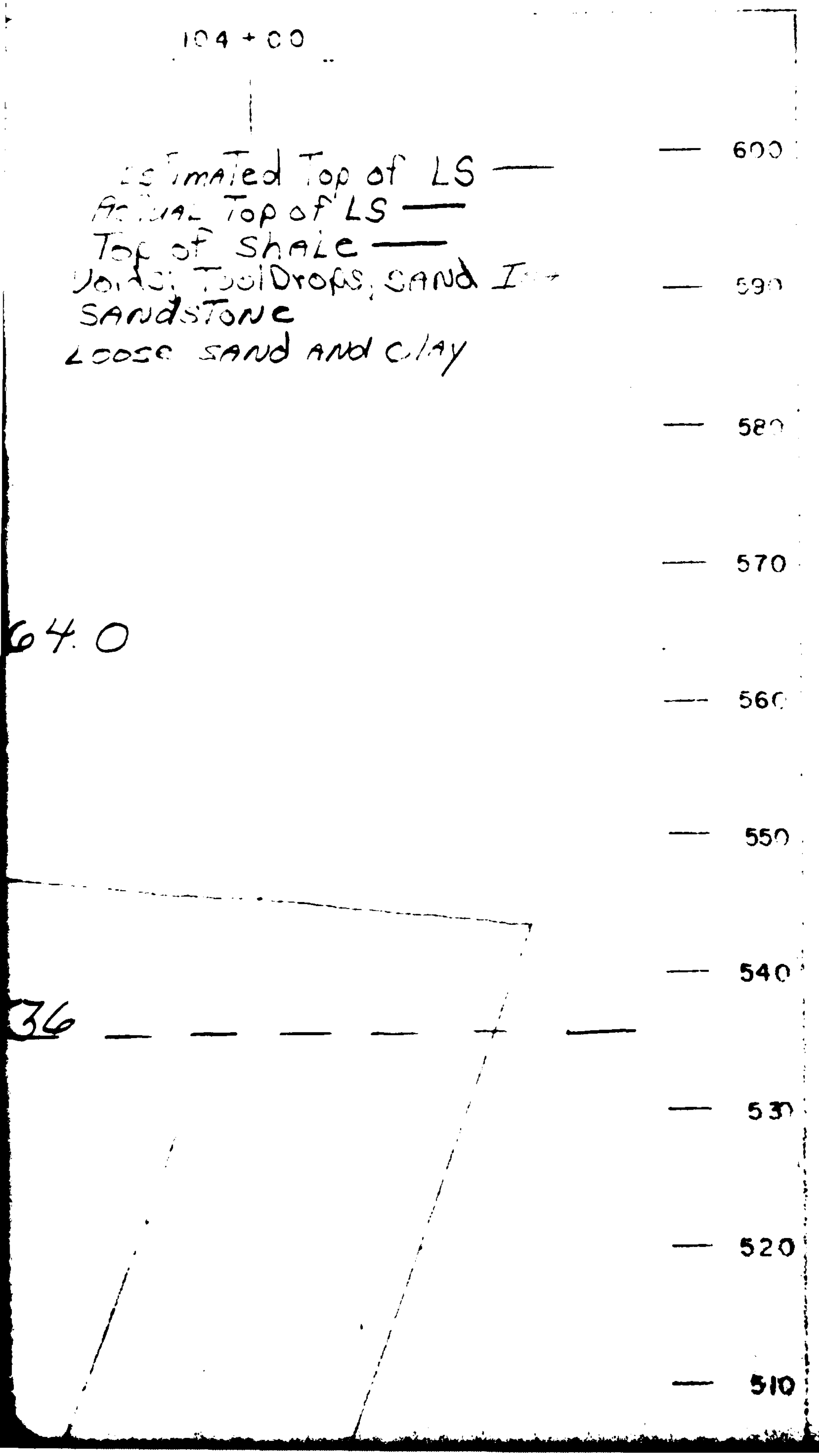
104+00

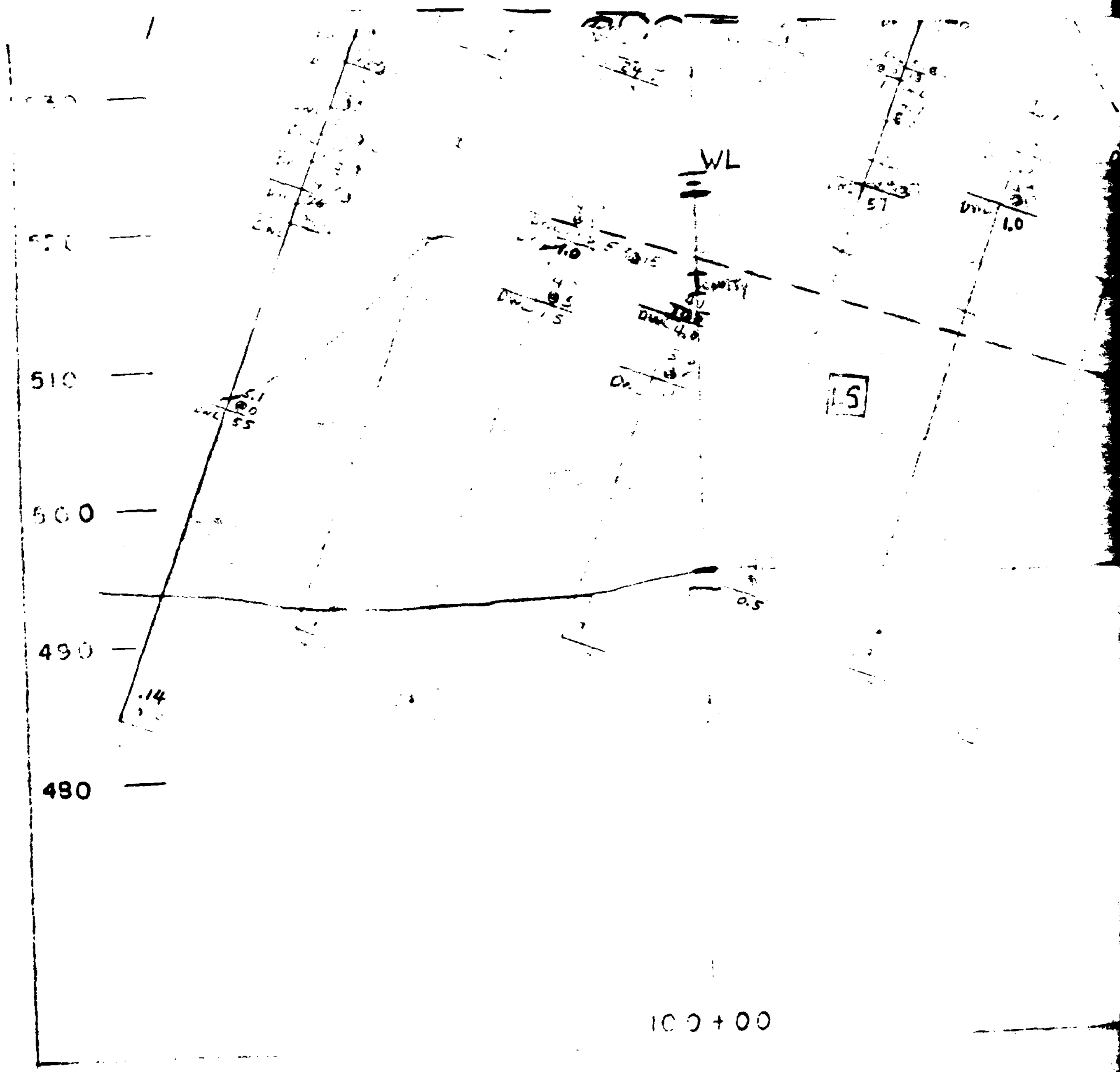
Estimated Top of
Actual Top of LS
Top of Shale
Voids; Tool Drop S
Sandstone
Loose Sand and C

Top of Dike EL 564.0

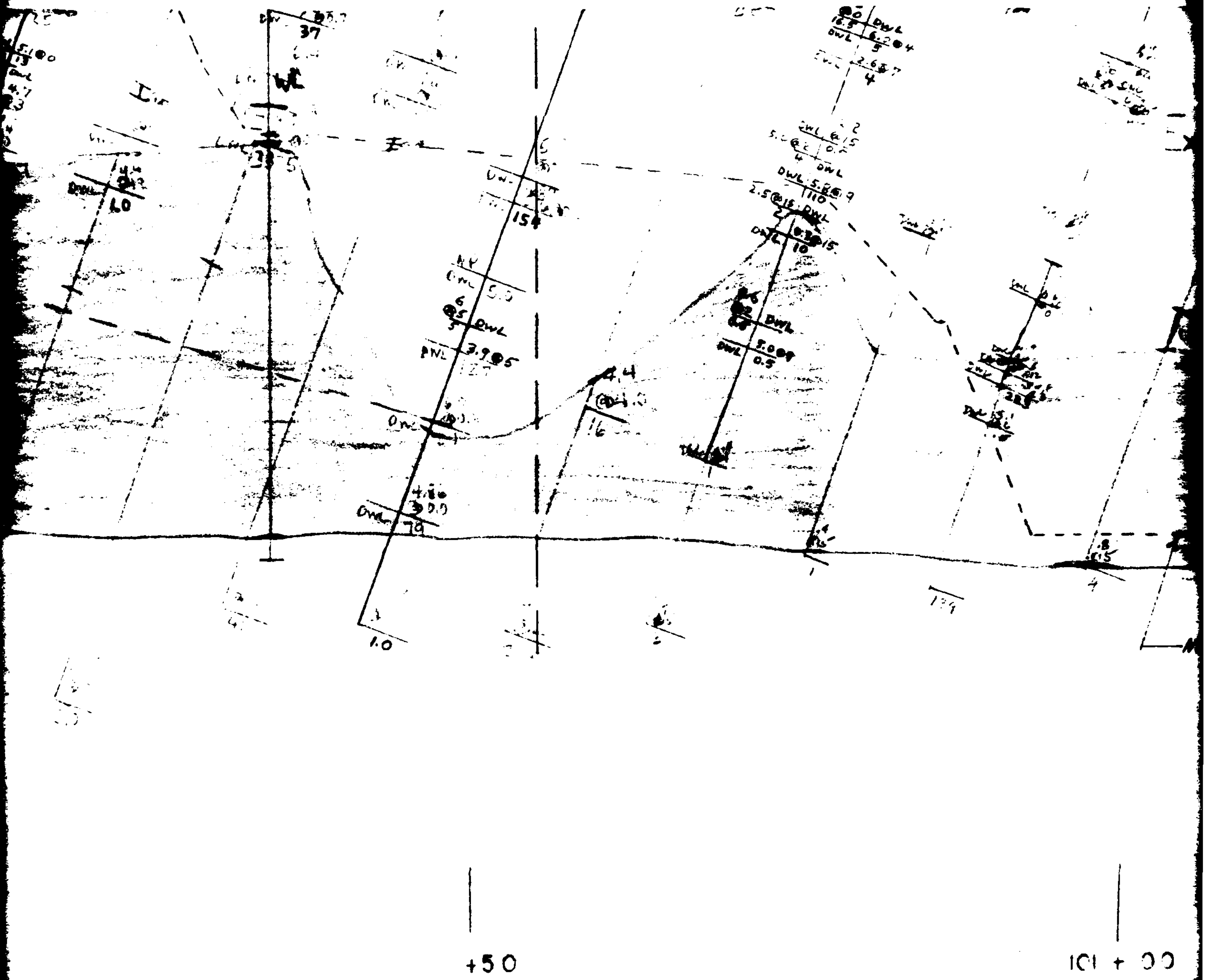
Summer Pool EL. 536

1 7

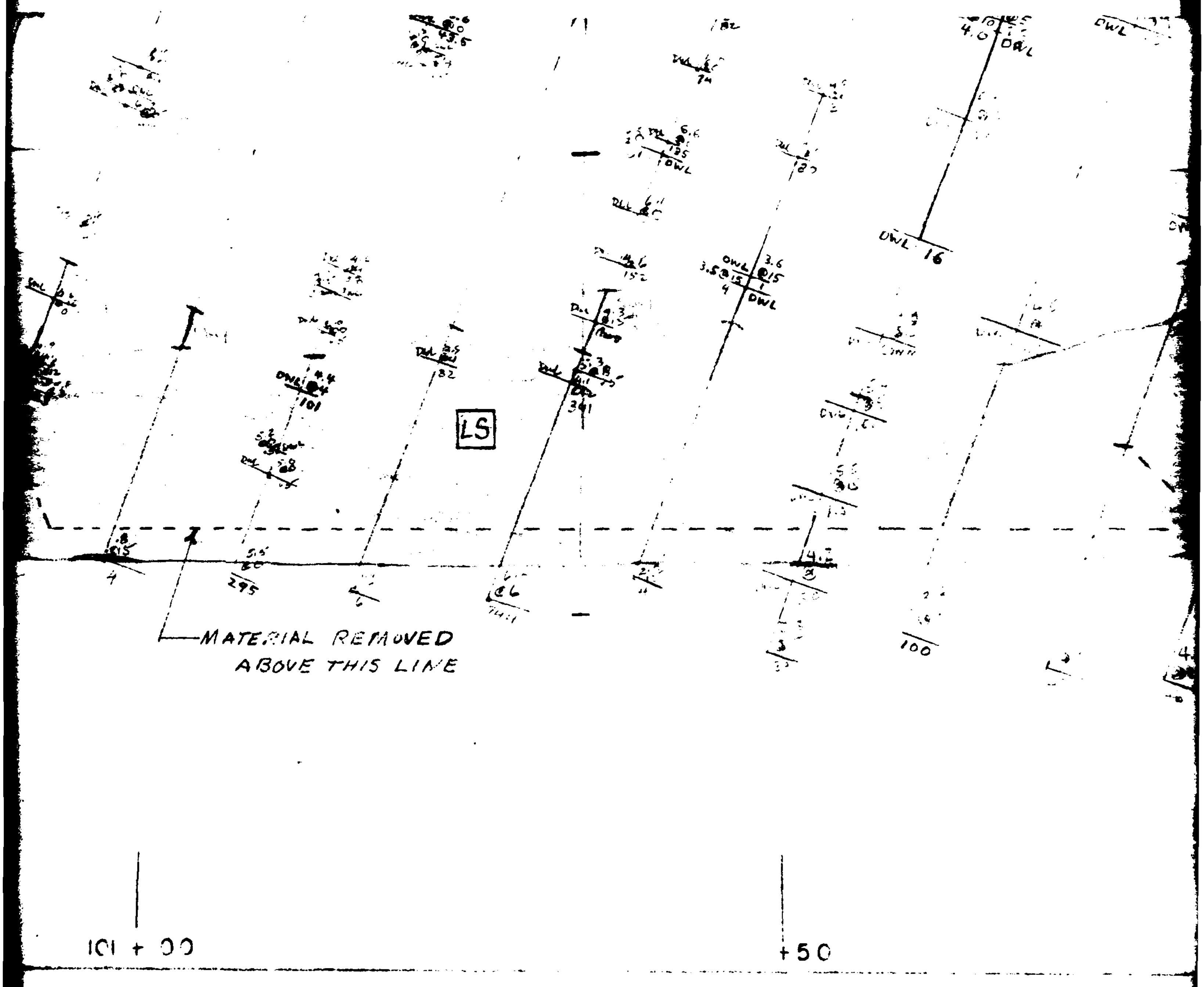

104 + 00
Estimated Top of LS
Actual Top of LS
Top of Shale
Voids, Tool Drops, Sand
Sandstone
Loose sand and clay
600
590
580
570
64.0
560
550
540
36
530
520
510



