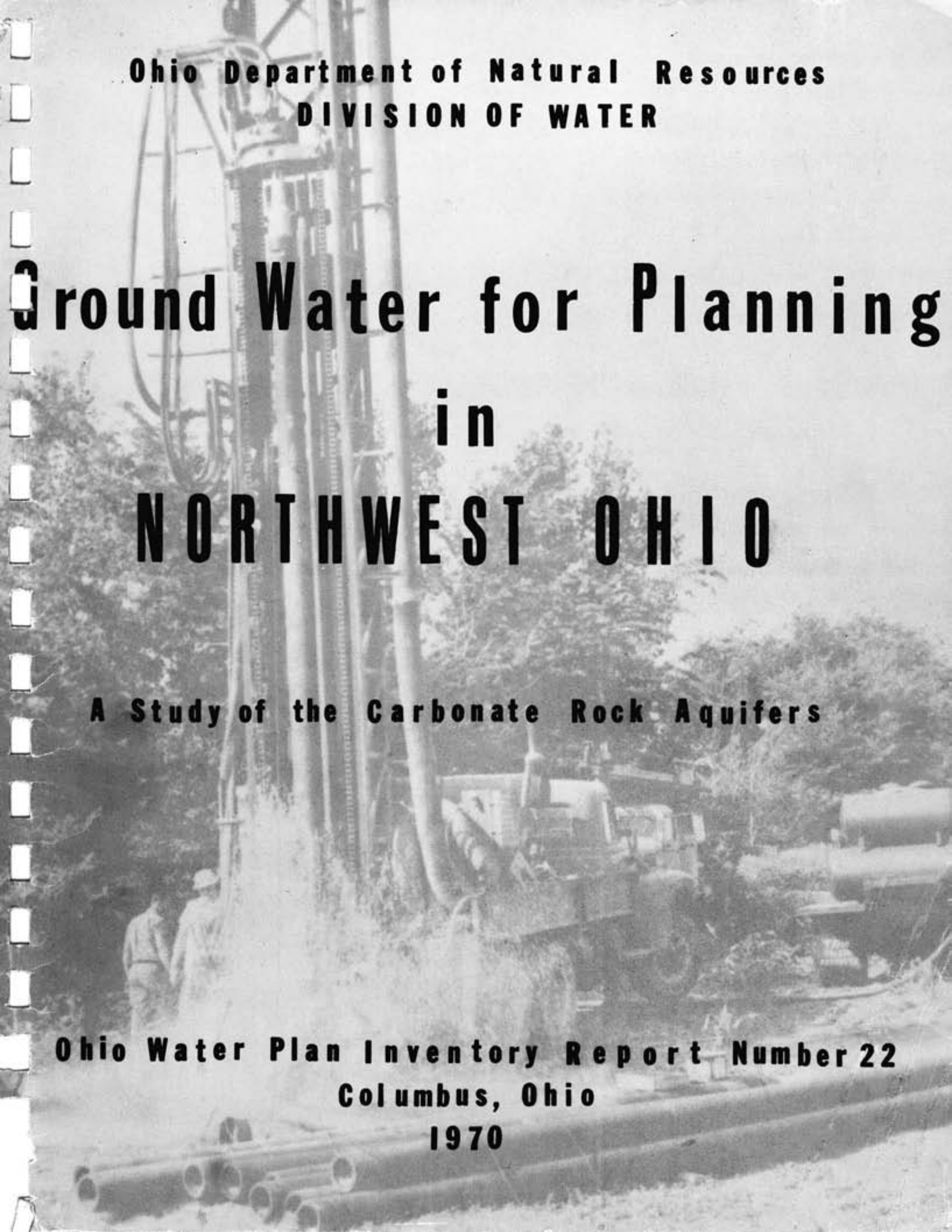

Ohio Department of Natural Resources
DIVISION OF WATER

Ground Water for Planning in NORTHWEST OHIO

A Study of the Carbonate Rock Aquifers

Ohio Water Plan Inventory Report Number 22
Columbus, Ohio
1970

Photo 1. Air rotary drilling rig at one of the seventy-six northwest Ohio test sites.

THE NORTHWEST OHIO WATER DEVELOPMENT PLAN

GROUND WATER FOR PLANNING IN NORTHWEST OHIO

A Study of the Carbonate Rock Aquifers

Ohio Department of Natural Resources
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1970

STAFF FOR THIS REPORT

DIVISION OF WATER

Project Supervision . . . . Alfred C. Walker

Hydrogeology . . . . James J. Schmidt

Michael V. Glaze

Hydrology . . . . Herbert B. Eagon, Jr.
David E. Johe

Leonard J. Harstine

Quality of Water . . . . Russell B. Stein

DIVISION OF GEOLOGICAL SURVEY

Stratigraphy . . . . A. Janssens

U. S. GEOLOGICAL SURVEY

Geophysical Logging . . . . Stanley E. Norris
Richard Fidler

CONSULTANT

Fred H. Klaer, Jr. and Associates

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ILLUSTRATIONS

SYNOPSIS

The Northwest Ohio Water Development Plan, prepared by the Ohio Water Commission (1967), recommended a drilling and testing program to evaluate the quantity and quality of the ground water available in the Northwest Ohio area.

Seventy-six large diameter limestone and dolomite wells were drilled, tested, and analyzed as the basis for this two and one-half year study.

Ground water in carbonate rocks moves through a complex network of interconnected openings, some of which have been enlarged by solution. Thus, although the carbonate aquifer in northwest Ohio is comprised of a number of geologic formations of Silurian and Devonian age, it is considered as a single hydraulic unit.

The stratigraphy and the areal distribution of buried valleys constitute the major geologic controls which affect the hydrologic characteristics. These two factors are interrelated but differential weathering in the vicinity of the buried valleys is considered to be the primary controlling factor.

The limestone-dolomite aquifer in northwest Ohio currently yields 32.69 million gallons per day to municipal and industrial wells. Large additional quantities are pumped for irrigation and domestic supplies. Estimates of well-field capacities in various undeveloped areas have been included in this report as a guide for potential development.

The quality of the ground water is equally as important as quantity in planning for future use. Softening is recommended for ground-water supplies throughout the study area. Hydrogen sulfide is often present in varying amounts. However, in nearly all instances, objectionable concentrations of hydrogen sulfide can be removed by simple and inexpensive processes. Ground-water development in some portions of the area would be restricted by quality considerations, with present treatment methods.

Even considering the quality limitations, the potential of the carbonate aquifer in northwest Ohio far exceeds the present ground-water development.

I. INTRODUCTION

Size and Location

The area described in this report includes the entire Portage and Sandusky river basins and a large part of the Maumee River basin. This area is immediately underlain by limestones and dolomites which constitute Ohio's second most important (and least studied) aquifer. The most productive ground-water source consists of permeable sand and gravel deposits within buried valleys elsewhere in the State.

This 4200 square mile study area (see plate 1) is bounded on the northwest by an arbitrary line approximating the boundary of the limestone-shale contact on the bedrock surface; on the west, by the Ohio-Indiana state line; on the south by the Lake Erie drainage divide; and on the east by the eastern boundaries of Sandusky and Seneca counties. The area extends, in the north and northeast, to the Ohio-Michigan state line and Lake Erie, respectively.

Purpose and Scope of the Investigation

In January, 1967, the Northwest Ohio Water Development Plan was prepared by the Ohio Water Commission. The objective of this plan was to provide a comprehensive program for development of water resources that would give maximum support to the overall growth and development of this region.

The plan contained recommended programs for total water management so that the greatest economic and social benefits might be realized. One of the recommendations was that a northwest Ohio ground-water study be initiated to better define this resource. It called for a drilling and testing program to evaluate the quantity and quality of the ground water available, and to encourage more complete ground-water development. This report contains the results of the ground-water investigation recommended by the Ohio Water Commission. Field work was begun in February, 1968, and was completed in the summer of 1970.

Although the entire area is covered with glacial deposits ranging from a few feet thick in some of the counties to 400 feet in portions of Mercer County, these deposits can supply large yields in rather limited areas only. The most extensive and thus the most promising sources of large ground-water supplies are the limestone and dolomite formations underlying all, or parts of seventeen counties. Therefore, discussion is limited to these carbonate aquifers.

Normally, an investigation of the carbonate rock aquifers of northwest Ohio should extend into northwestern Erie County, which lies to the east of the area covered by this report. Limestones and dolomites underlying this portion of Erie County are capable of supplying individual well yields in excess of 500 gallons per minute (gpm). At one time the area was considered to be a major ground-water source. However, direct disposal of sewage and other wastes into this once promising aquifer has rendered it unpotable. In 1961, a four-month field study was conducted in the area for the Ohio Water Commission by the Ohio Division of Water. The aquifer was shown to be widely contaminated. The report concluded that, although additional studies could be made of the situation to determine in detail the direction and movement of contaminated water through the limestone, further investigations of this nature would be of academic interest only.

Methods of Study

Unlike other sedimentary rocks in Ohio, limestone (and dolomite) contains few original interstices through which water can move. In these formations ground water moves through joints, fractures, solution channels, or minor permeable zones. Thus, the presence or absence of such openings determine where successful wells can be developed. High hardness and hydrogen sulfide often present quality problems. In spite of these variations in quantity and quality, numerous large-yielding wells of useable quality have been developed by "hit or miss" methods. Reliable technical information has been lacking. In order to obtain accurate data, seventy-six exploratory wells were drilled at selected sites in carbonate rock areas in northwestern Ohio.

Photo 2. Typical test well site in flat terrain of northwest Ohio.

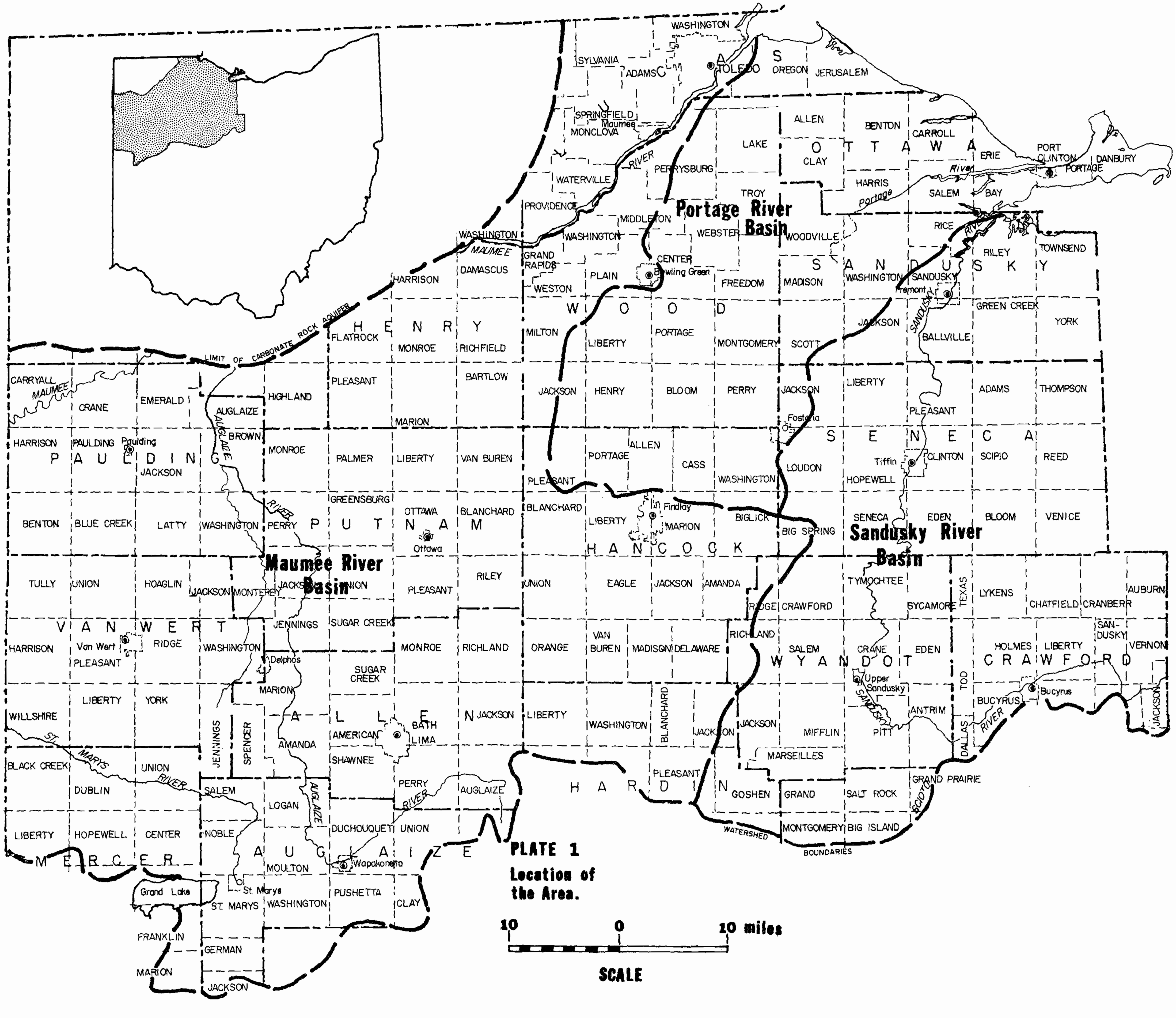

PLATE 1

Location of the Area.

Test Drilling:

These test wells (plate 2) were drilled to depths ranging from 108 feet to 580 feet. The average depth of the wells drilled was 302 feet. All wells were cased into the bedrock with 12-inch diameter casing and then reduced to 10-inch diameter in the rock. The exploratory drilling was done by private contractors based upon specifications prepared by the Ohio Division of Water. Division geologists supervised construction of all wells and made field decisions on well construction and drilling depths. In a few instances wells were double cased or plugged back in attempts to improve water quality. The wells were drilled by the air rotary method, using Schramm and Failing equipment.

Samples of the material encountered were collected at ten-foot intervals and at depths where changes wer' noted by the field geologist. During drilling operations, field logs were ke, . by the geologist. Samples of the well cuttings were later examined in greater detail. Water samples were collected at 20-foot intervals and analyzed at the site using field kits. These field chemical analyses gave an indication of quality changes as drilling progressed.

Pumping Tests:

Upon completion of each well, a deep-well turbine pump was installed. Pumps were powered by direct-drive gasoline engines. A six-inch discharge line was equipped with a gate valve, standard manometer hose, and a 3, 4, or 5-inch orifice plate. Measurements in the pumped well were made with an electric tape inside a 3/4-inch drop pipe, which provided a shield against cascading water in the borehole. Automatic water-level recorders were installed in available observation wells when possible.

Photo 3. Hydrologists adjusting manometer at test well M-25.

The testing of each well was conducted in three phases:

(1) A two-hour pump trial made it possible to determine the best pumping rates for subsequent tests and also verified that the equipment operated satisfactorily. In addition, increasing the rate by small increments made it possible to locate the water zones in many of the wells.

(2) A standard "step test" was conducted for the purpose of determining turbulent flow losses and information about the nature of the water zones. These tests were usually six hours in duration and consisted from four steps to as many as twelve steps, depending upon the characteristics of the individual well.

(3) "Constant rate" tests were usually 24 hours in duration with the frequency of measurements determined by the stability of the pumping level. Generally, recovery data was collected for the same time period as the test. Data was collected in existing wells at each site. Fully penetrating observation wells were available for about one of each ten test wells.

The above test procedures were varied somewhat in isolated cases because of unique circumstances, such as development or dewatering. However, particular effort was made to keep the procedure as consistent as possible.

Geophysical Logging:

Geophysical logs were made of all test wells by the U. S. Geological Survey Water Resources Division. The purpose of the logging was to provide criteria for stratigraphic correlation and identification of permeable zones. The logging was done with portable, hand operated equipment furnished by the U. S. Geological Survey Water Resources Division equipment unit in Denver, Colorado. The equipment makes natural gamma, single-point resistance, self-potential, temperature, and caliper logs.

Experimental logging was also done by personnel of the Borehole Geophysics Group, Water Resources Division, Denver, using truck-mounted equipment with the added capability of making neutron, gamma-gamma, long-normal, and short-normal resistivity logs.

Acid Stimulation:

Eight of the test wells were selected for acid stimulation to determine whether such procedures would increase their productivity.

Acidizing was accomplished by using numerous small charges of 31 percent hydrochloric acid containing inhibitors and stabilizers. Each charge consisted of from 55 to 275 gallons of acid. Individual charges remained in the well for less than four hours, after which the well was pumped. Total amounts of acid used ranged from 165 to 440 gallons per well. Waste acid was neutralized with soda ash before being disposed of into a surface stream.

On completion of the acidizing, a second pumping test was conducted on each well. Thus, comparative quantitative data, before and after stimulation was obtained.

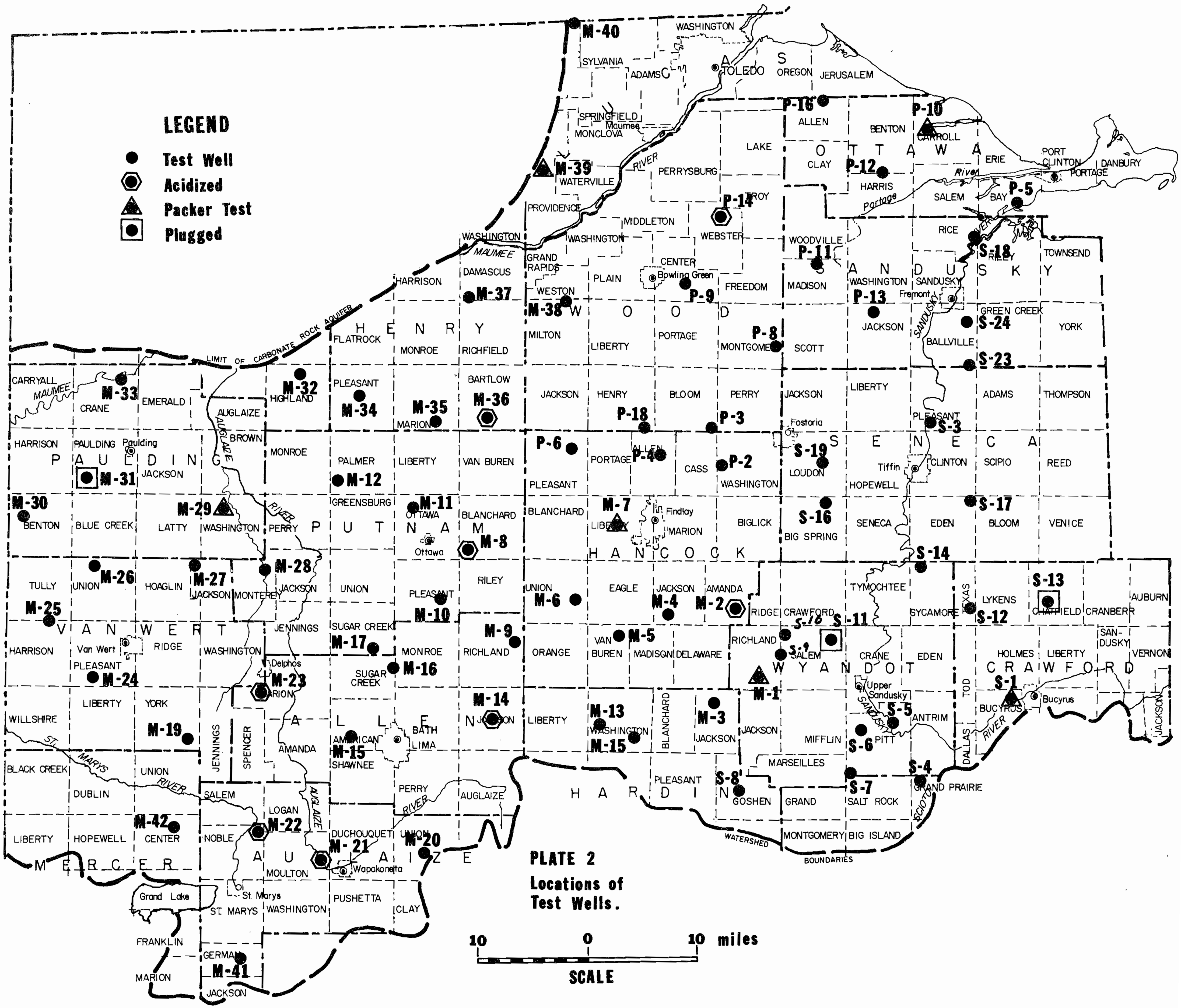

PLATE 2
Locations of Test Wells.

Chemical Analyses:

Water samples were collected from the test wells during, and at the completion of, each 24-hour constant rate pumping test.

Chemical analyses of these samples were made by the U. S. Geological Survey Water Resources laboratory in Columbus. Results of these analyses are contained in this report.

Packer Tests:

Selected zones in six of the test wells were isolated and tested by using inflatable packers above and below a submersible pump. By this means, it was possible to collect samples from specific zones and to determine water quality differences at various depths as well as the hydraulic connection between water zones and relative specific capacities.

This equipment was made available through the Hydrologic Equipment and Services Unit, Water Resources Division, U. S Geological Survey.

Photos 4 and 5. Inflatable packer used for isolating water-bearing zones. Packer is shown uninflated (left photo) and partially inflated in well casing (right photo).

Supplemental Data:

Approximately 50,000 well drilling records, which are on file for this area at the Division of Water, were used to supplement data collected during the field investigation. These drilling records, although largely for farm and domestic wells, include a number of large-yielding wells drilled for municipal, industrial, and irrigation supplies.

Also utilized were long-term water level records from sixteen observation wells in the carbonate rock aquifers.

A municipal survey was conducted of public ground-water supplies in the study area to determine (1) past history of well development, (2) the quantity and quality of ground water presently available, (3) methods of treatment and development, and (4) treatment and development costs.

Acknowledgements

The field investigation covered a period of two and a half years and involved numerous persons over a broad area of Ohio. It would not be possible to include a complete listing of all of those who aided in this study.

Important contributions were made by Stoepfel Brothers Drilling Company and by Dunbar Drilling, Incorporated. Many local residents cooperated by granting permission for exploratory work on their properties. We are also indebted to a number of county agricultural agents and U. S. Soil Conservation Service personnel.

In addition, the aid of the following persons is gratefully acknowledged: Henry L. Pree, Jr., James DeAngelis, Thomas Watson, and David Carpenter of the Ohio Division of Water; Andrew Spencer, Lynn Wilson, James Hallett, Ted Ramsey and Lowell Fess of the Ohio Department of Natural Resources; Thomas Prickett, Illinois State Water Survey; Warren Teasdale, Robert Pemberton, and Lawrence MacCarey of the U. S. Geological Survey.

Thanks are extended to Mrs. Ruth Haldeman and Mrs. Virginia Gregg for countless hours of manuscript typing in the preparation of this report.

Contours on the bedrock surface for Sandusky County and portions of Lucas and Ottawa counties were taken, in part, from unpublished data supplied by the Ohio Division of Geological Survey. Bedrock surface data in the Maumee River basin, compiled by Lawrence Brunstetter, was also used extensively.

Ground-Water Development

According to early reports published by the Geological Survey of Ohio, water wells in northwestern Ohio prior to 1880 were limited in depth to the bedrock surface. Water from the underlying "limestone" was described as "unsatisfactory and difficult to obtain." Shallow wells, drilled or dug, in the glacial drift were adequate for the limited quantities needed for domestic supplies in those early days.

Beginning in the late 1880's and continuing through the early part of the twentieth century, many towns and cities in northwestern Ohio became aware of the need for public water supplies. In order to develop larger supplies, municipalities found it necessary to drill deeper into the carbonate rocks. Although the water obtained was often extremely hard and sometimes contained objectionable amounts of hydrogen sulfide (H_2S), described by an early writer as "offensive to the nose and disagreeable to the taste but with definite health-giving properties, "wells played an important part in the development of the area.

