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DELAWARE GEOLOGICAL SURVEY

Robert R. Jordan, State Geologist

BULLETIN No. 13

**GEOLOGY, HYDROLOGY, AND GEOPHYSICS
OF COLUMBIA SEDIMENTS IN THE
MIDDLETOWN-ODESSA AREA, DELAWARE**



BY

NENAD SPOLJARIC AND KENNETH D. WOODRUFF

**NEWARK, DELAWARE
AUGUST, 1970**

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FOREWORD

The study reported on the following pages exemplifies the application of advanced techniques of the sciences of geology, geophysics, and hydrology to one of man's pressing environmental problems, the search for water. Most of Delaware's ground water must be derived from the upper layers of sediment covering the Coastal Plain portion of the State. This intensive investigation of those beds and their water-bearing characteristics in southern New Castle County has yielded information necessary to the exploration for, and development of, water resources in much of Delaware and, indeed, beyond her boundaries.

The project was made possible by the support of the Water Resources Center of the University of Delaware, Dr. Robert D. Varrin, Director, and is illustrative of outstanding cooperation between the Center, the Survey, and many others whom the authors have recognized in their acknowledgments. The initiative and initial guidance for the study came from Dr. Johan J. Groot, the original Principal Investigator. It has been the writer's privilege to complete this work and accept final responsibility for the judgments contained herein.

This Bulletin is organized in two sections: the first presents Dr. Spoljaric's special knowledge of the geology of the Columbia deposits, and the second Mr. Woodruff's application of the geology, plus geophysics, to hydrologic interpretations.

-Robert R. Jordan

The work upon which this publication is based was supported in part by funds provided by the United States Department of the Interior as authorized under the Water Resources Research Act of 1964, Public Law 88-379.

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GEOLOGY OF COLUMBIA SEDIMENTS IN THE MIDDLETOWN-ODESSA AREA, DELAWARE

by

NENAD SPOLJARIC

ABSTRACT

Columbia sediments in the Middletown-Odessa area are composed of boulders, gravels, sands, silts and clays. These sediments are exposed in four gravel pits where their structures and textures were studied. Subsurface geology was interpreted on the basis of the well-log data from 40 holes drilled in the area of study.

Columbia sediments were laid upon a surface made up of the greensands of the Rancocas Formation (Paleocene - Eocene age). The contact between the Rancocas and Columbia Formations is an erosional unconformity.

At the onset of the Columbia sedimentation the green-sand valleys were probably first deepened by eroding streams and hills were lowered by denudation. Filling of the valleys followed, with interruptions, until the Rancocas topography was completely covered with the Columbia sediments; the result was a flat, almost featureless surface.

The deposition of the sediments occurred in channels, flood plains, cut-off meanders, and levees. However, it is often difficult to recognize these various environments, particularly in the subsurface. Conditions of deposition ranged from those present in channels of high-velocity and high-competency streams to those of a tranquil environment. Most of the sediments were brought into the area and deposited there as a part of the sediment load of the streams; however, some large boulders, scattered throughout the area of study, are believed to have been transported by ice floes and similar means, independently of the stream loads.

The channels of the Pleistocene streams are shallow and rarely exceed 1/2 mile in width. These channels are either straight or meandering and they seem to have formed a braided stream system.

The relationship between present topographic highs and thickness of the Columbia sediments (Spoljaric, 1967) has not been confirmed by the present study; the reason for this is thought to be human activity that has distorted the original natural relationships. A new method of subsurface investigation was applied to this study which enabled the detection and delineation of ancient stream channels; the method, however, requires extensive drilling and is not economical for routine water exploration.

INTRODUCTION

Pleistocene sediments, which cover a vast area in the Atlantic Coastal Plain, consist of boulders, gravels, sands, silts, and clays.

In Delaware these sediments are important as a major building material source and the most economical source of ground-water supply. Ever increasing demand for building materials and cheap ground-water supply necessitates the development of techniques and methods that can be employed in search for such resources. This may be accomplished only through an understanding of the characteristics and origin of the Columbia sediments which contain these resources.

Since the time of McGee (1887), and before, these sediments have been studied and classified, but the many problems which they pose, such as origin and age, still baffle present-day geologists. Even their nomenclature is a subject of debate. McGee (1888) introduced the name Columbia, however, Shattuck (1901, 1906) called these deposits Sunderland, Wicomico, and Talbot, whereas Rasmussen et al. (1960) called them Palmlico, Walston, and Beaverdam. Jordan (1962) discussed these problems of nomenclature, and he has suggested a return to McGee's name, "Columbia"; his suggestion is followed in this study.

The origin and particularly the age of the Columbia sediments is still a controversial subject (Jordan, 1962, 1964). However, at present most agree on the fluvial origin of the deposits in the northern and central part of Delaware. Marine and Rasmussen (1955), Ward and Groot (1957), Rasmussen et al. (1960), and Jordan (1964) suggest melt-water flooded streams and lowered sea level as factors responsible for their deposition.

The purpose of the present study is to investigate the conditions and environments of deposition of the Columbia sediments in the area between Middletown and Odessa (Figures 1 and 2). The emphasis is placed upon sedimentary structures and textures which are thought to bear evidences of the geologic history of these deposits. The study was conducted in two major phases: investigation of outcrops of the Columbia sediments and the application of the results of this surface investigation to the interpretation of subsurface geology.

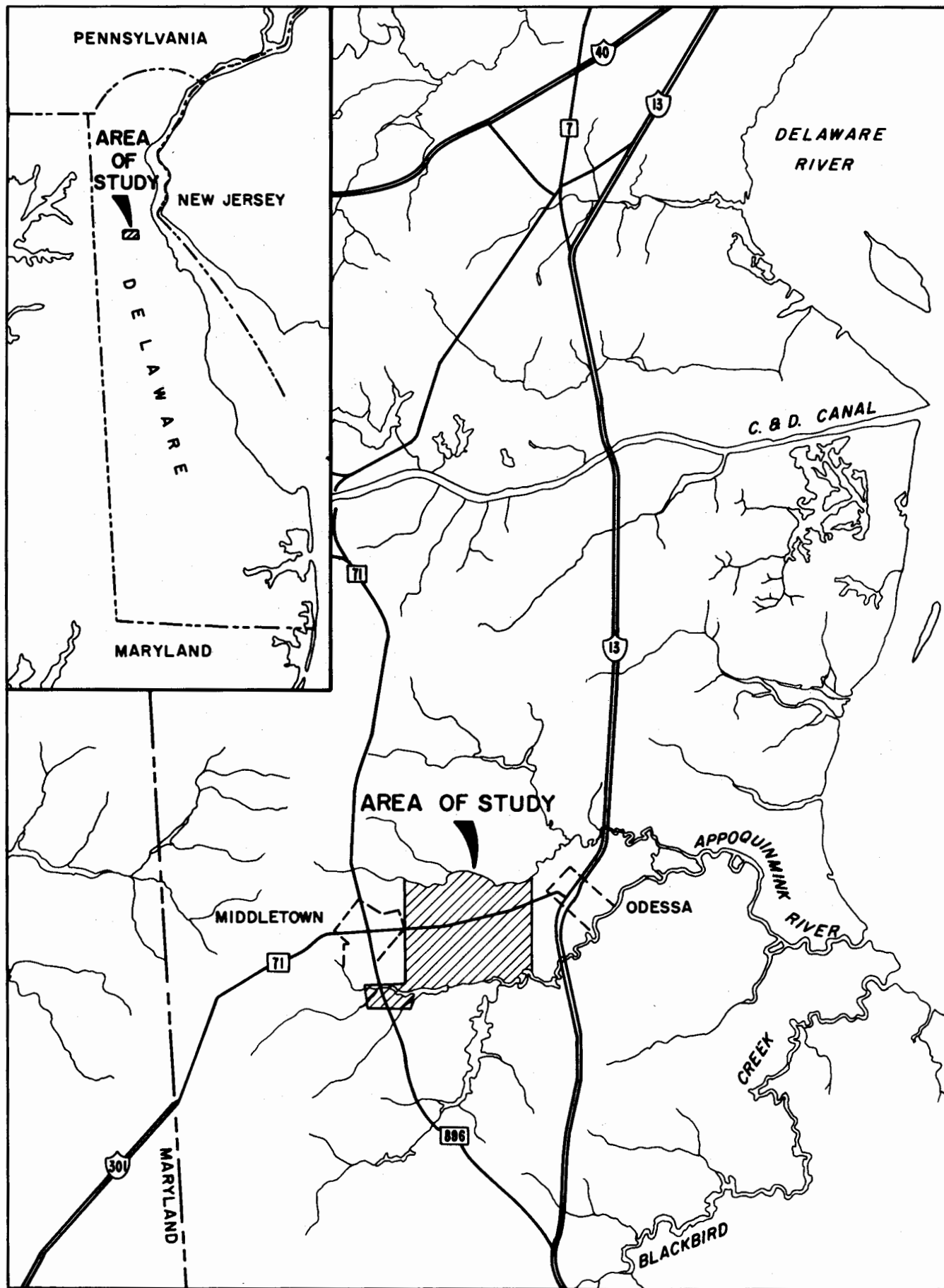


FIGURE I. LOCATION OF STUDY AREA.

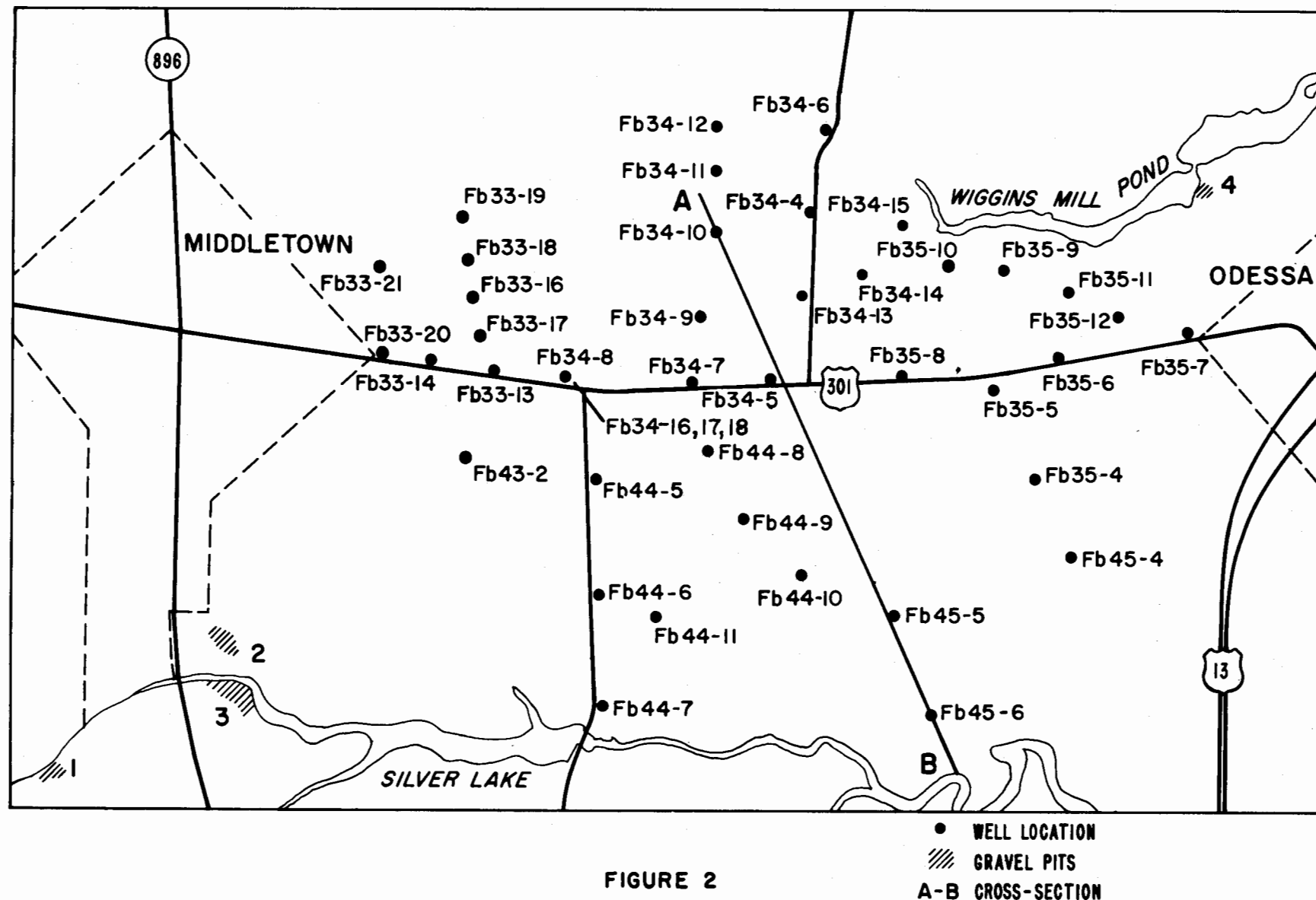


FIGURE 2

A major part of this report has to do with buried (or very rarely exposed) Pleistocene stream courses. A few such exposures in or near the Chesapeake and Delaware Canal led Groot, Organist, and Richards (1954, p. 23) to call valley fills "channels." Rasmussen et al. (1957, 1966) used the same word and concept in describing some morphologic characteristics of these deposits without proof that they were indeed stream-cut valleys. In the present study the name channel is restricted to the cases in which actual stream courses with valley walls are exposed or "seen" in the sub-surface.

Jordan (1964) studied structures, textures, mineralogy, and dispersal of the Columbia sediments in Delaware and concluded (page V): "The sands represent deposits of a major stream system; the distal portion of which has been reworked by a transgressing and regressing sea which at one time covered at least the southern half of Sussex County. The systematic variation of the properties studied suggests only a single cycle of deposition." The study of the dispersal pattern of these sediments indicates, according to Jordan (1964), that they entered Delaware through the Delaware River Valley and spread southeast over the State.

Spoljaric (1967) suggested that frequent flow-regime fluctuations of the streams, which deposited the Columbia sediments, are evidenced by the primary sedimentary structures observed in these deposits and also by a widespread distribution of gravels. It seems that during high stream flows most of the area (New Castle County) was submerged, while during low discharges large interstream areas and islands emerged. These fluctuations are thought to have been caused by short-term climatic changes rather than long-term effects of glaciers.

FIELD AND LABORATORY METHODS

Field Methods

Investigation of Outcrops

Columbia outcrops were studied in four gravel pits; three of them located south of Middletown and one northwest of Odessa (Figure 2). The thickness of exposed height of outcrop of the Columbia sediments ranges from about 3 feet to more than 30 feet, and at the top is a layer of Holocene soil usually less than 2 feet thick. The base of the outcrops in all cases is hidden under talus. The erosional unconformity between the Columbia sediments and underlying greensands may be seen only at Wiggins Mill Pond (Figure 2; Plate 1).

Primary sedimentary structures

Measurements taken from cross-bedded sands and gravels include both thickness of the cross-bedded layers and individual cross-beds, and inclination and dip direction of foresets. Sometimes it is difficult to measure the thickness of individual bottomsets because they are poorly defined. Samples were taken from foresets, toesets, and bottomsets.

The thickness of the sequence of the horizontally bedded coarse sand ranges from about 3 feet to a maximum of 14 feet. Individual layers of the horizontally bedded coarse sand sometimes do not have well defined boundaries; however, samples have been taken only from distinct layers.

The thickness of the individual laminae of the horizontally laminated clayey silt was measured and samples collected with a razor blade from selected laminae. The thickness of the laminae increases with the increase of silt content but it does not exceed 0.5 cm.

Small ripple-marks observed in some fine sediments were not studied in detail. Ripple-marks are asymmetrical and the sediments in which they are present lack induration. Different sets of these ripple-marks are superimposed on each other, forming a very complex network.



Plate 1. Erosional unconformity between Columbia gravels and underlying greensands of Rancocas Formation; gravel pit no. 4.

Subsurface Investigation

Subsurface geology was investigated in the area shown in Figure 2. Forty holes were drilled using a combination auger and hydraulic rotary drill. Samples were taken at 5-foot intervals and at lithologic and color changes in the sediments. Thirteen cores were also obtained. The surface elevations of the holes were measured with an engineering level and an altimeter and corrected to the bench mark in Middletown. The location of the holes is shown in Figure 2.

Laboratory Methods

Mechanical Analyses

Mechanical analyses of the sediments were done by the use of U. S. Standard sieves in increments of 10 unit in the size range from -10 to 40. The samples were first disaggregated and then shaken for more than 15 minutes in the set of sieves. The amounts of the sediment remaining on each sieve were then weighed. The fraction smaller than 40 was dispersed in distilled water, a small amount of Calgon being added to prevent flocculation of clay particles. This suspension was then centrifuged for 40 seconds at 2100 RPM to remove silt size material from suspension; silt size particles settle while smaller grains (clays) remain in suspension. Both fractions were then dried and weighed.

Separation of Heavy Minerals

The purpose of this analysis was to determine the amount of heavy minerals in the sand fraction (-10 to 40) of the sediments. The separation was done by flotation in tetrabromoethane after cleaning the grains of coating in dilute hydrochloric and nitric acids. The density of tetrabromoethane was maintained close to 2.93. Samples were weighed before and after separation so that the weight percentages of heavy minerals could be computed.

X-ray Analyses

The slides of the clay fraction for x-ray determination were made using a centrifuge: a glass slide was placed in the bottom of a large centrifuge container, clay suspension added and then centrifuged for at least 30 minutes. The water was then decanted, the slide removed from the container and placed under vacuum for speedy drying. Three slides of each sample were made. Two of these slides underwent special

treatment: one was exposed to saturated atmosphere of ethylene glycol at 60°C for one hour, and the other was heated at 575°C for one hour. A diffractometer pattern obtained from each slide served to identify the clay minerals.

Chemical Analyses

Chemical analyses of the sediments were done by wet chemistry, atomic absorption spectrophotometry, and visible spectrophotometry. Analyses were performed as described by Shapiro and Bannock, (1962) and Shapiro (1967).

Computation of Sedimentary Parameters

A computer program was specifically developed for this study by Miss Wendy Morrison and Mr. Brent Marsh, University of Delaware (Appendix III). It was written using the concepts of a similar program prepared by Pierce and Good (1966). The program computes mean grain size, standard deviation, skewness, and kurtosis by the method of moments; in addition it also gives the percentages of sand, silt, and clay fractions of the samples.

ACKNOWLEDGMENTS

I wish to express my deep appreciation to Dr. Lincoln Dryden, Bryn Mawr College, who directed this study in its original form as a part of doctoral dissertation. I am also grateful to Drs. William A. Crawford, Edward H. Watson and Maria L. Crawford, Bryn Mawr College, for their constructive criticism of various topics related to this study.

Many beneficial discussions held with the staff of the Delaware Geological Survey, particularly Dr. Robert R. Jordan, State Geologist, and Johan J. Groot, former State Geologist, who served as principal investigators, are gratefully acknowledged.

Dr. F. J. Pettijohn of the Johns Hopkins University and R. F. Siegel of George Washington University gave graciously of their time to discuss various aspects of the study. I am also grateful to Miss W. Morrison and Mr. B. Marsh, University of Delaware, who designed a computer program for sediment size analyses.

SURFACE GEOLOGY

Primary Sedimentary Structures

Introduction

Investigation of primary sedimentary structures has been undertaken with the purpose of determining the conditions under which the sediments of Columbia Formation were deposited.

In spite of a number of experimental studies done on the formation of various sedimentary structures (Hjulstrom, 1935; Einstein, 1950; Chien, 1956; McKee, 1957; Jopling, 1960, 1963, 1964, 1966; Simons, Richards and Albertson, 1961; and Simons, 1963), there is still no reliable technique that can be used in interpretation of ancient environments. In Jopling's words (1966, p. 64): ". . . there are many unknowns to contend with in the interpretation and synthesis of paleo-flow regimes. Field relationships are often complex, exposures poor, and the sedimentological record incomplete. Last, but not least, environmental reconstruction falls short of its avowed objectives because of the limited techniques available." Because of these inadequacies, results of the environmental reconstruction from sedimentary structures in the study area are limited to only very general statements which, nevertheless, give some idea of the conditions under which the Columbia sediments were deposited.

Cross-Bedding

Origin of cross-bedding

Laboratory studies made by Jopling (1960) contributed greatly to our understanding of the processes responsible for the formation of cross-bedding in sands and gravels. The mechanism is basically aggradation, resulting in the formation of a delta. The tendency of the process is to approach equilibrium and thereafter it responds according to any flow fluctuations and changes that may occur. A modified sketch (Figure 3) taken from Jopling (1963) illustrates this.

The area above the zone of mixing is characterized by the free transport of the sediment load at a given stream

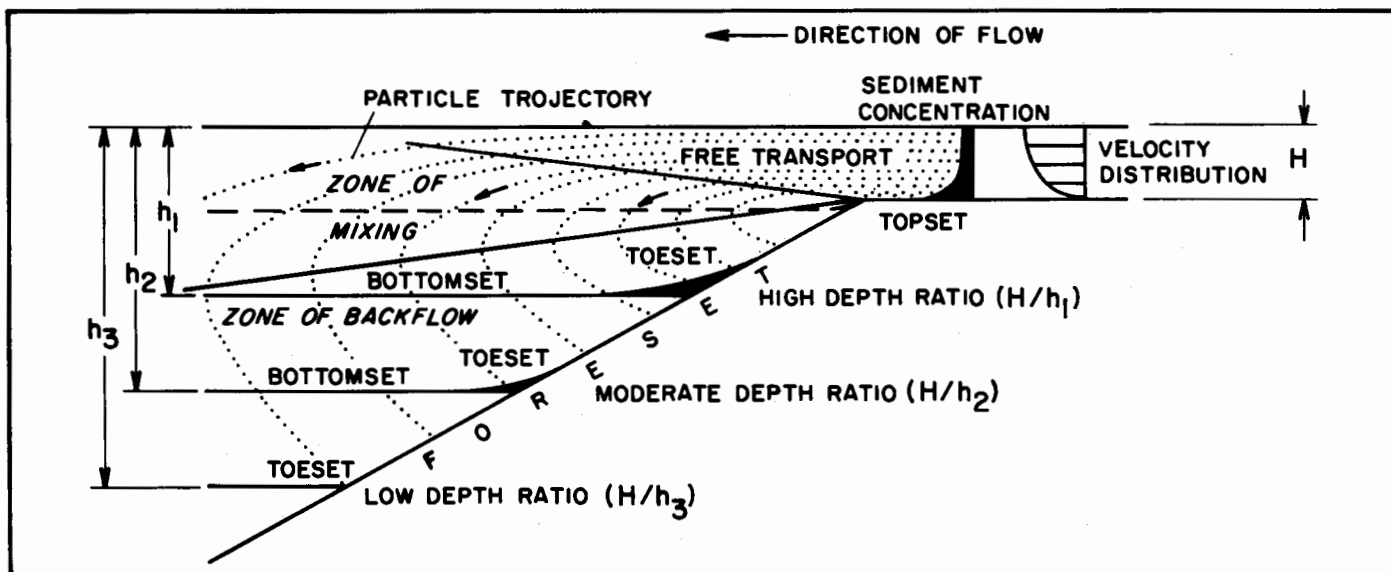


FIGURE 3. FORMATION OF CROSS-BEDS (MODIFIED AFTER JOPLING, 1963).

NOTE THE INFLUENCE OF VARIOUS DEPTH RATIOS (H/h_1 , H/h_2 AND H/h_3) ON THE TYPE OF CROSS-BEDS FORMED.

H = WATER DEPTH IN STREAM

h = WATER DEPTH IN FRONT OF DELTA

velocity. In the zone of mixing the particles are more and more influenced by gravity; they lose speed and start to descend toward the bottom. Those particles that reach the zone of backflow begin to travel in a direction opposite to that of the main stream flow and eventually they either settle on the bottom or are pulled back into the zone of mixing. It is apparent that the backflow is responsible for the formation of bottomsets and it also contributes fine material to the build up of toesets. Topsets and foresets and the greater part of toesets are produced by the deposition of the bed load material transported and rolled along the stream bottom. Most of the very fine material, however, goes through the system and is deposited elsewhere.

In reality, however, the origin of cross-bedding is far more complicated than the above description suggests. Many variables are involved (stream velocity, discharge, depth ratio, viscosity, bottom roughness, and others); their discussion is beyond the scope of this study. Nevertheless, it may be pointed out here that the change of any of the variables has a significant effect on the equilibrium conditions, and the type of cross-bedding formed is an expression of these conditions. Some of the more important changes are discussed on the following pages, with examples from the study area.

Cross-bedded sands and gravels

Cross-bedding in sands and gravels is well-developed in all outcrops; it is of tangential (predominant) and angular type. The foreset dip-directions range between S 82° W and S 82° E with the greatest frequencies at S 52° W and S 19° E. The dip of foresets varies between 36° and 12° with the mean value of 23.5° and mode of 27.5° (Figure 4). Characteristically all cross-bedded layers investigated lack topsets, (Plate 2). Thus the true thickness of the layers is unknown; the measured thicknesses range from less than a foot to more than 4 feet.

The absence of *topsets* suggests the existence of erosional unconformities between individual cross-bedded layers. This is also supported by the presence of thin beds of pebbles (Plate 3) that often separate adjacent cross-bedded layers. These thin pebble beds are laterally persistent and can be followed for the length of whole exposures (sometimes more than 40 feet).

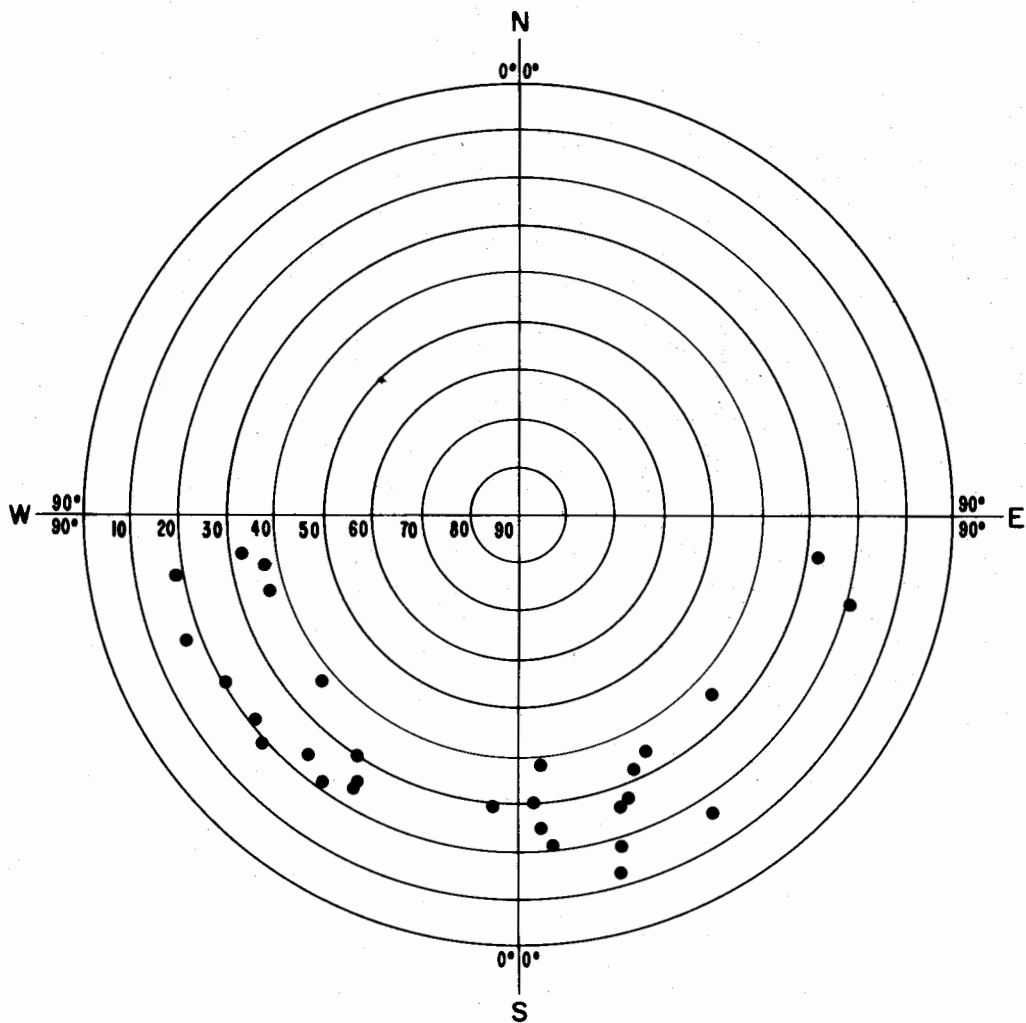


FIGURE 4. DIP ANGLE AND DIP DIRECTION OF FORESETS OF CROSS-BEDDED UNITS.

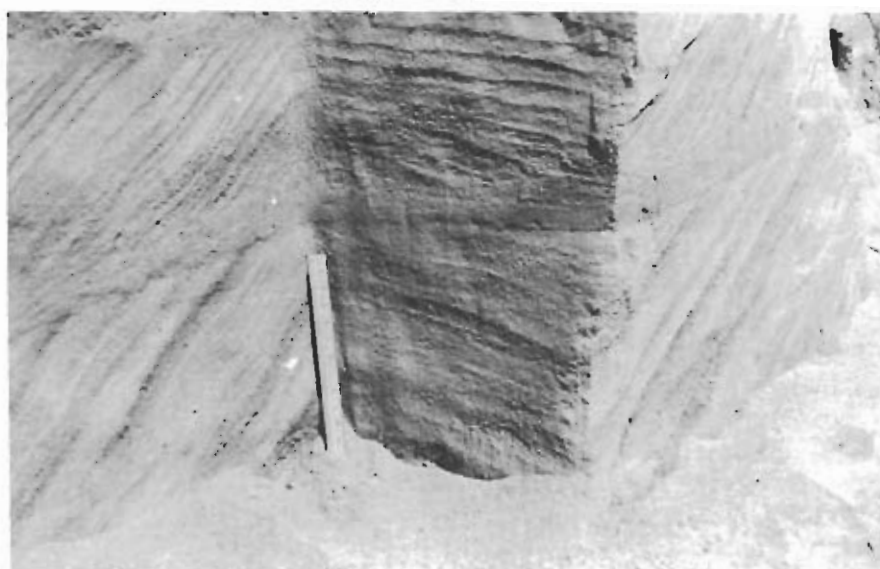


Plate 2. Sequence of cross-bedded sands; lack of topsets and well developed foresets, toesets, and bottomsets are apparent. Gravel pit no. 2.