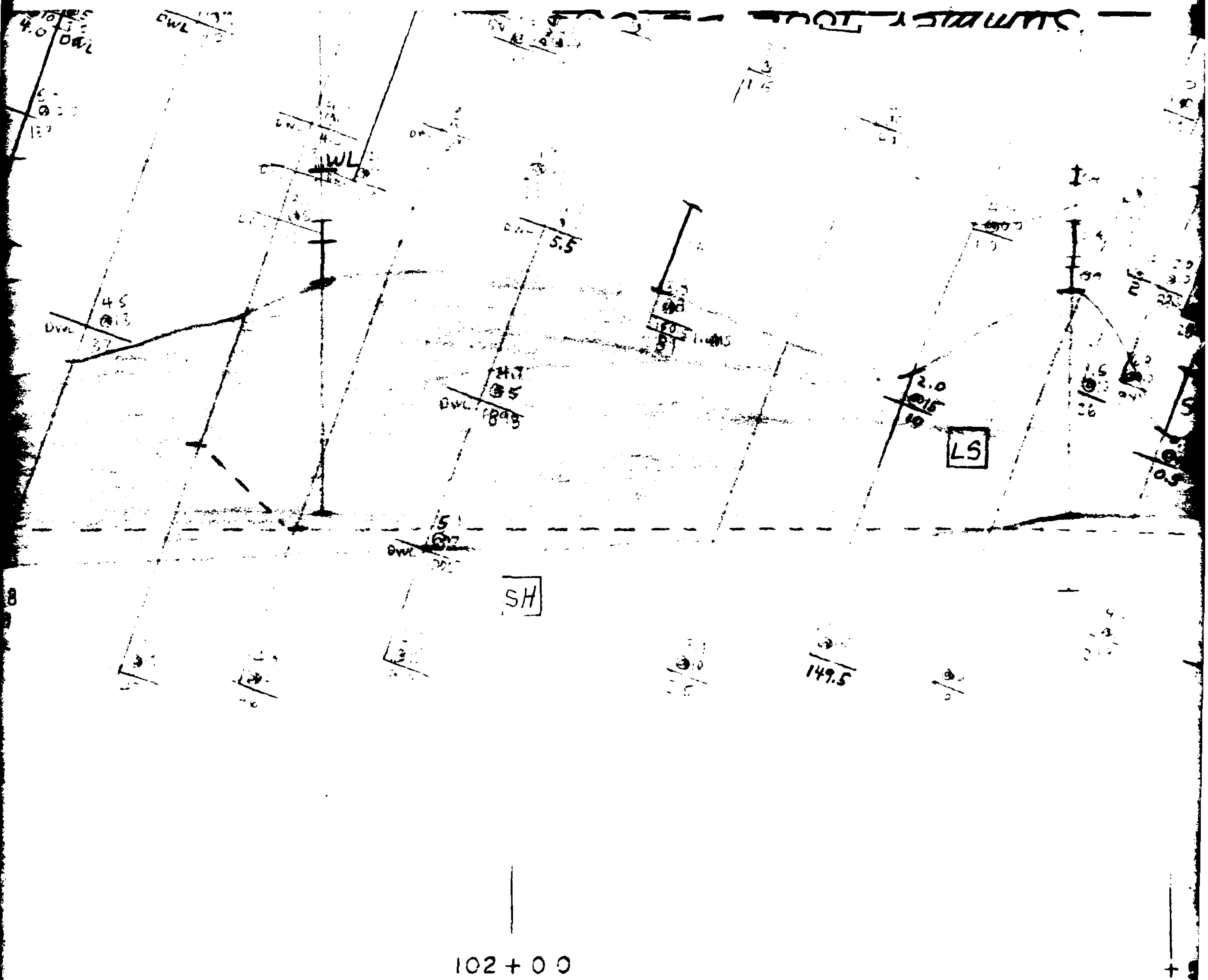
8



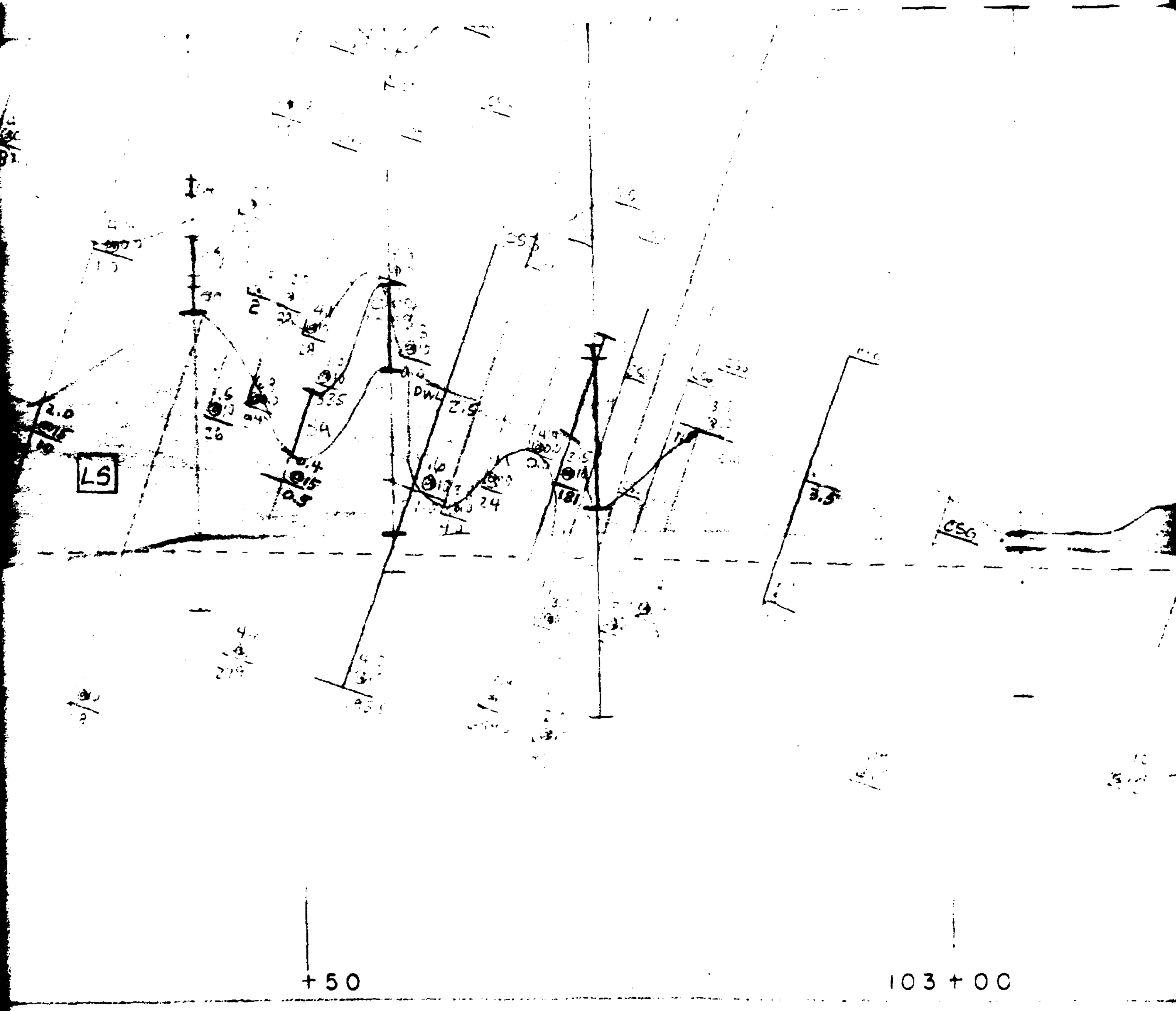
9



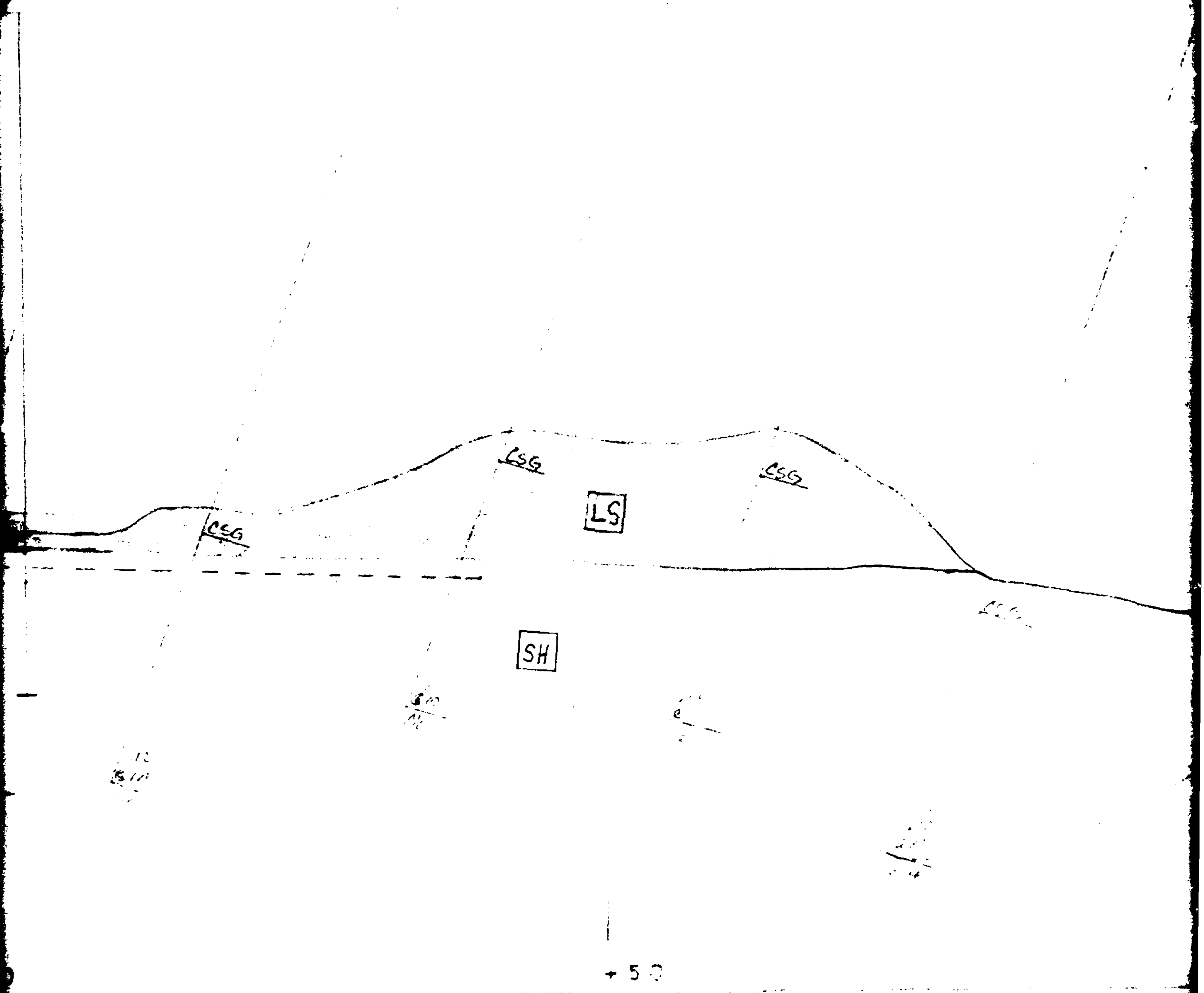
10



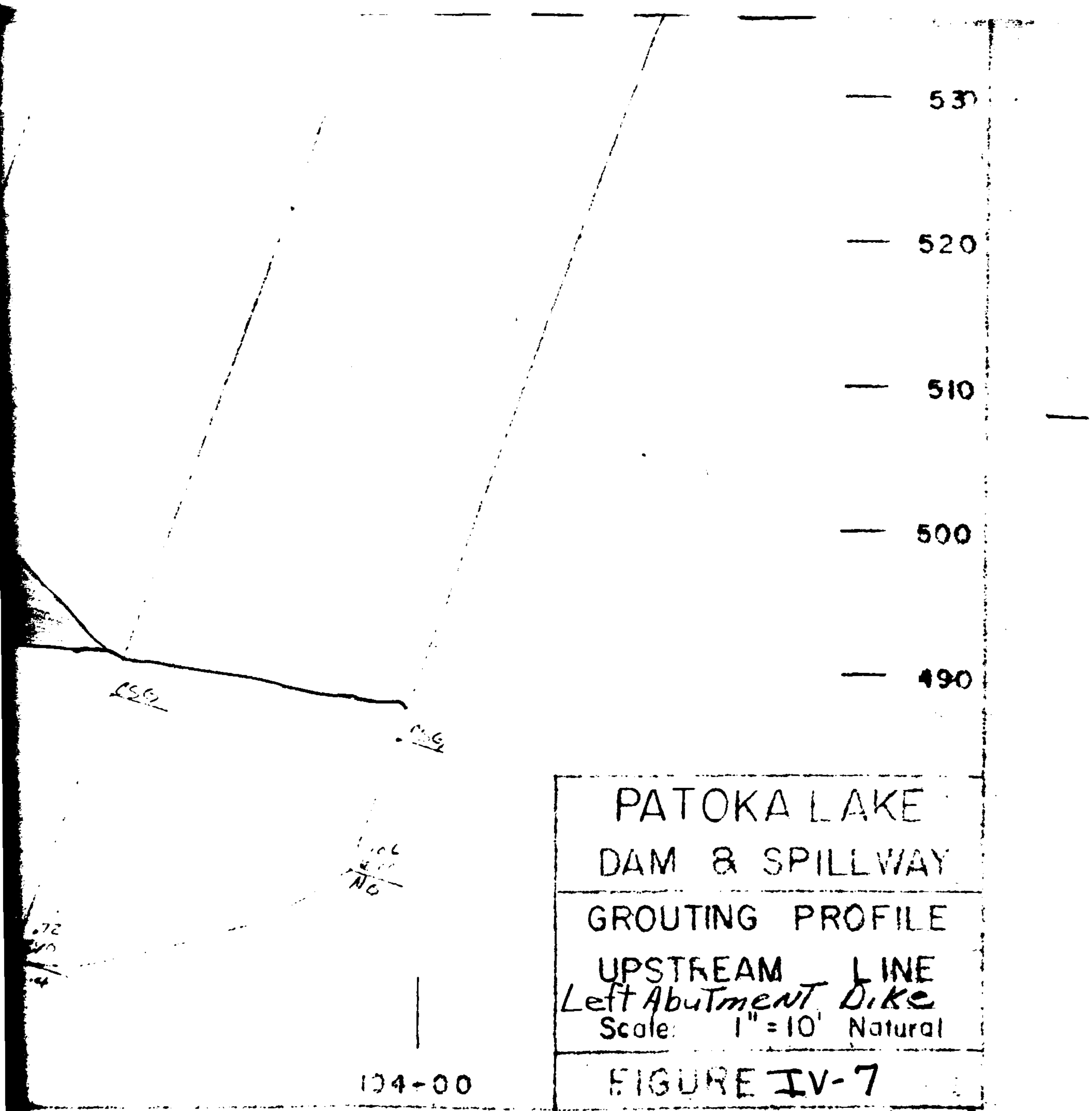
DWL
WL
5.5
2.0
LS
SH
149.5
102+00



LS
DWL
CSG
+50
103+00



1 13



PATOKA LAKE
DAM & SPILLWAY
GROUTING PROFILE
UPSTREAM LINE
Left Abutment Dike
Scale: 1" = 10' Natural
FIGURE IV-7

4-26. As the loose, caving sand pattern became more evident, the decision was reached to sample the zone in question. Two each, combination drive and core holes, showed a 6-foot loose wet sand zone just above the limestone contact.

4-27. At this point, nearly continuous grouting had been in progress for over a year, the prime contractor was being delayed, and little grouting progress was being made. A meeting between ORL, ORD and OCE personnel was held on August 24, 1976, to review the grouting problems on the dike and to examine similar problems expected betwen the dike and the dam. At this meeting, the decision was made to complete only the upstream grout line on 10-foot (secondary) centers, using circuit grouting methods if necessary. The 10-foot spacing was selected to locate any large collapse zones that might be present within the left abutment area.

4-28. Work on this modified grouting program was completed by October 1, 1976. The secondary holes on the completed grout line took considerably less than the primary holes, but this information was inconclusive since further split spacing was not performed. One secondary hole near the end of the curtain (100+30) took a very large quantity of grout (2,273 cu. ft.). Loose sand continued to be a problem and the grouting results in this area were considered unsatisfactory.

4-29. Table IV-2 is a computation of the completed portion of the upstream grout line. Only this line has been tabulated since it came closer to being completed than the other two grout lines. The information presented has been broken down according to stages for better definition of the grout take zones. Abbreviations and letters are defined as follows: A = upstream line, R = replacement hole, P = primary, S = secondary, T = tertiary, Q = quinternary, and DWL = drill water loss.

4-30. In summary, a discussion of grouting problems encountered on the left abutment of the dike can be delineated by rock types. The following problems were encountered in the sandstone above the limestone: soft and poorly cemented zones within the rock, frequent drill water losses causing excessive staging, large water takes with little or no grout takes, frequent negative staging, excessive tool losses, and excessively large grout takes in many holes. Open very thin bedding planes in the poorly cemented sandstone were thought to be responsible for the frequent drill water losses, excessive staging and negative staging. In addition, multiple drill holes resulting from a drift of successive redrilling in the same bedding plane was considered as a possible cause for the negative staging problem. However, the open bedding plane hypothesis was thought to better explain the situation. The excessive takes were thought to be caused by open

Table IV - 2

Upstream Grout Line Tabulation

Hole No.	Stage Depth	Stage Elevation	Water Test Cu Ft/Min	Grout Take Cu Ft	Remarks
100+00 AP	42.0	560.85	0.55	2.0	DWL
"	45±	558.0	--	-	Lost tools in hole
100+00 ARP	47.0	556.1	0.3	-	DWL, not grouted
"	50.0	553.3	3.9	1.0	DWL
"	61.0	543.0	5.4	1.5	Bottom Zone 1
"	54.0	549.5	--	-	Tools lost, aban. hole
100+00 ARRP	60.0	543.6	5.1	16.0	Bottom Zone 1
"	72.0	532.3	3.5	1.0	DWL
"	76.0	528.6	4.0	27.0	DWL
"	70.0	534.2	4.2	34.5	DWL
"	82.0	523.0	4.1	73.0	DWL
"	76.0	528.6	1.0	4.0	DWL
"	78.0	526.7	5.2	110.0	DWL
"	80.0	524.8	5.8	2.0	DWL
"	82.0	523.0	4.3	3.0	DWL
"	85.0	520.1	5.5	2624.0	DWL
"	99.0	507.0	5.1	55.0	DWL
"	123.0	484.4	0.14	69.0	Bottom Zone 2
100+10AS	53.0	550.2	6.9	22.0	DWL
"	60.0	543.6	3.8	2.0	DWL, Bottom Zone 1
"	72.0	523.3	5.6	16.0	DWL
"	116.0	491.0	1.6	4.0	Bottom Zone 2
100+20AP	45.0	557.9	0.5	1.0	DWL
"	60.0	543.5	4.0	1.0	Bottom Zone 1
"	60.0	543.5	3.7	1.0	DWL
"	60.0	543.5	2.4	3.0	DWL
"	63.0	540.7	4.4	3.5	DWL
"	63.0	540.7	4.6	92.0	DWL
"	71.0	533.2	2.2	43.0	DWL
"	71.0	533.2	--	-	Tools Lost, aban. hole
100+20ARP	53.0	550.2	4.6	2.0	DWL
"	56.0	547.3	3.0	2.0	DWL
"	72.0	534.1	6.6	7.0	DWL
"	71.0	533.2	3.5	2.0	DWL
"	73.0	531.3	4.6	18.0	DWL
"	86.0	519.1	5.3	1.0	DWL
"	91.0	514.4	3.9	1.5	DWL
"	85.0	520.0	4.2	0.5	DWL
"	85.0	520.0	6.0	19.0	DWL
"	122.0	485.3	2.6	125.0	Bottom Zone 2
100+30AS	70.0	532.7	6.9	26.0	DWL, Bottom Zone 1
"	70.0	532.7	2.6	1.0	DWL