As the communities grew and prospered, additional wells were drilled. Random drilling produced many excellent water supplies. Experience taught water developers that the often-present problem of hydrogen sulfide could be lessened by aeration. Some of the original production wells are still in service. The Village of Lindsey, in Sandusky County, is still using a municipal well which was drilled around 1896.

Although it has been estimated that only about twenty-seven percent of Ohio's total water use is from underground supplies, forty-four percent of the northwest area's population is now served by ground water through some 56 municipal systems. Private ground-water sources supply more than 20 million gallons per day (mgd) for industrial use and 1.5 mgd for irrigation in the area.

The area invites economic development. It has a moderate climate, adequate transportation and utilities, and an ideal location. Ninety percent of the land is still in agricultural use. The geology of the region contributes to its potential because the underlying limestone and dolomite provides aggregate for construction, raw material for agriculture and industry, and a valuable water source.

Nevertheless, the northwest carbonate rock area has always been regarded by some as a "problem region" where poor quality ground water in unknown amounts is a limiting factor for development. Well-planned development of the area's limestone and dolomite aquifers, based upon reliable hydrogeologic data appears to be the key to encouraging future growth in northwestern Ohio.

II. GEOLOGY

General

The stratigraphic sequence of formations beneath the Maumee, Portage, and Sandusky basins represent the principal regional bedrock aquifers for Ohio. These Devonian and Silurian formations are consistently thick layers of limestone and dolomite, somewhat uniform in their carbonate composition, yet quite dissimilar in their physical and hydrologic characteristics. Although the greater portion of the sequence is logged as dolomite, the erratic hydrology and chemical composition of the ground water owes its origin to the complex environment during the deposition of these formations in the Silurian and Devonian seas.

Almost all sedimentary formations are formed through the action or movement of water. As a result, there is a wide variety in the texture and structural features, exemplifying coarse to fine bedding planes, cross-bedding signifying the action of strong and weak currents, and often a very complex mixture representing non-uniform conditions.

Carbonate formations are also formed in this manner. However, superimposed on these mechanically sorted deposits are a myriad of features produced by chemical action within the body of water. Direct precipitation from supersaturated waters, chemical and biochemical deposits, large massive barrier reefs and much fragment deposition are just a few of the features which create a heterogeneous climate for the deposition of these carbonate formations.

Stratigraphy and Structure

The environment of these seas was further adjusted by the north-plunging Cincinnati Anticline which dissects the east-central portion of the study area. This structural feature, which extends northward from Tennessee to Canada, separates the Appalachian basin to the east from the Indiana, Illinois, and Michigan basins to the west and northwest. The crest of this structure may be considered as beneath western Wyandot, eastern Hancock, and Wood counties, and western Seneca, Sandusky, and Ottawa counties (see plate 3). Locally this structure is known as the Findlay arch. West of the structure the formations dip into the Michigan basin, and east, the regional dip is southeast into the Appalachian basin.

During the depositional period of these carbonate formations, a quiet and relatively shallow lagoonal type basin existed on the east flank of the arch and open sea to the west. The chemical composition of these formations was drastically changed as the supersaturated sea waters behind the barrier were periodically refreshed and renewed as the fresh sea waters breached the barrier. Thin to thick layers of carbonates, impregnated with gypsum and other evaporites, and often clay-laden silts emanating from the land mass to

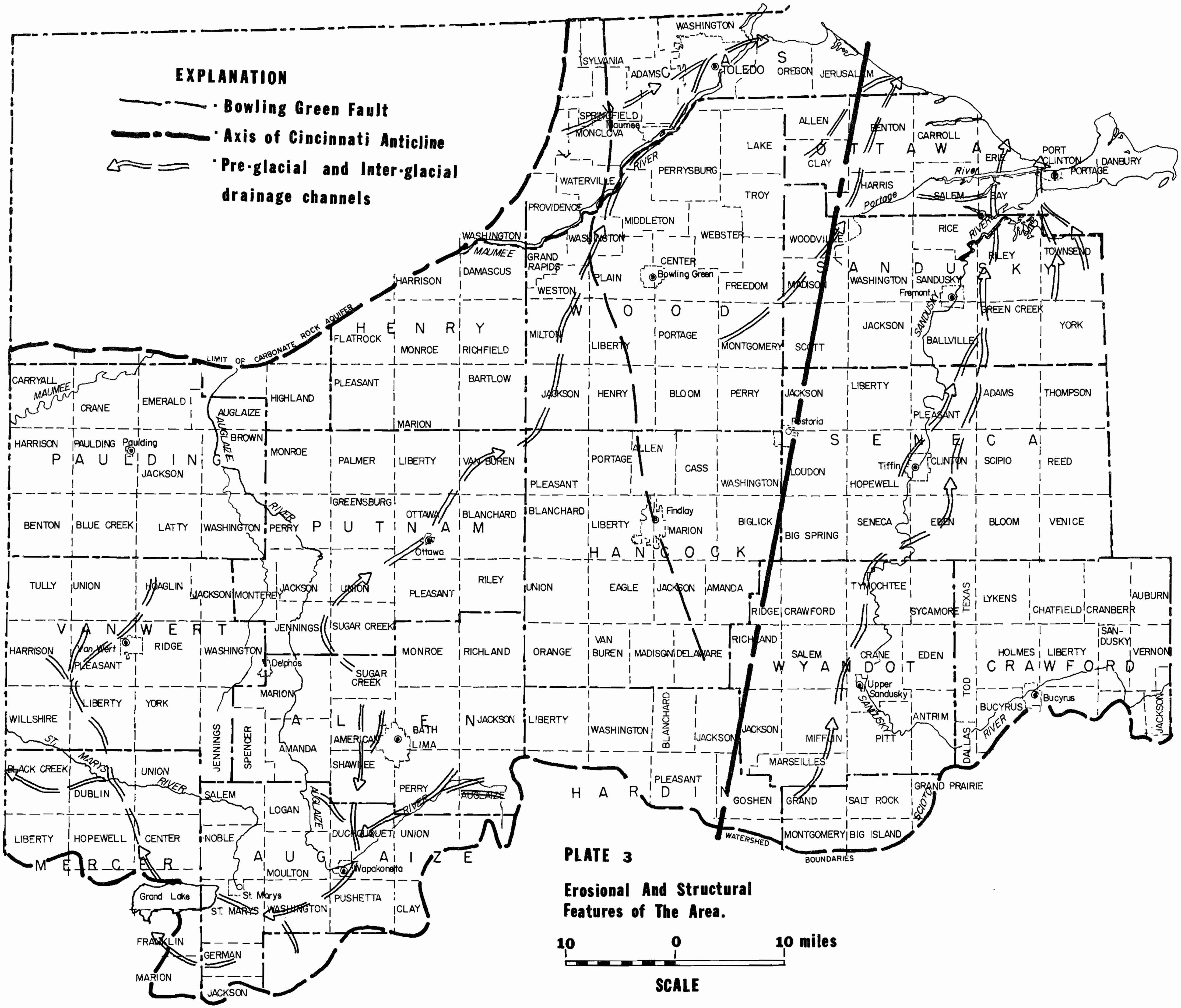

PLATE 3

Erosional And Structural Features of The Area.

the east, were deposited on the east flank of the barrier. The formations, although deposited on either side of the barrier during the same period of time, therefore the same age, do not have the same physical and hydrologic characteristics.

The sequence of events that are a part of geologic time are not foreign to this area. The fluctuating level of the seas created land masses partially subjected to weathering and erosion, and very uneven surfaces for the deposition of subsequent formations. Exceptionally thick formations were deposited on the flanks of the arch, yet some formations are missing, perhaps never deposited on the crest of the major uplift area, or the crest of minor areas of disturbance in Mercer and Van Wert counties. The Lockport Group, undifferentiated is as much as 156 feet thick in southern Hancock County, yet thickens to more than 336 feet in the northern portion of Ottawa County.

Vertical movement of land masses have created major faults on the western flank of the Cincinnati Anticline. The north-trending Bowling Green Fault, approximate location shown on plate 3, has a reported displacement of as much as 100 feet at Findlay, and about 200 feet just west of Bowling Green. These stresses have changed the entire stratigraphic sequence of formations east and west of this anomoly (see figure 1) and the hydrologic environment for the area. Although assumptions have been made as to the location and configuration of this anomoly, the limited data available precludes an absolute definition of this structural feature.

The final feature to be considered, which should have an equal if not preferential treatment to the environment of deposition, is the erosional surface formed on these consolidated formations prior to and during the glacial epoch. Consider the effects of weathering during the period of geologic history when the land mass lay barren prior to glaciation. Channels were carved into the carbonate surface, crevices and solution channels were formed and the degree to which formations were dissolved or altered by the movement of water was dependent upon the chemical characteristics of the carbonate formations. Therefore, the initial environment of deposition is the key to the degree of solubility of these formations. During this period of time, prior to glaciation, drainage patterns were developed on the bedrock surface, creating channels for infiltration. These distinctive patterns are shown on plates 3 and 4.

Glaciation brought an entirely new environment to increase or deter the infiltration capabilities of the carbonate formations. Where channels of drainage were carved into the bedrock surface, melt-waters from the glaciers often deposited relatively coarse sand and gravel creating excellent sources for recharge to the bedrock. Minor tributaries to the Teays stage of drainage or subsequent interglacial streams further served as channels for the deposition of washed, sorted permeable materials suitable for excellent recharge. However, in much of the area relatively thick impermeable glacial till was deposited detering direct infiltration eventhough soluble and cavernous conditions may exist within the rock formations.

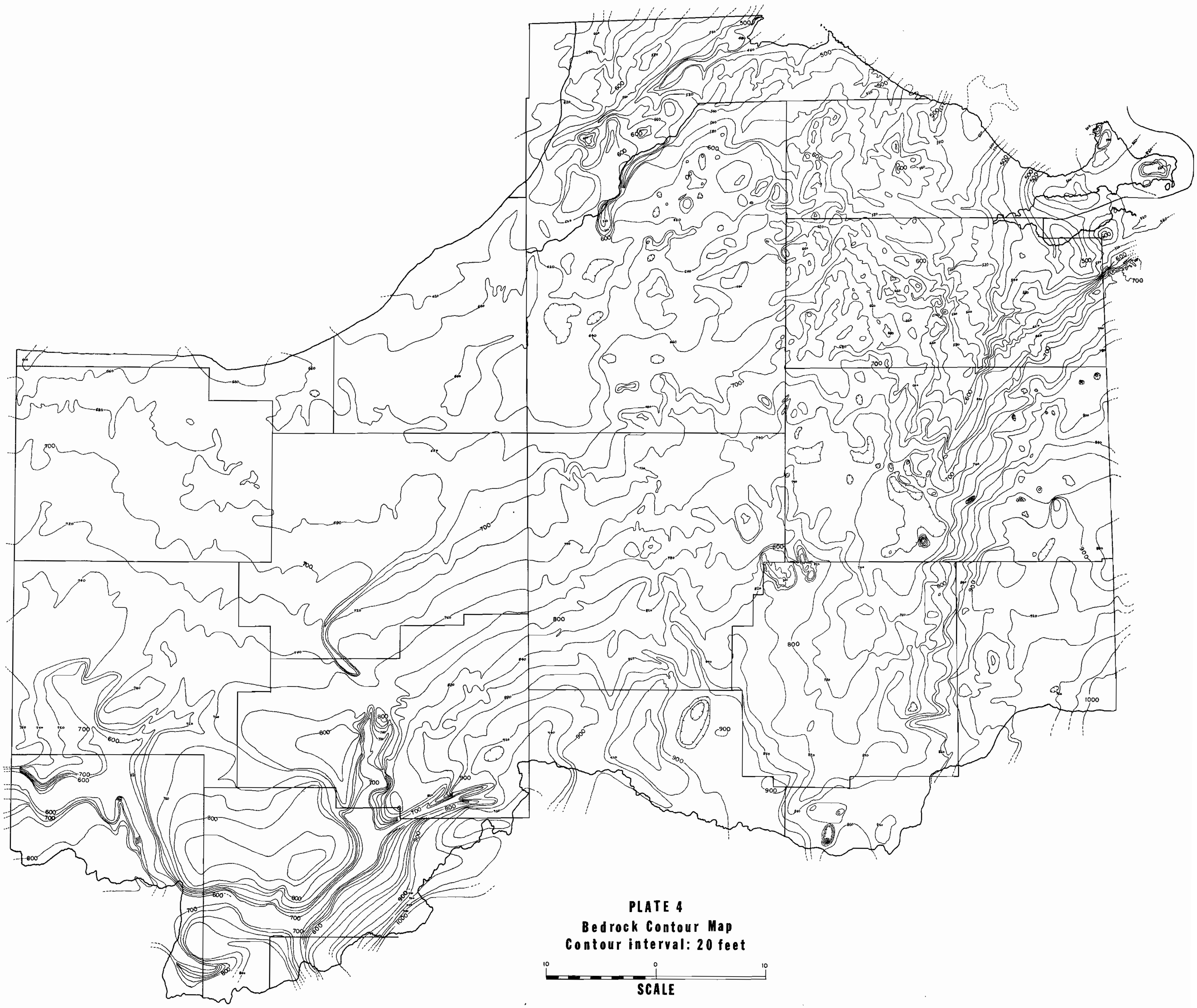

PLATE 4
Bedrock Contour Map
Contour interval: 20 feet

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SCALE

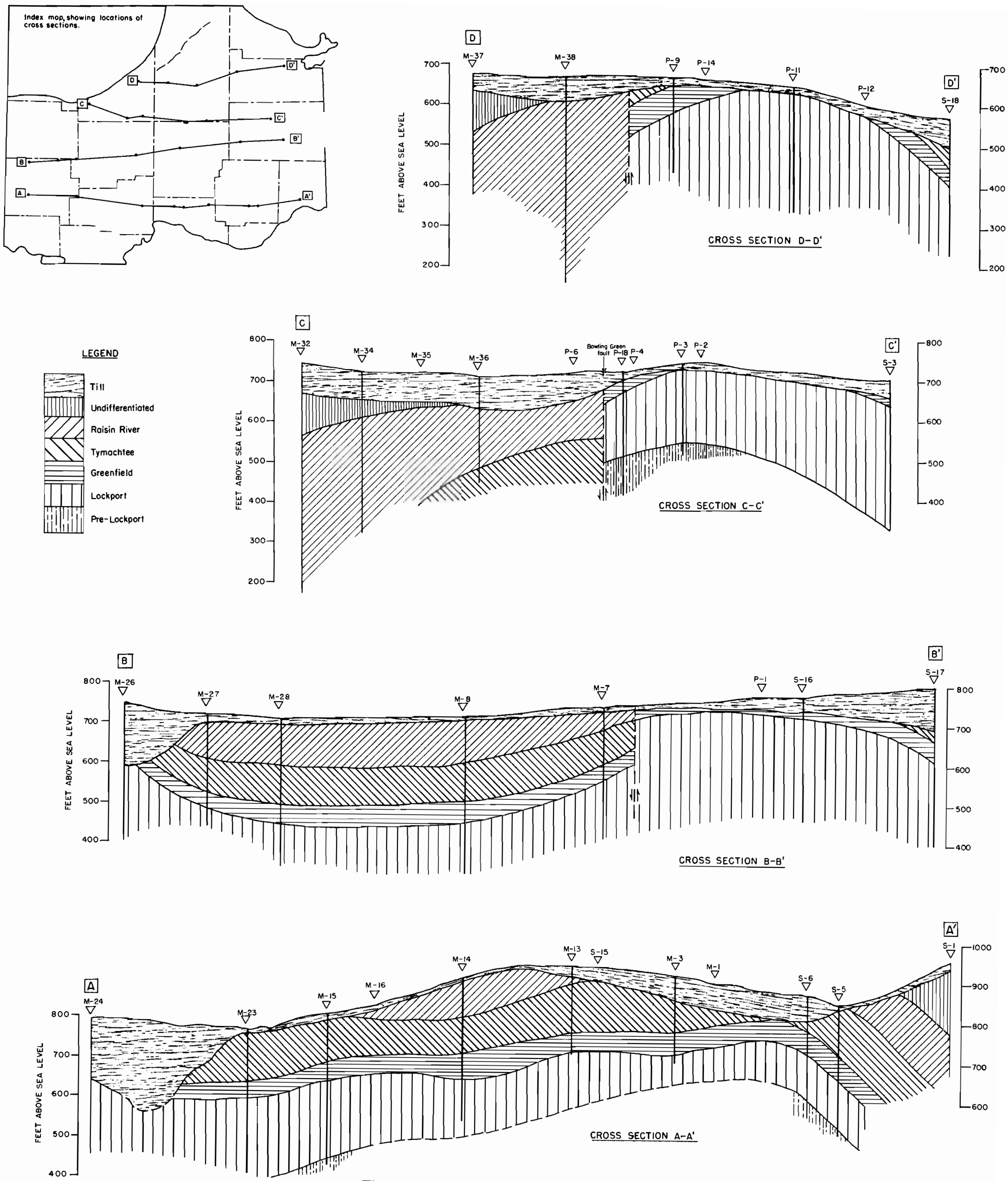


Figure 1. Geological cross sections.

The environmental conditions during the initial deposition, the catastrophic stresses which changed to surficial sequences, the erosional climate prior to glaciation, and the glacial epoch are factors which control the availability and quality of ground water within these carbonate formations. The "Big Lime" as known to the drilling contractor is indeed unique and ever so challenging in its ever changing physical, chemical, and hydrologic characteristics.

Discussion by Units:

The identity of these formations is most difficult. Samples collected as the test wells were drilled were logged in the field. Microscopic identification was made in the laboratory, and the description for each unit are shown in table 1. Gamma, self-potential, resistivity and caliper logs were made as each well was completed. Utilizing these three methods the approximate identification was made. Graphic logs for the test wells are shown in figure 3, A through Y.

It was noted during this procedure that key horizons aided the identity of an entire sequence of formations. The Tymochtee dolomite is quite uniform in thickness and physical appearance. If missing, (test well M-26) the true identity may be somewhat misleading. The Lockport or "white lime" as logged in the field, remains as a distinctive horizon and excellent guide, especially with air rotary drilling.

The base of the Lockport is easily identified owing to the grayish green color of the underlying shale. As the wells were drilled with air rotary, the slurry from the Tymochtee is grayish black, the Greenfield light brown, the Lockport dolomite whitish gray. In sequence, the green slurry provided instant knowledge as to the base of the "Big Lime".

The stratigraphic sequence and the water-bearing characteristics as logged for the 76 test wells are shown in table 2. Data for the hydrostratigraphic column is from the complete sections as logged for each specific formation penetrated. The range and average thickness of these complete sections, and the characteristics recognized as the wells were drilled are indicated. The water-bearing characteristics are not designated according to the volume obtained, but rather the zones that indicated an increase in yield as the wells were drilled.

In a few instances, logs have been prepared using the terms Upper Silurian or Devonian. Although the Devonian System is divided into specific formations, their hydrologic characteristics are not significant to discuss other than the basal Devonian - the Detroit River and the Dundee.

Rather than provide complete descriptions for the geographical location of each unit, plate 5 provides the areal extent of the bedrock geology in the study area.

TABLE 1

STRATIGRAPHIC COLUMN

(Division of Geological Survey)

System		Group	Formation	Average Thickness	Description	Remarks
Devonian	Upper		Ohio Shale	200	Shale, black and dark brown	
Devonian	Middle	Traverse	Ten Mile Creek Dolomite	35	Dolomite, yellowish-gray and grayish-brown, dense to medium crystalline; abundant nodular white chert	Correlative in Sandusky, Seneca, Wyandot and Crawford Counties as Prout Limestone.
Devonian	Middle	Traverse	Silica Formation	30	Limestone and shale, grayish-brown, very fossiliferous	Correlative in Sandusky, Seneca, Wyandot and Crawford Counties as Olentangy Shale.
Devonian	Middle		Dundee Limestone	50	Divided into lower and upper parts: lower of limestone and dolomite, grayish-brown, finely and medium-crystalline, sucrosic, sandy, upper part of limestone, yellowish-gray, fine- to coarse-grained, very fossiliferous; basal portion of upper Dundee lithographic limestone in much of northwest Ohio	Correlative in Sandusky, Seneca, Wyandot and Crawford Counties as Delaware Limestone.
Devonian	Middle	Detroit River	Undifferentiated	80	Dolomite, gray and brown, microcrystalline; stromatolitic in part; sandy at the base	Correlative in Sandusky, Seneca, Wyandot and Crawford Counties as Columbus Limestone.
Devonian	Middle	Detroit River	Sylvania Sandstone	25	Sandstone, white, fine- and medium-grained	
			-unconformity-			
Silurian	Upper		Raisin River Dolomite	350	Dolomite, brown, microcrystalline, medium- to thick-bedded	In VanWert County, these three formations change laterally into biohermal and biostromal dolomite that is considered an extension of the Fort Wayne carbonate bank described in adjacent areas of Indiana by Pinsak and Shaver (1964). Stratigraphic position of the Tymochtee is below the C-shale of the evaporite-bearing Salina Group in the subsurface of northwestern and northeastern Ohio
Silurian	Upper		Tymochtee Dolomite	100	Dolomite, grayish-brown, microcrystalline, thin-bedded; locally interbedded with very argillaceous dark-gray dolomite; numerous black carbonaceous partings upon weathering give shaly look to outcrops	
Silurian	Upper		Greenfield Dolomite	50	Dolomite, brown, microcrystalline, and very finely crystalline, medium-bedded, stromatolitic, sucrosic in part	
Silurian	Middle	Lockport	Undifferentiated	200	Dolomite, gray and white, finely to coarsely crystalline, fossiliferous, porous, biostromal and biohermal; in massive beds; nodular chert in lower half in many places	
Silurian	Lower		Rochester Shale	15	Shale, green; interbedded gray and greenish-gray crinoidal dolomite	

TABLE 2

HYDROSTRATIGRAPHIC COLUMN

Stratigraphic sequence and the hydrologic characteristics as logged from 76 test wells for carbonate study

System		Group	Formation	Symbols for complete sections * penetrated	Range and average thickness (feet)	Character of material	Water-bearing properties
Devonian	Upper		Ohio			Soft to fissile, dark gray to brownish-black shale.	Non-water-bearing.
	Middle	Traverse	Ten Mile Creek Silica Formation (Olentangy)	4	25-91 52	Soft, dary gray shaly limestone and dark brown shale with some greenish shale.	Non-water-bearing. Very meager yields -- less than 5 gpm.
			Dundee (Delaware	4	20-53 32	Light to medium buff limestone with medium to dark gray dolomite near the base.	Although entire thickness yields water, primary zones are 20' to 40' below top of formation
		Detroit River	(Columbus)	5	25-138 71	Light to medium gray limestone grading to brown dolomite.	Most wells produce at 40' to 60' below base of Dundee.
Silurian	Upper		Raisin River	1	230	Very hard, dense, medium to dark gray dolomite with some light gray dolomite.	Wells yield some water 20' to 50' above top of Tymochtee Formation. Not considered as good aquifer, however.
			Tymochtee	19	70-120 93	Medium grayish-brown dolomite with dark gray to black dolomite as distinctive horizon marker.	Typical wells yield 30 to 70 feet above Greenfield Formation. More than 73% of wells productive.
			Greenfield	29	32-65 45	Light gray to buff, hard dolomite with medium gray to buff dolomite.	Less than 31% of wells yield supplies. Typical zones are 20 to 30 feet above Lockport.
	Middle	Lockport		13	112-194 141	Light gray to blue gray dolomite, often grayish-white to very white. Distinctive horizon marker.	Water obtained from entire thickness. 81% of wells yield water 50 to 80 feet below top of formation.
	Lower	pre-Lockport				Darkish green shale, often relatively soft, and interbedded with limestone.	Non-water-bearing.