Plate 3. Cross-bedded sand containing thin pebble beds. Gravel pit no. 2.

Foresets are well developed in all cross-bedded layers. Their contact with the overlying beds is angular and sharp (Plate 2); the lower part gradually grades into toeset (Plate 4). In tangential cross-beds with small dip angle, it is sometimes difficult to determine where the foreset ends and the toeset begins.

Foresets are composed of a series of graded beds; grains increase in size from the top toward the base of each foreset bed (Plate 5). Cumulative curves (Figure 5, 6, 7 and 8) and Table 1 clearly illustrate this. The rhythmic nature of foresets has been explained by pulsations of stream flows (Gilbert, 1914; Bagnold, 1954). Jopling (1964) has also observed, in flume experiments, that the small scale fluctuations of velocity are characteristic of turbulent flows. Such pulsations or fluctuations are probably responsible not only for the cyclic nature of the foresets but also for their grading. The fact that individual foresets, within the same cross-bedded layer, vary greatly in thickness and texture indicates that the flow pulsations are highly irregular events. However, it would be erroneous to single out pulsations as the only mechanism responsible for a particular character of foresets. As Jopling (1964) has shown, a great number of variables act jointly in the formation of a cross-bedded unit and the determination of their relative importance is very difficult or impossible.

Grading of grain sizes parallel to foresets has also been observed; the grains increase in size downward toward the toeset. This type of grading is rare and is probably of secondary origin. The accumulation of coarse sediment at the lip of the foreset and its occasional sliding down the foreset (Jopling, 1964) seems to be a reasonable explanation for the origin of such grading.

Toesets are usually well developed; their sediments are generally coarser than those of foresets and bottomsets (Table 2). Sorting is poor and this is probably due to the admixture of finer sediment brought into toesets by backflow; coarseness of the material is attributed to sliding of coarse sand down the foreset. Thus, the sediment which accumulates in the toeset is deposited both by gravity settling and sliding of coarse material transported by the main current, and by the contribution of fine sediment by backflow.

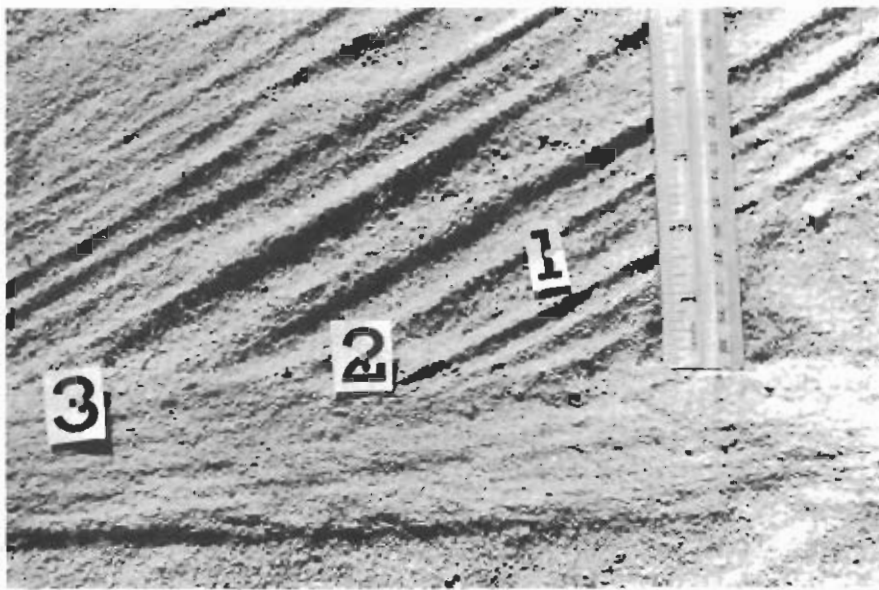


Plate 4. 1-foreset, 2-toeset, 3-transition of toeset into bottomset; note sharp contact between bottomset and underlying cross-bedded layer (topset is lacking). Gravel pit no. 3.



Plate 5. Close-up of foresets; vertical grading of grains is apparent (labels are 3/4" high). Gravel pit no. 3.

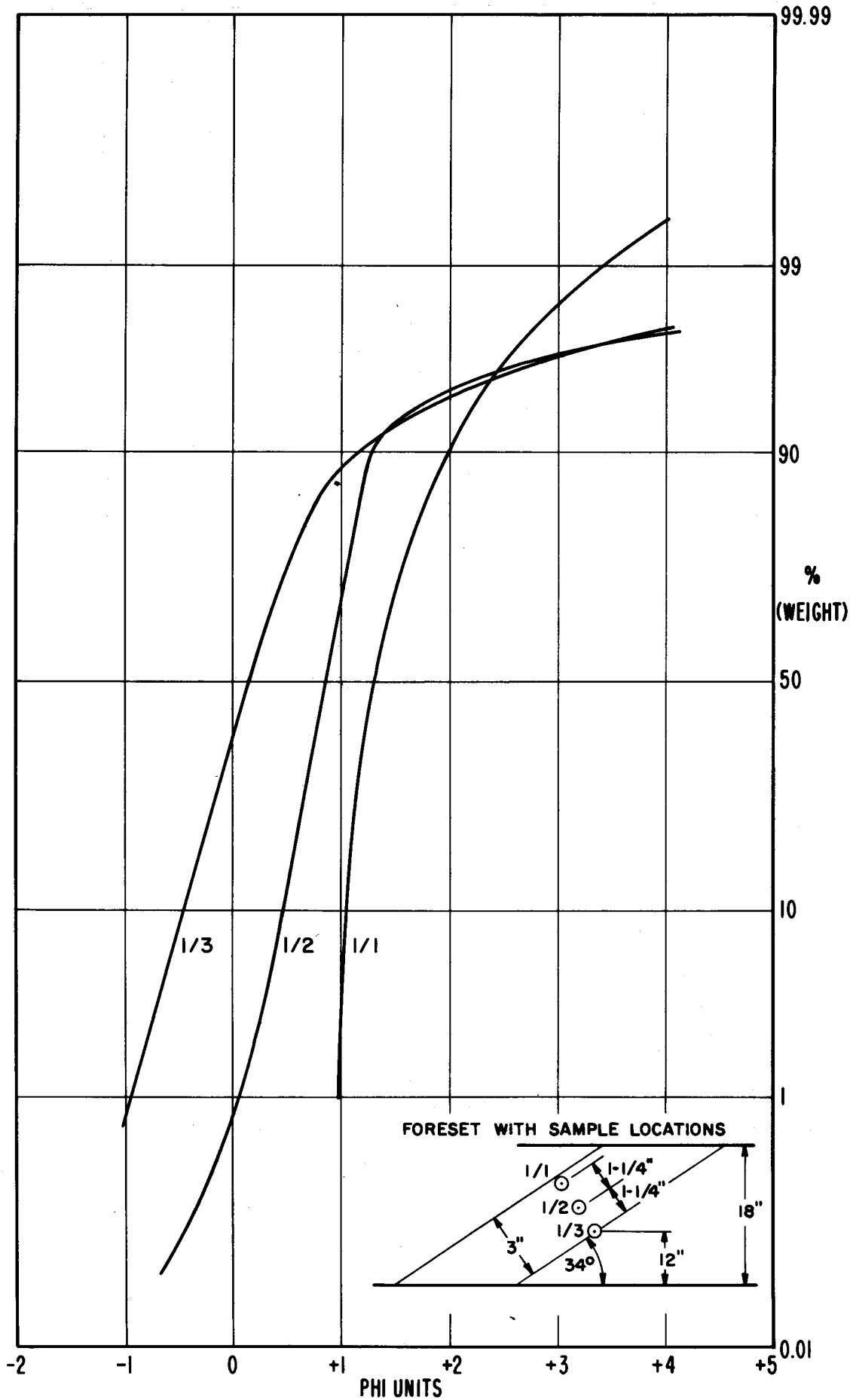


FIGURE 5

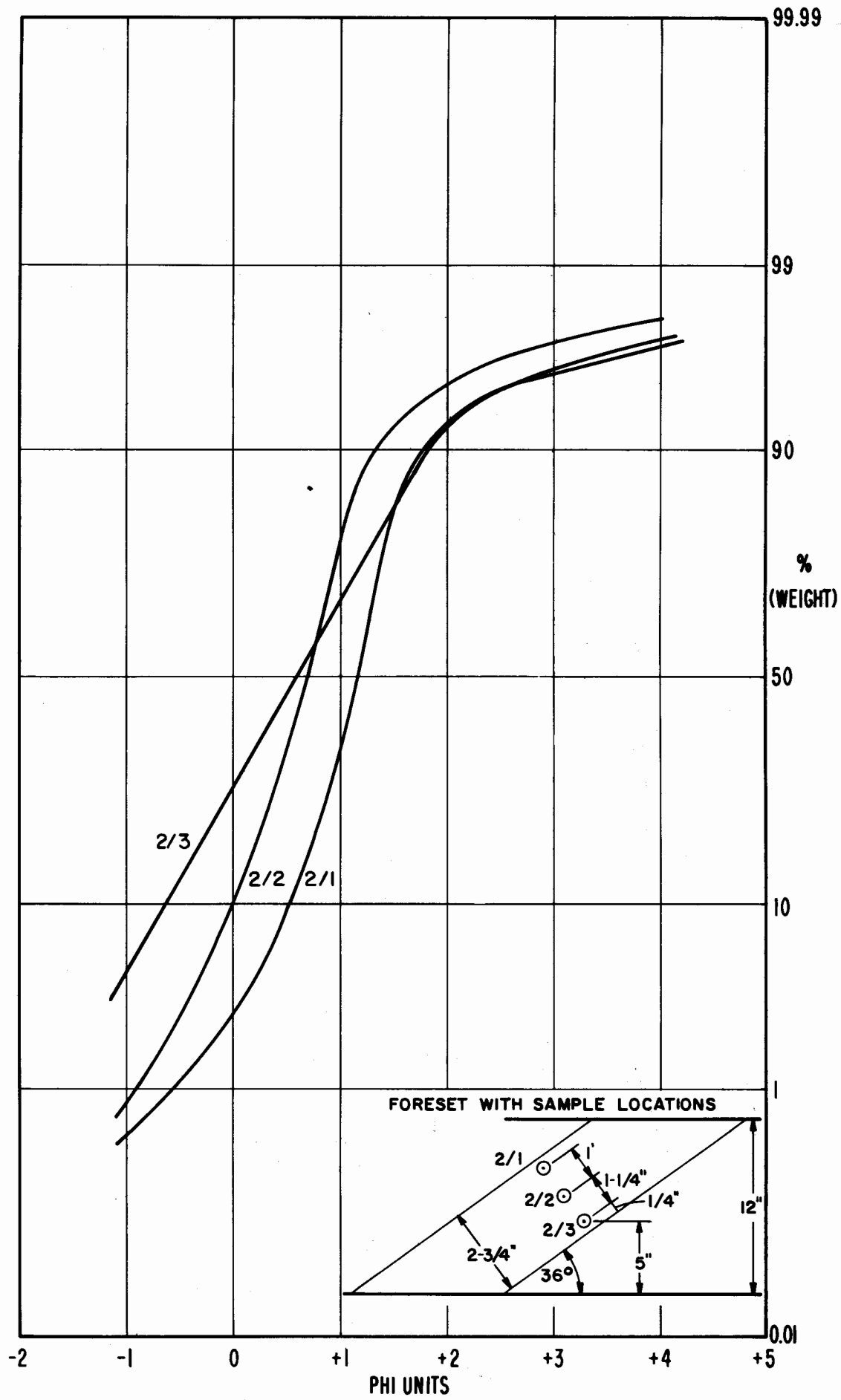


FIGURE 6

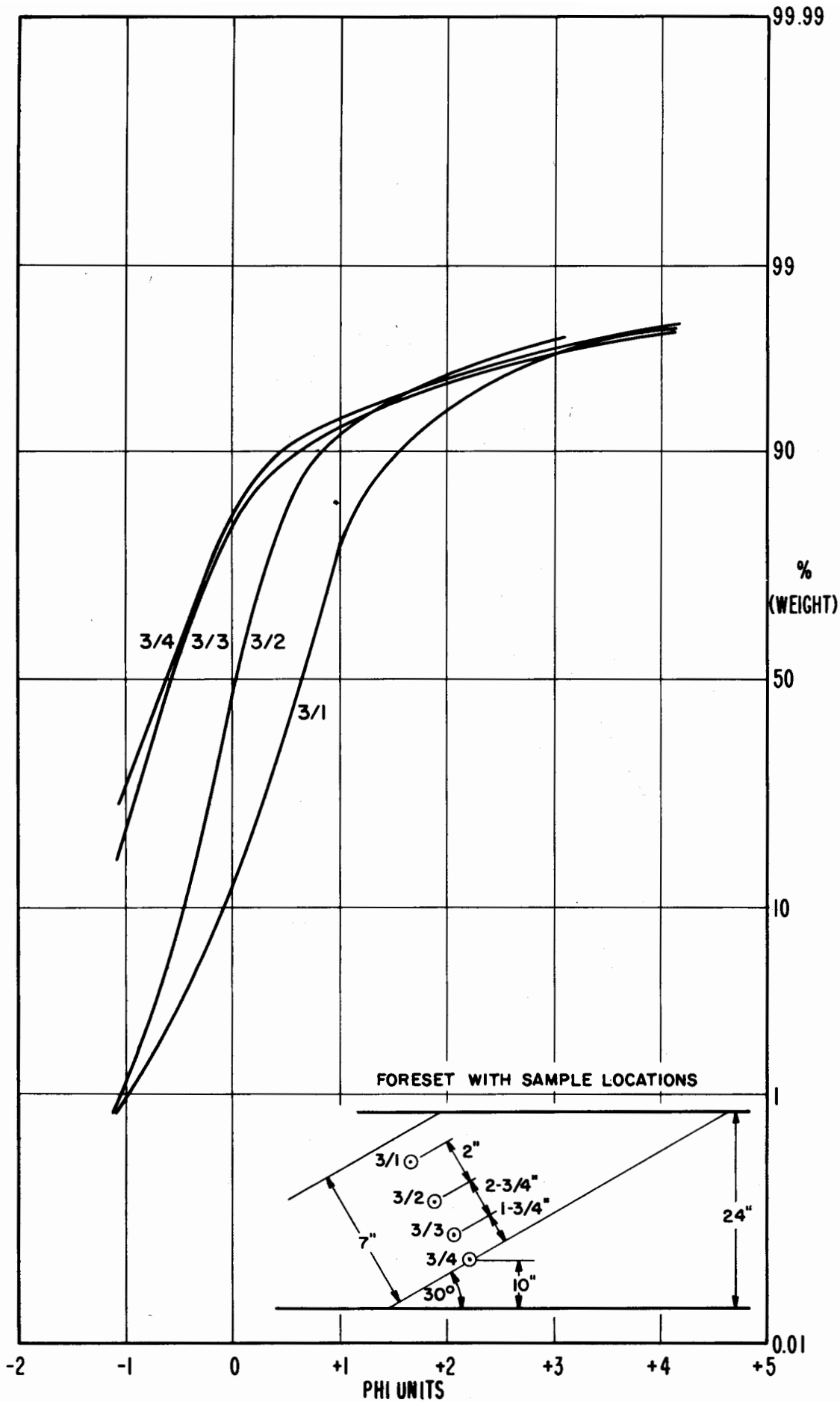


FIGURE 7

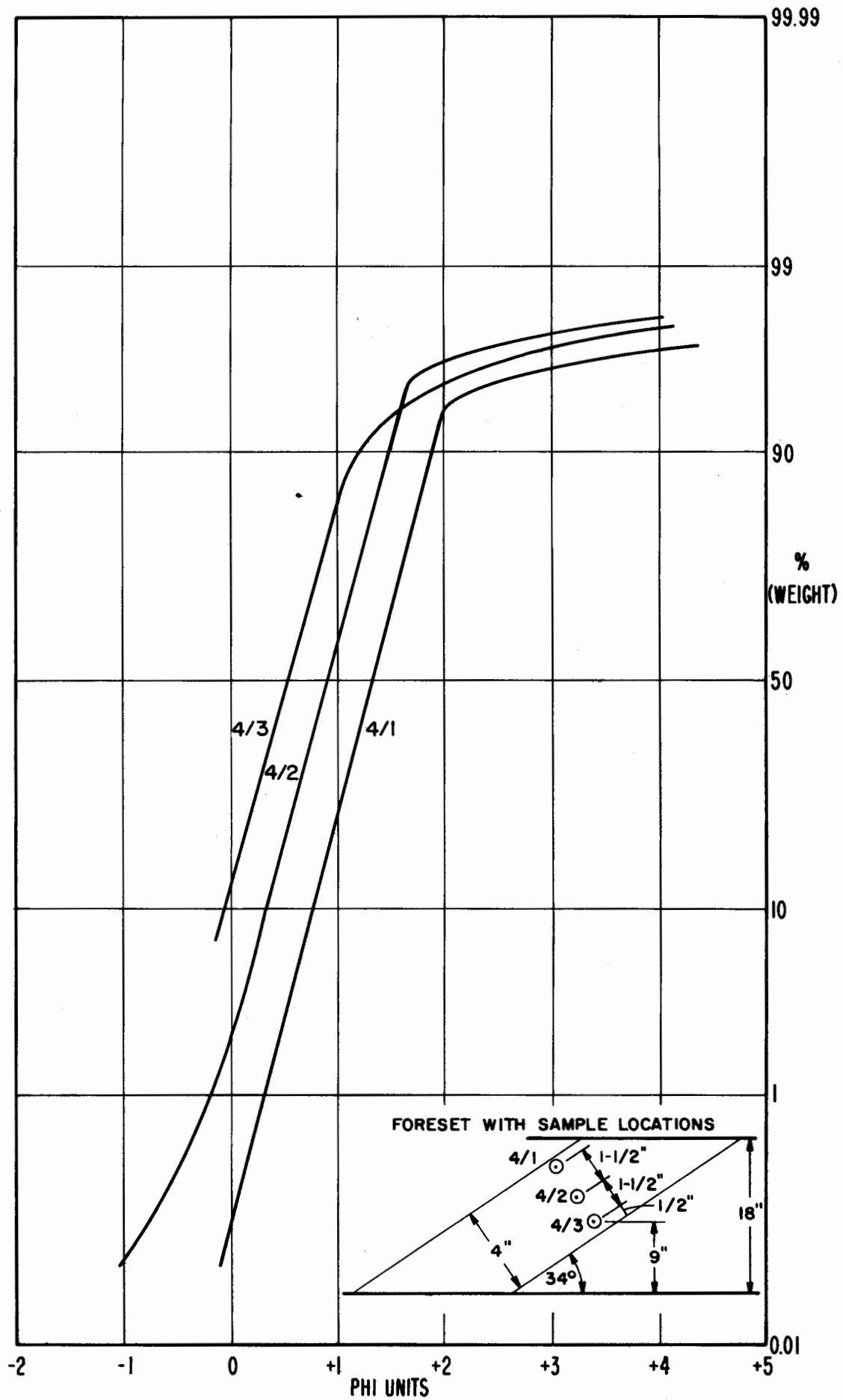


FIGURE 8

TABLE 1: Sedimentary parameters of foresets of cross-bedded sands

Sample number	Location	Percentage Sand	Percentage Silt	Percentage Clay	Mean Grain Size (ϕ)	Sorting (ϕ)
1/1	Gravel	99.47	0.43	0.05	1.71	0.44
1/2	pit no. 1	97.76	2.03	0.19	1.13	0.49
1/3	"	97.63	2.22	0.14	0.52	0.74
2/1	Gravel	97.17	2.68	0.14	1.37	0.60
2/2	pit no. 2	97.64	2.22	0.14	0.90	0.63
2/3	"	96.94	2.84	0.20	0.85	0.95
3/1	Gravel	98.01	1.84	0.14	0.90	0.70
3/2	pit no. 2	98.12	1.70	0.16	0.37	0.68
3/3	"	97.58	2.16	0.25	-0.16	0.85
3/4	"	97.68	2.10	0.21	-0.23	0.85
4/1	Gravel	96.95	2.68	0.38	1.87	0.51
4/2	pit no. 3	97.91	1.83	0.15	1.42	0.59
4/3	"	97.64	2.01	0.34	1.04	0.62

TABLE 2: Sedimentary parameters of cross-beds (sands)

Location	Sample Number	Percentage Sand	Percentage Silt	Percentage Clay	Mean Grain Size (ϕ)	Sorting (ϕ)	Heavy Minerals (weight percentage)
Gravel pit no. 3	1/1x	97.04	2.75	0.19	1.86	0.65	0.52
	1/2x	94.48	4.82	0.69	1.87	0.82	0.59
	1/3x	95.82	3.70	0.47	1.86	0.88	0.49
	1/4x	96.07	3.56	0.36	1.57	1.07	1.16
	1/5x	94.16	5.33	0.50	2.19	0.79	1.46
	1/6x	94.95	4.48	0.56	1.93	0.84	3.21
	1/7x	89.66	9.07	1.25	2.29	0.78	1.82
	1/8x	94.08	5.61	0.29	2.37	0.65	1.49
Gravel pit no. 3	2/1x	96.02	3.88	0.09	2.05	0.52	0.25
	2/2x	96.60	3.32	0.07	1.94	0.57	0.21
	2/3x	95.57	4.17	0.10	1.90	0.80	0.20
	2/4x	96.06	3.88	0.05	1.89	0.76	0.66
	2/5x	95.88	4.05	0.05	1.90	0.69	1.76
	2/6x	96.17	3.72	0.09	1.80	0.69	2.10
	2/7x	94.32	4.70	0.98	1.97	0.71	0.99
	2/8x	92.40	7.45	0.15	1.93	0.70	

Toesets gradually change into *bottomsets*; these are composed of fine sediment produced by backflow deposition only. The recognition of individual bottomset laminae in the area is limited to short distances, such as several feet. Sorting of the sediment is poor (Table 2) and grains decrease in size away from the toeset.

Conditions of formation

Dip direction of foresets in the study area is highly variable, indicating rapid and frequent shifts of the flow direction of Pleistocene streams. The dip of foresets ranges from 12° to 36° ; a decrease of dip is favored by an increase of stream velocity and depth ratio acting either jointly or separately (Jopling, 1960, p. 290). It also produces a change from an angular to a tangential type of cross-bedding.

Concentration of heavy minerals in distant, down current, portions of the bottomsets (Figure 9) suggests that they were transported high above the stream bottom as a part of the suspended load, which is silt and clay. Most of the fine suspended sediments, particularly clays, probably went through the system since only small amounts were trapped in bottomsets (Table 2).

Horizontal Bedding

The term "horizontal bedding" is here used to describe a type of sedimentary structure observed in some coarse sands. Bedding planes appear to be parallel and nearly horizontal; locally, however, they may be slightly inclined in relation to each other. Sorting of these sediments is poor. Scattered pebbles are quite common in the horizontally bedded coarse sands; layers containing such pebbles have less silt and clay matrix than those which lack pebbles (Table 3).

Conditions of formation

According to Jopling (1960), high depth ratio (Figure 3) and/or great velocity of the stream are necessary for the formation of horizontal bedding in coarse sediments.

Horizontally bedded coarse sands in the area of study seem to have been deposited in relatively deep water and in streams of high velocities. This is evidenced by the coarseness of the sediments, presence of scattered pebbles and great thickness of the uninterrupted sequence of horizontally bedded sands (a continuous sequence of 14 feet has been measured).

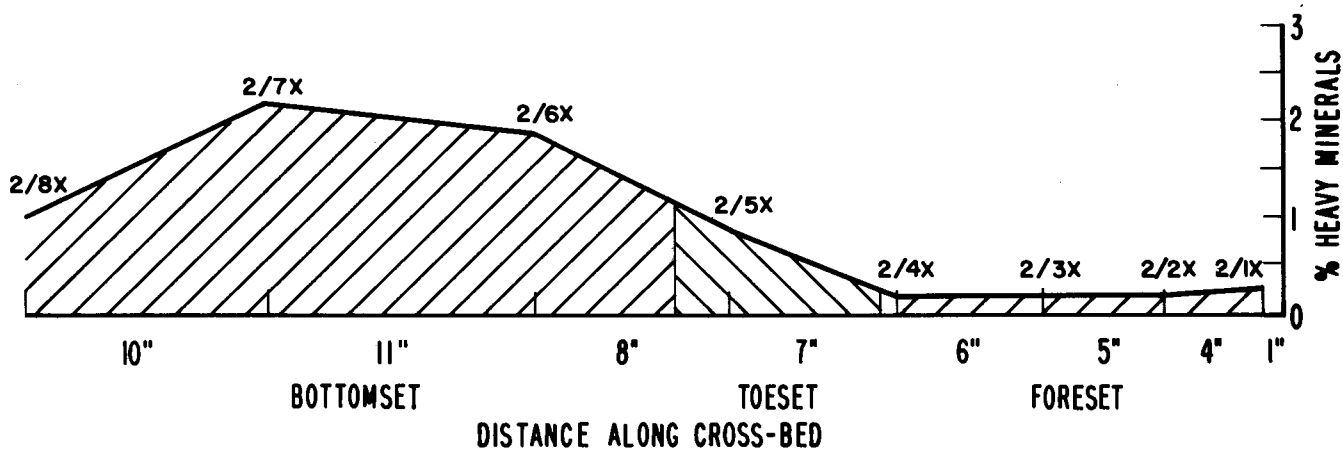
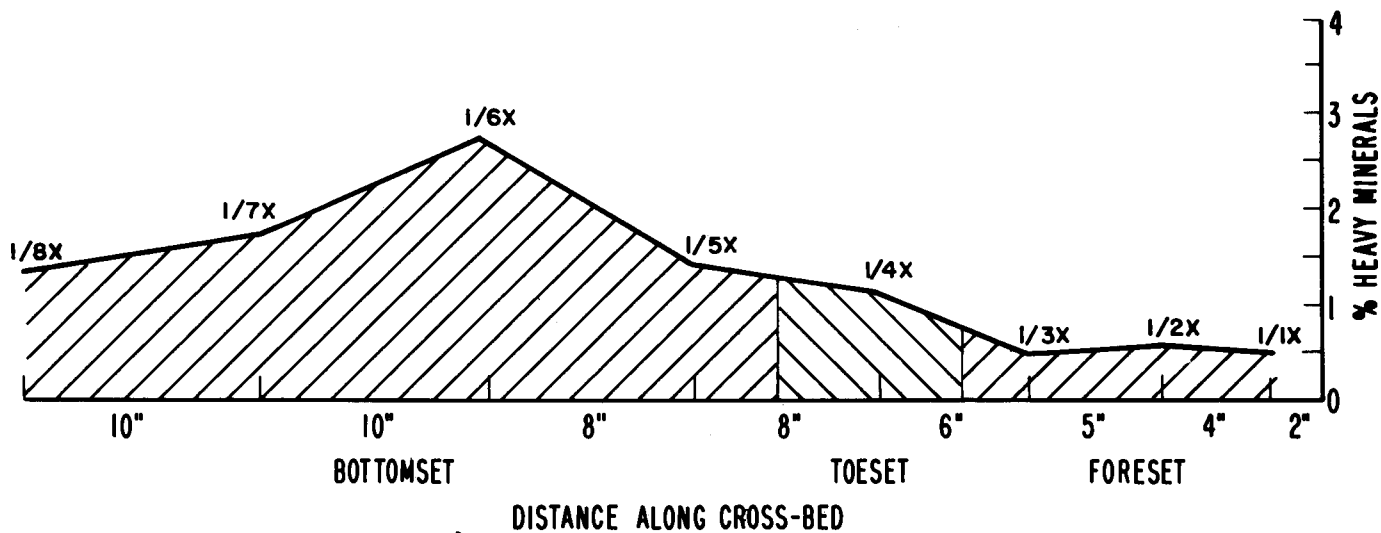


FIGURE 9. DISTRIBUTION OF HEAVY MINERALS IN CROSS-BEDS.
 1/1X, 1/2X.... 1/8X AND 2/1X, 2/2X.... 2/8X ARE SAMPLE NUMBERS.
 (SEE TABLE 2, P 25)

TABLE 3: Sedimentary parameters of horizontally
bedded coarse sands

Location	Sample Number	Percentage Sand	Percentage Silt	Percentage Clay	Mean Grain Size (ϕ)	Sorting (ϕ)
Gravel	*PB/1	96.55	3.27	0.17	1.41	0.98
pit no. 1	*PB/2	97.17	2.67	0.14	1.20	0.99
"	*PB/3	96.10	3.46	0.42	1.22	1.06
Gravel	PB/4	88.12	9.09	2.77	0.91	1.24
pit no. 2	PB/5	92.76	5.61	1.61	1.10	1.03
"	PB/6	94.02	4.61	1.36	0.97	0.98
"	PB/7	55.60	41.79	2.60	1.44	0.96
"	PB/8	59.62	31.14	9.22	1.17	1.12

*Horizontally bedded coarse sand containing scattered pebbles

These sediments are thought to be true channel deposits; their association with cross-bedded gravels and well-sorted gravels supports this.