Table IV - 2 (Cont'd)

Hole No.	Stage Depth	Stage Elevation	Water Test Cu Ft/Min	Grout Take Cu Ft	Remarks
100+30AS	72.0	530.9	5.4	21.0	DWL
"	72.0	530.9	5.0	2134.0	DWL
"	91.0	513.0	4.1	4.0	DWL
"	96.0	508.3	3.6	111.0	DWL
"	116.0	489.5	3.0	2.0	Bottom Zone 2
100+40AP	58.0	543.1	0.26	--	Bottom Zone 1/not grouted
"	72.0	529.9	5.02	1.0	DWL
"	65.0	536.5	1.4	1.0	DWL
"	71.0	530.9	5.1	17.0	DWL
"	78.0	524.3	3.4	98.0	DWL
"	80.0	522.4	5.4	39.0	DWL
"	75.0	527.1	4.7	6.0	DWL
"	67.0	534.6	5.2	10.0	DWL
"	80.0	522.4	5.2+	18.0	DWL
"	111.0	493.3	4.2	0.5	DWL
"	120.0	484.8	3.5	117.5	Bottom Zone 2, Comm. w/100+40C
"	120.0	484.8	0.75	13.0	Refusal
100+50AS	76.0	524.5	2.9	0.5	Bottom Zone 1, DWL
100+50AS	80.0	520.1	4.4	1.0	DWL
"	116.0	486.9	0.6	1.0	Bottom Zone 2
100+60AP	54.0	543.6	1.8	1.0	Bottom Zone 1
"	65.0	533.2	1.7	21.0	DWL
"	70.0	528.5	6.4	34.0	DWL
"	65.0	533.2	4.5	16.0	DWL
"	61.0	537.0	0.9	10.0	DWL
"	72.0	526.6	2.7	4.0	DWL
"	75.0	523.8	4.5	150.0	DWL, 1.5 ft. tool drop
"	75.0	523.8	3.5	0.0	DWL
"	75.0	523.8	5.7	3725.0	DWL
"	120.0	481.5	0.33	2.0	Bottom Zone 2
100+70AS	70.0	526.7	1.9	60.0	DWL, Bottom Zone 1
"	67.0	529.5	3.2	1.0	DWL
"	111.0	488.2	3.9	41.0	Bottom Zone 2
100+80AP	54.0	540.0	0.2	--	Bottom Zone 1
"	74.0	521.2	5.2	1689.0	DWL
"	76.0	519.3	--	115.0	DWL
"	88.0	508.0	3.9	122.0	DWL
"	76.0	519.3	5.6	39.0	DWL, Comm w/surface
100+80ARP	86.0	509.7	6.0	5.0	DWL, Hole Collapsed
"	101.0	495.6	4.9	79.0	DWL
"	94.0	502.2	6.0	27.0	DWL
"	110.0	487.1	4.9	1.0	Bottom Zone 2, Comm w/100+80C

Table IV - 2 (Cont'd)

Hole No.	Stage Depth	Stage Elevation	Water Test Cu Ft/Min	Grout Take Cu Ft	Remarks
100+90AS	53.0	538.7	3.9	28.0	DWL, Bottom Zone 1
"	57.0	534.9	5.7	45.0	DWL
"	108.0	487.0	4.2	128.0	Bottom Zone 2
"	90.0	503.9	4.4	14.0	DWL, Comm W/101+0 & 20 A & B
"	90.0	503.9	4.5	2.0	DWL, Comm w/101+0, 20A
101+00ARP	43.0	545.5	1.1	1.0	Bottom Zone 1
"	50.0	538.9	5.1	21.0	DWL
"	51.0	537.9	5.8	49.0	DWL
"	57.0	532.3	5.6	16.5	DWL
"	58.0	531.4	6.0	0.5	DWL
"	60.0	529.5	2.6	4.0	DWL
"	68.0	522.0	5.0	4.0	DWL
"	70.0	520.1	5.8	110.0	DWL
"	67.0	522.9	2.2	0.5	DWL
"	83.0	507.9	5.0	0.5	DWL
"	74.0	516.4	4.3	10.0	DWL
"	81.0	509.8	3.6	0.5	DWL, Comm w/101+60A
"	82±	508.0	--	--	Lost tools, hole aband.
101+00AP	72.0	518.2	2.5	2.0	DWL
"	92.0	499.4	4.4	--	DWL, Comm w/100+90A & 100+20A
"	78.0	512.6	4.5	1.0	DWL
"	105.0	487.2	0.7	3.0	Bottom Zone 2
101+10AS	36.0	551.2	--	--	Lost tools, hole aband.
101+10ARS	49.0	538.9	4.5	51.0	DWL, Bottom Zone 1
"	54.0	534.3	4.9	84.0	DWL
"	73.0	516.6	3.0	1.0	DWL
"	99.0	492.0	0.4	1.0	Bottom Zone 2
101+20AP	40.0	545.2	2.8	7.2	DWL, Bottom Zone 1
"	59.0	527.4	3.3	58.0	DWL
"	37.0	548.0	6.5	76.0	DWL
"	57.0	529.2	6.0	84.0	DWL
"	60.0	526.4	6.2	1.0	DWL
"	60.0	526.4	5.6	3.5	DWL
"	70.0	517.0	5.8	47.0	DWL
"	76.0	511.4	4.6	0.0	DWL
"	81.0	506.7	4.9	--	DWL, Comm w/101+40A
"	86.0	502.0	5.1	0.5	DWL, Comm w/101+80 & 60C
"	82.0	505.7	5.0	0.5	DWL, Comm w/101+80 & 60C
"	99.0	498.7	--	139.0	Bottom Zone 2
"	83.0	504.8	5.8	30.0	Comm w/101+0A, 100+0AR
"	83.0	504.8	4.5	--	Comm w/100+90A

Table IV - 2 (Cont'd)

Hole No.	Stage Depth	Stage Elevation	Water Test Cu Ft/Min	Grout Take Cu Ft	Remarks
101+20AP	83.0	504.8	4.5	19.0	Comm w/101+0A & 100+90A
"	83.0	504.8	1.0	174.0	Hole Complete
101+22.5AQ	40.0	545.0	0.5	0.5	Bottom Zone 1
101+25AT	37.0	547.4	3.7	33.0	DWL
"	40.0	544.6	3.8	19.0	DWL, Bottom Zone 1
101+27.5AQ	36.0	547.9	0.02	7.5	DWL, Comm w/OB & 101+32.5A
"	39.0	545.1	0.75	1.0	Bottom Zone 1
101+30AS	38.0	545.4	4.3	63.0	Bottom Zone 1
"	42.0	541.6	4.2	1.0	DWL
"	42.0	541.6	3.1	1.0	DWL
"	96.0	490.9	0.8	4.0	Bottom Zone 2
101+32.5AQ	37.0	545.7	2.5	--	Bottom Zone 1, Comm w/101±27.5A
101+35AT	31.0	551.1	3.3	25.0	DWL, Comm w/101+20A
"	37.0	545.4	4.9	39.0	DWL, Bottom Zone 1
101+37.5AQ	37.0	563.0	2.5	8.0	Bottom Zone 1
101+40AP	36.0	563.5	7.2	342.3	DWL
"	38.0	561.6	4.0	86.3	Bottom Zone 1
"	38.0	561.6	4.0	24.0	DWL
"	41.0	558.8	3.9	1.0	DWL
"	50.0	550.3	5.6	43.5	DWL
"	52.0	548.4	6.5	56.0	DWL
"	53.0	547.5	5.2	0.5	DWL
"	70.0	531.5	4.6	58.0	DWL, tool drop 0.5 ft.
"	75.0	526.8	6.0	0.5	DWL
"	72.0	529.6	4.5	--	DWL, Comm w/101+20A
"	85.0	517.4	5.2	0.5	DWL
"	87.0	515.5	5.0	0.5	DWL
"	95.0	508.0	4.4	394.5	Bottom Zone 2, Comm w/ 101+20A, 101+00 AR
"	79.0	523.0	0.3	2.0	Hole compl., circuit gr.
101+42.5AQ	26.0	554.7	2.4	--	DWL, Comm w/101+37.5A
"	36.0	545.3	1.2	2.0	Bottom Zone 1
101+45AT	33.0	547.6	6.8±	867.0	DWL
"	29.0	551.3	6.7	2.5	DWL
"	30.0	550.4	5.9	3469.0	DWL
"	37.0	543.8	2.0	6.0	Bottom Zone 1
101+47.5AQ	35.0	545.5	2.2	1.0	Bottom Zone 1, Comm. w/101+37.5A, 101+42.5,OB
101+50AS	37.0	543.2	4.8	28.5	Bottom Zone 1
"	45.0	535.7	4.5	59.0	DWL
"	46.0	534.8	4.5	124.0	DWL
"	76.0	506.6	3.9	32.0	DWL

Table IV - 2 (Cont'd)

Hole No.	Stage Depth	Stage Elevation	Water Test Cu Ft/Min	Grout Take Cu Ft	Remarks
101+50AS	95.0	488.7	1.4	6.0	Bottom Zone 2
101+52.5AQ	34.0	545.6	0.0	20.0	Bottom Zone 1, 101+57.5A, 60A, 72.5A, 77.5A
101+55AT	37.0	541.9	4.7	49.0	Bottom Zone 1
101+57.5AQ	33.0	545.6	1.1	--	Bottom Zone 1, Comm w/ 101+52.5A
101+60AP	32.0	545.8	6.2	18.0	DWL, Zone 1
"	40.0	538.3	4.5	21.0	DWL
"	44.0	534.6	5.9	82.0	DWL
"	49.0	529.9	6.0	74.0	DWL
"	55.0	524.2	6.6	135.0	DWL
"	56.0	523.3	6.0	61.0	DWL
"	65.0	514.8	4.5	152.0	DWL
"	61.0	518.6	6.1	257.0	DWL
"	70.0	510.1	4.3	--	DWL, Comm w/101+80C
"	74.0	506.4	5.3	0.5	DWL, Comm w/101+80C
"	93.0	488.5	6.0	744.0	Bottom Zone 2, Comm. w/101+80C
"	75.0	505.4	3.0	293.0	Redrill to LS
"	75.0	505.4	1.4	48.0	Redrill to LS, circ. grt.
101+65AT	39.0	538.7	1.2	1.0	Bottom Zone 1
101+70AS	29.0	547.1	4.0	21.5	Bottom Zone 1
"	50.0	527.4	4.8	3.0	DWL
"	55.0	522.7	5.3	8.0	DWL
"	65.0	513.3	3.6	1.0	DWL
"	66.0	512.4	3.5	4.0	DWL
"	90.0	489.8	2.0	4.0	Bottom Zone 2
101+72.5AQ	35.0	540.9	3.7	--	DWL, Bottom Zone 1, Comm. w/101+52.5A
101+75AT	30.0	545.0	3.9	34.0	Bottom Zone 1
101+77.5AQ	34.0	540.6	0.8	--	Bottom Zone 1, Comm. w/101+52.5A
101+80AP	23.0	550.4	6.0	32.4	DWL
"	29.0	544.7	3.0	33.0	Bottom Zone 1
"	33.0	541.0	3.3	7.0	DWL
"	36.0	538.2	6.1	152.5	DWL
"	41.0	533.5	--	1.0	DWL, Seal surface leak
"	41.0	533.5	5.8	1.5	DWL, Comm w/surface
"	42.0	532.6	5.2	4.0	DWL
"	49.0	525.9	5.8	133.0	DWL
"	59.0	516.5	--	16.0	DWL
"	67.0	509.0	4.8	--	DWL, Comm w/101+60C
"	73.0	503.4	5.4	0.5	DWL, Comm w/101+80C
"	80.0	496.8	5.5	1.0	DWL, Comm w/101+80C & 60C
"	87.0	490.2	4.2	150.0	DWL

AD-A127 937 PATOKA LAKE FOUNDATION REPORT BOOK 5 APPENDIX E SPECIAL GROUTING ANALYSIS REPORT(U) ARMY ENGINEER DISTRICT LOUISVILLE KY S BARTLETT ET AL. APR 83

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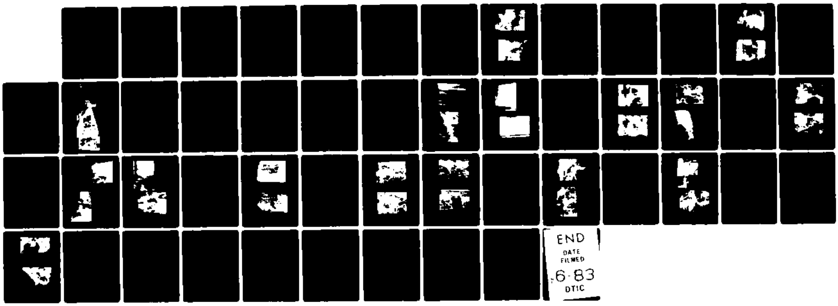
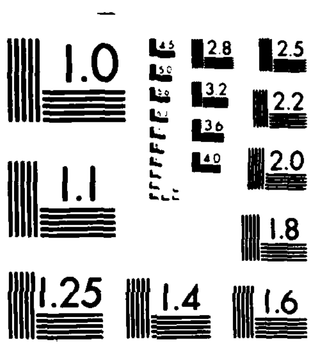




MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963 A

Table IV - 2 (Cont'd)

Hole No.	Stage Depth	Stage Elevation	Water Test Cu Ft/Min	Grout Take Cu Ft	Remarks
101+80AP	93.0	484.6	2.3	139.0	Bottom Zone 2
101+90A	31.0	541.8	2.6	1.5	Bottom Zone 1
"	40.0	533.3	5.4	28.0	DWL
"	65.0	509.8	4.5	32.0	DWL
"	90.0	486.3	3.8	100.0	Bottom Zone 2
102+00AP	32.0	538.4	7.4	14.1	Bottom Zone 1
"	33.0	537.5	3.5	2.0	DWL
"	46.0	525.3	4.4	4.5	DWL
"	50.0	521.5	3.7	70.0	DWL
"	54.0	517.8	3.1	30.0	DWL
"	50.0	521.5	5.1	--	DWL, Hole cave before grouting
"	90.0	483.9	3.3	47.0	Bottom Zone 2
102+05AT	50.0	520.9	2.7	2.0	Bottom Zone 1
102+10AS	25.0	543.8	3.0	5.0	DWL
"	35.0	534.4	3.3	5.0	Bottom Zone 1
"	45.0	525.0	6.5	69.0	DWL
"	90.0	482.7	5.0	46.0	Bottom Zone 2, circ. grt.
102+12.5AQ	37.5	531.1	1.3	0.5	Bottom Zone 1
102+15AT	37.0	531.2	4.2	24.0	Bottom Zone 1
102+17.5AQ	37.5	530.4	1.9	3.0	Bottom Zone 1
102+20AP	34.0	533.2	6.6	2.5	Bottom Zone 1
"	51.0	517.3	4.2	5.5	DWL
"	65.0	504.1	3.0	100.0	DWL
"	65.0	504.1	4.7	1798.0	DWL
"	77.0	492.8	5.1	1041.0	DWL
"	86.0	484.4	2.0	9.0	Bottom Zone 2, Comm. w/102+20C
102+30AS	36.0	530.2	3.0	1.5	Bottom Zone 1
"	75.0	493.5	--	--	Lost tool, aband. hole
102+30ARS	57.0	510.4	3.8	150.5	Sand
"	58.0	109.5	1.1	81.0	Redrill, circuit grout
102+40AP	38.0	526.0	4.6	87.2	Bottom Zone 1, DWL
"	83.0	483.7	3.9	1.0	Bottom Zone 2
"	76.0	490.3	1.0	--	Lost tools, grouted by Comm w/102+40CR
102+40ARP	83.0	483.7	2.0	1.5	Bottom Zone 2
102+50S	45.0	517.8	4.4	1.0	Bottom Zone 1, DWL
"	80.0	484.9	--	--	Bottom Zone 2, lost tools, comm w/102+50C, circuit grout
"	60.0	503.7	1.7	149.5	Redrill
102+50ARS	60.0	503.7	2.0	10.0	Hole complete
102+60AP	33.0	528.0	--	19.0	DWL
"	41.0	520.5	0.0	1.0	Bottom Zone 1
"	81.0	482.9	1.1	28.5	Bottom Zone 2

Table IV - 2 (Cont'd)