( ) Formation in eastern portion of study area. * Number of complete sections logged.

The formations logged as pre-Lockport consist of thin to relatively thick layers of gray to green shale, interbedded with thin layers of dolomite. Eighteen wells were drilled below the base of the Lockport. Test well S-8 was drilled 143 feet below the contact and brownish shale was logged, from 285 to 330 feet, as Rochester shale. These formations are considered as non-water-bearing, however they are a distinctive horizon marker for the base of the Lockport. The configuration of the surface of the pre-Lockport formations is shown on plate 6.

The Lockport was penetrated in 58 of the 76 wells drilled. It is usually a whitish gray to light blue-gray, porous dolomite, often sugary in texture. In some instances, especially test wells M-22 and M-41, the upper 30 feet of the formation is very white, however the majority of the logs indicate a whitish blue-gray grading to medium to dark blue-gray near the base of the formation.

The entire section of the Lockport was logged for 13 wells. Even though the average thickness is estimated as 141 feet, test wells M-15 and M-19 recorded nearly 200 feet. Exceptional thicknesses were recorded on the crest of the Findlay Arch, especially in Ottawa County. Logs of wells reveal as much as 203 to more than 336 feet of Lockport in more than nine test wells. Sparling (1965) has recorded more than 400 feet in a quarry test hole in Ottawa County. As shown on plates 6 and 7, this gradational thickening along the crest of the Cincinnati Anticline may be a depositional feature resulting from reef growth.

The geologic structure map plate 7, constructed on the Lockport, is based on the interpretation of geophysical logs of approximately 200 wells, supplemented by approximately six control points determined directly from quarry exposures. About 115 of the logs were of State test wells (see figure 13) and municipal and industrial wells. The remainder were natural gamma logs of oil and gas wells, from the files of the Ohio Division of Geological Survey.

Considered as an excellent aquifer, more than 80 percent of the test wells produced water from 20 to 110 feet below the top of the Lockport.

The basal portion of the Upper Silurian System is the Greenfield dolomite. It is quite uniform in thickness, very hard and difficult to drill. The physical characteristics of the Greenfield - light gray to buff with some medium to buff dolomite - are quite similar to the Raisin River formation. It may be identified as Raisin River, if the overlying Tymochtee formation is missing, or the underlying Lockport is not penetrated.

The Greenfield dolomite is encountered in 50 of the 76 test wells, yet water was logged near the basal contact with the Lockport in only 16 wells. Complete sections are logged in 29 test wells, having an average thickness of 45 feet. The maximum thickness of 65 feet is logged for test well M-8 in Putnam County.

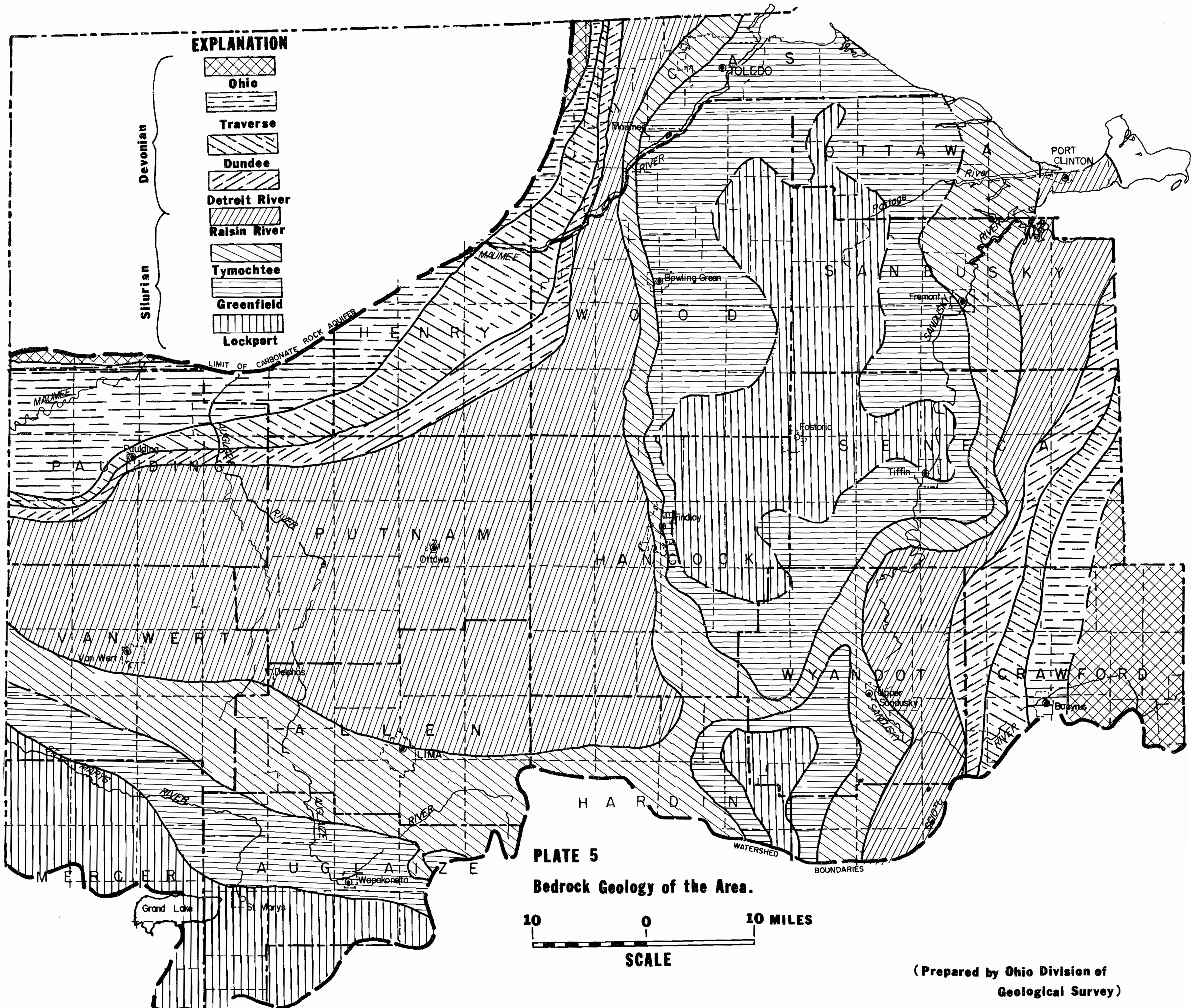


PLATE 5

Bedrock Geology of the Area.

(Prepared by Ohio Division of Geological Survey)

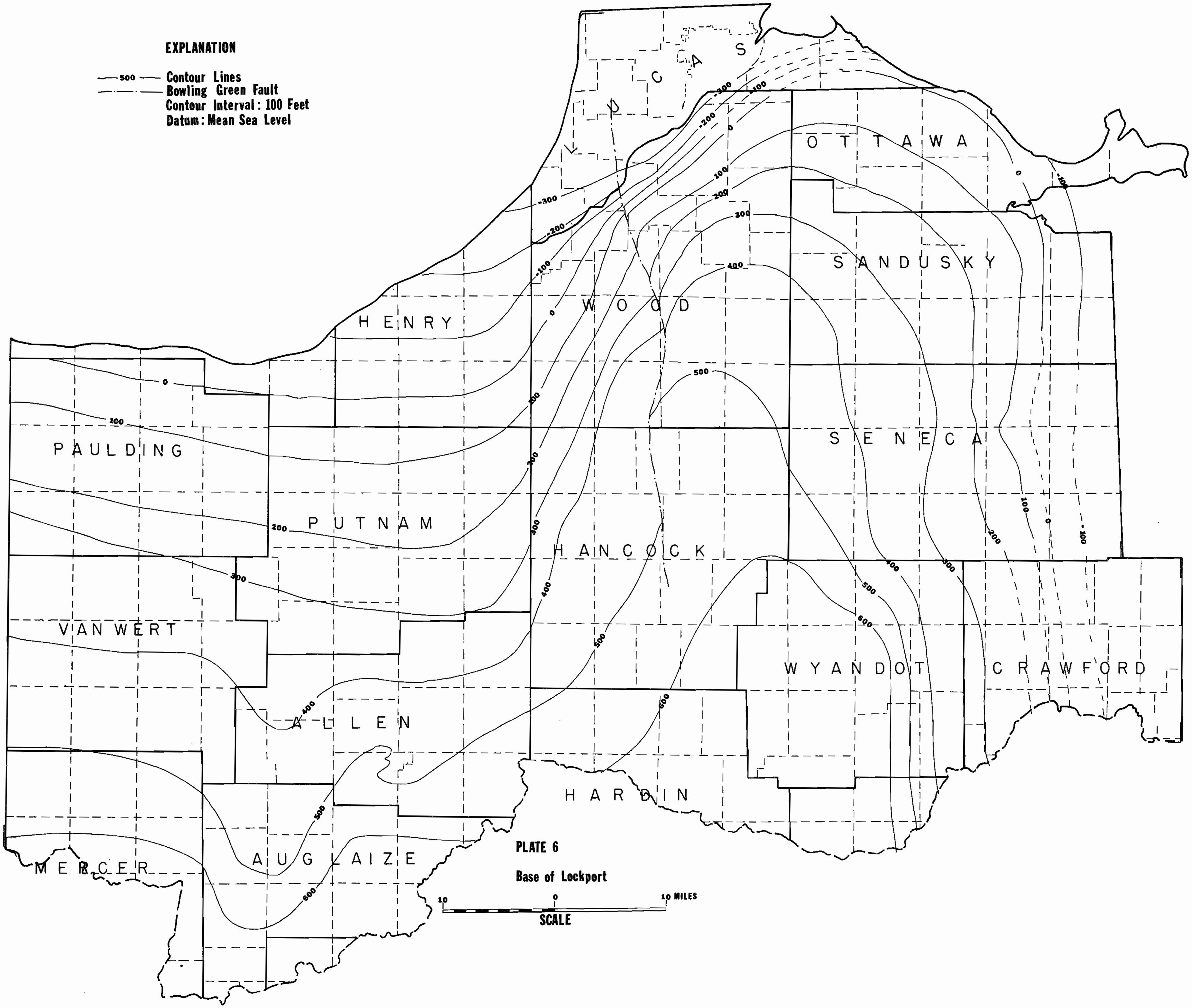


PLATE 6

Base of Lockport

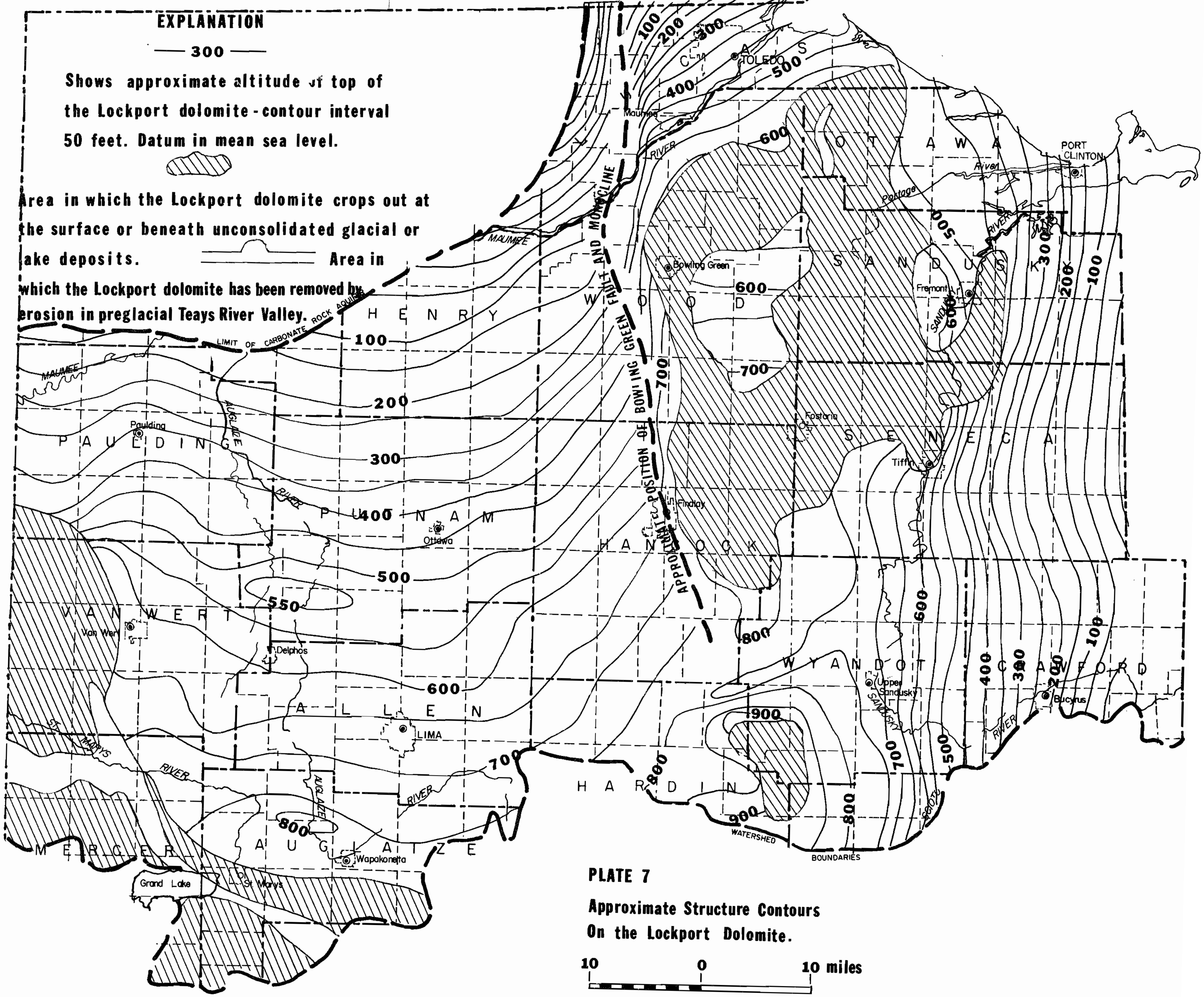


PLATE 7

Approximate Structure Contours On the Lockport Dolomite.

(Prepared by U.S. Geological Survey, Water Resources Division)

The type locality for the Tymochtee formation is an obscure crossroad in Wyandot County. However, this formation is perhaps the key horizon for the identity of the stratigraphic sequence of the Silurian carbonate formations in Ohio. The uniform thickness and distinctive physical characteristics provide a sense of assurance when it is encountered by the driller. Complete sections are logged for 19 of the 33 test wells that encountered the Tymochtee, and the average thickness is estimated as 94 feet. The logs reveal that most of the water occurs about 30 to 70 feet below the top in the upper portion of the Tymochtee, and that 73 percent are productive.

The Tymochtee dolomite is medium grayish brown grading from dark gray to black. It is often logged as black shale, since the slurry is usually dark grayish black. Yet, it is an excellent horizon marker separating two buff colored dolomites.

The Raisin River dolomite is often quite hard, dense, medium to buff, and dark gray in color. The only complete section logged is from test well M-31. Although 230 feet of Raisin River dolomite is recorded, the well was plugged, owing to the limited quantity and poor quality of water developed. A maximum thickness of 290 feet is logged for M-34 and a limited quantity of water was developed. However, approximately 59 percent of the test wells recorded some water from the Raisin River.

As shown in table 2, the Detroit River Group and the Dundee limestone are the carbonate formations for the basal portion of the Devonian System in this area. These formations and their correlative formations, Columbus and Delaware, respectively, in Crawford County, are considered as water-bearing, however yields are probably completely dependent upon the permeability of the surficial glacial deposits and the weathered surface of these formations.

The Detroit River Group ranges from 25 to 44 feet thick in test wells M-31 and M-37 in Paulding and Henry counties. M-39 in Lucas County recorded 70 feet, and test well S-1 in Crawford County logged as much as 138 feet.

Relatively uniform thicknesses are recorded for the Dundee limestone. Ranges of 20 feet (M-33) and 53 feet in test well M-39 were recorded for complete sections. However, more than 95 feet of the Dundee is logged for M-40 in the extreme northern portion of the study area.

These formations are somewhat uniform in their physical characteristics. Light to medium buff or gray limestone grading to dark gray or brown dolomite.

The Traverse Group and Ohio shale are considered as non-water-bearing formations. The Traverse Group is shown in table 2 as Ten Mile Creek Dolomite and Silica Formations, represented by the Olentangy shale in the eastern portion of the project.

The Traverse Group is logged as soft, dark gray shaly limestone and dark brown shale. The four sections range from 25 to 91 feet thick with an average thickness of 52 feet.

Ohio shale is logged in only two test wells; S-13 in Crawford County, and M-40 in Lucas County. However, this black fissile gray to browh shale is non-water-bearing and only considered as a horizon marker.

III. HYDROLOGY

General

The purpose of this section is to identify hydrologic mechanisms and discuss their effect on yields to wells tapping the carbonate aquifer in Northwest Ohio. Although concepts are simplified, the analytical methods used are fully described. Formulas and derivations are not always given, as they are available in many references on the subject. Practical solutions are emphasized.

Hydraulic Properties:

In making a quantitative evaluation of an aquifer, it is necessary to assign or determine values for various hydraulic parameters. These are expressed mathematically as transmissivity (T), permeability (P), and storage coefficient (S). Besides permitting computation of yield and drawdown in wells, numbers assigned to these terms provide an index of the capacity of formations to transmit ground water and of their storage properties. The coefficient of storage, defined below, is for artesian conditions, indicating that the aquifer is confined and the water is under sufficient pressure to rise above the water-bearing formation. The capacity of the confining bed to transmit water is expressed by its vertical permeability. Definitions of these parameters are as follows:

Transmissivity - the rate of flow of water in gallons per day, through a vertical section of the aquifer one foot wide and extending the full saturated thickness under a hydraulic gradient of one foot per foot at the prevailing temperature of ground water.

Storage coefficient - the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.

Vertical permeability - the rate of flow of water in gallons per day, through a horizontal cross-sectional area of one square foot of the confining bed under a hydraulic gradient of one foot per foot at the prevailing temperature of the ground water.

Properties of a leaky artesian aquifer are expressed by the leaky artesian formula (Hantush and Jacob, 1955). If leakage is not measurable or the confining bed is not present, the hydraulic system can be mathematically described by the nonequilibrium formula (nonleaky artesian formula) introduced by Theis (1935). The remaining variables which are used in these formulas are: distance from the pumped well, drawdown, discharge rate, time, and thickness of the confining bed. These variables can be determined from available data or measured during a pumping test.

Assumptions

Much has been said and written concerning the inadequacy of analytical methods to describe flow characteristics of carbonate aquifers. One of the basic assumptions of the aforementioned formulas is that flow takes place through a homogeneous medium having the same properties in all directions. Even casual inspection of carbonate rocks reveals little or no intra-granular porosity. The void space is in the form of joints, fractures, and solution channels. Flow in a carbonate aquifer is more analogous to flow through very rough pipes than through a homogeneous medium. There is some deviation from other basic assumptions, but to a lesser degree.

Although the basic assumptions are not met precisely, analytical concepts may still be applicable. Zeizel et. al. (1962) inferred that the dolomite in Illinois contains numerous fractures and crevices which are connected on an areal basis. They stated, "Such a network of openings can give a resultant regional effect equivalent to a radially homogenous aquifer. Because the water flows in fractures and crevices that bring the water directly or by complex interconnection into wells, the flow system assumes at least some of the characteristics of a linear channel in the immediate vicinity of a pumped well where the flow departs from laminar. Thus, the leaky artesian formula may describe drawdown on an areal basis with reasonable accuracy but does not completely describe the drawdown in a pumped well."

One of the difficulties in working with carbonate aquifers is the seeming inconsistency in the hydraulic characteristics of wells within a small area. To a great extent this is caused by conditions in the vicinity of the borehole. These irregularities may be of great consequence initially, but dwindle to small importance as the cone of depression becomes very large. The larger the area considered, the more nearly some carbonate aquifers assume the hydraulic characteristics of a homogeneous medium.

Carbonate aquifers in karst terranes or areas of considerable relief may never be analogous to a homogeneous medium. Large solution cavities and subterranian streams may be developed along zones of weakness leaving the adjacent rock relatively impervious. Under these conditions the occurrence of exotic flow systems resembling "siphons", "standpipes" and other hydraulic phenomena have been recorded. The resultant storage effect might resemble the emptying of a tank rather than reflect the instantaneous pressure release caused by the expansion of water and the elasticity of the aquifer skeleton represented by an artesian storage coefficient.

Caution is the rule in attempting quantative analysis of carbonate aquifers. Analytical methods may be applicable but one must be conscious of their limitations and be knowledgable of the physical characteristics of the aquifer. With this in mind, the following assumptions are specified for the study area:

1. The permeability of the aquifer is generally derived from secondary porosity including joints, fractures and solution channels.

2. These fractures and crevices are interconnected on an areal basis.

3. The extreme variability in the occurrence and movement of ground water seldom approaches that generally associated with karst type terranes.

4. The aquifer is confined beneath a layer of glacial till ranging in thickness from 20 to 40 feet throughout most of the area, except where closely associated with buried valleys.

5. Much of the recharge to the aquifer is derived from vertical leakage through the confining layer.

Discussion of Test Analyses

The data from each pumping test was analyzed by first attempting to employ the standard analytical methods. This resulted in varying degrees of success, but generally it was possible to obtain realistic values for hydraulic properties. As work progressed it became possible to use apparent anomalies in the analysis as aids in the interpretation. A description of these analyses along with specific examples illustrating the procedures are given herein.

A fundamental method of expressing the yield of a well is in terms of specific capacity, which is employed extensively throughout the analysis. Specific capacity ($^{Q}/s$) is commonly expressed as the yield of a well in gallons per minute per foot of drawdown (gpm/ft) for a specified time and rate. A common misconception is that specific capacity is constant for a given well regardless of the time period and pumping rate. In order to compare specific capacities these factors must be taken into account.

Specific capacity is related to the hydraulic properties of the aquifer and can be computed theoretically. However, theoretical specific capacity considers only head loss (drawdown) due to laminar flow and ignores head loss caused by turbulent flow in the well and in the immediate vicinity of the well. Considering the physical properties of the carbonate aquifer it is difficult to conceive of anything but turbulent flow as water enters the well and flows through the bore hole. The actual specific capacity is represented by the following equation:

$Q/s_w \quad = \quad Q/\ (s + s_t)$

where: Q = pumping rate, in gpm

s_w = drawdown in the pumped well, in feet.

s = drawdown due to laminar movement of water through the aquifer, in feet.

s_t = drawdown due to turbulent flow in and near the well bore, in feet.

The total drawdown in the pumped well, considering both laminar and turbulent flow, may be expressed by the following equation (Jacob 1946):

$$s_w \quad = \quad BQ + CQ^2$$

where: s_w = drawdown in the pumped well, in feet.

B = aquifer constant

C = well-loss constant, sec^2/ft^5

Q = pumping rate, in cubic feet per second (cfs)

The BQ term in the above equation is commonly known as "formation loss" and the CQ^2 term is "well loss". Values for C can be determined by another formula derived by Jacob (1946) which utilizes data obtained from a step test. The solution requires computations involving increments of drawdown and pumping rate for successive steps.