Horizontal Lamination and Small Ripple-Marks

Horizontal lamination in clayey silts and fine sands was observed both in the outcrops and in the subsurface (holes Fb34-9 and Fb34-12, Appendix II), commonly associated with small, asymmetrical ripple-marks. Sometimes a sequence of horizontally laminated fine sediments is interrupted by a layer of small-scale planar (angular) cross-bedded sand. Sedimentary parameters of these sediments are shown in Table 4.

Conditions of formation

Horizontal lamination in fine sediments is characteristic of deposition under tranquil flow conditions. Such deposition, in the area of study, may have occurred in cut-off meanders, abandoned stream channels, flood plains, or in ponds.

The local presence of small-scale cross-bedded sand layers indicates intermittent flows of current into the depositional environment of horizontally laminated fine sediments. Such currents may have been produced by increased water level and flooding in nearby streams. Also, small asymmetric ripple-marks are probably indicative of flooding; according to McKee (1965, p. 82) such ripple-marks are characteristic "... of areas in which sand accumulated periodically but rapidly, as in river flood plains where sand-laden waters of strong floods suddenly lose velocity."

Lithology of the Sediments

Boulders

Large, angular and rounded boulders of sandstone, crystalline rocks, quartzite, vein quartz, and chert (some more than 1 foot in diameter) are scattered throughout the area of study, and these are thought to have been deposited from ice floes.

Only rarely are the boulders found in depositional sites; mainly they lie at the base of outcrops mixed with other talus. Those found in the position of deposition offer clues to the ways in which they were transported.

TABLE 4: Sedimentary parameters of horizontally laminated fine sediment (samples HL/1 to HL/4) and small-scale cross-bedded sand (samples 5/1 to 5/3)

Location	Sample Number	Percentage Sand	Percentage Silt	Percentage Clay	Mean Grain Size (ϕ)	Sorting (ϕ)
Gravel pit no. 1	HL/1	89.70	9.69	0.59	2.21	0.57
	HL/2	93.83	5.95	0.21	2.20	0.56
	HL/3	90.51	9.07	0.41	2.27	0.55
	HL/4	89.50	9.97	0.52	2.28	0.58
Gravel pit no. 1	5/1	91.87	7.40	0.72	1.93	0.53
	5/2	92.20	7.10	0.68	1.97	0.51
	5/3	96.56	3.17	0.26	1.34	0.63

Some boulders in much finer sediments, particularly cross-bedded sand, were transported independently of the material they were buried in. Quite often the fall of the boulder onto the cross-bedded sand is shown by impact structures; its post-depositional sinking into the substratum is proved by small-scale faults in the overlying sand units (Plate 6). In addition to making impact structures, some boulders have also greatly affected the deposition of the sand and caused the formation of haphazard bedding (Plate 7).

In addition to the boulders deposited from ice floes and similar agents, there are also those which appear to have been transported and deposited as a part of the sediment load of the streams. These are smaller boulders and cobbles found in some cross-bedded gravel units, usually in the toe-sets and lower part of foresets. Such accumulations, if continuous, may eventually form a laterally persistent layer which can be easily mistaken for a unit formed independently of the cross-bedded gravel. However, inspection usually reveals the true origin of such layers.

Gravels

Gravels compose about 30 percent of the total volume of the sediments in the area. The framework of the gravel consists of several rock types; the voids are filled with a matrix of silty and clayey sand and clayey silt. The amount of matrix varies with the type of gravel. In the present work, three gravel types have been differentiated: massive, poorly-sorted; well-sorted; and cross-bedded.

Massive, poorly-sorted gravel

This type-paraconglomerate of Pettijohn (1957)-is an immature gravel characterized by: lack of stratification, excess of matrix over phenoclasts, and nearly complete absence of pebble orientation. It is restricted to the upper part of the Columbia sequence, is sporadic in occurrence and is impersistent laterally. Further, it is the only unit in the area, parts of which are relatively well consolidated.

The pebbles making up the framework are of ten rock types (Table 5); they have shapes shown in Table 6, and exhibit little preferred orientation (Figure 10). The voids in the framework are filled with a silty and clayey sand and clayey silt matrix, as shown in Table 7.



Plate 6. Impact structure produced by the boulder; note small faults and slumps in overlying sediments. Gravel pit no. 3.

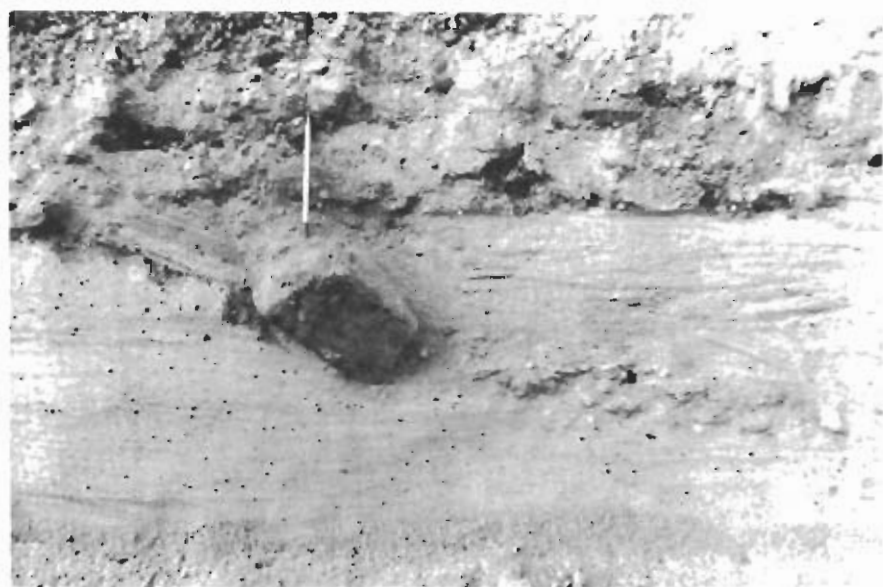


Plate 7. Haphazard bedding in the sand caused by interference of the boulder. Gravel pit no. 1.

TABLE 5: Petrographic composition of pebbles

Rock type	Massive, poorly-sorted gravel (percent)	Well-sorted gravel (percent)
vein quartz	33.5	24.7
quartzite	18.5	29.9
chert	14.0	9.1
crystalline rocks*	13.5	3.9
quartz conglomerate	9.0	16.9
sandstone	5.5	8.8
siltstone	4.0	-
slate	1.0	-
breccia	0.6	-
pegmatite	0.4	6.7

* schist, gneiss, gabbro - identification is often difficult because the pebbles are either partly or nearly completely weathered.

TABLE 6: Shapes of pebbles (Zingg, 1935)

Shape	Massive, poorly-sorted gravel (percent)	Well-sorted gravel (percent)
tabular	39	43
prolate	34	29
equant	20	19
bladed	7	9

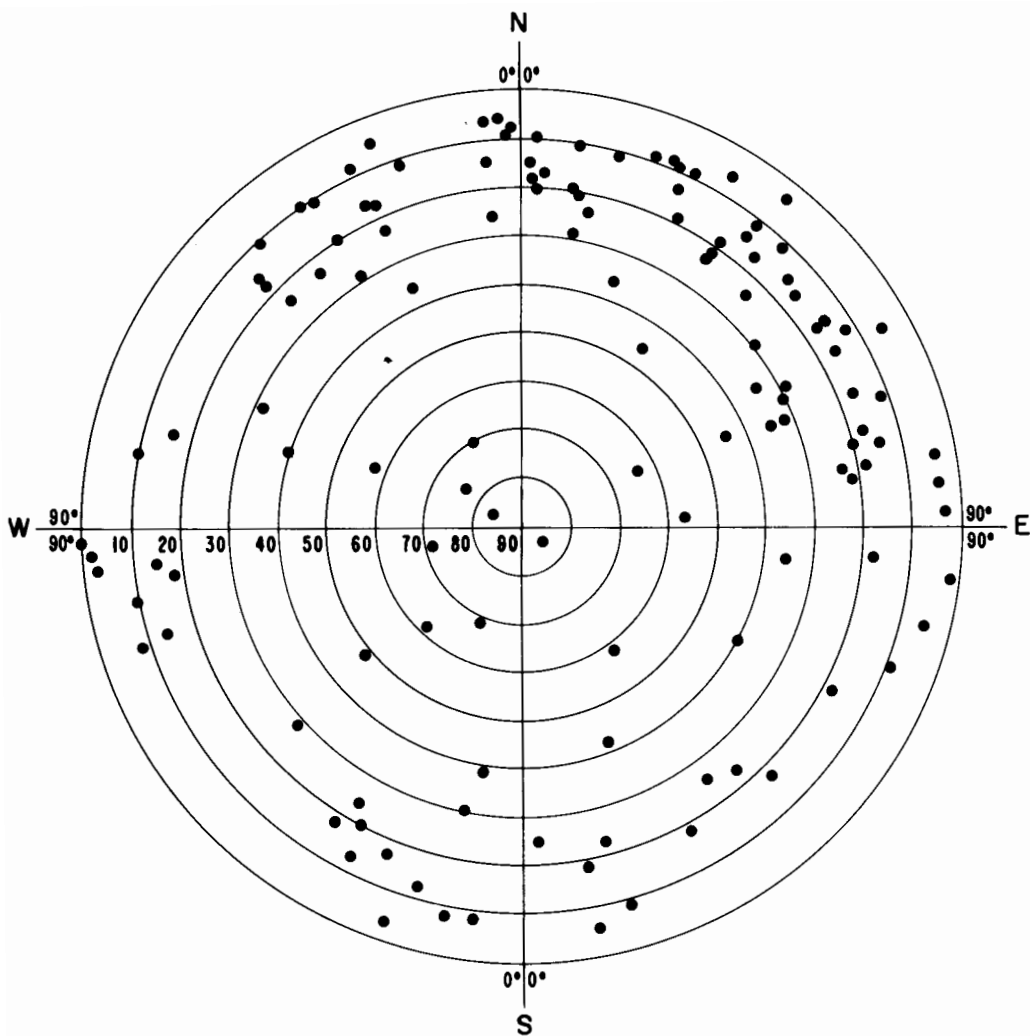


FIGURE 10. ORIENTATION OF LONG AXES OF PEBBLES IN MASSIVE, POORLY-SORTED GRAVEL.

TABLE 7: Sedimentary parameters of massive, poorly-sorted gravel (samples MG/1 to MG/8) well-sorted gravel (samples WG/1 to WG/4), and cross-bedded gravel (samples CG/1 to CG/8)

Location	Sample Number	Percentage Sand	Percentage Silt	Percentage Clay	Mean Grain Size (ϕ)	Sorting (ϕ)
Gravel pit no. 2	MG/1	27.05	70.11	2.83	1.86	1.24
"	MG/2	13.08	45.19	41.71	2.09	1.12
"	MG/3	28.02	60.39	11.58	1.87	1.42
"	MG/4	82.96	12.87	4.15	1.81	1.66
"	MG/5	73.66	24.48	0.85	1.69	1.30
"	MG/6	81.96	15.27	2.75	1.51	1.27
"	MG/7	77.98	19.05	2.95	1.35	1.39
"	MG/8	74.77	20.03	5.18	1.73	1.38
Gravel pit no. 2	WG/1	16.72	75.80	7.47	1.76	1.10
"	WG/2	15.87	71.30	12.81	1.89	1.08
"	WG/3	30.38	58.62	11.06	1.93	1.09
"	WG/4	83.82	12.18	3.98	1.87	0.81
Gravel pit no. 1	CG/1	93.97	5.68	0.34	0.06	1.30
"	CG/2	95.88	3.89	0.21	0.18	1.11
"	CG/3	95.74	3.96	0.29	0.98	0.92
"	CG/4	96.91	2.71	0.37	0.90	0.78
"	CG/5	96.42	3.31	0.26	0.61	0.92
"	CG/6	94.18	5.37	0.43	0.44	1.14
"	CG/7	96.71	3.02	0.26	0.66	1.03
"	CG/8	97.23	2.57	0.19	0.71	1.01

Lack of stratification and nearly complete absence of pebble orientation in the massive, poorly-sorted gravel may indicate a short distance slump that destroyed the original sedimentary structures. The only direct evidence of slumping is offered by a paleosol layer (?) with a distinctive, light gray color. The layer is nearly horizontal, and laterally persistent (Plate 8). However, at one locality it is greatly disturbed, probably as a result of slumping (Plate 9). A large amount of matrix may have contributed to the mobility of this slump and the necessary water saturation may have been achieved by heavy rains or by melting of snow and ice.

In many instances, lenses of cross-bedded sand are preserved in this gravel. They indicate periods of sand deposition interrupted by slumping (Fahnestock, 1963).

It is likely that collapse of river banks into the main stream channels would result in the rapid removal of slumped materials and in their transport and redeposition by the streams elsewhere. This is probably the reason why only the youngest massive, poorly-sorted gravel units are preserved; they are restricted to the uppermost part of the Columbia sequence. The fact that such slumps did exist in the area in the Pleistocene time may be indicative of an environment ". . . where there is a copious supply of moisture and unconsolidated or poorly consolidated clay rich material" (Crandell, 1968, p. 764).

Well-sorted gravel

This unit-petroclastic conglomerate of Pettijohn (1957)-is an immature gravel characterized by: well oriented pebbles, excess of matrix over pebbles, and good stratification. It is usually less than 2 feet thick and is laterally persistent. The framework is made up mostly of resistant rock types (Table 5) which have the shapes shown in Table 6. The voids of the framework are filled with a matrix of sand and silty sand. The petrographic composition is a little misleading since 3.9 percent for crystalline rock fragments (schist, gneiss, gabbro-identification often uncertain) is too low. A relatively large number of such fragments have been decomposed after deposition, most of them beyond identification of the original rock types. They have been transformed into clays and, in many cases, almost completely removed from the sediment, or redistributed within it. Also, the clays may have been incorporated into the matrix. Preferred orientation of the pebbles is so obvious that no measurement has been made. The direction and inclination of long axes correspond with the flow direction indicated by the cross-bedded sand.



Plate 8. Light gray paleosol layer (?) in massive, poorly-sorted gravel. Gravel pit no. 2.



Plate 9. Disturbed light gray paleosol layer (?) interpreted as an evidence of slumping. Gravel pit no. 2.

Cross-bedded gravel

Cross-bedded gravels are of larger scale than the cross-bedded sands and they compose about 40 percent of all gravels in the area of study. The cross-beds are of a tangential type, with well-developed foresets. Topsets are lacking and bottomsets are difficult to recognize because of the coarseness of the sediment. Cobbles, and even boulders, are frequently present and they seem to have been transported and deposited as an integral part of the sediment load.

The framework is composed of resistant clasts. Weathering and decomposition of less durable clasts have resulted in the formation of clays; these clays may have been redistributed as they were in the well-sorted gravel. Matrix is for the most part primary, poorly-sorted, and composed of silty and clayey sand (Table 7).

In outcrops cross-bedded gravel units form distinct channel-type cross-sections and are nearly always in direct contact with the well-sorted gravel. The close association of these two gravel types is not surprising as they are both formed by high velocity streams of great competency.

Cross-bedded gravels are good environmental indicators: their deposition is accompanied by deep erosion of the substratum, and they occur in the main stream channels.

The tangential type of cross-bedding is probably the result of a smaller angle of repose rather than being indicative of a particular flow condition; cobbles and large pebbles can easily roll down the foresets and accumulate in the toesets. There they may form a continuous layer and thus be mistaken for a well-sorted gravel unit. However, lack of pebble orientation, and close association with foresets of cross-bedded gravel are criteria sufficient for their recognition.

Sands

In the study area, sands make up about 60 percent of the total volume of the Columbia sediments. They are unconsolidated, with a matrix of silt and clay, but these finer sizes rarely make up more than 10 percent of the sediment. Sedimentary parameters are given in Table 8.

TABLE 8: Sedimentary parameters of cross-bedded sands (samples 1/1 to 2/3) and horizontally bedded coarse sands (samples PB/1 to PB/3).

Location	Sample Number	Percentage Sand	Percentage Silt	Percentage Clay	Mean Grain Size (ϕ)	Sorting (ϕ)
Gravel	1/1	99.47	0.43	0.05	1.71	0.44
pit no. 1	1/2	97.76	2.03	0.19	1.13	0.49
"	1/3	97.63	2.22	0.14	0.52	0.74
Gravel	2/1	97.17	2.68	0.14	1.37	0.60
pit no. 2	2/2	97.64	2.22	0.14	0.90	0.63
"	2/3	96.94	2.84	0.20	0.85	0.95
Gravel	PB/1	96.55	3.27	0.17	1.41	0.98
pit no. 1	PB/2	97.17	2.67	0.14	1.20	0.99
"	PB/3	96.10	3.46	0.42	1.22	1.06

Sand colors are light gray (10 YR 8/2), yellow (10 YR 7/4), light brown (5 YR 4/4), brown (10 R 4/6), dark brown (10 R 3/4), and purple black (5 R 2/2).

The mineral suite is dominated by quartz, which averages more than 60 percent (number percentages): feldspar is about 30 percent, and the rest is rock-fragments, heavy minerals, and other minor constituents (Jordan, 1964).

The most common sedimentary structure is cross-bedding, which is present in about 80 percent of the sands; horizontal bedding and ripple-marks are subordinate.

Chemical composition

Chemical analyses of two samples are given in Table 9. Silica is predominant by far. Potash exceeds soda, while calcium and magnesium are present in very small quantities. Most of the iron is in ferric form, reflecting highly oxidizing conditions in the depositional environment. The relative large amount of water (H_2O total) probably indicates the presence of hydrous aluminum silicates; a part of it may be incorporated into hydrous iron compounds.

Silica and iron contents are highly variable from sample to sample, and the increase in one is accompanied by a decrease of the other. Manganese is sometimes present in abnormally large quantities (more than 0.6% as MnO), but this is exceptional (Spoljaric, 1970).

Conditions and environment of deposition

Fluvial sands are ". . . as varied as the rivers that produce them, and until more is known about the action of living streams, fluvial deposits will be difficult to study and understand" (Stokes, 1961, p. 162). In addition, the study of sands in outcrop is impeded by one's inability to see the sedimentary body in three dimensions. Therefore, the interpretation of depositional environments of sand units in the area of study is very generalized; additional information is given in the section "Primary Sedimentary Structures."

Coarse to medium channel sands are easy to recognize; they are indicative of lower stream velocities and competencies than those producing horizontally bedded coarse sands. Vertical sections through a sequence of such coarse to medium sand units reveal the erratic shifting course of Pleistocene streams (Figure 11).

TABLE 9: Chemical composition of sands.

Sample Number	Gravel pit no. 2	Gravel pit no. 3		
	Ss/1	Ss/2		
	Percentage Weight	Percentage Cation	Percentage Weight	Percentage Cation
SiO ₂	79.70	87.32	85.80	91.95
TiO ₂	0.02	0.02	0.87	0.70
Al ₂ O ₃	5.06	1.63	5.50	1.74
Fe ₂ O ₃	6.68	1.38	2.00	0.40
FeO	0.08	0.07	0.10	0.09
MnO	0.51	0.47	0.04	0.04
MgO	0.01	0.02	0.23	0.37
CaO	0.36	0.42	0.48	0.55
Na ₂ O	0.26	0.14	0.09	0.05
K ₂ O	1.25	0.44	1.66	0.57
P ₂ O ₅	0.06	0.01	0.06	0.01
H ₂ O _T	4.42	8.08	1.98	3.54
CO ₂	0.36	-	0.17	-
	98.77		98.98	

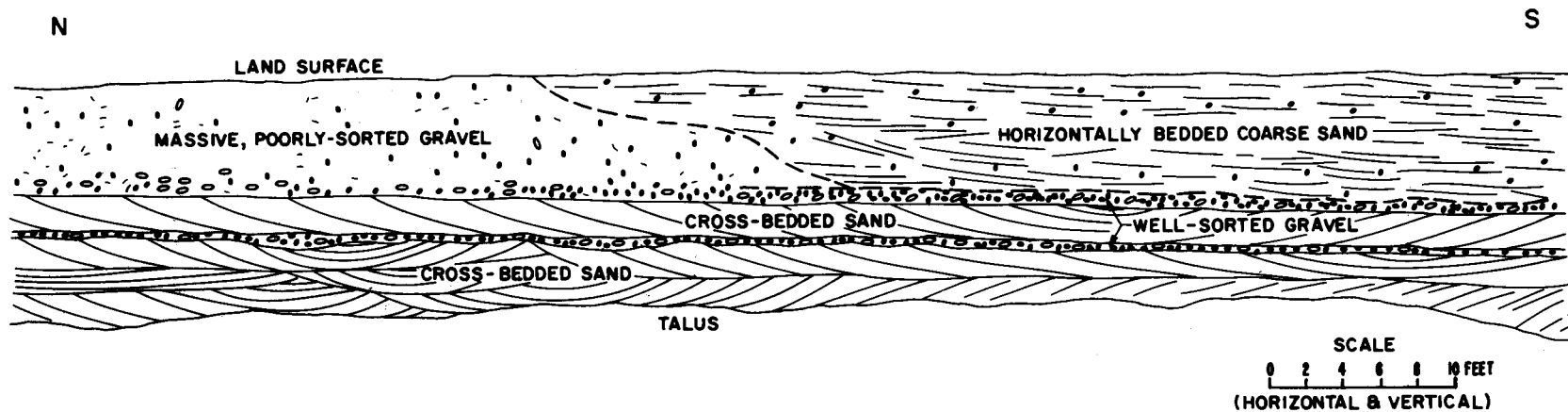


FIGURE II. OUTCROP OF COLUMBIA SEDIMENTS (GRAVEL PIT NO.1)

Cross-bedded fine sand interbedded with horizontally laminated clayey silt is interpreted as being an overbank and flood plain deposit. Coarse, horizontally bedded sand units are often associated with cross-bedded gravel and were probably deposited in stream channels.

Silts and clays

As separate rock units, silt and clay are extremely rare, making up only about 1 percent of the total sediment volume. However, combined in the form of clayey silt, they comprise about 10 percent, not counting the amount of fine material incorporated as matrix in sand and gravel units.

The color of the clayey silts is variable and ranges from light gray (10 YR 8/2) to yellow (10 YR 8/6) and red (10 R 6/6). The most common sedimentary structure is horizontal lamination which is rarely accompanied by small-scale ripple-marks.

The mineral assemblage, determined by X-ray diffraction and microscopic investigation, is quartz, feldspar, clay minerals (illite, chlorite, and some kaolinite) and minor constituents which were not studied. Montmorillonite has not been conclusively identified, though it may be present in some samples. Quantitative analysis of the clay mineral suite has not been undertaken because of uncertainties in the determination of the amounts of individual clay minerals from the x-ray diffractograms (Fenner, 1967; Gibbs, 1967, 1968; and Pierce and Siegel, 1969).

Chemical composition

The chemical composition of two samples of clayey silt is shown in Table 10. Silica is predominant; it is present partly as quartz and partly as a constituent of feldspar and clay minerals. Alumina is an essential component of clays. Most of the iron and probably all of the magnesium are present in chlorite. Small amount of calcium indicates the absence of carbonates, while alkalies are incorporated into feldspars and clay minerals. Titanium probably appears as rutile. Minor components are manganese, phosphorus, and carbon. Water (H₂O total) is a constituent of clays.

The chemical composition of clayey silt may be expected to vary from sample to sample, particularly in regard to silica and alumina content; silica increases and alumina decreases with the coarseness of the sediment (Pettijohn, 1957, p. 343).

TABLE 10: Chemical composition of clayey silts.

Sample Number	Gravel pit no. 1	Gravel pit no. 2		
	S1/1	S1/2		
	Percentage Weight	Percentage Cation	Percentage Weight	Percentage Cation
SiO ₂	68.20	77.58	72.80	79.28
TiO ₂	0.82	0.70	1.02	0.84
Al ₂ O ₃	17.00	5.70	14.50	4.65
Fe ₂ O ₃	1.07	0.23	1.59	0.33
FeO	1.26	1.20	0.08	0.07
MnO	0.03	0.03	0.04	0.04
MgO	0.37	0.63	0.18	0.29
CaO	0.40	0.49	0.43	0.50
Na ₂ O	0.21	0.12	0.28	0.15
K ₂ O	1.95	0.71	1.79	0.62
P ₂ O ₅	0.05	0.01	0.06	0.01
H ₂ O	6.65	12.62	7.28	13.22
CO ₂	0.28	-	0.31	-
	98.29		100.36	

TABLE 11: Sedimentary parameters of clayey silts

Sample Number	Percentage Sand	Percentage Silt	Percentage Clay	Mean Grain Size (Ø)	Sorting (Ø)
S1/1	16.87	70.36	12.77	1.9151	0.9838
S1/2	31.33	58.62	10.05	1.9807	1.0238
S1/3*	17.72	75.87	6.41	1.7837	1.0936

* Sample S1/3 taken from gravel pit no. 1.

Conditions and environment of deposition

Horizontal lamination suggests deposition under tranquil conditions. Frequently small-scale, cross-bedded fine sand is interbedded with horizontally laminated clayey silt. This is probably indicative of intermittent inflow of currents into the depositional environment of the clayey silts during flooding of nearby streams. In the outcrop, the sequence of laminated fine sediment is cut by later (younger) cross-bedded gravel, a true channel deposit (Plate 10). Such a relationship suggests, perhaps, a shift of the stream channel laterally into the flood plain. Structural and some textural (Table 11) characteristics of clayey silts, in addition to the evidences offered by their relation to other lithologic units, indicate that they were deposited in flood plains and similar environments.

SUBSURFACE GEOLOGY

Methods

A method of recognition of various sedimentary structures in the subsurface (Spoljaric, 1970), where these structures cannot be seen, was employed in the interpretation of subsurface geology in the area of this study. The method is based first on the investigation of outcrops and then the application of the results of such investigation to the interpretation of subsurface geology.

Mapping of Subsurface Sedimentary Structures

Forty holes were drilled through the Pleistocene sediments of the Middletown-Odessa area, and 468 drilling samples were obtained for study. In the absence of definite correlation between sedimentary units in the various wells, and in the absence of any other dependable horizon marker, the sediments have been thought of as divided into horizontal layers (or slices), spaced five feet apart, and referred to their height above sea level.

Sedimentary structures determined from the drilling samples (horizontal lamination in clayey silts, cross-bedding in sands and gravels, and horizontal bedding in coarse sands) were mapped for each 5-foot layer separately. In addition, the percentages of the coarsest sand (fraction 2mm to 1mm) were included in the maps and contoured. The amount of the coarsest sand seems to be related to the type of the sedimentary structures: increase in amount is accompanied by a change from horizontally laminated silt, through cross-bedded sand, horizontally bedded coarse sand, to cross-bedded gravel. Such progressive change of sedimentary structures is characteristic of gradually increasing velocity and competency of the stream.



Plate 10. Outcrop of Columbia sediments showing various lithologic units. Gravel pit no. 1.

Interpretation of Maps

Some problems

Fluviatile sedimentary bodies are characterized by great complexity of vertical and lateral lithofacies changes. Marker beds are generally lacking; thus it is practically impossible to establish the time correlation of various sedimentary units even when they are not far apart.

The environmental significance of sedimentary structures is not well known. The conditions under which they form, however, are relatively well understood. For instance, ripple-marks of a similar type may form in marine and continental environments, but the flow conditions under which they form in both environments are basically the same. The geometry of fluviatile sedimentary bodies is sometimes helpful; for example, sediments deposited in channels usually have a shoe-string form. The texture of the sediments is often altered by post-depositional processes (decomposition of less resistant minerals, addition or removal of materials by percolating ground-water, diagenesis) and is unreliable in environmental reconstructions.

Depositional processes

Cross-bedded gravel and horizontally bedded coarse sand were deposited by streams of high velocity and great competency and such sediments are thought to be true channel deposits. For this reason, the interpretation of depositional processes and behavior of Pleistocene streams is generally based on the distribution and areal extent of these particular sediments.

Layer No. 1, elevation +10 feet (p. 45). Distribution of the Columbia sediments is strongly controlled by the topography of the underlying greensands. The streams flowed diagonally through the area, from northeast to southwest. Branching of the stream in the southwestern part of the area may have been caused by a topographic high in the greensands. The cross-bedded gravel is restricted to the same southwestern part of the area.

Layer No. 2, elevation +15 feet (p. 47). The control of the underlying greensands on the distribution of the sediments is still apparent. However, the direction of the stream flow has changed to north-south; a well developed meander in the southwestern portion of the area has replaced the branches observed in layer no. 1; the southern branch was probably choked up by deposits and cut off from the main stream channel.

Layer No. 3, elevation +20 feet (p. 49). The stream has regained northeast-southwest flow parallel to the trend of the greensand body. A tributary stream has appeared in the west, flowing north-south; its great competency is evidenced by the coarse gravelly sediment deposited in its channel.

Layer No. 4, elevation +25 feet (p. 51). The confluence of the two streams was eventually blocked by sediments and the streams formed separate channels extending north-south. The influence of the greensand topography has almost completely disappeared.

Layer No. 5, elevation +30 feet (p. 53). The connection between the two streams is re-established; only small patches of the greensands remain at this elevation.