Hole No.	Stage Depth	Stage Elevation	Water Test Cu Ft/Min	Grout Take Cu Ft	Remarks
102+61.3AQn	46.0	515.4	5.2	6.0	Bottom Zone 1, Comm w/ 2 holes & surface
102+62.5AQ	47.0	514.4	0.1	2.0	Bottom Zone 1, Comm w/ 102+72.5A
"	57.0	505.0	0.5	26.0	Zone 1 complete
102+63.8AQn	42.0	519.1	5.1	5.0	Bottom Zone 1, Comm w/ 102+61.3A & surface
102+65AT	48.0	513.5	2.0	88.5	Comm. w/6 holes
"	56.0	506.0	2.4 - 6.8	940.0	Tool drop, bottom zone 1
102+66.3AQn	52.0	509.5	5.0	21.0	Bottom Zone 1, Comm w/ 102+68.3A
102+67.5AQ	52.0	509.3	4.1	28.0	Bottom Zone 1, Comm w/ 5 holes
102+68.8AQn	56.0	505.5	4.9	1.0	Bottom Zone 1, Comm w/ 3 holes
102+70AS	54.0	507.4	1.0	335.0	Bottom Zone 1, Comm w/ 2 holes
"	76.0	486.7	4.6	279.0	Bottom Zone 2, circ. grt.
"	62.0	499.8	0.4	0.5	Redrill
"	62.0	499.8	0.1	0.0	Redrill
102+71.3AQn	56.0	505.6	5.0	0.0	Bottom Zone 1, surf. leak
102+72.5AQ	46.0	515.2	3.9	0.0	Bottom Zone 1, grouted by Comm w/2 holes
102+73.8AQn	73.0	488.9	0.5	0.0	Bottom Zone 1, Comm w/ 102+71.3A
102+75AT	51.0	509.6	0.3	0.0	Bottom Zone 1, Grouted by Comm w/102+65A
102+80AP	54.0	506.4	--	2.5	DWL, Comm w/4 holes
"	54.0	506.4	0.6	1.0	Redrill
"	78.0	483.8	4.2	142.0	Bottom Zone 2, circuit grout, comm w/2 holes
"	78.0	483.8	2.2	53.0	Redrill
"	78.0	483.8	0.02	0.5	Redrill, hole complete
102+81.3AQn	65.0	495.6	5.2	0.0	Bottom Zone 1, Comm w/ 3 holes
102+82.5AQ	63.0	497.1	3.8	4.0	Bottom Zone 1, grouted by Comm w/5 holes
102+83.8AQn	65.0	495.1	4.8	3.0	Bottom Zone 1, grouted by Comm w/2 holes
102+85AT	61.0	498.9	1.1	24.0	Bottom Zone 1, Comm w/4 holes
102+86.3AQn	66.0	494.0	5.3	3.0	Bottom Zone 1, grouted by Comm w/3 holes
102+87.5AQ	57.5	501.8	4.4	0.0	Bottom Zone 1, grouted by Comm w/3 holes

Table IV - 2 (Cont'd)

Hole No.	Stage Depth	Stage Elevation	Water Test Cu Ft/Min	Grout Take Cu Ft	Remarks
102+88.8AQn	71.0	489.1	6.3	3.0	Bottom Zone 1, grouted by Comm w/3 holes
102+90AS	60.0	499.4	2.5	181.3	Bottom Zone 1 Comm w/4 holes
"	78.0	482.5	6.0	165.5	Bottom Zone 2, circuit grout, comm w/102+70A
"	58.0	501.3	2.9	474.0	Redrill, circuit grout
"	58.0	501.3	0.15	20.0	Redrill, circuit grout
102+91.3AQn	71.0	488.9	6.3	0.0	Bottom Zone 1, Comm w/3 holes, grouted by comm.
102+92.5AQ	71.0	488.6	3.0	2.0	Zone 1, grouted by comm.
102+93.8AQn	78.0	482.1	6.1	0.0	Zone 1, grouted by comm. w/3 holes
102+95AT	73.0	486.4	--	--	Lost tools
102+95ART	80.0	479.8	2.0	82.0	Zone 1, comm w/1 hole
102+96.3AQn	75.0	484.8	6.2	64.0	Zone 1, comm w/6 holes
102+97.5AQ	71.0	488.2	3.5	27.0	Zone 1, comm w/11 holes
102+98.8AQn	75.0	485.3	0.0	--	Zone 1, not grouted
103+00AP	57.0	503.2	--	--	Lost seal
"	72.0	489.1	0.8	2.0	Bottom Zone 1
103+10AS	61.0	499.1	--	3.5	Lost seal
"	71.0	489.7	2.2	3.5	Bottom Zone 1, grout thru Comm w/102+70C
103+20AP	81.0	476.7	0.14	1.0	Bottom Zone 1
103+40AP	80.0	476.0	0.12	--	Bottom Zone 1, not grouted
103+60AP	72.0	481.4	0.0	--	Bottom Zone 1, not grouted
103+80AP	72.0	479.9	0.0	3.0	Bottom Zone 1, casing leaked
104+00AP	81.0	469.7	0.72	3.4	Bottom Zone 1
104+20AP	72.0	476.0	0.06	--	Bottom Zone 1, not grouted

joints leading away from the grout curtain, primarily in a skewed downstream direction.

4-31. The following problems were encountered at the sandstone-limestone contact: loose sand and mud at the contact which could not be treated by circuit grouting, caving grout holes, inconsistent top of limestone, and large grout takes in final split spaced holes. The highly irregular erosional disconformity between the limestone and sandstone was believed to be responsible for these problems.

4-32. The following problems were encountered within the limestone portion of the grout curtain: frequent communications between holes, holes that could not be cleaned by washing, and caving holes making grouting results in the lower limestone highly questionable. These problems, again, were thought to be the result of extensive erosion between Mississippian and Pennsylvanian depositional sequences. The limestone was highly solutioned during this sequence and the resulting cavities were filled with clay and sand. Washing could not remove the clay entirely, leaving clay and grout intermixed. This residual clay and sand was also saturated and subject to collapsing in small diameter battered holes. During the grouting program in the left abutment ares, the dike right abutment excavation was in progress and the highly solutioned state of the limestone became evident.

4-33. As a result of the problems encountered during grouting on the left abutment of the dike, certain conclusions were reached. First, the grout curtain could not be completed in the allotted contract time. Secondly, the sandstone-limestone contact could not be grouted satisfactorily. Finally, the integrity of the completed curtain could not be assured.

4-34. Table IV-3 contains a summary of grouting for the dike portion of the grout curtain. All three lines have been included although the B line was not grouted in the second zone and the C line was not split spaced in the second zone. Caution should be used when analyzing this table since the second zone was not grouted to completion. Consequently, the grouting ratios are not truly representative of actual conditions.

Table IV-3

Summary of Grouting

	Drilling (l.f.)	Take (cu. ft.)	Take (l.f.)
Total	7,065	69,638	9.8
1st zone	4,320	10.885	2.5
2nd zone	2,745	58,750	21.4
Primary	3,115	50,690	16.3
Secondary	1,785	6,790	3.8
Tertiary	765	6,260	8.2
Quaternary	845	505	0.6
Quinternary	555	182	0.3
SS-LS contact	-	41,750	-

PART V - EXCAVATION

5-01. Upon completion of the modified grouting program on the left abutment of the dike, serious questions remained unanswered concerning the stability of the foundation in this area. Further studies in the form of four each 6-inch core holes were initiated. These holes were drilled between November 1976 and March 1977.

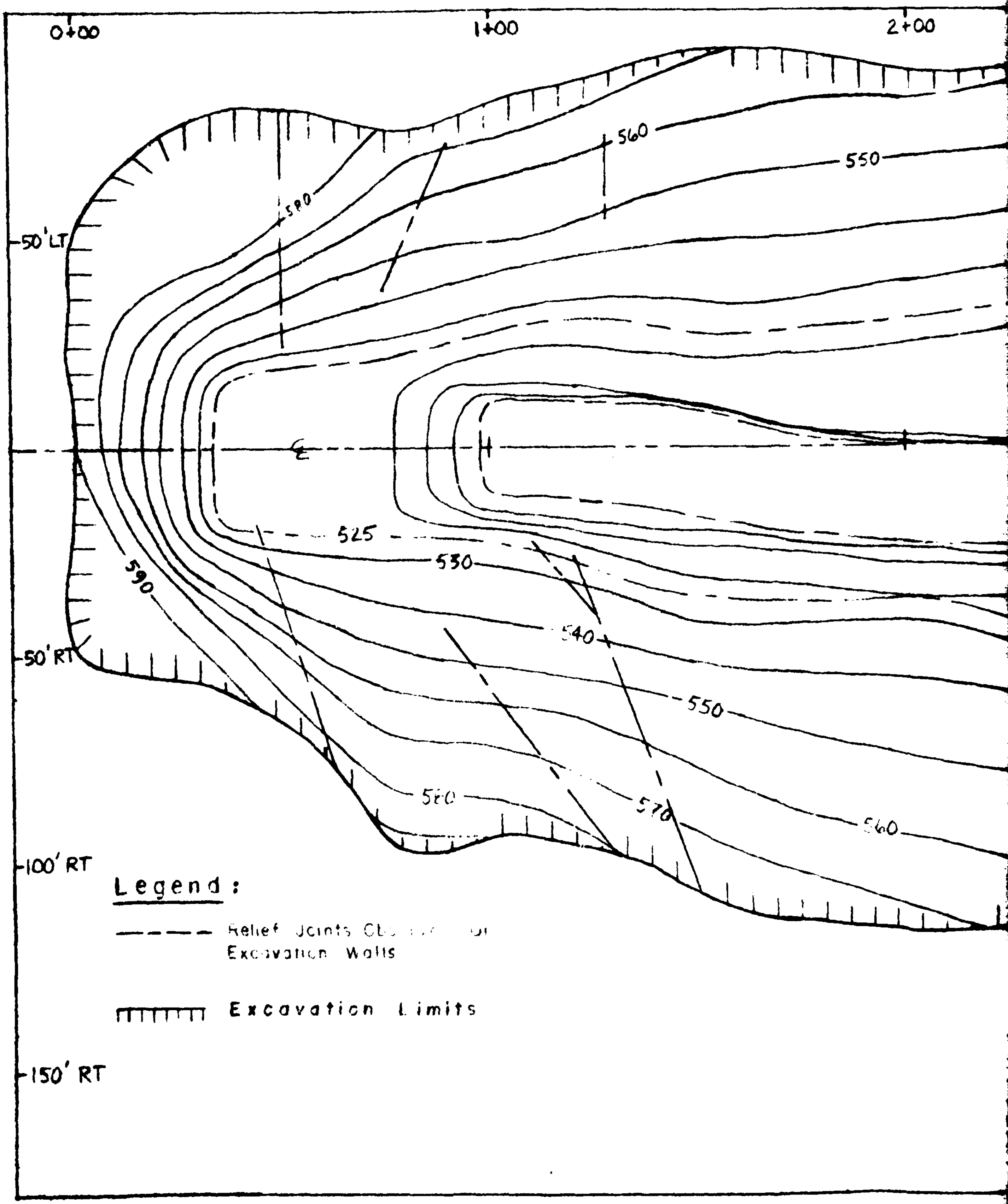
5-02. The locations for these core holes were selected from data obtained during grouting of the upstream line. Drilling problems were experienced when the first core hole at Sta. 102+72.5 was started. The top of rock could not be determined accurately. Coring was started at the hardest material close to where the top of rock was plotted on the grout profiles. The first three 5-foot runs recovered clay, grout, limestone, and sandstone fragments which indicated that the core barrel was following down the sides of a solutioned joint. On the fourth run, the core barrel was lost in the hole and the hole had to be replaced. The remaining three core holes were completed with fewer difficulties and good samples were obtained. Some core losses were experienced, especially at the sandstone-limestone contact.

5-03. Upon completion of the drilling in these four holes, each hole was examined with a bore hole camera from the Waterways Experiment Station. The bore hole camera showed relatively competent sandstone with very small cavities, thin, open bedding planes and small open fractures. The bore hole camera indicated small cavities in all holes at the sandstone-limestone contact with varying amounts of clay filling. Only one hole indicated solutioning within the limestone. The rock bitted replacement hole at Sta. 102+72 encountered only one foot of limestone above the lower shale contact. After photographing each hole, the holes were caliphered. Caliphering indicated the same results determined by coring and photographing, but gave a better indication of cavity sizes at the sandstone-limestone contact.

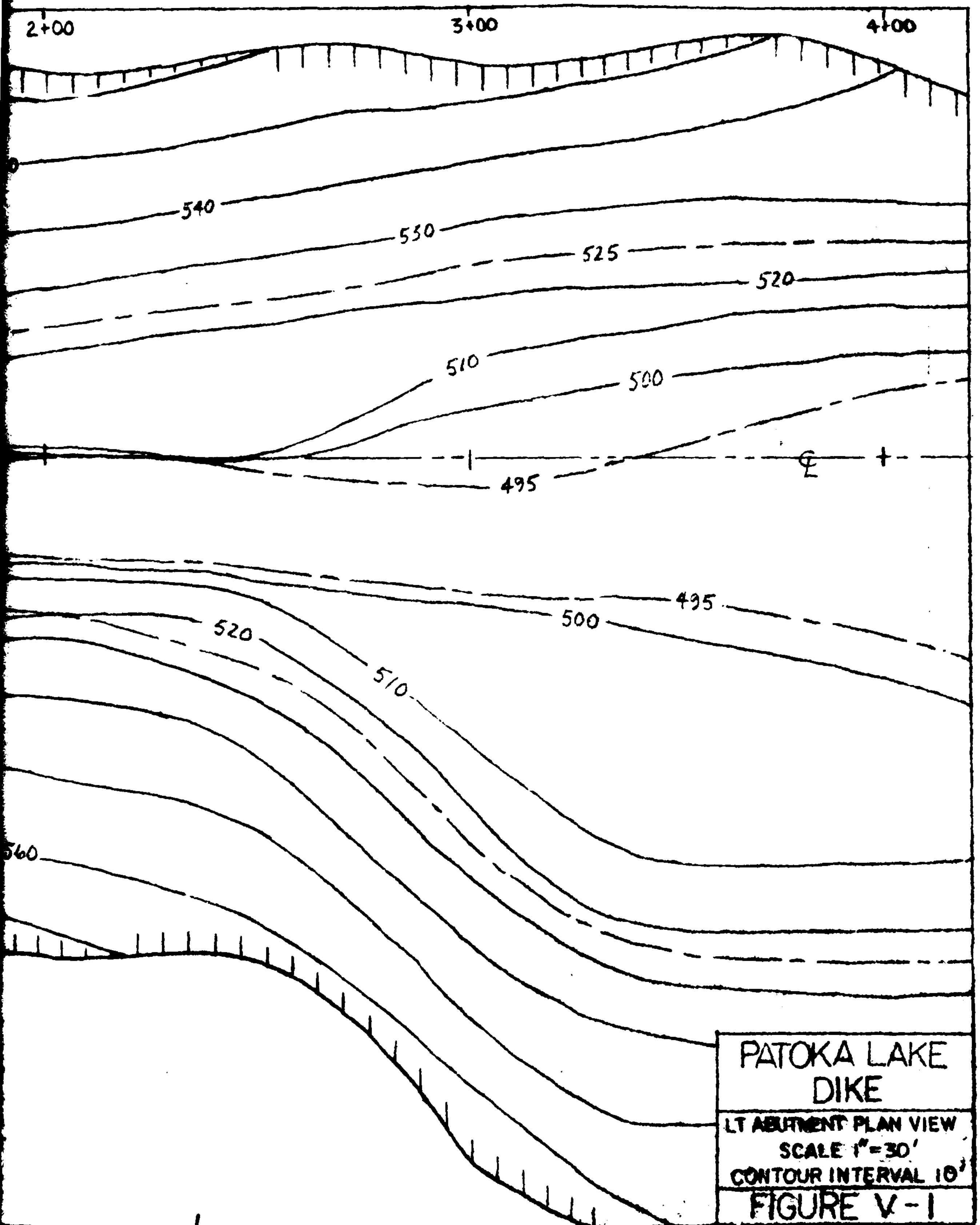
5-04. Between the cores, bore hole camera and caliphers, a good indication of in-situ conditions were obtained. The cores supplied the greatest source of information, but the small core loss zones could not be fully analyzed. The bore hole camera allowed direct observations of these core loss zones, but encountered different problems. The camera could not focus beyond a few inches and consequently, the size of the cavities could be neither measured nor sufficiently observed. In addition, the camera used was a black and white model. The sandstone presented many subtle color variations related to structure and weathering. These variations could not be properly analyzed due

Ripping neat and sanded grout.
8 ft $\pm$ above SS - LS contact

Large block of sanded grout at SS - LS contact. Sta. 0+40, DS and back wall



0+00
1+00
2+00
50' LT
50' RT
100' RT
150' RT
580
560
550
525
530
540
550
560
570
560
590
Legend:
Relief Joints
Excavation Walls
Excavation Limits



2+00
3+00
4+00
540
530
525
520
510
500
495
℄
495
500
520
510
560
PATOKA LAKE
DIKE
LT ABUTMENT PLAN VIEW
SCALE 1"=30'
CONTOUR INTERVAL 10'
FIGURE V-1

to the lack of color differentiation. Also, with the black and white camera, different rock types were difficult to distinguish due to the lack of color differentiation. In addition, the bore hole camera required absolutely clear water. The replacement hole was drilled with a rock bit and a considerable amount of suspended cuttings were left in the hole. Consequently, less than satisfactory results were obtained with the bore hole camera. The calipher, on the other hand, proved to be the best tool to determine the location and size of the various small cavities.

5-05. Upon completion of the core holes, a meeting between OCE, ORD and ORL personnel was held to review the foundation conditions on the left abutment. At this meeting, the decision was reached to remove all unsuitable limestone to protect the dike structure and to provide a positive cutoff beneath the dike embankment.