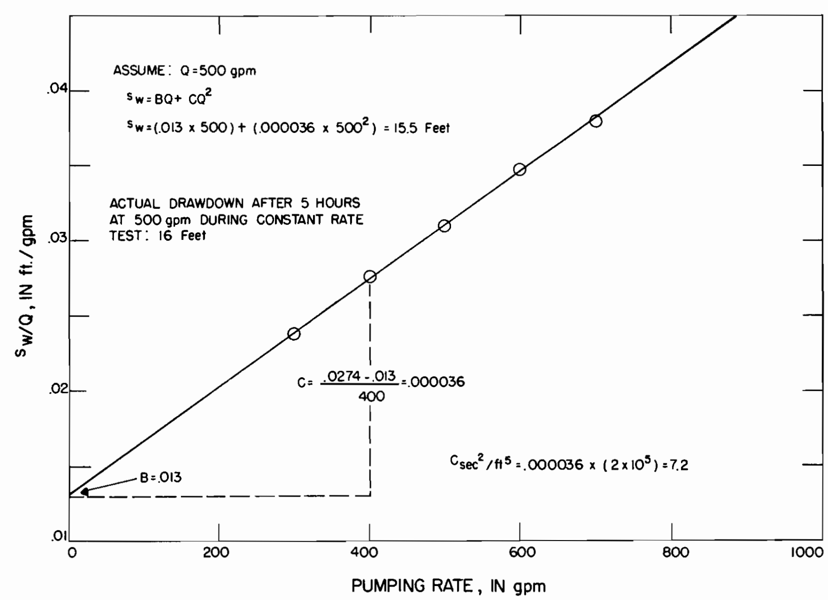
Rorabaugh (1953) derived a more exact method for evaluation of well loss. He proposed that the exponent for turbulent flow should be expressed as an unknown constant "n". The "well loss" term in the equation is then CQ^n. An empirical solution can be obtained from step-test data by a graphical solution of the equation on logarithmic coordinate paper. The graphical solution affords the advantage of averaging field data and eliminating or adjusting poor data. This method is fairly straight forward, but does require some trial and error computations to reach a final solution.

Another graphical solution was presented by Bruin and Hudson (1955) which solves the original equation where well loss is represented by the term CQ^2. This is a simple solution and does not require the conversion of the pumping rate to cubic feet per second. Values for C are in units of ft/gpm . Multiplying by a conversion factor of 2 x 10^5 gives C in the units of the other two solutions.

The step test data from each test well was analyzed by all three methods. Graphical solutions have a definite advantage over averaged results obtained from successive groups of data as in the Jacob method. In most instances, it is believed that the CQ^2 relationship gave an adequate approximation of the well loss for the practical range of pumping rates. Therefore, the Bruin and Hudson method is considered to be the most practical for use with data from the northwest Ohio carbonate aquifer. As will be demonstrated, this method was also useful in locating the depth at which significant dewatering occurred in some wells.

Well-loss solutions seem valid as long as pumping levels are above significant water-bearing zones. Once dewatering occurs, the hydraulic character of a given well may change drastically. When the pumping level falls below a water-yielding zone, the maximum contribution of water is obtained from that zone. That contribution cannot be increased by additional drawdown, in fact the rate of flow from that zone will decrease with time. As the pumping rate is increased, the additional water must be supplied by the lower zones. Turbulence and, therefore, well loss is greatly increased. The well-loss constant is related to the number and properties of the openings contributing water to a given well. As dewatering occurs the effective number of openings is decreased, thereby increasing the value of C for that well. The result is additional drawdown due to a combination of dewatering and increasing well loss which compound each other. Since the two variables cannot be separated, realistic values for C can no longer be computed. In some wells this change may be gradual. However, in many instances it occurs abruptly upon dewatering of a significant water-yielding zone. The depth at which this occurs becomes the critical pumping level for that well, below which excessive drawdowns will occur.

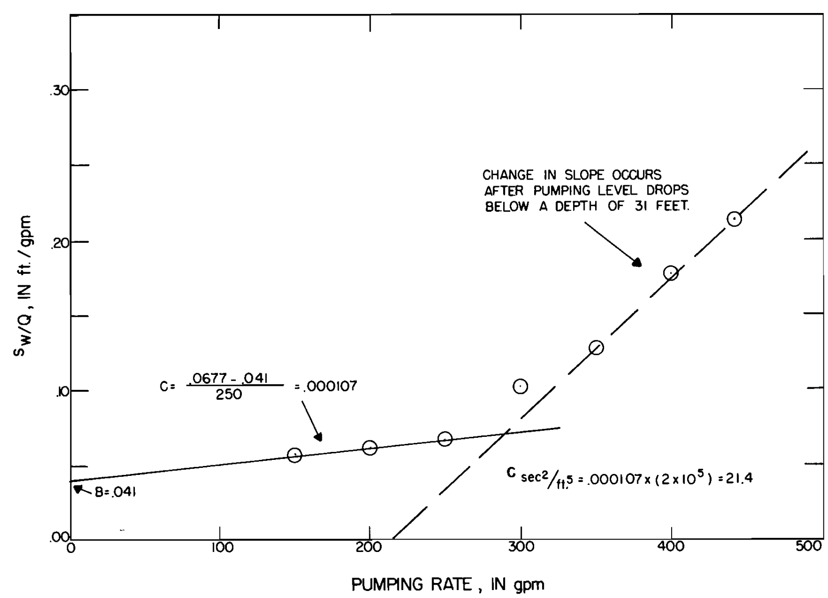
Figure 2a. Graphical solution for well loss, test well M-40



In many instances the Bruin and Hudson method has been a useful tool for gaining insight into the properties of individual wells. Figure 2a illustrates the analysis of the step test data from test well M-40. Values of specific drawdown s_w/Q are plotted against the total pumping rate for each step on plain coordinate paper. A straight line is drawn through the plotted points and extended to zero pumping rate. The value for B is determined from the intercept with the s_w/Q axis and C is the slope of the line. Note how closely the computed value of s_w (shown on the figure) compares to the total drawdown observed after 5 hours of pumping during the constant rate test.

Figure 2b represents the same procedure using data from test well S-19, only here significant dewatering has occurred. Note the break in slope between steps 3 and 4. This corresponds to a depth of 31 feet, where the driller reported a significant water zone. A line drawn at the second slope intersects the s_w/Q axis at a point where B is negative, and the new value of C gives a computed well loss in excess of the actual depth of the well. Although these values are meaningless, the location of the critical pumping level is indicated and one can infer that the value of $C = 21.4\ sec^2/ft^5$ is valid for pumping levels above 31 feet. If the Rorabaugh method were applied to the data in figure 2b, the critical pumping level would not be disclosed, because a "trial and error" method is used until all points fall on a straight line when plotted on logrithmic paper. Hence, no break in slope can be observed. The slope of the line would be very steep giving an unrealistic value for n, indicating only that there was dewatering in the well.

Figure 2b. Graphical solution for well loss, test well S-19



Many times the step-test data will show a slight curvature, as shown by the examples in figure 2c. Very likely the well-loss values for test well S-16 are more accurately given by CQ^n as determined by Rorabaugh's method, than the values obtained by the Bruin and Hudson method shown here. However, usable values of C can be obtained by averaging the data with a straight line.

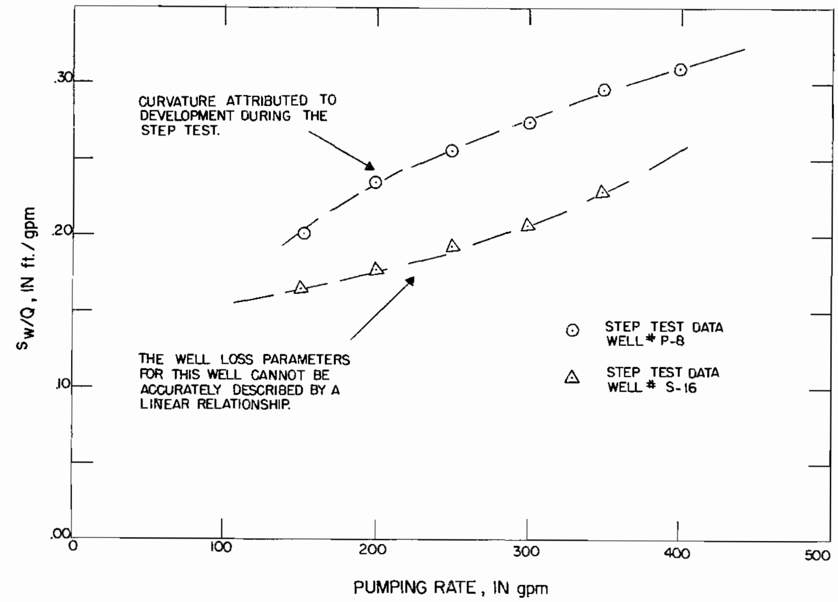


Figure 2c.
Graphical solution for well loss, test wells P-8 and S-16

Another type of curvature which was observed occasionally in the Burin and Hudson solutions is that shown by well P-8 in figure 2c. This data indicates that the specific capacity increased slightly during each step Apparently, this well was still being developed during the step test. The drawdown after 24 hours pumping at the rate of 500 gpm was less than the drawdown at the same rate during the step test.

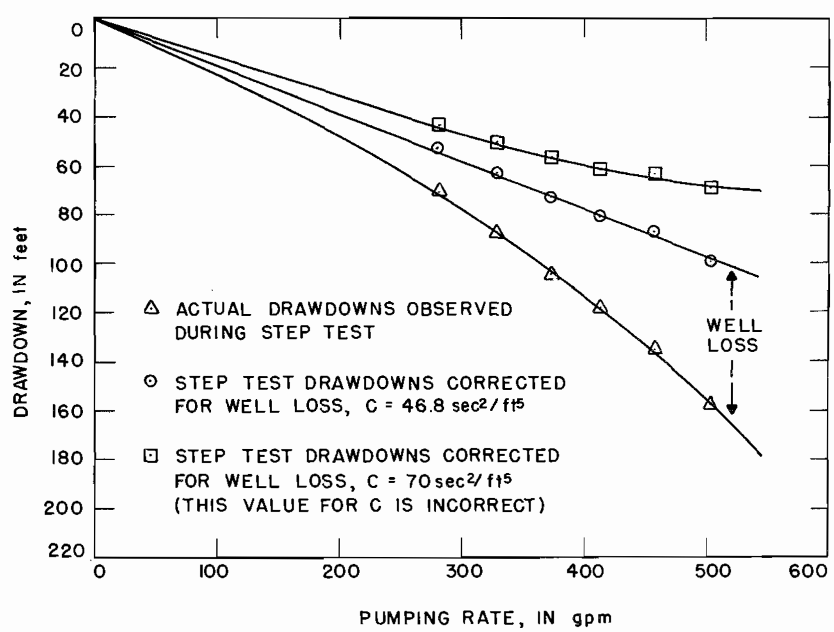


Figure 3a.
Verification of well loss computations, test well M-24

Because there are many pitfalls in the determination of well loss under conditions described, a simple verification of the C value assumed was made for every test well. Values of s versus Q for each step were plotted on rectangular coordinate paper as shown in figure 3a. Values of s represent total incremental drawdowns and Q represents total pumping rate of each step. Each value of drawdown was corrected for well loss and replotted against the corresponding pumping rate. As the theoretical drawdown is directly proportional to the pumping rate, the corrected drawdowns should fall on a straight line drawn through the point of origin. If necessary, values of C can be adjusted to give a better straight-line approximation. Many times the C value determined by the Jacob solution showed a curvature (Figure 3a), while the Bruin and Hudson solution was valid in about 90 percent of the tests analyzed. It is also interesting to note that dewatering may be revealed as shown by figure 3b.

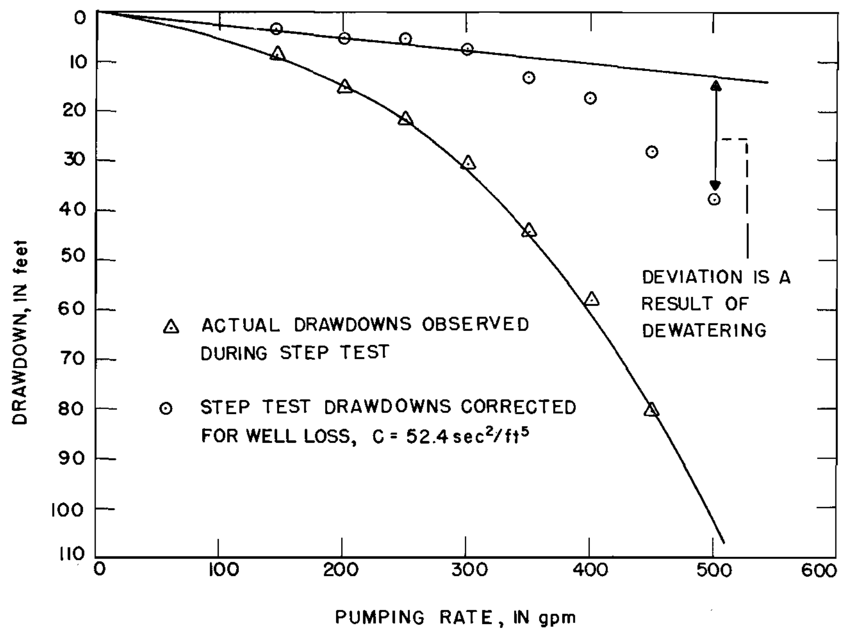


Figure 3 b. Verification of well loss computations, test well M-7

The specific capacity for a pumping period of 24 hours was computed from the constant rate test data for each well. Drawdowns were corrected for well loss and the corrected specific capacities were also computed for the same time period. These values are given in table 7a in the Appendix. The graph in figure 4 shows the relationship between uncorrected specific capacity and the well-loss constant.

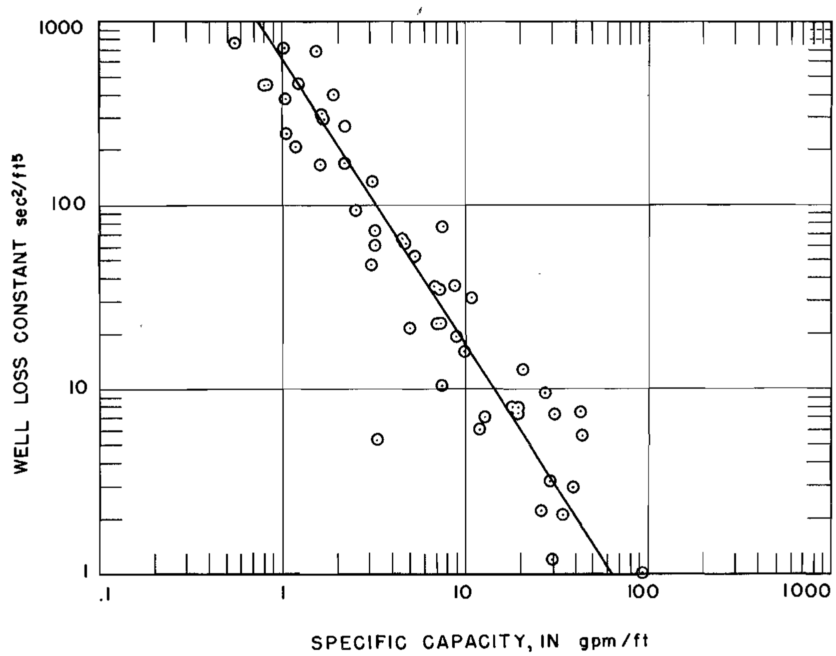


Figure 4 Well-loss constant versus specific capacity (24 hr)

Similar work in Illinois (Zeizel et. al. 1962) revealed a different relationship between specific capacity and C, depending upon whether the pumping levels were above or below the top of the aquifer. Separate graphs were plotted for wells in which dewatering occurred but the relationship was generally the same as shown in figure 4. However, data from tests in northwest Ohio where realistic values of C could not be determined because of severe dewatering are not included. The graph does demonstrate a general relationship and is somewhat useful for estimating the well-loss constant when step test data is not available.

The analysis of the constant rate tests to determine values for transmissivity and the storage coefficient is based primarily on time-drawdown data. The shape of the cone of depression, for a given pumping rate, is determined by the hydraulic characteristics throughout the entire area encompassed by the cone. In considering the variable nature of carbonate rocks it is unrealistic to assume that distance-drawdown relationships in given directions are representative of the entire area. However, after the cone becomes very large, local variations become relatively insignificant. The rate of decline of the cone becomes an integration of the hydraulic characteristics in the area of the cone.

Drawdown data was collected from existing wells located within one-half to one mile of the test well when available. Unfortunately, most of these were shallow domestic wells. Time-drawdown derived values of T obtained from shallow well data were usually too high to be consistent with values obtained from the test well or deep observation wells. This is attributed to the use of the test Q (pumping rate) in the artesian formulas. Since the zones penetrated by these wells were only contributing part of the water being pumped from the test well, the discharge which caused drawdown in the shallow well was some value less than the test Q and cannot realistically be determined. It would be just as unrealistic to attempt standard partial penetration corrections since the degree of hydraulic connection may be as variable as the rock itself. The same uncertainty is possible in fully penetrating observation wells, but is not considered to be as likely or as significant.

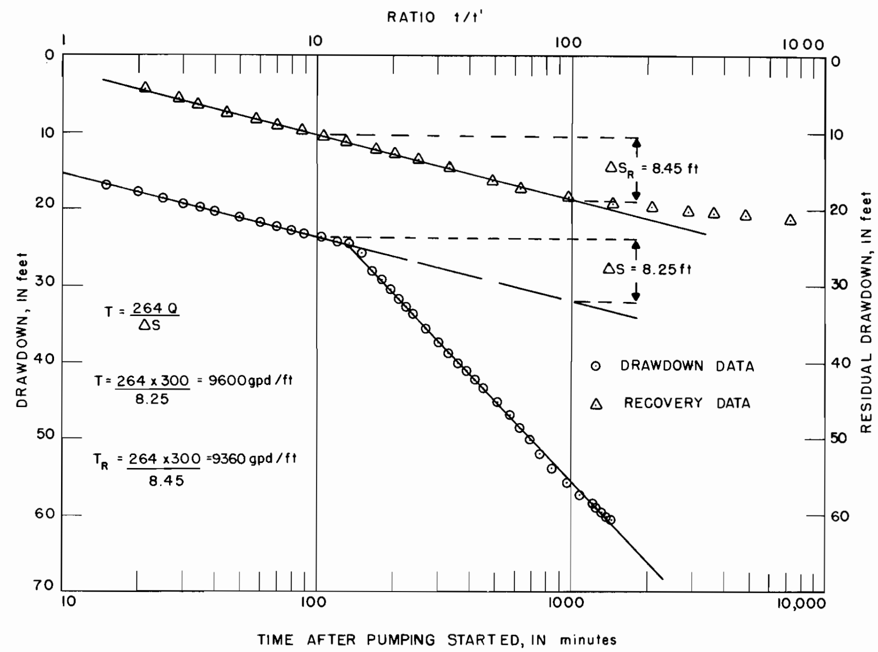
As long as pumping levels were maintained above the water-yielding zones, time-drawdown derived values of T computed from test well data are considered valid. Once dewatering occurs, the hydrologist is plagued by erratic data as he is in well loss computations. In analyzing pumping-well data, the graphical solution of the modified nonleaky artesian formula (Cooper and Jacob, 1946) was employed for the determination of transmissivity:

$$T = 264\, Q/\Delta s$$

where: T = transmissivity
Q = discharge, in gpm
Δs = drawdown difference per log cycle, in ft.

It was necessary to use this method because pumping well data usually falls on the flat portion of the type curve, precluding accurate solutions. The graphical method affords the advantage of working with a straight line on semi-logarithmic paper. Dewatering is evidenced by a break in slope as shown by the example in figure 5. The break resulting from dewatering is usually abrupt rather that the transitional change typically associated with a boundary. Moreover, the depth at which dewatering occurs can usually be corroborated by the step-test analysis.

Figure 5
Time-drawdown graph, test well S-19



The slope observed after dewatering represents a reduction of T in the vicinity of the well and is not representative of the aquifer in the area encompassed by the cone of depression. Transmissivities were not considered valid unless they could be determined from data obtained prior to dewatering.

Recovery data was used when dewatering effects precluded realistic computations from drawdown data. However, the common practice of computing recovery values as the difference between the recovery levels and the extended pumping trend could not be used. This method will not eliminate the effects of dewatering as they are included in the extended trend. These effects can be eliminated by making computations using residual drawdowns, which are the differences between the projected non-pumping levels and recovery levels. It is recognized that the time-recovery relationship may be distorted somewhat as water zones are filled and the aquifer again becomes completely artesian. This occurs rapidly and the effects are not thought to be particularly significant. Collection of recovery data is imperative when valid observation well data is not available.

There were several opportunities to check the validity of recovery data. Figure 5 shows a comparison of the T values computed from recovery data and drawdown data prior to dewatering. Figure 6a illustrates a solution obtained from observation well data and compares the T value with that obtained from recovery data. Other comparisons yielded similar agreement which supports the use of recovery data.

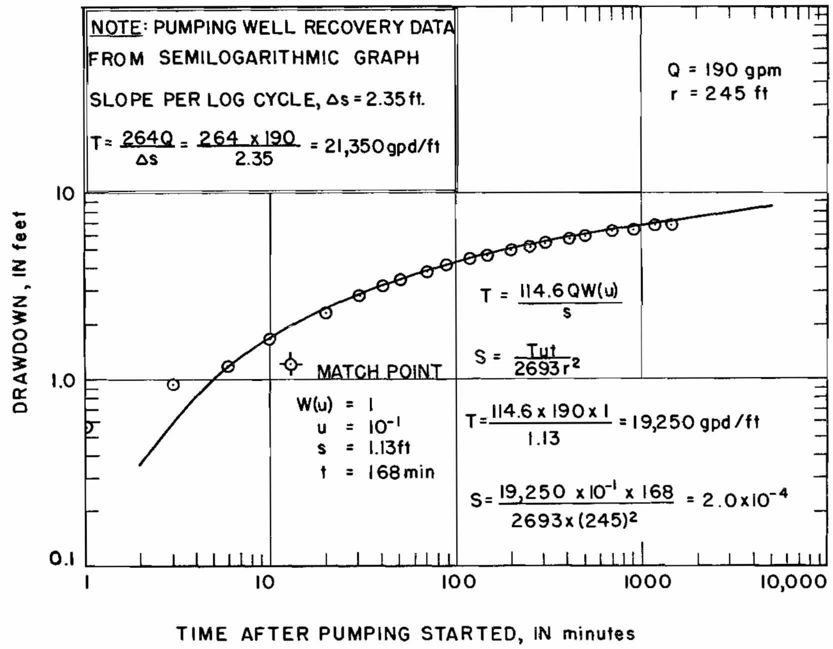


Figure 6a.
Time-drawdown graph, observation well M-14-1

Fully penetrating observation wells were available for several of the tests. Because storage coefficients cannot be obtained from pumped well data, these tests afforded the only opportunities to evaluate storage properties of the carbonate aquifer. Values determined as in figure 6b were typically artesian, except in one instance where the magnitude was 10^{-3}. This appears to justify the assumption that $S = 10^{-4}$ where data is inadequate for the determination of the exact value.