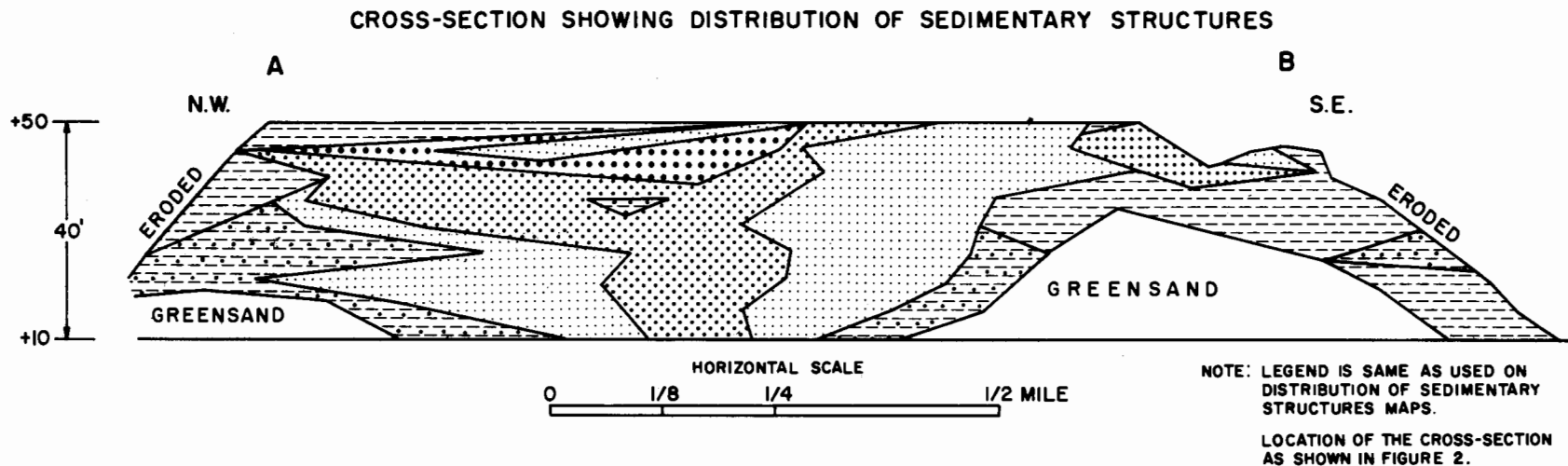
Layer No. 6, elevation +35 feet (p. 55). The western stream dominates the depositional processes at this elevation; large amounts of gravel bear witness to its great competency and high velocity. At the same time, the eastern channel was the site of sand deposition; its branching in the northern part of the area may indicate a decrease in depth of water.

Layer No. 7, elevation +40 feet (p. 57). The dominance of the western stream continues; the confluence of the two streams has shifted eastward and the amount of gravel has increased. This increasing amount of coarse sediment is an indication of an oncoming great flood, which reached its climax at the +45 foot elevation (layer no.8).

Layer No. 8, elevation +45 feet (p. 59). Complex stream pattern and large masses of gravel brought into the depositional sites are a strong indication of extensive flooding. In addition, the continuity of the gravel bodies suggests steady direction of main stream flow and intensive erosion of stream channels.

Layer No. 9, elevation +50 feet (p. 61). The flooding ceased and was followed by a decrease in water and sediment discharge; water retreated into narrow, gently meandering channels. Gravel is scarce at this elevation.

At higher elevations, interpretation becomes difficult because only erosion remnants of the Columbia sediments are preserved; these remnants are hard to relate to each other.



CHANNEL DEPOSITS (HORIZONTALLY BEDDED COARSE SAND AND CROSS-BEDDED GRAVEL) FORM A CONTINUOUS VERTICAL SEQUENCE.

The subsurface geometry of flood plains, levees, and other features associated with stream channels is difficult to recognize and delineate.

SUMMARY AND CONCLUSIONS

Geologic History of the Columbia Formation

Columbia sediments in the area of study were deposited upon a surface made up entirely of Rancocas (Paleocene-Eocene) greensands. This surface is composed of wide, shallow valleys and gently rolling hills trending north-south and north-east-southwest. The contact between the greensands and the sediments of the Columbia Formation is an erosional unconformity.

At the onset of Columbia sedimentation, the greensand valleys were probably first deepened by eroding streams and the hills were lowered by denudation. Filling of the valleys with Pleistocene sediments followed; this process, however, was now and then interrupted by periods of erosion. Since net deposition exceeded erosion, eventually the topography on the Rancocas surface was completely covered by Columbia sediments; the result was a flat, almost featureless surface.

Locations of stream courses at elevations below about +25 feet were controlled by the greensand topography; above this elevation, however, the influence of this topography disappeared almost completely, and the streams shifted their courses without deterrence in areas formerly occupied by Rancocas hills.

Columbia sediments were deposited in stream channels, flood plains, cut-off meanders, and levees. The recognition of these various environments, particularly in the subsurface, is often hindered by one's inability to see sedimentary bodies in three dimensions.

Conditions of deposition ranged from those present in channels occupied by high-velocity and high-competency streams, to those of a tranquil environment. High velocity and great competency is evidenced by well-sorted gravels, cross-bedded gravels, and horizontally bedded coarse sands. All of these units contain cobbles, and most of boulders, which seem to have been deposited as a part of the sediment load of the streams. Deposition under tranquil conditions, on the other hand, is evidenced by horizontally laminated clayey silts. All gradations between these two extreme flow conditions are revealed in cross-bedded sands; these range from angular to tangential type and the sediments are characterized by great variability of their textures.

In addition to materials brought into the area as a part of the sediment load of the streams, there are also those that are thought to have been transported independently of the sediment load. These are large boulders, scattered throughout the area of study; such large boulders are believed to have been transported by ice floes and similar agents.

The channels of Pleistocene streams are shallow and they rarely exceed 1/2 mile in width. Frequent flooding of such streams contributed large amounts of coarse gravelly sediment to the area. These large water and sediment discharges, however, seem to have been of short duration, caused by small climatic changes.

Slumped river banks (massive, poorly-sorted gravel) indicate a copious amount of moisture in the Columbia sediments. Stream banks or levees which became unstable collapsed and slid into the stream channel. This slumped material was rapidly incorporated into the sediment load of the stream and transported elsewhere. This removal is thought to be the reason why only the youngest slumps of this kind are preserved: they are always found at the top of the Pleistocene sequence. In the process of slumping, most original sedimentary structures were completely destroyed; locally, however, remnants of these original structures may be found.

Practical Application of Results

This study has revealed that, in the area of present study, there are no morphologic features of the land surface that can be used in recognition of areas of thick deposits of sand and gravel. Two explanations are offered to account for this: either areas containing thick deposits simply do not have distinct expressions in the present surface topography, or the original topographic features have been modified and distorted by human activity. As the relationship between present topography and thicknesses of the Columbia sediments has been recognized on a large scale (Spoljaric, 1967), the lack of such relationship in the study area is probably the result of human activity such as farming for example.

The channels of Pleistocene streams are less than 1/2 mile wide and at elevations above +25 feet (SLD) they are not confined to the valleys in the greensand surface. Therefore, it becomes important to make a clear distinction between stream channels and valleys filled with the Columbia sediments. The channels are narrow, shallow, and meandering or straight, and they contain almost exclusively coarse sand and gravel (cross-bedded gravel). Valleys, however, are much larger, wider, and are filled with a variety of sediments.

A method of recognition of primary sedimentary structures in the subsurface (Spoljaric, 1970) was found helpful in detection and delineation of ancient stream channels in the area of present study. The method is direct, reliable, but it requires extensive drilling.

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HYDROLOGY AND GEOPHYSICS OF COLUMBIA SEDIMENTS IN THE MIDDLETOWN-ODESSA AREA, DELAWARE

by

KENNETH D. WOODRUFF

ABSTRACT

The Columbia Formation in Delaware is generally an excellent water producer where sufficient saturated thickness is available. The usual method of locating thick areas of Columbia sediments has usually been by carefully controlled drillings, a reliable but often expensive technique. Twenty-two electrical resistivity soundings, and two traverses were made in an attempt to determine the usefulness of the resistivity method in predicting Columbia thickness. These results were compared with data obtained from test holes augered for control purposes. Results show that resistivity techniques appear to be useful in determining gross lithologies but accurate depth solutions are not always possible. Prior information on the geology and hydrology of an area are necessary before interpretations can be made with confidence. Resistivity work in areas of the State outside of the main study area (Middletown-Odessa) has proven quite promising in determining the water productivity of an area.

The Columbia Formation is the water-table aquifer in the Middletown-Odessa area and in most other parts of the State. Saturated thickness and water levels were determined in the study area by temporary installation of piezometers. The water-table was found to average about 30 feet below land surface in the central part of the study area. This is lower than in most places throughout Delaware. A forty-eight hour pump test showed that the transmissivity of the main paleochannel east of Middletown is about 40,000 gpd/ft. High iron content (1-2 mg/l) and low pH are common in water from the Columbia Formation and may present treatment problems.

Review of available data shows that extrapolation of Columbia aquifer coefficients from one area to another is not reliable and may produce erroneous results.

INTRODUCTION

Much of Delaware's future ground-water development will be from the Columbia Formation (or Columbia Group) which is the water-table aquifer throughout most of the state. In southern Delaware, Columbia sediments are generally thick over wide areas and, with some exceptions, little trouble is encountered in finding enough saturated thickness for high-yielding wells. However, in northern Delaware, the Columbia Formation is usually thin with local occurrences of thicker paleochannels. To date, only controlled drilling has been able to delineate Columbia thickness with reliability. This is due to (1) the lack of any major surface expressions of Columbia paleochannels and (2) the gross similarity of Columbia sediments to other underlying or adjacent Coastal Plain formations. Development of a technique other than drilling for locating such channels would be of great value in delineating future ground-water supplies.

Reliable data on aquifer characteristics are not readily available for the Columbia Formation. Most aquifer tests on record are only a few hours in length and the interpretations are somewhat questionable. Yet such data must be had to accurately determine the performance and effects of proposed wells. Thus, the present study was designed to gain some information on ways of locating potentially productive ground-water areas and, if possible, to determine a possible range of aquifer coefficients. The study is of immediate practical importance in that several communities in Delaware are looking to expand their water supply systems. The Pleistocene aquifer is the logical and in some cases, the only source available.

ACKNOWLEDGMENTS

Appreciation is extended to the Delaware Geological Survey for the use of laboratory facilities and equipment and to the Department of Geology, University of Delaware for the use of their portable seismic refraction unit.

Mr. John Talley and Mr. Boris Bilas, both of the Delaware Geological Survey, assisted in various aspects of the

field investigations, particularly the resistivity surveys. Mr. Richard Johnston of the U. S. Geological Survey and Mr. John Miller of the Delaware Geological Survey helped in conducting the aquifer test near Middletown and in interpretation of the results. The conclusions published in this report however, are solely the responsibility of the author.

Dr. Johan J. Groot, State Geologist of Delaware until January, 1969, initiated the project and provided general supervision. Dr. Robert R. Jordan, present State Geologist, then assumed supervision and reviewed the final manuscript.

Recognition is also due the many private citizens in the Middletown-Odessa area who allowed use of their land for test drilling and resistivity measurements.

RESISTIVITY SURVEYS

Background

Several attempts have been made by other workers to use electrical resistivity methods as an exploration tool in the Coastal Plain sediments of Delaware. Spicer et al. (1955), used resistivity techniques in prospecting for sand and gravel aquifers in northern Delaware. More recently, Bonini (1967) applied the method to a few selected areas in Delaware. Bonini's results were not entirely conclusive, but indicated that resistivity might be useful as a qualitative tool. However, this work, by design, was not extensive in scope and was limited to areas of known Pleistocene thickness.

The chief aim of the present study was to elaborate further on the resistivity method and to develop, if possible, a field procedure that would give a reliable basis for determining test well locations. The theory of earth resistivity measurements has been discussed in any number of publications and are not dealt with here in detail.

A somewhat easily understood discussion is presented by Kelly (1962). Basically, the field procedure is to place four electrodes in the ground in a straight line. A known current is passed through the two outer electrodes and the resultant voltage drop caused by the sphere of earth through which the current passes is measured by the two inner electrodes. The distance between any two electrodes is designated the "A" spacing, and in the Wenner method, (Wenner, 1915-1916), the "A" spacing between all electrodes

is equal. In resistivity sounding techniques, the "A" spacing is changed for each reading in some orderly sequence but the center of the spread remains at the same point. In traversing techniques, the "A" spacing remains constant but the entire electrode arrangement is moved a fixed distance for each reading.

There are several methods of plotting data obtained from resistivity surveys. The most theoretically valid technique is to match log-log plots of "A" spacing vs. apparent resistivity against published type curves. Depths and apparent resistivities of up to three layers can then be calculated. The Moore method (Moore, 1945) plots cumulative resistivities obtained at each "A" spacing against "A" spacing. Lithologic breaks are assumed to occur at the depths for which changes of slope are noted on the plot. The simplest technique is to plot apparent resistivity against "A" spacing on linear paper. This usually gives a rather smooth curve, somewhat similar to that obtained by conventional down-hole electric logging. However, accurate depth determinations of lithologic changes can be rather difficult to make by this technique.

In the beginning of the study, most data were plotted on log-log paper, semi-log paper, and linear paper as a routine check on instrument performance. Several interpretations were then tried, including curve matching. The authors are aware that there is not universal agreement on the validity of the various interpretive techniques, especially the Moore cumulative method. However, one of the purposes of the study was to find a practical geophysical method that gave reasonably consistent results in the study area and, hopefully, in other parts of Delaware. It was not the purpose of the study to investigate in detail the theoretical aspects of any field procedures, although such aspects are certainly not to be minimized.

An ER-2 earth resistivity meter, with 200 feet of cable either side of center, was used in all resistivity determinations. The commercial cable arrangement is rather cumbersome as supplied and was modified to a quick change plug and reel assembly for rapid field handling. In the first half of the study, various resistivity techniques were briefly tried. However, it was felt that the most reliable information for the purposes of this study was obtained by resistivity soundings using either the Lee or Wenner electrode arrangement. The Lee method is similar to the Wenner arrangement, except that a fifth electrode is placed in the center of the electrode spread. Additional readings are then made to the left and right of center. Concurrent drilling and geologic mapping of the study area provided excellent

control for determining the effectiveness of resistivity measurements and validity of the interpretation.

Twenty-two soundings and two traverses were run as part of this study. The "A" spacing range for the soundings was from four feet up to a maximum of one hundred thirty-two feet in four foot intervals. The "A" spacing of one hundred thirty-two feet used nearly all the available cable and may have been near the limits of the instrument's capability in many cases. Most surveys were in areas where the thickness of Pleistocene sediments was known fairly accurately. The results of the soundings are discussed below and the locations of soundings in the Middletown-Odessa area are shown on Figure 12. The data plots will be found in Appendix IV.

Eastern Middletown-Odessa Area

Sounding A

The curve matching method fitted best the three layer curve of the type $p_1:10 p_1:3 p_1$ (top to bottom layer resistivities). However, depth determinations were not conclusive and could not be matched with the lithology found in the control test holes Fb33-14 and Fb33-20. The Moore cumulative method gave several breaks, with two shallow breaks occurring at 12 feet and 20 feet. The water table was measured in the test holes at 21 feet below land surface, which agrees reasonably well with the 20 feet break. A less well-defined break which may be indicative of the base of the Columbia Formation occurred at about seventy-one feet. However, the driller's log of the control test holes indicated that the base of the Columbia Formation was sixty-one feet below land surface. Linear plots, log-log plots, and semi-log plots all showed some type of boundary at twelve feet, but an inflection marking the base of the Pleistocene was not clear in all plots. Overall apparent resistivities were generally high with the total cumulative resistivity at a spread of 132 feet, being about 50,000 ohm-feet.

Sounding B

A log-log plot of data from sounding B did not match any theoretical curve, although the plot had the general slope of a three layer curve. The Moore cumulative plot showed a pronounced break at forty-eight feet, which corresponded very well with the base of the Columbia Formation recorded at forty-six feet in the control test hole (Fb44-6).

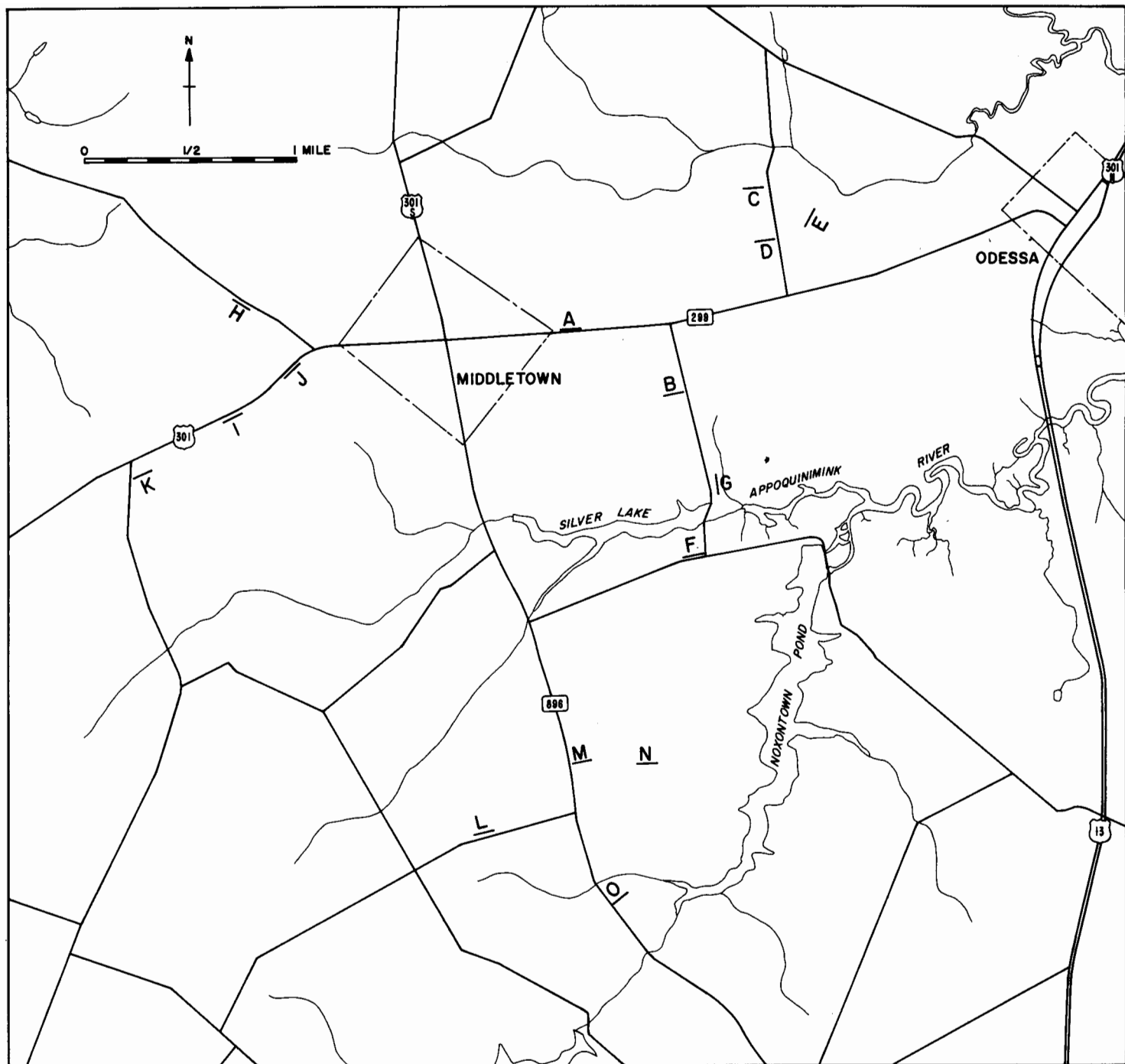


FIGURE 12. LOCATION OF RESISTIVITY SOUNDINGS IN THE MIDDLETOWN -ODESSA AREA, DELAWARE.

A shallow boundary also occurred at ten feet on the Moore cumulative plot. Overall resistivities were again quite high, but the total cumulative resistivity was somewhat less than that for sounding A. The total thickness of Columbia sediments was also less at the location of sounding B than at the location of sounding A.

Sounding C

The Moore cumulative plot showed two rather distinct breaks at fourteen feet and thirty-four feet. The break at thirty-four feet may correspond to the water table which occurred at about thirty feet below land surface in the area of sounding C. No break was seen at the depth for which the base of the Columbia Formation was observed in the control test hole. However, it seems significant that this sounding was made in one of the thickest Columbia sections in the study area, and the Moore plot changed little below about thirty-four feet. Thus, the apparent resistivity was seemingly influenced almost entirely by the eighty foot-thick Columbia sands present at this location.

Sounding D

The Moore cumulative plot of data from this location very closely resembled the plot of sounding C. Again, two shallow breaks were observed with a constant slope below about thirty-eight feet and no indication of the base of the Columbia Formation. The overall cumulative resistivity was nearly 60,000 ohm-feet at the maximum electrode spacing of 132 feet. The Columbia Formation is at least 80 feet thick at this location.

Sounding E

Results from this sounding were not considered. The extremely high apparent resistivities were due probably to the effect of a nearby gully.

Sounding F

Two distinct shallow breaks were noted on the Moore cumulative plot with the break at ten feet possibly corresponding to the base of the Columbia Formation. Previous work at this site by the U. S. Geological Survey in 1958 (unpublished) indicated that the Pleistocene age sediments were only about eight feet thick. The break at twenty-three feet is an excellent correlation with the water table as reported by Boggess and Adams (1964). Again, overall resistivities were comparatively high. However, in this case it is thought

that such high readings are due to the presence of the Rancocas Formation directly beneath the Columbia Formation. Hydrologically the weathered portion of the Rancocas and the bottom of the Columbia Formation appear to function as a single unit, and surface resistivity methods could not always distinguish between the two formations.

Sounding G

This sounding was made in order to get some idea of what apparent resistivities were in the finer-grained sediments of the Rancocas Formation. A test hole had already shown that the Columbia Formation was only about five feet thick at this location. Nearly all apparent resistivity readings were well under 100 ohm-feet, and the cumulative resistivity at a Wenner spacing of 120 feet was only about 15,700 ohm-feet. The lowest apparent resistivities of any of the soundings in the Middletown-Odessa area were found at this site due probably to the characteristics of the Rancocas Formation and the interstitial water.

Western Middletown Area

Following completion of resistivity surveys on the eastern side of Middletown, it was decided to extend the resistivity work to the western side. This was prompted by a request from the Town of Middletown for help in selecting additional town well sites. Previous work by Spoljaric (1967) also indicated the possible presence of a filled Pleistocene valley in the general area. In this portion of the study, resistivity sites were chosen on the basis of topography and the location of drill holes were based on the results of the resistivity work. Soundings made for this part of the study are discussed below.

Sounding H

This site was chosen because it occupies a very broad, gentle topographic rise. The Moore cumulative plot showed only a single, poorly defined break at fifty-six feet and, overall, apparent resistivities were not exceptionally high. A log-log data plot also gave a solution at 60 feet, although the plot is somewhat questionable. A subsequent test hole showed about thirty-one feet of Columbia Formation, underlain by weathered Rancocas Formation. This is one of the few soundings where correlations could not be made with drilling results and, at present, no explanations can be given for this inconsistency.

Soundings I and J

Both of these soundings gave low apparent resistivity values, and, on this basis, no test holes were drilled. The data plot from sounding J showed an especially distinctive break at thirty-six feet. This was interpreted to be the base of the Columbia Formation. A shallower break at fourteen feet may be the water table, and if so, agrees quite well with the earlier mapping by Boggess and Adams (1964) in this area.

Sounding K

The first break on the plotted data from this sounding was noted at forty-eight feet. However, resistivity values were generally low and it was believed that the break represented a low resistivity layer well into the Rancocas Formation. A subsequent test hole showed that only thirty-three feet of Columbia sands are present, underlain by rather fresh Rancocas sediments, which become increasingly finer-grained with depth. The boundary at forty-eight feet on the data plot may not physically exist, but could represent the cumulative resistivity effect of a generally fine-grained sediment sequence beneath the coarser Pleistocene material.

Southern Middletown Area

Soundings were next made south of Middletown in an attempt to locate any southern extension of the main paleo-channel located just east of Middletown. The following soundings were made in this part of the investigation:

Soundings L, M, N, O

Data from location L revealed that the thickness of the Columbia Formation at this location was less than about thirty feet. Apparent resistivity values were far lower than were values for most other soundings run in the study. The location, thus, was not considered for a test hole.

Sounding M, about 3000 feet to the northeast of sounding L, showed relatively high apparent resistivities. Breaks were noted at forty-five and sixty-eight feet on the Moore cumulative plot of sounding M. The log-log plot matched, generally, a three layer type curve, but no match with a specific three layer curve could be made. A test hole (Fb53-6) at this location showed only twenty feet of Pleistocene sand, underlain by forty feet of generally sandy clay. The break at sixty-eight feet on the Moore plot may correspond to a lithologic and/or formation boundary at sixty-five feet

as noted on the driller's log (see Appendix IV). The thick section of clay and sandy clay found in the test hole is very possibly part of the Columbia Formation rather than the older Rancocas Formation. The location of this sounding is apparently south of the main portion of the paleo-channel, and the lithology may represent filled valley-type deposits outside of the main paleochannel.

Sounding N was located about 1500 feet east of sounding M. The apparent resistivity values were quite low and the sandy portion of the Columbia Formation is probably not over thirty-five feet thick here. The location was not considered for a test hole.

Sounding O gave slightly higher resistivity values than at N and the bottom of the Columbia Formation was picked at forty feet, based on the Moore cumulative plot. However, the overall data did not appear favorable enough to drill a test hole.

Milford Area

The Milford area was selected for resistivity surveys for two reasons: (1) The City of Milford had an immediate need for water and had asked the Delaware Geological Survey for assistance in choosing well locations and (2) some older driller's logs indicated scattered areas of apparently thick surficial sands. On this basis, it was thought that possibly a Pleistocene channel did exist in the southern half of the city.

In order to obtain control, the first sounding M-1 (see Figure 13 for location of soundings) was located at the site of a previous test hole drilled by the town. The Moore cumulative plot showed the base of the Columbia Formation at about 34 feet, but a linear plot showed the base at about 48 feet. Both the driller's log and an electric log from the control test well (Mel5-31) showed the base to be at 48 feet. Relative resistivities were fairly high and a short pump test run at this location in well Mel5-31 produced a yield from the Columbia Formation of 250 gpm with 26 feet of drawdown.

A second sounding (M-2) was made about 180 feet north of sounding M-1. So significant difference in resistivities were noted. However, the Moore cumulative break appeared slightly deeper, at about 40 feet. The location of this second sounding was based on a horizontal traverse run in a west to east direction, starting just west of the test well

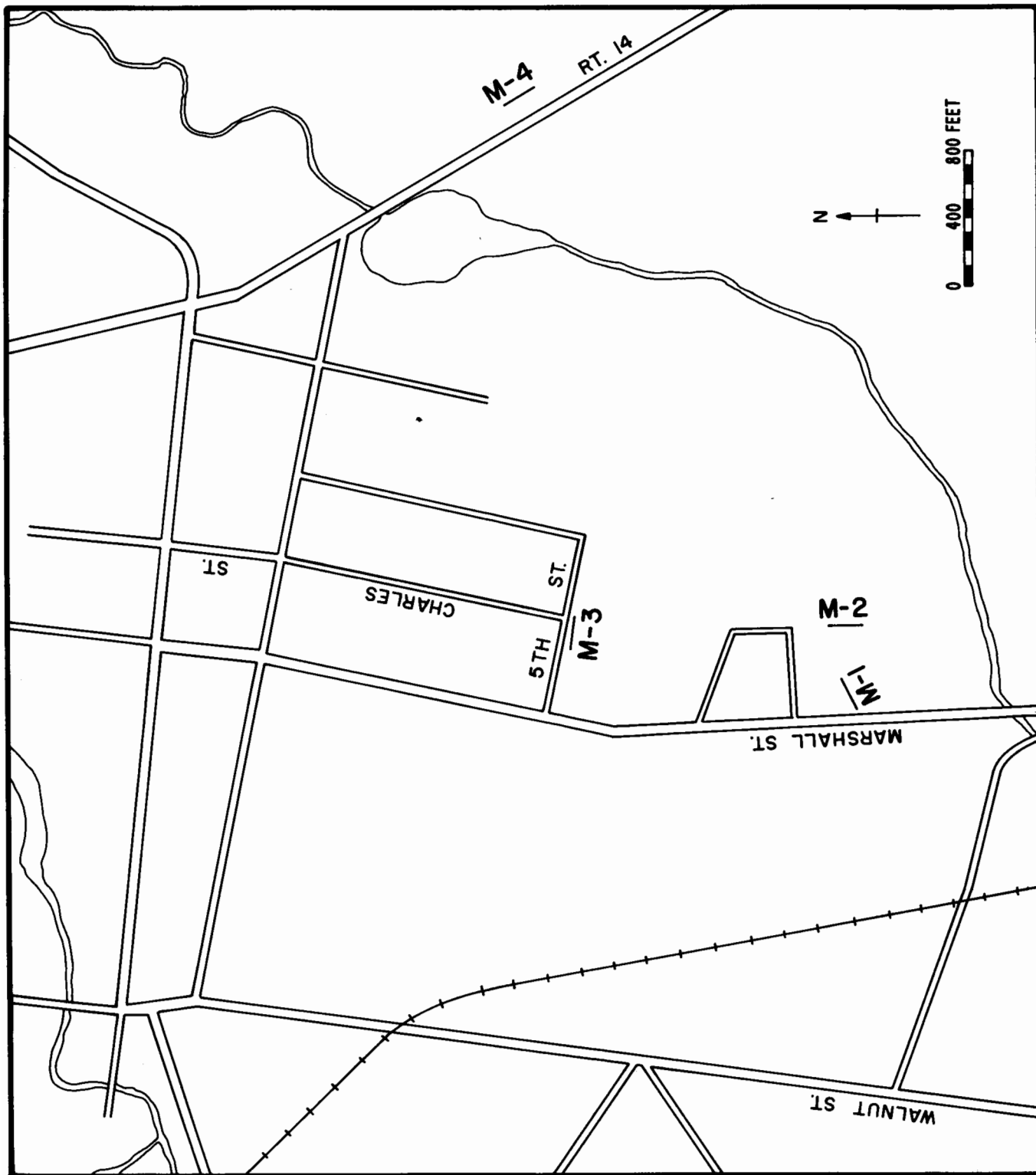


FIGURE 13. LOCATION OF RESISTIVITY SOUNDINGS IN THE MILFORD AREA, DELAWARE.