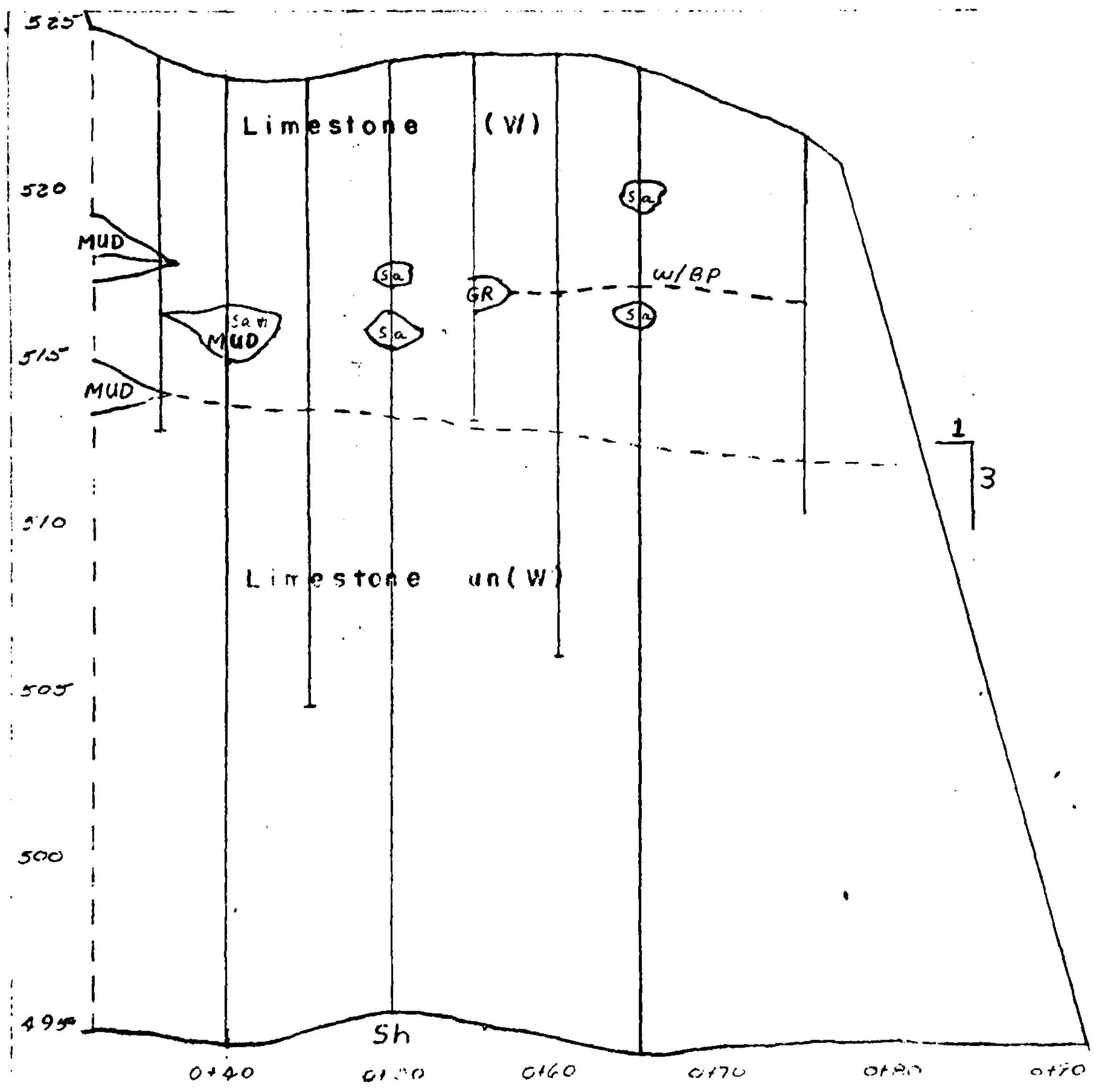
5-06. The general details of the excavation were outlined at this meeting. Station 0+40 was picked as the toe of the excavation back slope at the sandstone-limestone contact. Side slopes of 1:1 in sandstone and 1.5:1 in overburden were chosen. A back slope of 0.5:1 was decided upon in sandstone. An exavation width of 24 feet was required at the base of the sandstone. Upon completion of the sandstone excavation, the top of the limestone would be examined to determine removal limits. If the limestone required removal, vertical side slopes would be used. Excavation of the limestone could be expected from Sta. 2+30 forward. From Sta. 2+30 back, the limestone was expected to be left in place. In this area, low or solutioned portions of the limestone would be cleaned and backfilled with lean concrete to grade. In addition, percussion holes on 10-foot centers would be drilled to determine the soundness of the limestone between Sta. 0+40 and 2+30.

5-07. Excavation was started on March 30, 1977. The sandstone portion of the excavation was divided into two lifts. Pre-split holes for the first 40-foot lift were drilled on 2-foot centers and alternate holes only were loaded. Tovex T-1 (1/4-pound per foot) explosive with detonating cord and without delays was used to presplit. Production blasting was not necessary in the sandstone portion of the excavation.

5-08. Upon completion of prespliting, excavation of the first 40-foot lift of sandstone was started. The thin overburden cover at higher elevations was removed and stockpiled on the upstream side of the dike for future use in the embankment. The sandstone was excavated with D-9 and D-8 dozers using single bladed ripper attachments. Caterpillar Model 631 scrapers were utilized to transport the excavated rock to stockpiles upstream of the dike for future use. No problems were encountered with this

Offset in LS, Elev. 500, caused by blasting.

Overall view of LS left in place, Sta. 0+35 to 0+75.
Note two large grout filled Jts. Fill at Elev. 522±.



PATOKA LAKE
DIKE LEFT ABUTMENT
℄ PROFILE of LIMESTONE
LEFT IN PLACE
Scale: Vert.1" = 5', HORZ. 1" = 10'

FIGURE V - 2

method of excavation and side slope pre-split lines were not disturbed. Transition between 1:1 and 1.5:1 side slopes was made between Sta. 1+0 and 1+50. The contact between sandstone and overburden was very indistinct; consequently, slope changes were arbitrarily chosen.

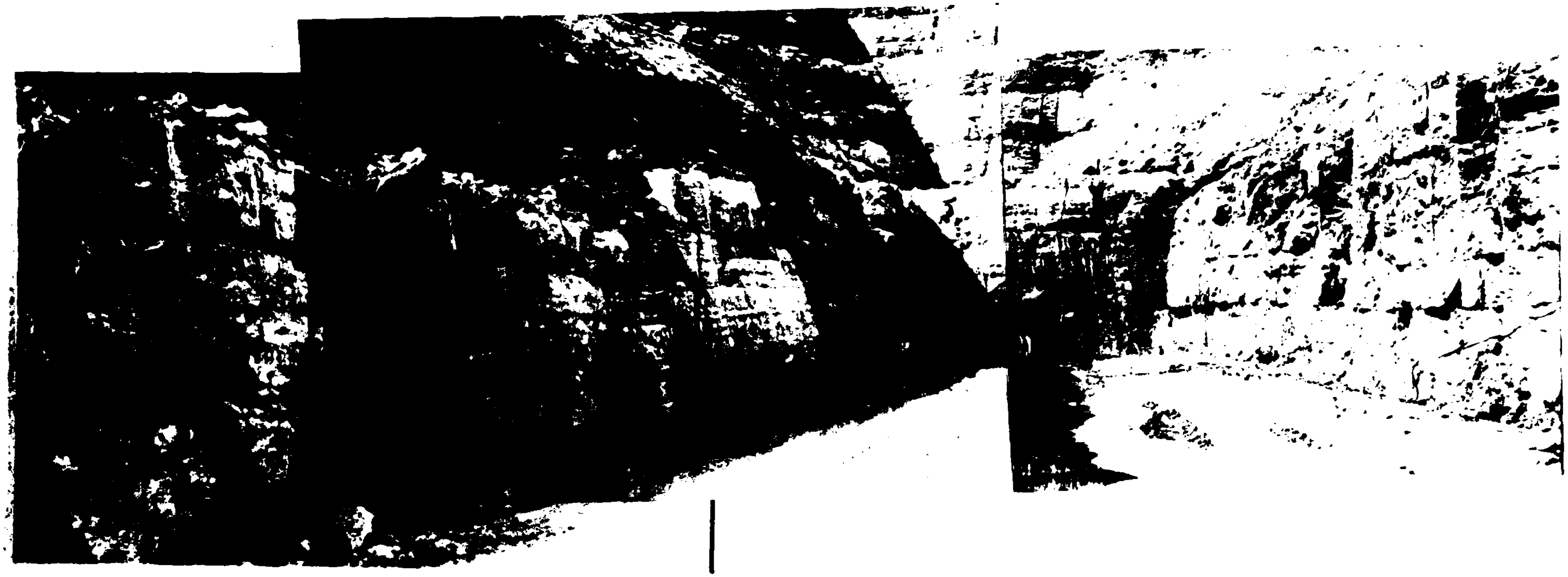
5-09. After excavating the first 40-foot lift, the pre-split line was offset four feet and the remaining sandstone was presplit to the limestone contact on 2-foot centers. Again, only the alternate holes were loaded and shot. After presplitting, the remaining sandstone was excavated in the manner described above. No problems were encountered in the second sandstone lift. Difficulties in removing the large blocks of grout at the limestone contact occurred, but did not impede progress.

5-10. Simultaneously with sandstone excavation (Sta. 0+0 to 2+50), deep overburden excavation was performed (Sta. 2+50 to 4+0). This material was also ripped and removed with scrapers. The deep clay overburden material was also stockpiled upstream of the dike for further embankment utilization.

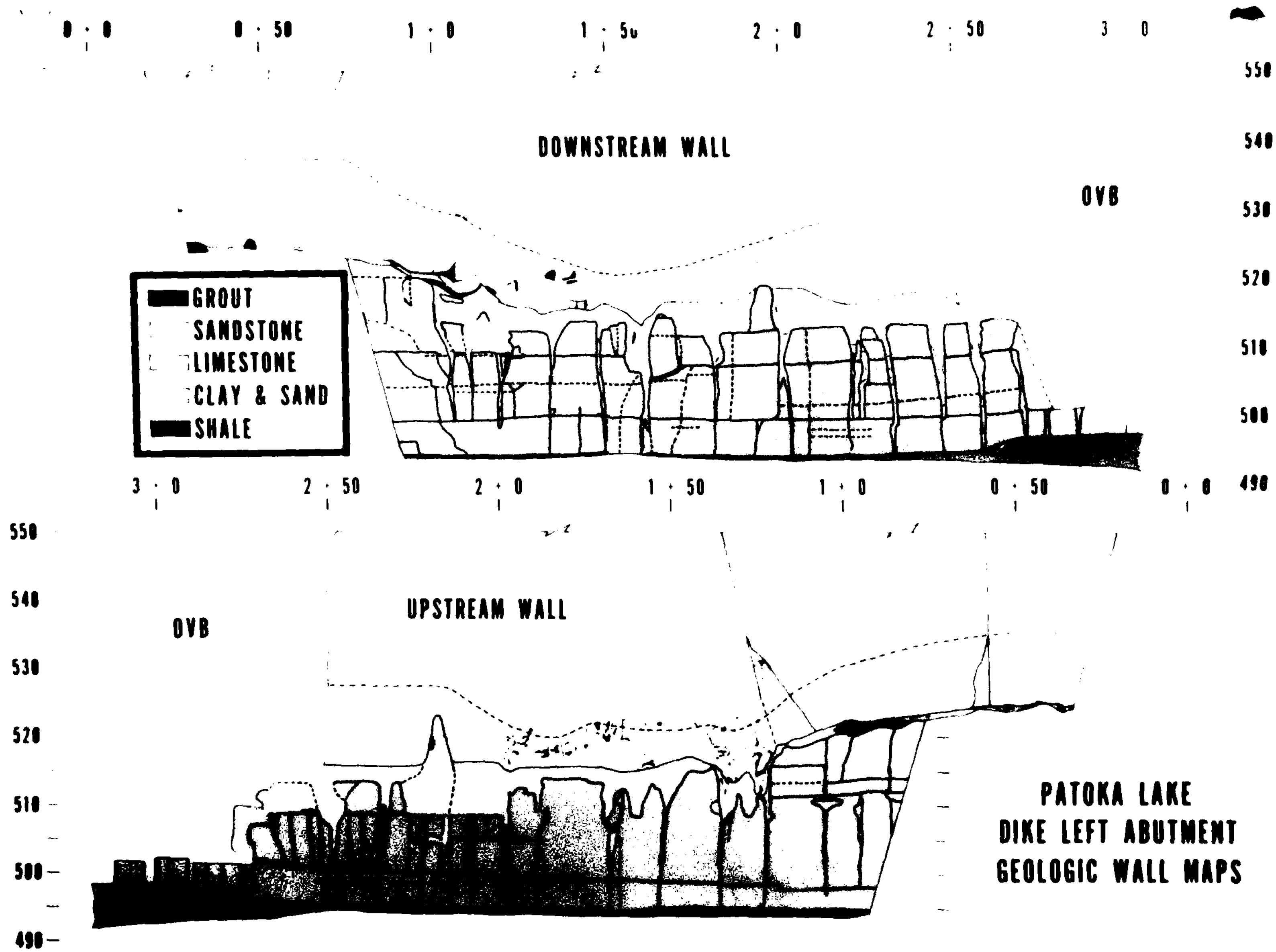
5-11. Upon completion of sandstone excavation, the limestone was examined to determine removal limits. A series of percussion holes on 5 to 10 foot centers were drilled along the centerline. From the results of this drilling and further studies, the decision was reached to remove the entire limestone back to Sta. 0+76. At the same time the centerline was moved slightly upstream to preserve the current downstream slopes above which spoil had been wasted. Figure V-2 shows the condition of the limestone left in place between Sta. 0+32 and 0+92.

5-12. The limestone from Sta. 0+76 ahead was removed in either one or two lifts depending upon the limestone configuration. Where the limestone was relatively competent, one lift was used. The entire limestone was pre-split at one time. Side slopes in limestone were vertical. The back slope in limestone was drilled on a 1 horizontal to 3 vertical slope, Sta. 0+76 to 0+92. Pre-split holes were drilled on 2-foot centers. Again, alternate holes were loaded with "Tovex" T-1 (1/4-pound per foot) and detonated with primacord. No delays were used.

5-13. Production blasting varied, but was usually accomplished in a V pattern with delays between rows. Vertical 3-inch blast holes were drilled in a 4 x 4 pattern. "Tovex" waterproof gel in 2 x 16 inch cartridges was used as the blasting agent. Soft seams were not stemmed. Detonating cord with MS-5 connectors was used to activate the explosives. The powder factor varied from 1.02 to 1.14 pounds per cu. yd. The shot rock was removed



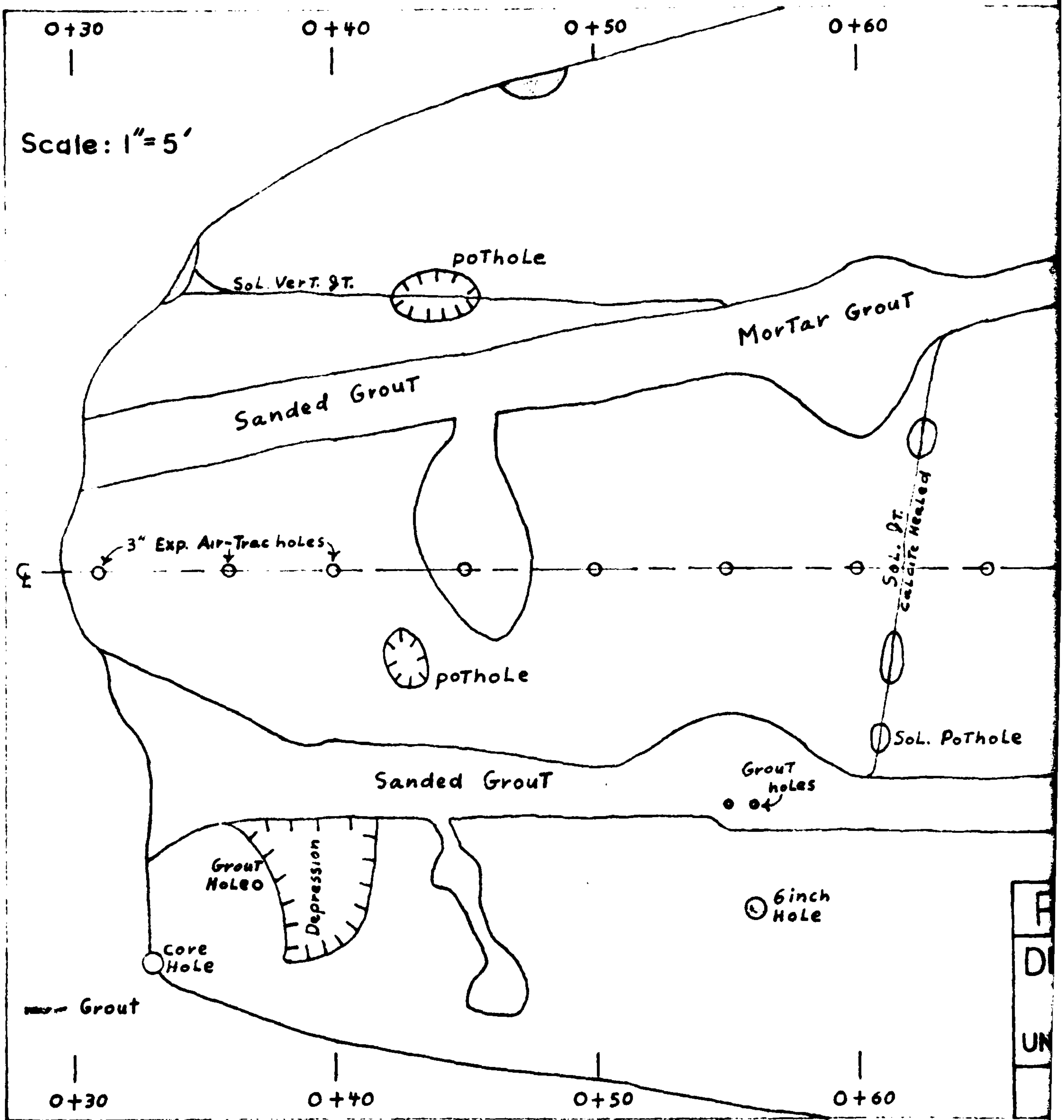
Overall view of completed excavation, upstream wall is at left of photograph.
Note shale surface at bottom of excavation.