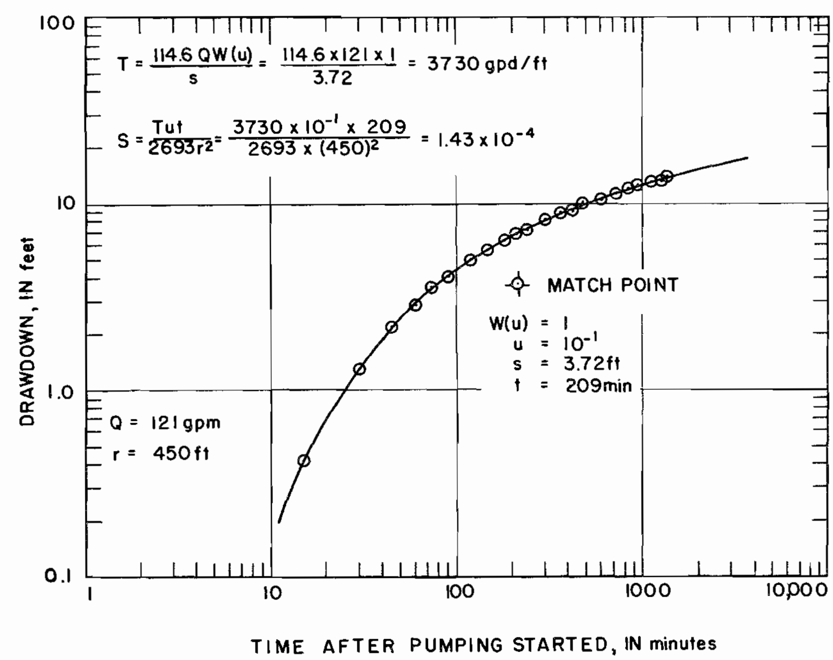
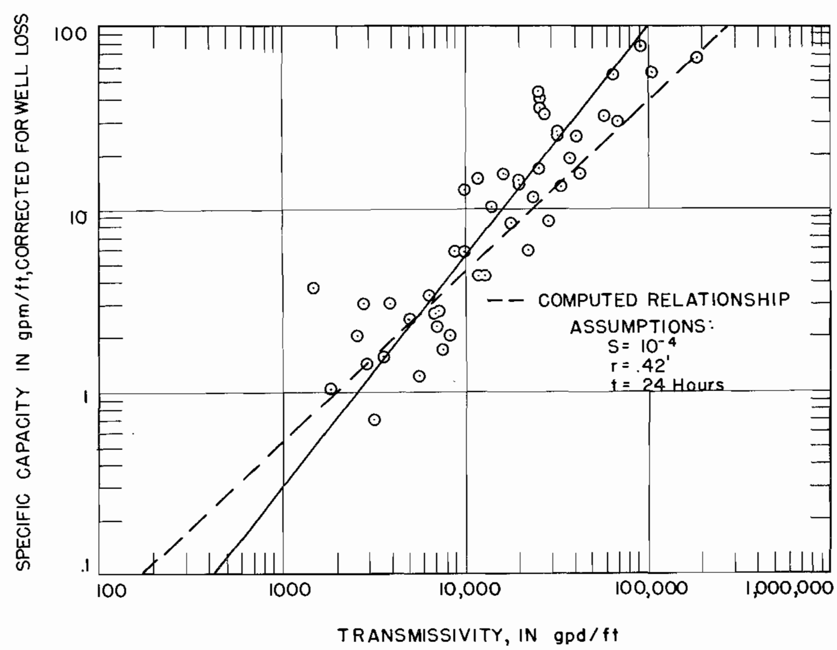


Figure 6b.
Time-drawdown graph, observation well P-13-1

The theoretical relationship between specific capacity and transmissivity may be computed by the nonleaky artesian formula (Walton 1962). Storage coefficient, time, and well radius are all factors which affect this relationship. Because time and well radius for each test was the same, and the storage coefficients were assumed to be of similar magnitude, the test data was expected to demonstrate that high and low values of specific capacity correspond to high and low values of T, respectively. Specific capacity data could, however, produce a false relationship since it is also affected by well loss and boundary conditions. Therefore, corrected specific capacities were plotted against the values of T listed in the Appendix (table 7a). The comparison of field data and the theoretical relationship is shown in figure 7. The deviation of field data from the theoretical for the high range of values may be due in part to exceptionally large effective radii in the highly productive carbonate rocks.

Figure 7
Comparison of field relation and theoretical relation between specific capacity and transmissivity



The scatter of data in figure 7 indicates that values of T determined from specific capacity data are no substitute for the results of controlled pumping tests. However, in the absence of this data, it is a useful tool. Actual specific capacities can be corrected for well loss by use of figure 4, and the corrected specific capacity value can be applied to the graph in figure 7 to obtain an estimate of the transmissivity. It is emphasized that no great accuracy can be inferred, but this technique of analyzing well data can be useful for reconnaissance work.

Specific capacity decreases with time as the cone of depression deepens and expands until vertical leakage through the confining bed, or some other source of recharge, balances discharge. The 24-hour pumping period was generally not long enough for the effects of vertical leakage to be detected. Determinations of vertical permeability by the leaky artesian formula were attempted where leakage did occur and observation well data was available.

Although the results were less than desirable, it is believed that vertical permeabilities based on pumping test analysis are usually inadequate to accurately describe field conditions. More realistic values can be determined from detailed studies of pumping centers where equilibrium has been established.

Application of the Analysis

The purpose of pumping tests and subsequent analysis is to enable predictions of well yields. Computed hydraulic characteristics are used to mathematically simulate various schemes of development. The magnitude of interference between wells is computed to determine the practical design of well fields. Recharge must be considered in determining the potential yield. Unfortunately, in carbonate aquifers these techniques yield only estimates at best, when done prior to drilling and testing the actual wells. In areas where data is abundant these estimates may be very good. In undeveloped areas it is impossible to predict with a high degree of accuracy the yield of a well before drilling.

Adequate pump-test data makes it possible to predict well yields with a reasonable degree of accuracy. The well loss, dewatering, critical pumping level and the rate of drawdown with time must be considered in determining the yields of individual wells. If critical pumping levels are above the top of the aquifer, a straight forward solution is possible. Theoretical drawdown is directly proportional to the pumping rate for a given time, so test drawdowns are corrected for well loss. The theoretical drawdown for any rate can then be easily computed and the actual drawdown for a given time can be predicted by adding the well loss for the new pumping rate. The rate of drawdown can be determined by the modified nonleaky artesian formula, using the T determined from the test and extending the results. When recharge characteristics are not known, an arbitrary period of no recharge is selected. For the purposes of determining the yield of the test wells a period of 180 days was selected. Interference from other wells and seasonal low non-pumping levels must also be taken into account.

If dewatering of some water zones is to be tolerated, the above analysis no longer applies. If a critical pumping level is selected which is below pumping levels produced during the step test the hydrologist must base his judgement on other data and should be very cautious. Disregard for the relationship of pumping levels and water zones can cause erroneously optimistic prediction of yields. Walton (1962) suggest an empirical projection of yield-drawdown relationships under these conditions based on step test data. Drawdown at the end of each step is plotted against the corresponding pumping rate and a curve is drawn through the points. Figure 8a gives an example of this technique, only here water levels are plotted instead of drawdowns so a comparison with the well log can be made.

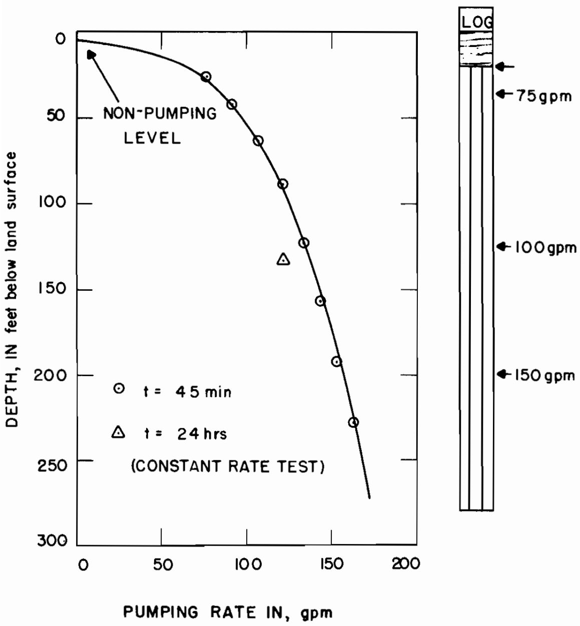


Figure 8a.
Step test data, test well
P-13

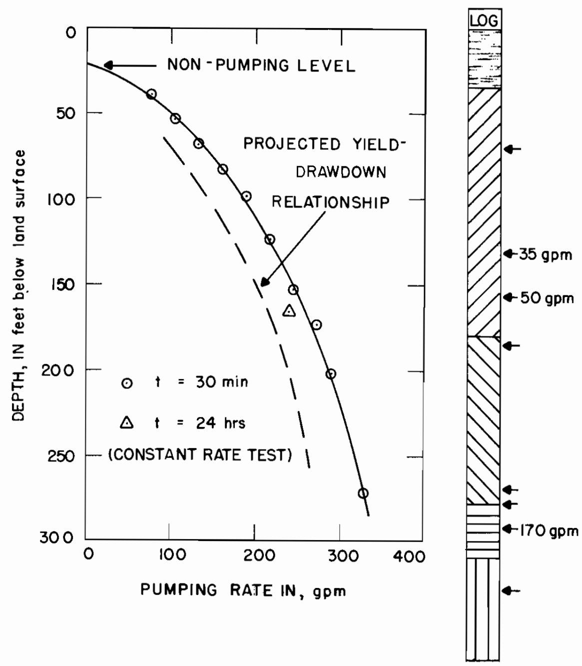


Figure 8b.
Step test data, test well
M-29

In using the step test data empirically to predict yields, the effect of time must also be considered. Figure 8b illustrates how this might be accomplished. The 24-hour test drawdown plotted against the pumping rate falls beneath the corresponding step-test curve because it represents a longer time period. By applying a little judgement, a second curve can be synthesized for the test period. Carrying this reasoning further, a yield-drawdown relationship for the desired period can be approximated. Consideration of the time-drawdown data such as the extension of slopes resulting from dewatering may be useful for predicting yields. The yield-drawdown curve of the step-test data can be used to check the validity of these extensions. For example, a predicted yield and drawdown which falls to the right of the step-test curve cannot possibly be correct. This method does not yield an exact solution, but if used properly it should give practical results.

At no time should mathematical computations with the nonleaky artesian formula be used to predict drawdowns for a pumped well in the carbonate aquifer. This would require the assumption that the effective radius is equal to the nominal radius of the well. It is the author's opinion that this assumption is seldom justified for rock wells. Corrected test drawdowns were compared with distance-drawdown graphs based on the hydraulic characteristics determined from each test analysis. The apparent radii of the wells were found to vary by as much as six log cycles for a very small range in transmissivity. This seems to point out the futility of assuming any radius for a rock well. The nominal radius is assumed for the prediction of general relationships as specific capacity versus T in figure 7. However, it should not be used when empirical data from pumping tests is available.

Consideration of the relationship of pumping levels and producing zones may also provide some insight into the seemingly eratic response of certain wells which often harasses water-well contractors and water superintendents. Ignorance as to the depth of the critical pumping level may often be the problem. As pointed out, that is the level in a given well below which drawdowns rapidly become intolerable. Some examples will serve to illustrate this point:

> A contractor had just completed the drilling and testing of a production well and had installed a permanent pump. The well was put into service, but a week later, the pump was breaking suction. During a service call the well was pumped at the initial rate for 24 hours with no problem. Less than a week later the pump was again breaking suction. After several trips and much distress, it was determined that it took about a week for the critical level to be reached and that the water level had recovered between service calls. A moderate reduction in the pumping rate solved the problem.
>
> Another instance involved a well with a fairly shallow pumping level and a capacity of several hundred gallons per minute. This well had given faithful service for years. Suddenly pumping levels dropped to the bowls of the pump. After a lengthy investigation it was determined that additional interference resulting from increased pumpage nearby caused the critical pumping level to be reached. The same effect could be caused by reduction in well efficiency due to encrustation.

When evaluating quantitative data pertaining to carbonate aquifers, the hydrologist is plagued by many problems. It is wise to employ regional concepts where possible and not become bogged down with minor inconsistencies. In predicting the yield of wells, there is no substitute for a good step test, experience, and sound judgement.

IV. RELATIONSHIP OF GEOLOGY TO GROUND WATER

Statistical Analysis of Geologic Units

The carbonate aquifer in the study area is comprised of several formations. The concept that these formations act as a single hydraulic unit seems justified when considering the relative uniformity of the piezometric surface and its general gradient to the northeast shown in plate 8. Ground water moves through a complex network of interconnected openings. These openings consist of fractures, bedding planes and joints, some of which have been enlarged by solution.

Although the aquifer is a single unit, the capacity of water-yielding zones varies over a wide range both vertically and horizontally. In attempting to discover some correlation between geology and ground water, it was necessary to eliminate as many variables as possible and to select some hydrologic characteristic to use as the basis for comparison. After attempting many different approaches, it was determined that the concept of "specific capacity per foot of penetration" provided the most meaningful relationship.

The basic procedure described in Zeizel et. al. (1962) was followed in making the statistical analysis. Specific capacities per foot of penetration consider only that portion of the carbonate aquifer which is exposed by the open bore hole. Cased off portions of the aquifer and penetration into shale were deducted from well depths. In order to determine hydrologic differences based on geologic characteristics, wells were separated into groups based on a common geologic feature. Specific capacities per foot of penetration were arranged in their order of magnitude, and frequencies were computed by the Kimball (1946) method. Values of specific capacity per foot of penetration were then plotted against frequency (percent of wells) on logarithmic probability paper.

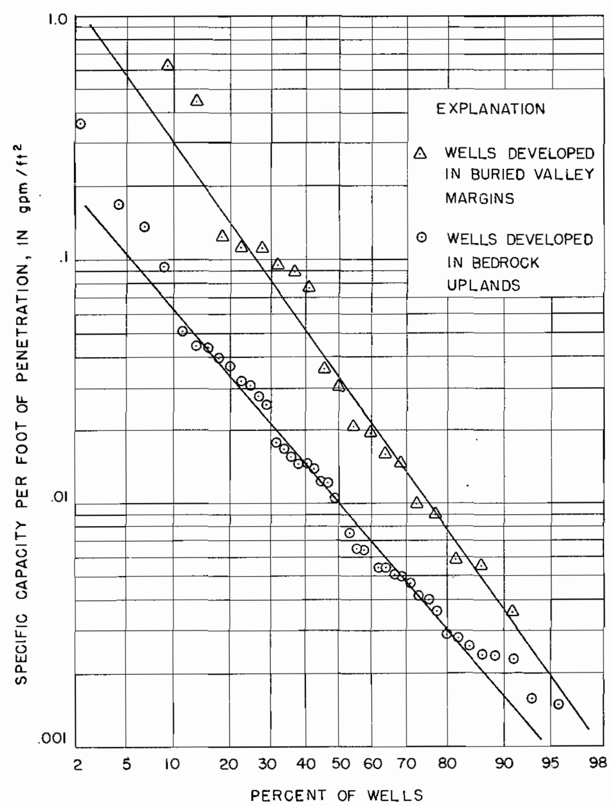


Figure 9a
Relation between specific capacity and bedrock topography

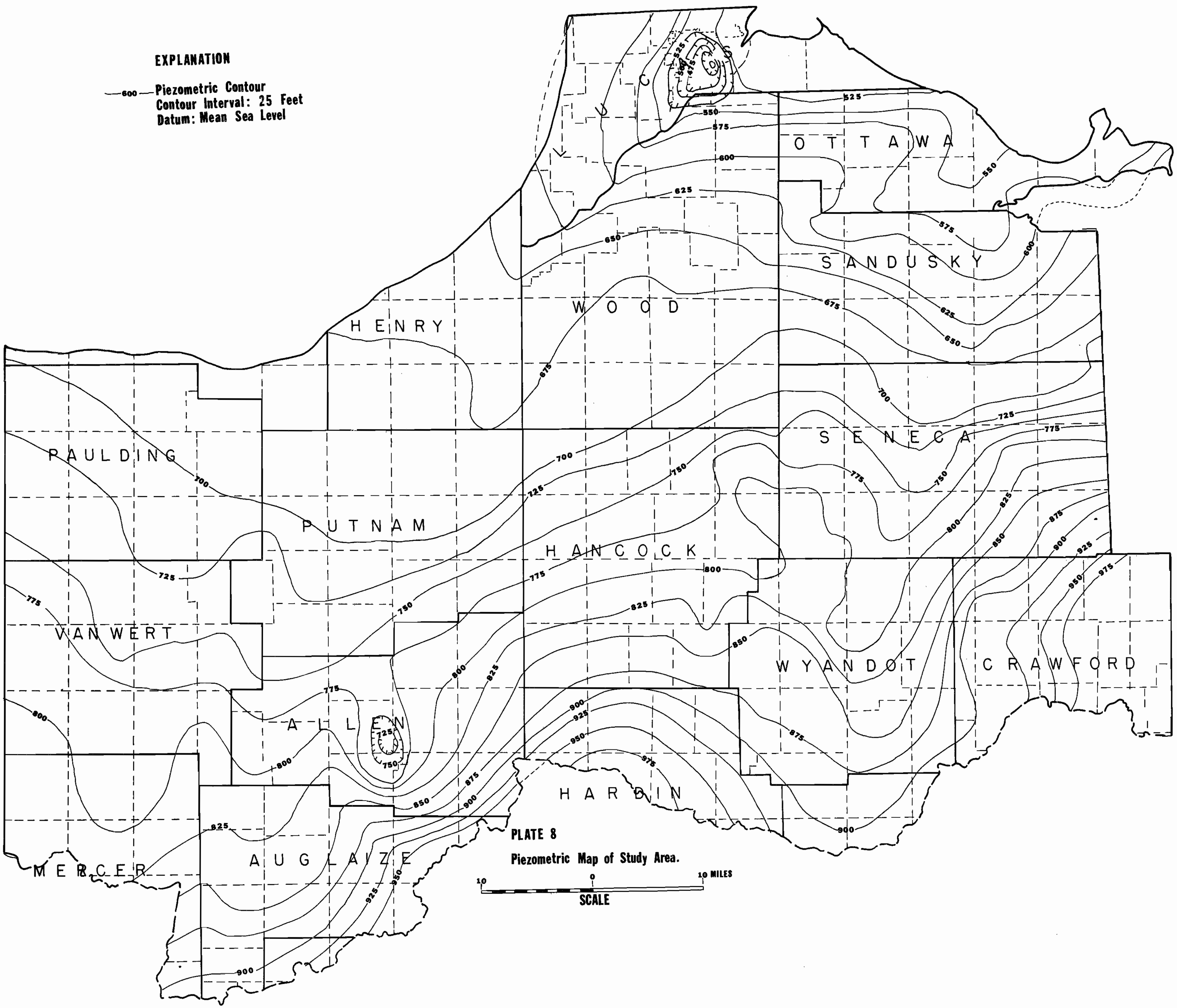


PLATE 8

Piezometric Map of Study Area.

The test well data (Appendix, table 7a) was separated into various groups based on formations penetrated and proximity to buried valleys. The frequency graph in figure 9a demonstrates that specific capacity per foot of penetration is greater for wells located in buried valley margins than for wells located in bedrock uplands. This was the only relationship which seemed to give any particular separation between groups when all the test wells were considered.

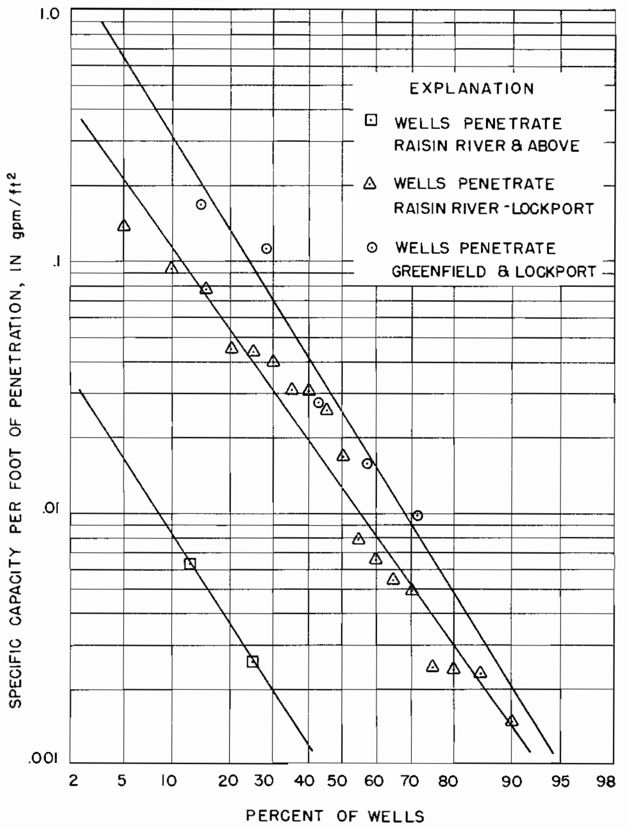


Figure 9b.
Relation between specific capacity and formations penetrated west of Bowling Green fault.

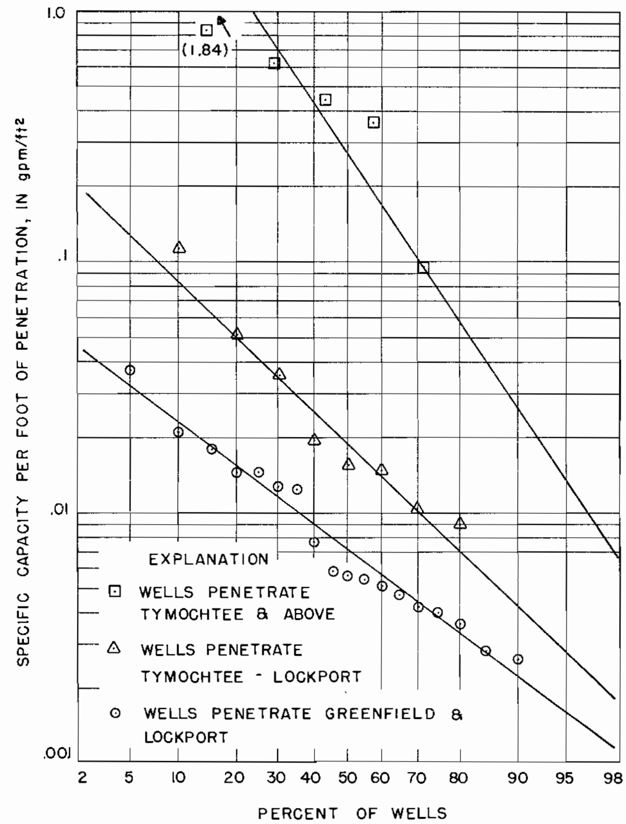


Figure 9c.
Relation between specific capacity and formations penetrated east of Bowling Green fault.

Consideration of formation differences in individual wells show that hydrologic differences were somewhat dependent on the stratigraphic units penetrated. To pursue this relationship, wells were separated for specific areas based on formations penetrated. Figures 9b and 9c demonstrate a definite relationship between specific capacity per foot of penetration and stratigraphy in areas east and west of the Bowling Green fault. Since it has been established that the Greenfield formation is essentially non-water bearing, it has arbitrarily been included with the Lockport on the frequency graphs.

West of the fault the specific capacity per foot of penetration is greatest for wells tapping only the Greenfield and Lockport and seems to decline as stratigraphically higher formations are included. This indicates that here the Lockport is the most productive. The Raisin River is the least productive of the stratigraphic units, in fact, several wells penetrating only this formation were not tested because of extremely low capacity. East of the fault the reverse is true. The Lockport is the least productive and the formations higher in the stratigraphic column are the most productive.

The differences in yield of the formations between these respective areas may be due in part to the location of buried valleys. Prior to glaciation, solutioning of the limestone at and near the base levels of former streams probably occurred. Generally, the Lockport is exposed in the buried valley area west of the fault, and is exposed in the bedrock upland region east of the fault. Contact with potentially large sources of recharge afforded by permeable materials within the bedrock valleys is also an important factor in the development of secondary channels. These solution channels would be expected to diminish with distance from the source. Norris and Fidler (1970, in preparation) believe that much of the ground-water solution took place in the geologic past when structurally higher areas were periodically above sea level.

The areal distribution of buried valleys and differences in lithology are important geologic controls affecting the hydrologic characteristics of the carbonate aquifer. These factors are interrelated but the effect of the buried valleys is dominant.