Me15-31. An "A" spacing of 44 feet was used and readings made every 65 feet for a total distance of 650 feet. Apparent resistivities generally increased to the east for a short distance, and then decreased again.

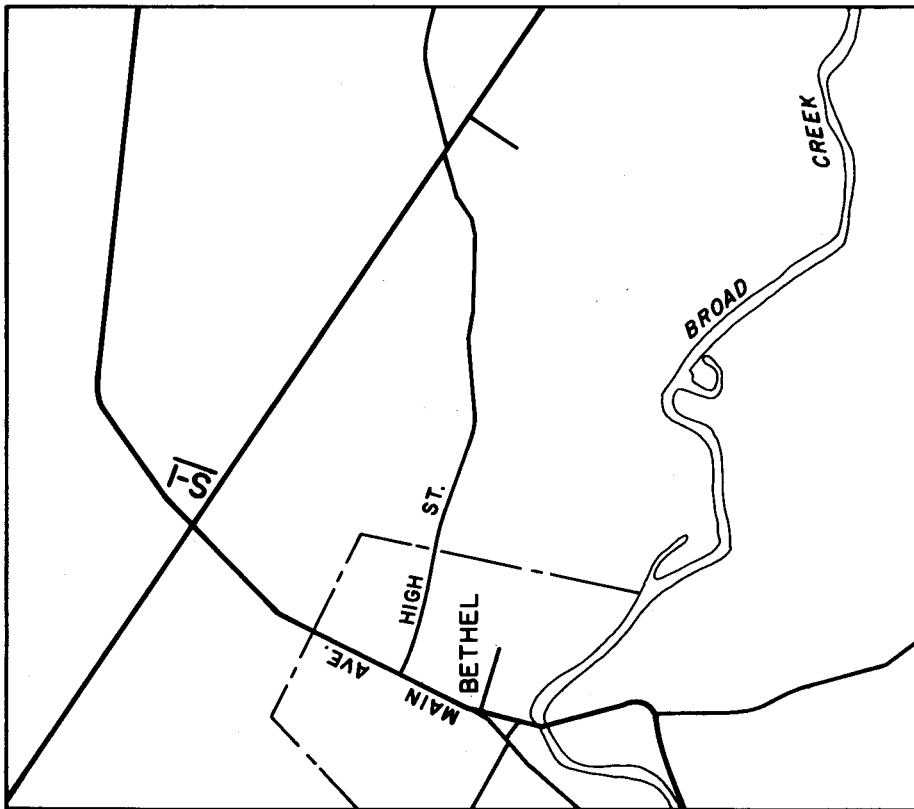
A third sounding (M-3) was made about 1500 feet north of location M-2. This location was based on land availability and the desire of the town to locate a well near a main water line. Overall cumulative resistivities were considerably higher than at the two previous locations. The Moore plot indicated the base of the Columbia Formation to be at about 48 feet below land surface, while interpretation of the linear plot (Appendix IV, sounding M-3) placed the base at about 40 feet. A 100-foot deep test hole was later drilled here as part of the study and showed the thickness of the Columbia Formation to be about 36 feet. However, silty sands of Miocene age were found to occur beneath the Columbia Formation, separated from the Columbia by only four feet of clay. The test hole also showed that the Miocene sands became coarser at about 85 feet. This is reflected in both the linear and Moore cumulative data plots (see Appendix IV, M-3 plots). The coarser material was correlated with a minor Miocene aquifer which is known to occur in other places beneath the Milford area. This aquifer is already heavily used and, thus, a production well was not recommended at the 85 foot depth.

Sounding M-4 was located southwest of Marshall's Pond in an attempt to check a promising driller's log from a nearby well. However, it became apparent that surficial sands were quite thin, probably not over 20 feet thick. Extremely low resistivities were obtained with nearly all electrode spacings, and no further work was attempted at this location.

Work is continuing in the Milford area and concentration is now on locations farther to the south. All indications are that the Columbia Formation is less than 50 feet thick at most places within the city limits but thickens rapidly to the south.

Other Soundings

Soundings were also made at three other locations in the State, other than those discussed above (see Figure 14). The purpose was to gain some idea of what resistivities were in thick Pleistocene sediments of various geological environments.



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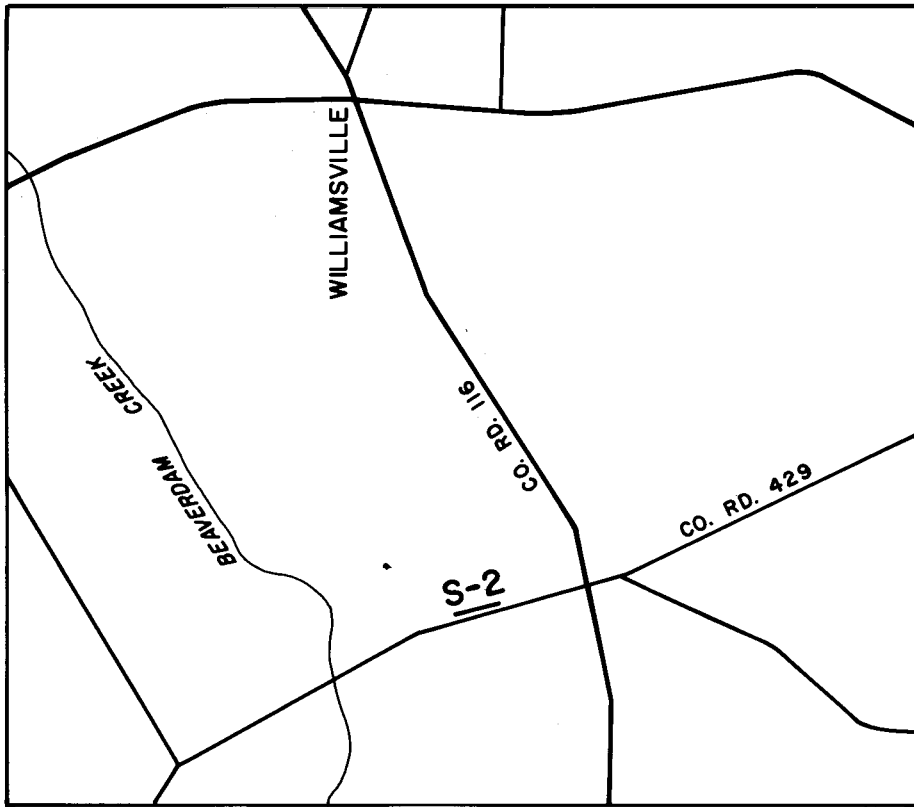


FIGURE 14. LOCATION OF RESISTIVITY SOUNDINGS S-1 AND S-2.

Sounding S-1 was made near a high-yielding irrigation well south of Seaford, Delaware, for which a driller's log was available. The total depth of Pleistocene material at this location is apparently greater than 92 feet, the total well depth. According to the driller, some changes occurred in the grain size of sediment, but the entire 92 feet was predominantly sand. The top few feet appeared to be sand associated with "elongate mounds" of undetermined origin (Jordan, 1967) and extremely high resistivities were obtained. Sharp breaks occurred between 12 and 14 feet on both the linear and Moore cumulative curves, and probably reflect the texture and unsaturated condition of these features. No other clearly defined breaks were observed, and the general slope of the Moore cumulative plot remained relatively unchanged below the shallow break.

Sounding S-2, located about four miles southeast of Harrington, in Kent County, was made in an area where Pleistocene sediments were over 100 feet thick, as determined by data from well Md24-1. The "mound" feature present at the location of sounding S-1 is not present here and the lack of an associated shallow break can be clearly seen in the resistivity data plots (Appendix IV). Again, the slope of the Moore plot remained relatively constant with no noticeable change at depth. This area was later selected as a site for a second aquifer test and two test wells were installed. The pumping test will be conducted as part of a cooperative program between the U. S. Geological Survey and the Delaware Geological Survey, on the base flow of streams that drain areas of thick Pleistocene sediments.

Sounding S-3 was made near a stream gaging station on Beaverdam Creek in southern Delaware. Recent work by the U. S. Geological Survey indicated that the base flow of this stream is exceptionally high, and it was hoped that resistivity work would help in interpretation of Pleistocene thickness. However, the data are not reliable due to interference from nearby utility lines and no interpretation was made. A new sounding is planned at some future time as part of the same cooperative program mentioned above.

Summary of Resistivity Results

Overall, it appears that the resistivity sounding method cannot be relied upon to provide accurate depth solutions in every case. This is due to a number of factors which include (1) the inherent conductance of a given bed, (2) boundary conditions, and (3) ground-water quality. In general, however, the sounding technique, cautiously applied, can be a

valuable guide in locating test holes. In any given area, the trend of a Moore cumulative plot seems to indicate the approximate thickness of surficial water-table sands. A constant slope, especially on the bottom portion of the curve ("A" spacings greater than about 60 feet in this study), usually indicates little change in gross lithology to approximately the depth of the greatest "A" spacing. If the slope is relatively high, possibly 3 : 1 or greater, the lithology appears to be that of a clayey nature. A low, constant slope, 1.5 : 1, or less, seems to be indicative of a thick sand section. This latter point is exemplified particularly well by soundings S-1 and S-2. Any interpretation must be based on some prior knowledge of the area and, in general, any depth interpretation is better when there are marked vertical differences in lithology. The interpretation of sounding data is more uncertain where vertical changes are gradational and, in many cases, an accurate interpretation is not possible.

The results of sounding data for this study are summarized in Table 12, which compares drill hole results with interpretation of sounding data. It should be kept in mind that not all errors are due to the resistivity technique. The auger method of sampling may introduce appreciable error; although, in this study the determination of gross changes in lithology was thought to be fairly accurate.

Future work might include more horizontal traversing. This was done on a limited basis, but results were not conclusive. Long traverses in any kind of regular pattern are limited mainly by availability of land. However, spot checking with a constant electrode spacing in a systematic manner would undoubtedly be of some value.

The soundings made in marine Pleistocene sands seemed to show more uniform and constant apparent resistivities with depth as opposed to resistivities measured in fluvial Pleistocene sands. This seems logical in view of the rather wide range of textures associated with the fluvial material.

HYDROLOGY

Background

The initial study area is bounded on the north by a tidal tributary of Drawyer's Creek; on the extreme east by tidal marsh; on the south by both the tidal Appoquinimink River and by a fresh water lake impounded at the head of the

TABLE 12: Comparison of resistivity sounding interpretations with results from test holes.

<u>Sounding</u>	<u>Bottom of Columbia</u> <u>Form. (lsd)</u>	<u>Control Test</u> <u>Hole</u>	<u>Bottom of Columbia</u> <u>Form. (lsd)</u>
A	71	Fb33-14, Fb33-20	61
B	48	Fb44-6	46
C	Not discernable	Fb34-4	80
D	Not discernable	Fb34-13	80
E	Affected by topography	Fb34-14	47
F	10	Fb44-4	8
G	0	Fb44-7	8
H	60	Fb31-3	31
I	40	None	-
J	36	None	-
K	48	Fb41-3	33
L	Not plotted	None	-
M	45	Fb53-6	25 (?)
N	Not plotted	None	-
O	40	None	-
M-1	34, 48	Me15-31	48
M-2	40	None	-
M-3	40, 48	Me15-32	36
M-4	Not plotted	None	-
S-1	Not discernable	Qc14-6	92+
S-2	Not discernable	Md24-1	100+
S-3	Affected by utility lines	None	-

Appoquinimink River. Drainage areas are small and the fresh water contribution to these streams is probably under about 0.5 cubic feet per second per square mile (cfs/m).

The highest altitude, slightly greater than 70 feet above mean sea level, is found approximately in the center of the study area. Near streams, elevations drop off sharply to about sea level.

The average annual rainfall in the Middletown-Odessa area for the years 1966-69 was 34.09 inches as computed from U. S. Weather Bureau Records. At least two of these years, 1966 and 1967, can be considered drought years for the general area, and rainfall was considerably less than the State's average of about 44 inches. No attempt was made to define the hydrologic budget in detail. Other studies in progress at the same time (Mather, 1969) were considering this aspect and thus, it was not an essential part of the study.

Except for the communities of Middletown and Odessa, the area is mostly rural and extensively farmed. Corn, wheat, and potatoes are the major crops. Middletown, however, is developing to the east, along Route 301, and will be needing additional sources of water as more homes are added to the municipal water supply system.

Field Methods

Initially, it was planned to install only three wells and drill a limited number of test holes, all on a contract basis. The test holes would serve the dual purpose of obtaining stratigraphic data and, hopefully, ground water levels. Soon after the study began, a combination auger and rotary drill rig became available to the University of Delaware for research purposes. The scope of the study was then broadened considerably so that additional test holes and water level measurements could be made within the existing budget limitations. Thus, in addition to the water levels obtained from the commercially installed well, twelve additional water levels were measured by temporarily installing two-inch slotted plastic pipe in selected test holes. Backflushing the pipe showed if the slots were open, and in every case the installation seemed to work satisfactorily. Legal and safety stipulations prevented leaving any installation in the ground over a few hours but it is thought that most water level measurements were essentially correct.

Occurrence of Ground Water

Ground water in the Columbia Formation is mostly unconfined but locally, confined conditions may exist due to

interbedded clay lenses. Such clays were found much more frequently than had been anticipated, although they seemed to be of limited areal extent. Test holes Fb33-14 and Fb33-20 (see Figure 2) revealed a much higher than normal water table held up by one of these clay lenses. It was not determined if the high water table was indeed a true perched water table or simply a mounded one.

Figure 15, resulting from this study, shows that the water table elevations in the prime study area have the same general configuration as those mapped by Boggess and Adams (1964) except that some detail has been added. In general, ground-water flow is controlled by topography, except in the vicinity of clay lenses as mentioned above, and appears to be towards surface streams during nearly all times of the year. There is the possibility that ground-water flow could be away from the stream during high stream flows. A concurrent cooperative program between the Delaware Geological Survey and the U. S. Geological Survey is considering this aspect.

A notable difference between this area and most other areas in the State underlain by permeable Pleistocene materials is the depth to the water table. The water table is extremely low in the Middletown-Odessa area and, apparently, vertical recharge is quite slow as indicated by the levels in observation well Fb34-17, installed as part of this study. Nearly all levels measured in the observation well (see Figure 16) were deeper than 35 feet below ground surface, and there was little fluctuation in levels throughout the year. It appears that Drawyer's Creek and the Appoquinimink River, draining the area to the north and south respectively, function as natural drains and greatly dampen fluctuations in ground water levels. A similar situation apparently exists on the southern side of the eastern end of the Chesapeake and Delaware Canal where mapping by Boggess and Adams (1963) shows that in parts of the area the water table is as much as 40 feet below ground surface. Another area with much the same water table configuration also exists just north of the Chesapeake and Delaware Canal where Army Creek, Delaware Bay, and Red Lion Creek bound a relatively high land area on the north, east, and south respectively. Here, the water table is as much as 30 feet below land surface. Thus, the total saturated thickness in such areas is much less than might be expected from a cursory glance at the total thickness of Pleistocene materials. Figure 17 shows the saturated thickness of the Columbia Formation in the Middletown-Odessa area.

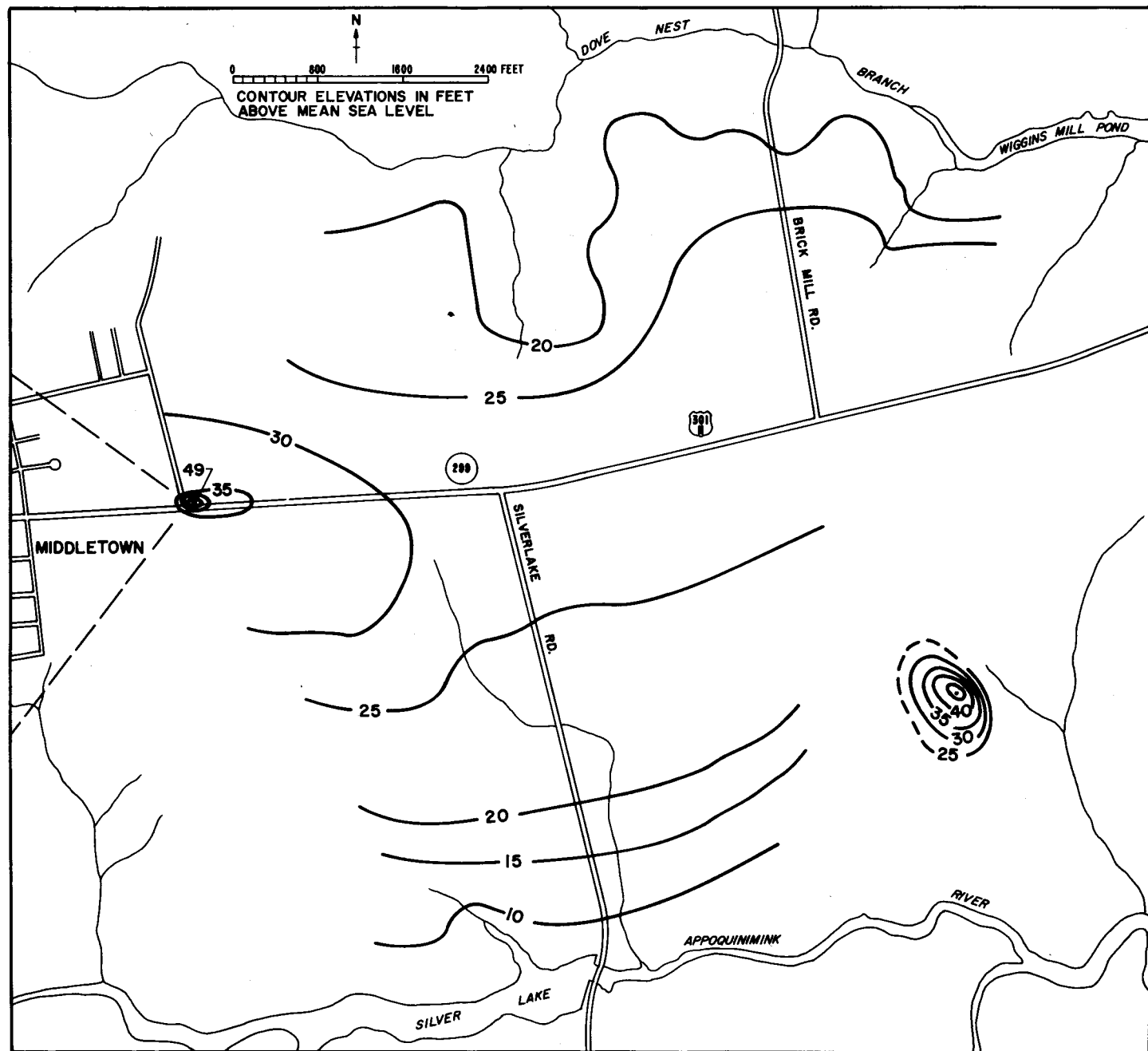


FIGURE 15. WATER-TABLE CONTOUR MAP OF THE MIDDLETOWN-ODESSA AREA.

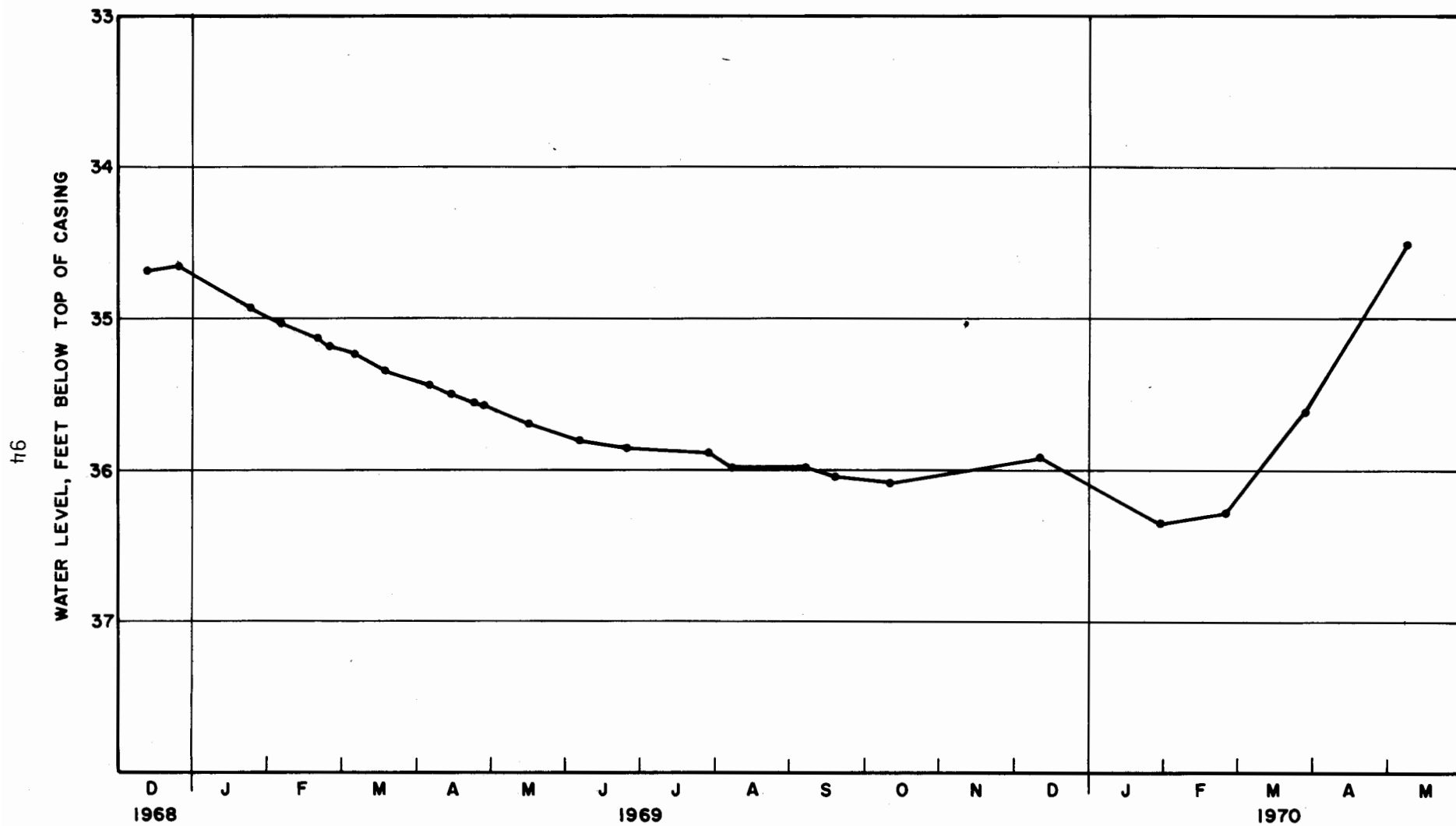


FIGURE 16. LEVELS IN OBSERVATION WELL Fb34-17, NEAR MIDDLETOWN, DELAWARE.

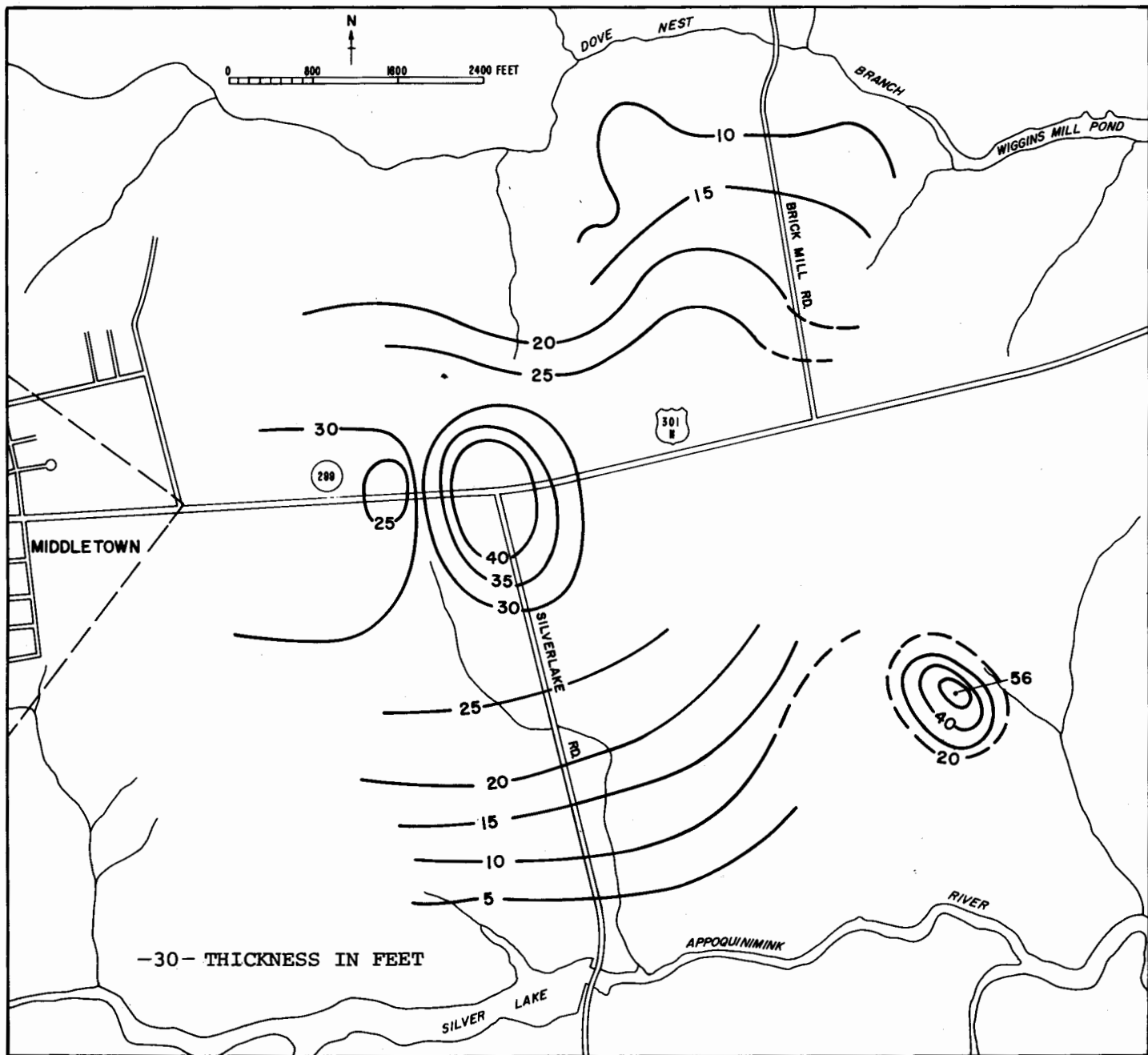


FIGURE 17. SATURATED THICKNESS MAP OF THE COLUMBIA FORMATION IN THE MIDDLETOWN-ODESSA AREA.

Pump Test of the Columbia Formation at Middletown

Three permanent, steel cased, gravel-packed wells (Fb34-16, 17, 18) were installed for the purpose of test pumping the Columbia sands. The pumping well, Fb34-16, was eight inches in diameter and screened from 54 to 74 feet below land surface. The two six-inch observation wells, Fb34-17 and Fb34-18, were placed in a line west of the pumping well at distances of 26 feet and 103 feet respectively, and each fitted with bronze screen from 64 to 74 feet below land surface. All wells were developed by surging and pumping with air. Over a year's record of water levels was obtained in well Fb34-17 (see Figure 16) before running the pump test. It was originally planned to install a continuous water-level recorder on one of the observation wells and collect records for the length of the study. Due to vandalism, it became necessary to revert to periodic tape measurements.

A 15-minute test run a day prior to the main pumping test showed that, theoretically, up to about 110 gallons per minute could be pumped from the production well, taking into account the reduction in saturated thickness. However, problems developed in removing water from the pumping site and in locating pipe of sufficient diameter to handle 110 gpm without friction losses. Consequently, the pumping rate for the final test was lowered to 60 gpm. Flow was regulated by a valve on the discharge side of the pump, and measured by a circular orifice and piezometer tube at the end of the discharge line. It was possible to remove about 75% of the water to a distance of about 300 feet away from the pumping site. Apparently, the low water table and clayey nature of the soil prevented any recycling of water during the length of the test.