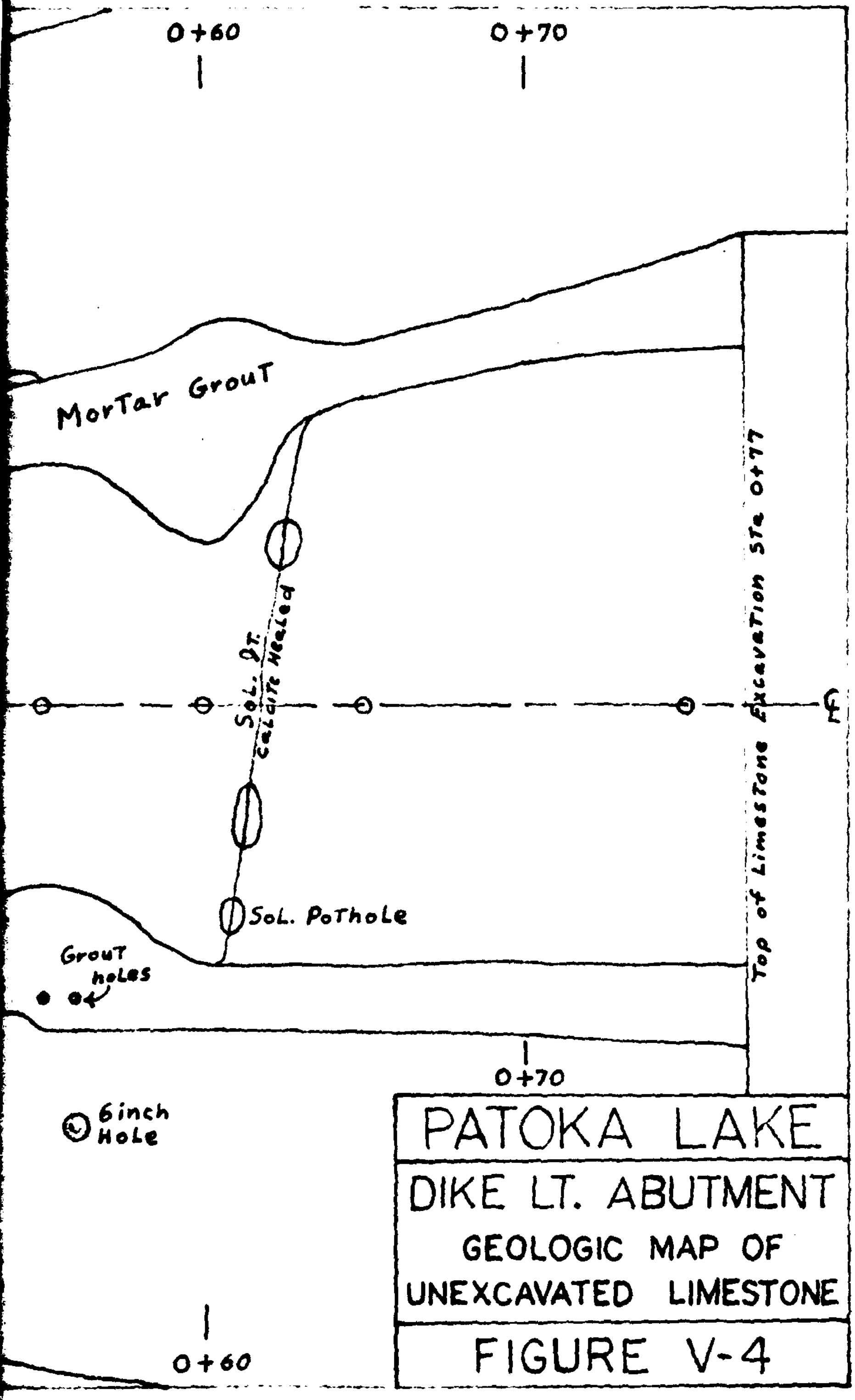
PATOKA LAKE
DIKE LEFT ABUTMENT
GEOLOGIC WALL MAPS

by dozers, high lifts, and dump trucks. The limestone was further broken and used as riprap on the upstream slope of the dam.

5-14. Upon completion of limestone excavation, the lower shale was cleaned. All solutioned seams in the limestone side walls downstream were cleaned to a depth of two times their width and filled with lean concrete. The solutioned areas in limestone upstream were left and filled with crushed stone filter material as the impervious fill was placed. The end wall did not require extensive treatment other than filling the solutioned joints and small overhangs with lean concrete. The impervious core was protected from piping by a 6-foot wide double zoned reverse filter against the downstream face of the limestone excavation. The filter consisted of Ind. #7 stone on the outside and Ind. #14-1 sand on the inside against the impervious core.



0+30
0+40
0+50
0+60
Scale: 1"=5'
poThoLe
SoL. VerT. JT.
MorTar GrouT
Sanded GrouT
3" Exp. Air-Trac holes
SoL. JT. Calcite Healed
poThoLe
SoL. PoThoLe
Sanded GrouT
GrouT holes
GrouT HoLes
Depression
6inch HoLe
Core HoLe
Grout
0+30
0+40
0+50
0+60



PATOKA LAKE

DIKE LT. ABUTMENT

GEOLOGIC MAP OF UNEXCAVATED LIMESTONE

FIGURE V-4

2

PART VI - GROUT DISTRIBUTION

6-01. During excavation grout distribution was carefully observed, mapped and photographed. The discussion of grout distribution has been arranged by rock types in *descending* order.

A. Overburden

6-02. Generally, very little grout was found in the overburden. Near the surface, a large chunk of grout was found close to Sta. 2+40 where a large breakout occurred during grouting. The thin overburden portion of the curtain between 0+0 and 2+30 displayed no grout. In spite of the many grout outbreaks near the casings experienced during grouting, very little grout was observed in the thick overburden area between 2+30 and 3+0 during excavation. One major and two minor grout stringers were found on the side slopes of the excavation within the deepest portion of the overburden. One of the two minor grout stringers was found on the downstream slope and the other minor seam was found on the upstream slope.

6-03. The major grout seam on the downstream slope ranged from 0.6 to 0.05 foot in thickness, with the grout thinning at higher elevations until the seam stopped altogether. The seam stopped well below the top of ground. The lower portion of the grout seam was not observed due to overlying rubble, but probably started at or near the limestone overburden contact near Sta. 2+70. Grout consisted of both sanded and neat grout with sanded grout forming the lower, thicker portion of the seam. Apparently, grouting pressure relief with decreasing depth caused the seam to thin and finally stop at Elev. 544. The difference between sanded and neat grout was more difficult to explain. Apparently this seam was the result of two different grouting operations, sanded grout first and neat grout second.

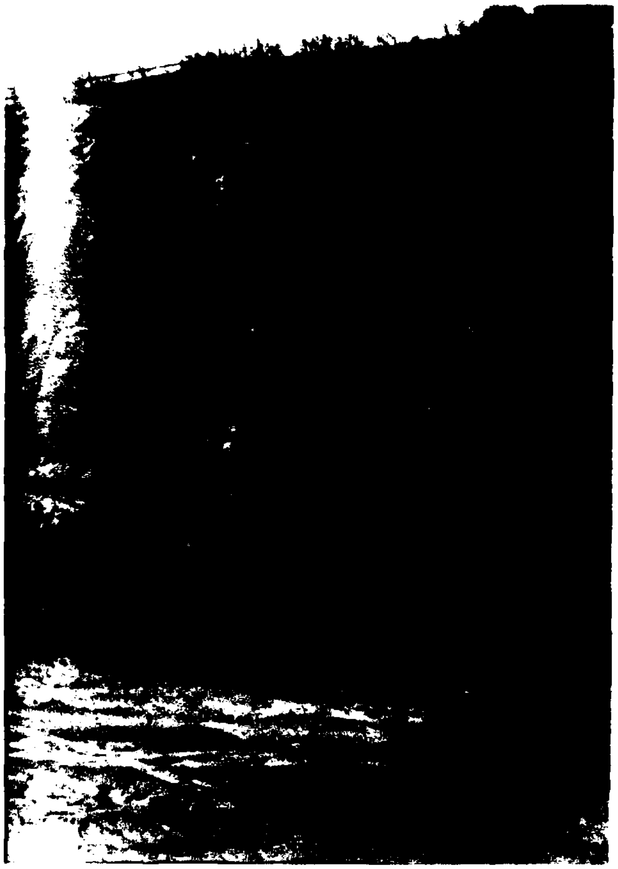
6-04. The first of the two minor grout seams was observed on the downstream wall near the limestone-overburden contact. This seam was close to the major seam discussed in the preceding paragraph. These two seams were probably related and could have been part of the same seam.

6-05. The second minor seam was found on the upstream slope near Sta. 2+70 between Elevs. 533 and 535. This seam was approximately 4 feet long, 0.1 to 0.4 foot thick, and was composed of neat grout. However, the base of this seam was not observed. The seam was within 10 feet of the sandstone-overburden contact, but was not connected within view. No other grout seams were observed in the lower portion of the overburden.

Trace of long grout
seam in OB on DS wall

Clay filled sol. jt.
in lower LS. Elev.
498. No grout

Plate 6 - I



Large relief Jt. on US wall. Note small cave. Embankment Elev. 546.5±.

Grout swarm Elev. 535-545±. Grout traces mostly along B/ps. Note IIA clay filled relief Jt. near center of photo.

B. Sandstone

6-06. Generally, little grout was found in the sandstone above the grout curtain (Elev. 564). Occasionally a few very thin grout laminae were found along bedding planes just above the top of the curtain. This general lack of grout is surprising in view of the method used to seal this zone; i.e., pouring thick grout down the holes to the top of the curtain, then drilling back through the set grout.

6-07. The first significant amount of grout discovered during excavation occurred in the large vertical, infilled relief joint striking N8 W across the excavation. This 0.95-foot average width relief joint intersected the upstream wall at 0+62 near the top of the excavation and intersected the downstream wall at Sta. 0+50 near the top of the excavation. Small blocks of grout were found at intervals along the exposed length of this relief joint near Elev. 570. Additional stringers of grout were found within the relief joint down to Elev. 560. Both walls also displayed small blocks of grout in this relief joint. Generally, this joint was completely filled with clay and sandstone rubble, and displayed few voids. The small blocks and stringers of grout mentioned above did not indicate large grout takes within this relief joint. To a lesser degree, this situation occurred in other high angle relief joints between Sta. 1+0 and 2+0. All these high-angled relief joints narrowed with depth to less than 0.1 foot and stopped at or above the sandstone-limestone contact. (See Figure V-1.) These minor high angle relief joints were filled entirely with clay, rubble and small blocks of grout. Whenever observed in fresh cuts, all of these joints appeared to be tight with all voids being grout filled below Elev. 564.

6-08. The sandstone below the top of the grout curtain displayed proportionately more grout than found above the curtain (Elev. 564). Large numbers of very thin grout traces were frequently found along bedding planes. Occasionally larger grout seams along bedding planes were found in isolated areas. Between Stas. 1+05 and 1+20, at Elev. 560, a large concentration of grout was found near the centerline. In addition to medium sized blocks, this concentration consisted of a larger number of grout stringers found along bedding planes. These stringers varied up to 0.5 foot thick. Some bedding planes were also coated with clay ranging from 0.005 to 0.01 foot thick. This grout concentration zone did not continue deeper and apparently resulted from the grouting of a small highly fractured zone within the sandstone. Occasional similar localized grout areas were found in other portions of the sandstone.

Multiple grout holes on back wall. Pre-split hole thru center. Note very thin grout traces along B/ps.

Multiple grout holes. Large grout mass displays evidence of five separate holes. Note thin grout traces along B/ps

Drill rods wedged and lost in LS during grouting operations.

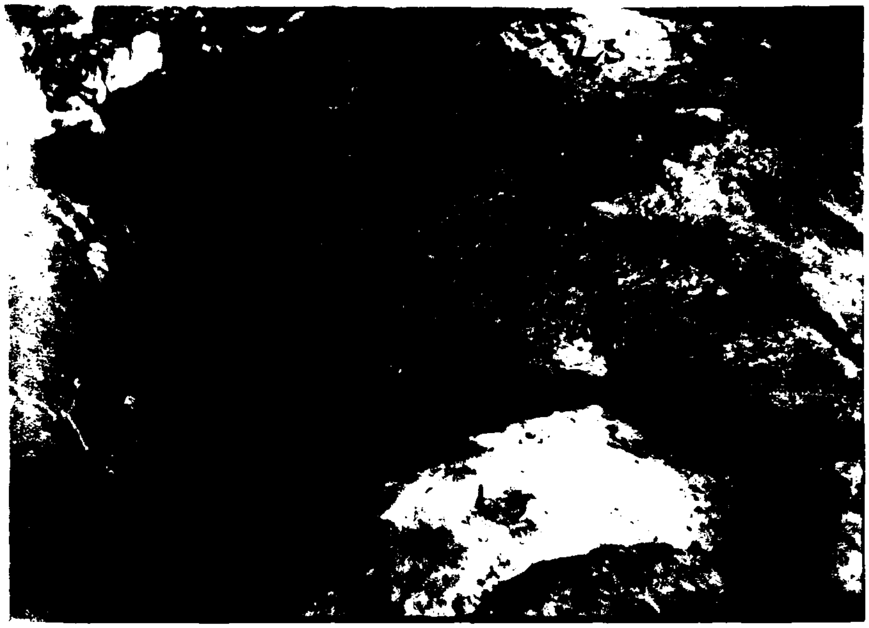
Four drill rods lost in clay filled cavity within LS. Rods are oriented at reversed angle to original drilling.

6-09. In the sandstone and to a lesser degree in the limestone below, numerous multiple grout holes (see Plate 6-III) were found at the same location. At one location within the sandstone, as many as eight separate grout-filled holes were found within a 1-foot radius. At another location, 15 separate grout-filled holes were found in the sandstone at the same location. Similar composite grout holes were found at numerous other locations. At one location in the limestone, four separate grout holes were found within a 2-foot radius. All except one of these last four holes were filled with grout. This phenomenon will be discussed further in the review and discussion section of this report.

6-10. Generally, the sandstone below the top of the curtain, excluding the zone at the sandstone-limestone contact, displayed much less grout than accounted for during grouting. Several large takers were noted in the sandstone during grouting, but the corresponding grout was not found during excavation. Apparently the grout traveled away from this zone. The small amounts of grout found in the vertical fractures and along bedding planes can account for only a very small portion of the grout placed in the sandstone portion of the curtain. In addition, the sandstone on the left abutment was found to be much more competent than indicated during grouting.

C. Sandstone-Limestone Contact

6-11. The zone at the sandstone-limestone contact accounted for the largest percentage (over 90%) of the grout uncovered during excavation. This zone also included the highly fractured sandstone up to 10 feet above the contact. Very large amounts of grout were noted at the very top of the limestone. Large blocks up to 2 feet thick and over 6 feet wide were removed from this contact. The grout was not uniformly distributed on the contact, but was found in large irregularities and in small depressions on the limestone surface. The immediate contact between the sandstone and limestone was highly irregular due to solutioning and erosional sequences. Consequently, grout distribution was generally confined to the small open cavities at this contact. The large blocks of grout observed were not bonded to the limestone, but were nonetheless difficult to remove with D-8 dozers. Thin clay seams were discovered between the grout blocks and the limestone making removal mandatory. Some of the grout blocks in the deeper cavities at the contact between Sta. 0+30 and 0+75 could not be removed and were consequently left in place (see Figure V-4). The cavities in which the grout was found were not clean and displayed varying amounts of mud, clay, and sandstone rubble. Contacts between the grout



Large sanded grout seam in solutioned Jt. at top of LS. Largest width is approx. 5 ft. Mud coated from cleaning operations. Sta. 0+40, 10 ft. ± US.

Grout filled pothole in top of LS. Grout mostly bonded to LS surfaces. Length is approximately 6 feet. Station 0+45, 10 - 15 feet upstream.

and the surrounding materials appeared to be tight with all voids being filled. In addition, excessive amounts of grout were found outside the limits of the grout curtain.

6-12. The grout found at the limestone contact was not limited to large blocks. Numerous stringers and small blocks were also found at this contact. The sandstone-limestone contact zone ranged from less than 1 foot to more than 10 feet thick, with large amounts of grout occurring throughout the zone.

6-13. Physically, the grout observed was composed of neat and sanded grout. In the large blocks, sanded grout formed the core with neat grout forming the contacts. Most grout found in the large blocks also appeared banded with alternating shades and types of grout. This banding can clearly be seen in detailed photographs of large grout blocks (see plate 5-I). Solid neat grout of varying width usually formed the basal contacts. The next bands in order consisted of sanded grout. These sanded grout bands usually comprised the bulk of the grout found in the large blocks. Additional neat grout in thin alternately colored bands usually formed the top contact between grout and rock. The top contacts were consistently tight and completely filled. The color variations in the top of the grout bands were mainly due to the varying consistency of the grout. The dark gray zones represented hard, solid, uniform, high strength grout. The light gray bands represented grout with varying amounts of entrapped air. Rare instances of soft, spongy, unset grout were noted. Occasionally, some frothy, very weak grout was found at the extreme top of the larger grout seams. Generally, the lighter gray grout was not weaker than the darker grout. Occasionally, inclusions of sandstone and clay were found within the larger grout blocks.

6-14. The banding described in the preceding paragraphs was representative of the grouting method. The bottom bands of neat grout represented up to 150 cu. ft. of neat grout initially pumped into the hole. The sand grout bands represented successive injections of sanded grout. Upon refusal, the grout holes were usually redrilled and the small voids above the sanded grout were sealed with neat grout. Between successive sanded grout injections, small amounts of neat cement were pumped. This sequence was represented by small bands of neat grout sandwiched between larger bands of sanded grout in the larger grout blocks.

6-15. Except for the occasional frothy grout noted in the preceding paragraphs, most of the grout, especially the sanded grout, appeared to be of uniform consistency. No segregation was noted in any of the sanded grout observed. Sand and cement appeared to be thoroughly mixed with no lumps of unmixed materials.

Grout sequence between SS and LS contacts. Note tight upper contact. LS is below photograph.

End view of large grout block found at SS - LS contact. Note banding, sanded and neat grout.

Large grout seams at SS-LS contact. Back wall 0-15 ft. US. Limestone. Elev. 523.