Determination of Hydrologic Units

Quantitative information derived from the pumping tests was augmented by data already available, which helped in making the statistical analysis and in determining the areal relationships. Controlled pumping tests on file with the Ohio Division of Water and the Water Resources Division, U. S. Geological Survey, were reviewed. In addition, all of the well records in the area of interest, on file with the Division of Water, were screened. To insure that information was representative, the following criteria were utilized in selecting the data from the well logs: Each well penetrated a substantial thickness of the aquifer, was a minimum of 6 inches in diameter, and had at minimum an 8-hour constant rate pumping test. These criteria provided valuable information from an additional 122 wells which was utilized to supplement the project test well data. As with the test wells, the specific capacity per foot of penetration was found to provide the most meaningful method of comparison. The locations of all wells used in the analysis are shown on plate 9. Data from the individual well logs is listed in tabular form in the Appendix, table 7B. The non-pumping (static) levels in these wells, and those of the test wells, were used to construct the piezometric surface map (plate 8).

EXPLANATION

⊙ Denotes Wells Drilled And Tested Under Northwest Ohio Project.

• Denotes Wells With Test Data On File With Division of Water.

Wells Are Numbered By County And Are Described In Table

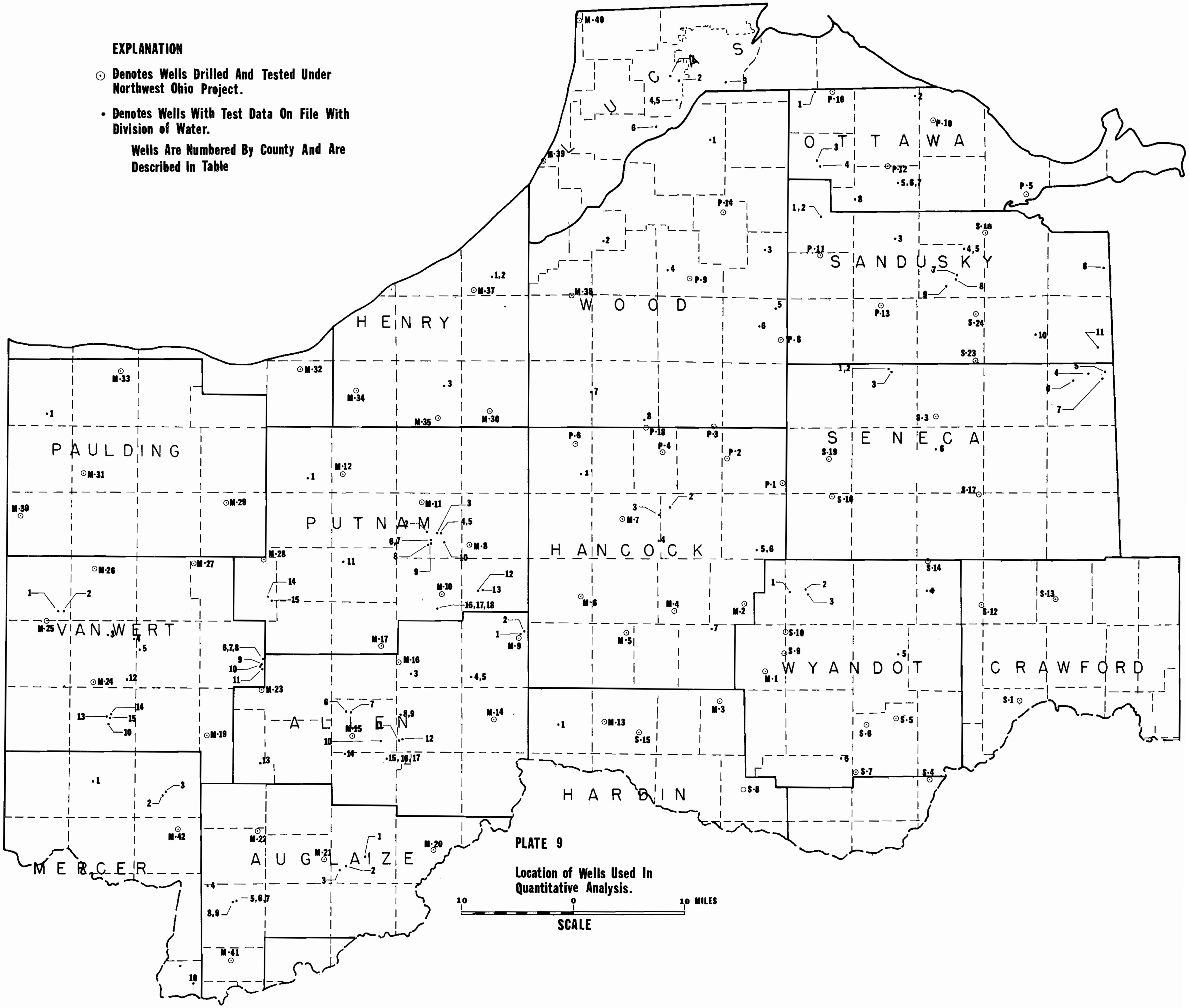


PLATE 9

Location of Wells Used In Quantitative Analysis.

To pursue the relationships of the stratigraphy to hydrologic characteristics, the data was separated into groups based on geologic boundaries. Several trials were made by adjusting formation controls, and specific capacity frequency graphs were made for each grouping. This technique demonstrated that stratigraphy did have hydrologic control, with the exception of a few areas.

In the final analysis the well data was divided into areas using buried valleys as the primary controlling factor and the stratigraphy or geologic boundaries as the secondary control. Specific capacity frequency graphs were again made using these criteria and the results were conclusive. Figure 10 is a composite of these graphs demonstrating that six separate areas are justified. Areas 7 and 8 are treated separately in the discussion of the individual areas.

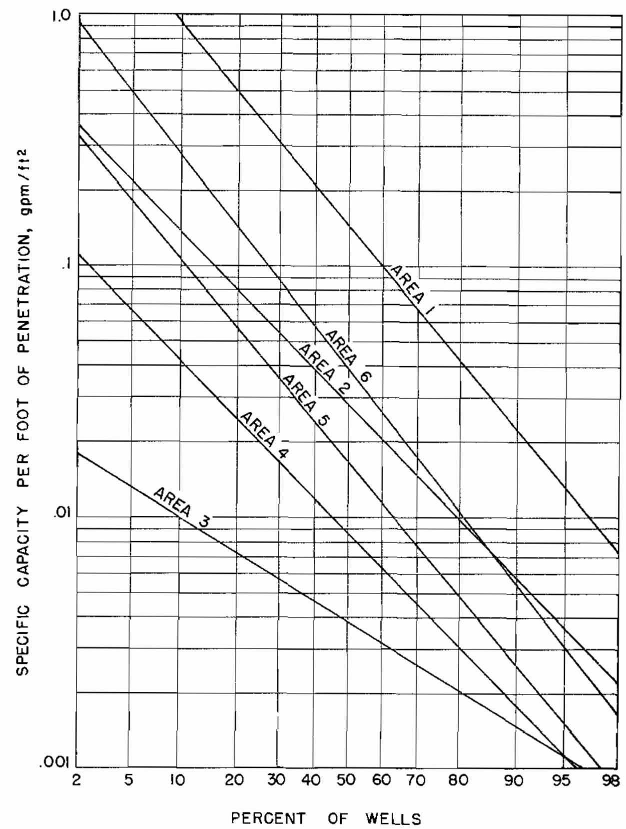


Figure 10
Relation between specific capacities of wells in Areas 1 through 6

It is believed that the stratigraphy and the proximity to buried valleys provide the keys to differentiate the individual areas within the carbonate aquifer. When rocks are not uniform in character but are softer or more soluble in some places than in others, an uneven surface may be developed. In humid regions the cause can be attributed to solution. This definition of differential weathering (A. G. I., 1962) describes the conditions found in the carbonate rocks in the area of this study. It is believed that the extremes in the ranges of specific capacity per foot of penetration within each grouping can be attributed to differential weathering, particularly in the marginal areas of the buried valleys. The map (plate 10) shows the range of yields which can be anticipated. Since the aquifer thickness and available drawdown for the test wells is considered representative, the frequencies of the yields of these wells were used to determine reasonable ranges for each area. Although the lines enclose areas having distinctive hydrologic characteristics, they are somewhat arbitrary in that the lines themselves should be viewed as transitional zones rather than distinct boundaries between the areas.

Discussion of each area

The following section gives a discussion of the characteristics which differentiate the eight areas shown on plate 10. In predicting the yields of wells, reference is made to the maximum safe yield. Safe yield is here defined as the maximum rate at which a well can be pumped without exceeding the critical pumping level, assuming that conditions in the area remain unchanged. The critical level is usually established at that level below which significant dewatering occurs, resulting in drastically increased drawdowns. Overpumping a well ultimately results in reduced yields.

Area 1 comprises the region with the highest potential yields in the area of the study. The thickness of the overburden ranges from 19 to 95 feet with an average of 65 feet. The uppermost formation in the majority of the wells is the Tymochtee with the exception of the wells along the southeast boundary of the area which encountered the Delaware, Columbus, and Raisin River as the bedrock formation. Formations penetrated by wells in this area include the Delaware, Columbus, Raisin River, Tymochtee, Greenfield and the Lockport dolomite.

Most of the water in the wells in Area 1 is encountered in the upper few feet, or weathered portion of the bedrock, regardless of the formation. From well log data it is known that a shallow buried valley transverses this area from south to north. This valley can be seen in the contour map of the bedrock surface, plate 4. The lower portion of the unconsolidated material filling the valley consists of permeable saturated, water-bearing materials. These facts point to the assumption that the source of water and recharge to wells developed in this area is the relatively thick unconsolidated material overlying the bedrock.

Ground water obtained from Area 1 is very low in hydrogen sulfide content except in Ottawa County. The water in eastern Sandusky and Ottawa counties is highly mineralized due to the occurrence of gypsum. General water-quality data is shown on plates 14 and 15 in Section VI. Detailed analyses of the quality of water from each test well are listed in the Appendix.

Specific capacity per foot of penetration for the wells in this area (figure 11a) ranges from .0270 to 1.8400 with a 50 percent or median value of .1440 gallons per minute per foot of drawdown per foot of penetration (gpm/ft/ft). The maximum safe pumping rates for the test wells range from 750 to 1,000 gpm.

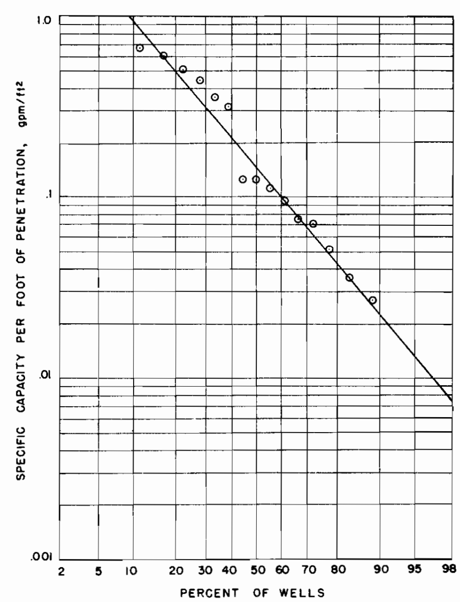


Figure 11a
Specific-capacity frequency graph for wells in Area 1

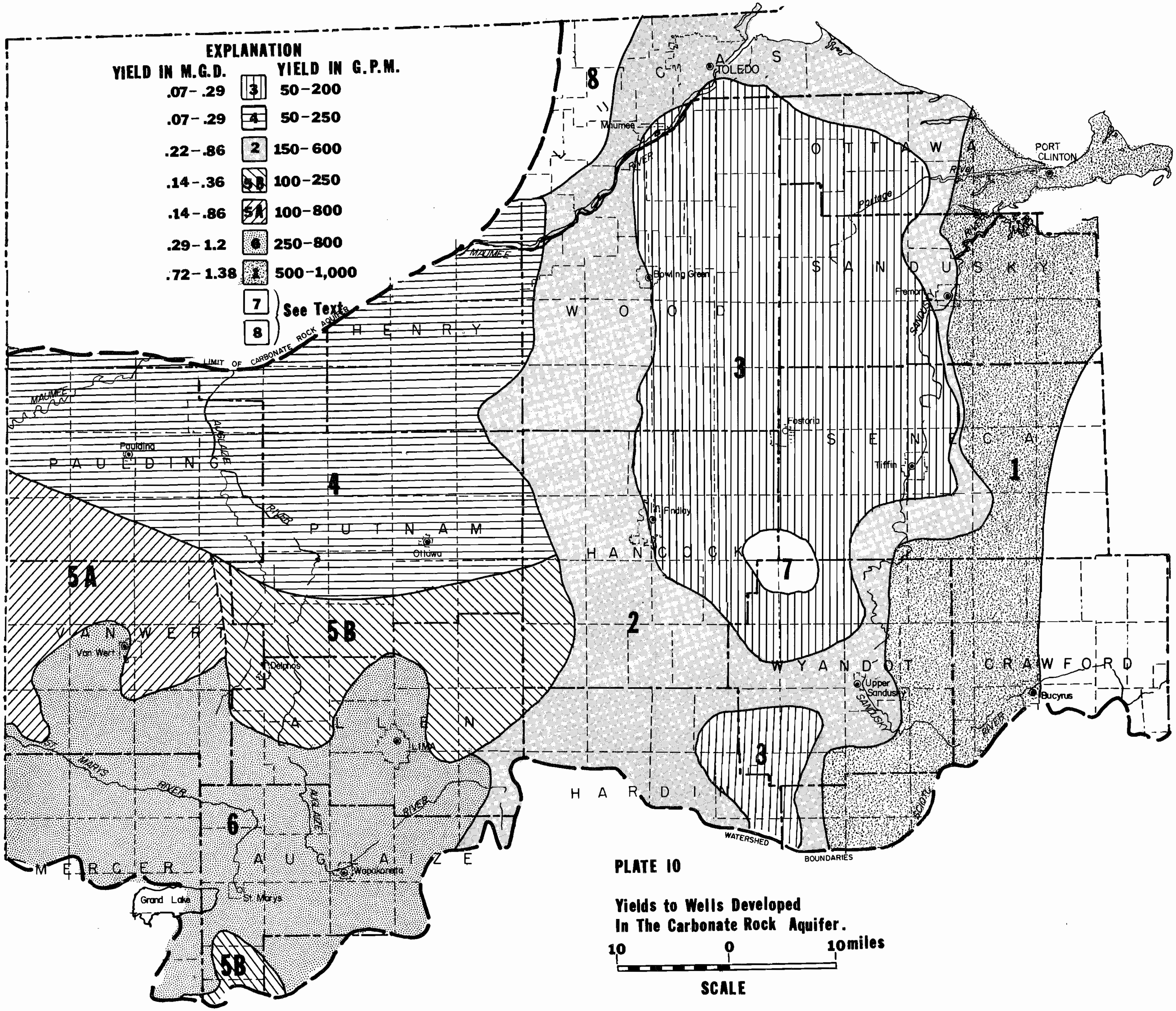


PLATE 10

Yields to Wells Developed In The Carbonate Rock Aquifer.

It is believed that wells drilled in Area 1 will safely yield from 500 to 1,000 gpm when continuously pumped.

Formations penetrated by the test wells in Area 2 include the Raisin River, Tymochtee, Greenfield, Lockport dolomite, and in a few cases the pre-Lockport. In the western portion of the area the bedrock is Raisin River and in the eastern portion it is generally the Tymochtee formation. The thickness of the unconsolidated material varies from 4 feet to 115 feet with an average of 44 feet. This material is comprised primarily of impermeable clay throughout the area. There are no significant bedrock features, with the exception of a buried valley in the northwest corner of the area. This valley underlies the Maumee River and trends northeast into Lake Erie at Toledo.

The most significant water producing zones were encountered in the Lockport dolomite and Tymochtee formations. The overburden is essentially glacial till with relatively low vertical permeability, limiting recharge within the confines of the area. Wells along the northern boundary of the area should receive recharge from Lake Erie since the formations in which they are developed underly, and are in direct contact with the lake.

The Bowling Green fault extends through the western portion of Area 2. As was mentioned earlier in the report, wells on the western (downthrust) side of the fault had the highest specific capacity per foot of penetration when they penetrated only the Lockport. When stratigraphically higher units were penetrated, the specific capacity per foot of penetration decreased.

Specific capacity per foot of penetration for the wells in Area 2 (figure 11b) ranges from .0091 to .1360 with a median of .0280 gpm/ft/ft. The safe yield of the project test wells ranged from a minimum of 130 to a maximum of 600 gpm. The average (50 percent) yield was 400 gallons per minute. Based on continuous pumping for extended periods, wells drilled in Area 2 can be expected to yield from 150 to 600 gpm.

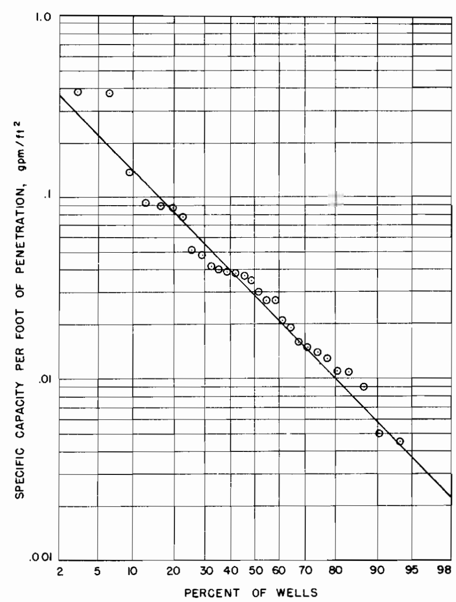


Figure 11b.
Specific-capacity frequency graph for wells in Area 2

Area 3 provides the most consistent parameters of any of the areas in the study. The range in the specific capacity per foot of penetration is relatively small and the yields to wells are uniformly poor throughout the area. The primary stratigraphic units penetrated by wells in this area include the Greenfield and Lockport. In one well a small amount of Raisin River and

Tymochtee were present over the Greenfield. Several of the wells fully penetrated the Lockport and entered the pre-Lockport. Although the area consists of two separate areas, they both have the same hydrogeologic characteristics: Area 3 consists of a bedrock high in which the Greenfield and Lockport form the bedrock surface, the Greenfield around the outside of the areas and the Lockport in the center. The boundary of the area is the bedrock surface contact between the Tymochtee and Greenfield. Additionally, the Bowling Green fault passes along the greater portion of the western boundary.

The thickness of the overburden ranges from 19 to 54 feet with an average of 33 feet. It is uniform in composition and consists primarily of clay. No buried valleys or significant bedrock surficial features are known to exist in this area.

Wells developed in the area are quite consistent in that the only appreciable amounts of water were encountered in the Lockport. The Greenfield was, for all practical purposes, non-water bearing. As in Area 2, there are no outstanding recharge characteristics within the confines of the area.

Specific capacity per foot of penetration (figure 11c) varies in the wells from a minimum of .0016 to a maximum of .0170 gpm/ft/ft. The median was .0038. Maximum safe pumping rates in the test wells varied from 25 to 300 gpm although the 50 percent or median yield is only 100 gpm.

Projected maximum safe yields to wells developed in Area 3 range from 50 to 200 gpm based on periods of continuous pumping.

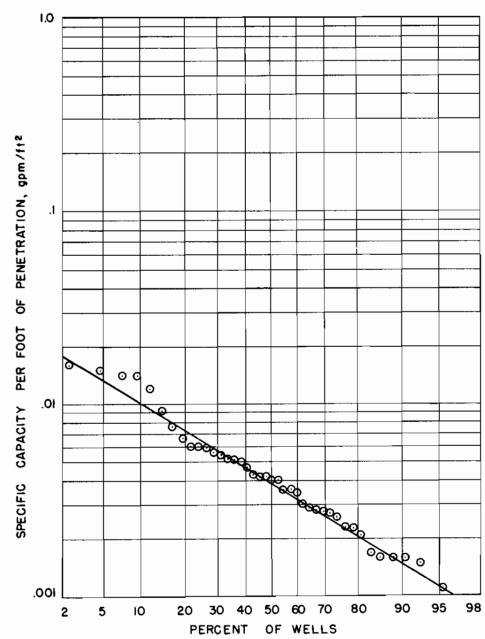


Figure 11c.
Specific-capacity frequency graph for wells in Area 3

Area 4 has very consistent parameters and is the least favorable portion of the study area for the development of a ground-water supply. Potential yields to wells are low and the hydrogen sulfide content in the water is high.

Test wells in the southern portion of the area penetrated the Raisin River, Tymochtee, Greenfield formations and the Lockport dolomite. In the northern portion these formations are overlain by the Silica shale, Dundee limestone, and Detroit River dolomite. Only meager quantities of water were encountered in any formation located stratigraphically higher than the Tymochtee. The Silica, Dundee, Detroit River, and Raisin River have exceptionally poor water-bearing qualities in this area.

The bedrock surface is essentially featureless except for a shallow buried valley which extends from the southwest to the northeast corner of Putnam County (see plate 4).

The entire area is covered with unconsolidated material ranging from 12 to 74 feet in thickness. It is predominantly impermeable clay with an average thickness of 43 feet. No significant areas of permeable materials were noted during the investigation and it is believed that recharge in the area is limited to leakage through glacial till.

The northern boundary of the area is the bedrock contact between the Silica and Ohio shale formations. The southern boundary is through a zone where significant changes were noted in the specific capacity per foot of penetration in the wells rather than a geologic boundary or contact.

Specific capacity per foot of penetration in wells in this area (figure 11d) ranges from .0024 to .0147 with a median of .0086 gpm/ft/ft. Test yields ranged from less than 5 to 200 gpm. The median yield was 80 gpm.

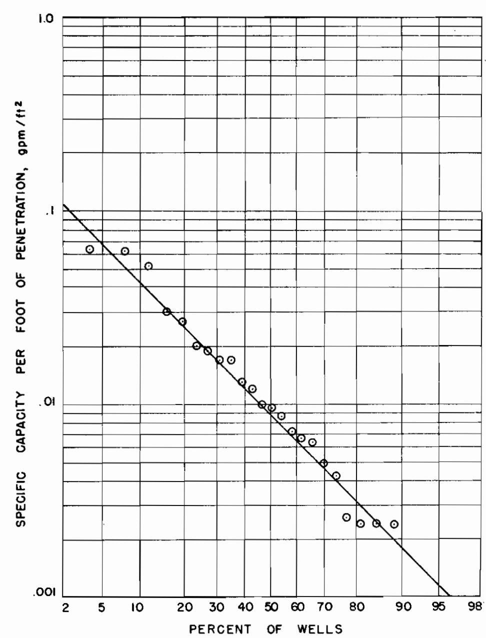


Figure 11d.
Specific-capacity frequency graph for wells in Area 4

Deep wells drilled in Area 4 can be expected to yield from 50 to 200 gpm. The yields will be greatest in the southern portion of the area and will diminish toward the northern boundary as stratigraphically higher formations occur.

Area 5 has been subdivided into two areas, 5A and 5B. The geologic formations penetrated by wells, in the area taken as a whole, include the Raisin River, Tymochtee, Greenfield, and the Lockport Group. In all of the wells, with the exception of two, the bedrock was the Raisin River formation.

The largest amount of water was encountered in the Lockport. Small amounts were noted in the Tymochtee and Greenfield formations. No appreciable amounts of water were obtained from the Raisin River formation.

The bedrock surface is flat and featureless. The overburden is thin throughout the area, ranging from 5 to 37 feet in thickness, with an average of only 16 feet. It consists primarily of clay, limiting recharge to the rock aquifer. Area 5 adjoins the region in proximity to the deep buried valley (Area 6) to the south. It is believed that permeable materials in this valley are a distant source of most of the water in Area 5.