Pumping continued for 24 hours in the main aquifer test, followed by 22 hours of recovery measurements. Levels were measured in the pumping well by an electrical tape, and in the two observation wells by automatic water level recorders. Both drawdown and recovery data were plotted for all wells, but the data obtained from observation well Fb34-18 ($r = 103'$) were in considerable doubt because either the well was not responding properly, or there was some hydrologic boundary between the observation well and the pumped well. A log-log plot of the drawdowns corrected for saturated thickness in observation well Fb34-17 ($r = 26'$) could be divided into three rather distinct phases (see Figure 18): (1) an early portion that could be matched to the Theis non-leaky aquifer curve; (2) a portion that indicated recharge, probably gravity drainage, and could not be reliably matched; (3) the portion, after about 100 minutes, that matched the later part of the Theis

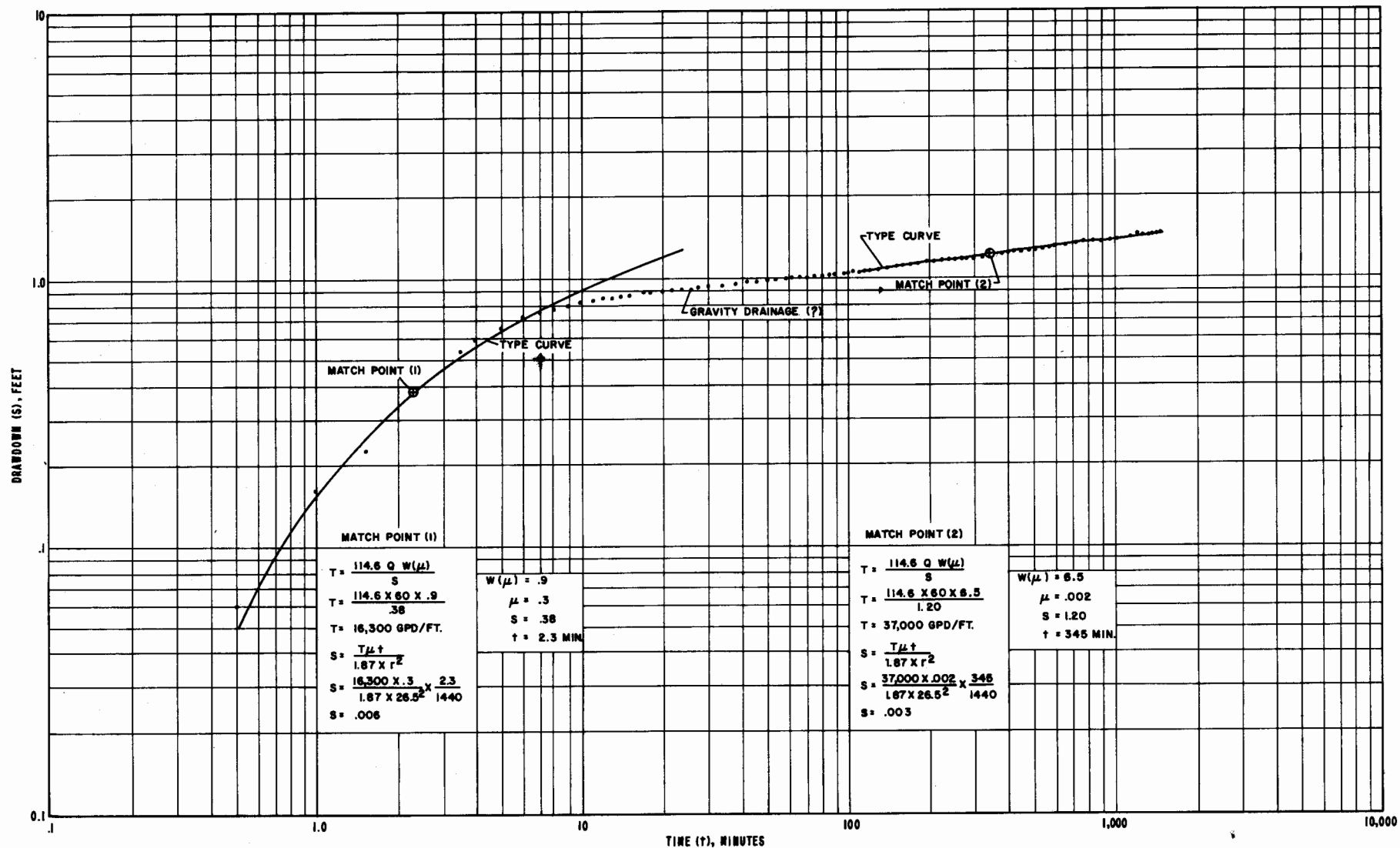


FIGURE 18. LOG-LOG PLOT OF DRAWDOWNS IN OBSERVATION WELL Fb 34-17, MIDDLETOWN, DELAWARE.

curve. The transmissivity calculated from the early portion of the drawdown curve is about 16,000 gpd/ft. however this is probably not correct. A transmissivity of about 40,000 gpd/ft., calculated from the last part of the curve appears to be more correct. The storage coefficient in the latter case is about .003. The storage coefficient is somewhat less than that for a true water table aquifer, but is not entirely unexpected. The uncertainties inherent in a water-table pumping test, and the variable geology of the Columbia Formation, affect accurate determination of the storage coefficient. Also, selections of a later match point would probably have given a higher storage coefficient.

Recovery data from well Fb34-17, plotted according to the Jacob straight line method, also showed the same three-fold division (see Figure 19). The transmissivity calculated from the last third of the recovery curve was 41,600 gpd/ft. A storage coefficient of .01 was obtained by extrapolating the last portion of the curve back to its intersection with the zero recovery axis. This latter procedure may be a bit tenuous, although the result is quite reasonable.

If a transmissivity of 40,000 gpd/ft. is taken as reasonably accurate, then the efficiency of the pumped well was calculated to be very low. This was probably due mostly to partial penetration. The efficiency could also have been approximated by comparing the actual drawdown in the pumped well (17.3 feet after 24 hours) with the theoretical drawdown obtained by extrapolation from a distance-drawdown curve. However, the uncertainty of the measurements in observation well Fb34-18 made this method invalid.

Theoretically, the longer the pumping test, the better would have been the chance that the effect of gravity drainage on the drawdown curve was no longer being felt. In this test it was felt that reasonably accurate values of aquifer constants were obtained but by no means should they be taken as inflexible in their application.

In the study proposal, it was thought that recharge might occur from a stream some distance away; however, the low pumping rate prevented such recharge.

Prediction of long-term yields is extremely difficult in water-table tests. One of the limiting factors in this study was the relatively low static water level. Only about 40 feet of saturated thickness is available at most (see Figure 17), even though the Columbia Formation is about 75 feet thick at the test well site. Thus, the highest yielding wells would be found in this area of greatest saturated thickness. A great deal also depends on the efficiency of the pumped well. The specific capacity of the pumped well obtained in this test was about 3.5 gallons per foot. In a fully penetrating well, losses would be somewhat less and a

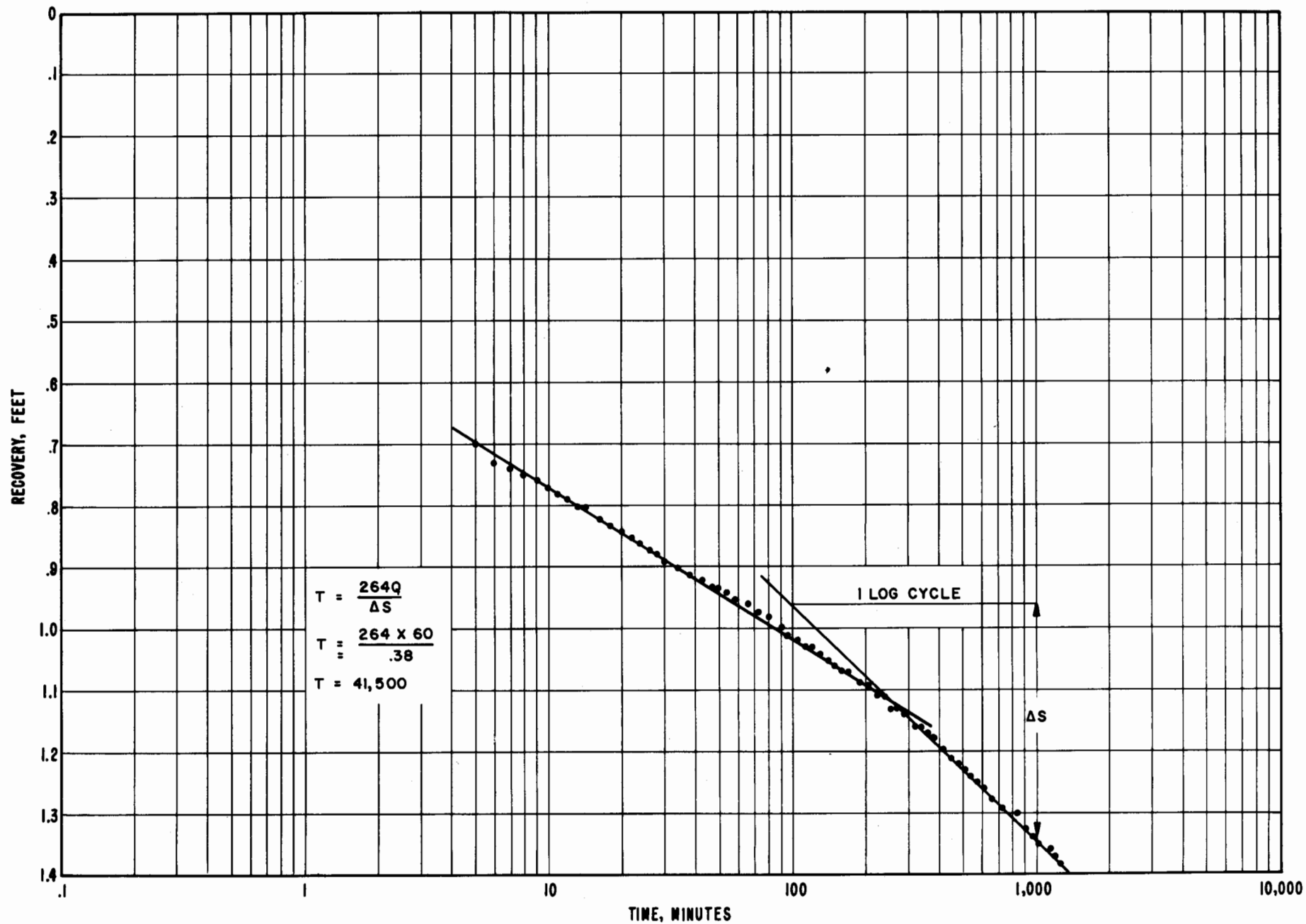


FIGURE 19. PLOT OF RECOVERY DATA FOR WELL Fb34-17, MIDDLETOWN.

higher specific capacity could probably be obtained. Theoretical drawdowns at specified withdrawal rates could be calculated but would not be strictly valid in a water-table aquifer. It does appear that between 300 and 450 gpm could be obtained on a regular basis (90 days) from at least one well (50% efficiency) assuming a saturated thickness of 35 feet or more. At about 1000 feet from the pumping well, the drawdown would be slightly under seven feet with a pumping rate of 400 gpm, using the aquifer constants calculated from observation well Fb34-17. Practically, it would be difficult to install more than one well under the conditions above because of the limited area of saturated thickness greater than 35 feet. Another approach would be to install a number of lower yielding wells, perhaps averaging about 200 gpm each, and reduce the well spacing. At least three such wells could be installed in the areas around the intersection of Route 301 and Silver Lake Road assuming a 500 foot spacing with the middle well in the area of greatest saturated thickness (see Figure 17). Such an arrangement might serve the planned expansion of Middletown to the east along Route 301.

Water Quality

Water quality can be a limiting factor in the use of water from the Columbia Formation. High iron content and low pH are common in many wells tapping the Columbia Formation in Delaware. Field measurements made at the well site during pumping of well Fb34-16 (Middletown) showed the total iron content to be about 2.0 ppm, and the pH about 5.9. The iron content was determined colormetrically and the pH by an Orion pH meter. Two water samples were also taken for more complete analysis by the Delaware Water and Air Resources Commission and these results are given in Table 13. It appears that ground water from the Columbia Formation at this location would indeed require some treatment for iron. Local drillers report a reluctance to use the Columbia Formation because of the high iron content, but it should be stressed that the water is not totally unusable and can be treated, if necessary. Drillers also indicate that the iron content seems to increase with depth although this is not entirely proven by existing chemical analysis.

Other Pump Tests

Few good pump tests exist for the Columbia Formation. Most tests from which data are available are of short duration and lack observation wells. Also, in most areas throughout the State, as at Middletown, the Pleistocene sands form a water table aquifer rather than a confined aquifer which adds to the difficulty of analyzing pumping test data.

TABLE 13: Chemical analysis of water from well Fb34-16.

Substances	Milligrams Per Liter	
	Pumping Time 75 Min.	Pumping Time 1400 Min.
Chloride	37	25
Iron	1.5	1.0
Manganese	0.24	Less than 0.10
Nitrate nitrogen	4.0	4.0
Total phosphate	2.1	2.2
Acidity, CaCO_3	6.3	6.6
Alkalinity, CaCO_3	17	17
Hardness, CaCO_3	62	60
Specific conductivity	-	205 Micromhos
pH	-	5.9

Analysis by State of Delaware, Division of Environmental Control

One test with some measure of control was conducted in September, 1963, for the Delaware State Hospital near Smyrna, Delaware, where exploration had shown that the Columbia Formation was over 100 feet thick in places. A test well was subsequently screened from 80 to 90 feet (land surface datum) and pumped for nearly seven hours at varying rates, although, the rate was held constant at about 400 gpm during the last four hours. Recovery measurements were also made and it is thought that these measurements are probably more meaningful than the drawdown data. A straight line plot of the recovery data is shown in Figure 20. Recharge occurred near the end of the test and undoubtedly came either from a lake situated about 150 feet away or from recycling of the pumped water. The transmissibility of the Columbia Formation was calculated to be about 60,000 gpd/ft., but determination of the storage coefficient was not possible due to the lack of observation wells. It was assumed that the conditions necessary for a valid interpretation by the Theis non-leaky recovery formula were met. As usual with a water table aquifer, such assumptions are somewhat tenuous and very possibly the test did not extend beyond the gravity drainage phase.

A relatively long-term test was conducted south of Newark, Delaware, in July, 1969, by the E. I. DuPont Company. The Columbia Formation at the test site is between 70 and 80 feet thick and underlain by clays of the Potomac Formation (Lower Cretaceous). An eight-inch test well was screened near the bottom of the Columbia Formation and pumped for approximately 95 hours at a constant rate of 500 gallons per minute. Drawdowns were measured in five observation wells, two of which were equipped with automatic water level recorders. A variety of methods were used to analyze the data but no one method gave results that were thought to represent fully the aquifer coefficients. However, a probable range of coefficients could be determined. Transmissibilities calculated for three wells from drawdown data uncorrected for saturated thickness ranged from 5800 to about 7800 gpd/ft. Data from a fourth well gave a transmissibility of 17,400 gpd/ft. which is probably not a reliable figure. There is some doubt about the exact screen setting in the fourth observation well and the screen may be set above a local confining clay layer. Screens in the other wells appear to be set below this layer. Slightly higher values of transmissibility were obtained, about 9000 gpd/ft., when drawdown data were corrected for dewatering. However, curves drawn from the corrected data gave some difficulty in obtaining a proper match with the type curve according to Boulton's time factor. Failure to obtain a good match was due probably to recharge that occurred after about 300 minutes of pumping (see Figure 21).

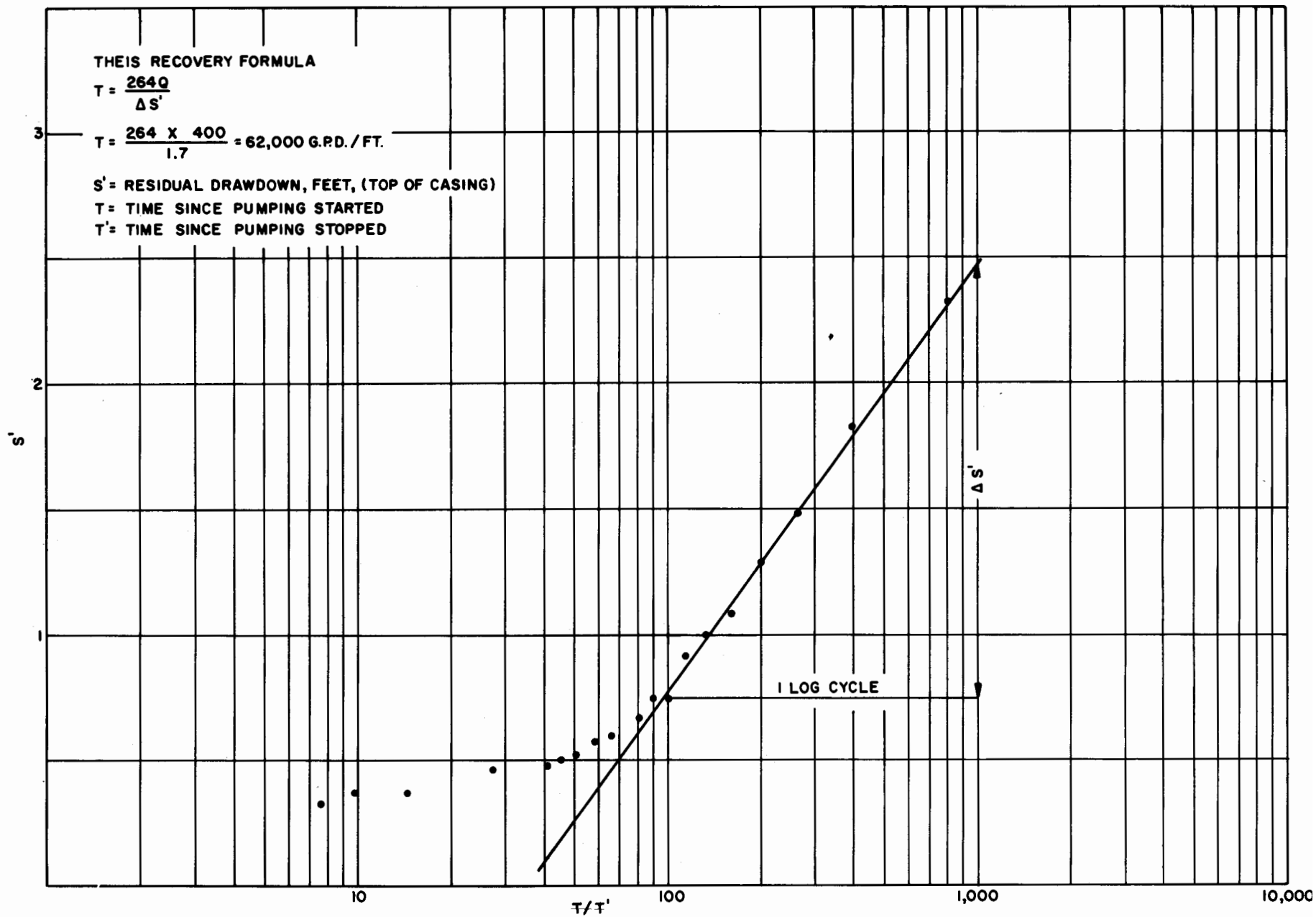


FIGURE 20. PLOT OF RECOVERY DATA FOR WELL Hc34-25, STATE OF DELAWARE.

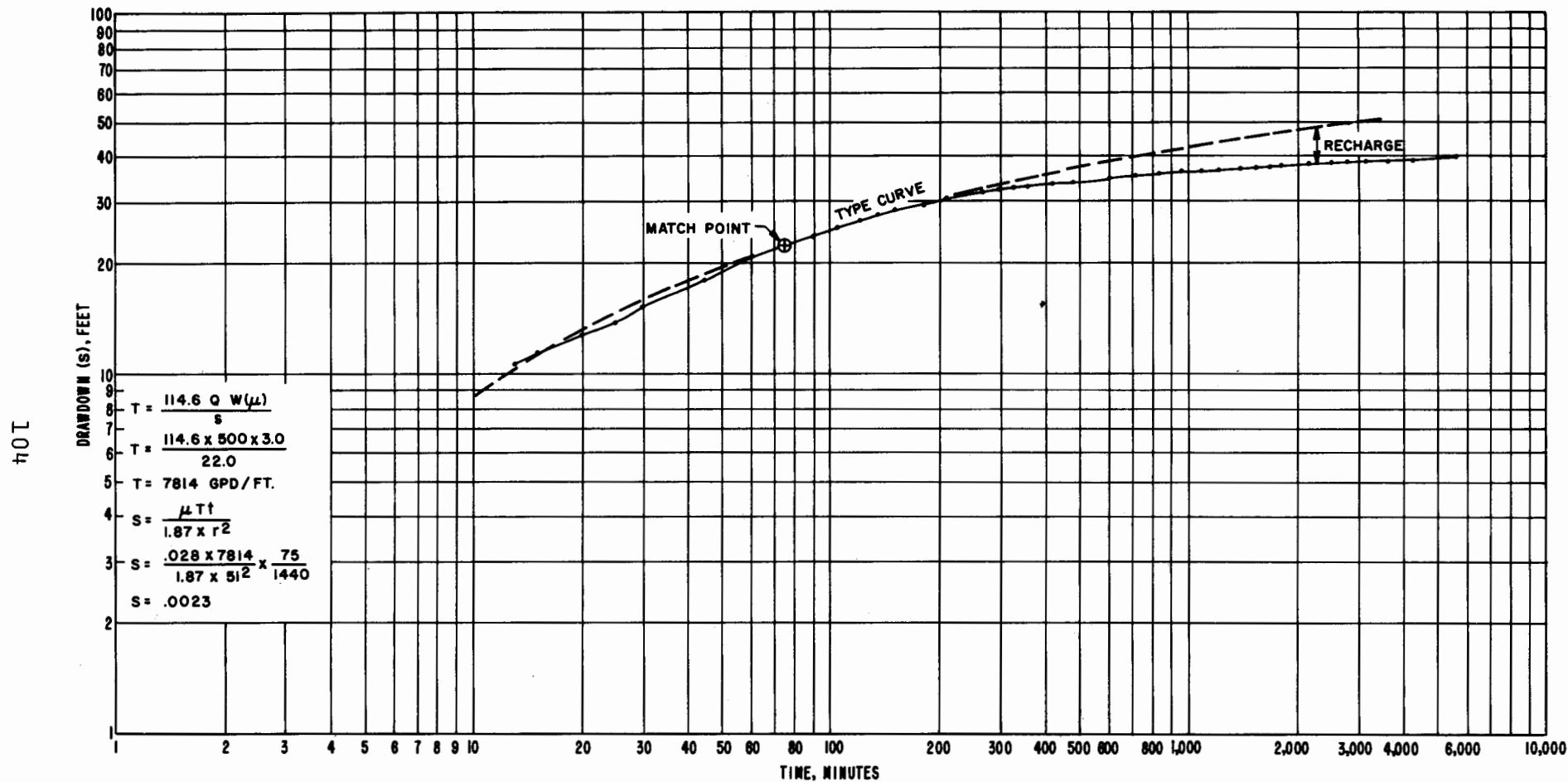


FIGURE 21. LOG-LOG PLOT OF DRAWDOWNS IN WELL D6 31-37, E.I. DUPONT CO..

The recharge boundary was calculated to be from about 400 to 700 feet southeast of the test well and fell within the areal limits of a small lake. However, it is quite possible that the recharge was again caused by recycling of the water from the pumped well. Storage coefficients for all analyses ranged from .0006 to .003, with most values falling around .002. The average value approaches that for a water-table aquifer, but the accuracy of the figure is in doubt.

Plots of the recovery data from two wells used in the DuPont test (see Figures 22 and 23) gave transmissibilities of 6950 and 6750 gpd/ft. which agrees quite well with the transmissibilities obtained from the drawdown data.

Data are also available in the files of the Delaware Geological Survey for pump tests in the Columbia Formation at two other locations, the Atlas Chemical Company plant near Wilmington, Delaware, and a municipal water company test well site near Brookside, Delaware. The control was excellent in both tests but, boundary conditions prevailed in the Atlas test, due to the nearness of the site to the Delaware Estuary. The Brookside well was multiple-screened and review of the data shows that part of the screen may have been set in underlying sands of the Potomac Formation. A transmissibility of 100,000 gpd/ft. was obtained from the Brookside test. Thus, in view of these conditions, some doubt is cast on the validity of the aquifer coefficients that were calculated from either of the above tests.

Summary of Aquifer Constants for the Columbia Formation

A review of available data shows that aquifer constants vary widely, depending on local conditions. This is expected in a water-table aquifer, and it is difficult to assign a set of values to the aquifer as a whole. The test at Smyrna, discussed previously ("Other Pump Tests"), gave a questionable transmissibility for the paleochannel there of 60,000 gpd/ft. Transmissibilities of between 16,000 and 39,000 gpd/ft. were calculated from the series of pump tests run by the Atlas Chemical Company near Wilmington, Delaware. However, the test was influenced by boundary conditions and the results would be applicable only in the immediate area of the test site. The E. I. DuPont Company test gave transmissibility values considerably less than any of the above, averaging about 9000 gpd/ft.

The test near Middletown, made as part of this study, gave calculated transmissibilities of about 40,000 gpd/ft., and a storage coefficient of about .006.

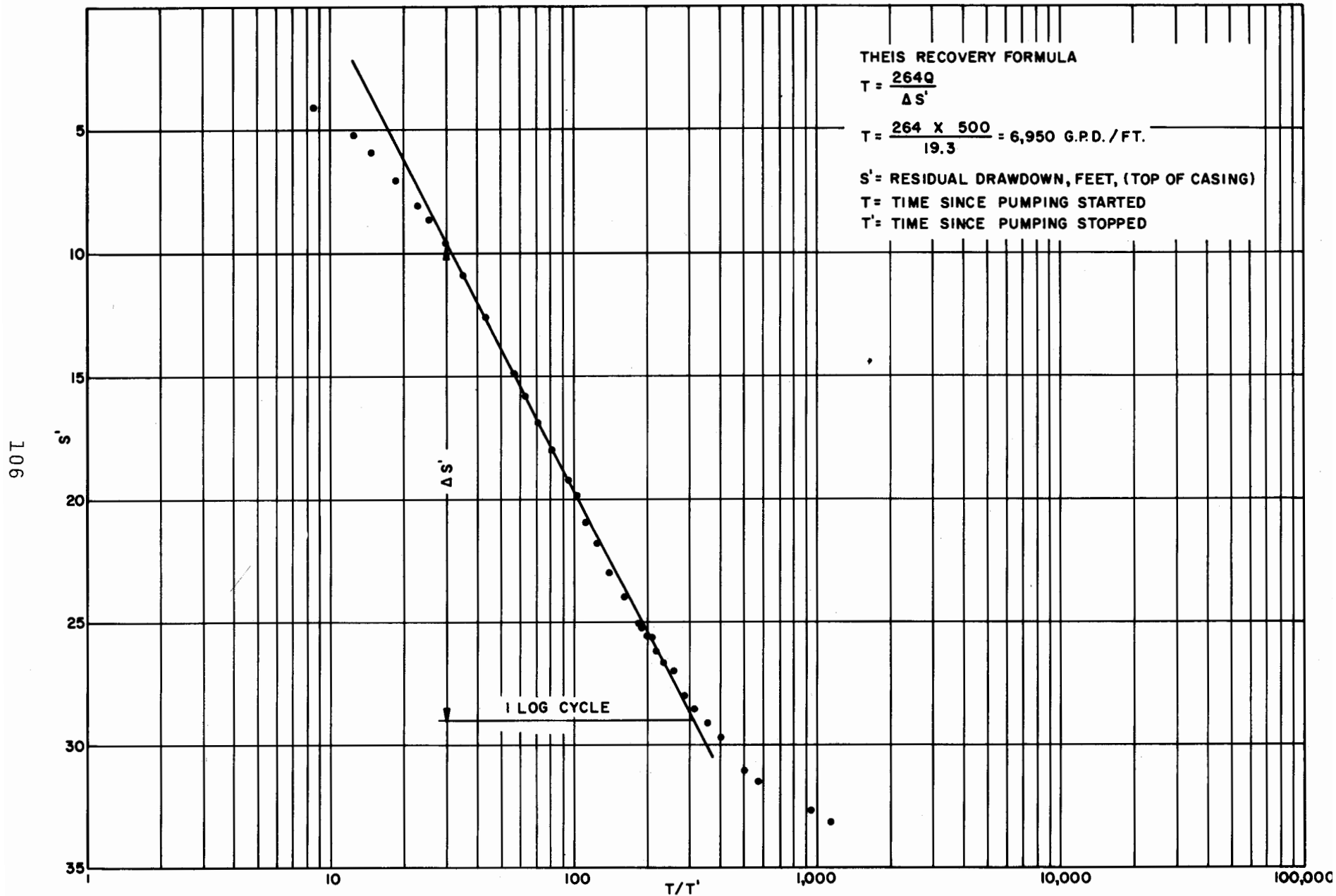


FIGURE 22. PLOT OF RECOVERY DATA FOR WELL Db31-39, E. I. DuPONT CO.