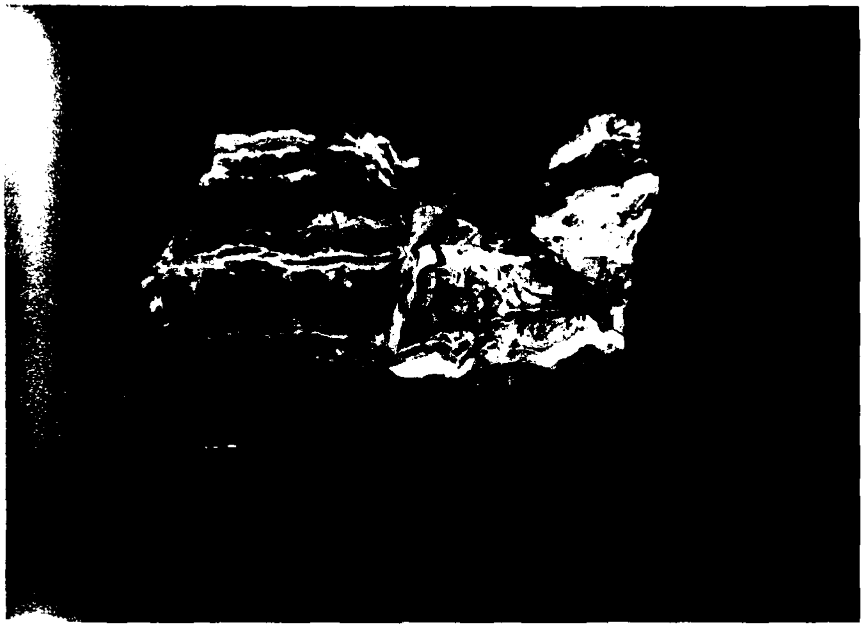
Grout seam is SS near LS contact. Note complete filling of voids. Back wall. Core hole (GCH-4) at left edge of photo.

Neither was segregation nor poor mixing noted in the neat grout. The flyash could not be distinguished from the remainder of the grout and was consequently well mixed. All the grout, with the exception of the frothy grout noted previously, appeared to be hard and durable. Infrequently, very small cavities were found in the grout masses. These small to minute cavities were usually lined with aragonite crystals. As noted previously, the grout appeared to fill all voids in the rock at the sandstone-limestone contact. In these and other locations, the sanded grout filled voids ranging down to 0.1 foot in width.

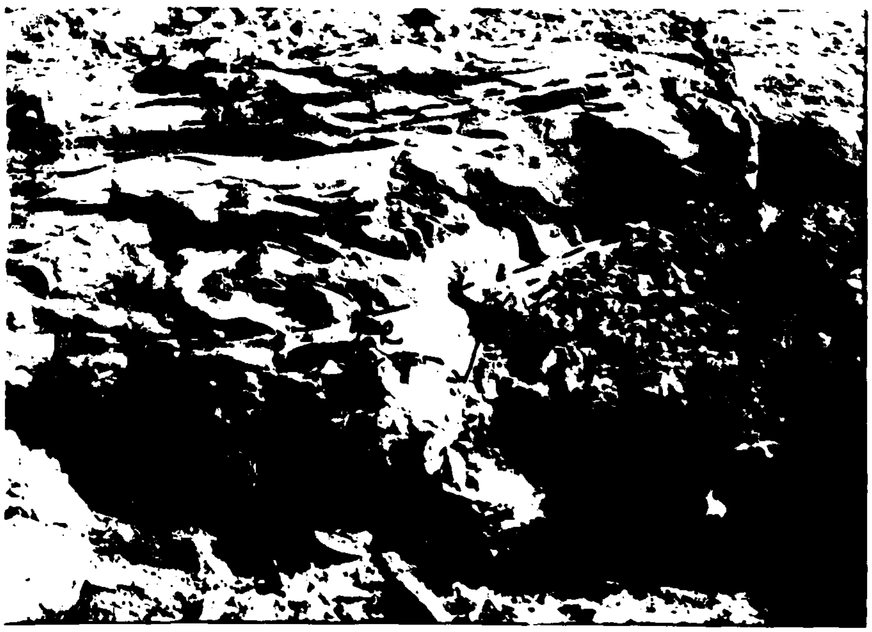
6-16. As noted in the grouting portion of this report, a large (24.5 cu. yd.) amount of ready-mix mortar grout was placed in one 6-inch diameter hole located at Sta. 100+58C. This mortar grout was also found at the sandstone-limestone contact during excavation in the downstream joint of a pair of vertical clay and rubble-filled solutioned joints running at very low angles to the centerline (Figure V-4). Mortar filled approximately the top 3 feet of this joint. The aerial limits of the mortar grout did not extend far from the limits of the solutioned joint. This grout could not be removed and was left in place. No segregation was noted in this grout. The 6-inch hole drilled at Sta. 101+34 was observed in the shale portion of the foundation. The hole at this point was filled with mortar grout. The mortar grout placed in the other vertical 6-inch holes was not found.

6-17. In addition to the large blocks of grout found at the sandstone-limestone contact, many small grout stringers were found at the contact zone. Usually, the small grout stringers extended away from the large grout blocks noted previously. Additionally, thin stringers of grout were found in predominantly clay and sand seams near the sandstone-limestone contact. In some cases, the clay seams were associated with grout-filled voids and in other cases the clay seams completely filled the irregularities at the contact.

6-18. The distribution of grout in these clay seams varied from small veins to extremely thin laminae. The laminae were of particular interest. Formation of these thin laminae apparently started with the grouting of a larger void. As the void became filled with grout, pressure would build up and eventually become greater than the cohesive strength of the weak clay. At this point, the grout was injected in fine rivulets throughout the clay mass. As one rivulet would fill, pressure would build and start another. Sand within the clay seams would further enhance this action by forming zones of widely varying cohesive strengths. The end result was a marbled appearing mass of alternating clay and grout (see Plate 6-VIII). Laminae varied down to 0.5 MM. Within each grout laminae the grout was further



Detail of grout laminae in clay seam. Brown material is dried clay.



Grout details at SS-LS contact. Sta. 1+10, Elev. 515-520. Nearly all voids are grout filled.

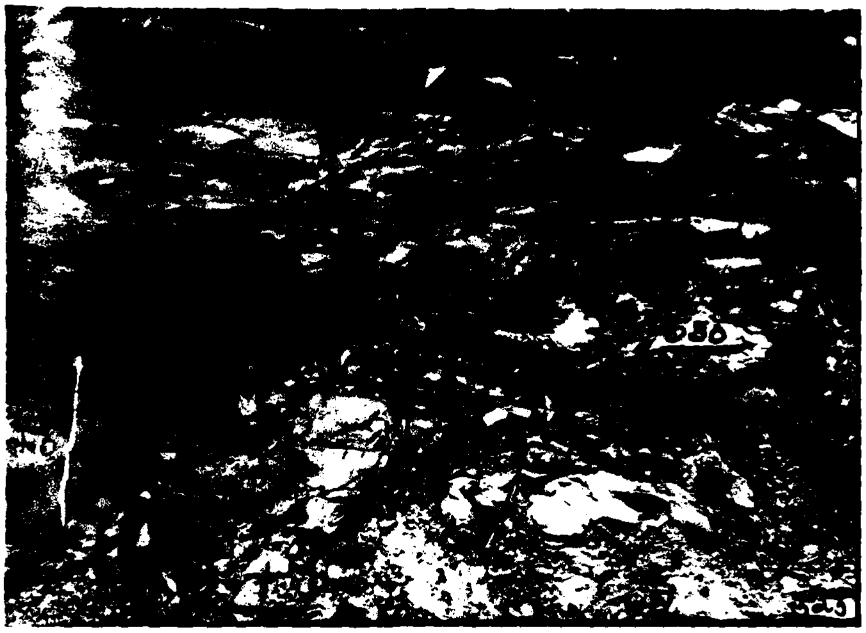
segregated into light and dark bands. As discussed previously, the light gray usually represented air entrained grout while the darker gray represented purer hard grout. The majority of the grout laminae were light gray.

6-19. Occasionally, sanded grout would react in the same manner, forming laminae down to 0.02 foot in width. Due to the extremely low cohesive strengths of the saturated clay and sand cavity fillings and the deep grout injection points, this type of grouting situation could not be avoided. As mentioned previously, all the cavities could not be washed clean. Generally, all cavities at the sandstone-limestone contact were filled. In most cases, clay and sand still comprised the majority of the cavity fillings near this contact.

6-20. The grout distribution within the 10-foot section of sandstone just above the sandstone-limestone contact was very closely related to the grout distribution in the immediate contact area. For this reason, the lower 10 feet of the Mansfield sandstone has been included with the sandstone-limestone contact study area. This 10-foot section of sandstone was very highly fractured, resulting from partial settlement into the underlying eroded and solutioned limestone. Throughout this 10-foot zone, grout seams of varying width extended from the contact up to the individual fracture closures. From close obervations, all fractures within this 10-foot extensively fractured zone connected directly with the large grout blocks at the immediate sandstone-limestone contact. In addition, great quantities of grout were removed during excavation from this 10 foot extensively fractured sandstone zone. Grout varied from neat to sanded grout depending upon the width of the fractures. Fractures down to 1 mm were sealed with grout. Judging from the extensive filling of exposed fractures, this 10-foot zone of highly fractured sandstone represented the area of greatest grouting success. One fractured sandstone area occurring at Sta. 1+05 25 feet downstream, Elev. 530, can be seen in Plate 6-IX. Grout in this photo consisted of neat and sanded grout, approximately 0.5 foot thick and parallel to normal bedding planes.

D. Limestone

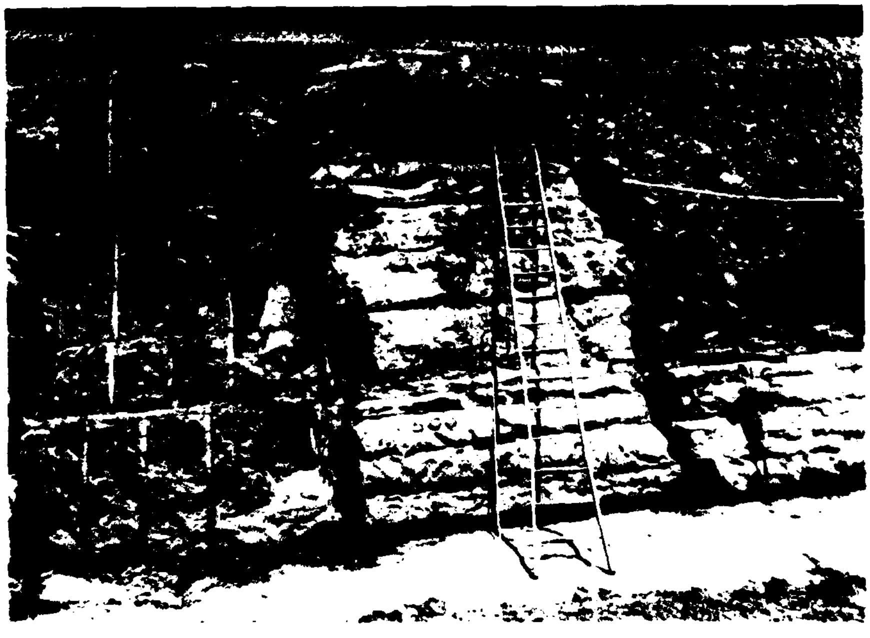
6-21. The limestone below the sandstone-limestone contact displayed less grout than expected from recorded grouting takes. This rock was also more solutioned than previously expected. Two large solutioned joints running at very low angles to the centerline were found that were not indicated during grouting. Numerous extensively solutioned joints at oblique angles to the centerline were also found. These numerous oblique solutioned joints were known to exist, but the degree of solutioning was



Grout details in fractured SS. DS wall.
Note dipping B/ps. Station 1+05±.

Close-up details of grout seams in above
photo. Tin can location is same in both
photos. Also note grout seams along B/ps.

DS wall in LS Sta. 1+50 to 1+80. Note solutioning activity. Also note greenish shale at bottom of photo.



DS wall in LS Sta. 2+45 to 2+80. Vert. face near ladder is contact between OB and LS. Lower portion of solutioned joints have been packed with lean concrete.

greater than expected. The area between Sta. 2+30 and 3+0 was known to be highly solutioned and was scheduled to be removed. However, the limestone between these stations was far more solutioned than expected. One air-trac exploratory hole drilled at Sta. 1+85 indicated solutioning to 10 feet below the top of the limestone. In spite of this unexpected degree of solutioning, this portion of limestone was much sounder than the limestone observed on the right abutment of the dike.

6-22. As a result of this high degree of solutioning, large amounts of clay and mud were observed within the limestone. Consequently, less grout was observed in this rock type than anticipated. Still in most clay, sand and mud seams some grout was observed. Nearly all the voids observed between the top and sides of clay seams and limestone were grout filled. However, occasional open voids were observed between the top of the clay seams and rock. These open voids were probably the result of clay slumping after excavation. As noted previously, the Glen Dean Limestone was entirely below the water table. Consequently the mud and clay seams found within the limestone were saturated. In addition, the clay in these seams was very near its liquid limits with very low cohesive strengths. With these parameters, flowage and slumping of the clay and mud seams following explosure was most likely. In addition, the method of excavation caused much disturbance in these clay and mud filled seams.

6-23. Grout distribution within the clay, sand and mud seams appeared to be of three varieties. As mentioned earlier, small rivulets of grout forced entirely through the clay seams constituted the first variety of grout distribution. The second form consisted of small single grout seams at varying attitudes within the clay seams. These single grout seams varied up to several tenths of a foot in width. The third variety of grout distribution consisted of void filling between the top of the clay seams and the rock as discussed earlier.

6-24. A good example of this third variety of grout distribution was found on the upstream wall within a small clay-filled tube associated with a solutioned joint. This tube was found lower in the limestone and was consequently unaffected by the disturbances occurring at the sandstone-limestone contact. The majority of this small (0.4 ft. diameter) tube was filled with clay. The top 0.1 foot was completely filled with grout forming a tight contact between the clay and the limestone. The open joint associated with this tube continued vertically above and below. The joint was open up to 0.01 foot, but contained no grout. Additionally, most of the open joints occurring in the lower portion of the limestone contained no grout. In addition,

Grouting details in clay filled solutioned joint. LS at right and left sides of photo.

Small solutioned tube along jt. in LS. Clay filled with grout seam at top. Tight contacts. Approx. 0.4 ft. diam. Sta. 0+86, Elev. 516. Vert. jt. is open and slightly solutioned.

blasting induced additional open fractures, giving misleading information on the number of ungrouted joints and fractures in the lower limestone.

6-25. On the downstream wall near Sta. 2+80 the lower portion of the Glen Dean Limestone was naturally benched with the lower bench at Elev. 500 and the upper bench at Elev. 515. A vertical joint running transverse to the centerline at this location separated the two benches. This vertical surface formed the limestone-overburden contact at this point. The contact was irregular, solutioned, and displayed some grout, but was very distinct. Furthermore, this contact was not as badly decomposed as was expected during grout operations. The overburden at the immediate contact in this area was composed entirely of sandstone rubble. This situation made differentiation between rock and overburden very difficult from the surface during grouting.

6-26. During excavation, grout casings were observed in this area between Sta. 2+70 and 3+0. The angle and seating of these casings were of particular interest due to the highly irregular top of rock contact discussed in the previous paragraph. Of the casings observed at this limestone-overburden contact, most were well seated and followed the rock contours. The angles of the casings were difficult to determine, but most casings appeared to be parallel at this contact. These findings generally agreed with the conclusions reached during the grouting phase of construction. This area will be further discussed in the review section of this report.

E. Shale

6-27. The Hardensburg Shale below the limestone displayed no traces of grout. This rock was found to be tight during water testing and grouting. Consequently, no grout take was anticipated in this rock. A frequent number of compaction slickensides were evident in this rock, but they did not contain or require grout. Also, in areas where solutioning along joints extended through the limestone, weathering in the immediate area below the joints was noted in the shale.

6-28. In summary, the majority of grout found during excavation occurred at the sandstone-limestone contact. A lesser amount was found in the sandstone within 10 feet of the limestone contact. Proportionately little grout was found in the remainder of the grout curtain. This distribution corresponded generally to the conclusions formulated during grouting. However, the amount of grout found at the sandstone-limestone contact was considerably less than the amount of grout pumped into this contract.

DS wall Sta. 2+80. Circled area indicates grout casing at LS - OB contact. Disturbed but original attitude is evident.

Weathering and discoloration in lower shale at base of clay-filled solutioned joint. DS wall Sta. 2+60.

PART VII - REVIEW AND DISCUSSION

7-01. As discussed in the previous sections of this report, the bulk of the grout was found at the sandstone-limestone contact. In addition, large quantities of grout were found in the lower 10 feet of the sandstone, particularly between Stas. 0+30 and 1+30. Less grout than expected was found in the sandstone above Elev. 535 and as suspected, very little grout was found in the limestone below the sandstone contact. Also, as expected, little grout was found in the shale below the Glen Dean limestone. The thick colluvial overburden at the limestone contact also displayed very little grout.

A. Sandstone

7-02. Within the sandstone, fracturing had the greatest effect on grout distribution. As noted, large quantities of grout (6,450 cu. ft. in the upstream line alone) were pumped into the sandstone above Elev. 535. Apparently, the grout pumped at these higher elevations migrated vertically through open joints and fractures to the sandstone-limestone contact. This mobility of grout was surprising in view of the thick mixes pumped and the lack of observed continuous fractures.

7-03. The observed physical condition of the sandstone above Elev. 535 was much sounder than anticipated during the grouting program. The sandstone was much harder and better cemented than expected. Numerous very thin open bedding planes were evident, but little grout was observed along these bedding planes. The steep excavation walls held up well with little spalling during one extreme winter season, thus indicating the competency of the sandstone portion of the foundation.