In analyzing the tests from the wells in Area 5 it was noted that the data fell into two distinct groups. The wells in the western half of the area had much higher yields than those in the eastern half. The area was therefore subdivided into areas 5A and 5B. Wells in 5A had specific capacities per foot of penetration ranging from .0274 to .0466 with an average of .0359 gpm/ft/ft. Maximum safe yields to the test wells ranged from 450 to 900 with an average of 675 gpm. In Area 5B the specific capacities per foot of penetration ranged from .0023 to .0079 with an average of .0050 gpm/ft/ft and the yields ranged from 75 to 250 gpm with an average of 155 gpm.

Wells in both 5A and 5B (figure 11e) penetrated the same amount of overburden and the same geologic formations. The distinct differences between the areas is believed due to a change in the physical character of the formations. In Area 5A the formations are much more permeable than those in 5B.

Potential maximum safe yields to wells in Area 5A range from 200 to 800 gpm. In 5B the maximum safe potential yields range from 100 to 300 gpm.

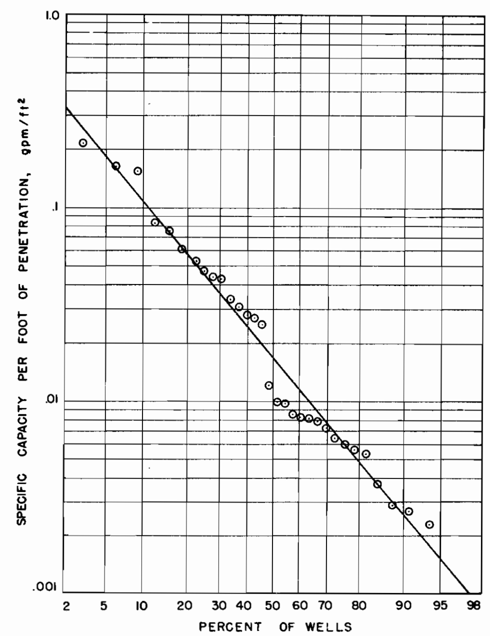


Figure 11e.
Specific-capacity frequency graph for wells in Area 5

Area 6 has the second best potential for ground-water development within the study area, but it also has the greatest range in parameters. It is located within and around the perimeter of the ancient Teays valley (see plate 4). This buried valley has been filled with unconsolidated deposits which contain considerable amounts of permeable water-bearing sand and gravel. These thick, saturated unconsolidated materials are a source of recharge to the consolidated rock formations under and around the perimeter of the valley. The boundary of Area 6 transcends the stratigraphy and includes instead the area influenced by recharge from the buried valley.

All of the test wells were located around the perimeter of the valley where the thickness of the unconsolidated overburden ranged from 15 to 147 feet. The average thickness was 43 feet. Formations penetrated by the test wells include the Raisin River, Tymochtee, Greenfield, and the Lockport Group. All of the wells penetrated the Lockport and in all cases the greatest amount of water was encountered in the Lockport.

The extensive range in the specific capacity per foot of penetration of the wells is attributed to differential weathering of the rock walls during the period of active erosion in the valley and to differences in the amount and size of secondary solution openings with in the rock aquifers.

Maximum safe yields to the test wells ranged from 175 to 1000 gpm with a median of 500.

The specific capacity per foot of penetration (figure 11f) ranged from a minimum of .0036 to a maximum of .1680 gpm/ft/ft. The median was .0380.

Although this area contains large variations in the parameters, it has one of the best potentials of any of the areas in the study. Yields of from 250 to 800 gpm can be anticipated based on extended periods of continuous pumping.

Northwest of the Village of Carey in Wyandot County are two bedrock high areas or ridges. These ridges are composed of Lockport dolomite and rise some 40 to 50 feet above the surrounding flat terrain. The line which encloses these two areas denotes Area 7 on the yield map (plate 10).

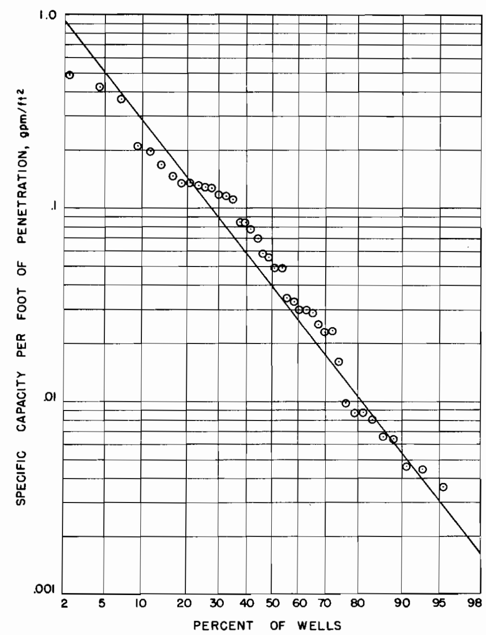


Figure 11f.
Specific-capacity frequency graph for wells in Area 6

In the area surrounding the ridge, the overburden averages 43 feet in thickness. On the ridge itself the overburden is thin and patchy and in some places the bedrock crops out. The Lockport is highly porous and crystalline in structure. Quarry faces show extensive joint and fault patterns with associated solution channels. Several caves exist beneath the area. The highly permeable nature of the bedrock makes it an excellent aquifer. Although none of the project test wells are located within this area, well logs show three deep, large diameter wells with yields of 500, 650, and 704 gpm (see appendix, table 7b, Wyandot County log numbers 2, 3, and 5). The specific capacity per foot of penetration of each well is .4130, .8020, and .1290 respectively.

Wells developed within Area 7 have potential yields of as much as 700 gpm. Due to the lack of appreciable amounts of overburden, the upper portions of the bedrock are extremely susceptible to surface water contamination (Stein, 1966). Caution should be exercised to assure that well casing is placed deep enough to eliminate this problem.

Area 8 is a small area to the northeast of Area 4 and is differentiated because of acute differences in the composition of the overburden. In Area 4 the overburden consists predominatly of impermeable clay. In contrast, the overburden in Area 8 contains thick deposits of permeable sand. The underlying bedrock surface is flat with no major surficial features and the overburden averages 50 feet in thickness.

Rock formations penetrated by test wells in Area 8 include the Ohio shale, Ten Mile Creek, Silica, Dundee, and Detroit River Group. In one of the wells, large quantities of water were encountered in the upper weathered portion of the bedrock. In another well, most of the water was encountered below 240 feet in the Tymochtee. In both of these wells, and in the entire area it is believed that recharge is received from the thick saturated sand deposits which overlie the rock. Most wells in this area are developed in these sand deposits and do not penetrate the rock.

The two test wells developed in this area had specific capacities per foot of penetration of .0114 and .1565 gpm/ft/ft. Maximum safe yields of these wells were 800 and 1000 gpm. Yields similar to those of the test wells can be anticipated in this area.

V. GROUND WATER DEVELOPMENT AND POTENTIAL

Present Development

Plate 11, is a presentation of the current total municipal and industrial ground-water usage in the area of the Northwest Ohio study. The circles on the map are drawn to scale around a point which indicates the center of pumpage. The scale, 1 inch diameter equals 1 mgd, was chosen for ease of use and interpretation. The patterned circles represent municipal pumpage and the open circles represent industrial pumpage. Where there is municipal and industrial pumpage, the patterned circle represents the municipal pumpage and the larger circle represents the combined total.

The data pertaining to the municipal water supplies was obtained from the Ohio Department of Health (1969). The industrial usage figures were obtained from data compiled by Burgess and Niple, Consulting Engineers, for use in "The Northwest Ohio Water Development Plan," January 1967.

Ground-water sources currently serve 56 communities in northwest Ohio. Total pumpage for these municipal supplies approximates 12.27 mgd. Industrial pumpage amounts to 20.42 mgd.

The limestone-dolomite aquifer of northwest Ohio currently yields a total of 32.69 mgd to municipal and industrial wells. Considerable quantities are pumped daily for private domestic wells, and irrigation wells use large volumes of water seasonally.

Water-level fluctuations

Water levels in wells in the dolomite and limestone aquifers of northwest Ohio have been measured continuously since 1946 through a cooperative program between the Ohio Division of Water and the Water Resources Division of the U. S. Geological Survey. There are 16 observation wells (plate 12) in operation at the present time recording fluctuations in areas representing natural conditions or the effects of domestic, municipal, and industrial pumping. Records of these wells and 124 others representing aquifers throughout the State are available in Kaser and Harstine (1966).

The aquifers of the study area are generally recharged by vertical leakage through the overlying glacial drift. Thus, water levels in the aquifers do not respond immediately to rainfall. Instead of the water level reaching a peak within hours after heavy rainfall, it may be a period of 2 or 3 days before the peak levels occur.

The annual fluctuations in the carbonate rock aquifer average 3 to 5 feet under the influence of normal rainfall conditions. During periods of deficient precipitation, especially during the nominal recharge period from October through April, the recharge may be negligible. The hydrograph for well Hn-2a (figure 12a) is an example of the typical pattern of the annual fluctuations in a dolomite aquifer under natural conditions. This well is located at Dola, about 1.5 miles northwest of test well S-15. Daily fluctuations are primarily due to changes in atmospheric pressure. Monthly precipitation for the Kenton Weather Bureau station is shown at the bottom of the hydrograph for Hn-2a for comparative purposes. It is rather significant to note that the lowest water levels were recorded in December or January when the nominal ground-water depletion period was extended into these months because of deficient precipitation. The distribution of precipitation throughout the year can be just as important as the amount.

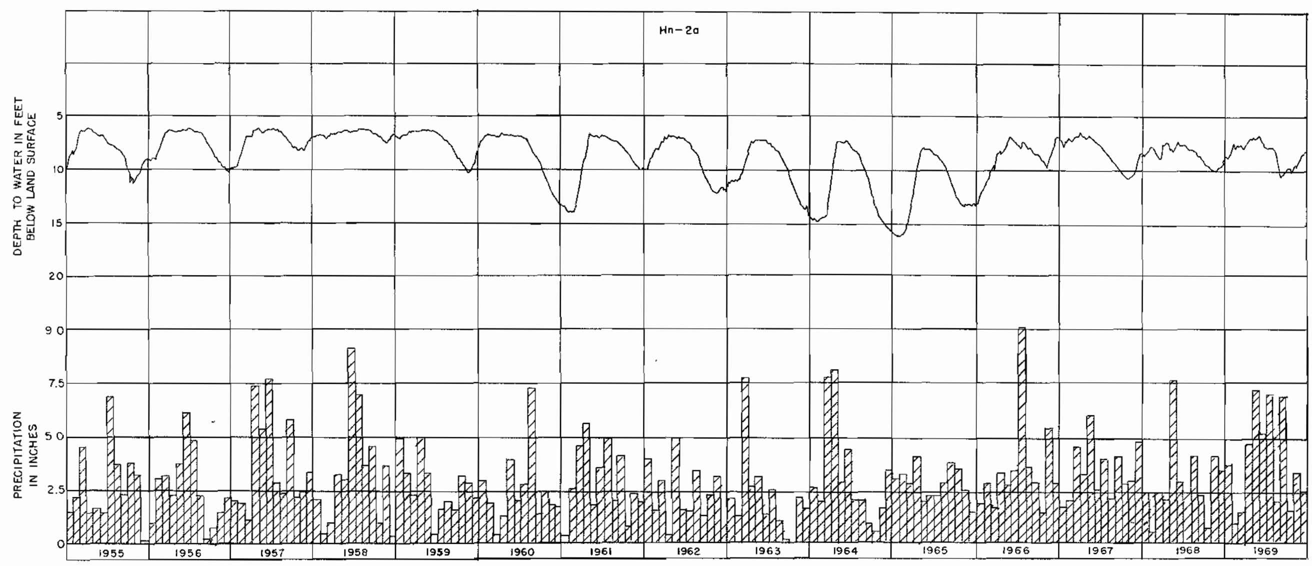


Figure 12a Water levels in observation well Hn-2a, Hardin County at Dola

In 1958 there was very little decline in water levels because of the excessive precipitation which persisted throughout the summer and fall months. Following this, the effects of one of the most notable drought periods in the past 100 years were recorded. Water levels declined to lower levels, year after year, from 1961 through 1964. During this period, precipitation deficiencies accumulated throughout the State. These deficiencies were greatest during the prime months of the nominal ground-water recharge period. As a result, the ground-water depletion periods extended into January and February, the prime months for recharge. Thus, during the fall of 1964 and winter of 1965, water levels in many wells declined to the lowest levels observed in the period of record. However, in the succeeding years, ground-water levels recovered very rapidly from these low levels as they have after previous drought periods. Ground-water levels in northwest Ohio have generally remained stable throughout the years, despite cyclic trends which have sometimes been misinterpreted as "falling water levels."

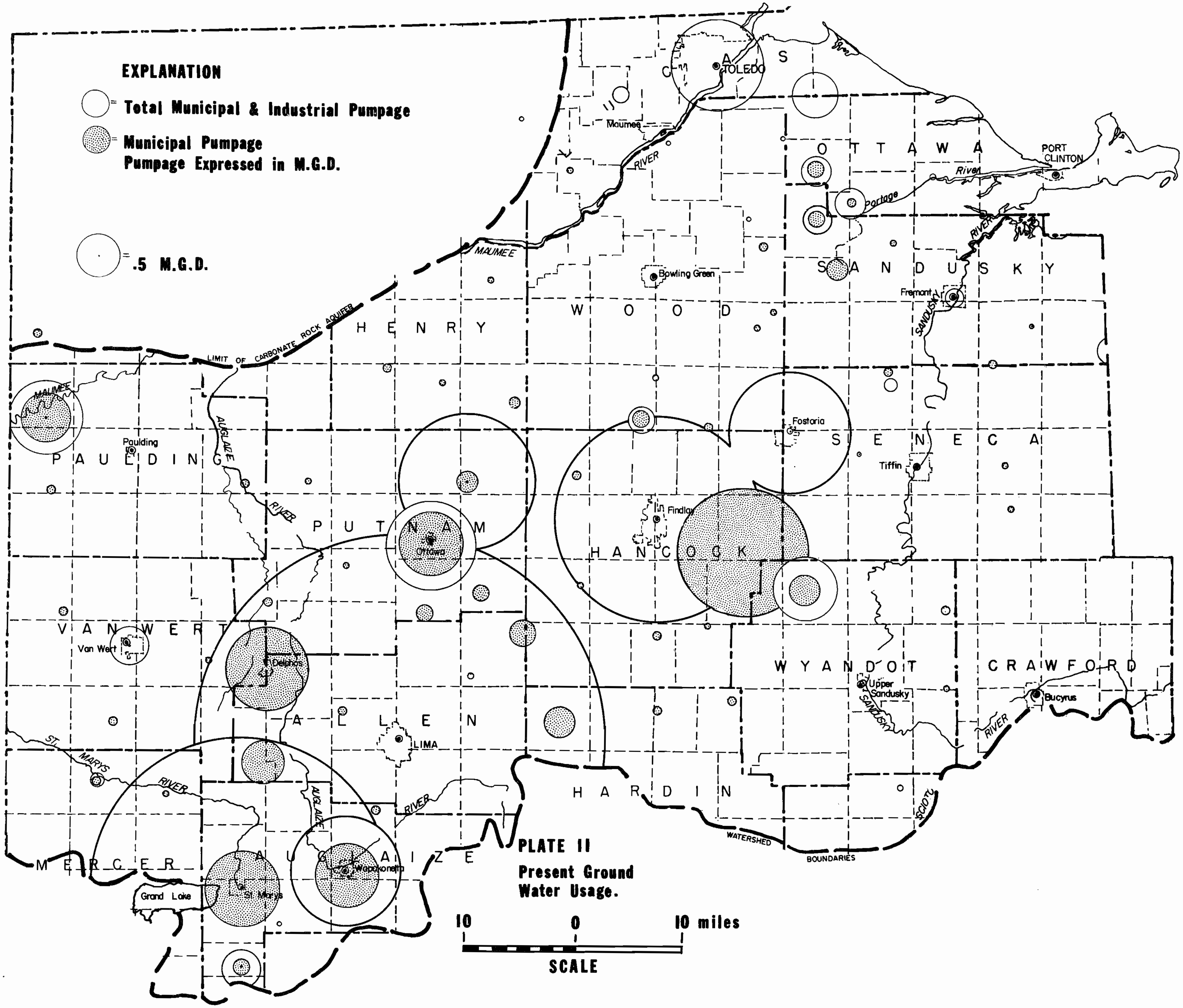


PLATE II

Present Ground Water Usage.

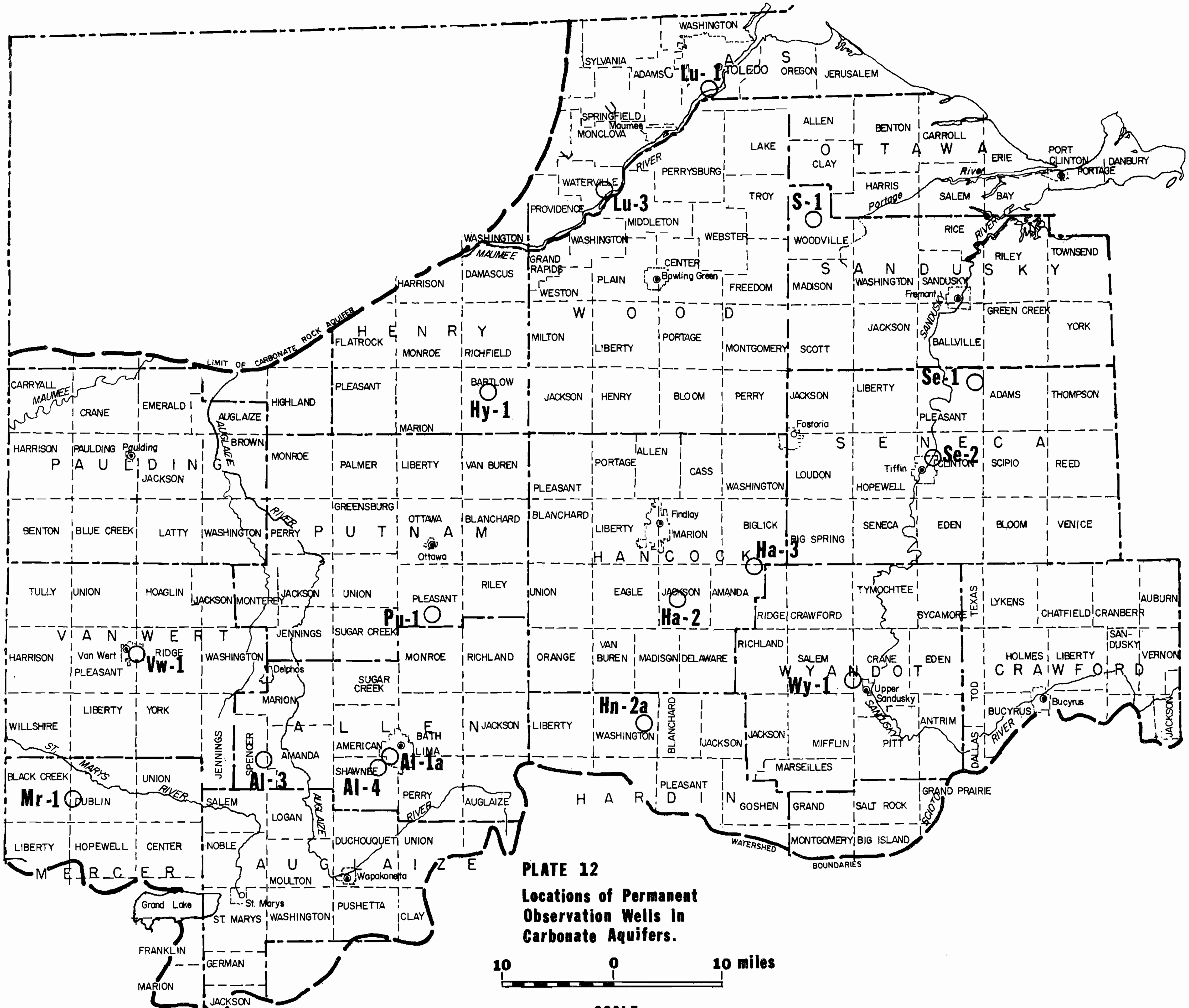


PLATE 12

Locations of Permanent Observation Wells in Carbonate Aquifers.

The effects of pumping on water levels vary with the amount pumped, the efficiency of the well, the hydraulic properties of the aquifer, the pumping time, and the spacing of wells. Many times the water-level fluctuations under pumping conditions are very similar to those under natural conditions with only slight modifications. Such is the case at Woodville, Ohio, where pumping from the aquifer has not varied greatly from year to year. The hydrograph of observation well S-1 (figure 12b) illustrates that water levels fluctuate within a range which is 5 to 10 feet lower than non-pumping levels. Thus, even though the aquifer has been pumped continuously throughout the period of record, the annual fluctuations are very similar to those under non-pumping conditions as shown in the hydrograph for well Hn-2a (figure 12a).

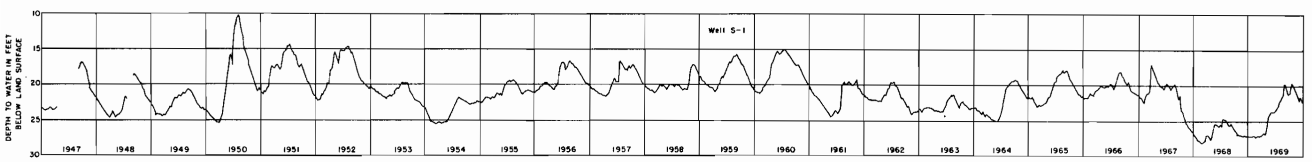


Figure 12b Water levels in observation well S-1, Sandusky County at Woodville

The hydrograph for Ha-3 (figure 12c) represents water levels in the Findlay well field where a surface water supply is augmented by ground water. The aquifer has been pumped at rates of 1.5 to 2.5 mgd for periods of from 3 to 12 months. The initial drawdown was about 12 feet. Despite continuous pumping for periods of several months the water level was not significantly lowered, indicating that pumping was balanced by recharge. It is interesting to note that during periods of non-pumping the water level rose to original levels year after year. These facts indicate that the aquifer is capable of yielding large quantities of water with no permanent depletion of storage.

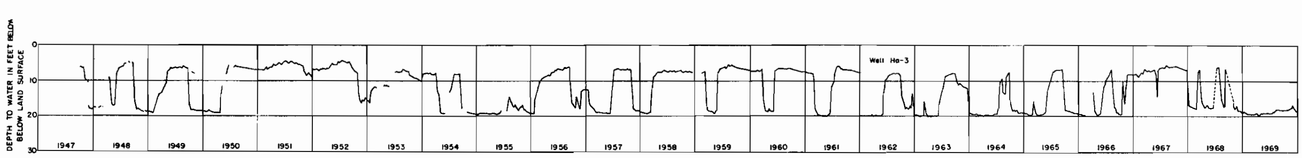


Figure 12c Water levels in observation well Ha-3, Hancock County at Vanlue

The hydrograph for well Al-1a at Lima (figure 12d) represents the effects of heavy industrial pumpage in excess of 5 mgd throughout the period of record. The pumping of this aquifer is from a large number of wells creating an extensive area of influence. All evidence of fluctuation from annual recharge and depletion is obscured by the widespread pumping. The only time the water levels in this area rise significantly are during extended periods of nonproduction, primarily "strike" periods. Even though rates of withdrawal have been periodically increased the water level has only declined about 10 feet in 20 years.

or water-based products. Practically any dissolved constituent may prove objectionable to a particular user if present in high enough concentrations. A few substances may even reach levels that render the supply unfit for domestic consumption because of harmful physiological effects. When water supplies contain impurities in concentrations that exceed recommended limits, reduction or removal of the objectionable matter must be accomplished or another supply of suitable quality must be developed.