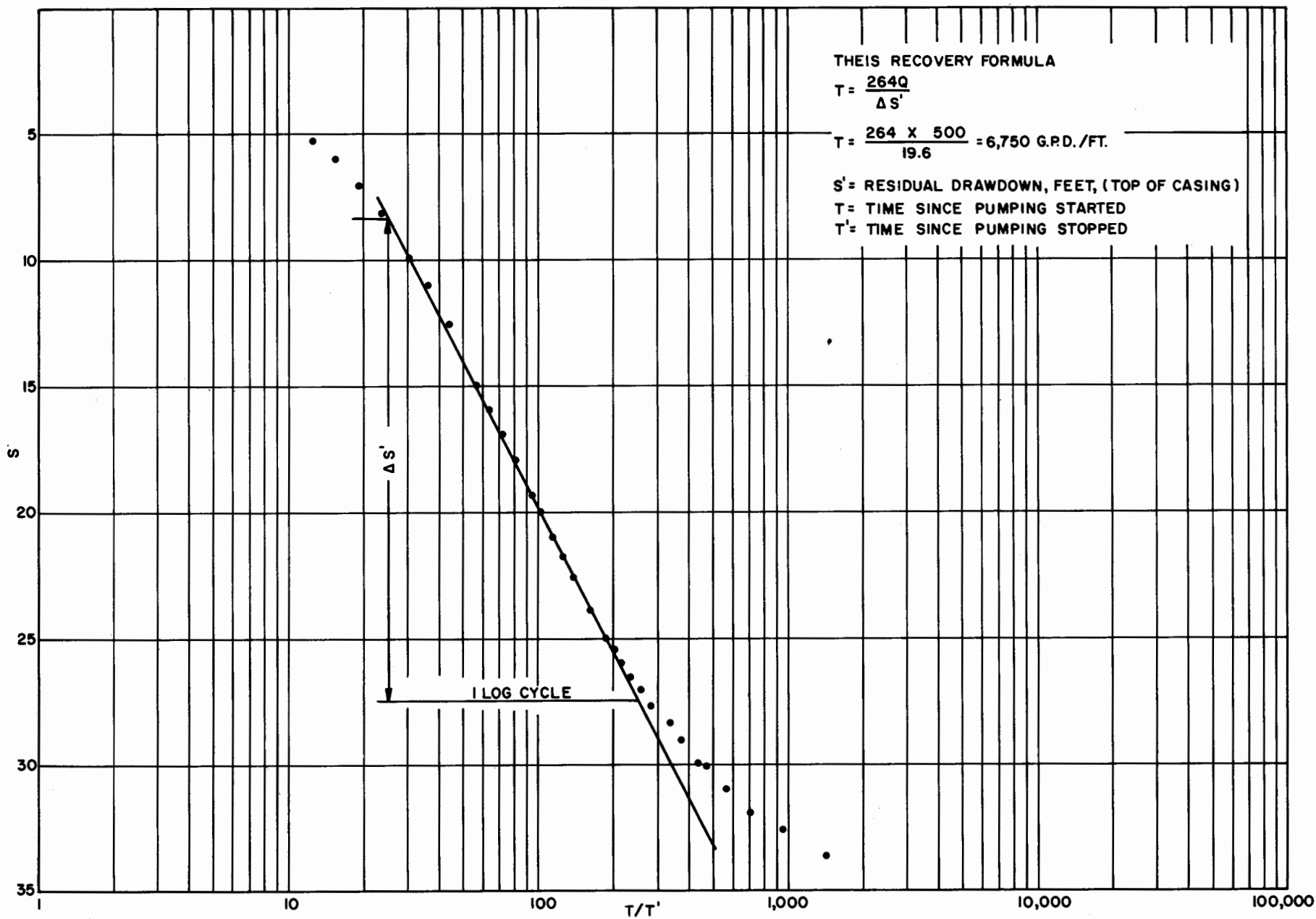


FIGURE 23. PLOT OF RECOVERY DATA FOR WELL Db31-40, E. I. DuPONT CO.

Many of the differences noted in transmissibilities are undoubtedly due to the variable nature of Pleistocene age sediments. The fluvial deposits alone, with which this report is mainly concerned, show great ranges in grain size over short vertical and lateral distances. In parts of southern Delaware, Pleistocene sediments were deposited under various environments and thus differences would occur in grain size and sorting, both of which affect aquifer coefficients. Sundstrom and Pickett (1969) reported on the transmissibilities of the water-table aquifer in Southern Delaware, and listed coefficients of between 45,000 to 135,000 gpd/ft. It should be recognized that in some places the water-table aquifer is composed of both Pleistocene and subcropping Miocene sands.

Storage coefficients for the Pleistocene aquifer as a whole are generally close to those of a water-table aquifer and, at face value, are indicative of leaky aquifer conditions. This is not unexpected, considering that (1) most water-table tests are not run long enough to obtain a true water-table storage coefficient; and (2) local clay lenses may indeed cause semi-confined conditions. In the Middletown-Odesa area such clay lenses were generally between one and two feet thick, but discontinuous laterally.

The specific yield of water-table sands appears to be quite uniform. Sundstrom and Pickett, in two separate studies (1968, 1969), calculated that the specific yield of the water-table sands was about 15% in Kent County, and about 16% in Sussex County. This is probably close to the value for the Columbia sands in New Castle County. Saturated thicknesses in New Castle County are considerably lower, however, than the saturated thicknesses in southern Kent and Sussex Counties.

One of the problems encountered in analyzing pumping tests in the Columbia Formation was to distinguish between recycling of the pumped water, gravity drainage, and a true recharge boundary. In most cases, this problem could not be resolved satisfactorily. A thorough knowledge of local geology and a pumping test of possibly several days is usually needed to overcome this difficulty. Overall, boundary conditions should be expected in Columbia Formation paleochannels during long-term pumping. The width of the main paleochannels does not usually exceed one-half mile in New Castle County and they are often cut into relatively impermeable materials, such as Potomac Formation clays. On the other hand, most surface water sources are underlain by, or are adjacent to, the Columbia Formation, providing opportunity for recharge to the aquifer. Thus, the performance of any well in the aquifer must be analyzed within its particular hydrologic and geologic setting, and great care must be used in extrapolating data from other pump tests.

Proceeding naturally from the study in the Middletown-Odessa area will be a determination of aquifer constants in the Columbia Formation by indirect methods. Such a study will be carried out by the U. S. Geological Survey as part of an existing cooperative ground-water program with the Delaware Geological Survey. Observation well Fb34-17 will continue to be used to collect data that will aid in the indirect analysis method. These results will be compared with the pumping test results at the same location.

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APPENDIX I

Log of Wells

Well Number	Elevation (in feet, SLD)	Depth (in feet, below land surface)	Description of Lithology
Fb33-13	60.51	0-5	Top soil with some yellow, medium sand
		5-10	Sand, coarse, yellow
		10-17	Sand, coarse, light brown
		17-17.5	Gravel
		17.5-20	Sand, coarse, yellow
		20-24	Same
		24-27	Same; some gravel
		27-30	Sand, coarse, yellow
		30-36	Same, gravel at 32' and 34'
		36-40	Sand, coarse, light brown
		40-45	Same
		45-50	Sand, coarse, yellow
		50-56	Sand, coarse, light brown; gravel at 52'-52.5'
		56-60	Greensand, weathered
Fb33-14	62.12	0-5	Top soil with some brown, medium sand and gravel
		5-10	Sand, medium, silty, light brown
		10-15	Sand, medium, light brown with some gravel
		15-17	Sand, coarse, yellow to white with some gravel
		17-20	Sand, coarse, light brown with gravel
		20-24	Sand, medium, reddish-brown
		24-25	Gravel
		25-33	Sand, medium, reddish-brown
		33-35	Clay, silty, gray
		35-40	Sand, medium, brown with clay brown to gray
		40-45	Sand, medium, clayey, brown
		45-50	Sand, medium, light brown
		50-55	Same
		55-61	Same
		61-65	Greensand

Well Number	Elevation (in feet, SLD)	Depth (in feet, below land surface)	Description of Lithology
Fb33-16	64.23	0-5	Top soil with some yellow, medium sand
		5-12	Sand, medium, light brown; gravel at 7'-7.5'
		12-18	Sand, coarse, light brown with some gravel. Sand is yellow from 14' to 15'
		18-20	Sand, coarse, brown with some varicolored clay
		20-25	Sand, gravelly, brown
		25-27	Gravel
		27-30	Sand, medium, yellow to white
		30-35	Sand, coarse, brown; gravel at 31'-33'
		35-39	Same
		39-44	Sand, coarse, dark brown
		44-45	Sand, coarse, light brown
		45-50	Sand, coarse, yellow
		50-55	Same
		55-59	Sand, medium, dark brown; gravel at 58'-58.5'
		59-60	Greensand
		60-70	Same
Fb33-17	61.92	0-5	Top soil; gravel at 4'-5'
		5-10	Sand, silty, medium, light brown; gravel at 8'-9'
		10-15	Same
		15-20	Sand, coarse, light brown; gravel at 17'-17.5'
		20-27	Same; gravel at 22'-23', some ironstone
		27-30	Sand, medium, yellow
		30-35	Sand, coarse brown (30'-32') and light brown (32'-35')
		35-40	Sand, gravelly, gray to light brown
		40-45	Same
		45-50	Sand, coarse, light brown
		50-55	Same
		55-59	Sand, coarse, brown
		59-70	Greensand, weathered

Well Number	Elevation (in feet, SLD)	Depth (in feet, below land surface)	Description of Lithology
Fb33-18	58.41	0-5	Top soil with some yellow, medium sand
		5-9	Sand, medium, yellow
		9-13	Gravel
		13-18	Sand, medium, yellow
		18-24	Sand, medium, dark reddish- brown
		24-27	Sand, coarse, dark brown to purple
		27-33	Sand, silty, medium, dark gray with some vari- colored clay
		33-35	Sand, fine, yellow with varicolored clay
		35-42	Same; more clay
		42-45	Clay, silty, gray
		45-50	Sand, fine, light brown to red
		50-53	Sand, coarse, brownish- gray
		53-60	Greensand, coarse
		60-65	Sand, fine, bluish-green
Fb33-19	60.74	0-5	Top soil with some brown, medium sand and pebbles
		5-10	Sand, coarse, yellow; gra- vel from 8'-10'
		10-13	Same
		13-15	Sand, coarse, dark brown with some pebbles; gra- vel at 14'
		15-16	Same
		16-20	Sand, gravelly, coarse, light brown
		20-25	Same
		25-28	Sand, gravelly, coarse, brown
		28-35	Sand, silty, fine, dark brown with varicolored clay
		35-40	Same
		40-45	Sand, medium, yellow

Well Number	Elevation (in feet, SLD)	Depth (in feet, below land surface)	Description of Lithology
Fb33-19	60.74	45-50	Sand, coarse, yellow
		50-51	Same
		51-55	Sand, coarse, yellow
		55-58	Same
		58-60	Sand, coarse, light brown with a greenish tint
		60-65	Greensand, weathered
		65-67	Same, becoming clayey and sticky
Fb33-20	68.84	0-5	Top soil with some coarse, yellow sand and gravel
		5-10	Sand, coarse, light brown becoming yellow; gravel from 9'-9.5'
		10-13	Same, some pebbles
		13-15	Sand, coarse, light brown with pebbles
		15-20	Same; gravel layer from 19.5'-20'
		20-22	Same
		22-28	Sand, medium, light brown; gravel at 21.5'
		28-31	Sand, gravelly, coarse, brown
		31-34	Sand, medium, light brown
		34-40	Sand, silty, dark gray to nearly black with vari- colored clay
		40-45	Sand, medium, brown with varicolored clay (from 43'-45' only clay)
		45-50	Sand, coarse, yellow
		50-54	Sand, coarse, light brown
		54-50	Greensand, rather coarse
		60-65	Greensand
		65-67	Same, more clayey and sticky

Well Number	Elevation (in feet, SLD)	Depth (in feet, below land surface)	Description of Lithology
Fb33-21	62.82	0-5	Top soil with some brown, medium sand and pebbles
		5-11	Silt, clayey, yellow with some fine sand and clay
		11-14	Sand, silty, fine, brown
		14-15	Gravel
		15-17	Sand, medium, brown
		17-18	Gravel
		18-26	Sand, very coarse, light gray with pebbles
		26-27	Gravel
		27-30	Sand, coarse, gravelly, dark gray
		30-35	Sand, coarse, dark brown
		35-43	Same
		43-45	Clay, light gray
		45-51	Same
		51-53	Sand, fine, brown
		53-54	Clay, light gray
		54-57	Sand, medium, brown
		57-60	Sand, medium, dark brown and green (Greensand)
Fb34-4	55.38	0-9	Top soil with some brown gravelly sand
		9-13	Sand, coarse, yellowish- brown with some gravel
		13-16	Gravel, coarse
		16-22	Sand, coarse, yellowish- brown
		22-25	Sand, coarse, yellowish- brown with some gravel
		25-30	Sand, coarse, brown
		30-34	Same
		34-34.5	Gravel, coarse
		34.5-40	Sand, coarse, brown
		40-45	Same
		45-50	Sand, coarse, dark-brown
		50-55	Same
		55-60	Sand, coarse, light brown
		60-65	Sand, coarse, yellow
		65-70	Sand, medium, yellow
		70-75	Same
		75-80	Same
		80-85	Greensand

Well Number	Elevation (in feet, SLD)	Depth (in feet, below land surface)	Description of Lithology
Fb34-5	65.57	0-5	Top soil, sandy, yellowish-brown
		5-10	Sand, coarse, yellowish-brown
		10-15	Same
		15-20	Sand, coarse, yellow with gravel at 15' and 16'
		20-25	Gravel with some coarse, brown sand
		25-30	Sand, coarse, yellowish-gray with gravel and ironstone (at 29')
		30-35	Sand, coarse, dark brown
		35-40	Sand, coarse, yellow
		40-45	Same
		45-50	Same
		50-55	Same
		55-60	Same
		60-65	Sand, coarse, light brown
		65-70	Same
		70-75	Same
		75-80	Same
		80-81	Same
		81-85	Greensand
Fb34-6	31.27	0-5	Top soil and some medium, brown sand
		5-10	Sand, coarse, yellowish-brown
		10-15	Sand, coarse, yellow. Dark brown medium sand layer at 13'
		15-20	Sand, medium, reddish-brown
		20-25	Greensand
Fb34-7	61.21	0-5	Top soil with some medium brown sand
		5-10	Sand, coarse, brown
		10-15	Sand, coarse, yellow. Gravel layer at 13'
		15-20	Same

Well Number	Elevation (in feet, SLD)	Depth (in feet, below land surface)	Description of Lithology
Fb34-7	61.21	20-25	Sand, coarse, light brown
		25-30	Sand, coarse, yellow; gravel layer at 26'
		30-35	Same
		35-40	Same
		40-45	Sand, coarse, brown
		45-50	Sand, coarse, dark brown
		50-55	Sand, coarse, dark brown with some gravel
		55-60	Same
		60-65	Sand, medium, dark brown (weathered greensand)
Fb34-8	60.48	0-5	Top soil, sandy
		5-10	Sand, coarse, yellow, gravel layer at 8'
		10-13	Same; gravel at 13'
		13-15	Sand, coarse, dark brown to gray
		15-20	Same; some gravel at 16'-17'
		20-25	Gravel with some yellowish-brown, coarse sand
		25-33	Sand, coarse, yellow
		33-35	Sand, gravelly, dark brown to gray
		35-40	Sand, coarse, yellow
		40-45	Same
		45-50	Same
		50-55	Sand, coarse, light brown
		55-60	Sand, medium, brown
		60-65	Sand, coarse, yellowish brown
		65-70	Same
		70-76	Sand, coarse, brown
		76-80	Greensand

Well Number	Elevation (in feet, SLD)	Depth (in feet, below land surface)	Description of Lithology
Fb34-9	64.69	0-5	Top soil with some fine, yellow sand
		5-10	Sand, medium, yellow
		10-15	Sand, medium, light brown; gravel at 12'-12.5' and 14'-14.5'
		15-20	Sand, coarse, yellow with some gravel
		20-24	Same
		24-30	Clay, silty, varicolored
		30-35	Clay, silty, varicolored
		35-40	Clay, silty, varicolored
		40-45	Sand, silty, medium, yellow
		45-50	Sand, medium, yellow
		50-53	Same
		53-55	Greensand, weathered
Fb34-10	63.76	0-5	Top soil with some yellow, medium sand
		5-9	Sand, coarse, yellow with gravel
		9-13	Sand, coarse, light brown
		13-18	Gravel
		18-20	Gravel with brownish-pur- ple coarse, sandy matrix
		20-25	Sand, coarse, light-brown with some gravel
		25-30	Same
		30-35	Same
		35-40	No return
		40-45	Sand, coarse, yellow
		45-48	Same
Fb34-11	60.48	0-5	Top soil with some gravel
		5-9	Gravel with purple to brown coarse sandy matrix
		9-15	Sand, clayey, medium, yellow
		15-22	Silt, clayey, gray
		22-25	Sand, coarse, yellow
		25-32	Same

Well Number	Elevation (in feet, SLD)	Depth (in feet, below land surface)	Description of Lithology
Fb34-11	60.48	32-35	Sand, coarse, dark brown
		35-40	Sand, coarse, light brown
		40-45	Same
		45-47	Same
		47-55	Greensand
Fb34-12	62.00	0-5	Top soil with some yellow, medium sand
		5-10	Sand, coarse, yellow. Gra- vel at 5'-5.5' and 9'-10'
		10-15	Sand, coarse, light brown. Clay varicolored at 12'- 12.2'
		15-20	Clay, silty, varicolored with some light gray to white "clean", fine sand
		20-25	Clay, silty, mostly light gray
		25-30	Sand, medium, brown
		30-35	Same
		35-38	Sand, coarse, brown
		38-45	Same
		45-50	Same
		50-55	Same
Fb34-13	63.60	55-60	Greensand
		60-65	Same
		0-5	Top soil with some yellow medium sand
		5-10	Sand, medium, light brown; gravel at 6'-6.5'
		10-14	Sand, coarse yellow
		14-16	Gravel
		16-20	Sand, coarse, yellow
		20-25	Sand, coarse, dark gray to purple. Color becomes lighter downward

Well Number	Elevation (in feet, SLD)	Depth (in feet, below land surface)	Description of Lithology
Fb34-13	63.60	25-30	Sand, coarse, light brown
		30-37	Same
		37-40	Sand, coarse, dark brown
		40-45	Sand, coarse, dark brown to purple
		45-50	Sand, coarse, brown
		50-55	Same; color gradually be- comes light brown
		55-60	Same. Rare silt layers-- dark brown to purple
		60-63	Sand, coarse, yellow
		63-68	Greensand, weathered
Fb34-14	55.63	0-5	Top soil with some fine brown sand
		5-11	Sand, medium, dark brown (purple at 10')
		11-15	Sand, coarse, yellow; gra- vel at 14.5'-15'
		15-20	Sand, coarse, yellow; gra- vel at 18'-19'
		20-25	Sand, coarse, purple to darkbrown (light gray layer at 24')
		25-30	Sand, coarse, reddish- brown; gravel at 29'- 29.5'
		30-35	Same
		35-40	Same
		40-45	Sand, coarse, light brown
		45-47	Same
		47-50	Greensand, weathered, clayey
Fb34-15	54.20	0-5	Top soil with some fine, reddish-brown sand
		5-8	Gravel
		8-10	Sand, coarse, reddish- brown
		10-15	Same; color gradually be- comes lighter-yellow at 14'

Well Number	Elevation (in feet, SLD)	Depth (in feet, below land surface)	Description of Lithology
Fb34-15	54.20	15-20	Same; color is dark brown at 19'-20'
		20-25	Sand, coarse, yellow. At 24' color becomes dark gray to purple
		25-29	Sand, coarse, dark gray to purple. Color gradually becomes lighter-yellow at 29'
		29-35	Sand, gravelly, yellow
		35-40	Sand, coarse, brown
		40-45	Same. At 43'-45' color is yellow
		45-47	Sand, coarse, light brown
		47-50	Greensand, weathered
Fb35-4	61.16	0-5	Top soil and some yellow, medium sand
		5-6	Gravel
		6-10	Sand, coarse, yellow with some red clay
		10-15	Sand, coarse, yellow with some gravel
		15-19	Same
		19-25	Sand, medium, reddish-brown
		25-30	Sand, coarse, yellowish-brown with some gravel
		30-35	Sand, coarse, brown
		35-40	Same
		40-45	Same
		45-47	Same
		47-50	Greensand
Fb35-5	67.60	0-5	Top soil with some yellow, medium sand
		5-10	Sand, coarse, yellow with some gravel
		10-15	Sand, coarse, yellowish-brown; gravel 14'-14.5'

Well Number	Elevation (in feet, SLD)	Depth (in feet, below land surface)	Description of Lithology
Fb35-5	67.60	15-20	Same, some gravel
		20-25	Sand, coarse, yellow
		25-30	Sand, coarse, grayish- yellow
		30-32	Same
		32-35	Greensand
Fb35-6	52.16	0-5	Top soil with some medium, yellow sand
		5-10	Sand, coarse, yellow; some gravel
		10-15	Same; some gravel
		15-20	Sand, coarse, brown with some gravel
		20-25	Sand, coarse, reddish- brown
		25-32	Same
		32-33	Greensand
Fb35-7	64.95	0-5	Top soil with brown clayey sand
		5-10	Sand, medium, brown with some gravel
		10-15	Sand, fine, silty, brown
		15-23	Sand, fine, brown with some yellow clay
		23-25	Sand, reddish-brown with varicolored clay
		25-30	Sand, medium, reddish-brown with small pebbles
		30-35	Same
		35-40	Same
		40-43	Same
		43-45	Greensand

Well Number	Elevation (in feet, SLD)	Depth (in feet, below land surface)	Description of Lithology
Fb35-8	77.91	0-5	Top soil and brown clayey sand
		5-10	Sand, fine, silty, brown
		10-15	Same; some gravel
		15-20	Sand, medium, brown with some gravel
		20-25	Same
		25-30	Same
		30-35	Sand, fine, silty, reddish-brown
		35-40	Sand, medium, brown with some gravel
		40-45	Sand, medium, brown
		45-50	Same
		50-55	Sand, coarse, brown with some gravel
		55-60	Sand, coarse, brown
		60-65	Same
		65-70	Same
		70-75	Sand, fine, silty, brown
		75-81	Same
		81-85	Greensand
Fb35-9	50.28	0-2	Top soil
		2-5	Gravel
		5-10	Sand, coarse, reddish-brown with some clay
		10-15	Sand, coarse, yellow to light brown
		15-20	Sand, gravelly, brown
		20-25	Same
		25-30	Same
		30-34	Sand, coarse, brown
		34-35	Gravel
		35-40	Sand, coarse, dark brown
		40-45	Same
		45-50	Same
		50-55	Sand, coarse, yellow
		55-60	Same
		60-65	Sand, medium, dark brown (weathered greensand)
		65-70	Same

Well Number	Elevation (in feet, SLD)	Depth (in feet, below land surface)	Description of Lithology
Fb35-10	54.42	0-3	Top soil
		3-5	Gravel
		5-10	Sand, coarse, brown with some gravel
		10-15	Same
		15-20	Sand, coarse, yellowish- brown
		20-25	Same
		25-30	Sand, coarse, light brown with some gravel at 27'
		30-35	Same
		35-40	Sand, medium, yellow
		40-45	Same
		45-50	Sand, coarse, light brown with some silt
		50-55	Sand, coarse, brown
		55-60	Same
		60-65	Sand, medium, dark brown (weathered greensand)
		65-70	Same
		70-75	Same
		75-80	Sand, coarse, yellow (contamination)
		80-85	Contamination
		85-90	Same
		90-95	Same
		95-100	Same
Fb35-11	56.72	100-105	Same
		105-109	Same
		109-115	Greensand (sample taken from the auger after it was pulled out)
		0-5	Top soil with some medium brown sand
		5-10	Sand, coarse, brown; gra- vel at 6'-6.5'
		10-15	Sand, coarse, light brown with some gravel and ironstone
		15-20	Sand, coarse, dark brown with some gravel and ironstone

Well Number	Elevation (in feet, SLD)	Depth (in feet, below land surface)	Description of Lithology
Fb35-11	56.72	20-25	Sand, coarse, light brown with gravel at 23'
		25-30	Sand, coarse, grayish- brown with some gravel
		30-35	Sand, coarse, yellow with gravel at 31' and 33'
		35-40	Sand, coarse, dark brown with gravel
		40-43	Greensand
Fb35-12	55.24	0-5	Top soil
		5-10	Sand, coarse, reddish- brown with gravel at 5' and 9'
		10-15	Same with ironstone at 14'
		15-20	Sand, coarse, brown with some gravel
		20-23 23-25	Sand, coarse, reddish-brown Greensand
Fb43-2	63.66	0-5	Top soil with some light brown medium sand and pebbles. Gravel from 4'-4'5
		5-9	Sand, coarse, yellow with some small pebbles
		9-15	Sand, medium, light brown. Brown from 14'-15'
		15-18	Sand, coarse, yellow
		18-28	Sand, coarse, brown, be- coming light brown and light gray at the base.
		28-31	Sand, coarse, brown with gravel
		31-34	Sand, coarse, light gray with some pebbles
		34-40	Sand, coarse, gravelly, yellow to light gray
		40-45	Same; more pebbles
		45-50	Same
		50-55	Same; more pebbles

Well Number	Elevation (in feet, SLD)	Depth (in feet, below land surface)	Description of Lithology
Fb43-2	63.66	55-60	Same
		60-61	Sand, coarse, dark brown
		61-65	Sand, medium, brown
		65-70	Greensand, dark brown, weathered
Fb44-5	54.78	0-5	Top soil with some medium brown sand
		5-10	Sand, coarse, brown; some gravel
		10-15	Sand, coarse, yellowish- brown with gravel
		15-22	Sand, coarse, yellow. Gra- vel at 15'-15.5' and 17'-18'
		22-24	Sand, coarse, dark brown
		24-25	Sand, coarse, yellow
		25-30	Sand, medium, yellow
		30-35	Same. Some ironstone
		35-40	Sand, medium, dark gray to purple
		40-45	Sand, medium, gray
		45-50	Same
		50-55	Sand, medium, light gray
		55-60	Same
		60-65	Same, becoming yellow at the base.
		65-67	Sand, medium, yellow
		67-70	Greensand, weathered
Fb44-6	42.79	0-5	Top soil with some medium, yellow sand
		5-10	Sand, coarse, yellow
		10-15	Sand, coarse yellowish- brown (till 12') then yellow
		15-18	Same; gravel at 17'-17.5'
		18-20	Sand, coarse, reddish-brown
		20-25	Sand, coarse, brown
		25-30	Same

Well Number	Elevation (in feet, SLD)	Depth (in feet, below land surface)	Description of Lithology
Fb44-6	42.79	30-35	Same; some gravel
		35-40	Sand, coarse, light brown
		40-46	Same
		46-50	Greensand
Fb44-7	29.16	0-8	Sand, medium, clayey, red- dish-brown; gravel at 4'-5'
		8-10	Greensand
		10-15	Same
Fb44-8	55.72	0-5	Top soil and brown, clayey, medium sand
		5-10	Sand, clayey, medium, light brown; gravel at 7'-7.5'
		10-14	Sand, coarse, brown with some gravel
		14-20	Sand, medium, light brown
		20-25	Sand, medium, brown with some gravel
		25-30	Sand, medium, reddish-brown
		30-35	Sand, medium, reddish-brown with some gravel
		35-40	Same
		40-45	Same
		45-47	Same
		47-50	Greensand
Fb44-9	63.32	0-5	Top soil with yellow clayey sand
		5-10	Sand, medium, brown with some gravel
		10-12	Sand, gravelly, brown
		12-15	Sand, medium, dark brown with some gravel
		15-20	Sand, coarse, brown with gravel
		20-25	Same

Well Number	Elevation (in feet, SLD)	Depth (in feet, below land surface)	Description of Lithology
Fb44-9	63.32	25-30	Sand, coarse, light brown
		30-35	Same
		35-40	Sand, coarse, brown
		40-45	Sand, coarse, dark brown
		45-51	Same
		51-55	Greensand
Fb44-10	58.66	0-5	Top soil with some brown, medium sand
		5-9	Sand, medium, light brown
		9-10	Gravel
		10-15	Sand, coarse, brown with gravel
		15-17	Gravel
		17-20	Sand, coarse, brown to gray ish brown
		20-25	Same
		25-27	Sand, medium, reddish-brown
		27-30	Greensand
Fb44-11	45.54	0-8	Top soil with some yellow, medium sand
		8-10	Gravel
		10-15	Sand, coarse, yellow
		15-20	Same
		20-25	Sand, gravelly, yellow
		25-30	Same
		30-33	Same; gravel at 31'-31.5'
		33-35	Gravel
		35-37	Sand, gravelly, yellow
		37-40	Greensand; greenish-blue clayey silt

Well Number	Elevation (in feet, SLD)	Depth (in feet, below land surface)	Description of Lithology
Fb45-4	65.16	0-5	Top soil, brown clay and some gravel
		5-10	Sand, fine, clayey, brown. Some gravel at 7'
		10-15	Clay, brown and gray
		15-20	Sand, fine clayey, brown
		20-25	Sand, medium, brown
		25-30	Sand, medium, dark brown
		30-35	Sand, medium, yellowish- brown
		35-40	Same
		40-45	Same
		45-50	Sand, medium, brown
		50-55	Sand, slightly clayey, medium
		55-57	Greensand
Fb45-5	46.11	0-5	Top soil with brown sandy clay
		5-10	Sand, medium, reddish-brown
		10-15	Same
		15-21	Same
		21-25	Greensand, partly weathered
Fb45-6	16.25	0-2.5	Top soil
		2.5-5	Sand, medium, yellow
		5-9	Same
		9-10	Gravel
		10-15	Sand, coarse, yellow
		15-19	Sand, gravelly, reddish-brown
		19-20	Greensand, green clay at the base

APPENDIX II

Description of Cores

Well no: Fb34-9
Interval cored: 18' - 27'2.5"
Depth: in feet, below land surface

<u>Core no. 1</u>	<u>Description of Lithology</u>
18'3.5" - 18'4"	Contamination
18'3.5" - 19'2.5"	Clay, yellowish-gray and mottled light gray to bluish-gray
19'2.5" - 19.3"	Sand, medium, brown
<u>Core no. 2</u>	
19.5" - 19.9.5"	Contamination
19'9.5" - 20'1"	Clay, yellow containing laminae of fine to medium yellow sand
20'1" - 20'2.5"	Sand, silty, yellow with laminae of dark gray clay
20'2.5" - 20'4.5"	Clay, reddish brown with thin layers of fine grayish-green sand
20'4.5" - 20'8.5"	Clay, yellowish-gray mottled brown
20'8.5" - 21'	Clay, silty, brownish-red
<u>Core no. 3</u>	
21' - 21'1"	Contamination
21'1" - 21'8"	Clay, dark brown. In the upper 1.5' clay is silty
21'8" - 21'8.5"	Sand, medium, light gray to yellow
21'8.5" - 21'9"	Clay, yellowish-brown
<u>Core no. 4</u>	
21'9.5" - 22'1"	Contamination
22'1" - 22'2.5"	Clay, brownish-gray grading into gray clay at the bottom
<u>Core no. 4</u>	
22'22.5" - 22'3"	Sand, medium to fine, light gray
22'3" - 22'10"	Clay, grayish-brown containing thin layers of sand, medium to fine, light gray
22'10" - 23'1.5"	