7-04. The numerous high angle infilled fractures in the sandstone between Sta. 0+70 and 1+50 had little apparent effect upon the distribution of grout. Several large joints or fractures running upstream and downstream were suspected during grouting and a large amount of grout was believed to have been lost downstream through these fractures. This apparently was not the case. Of the several high angle fractures, none displayed appreciable amounts of grout. The large clay and rubble infilling within the fracture at Sta. 0+60 was generally tight and well packed against the walls. Small voids and grout pockets were observed along its length, but no indications of large grout takes were evident. The remaining smaller high angle fractures indicated the same type of compact infilling and displayed proportionately less grout. Consequently, little grout was lost through these high angle fractures.

7-05. In general, grouting in the sandstone portion of the grout curtain proved to be very effective. All fractures and joints of any significance were filled with grout and appeared tight. The highly fractured sandstone near the limestone contact was effectively grouted with nearly all fractures down to 1 mm being filled.

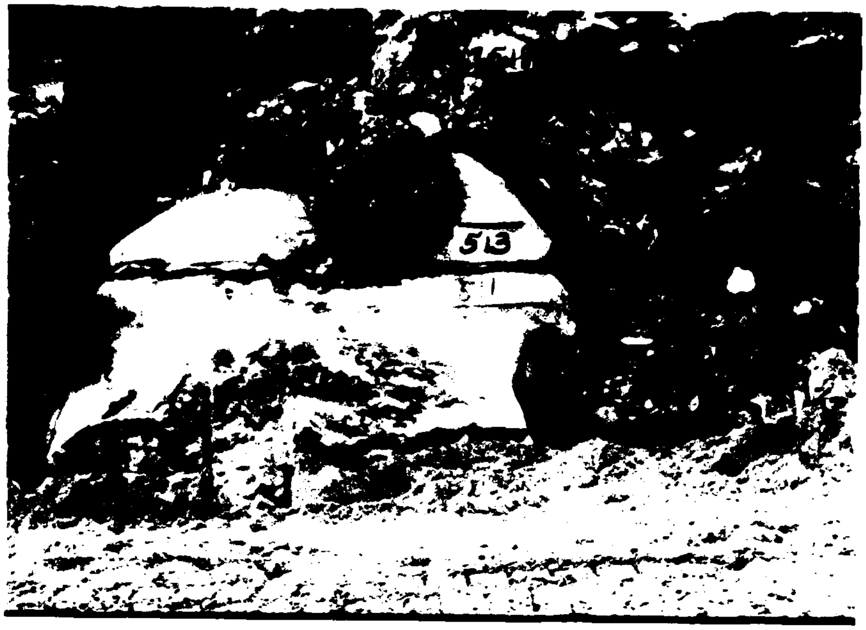
B. Sandstone-Limestone Contact

7-06. At the sandstone-limestone contact, grout distribution was controlled by large voids resulting from solution and collapse activity. Although the bulk of the grout was found in this area, larger amounts must have escaped from the curtain limits in this zone because much more grout was pumped in this zone than was observed during excavation.

7-07. During the grouting phase of construction, many discussions took place concerning grout escaping from the confines of the grout curtain. During excavation, two possible routes of escape were discovered. Both areas occurred at the sandstone-limestone contact near the toe of the backslope. The two routes of escape were oriented along solutioned joints in the limestone forming hollow tubes at the upper contact. These joints were not excavated through the limestone. Consequently, the conditions within the limestone were not observed. However, air-trac exploratory holes indicated a sound limestone at this location.

7-08. These two grout-filled solutioned joints have been plotted on Figure V-4. The upstream joint of this pair trends nearly parallel to the dike centerline. The downstream joint of this pair trends away from the centerline at a low angle upstation. Both photos on Plate 6-VII clearlly show the upstream grout filled joint. When excavated, both joints were completely grout filled and the voids at the intersection with the back slope were also completely filled with grout. This complete filling indicated that the curtain was starting to seal off at the conclusion of grouting operations.

7-09. The contact zone betwen sandstone and limestone was found to be extremely irregular as a result of the complex depositional history of the damsite area. The long interval of erosion between deposition of the two rock types sculptured the surface of the limestone into multi-leveled and pinnacled forms. Consequently, elevation could not be relied upon as a key to rock types. Below the original top of limestone elevation, any type of material ranging from unconsolidated sand and clay to unweathered sandstone and limestone could be encountered. Plate 2-1 clearly shows the complex nature of this contact zone. The large pinnacle of limestone at the original elevation is surrounded on



US wall Sta. 1+30 to 1+50. Extensive solutioning with clay filling. Abundant grout at lower SS contact. Dike embankment in foreground.

Details of above photo. Note tightness of clay - LS contact. Also note bedded SS below upper LS contact.

all sides by normally bedded sandstone. In addition, the entire limestone pinnacle is sheathed in a thin coat of reddish brown clay.

C. Limestone

7-10. The poor grouting results and the subsequent decision to excavate this portion of the dike foundation were mainly the consequences of the clay and sand filled cavities found within the limestone. The clay and sand filling in these cavities, including the fillings at the sandstone-limestone contact, consisted of clay, mud, sand, and sandstone fragments in varying proportions. The clay and loose sand proved to be the most difficult materials to grout and consequently had the greatest effect upon grout distribution and stability. Due to the impossibility of thoroughly washing these clay and sand filled seams, as discussed in the grouting portion of this report, the potential for piping remained in spite of the intensive grouting effort.

7-11. As observed, nearly all voids above the clay seams were sealed with grout and in may areas the clay was marbeled with rivulets of grout. The phenomenon of "Ratholing" was probably responsible for most of the grout found within these clay seams. In this process, clay was removed during washing to the maximum capacity of the pump. At this point a hole large enough to accommodate the maximum flow of water was forced through the clay seam, and no further clay could be removed. During grouting, this hole was filled with grout leaving the larger mass of clay intact. When the grout hole was redrilled, this process was repeated.

7-12. The sand in the solutioned cavities represented an even greater hindrance to grouting. As discussed earlier, the caving sand created an extremely difficult grouting problem that was never fully resolved. Circuit grouting was used, but was generally unsuccessful. When grouting operations were completed, caving sand still persisted. During excavation, the full extent of this problem became evident. Large areas at the sandstone-limestone contact were filled with loose sand as a result of weathering, transportation, and poor consolidation during and following deposition. In addition, thin sand seams and loose rubble in solutioned joints made thorough grouting of these zones very unlikely.

7-13. As a consequence of the clay seams and loose sand near the sandstone-limestone contact, little grout was found in the limestone below the highly solutioned zones. During grouting, this situation was suspected, but the magnitude was not realized until excavation was complete. Numerous thin open joints were evident below the clay and sand horizons which contained little or no grout. These joints in themselves presented no grouting problem and would have been sealed under normal grouting conditions. However, if left ungrouted, these open joints would have presented a potential seepage problem.

D. Limestone-Sandstone-Overburden Contact

7-14. The highly irregular limestone-sandstone-overburden contact betwen Sta. 2+60 and 3+0 presented another difficult grouting problem. The limestone contact in this area, as discussed in paragraph 6-26, was irregularly stairstepped with nearly vertical faces between steps. Covering and masking these vertical features were varying thicknesses of sandstone colluvial rubble. Some residual clay was present in this zone, but extensive patterns of openings and loose sand pockets extended from one to ten feet away from the rock contacts.

7-15. Contract specifications stipulated that casings would be seated a minimum of 1 foot into rock. From the information gathered during casing installation and during excavation, most casings were seated in the limestone with the resultant casing off of the rubbly zone. Some grout leakage into this rubbly zone was suspected during grouting. However, few grout stringers were observed in this immediate rubble zone during excavation and subsequent mapping.

7-16. From these observations, the contract method of grouting clearly did not provide for adequate grouting of this rubbly contact zone. If left ungrouted, a very serious potential for seepage and piping would occur. Further, this highly irregular contact zone was not discovered during exploration for the design phase. From the alluvial history of the dike area, this type of contact could have been expected and separate grouting methods for this zone should have been specified.

7-17. In addition, the problems encountered between Sta. 3+0 and 4+20 very likely stemmed from this rubbly overburden contact zone. As shown on the grouting profiles (Figures IV-2 to IV-7), the casings in this area were set considerably higher than the top of shale contact. Also at the time of drilling and grouting, the limestone was known to be absent from this area. However, the driller's judgment was relied upon to set the casings into rock. The final profile presented at the March 8, 1977 meeting indicated that the zone between the casings and the shale was limestone. This assumption was based strictly on the seated casing depths. Subsequent observations during excavation voided this conclusion. Consequently, the high casing must have been seated in the rubbly slope wash material overlying the shale. However, little or no grout was observed at this location. This situation would also account for the large number of pulled casings in this area.

E. Shale

7-18. The grout distribution in the shale below the Glen Dean Limestone met expectations. The shale was tight and no grout was observed. Numerous compaction slickensides were noted, but no open features requiring grout were observed. The 6-inch diameter grout hole drilled at Sta. 1+34 was observed in the shale portion of the foundation. At this point, the hole was filled with sanded grout, the sides were tight, and no mud was observed. The complete filling of the hole indicated that little or no caving occurred during the final drilling of this large diameter hole.

7-19. Grouting in the shale proved to be effective. Actually, grouting in the shale was intended as a check measure and grouting proved to be unnecessary. Problems with casing anchoring occurred between Sta. 3+0 and 4+20, but did not involve grouting problems within the rock.

F. Discussion

7-20. Contract specifications stipulated that grout holes would either be washed out after grouting operations, after allowing enough time for initial grout set, or that the grout holes would be redrilled at the contractor's expense. The contractor elected to redrill the holes rather than waiting the required 3-hour set time to wash. Due to the softness of the sandstone, the set grout within the grout holes became harder than the surrounding rock. When redrilled, the drill bit tended to drill a new hole in the soft sandstone rather than drill through the harder grout. This phenomenon accounted for the large number of grout holes found in the same relative location near the base of the sandstone (see Plate 6-III). In one instance, over 15 separate grout holes were found at the same location. In general, the contractor's selection of redrilling rather than washing benefitted the grouting program greatly in that a greater area could be grouted with a single hole. In addition, a better curtain was obtained in the sandstone due to the larger number of fresh grout holes.

7-21. These multiple grout holes also offered an explanation of the excessive negative staging in the sandstone. In each grouting stage, the grout would travel only a very short distance from the grout hole due to the very thin openings between bedding planes. Each time a grout hole was redrilled, the bit would miss the grout in the original hole and lose drill water along the same bedding plane.

7-22. In spite of the greater number of holes in the same general location, the angles of the individual grout holes did not vary in the sandstone as greatly as suspected during grouting operations. Most redrill holes in sandstone were found within a 5-foot radius of the original holes. Given the length of drill hole, up to 82 feet in sandstone, the deviation of the redrilled holes would be less than 10 percent. Relatively few holes were observed and variations greater than this may have occurred in other holes.

7-23. Deviations in multiple grout hole angles were much more erratic in the limestone portion of the grout curtain. Generally, holes remained true in competent limestone, but several outstanding deviations in weathered limestone were noted. Near Sta. 2+60, several broken drill rods were observed in a clay-filled solution joint (see Plate 6-IV). These rods were found at widely varying angles and were found at reversed angles to the original hole. In this and other instances, the drill rods and bit would follow the sides of the joint rather than punch through the irregular rock surface. This phenomenon was also noted during drilling of the core hole (GCH #7) at Sta. 2+72.5.

7-24. In the case of the grout holes, the type of bit may also have influenced the deviations noted in limestone. Carborundum tipped, fishtail bits were used in lieu of diamond bits. The softer, irregular bits would have a greater tendency to follow the softer weathered rock on joint faces rather than continue through the hard side walls of these joints.

7-25. Holes drilled through the overburden were not observed closely enough to determine general deviations in drilling angles. One cluster of four grout casings was observed near Sta. 2+80 at the limestone overburden contact (see Plate 6-XII). These four casings were found within a 2-foot square area and seemed to vary from the intended drill angles. However, the close spacing of the grout holes in this area made it difficult to reach any conclusions based on just these four holes. No other in place casings were observed in this area.

7-26. Many grout-filled holes found during excavation displayed a concentric circular and oval banding of the hardened grout. Banding consisted of alternating light and dark grout. The lighter bands were probably the result of a higher air content while the darker bands probably represented consistently denser grout.

7-27. Indirectly the grout banding could also be related to the method of grouting. Very frequent premature plugging of holes was noted during grouting. This phenomenon was especially evident while pumping the thicker mixes. As grouting progressed with no pressure build-up, progressively thicker mixes were introduced into the hole. At some point during this process, often between 100 and 150 sacks, the hole would suddenly refuse with pressures rising from 0 to 15 psi instantly.

7-28. Many explanations can be hypothesized to explain this premature plugging, but the grout banding noted above suggests one of the most plausible explanations. Grout holes in sandstone were generally drilled with a carborundum tipped fishtail bit. The fishtail bit combined with whipping of the drill rods, due to excessive drill speeds, left a much rougher edged hole than similar drilling with diamond bits. During grouting operations the rough edged holes would tend to impede the flow of grout within the hole. In addition, the velocity of grout would tend to slow at the outer edges of the fluid. Grout would also tend to to cake on the outside of the rough holes and further restrict the flow of grout. Eventually, the flow of grout would become so constricted that the hole would plug completely. Other causes are possible, but the banded grout phenomenon suggests one plausible explanation for grout hole plugging.

7-29. In practice, the contractor was required to redrill any hole in which the Government representative suspected premature plugging. Larger diameter (NX) holes might have alleviated the premature plugging problem, but would not have completely solved this problem.

7-30. The analysis of rock conditions made during grouting (Figure IV-7) and used as a basis for the final excavation design proved to be generally correct. However, details varied slightly. The limestone, for example, was in a worse condition than expected. Grouting indicated the limestone to be tight below the solutioned zone at the sandstone contact. However, when uncovered, solutioning within the limestone extended much further into the abutment than anticipated. Consequently, more limestone had to be removed than planned. Specifically, the limestone had to be removed completely back to Sta. 0+76, whereas final plans called for complete removal only to Sta. 2+40. The sandstone, on the other hand, proved to be sounder than assumed during grouting.

7-31. At the time the decision was made to excavate a cutoff into the left abutment, alternate methods of treatment were not considered. However, two alternate methods were considered on otherportions of the project where similar conditions were encountered. A 5-foot wide cutoff trench excavated 30 feet through the limestone was utilized between the dike and the spillway. At the dike left abutment, greater depths would probably have precluded this method of treatment. A drilled wall consisting of 24-inch overlapping holes was considered at the right abutment of the dike, but was not utilized. This method could have been utilized at the left abutment of the dike as an alternative to complete excavation, depending upon cost and other considerations.

7-32. Chemical grouting was considered during grouting operations, but was not utilized due to contractual restraints. This type of grouting would greatly have improved the results in the loose sand encountered at the limestone-sandstone contact. Used in conjunction with cement grouting, chemical grouting might also have facilitated the grouting of the rubble overlying limestone at station 3+00 if that condition was known to have existed during the grouting phase of construction. However, the stability of the clay in the solutioned zones of the limestone could not be improved by utilizing chemical grout. In addition, the settlement of the foundation upon loading with embankment could not have been prevented by this grouting method. As a result, the integrity of the foundation could not be insured throughout the life of the project.

7-33. The left abutment of the dike would have provided an ideal area for a test grouting program. Similar rock conditions prevailed for a large portion of the total grout curtain. Consequently, the dike section would have provided an isolated, short study area for the remaining curtain. Alternate methods of grouting, such as large diameter holes, stop grouting, and combination chemical grouting and cement grout could have been used and evaluated without costly contract modification or holding up the dike excavation. Further, alternate solutions to grouting, such as excavation or drilled cutoff wall, could have been analyzed before awarding the construction contract.

PART VIII - CONCLUSION

8-01. Stage grouting as envisioned during the design phase of this project proved to be inadequate to seal the complex rock structure encountered at the left abutment of the dike. The inability to treat the loose sand at the sandstone-limestone contact, the clay-filled solutioned joints and the open voids within the colluvium-limestone contact finally caused abandonment of the grouting program. Additional methods of grouting contemplated during construction, such as backfilling 6-inch diameter holes with high slump mortar grout, circuit grouting and stop grouting in 3-inch holes either did not nor would not have increased the effectiveness of the grouting program in this area. Chemical grouting could have improved the grouting results in loose sand areas, but probably would not have improved the grouting effectiveness in the clay-filled zones.

8-02. Subsequent reevaluation of the structural integrity of the dike structure, with regard to piping, led to complete excavation of the objectionable material to provide a positive tie-in to the underlying impervious rock. During the final rock excavation of the dike left abutment, the magnitude of the grouting difficulties became readily apparent. Most open voids were filled with grout, but the clay-filled solutioned joints remained and loose sand was observed within these joints. The unconsolidated colluvium at the limestone contact remained ungrouted and posed a real threat to future structural integrity through extensive seepage and resulting piping of finer materials. Excavation allowed removal of unsuitable material back to a point where the safety of the structure was insured.

8-03. During design, too great a reliance was placed on cement grouting to cure the problems of a weak foundation. The state of the art, since the design of this project, has progressed to the point of less dependence upon grouting in complex solutioned limestone areas. Grouting often has only short term effectiveness in solutioned limestone and quite often the area has to be continually regrouted during the life of the structure to control seepage.

8-04. In the future, greater care should be given to determining groutable and nongroutable solutioned limestones. Less dependence should be placed on grouting in a badly solutioned limestone with extensive clay-filled joints or cavities. These clay-filled cavities and joints cannot be effectively washed or grouted and present a very high potential for future seepage and piping. Any limestone that has been subjected to surface erosional cycles should be highly suspect for grouting incompatibility.

8-05. Greater emphasis should be placed on foundation exploration and in-situ observations of the limestone contacts. Grouting should not be relied upon for any structural foundation where seepage and resultant piping could threaten the integrity of that foundation. Instead, positve cutoff methods such as drilled-in walls, cutoff trenches, or complete removal should be utilized to insure the structural integrity of the critical foundations in highly solutioned limestones.