Core no. 5Description of Lithology

22'10" - 23'2"

Contamination

23'2" - 23'6"

Clay, gray, mottled reddish-brown

23'6" - 23'7"

Sand, fine light gray containing
laminae of gray clay

23'7" - 23'9.5"

Clay, gray containing thin layers
of fine light-gray sand

23'9.5" - 24'1.5"

Clay, dark gray

24'1.5" - 24'2"

Sand, fine, light gray

Core no. 6

24'2" - 24'6"

Contamination

24'6" - 24'6.5"

Sand, fine, bluish gray

24'6.5" - 24'7.5"

Sand, medium, light gray to yellow
containing laminae of gray clay

24'7.5" - 24'9"

Clay, dark gray

24'9" - 24'10"

Sand, medium to fine, light gray

24'10" - 25'2.5"

Clay, dark gray

25'2.5" - 25'4"

Sand, medium to fine, yellow con-
taining laminae of gray clay

25'4" - 25'4.5"

Clay, gray

25'4.5" - 25'5"

Sand, medium to fine, light gray
to yellow

25'5" - 25'6.5"

Clay, yellowish-gray

25'6.5" - 25'8"

Sand, medium to fine, yellow

Core no. 7

25'5" - 25'9"

Contamination

25'9" - 26'0"

Clay, gray

26'0" - 26'1.5"

Sand, fine, light gray containing
laminae of gray clay

26'1.5" - 26'4.5"

Clay, gray with thin layers of
sand, fine, yellow

26'4.5" - 26'5.5"

Sand, fine to medium, yellow with
laminae of reddish-brown clay

26'5.5" - 26'7.5"

Clay, reddish-brown containing
laminae of light colored gray clay

26'7.5" - 26'8.5"

Sand, medium, yellow with large
amount of clayey matrix

Well no: Fb34-12
Interval cored: 10'9.5" - 19'
Depth: in feet, below land surface

<u>Core no. 1</u>	<u>Description of Lithology</u>
10'9.5" - 10'11.5"	Contamination
10'11.5" - 11'0"	Sand, medium, dark gray, limonitic
11'0" - 11'3"	Sand, medium, yellow, parallel bedded
11'3" - 11'4.5"	Clay, dark brown
11'4.5" - 11'7.5"	Clay, yellow to reddish-yellow, slightly silty in the lower part
11'7.5" - 11'8"	Sand, fine to medium, dark brown topped with a thin layer of limonite
11'8" - 11'9"	Sand, fine to medium, light brown
<u>Core no. 2</u>	
11'6" - 11'8"	Contamination
11'8" - 12'0"	Sand, fine to medium, light brown to yellow, parallel bedded
12'0" - 12'2"	Sand, medium, yellow, containing thin layers of limonite
12'2" - 12'3.5"	Sand, fine to medium, black limonitic
12'3.5" - 12'7"	Clay, light gray and red
<u>Core no. 3</u>	
12'3" - 12'7"	Contamination
12'7" - 12'9"	Clay, gray
12'9" - 12'11.5"	Sand, fine to medium, white to yellowish-white. The upper 1/2" is interlayered with gray clay
12'11.5" - 13'3.5"	Sand, fine, light yellow containing small patches of limonite
13'3.5" - 13'6"	Clay, gray
13'6" - 13'8"	Clay, yellowish-brown
13'8" - 13'9"	Sand, fine, dark brown to reddish-brown

Core no. 4

13'9.5" - 14'4"

14'4" - 14'5"

14'5" - 14'8"

14'8" - 14'10.5"

14'10.5" - 14'7"

Description of Lithology

Contamination

Sand, fine, yellow to light brown

Sand, medium to fine, brown, topped with a dark brown sand, fine and limonitic

Clay, gray

Sand, medium to fine, light gray to yellow containing layers of gray clay

Core no. 5

15'5" - 15'7"

15'7" - 15'8.5"

15'8.5" - 15'11.5"

15'11.5" - 16'3.5"

16'3.5" - 16'7.5"

16'7.5" - 17'2"

Contamination

Sand, medium, light gray to yellowish-gray, parallel bedded

Clay, light gray containing small packets of fine yellow sand

Clay is dark gray at the bottom

Sand, coarse to medium, white

Sand, medium, yellow becoming darker upward

Sand, grading from coarse in the lower part to fine in the upper part, dark brown; topped with a layer of limonite

Core no. 6

17'4" - 17'6"

17'6" - 19'0"

Contamination

Sand, medium, dark brown containing some thin layers of limonite.

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100 101 102 103 104 105 106 107 108 109 110 111 112 113 114 115 116 117 118 119 120 121 122 123 124 125 126 127 128 129 130 131 132 133 134 135 136 137 138 139 140 141 142 143 144 145 146 147 148 149 150 151 152 153 154 155 156 157 158 159 160 161 162 163 164 165 166 167 168 169 170 171 172 173 174 175 176 177 178 179 180 181 182 183 184 185 186 187 188 189 190 191 192 193 194 195 196 197 198 199 200 201 202 203 204 205 206 207 208 209 210 211 212 213 214 215 216 217 218 219 220 221 222 223 224 225 226 227 228 229 230 231 232 233 234 235 236 237 238 239 240 241 242 243 244 245 246 247 248 249 250 251 252 253 254 255 256 257 258 259 260 261 262 263 264 265 266 267 268 269 270 271 272 273 274 275 276 277 278 279 280 281 282 283 284 285 286 287 288 289 290 291 292 293 294 295 296 297 298 299 300 301 302 303 304 305 306 307 308 309 310 311 312 313 314 315 316 317 318 319 320 321 322 323 324 325 326 327 328 329 330 331 332 333 334 335 336 337 338 339 340 341 342 343 344 345 346 347 348 349 350 351 352 353 354 355 356 357 358 359 360 361 362 363 364 365 366 367 368 369 370 371 372 373 374 375 376 377 378 379 380 381 382 383 384 385 386 387 388 389 390 391 392 393 394 395 396 397 398 399 400 401 402 403 404 405 406 407 408 409 410 411 412 413 414 415 416 417 418 419 420 421 422 423 424 425 426 427 428 429 430 431 432 433 434 435 436 437 438 439 440 441 442 443 444 445 446 447 448 449 450 451 452 453 454 455 456 457 458 459 460 461 462 463 464 465 466 467 468 469 470 471 472 473 474 475 476 477 478 479 480 481 482 483 484 485 486 487 488 489 490 491 492 493 494 495 496 497 498 499 500 501 502 503 504 505 506 507 508 509 510 511 512 513 514 515 516 517 518 519 520 521 522 523 524 525 526 527 528 529 530 531 532 533 534 535 536 537 538 539 540 541 542 543 544 545 546 547 548 549 550 551 552 553 554 555 556 557 558 559 560 561 562 563 564 565 566 567 568 569 570 571 572 573 574 575 576 577 578 579 580 581 582 583 584 585 586 587 588 589 590 591 592 593 594 595 596 597 598 599 600 601 602 603 604 605 606 607 608 609 610 611 612 613 614 615 616 617 618 619 620 621 622 623 624 625 626 627 628 629 630 631 632 633 634 635 636 637 638 639 640 641 642 643 644 645 646 647 648 649 650 651 652 653 654 655 656 657 658 659 660 661 662 663 664 665 666 667 668 669 670 671 672 673 674 675 676 677 678 679 680 681 682 683 684 685 686 687 688 689 690 691 692 693 694 695 696 697 698 699 700 701 702 703 704 705 706 707 708 709 710 711 712 713 714 715 716 717 718 719 720 721 722 723 724 725 726 727 728 729 730 731 732 733 734 735 736 737 738 739 740 741 742 743 744 745 746 747 748 749 750 751 752 753 754 755 756 757 758 759 760 761 762 763 764 765 766 767 768 769 770 771 772 773 774 775 776 777 778 779 780 781 782 783 784 785 786 787 788 789 790 791 792 793 794 795 796 797 798 799 800 801 802 803 804 805 806 807 808 809 810 811 812 813 814 815 816 817 818 819 820 821 822 823 824 825 826 827 828 829 830 831 832 833 834 835 836 837 838 839 840 841 842 843 844 845 846 847 848 849 850 851 852 853 854 855 856 857 858 859 860 861 862 863 864 865 866 867 868 869 870 871 872 873 874 875 876 877 878 879 880 881 882 883 884 885 886 887 888 889 890 891 892 893 894 895 896 897 898 899 900 901 902 903 904 905 906 907 908 909 910 911 912 913 914 915 916 917 918 919 920 921 922 923 924 925 926 927 928 929 930 931 932 933 934 935 936 937 938 939 940 941 942 943 944 945 946 947 948 949 950 951 952 953 954 955 956 957 958 959 960 961 962 963 964 965 966 967 968 969 970 971 972 973 974 975 976 977 978 979 980 981 982 983 984 985 986 987 988 989 990 991 992 993 994 995 996 997 998 999 1000 1001 1002 1003 1004 1005 1006 1007 1008 1009 1010 1011 1012 1013 1014 1015 1016 1017 1018 1019 1020 1021 1022 1023 1024 1025 1026 1027 1028 1029 1030 1031 1032 1033 1034 1035 1036 1037 1038 1039 1040 1

PROGRAM FOR STANDARD-SIZE ANALYSIS OF
UNCONSOLIDATED SEDIMENTS

ANY MACHINE WITH A FORTRAN II OR FORTRAN IV
COMPILER

CALCULATE THE WEIGHT PERCENTAGE OF SILT, CLAY, AND SAND.
CALCULATE THE MEAN, STANDARD DEVIATION, SKEWNESS, AND KURTOSIS FOR STANDARD SEDIMENT-SIZE ANALYSIS.

STATISTICAL METHOD OF MOMENTS FOR SIZE PARAMETERS

FOR 500 SAMPLES WITH 6 SIEVE-SIZE CLASSES EACH

XDS	9300	40	SEC
-----	------	----	-----

INPUT**CONTROL CARDS AND DATA CARDS

COL 1-5 (RIGHT JUSTIFIED)

THE NUMBER OF SIEVE SIZE CLASSES
MAXIMUM IS 50

(NOTE—RIGHT JUSTIFICATION IS UNNECESSARY BUT THE DECIMAL POINT MUST BE PUNCHED FOR EACH NUMBER IN THE FOLLOWING CARD)

MIDPOINT OF 1ST SIEVE-SIZE CLASS IN PHI UNITS

MIDPOINT OF 2ND SIEVE-SIZE CLASS IN PHI UNITS
ETC.

MIDPOINT OF 8TH SIEVE-SIZE CLASS IN PHI UNITS

CONTROL CARD 3 (IF NECESSARY)
COL 1-10
MIDPOINT OF 9TH SIEVE-SIZE CLASS IN PHI UNITS
COL 11-20
MIDPOINT OF 10TH SIEVE-SIZE CLASS IN PHI UNITS
ETC. UP TO A MAXIMUM OF 50 SIEVE-SIZE CLASSES

DATA CARDS

DATA CARD 1

COL 1-4

SAMPLE NUMBER(RIGHT JUSTIFIED)
(NOTE-FOR THE FOLLOWING NUMBERS, RIGHT
JUSTIFICATION IS NOT NECESSARY, BUT THE DECIMAL
POINT MUST BE PUNCHED)

COL 5-13

WEIGHT OF CLAY

COL 14-22

WEIGHT OF SILT

COL 28-31

WEIGHT OF 1ST SIEVE-SIZE CLASS

COL 37-40

WEIGHT OF 2ND SIEVE-SIZE CLASS

COL 41-49

WEIGHT OF 3RD SIEVE-SIZE CLASS

COL 50-58

WEIGHT OF 4TH SIEVE-SIZE CLASS

COL 59-67

WEIGHT OF 5TH SIEVE-SIZE CLASS

COL 68-76

WEIGHT OF 6TH SIEVE-SIZE CLASS

COL 77-80

BLANK

DATA CARD 2 (IF NECESSARY)

COL 1-4

SAMPLE NUMBER(RIGHT JUSTIFIED)

COL 5-13

WEIGHT OF 7TH SIEVE-SIZE CLASS

COL 14-22

WEIGHT OF 8TH SIEVE-SIZE CLASS

ETC. UP TO A MAXIMUM OF 50 SIEVE-SIZE CLASS WEIGHTS

THE ABOVE DATA CARD FORMAT IS USED FOR EACH SAMPLE

OUTPUT

SAMPLE NUMBER
SAND WEIGHT PERCENTAGE

```

C      CLAY WEIGHT PERCENTAGE
C      SILT WEIGHT PERCENTAGE
C      MEAN
C      STANDARD DEVIATION
C      SKEWNESS
C      KURTOSIS
C
C
C      DIMENSION AMPHI(50),WTPHI(50)
C      NOTE--FOR FORTRAN IV
C      N105 IS INPUT UNIT
C      N106 IS OUTPUT UNIT
C      FOR FORTRAN II,PLACE A C IN COLUMN 1 OF
C      ALL FORTRAN IV INPUT/OUTPUT STATEMENTS
C      AND REMOVE C'S FROM FORTRAN II
C      STATEMENTS.
C
C      N105 = 105
C      N106 = 108
C
C      N IS THE NO. OF SIEVE-SIZE CLASSES
C      AMPHI(I) IS THE MID-POINT OF EACH
C      SIEVE-SIZE CLASS
C      AMPHI(I) ARE IN PHI UNITS
C
C      READ FROM CARDS N AND AMPHI(I)
C      FOR I FROM 1 TO N
C
C      FORTRAN IV
C      READ (N105,1000)N,(AMPHI(I),I=1,N)
C      FORTRAN II
C      READ 1000,N,(AMPHI(I),I=1,N)
C      1000 FORMAT (I5/(8F10.5))
C      FORTRAN IV
C      WRITE(N106,1090)(AMPHI(I),I=1,N)
C      FORTRAN II
C      PUNCH 1090,      (AMPHI(I),I=1,N)
C      1090 FORMAT( 12H PHI UNITS      /(8F10.5))
C
C
C      PRINT HEADING
C
C      FORTRAN IV
C      WRITE(N106,1010)
C      FORTRAN II
C      PUNCH 1010
C      1010 FORMAT(40H SAMPLE    SAND PART CLAY PART SILT PART ,
C      140H MEAN    STD. DEV.  SKEWNESS  KURTOSIS    )
C

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```

C          NSAMPL IS THE SAMPLE NO.
C          WTCLAY IS THE WEIGHT OF THE CLAY
C          WTSILT IS THE WEIGHT OF THE SILT
C          WTPHI(I) ARE THE SAND WEIGHTS IN
C          EACH SIEVE-SIZE CLASS
C
C          BEGIN READING DATA
C
C 1001 CONTINUE
C          NEED TWO KINDS OF FORMATS
C          (SINGLE CARD AND MULTIPLE CARD)
C          IF(N-6)2001,2001,3001
C          FORTRAN IV
C 2001 READ (N105,1002)NSAMPL,WTCLAY,WTSILT,(WTPHI(I),I=1,N)
C          FORTRAN II
C 2001 READ 1002,          NSAMPL,WTCLAY,WTSILT,(WTPHI(I),I=1,N)
C 1002 FORMAT (I4,8F9.4)
C          GO TO 3000
C          FORTRAN IV
C 3001 READ (N105,3002)NSAMPL,WTCLAY,WTSILT,(WTPHI(I),I=1,N)
C          FORTRAN II
C 3001 READ 3002,          NSAMPL,WTCLAY,WTSILT,(WTPHI(I),I=1,N)
C 3002 FORMAT (I4,8F9.4,4X/(4X,8F9.4,4X))
C 3000 CONTINUE
C
C          WRITE OUT SAMPLE NO.
C
C          FIND GROSS WT.
C
C          GROSS = WTCLAY + WTSILT
C          DO 1004 I=1,N
C 1004 GROSS = GROSS + WTPHI(I)
C
C          FIND TOTAL WT OF SAND
C
C          SANDWT = 0.
C          DO 1005 I=1,N
C 1005 SANDWT = SANDWT + WTPHI(I)
C
C          COMPUTE PARTIALS
C
C          DIV2 = 1./GROSS
C          PTCLAY = WTCLAY *DIV2
C          PTSILT = WTSILT * DIV2
C          PTSAND = SANDWT * DIV2
C
C          COMPUTE SAND DIVISOR
C
C          DIV1 = 1./SANDWT

```

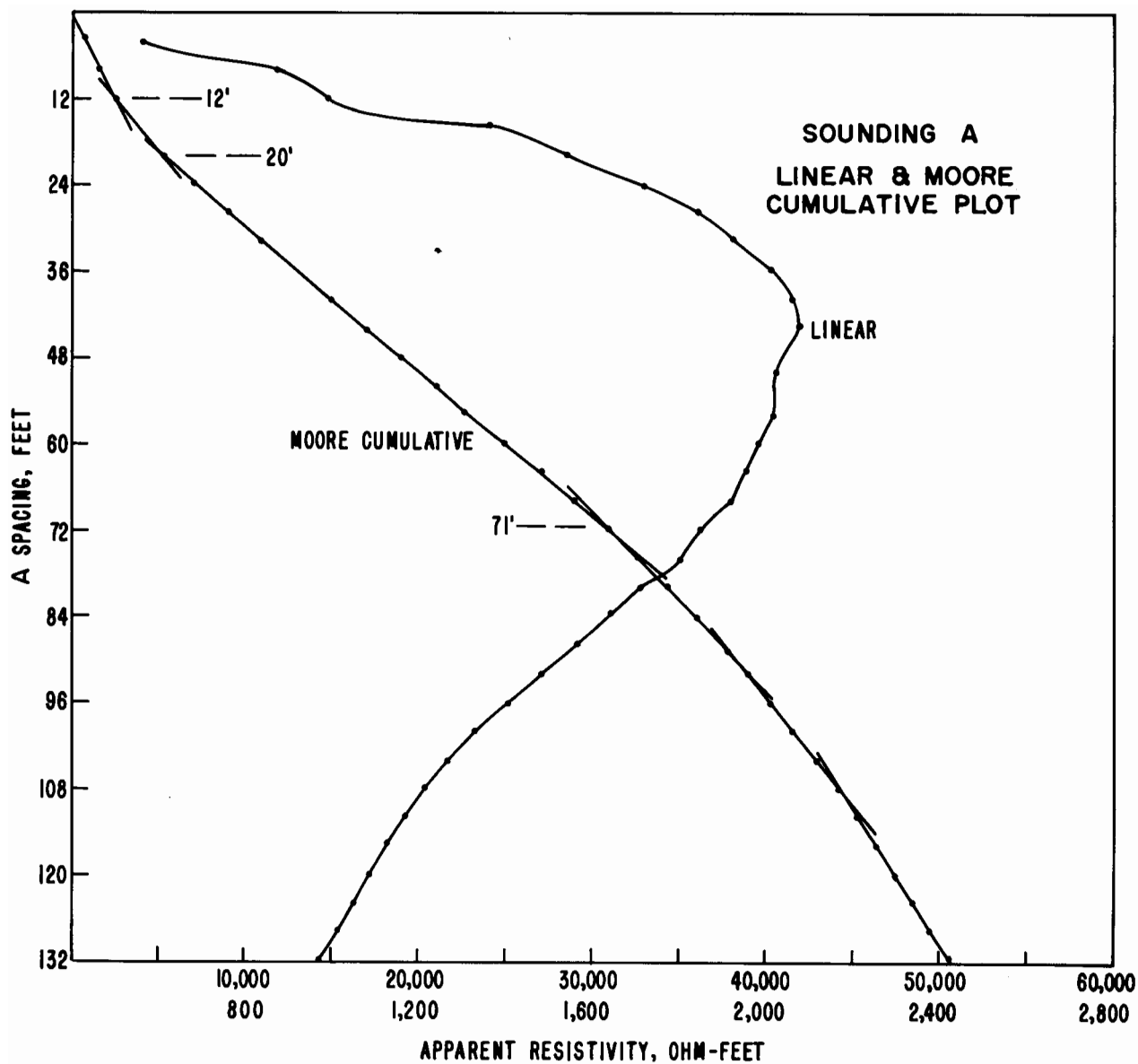
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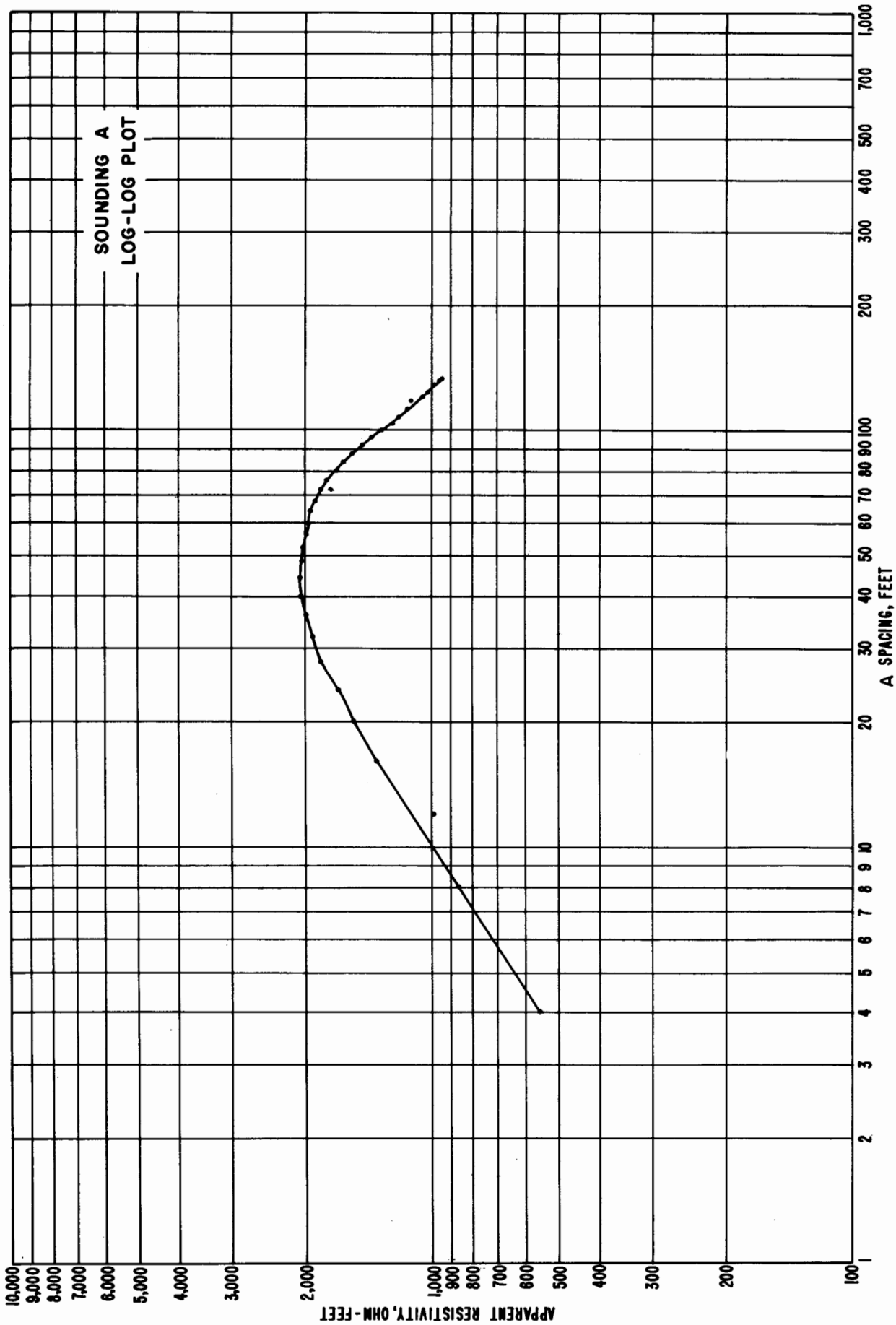
C
C
C      COMPUTE SUM OF WT/SIEVE-SIZE CLASS
C      TIMES MIDPOINT OF CLASS
C
      SUMX1 = 0.
      DO 1006 I=1,N
1006  SUMX1=SUMX1 + WTPHI(I)*AMPHI(I)
C
C      FIND MEAN OF SAND WTS.
C
      XMEAN = SUMX1/DIV1
C
C      COMPUTE SUM2A,SUM3A,SUM4A
C
      SUM2A = 0.
      SUM3A = 0.
      SUM4A = 0.
      DO 1007 I= 1,N
      SUM2A = SUM2A + WTPHI(I) *((AMPHI(I)-XMEAN)**2 )
      SUM3A = SUM3A + WTPHI(I)*((AMPHI(I)-XMEAN)**3 )
1007  SUM4A = SUM4A + WTPHI(I)*((AMPHI(I)-XMEAN)**4 )
C
C      COMPUTE SIGMA
C      COMPUTE SIGMA CUBED
C      COMPUTE SIGMA TO THE FOURTH
C
      SIGMA = SQRTF(SUM2A/DIV1)
      SIGMA3=SIGMA**3
      SIGMA4=SIGMA**4
C
C      FIND SKEWNESS
C
      SKEW = (0.5*SUM3A/DIV1/SIGMA3)
C
C
      AKURT = 0.5*(((SUM4A/DIV1)/SIGMA4)-3.0)
C
C      PRINT ALL OUTPUT NEEDED
C
      FORTRAN IV
      WRITE(N106,1009)NSAMPL,PTSAND,PTCLAY,PTSILT,XMEAN,
1SIGMA,SKEW,AKURT
C
      FORTRAN II
      PUNCH1009,      NSAMPL,PTSAND,PTCLAY,PTSILT,XMEAN,
C      1SIGMA,SKEW,AKURT
1009  FORMAT(1X,I4,2X,7F10.4)
      GO TO 1001
C
      END

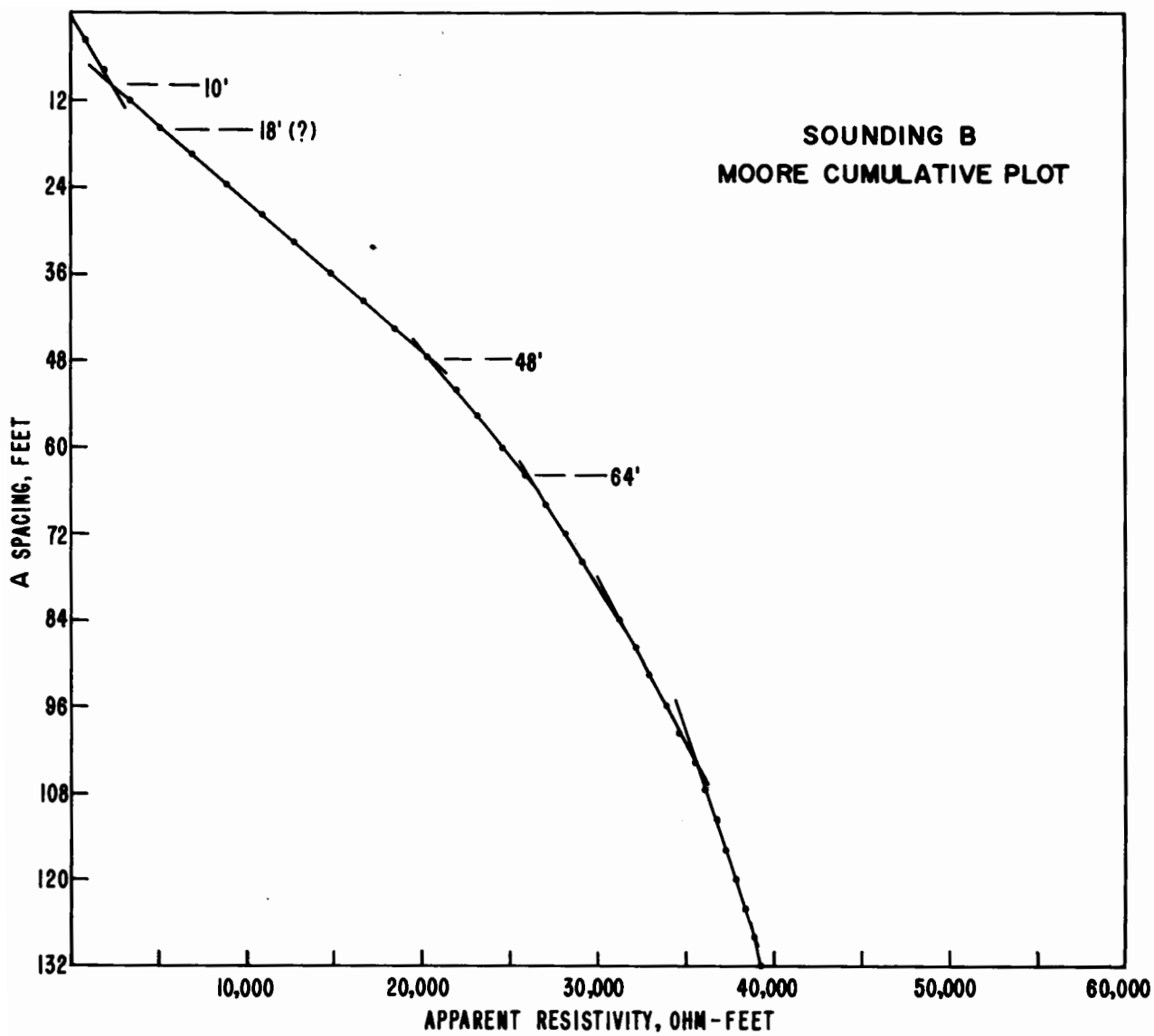
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APPENDIX IV

Data Plots for Resistivity Soundings







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