Chemical analyses are the basic tools in the study and interpretation of water quality data. Various dissolved substances in a sample are identified and the concentrations of each are determined. Constituents are usually reported in terms of individual ions and are expressed in parts per million (ppm) by weight or milligrams per liter (mg/l) on a unit volume basis. Because of the wide use of volumetic glassware, milligrams per liter have now become the standard in most water quality laboratories. In the range of fresh to slightly saline waters, the two units are essentially equal.

Although bicarbonate and calcium are often the predominant ionic constituents in ground water, sulfates, chlorides, sodium and magnesium may also occur in local waters as major dissolved substances due to the relatively high solubility of many of their compounds. Silica, iron, manganese, potassium, fluoride and nitrate are generally regarded as trace elements in water and are derived from minor rock impurities and various other sources. The more common constituents in ground water and the normal concentrations in the study area are listed in table 5 along with their significance and the conventional means of treatment.

Detailed chemical analyses of water samples were obtained from all but one of the 76 test wells drilled in the study area. Most of the samples were collected after a continuous pumping cycle of 22 to 24 hours in an effort to determine water quality under similar pumping conditions. Nine of the test-well analyses were secured after the pumps had been removed or where no pumping test was performed using a down-the-hole sampling device. Analyses were performed by the Water Resources Division, U. S. Geological Survey, and are listed in table 8A. The depth of well, date analyzed, and water-bearing formations penetrated have been included in the appropriate columns.

Sixty-one additional analyses used in this study were obtained from the files of the Division of Water and the Ohio Department of Health. These are listed in table 8B as supplemental analyses and are mostly for samples from existing municipal wells collected and analyzed by Health Department personnel. The locations of all sampling sites are shown on plate 13.

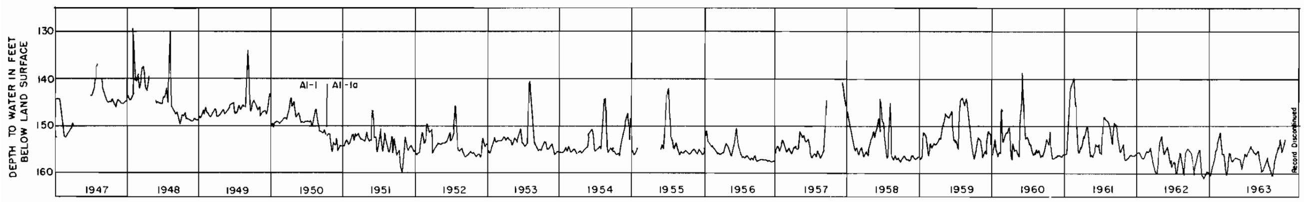


Figure 12d Water levels in observation well Al-1a, Allen County at Lima

The hydrograph for well Lu-1 (figure 12e) represents the dolomite aquifer in the Toledo area. The pumping in this area is almost entirely for industrial purposes. The piezometric map (figure 8) indicates a sizeable area of influence. During the period from 1948 to 1958, water levels were affected by pumping at an industry about 4000 feet from the observation well. This pumping resulted in increased seasonal drawdowns and a noticeable declining trend. In these years pumping probably exceeded recharge, which was potentially reduced during the 1952-54 drought. Following cessation of pumping the water level in this well returned to the level which had been observed prior to 1948. The trend recorded for the past 12 years demonstrates a balance between current withdrawals and recharge within this pumping center.

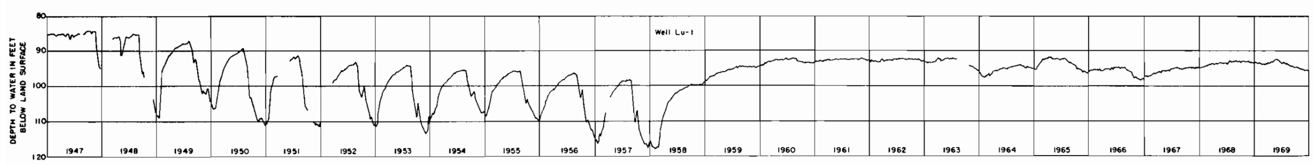


Figure 12e Water levels in observation well Lu-1, Lucas County at Toledo

Water-level records are a valuable part of a ground-water development plan. Much information can be obtained from studies of individual well records. The records shown here illustrate that water levels have been sustained despite two major drought periods. In addition, it has been demonstrated that large quantities are being withdrawn without permanently depleting ground-water storage. With proper development, pumping can be balanced by recharge. An adequate observation well program is essential as ground-water development continues. This is especially important in major pumping centers where water level records provide data useful in studying recharge rates and indications of overpumping, should it occur.

Effects of Acid Stimulation on Yields

Acid stimulation has been used with varying results in carbonate rock wells in many parts of the country. This is generally considered as a method of rehabilitating older wells which have decreased in yield due to calcium carbonate deposits. In such instances, the original yields are often restored by acidizing.

Acid stimulation was performed on eight of the northwest Ohio test wells to determine if their productivity could be increased. Locations of the acidized wells are shown on plate 2. It was assumed that fine drill cuttings could be removed from partially clogged openings in the dolomite and that minute openings could be enlarged.

Inhibited 31 percent hydrochloric acid was introduced into the wells in amounts ranging from 165 to 440 gallons per well. Charges of acid were generally left in the wells for four-hour periods, after which the waste acid was neutralized with soda ash prior to disposal. The acid was removed before it was entirely spent to avoid clogging of the well due to precipitation. On completion of the acidizing, pumping tests were conducted on each well using procedures identical to the initial tests. Comparative quantitative data, before and after stimulation is shown in table 3.

Table 3
Effects of Acid Stimulation

Well Number	Quantity of acid used (gal)	Reaction time (hours)	Specific Capacity, 8 hours (gpm/ft)		Percent improvement in specific capacity
			Before acid treatment	After acid treatment	
M-14	165	3	3.00	3.78	26
M-23	220	6	1.20	1.31	9
P-14	165	4	.86	.89	4
M-2	220	4	1.87	2.64	41
M-36	330	10	15.75	16.00	2
M-8	440	10	1.20	1.22	2
M-21	165	5	2.25	3.52	56
M-22	330	5	No	increase	

True dolomite displays little or no reaction with cold hydrochloric acid. According to Farnsworth (unpublished), few dolomite formations throughout the world are much purer than the Lockport, Greenfield and Tymochtee of northwestern Ohio. The results obtained from acidizing appear to verify this, since only three of the test wells were significantly improved.

Although the degree of success cannot be predicted, acid treatment increases the efficiency of some wells. It should be kept in mind that increased permeability in the vicinity of the well bore does not change the overall capacity of the formation. If the potential of an area is limited because of available recharge, well efficiency may be of little importance. However, where critical pumping levels are shallow, or where actual pumping levels are approaching critical stages, an improvement of a few percent may be significant. Each situation must be evaluated separately to determine the practicability of acid treatment in well field development or rehabilitation.

Ground Water Potential

The carbonate aquifer is regionally extensive and areas of influence of wells and well fields can extend for considerable distances. However, in much of the area critical pumping levels are fairly shallow and the aquifer is not so extensive that long-term yields can be projected without considering the effects of recharge. The quantities being withdrawn in some of the larger pumping centers shown in plate 11 would not be possible without the benefit of recharge A good definition of potential yield is given in Zeizel, et. al., (1962) as "the maximum amount of ground water that can be developed from a reasonable number of wells and well fields without creating critical pumping levels or exceeding recharge."

In some of the lower yielding areas the potential may be limited by very shallow critical water levels. The greater and more significant portion of the area is limited by the recharge potential, unfortunately, little is known about the rates of recharge. The only way to accurately estimate the potential yield of existing pumping centers developed in the carbonate aquifer is to study past records of pumpage and water levels, and collect field data for the construction of piezometric maps. The necessary historical data for many of the areas is inaccurate or nonexistent.

Preliminary work on recharge rates was done by Rowland and Kunkle (1970) who analyzed 18 pumping centers in the Maumee River Basin with data presently available. They found that areas of influence ranged from 4 to 87.6 square miles and determined values for recharge rates ranging from 6,800 to 75,300 gpd/sq. mi. Values given will be very useful until more detailed studies can be made. Until that is done, estimates of recharge in specific areas must be based on these figures or on recharge rates which have been determined in areas with similar hydrologic characteristics.

Estimates of the potential in areas outside of existing pumping centers must be based on projections from developed areas having similar characteristics. As already pointed out, it is impossible to accurately predict the yield of wells in undeveloped areas. Estimation of well field potential is obviously subject to a great deal of judgement and any of the necessary assumptions may be invalid at a specific location. However, it is possible to make some generalizations as to well field capacity and the relative merit of the areas already delineated.

Table 4 lists estimated ranges of yields to well fields for areas which correspond to those shown in plate 10. It is imperative that these values be kept in their proper perspective. They should in no way be misconstrued as the potential of existing or assumed pumping centers. These ranges are judgements as to the capacity which could be obtained from reasonably practical schemes of well field development. They are included here only to give the reader or planner a guide as to the relative potential for development in the areas shown.

Table 4
Estimated Yields to Well Fields

Area 1	1.0-3.0 mgd
Area 2	.5-1.5 mgd
Area 3	.1- .5 mgd
Area 4	.1-1.0 mgd
Area 5	.5-1.5 mgd
Area 6	1.0-4.0 mgd

An inspection of the present Ground-Water Usage map (plate 11) illustrates that development in some areas exceeds the estimated yields listed here. As indicated, the assumed schemes of development on which the table is based do not reflect the extent and complexity of some existing pumping centers.

The recharge potential in some areas may exceed that expected from leakage through glacial drift. Recharge from vertical leakage through the glacial drift increases in proportion to increased pumpage as vertical head differences become greater and areas of influence expand. More efficient recharge mechanisms are undoubtedly afforded by proximity to thick, highly permeable sand and gravel deposits associated with buried valleys in areas such as Lima, Wapakoneta, St. Marys, and portions of Area 5. For example, the effects of recharge were evident within the first two hours of a pumping test recently conducted on a new rock well at St. Marys. The city pumped nearly one mgd from a well field developed in unconsolidated material until the summer of 1970, at which time pumpage was shifted to rock wells. Municipal pumpage is now included in the nearly 3.5 mgd locally being withdrawn from the carbonate aquifer with relatively minor drawdowns. The potential in this area is much greater than current development. This area is unique in that Grand Lake is likely an ultimate source of recharge.

Other regions with very favorable recharge conditions are found in Areas 7 and 8. The overlying drift in Area 8 is primarily water-bearing sand. Although quantitative data is lacking, relatively high rates of vertical leakage can be anticipated. Area 7 encompasses the cavernous structure in the vicinity of Carey. This provides a direct intake area and highly permeable zones resulting from differential weathering may extend through the aquifer for some distance. This type of recharge potential also exists in Bellevue-Castalia area where, unfortunately, the aquifer is contaminated.

Area 3 apparently has the least potential for development of sizeable ground-water supplies. The aquifer is relatively thin, critical pumping levels are shallow, and there are no outstanding recharge characteristics. This seems contradictory in view of the use of nearly 4 mgd at Findlay. However, the municipal ground-water use of 1.5 mgd is supplied by a well field located in the Carey vicinity which has been described. The industrial ground-water use of slightly more than 2.4 mgd is supplied by two well fields located west of the Bowling Green fault in Area 2. Fracture zones associated with the fault may be responsible for excellent local conditions.

Ground-water development has generally corresponded to the potential of the various areas, although it has largely been "hit or miss" over the years. One major exception is in Area 1 where little ground-water development has occurred. This is probably due to water quality or a lack of demand. Pumping centers have expanded gradually in response to increasing demand. Each increase in pumpage was accompanied by the expanding and deepening of the area of influence and subsequent stabilization as recharge balanced discharge.

One factor which is often overlooked in the development of areas where ground-water withdrawals have been minimal is the effect on domestic wells. Usually these wells tap only the upper portion of the aquifer and in many areas shallow well pumps are adequate. In some areas, withdrawal of even moderate supplies may spread areas of influence for several miles. This may necessitate deepening of wells and replacement of pumps. While this is an unfortunate by-product of developing the resource to its potential, the effects should be considered. For example, there are areas where the quality of the upper water is good but the necessity of deepening wells would make it extremely difficult to attain an acceptable supply from an individual water system.

Another consideration frequently neglected in the development of ground-water supplies in carbonate aquifers is adequate testing to evaluate the aquifer and production wells. Many times subsequent problems can be avoided if critical pumping levels, interference and individual well capacities are determined. The addition of a new well into a system may reduce the available drawdown and thus the yields of existing wells. Without this type of information, well field management is difficult and will probably be inefficient.

Although much useful information is contained in this report for planning ground-water development and estimating yields, exact potential must be determined at the time of development. When requirements are known for specific locations, it is possible to make an accurate judgment of the availability of ground water. The potential of the carbonate aquifer in northwestern Ohio far exceeds present ground-water development. The refinement of estimates of that potential is by necessity, a continuing process.

VI. CHEMICAL QUALITY OF GROUND WATER

Dissolved substances in varying concentrations are carried in all natural waters above, on or below the earth's surface and are derived from the solid, liquid or gaseous materials in contact with water. Climate, geology, geography and the influence of plants and animals all have an important effect upon the chemical characteristics of water. Certain mineral constituents of rock and other foreign matter may pass into solution due to waters remarkable solvent power.

Although a number of mineral substances will readily dissolve in pure water, others require the presence of carbon dioxide. When water falls as precipitation, carbon dioxide is absorbed from the atmosphere while additional gas is obtained from the soil zone as a result of organic decomposition. Water and CO_2 combine to form a weak solution of carbonic acid. Percolating waters saturated with the gas react slowly with carbonate minerals which are converted into more soluble bicarbonates and thus carried into solution. Because of the great abundance of calcareous matter in the earth's crust, bicarbonate along with calcium are normally the primary dissolved constituents in waters of humid regions.

Ground-water quality is largely controlled by the soluble mineral constituents of the aquifer or water-bearing unit. Materials lying above, below, or adjacent to the aquifer may likewise contribute dissolved substances including artificial influences resulting from man's activities. While the aquifer composition and other nearby mineral sources govern the kinds of dissolved matter in water, the amount, or concentration, is controlled, in part, by the physical texture of the strata and is a function of time.

Under normal conditions, ground waters are usually more highly mineralized than surface waters of the same region due to their relatively slow movement and more intimate contact with soluble mineral sources. The concentrations of dissolved constituents in ground water generally increase with greater depth and greater distance from recharge areas. Another basic difference between waters of surface and subsurface origin is the presence of suspended matter and numerous micro-organisms in surface water supplies. Most ground waters are relatively free of those substances due to the filtering action through granular rocks and soils. Ground waters have a relatively cool and constant temperature as opposed to wide seasonal variations in surface water. The temperature of Ohio ground waters usually falls between 51 and 55 degrees F. which approximates the mean annual air temperature.

Dissolved substances in water account for certain properties which have a direct bearing upon the usefulness and suitability of the supply. Some impart undesirable tastes and odors while others may cause staining, corrosion, scale formation and precipitation in water systems, water-using appliances,

TABLE 5

CHEMICAL CONSTITUENTS AND PROPERTIES OF GROUND WATER

Constituent or Property	Most Common Range in Study Area	Source or Cause	Significance	Methods of Treatment
Silica (SiO_2)	10 - 20 mg/l	From clay, sand and igneous fragments of glacial drift. Minor impurity in carbonate rocks.	In the normal range, not objectionable for domestic uses. Forms hard scale on turbine blades or boilers.	Basic anion exchange. Demineralization.
Iron (Fe)	.05 - 3.0, or more, mg/l	Constituent of clay. Dissolved from iron piping. Minor impurity in carbonate rocks.	Above 0.3 mg/l, iron causes metallic tastes, staining of fixtures, utensils, and laundry. Higher concentrations form reddish-brown sediment and water line deposits.	Aeration, chlorination, and filtration. Oxidizing filters. Zeolite or lime softening. Iron retention with surface active agents.
Manganese (Mn)	0 - 0.2 mg/l	Mineral sources same as iron, but less common.	May cause dark brown or black staining as low as 0.1 mg/l. Usually not significant in range of study area.	Same as iron.
Calcium (Ca)	75 - 200, or more, mg/l	Major constituent of limestone ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), gypsum ($CaSO_4$) and glacial drift.	Hardness forming element (see below).	Zeolite or lime-soda ash softening.
Magnesium (Mg)	30 - 100, or more, mg/l	Dissolved from dolomite and a constituent of brine.	Hardness forming element (see below).	Zeolite or lime-soda ash softening.
Sodium (Na)	15 - 100, or more, mg/l	Major component of brine. Minor impurity of clay and shale.	Causes foaming in boilers above 50 mg/l. Higher concentrations may impart a soda taste.	Demineralization.
Potassium (K)	2 - 5 mg/l	Same as sodium.	Little or no significance in range of study area.	Same as above.
Bicarbonate (HCO_3)	150 - 400, or more, mg/l	Major constituent of carbonate rocks and glacial drift.	Scale-forming solid with calcium. When heated, produces CO_2, a source of corrosion.	Lime-soda ash softening. Demineralization.
Sulfate (SO_4)	100 - 1000, or more, mg/l	Primarily dissolved from gypsum. Minor sources are brines and the oxidation of metallic sulfides.	Combined with calcium, forms hard scale in boilers and water heaters. Causes laxative effects and bitter taste above 500 to 600 mg/l, depending upon individuals' tolerance and other dissolved constituents in the supply.	Demineralization.

TABLE 5 (Continued)

CHEMICAL CONSTITUENTS AND PROPERTIES OF GROUND WATER

Constituent or Property	Most Common Range in Study Area	Source or Cause	Significance	Methods of Treatment
Chloride (Cl)	5 - 50, or more, mg/l	Major component of brine, sewage and industrial wastes.	Causes salty taste above 200 to 400 mg/l, depending upon individuals' tolerance. High concentrations are corrosive to most metals.	Demineralization.
Fluoride (F)	1.0 - 2.5, or more, mg/l	Derived from the mineral fluorite (CaF_2), a minor impurity of most carbonate rocks.	From 1.0 to 1.5 mg/l, fluoride aides in the prevention of tooth decay. Concentrations above 2.5 mg/l may cause mottling of tooth enamel.	Various absorption processes.
Nitrate (NO_3)	0 - 1.0, or more, mg/l	From decaying organic matter and chemical fertilizers.	High concentrations are usually confined to shallow wells receiving direct surface drainage. Concentrations above 45 mg/l may cause infant cyanosis.	Demineralization.
Hydrogen Sulfide (H_2S)	0 - 10, or more, mg/l	From metallic sulfides and the chemical reduction of sulfates.	Imparts objectionable rotten egg odor above 0.5 mg/l. Highly corrosive to pump parts and metal fixtures.	Aeration, chlorination. Oxidizing filters.
pH	6.8 - 8.1	Acids and acid-generating salts lower pH values.	pH values below 7.0 are acidic and corrosive to pump parts or metal fixtures. Highly alkaline water may also be corrosive.	Alkaline filters and solution feeds for correcting acid problems.
Total Dissolved Solids	400 - 2000, or more, mg/l	A measure of the total dissolved minerals in the water.	Concentrations above 1000 mg/l may cause objectionable tastes, laxative effects, corrosiveness and foaming.	Lime-soda ash softening. Demineralization.
Total Hardness	300 - 1200, or more, mg/l	Combined calcium and magnesium expressed as mg/l $CaCO_3$.	Hardness causes increased soap consumption and scale formation. Softening is advisable above 200 to 300 mg/l.	Lime-soda ash or zeolite softening.
Non-carbonate Hardness	100 - 1000, or more, mg/l	Combined calcium and magnesium in excess of bicarbonate content.	Same as above.	Same as above.

Ground waters from the carbonate rock aquifers exhibit rather wide ranges in most of the individual chemical constituents. Differences in quality occur not only on an areal basis within a particular formation but also with depth. Analyses grouped according to major producing formations display numerous overlaps in individual constituent ranges with no clear distinction between different stratigraphic units. True samples from a specific unit are difficult to obtain because most of the test wells penetrate two or more formations with several producing zones. The overall quality from a pumping well is sometimes drastically altered by discreet zones of highly mineralized water from one of the less productive formations. Essentially, the final analysis represents a composite of all water-yielding strata penetrated and not necessarily that of the major source. Consequently, for the purpose of this discussion, the carbonate rocks in the study area have been considered as one major aquifer system with highly variable water-quality characteristics. Emphasis has been placed upon areas with specific quality problems.

Depth Oriented Sampling

During the actual drilling of test wells, field analyses were collected at approximately 20-foot intervals for the purpose of determining quality changes with depth. In some of the deeper wells, as many as 25 separate samples were tested as the drilling progressed. As in the final laboratory analyses, these tests (except for the first water) represent a mixture from all producing zones that were penetrated. In some wells, the results revealed numerous and sometimes substantial changes in quality while in others, the mineral concentration at all depths were virtually the same.

Using stratigraphic data and field analyses as guides, seven of the test wells were double-cased or plugged back from the original depth in an effort to eliminate zones of highly mineralized or sulfurous waters. Wells constructed in this manner are indicated in the remarks column of the table of analyses. The double-casing technique involved the installation of a liner pipe to a pre-determined depth and back-washing the annular space with drill cuttings. This procedure was tried on four wells in order to seal off upper zones of poor quality water. Two of the wells (P-5 and P-10) showed a slight reduction in total hardness and various other constituents. In well S-18, hydrogen sulfide (H_2S) showed a slight increase after double-casing. The installation of 410 feet of liner pipe resulted in no significant quality change in well M-38 at Weston. Of the three wells where bottom zones were sealed off with a cement plug, two showed a marked reduction in total dissolved solids but in the third well, water quality was not improved. In test well M-36, near Deshler, total hardness was reduced from 1453 mg/l to 628 mg/l by cementing the lower 45 feet of hole.

Specific producing zones in six of the wells were isolated by means of temporarily installed inflatable packers. Samples for analyses were obtained through a submersible pump set above or below the packers at various intervals down the hole. Although minor quality changes were apparent in all of the samples tested by this means, substantial differences were noted in wells M-1, P-10, and S-1. Water below a depth of 180 feet in M-1 was slightly salty which altered the overall quality in the final laboratory analysis. In well P-10, the total hardness of water from the Lockport (below 300 feet) was nearly 400 mg/l lower than that from the overlying Greenfield formation, and free of hydrogen sulfide. Six separate analyses were secured from well S-1 at selected intervals from the top to the bottom of the well. Hardness increase with depth from 489 mg/l at 110 feet to 834 mg/l at 250 feet. Conversely, hydrogen sulfide showed a substantial reduction of more than 50 percent in the samples. In this particular well, each producing zone was pumped for a period of 15 minutes and samples were field tested at 5, 10, and 15 minute intervals. These analyses revealed a drifting of mineral concentrations toward the next higher producing zone which suggests vertical leakage between various water-bearing strata. Under these conditions, it is unlikely that specific zones could be sealed off by the conventional method of double-casing.

Constituent Ranges in Study Area

Although the limestones and dolomites of northwest Ohio are regarded as rocks of high purity, they invariably contain small but highly significant percentages of other minerals which affect water quality. Added factors which locally influence certain chemical characteristics of rock waters are the thickness, texture, and composition of the overlying glacial material as well as by-products associated with man.

Quality of water from this aquifer system is strongly influenced by the basic dolomitic composition of the formations, yet less than half of the samples analyzed are of the calcium magnesium bicarbonate type. In the majority of cases, calcium and sulfate are the predominant dissolved constituents derived from the mineral gypsum. Gypsum is not restricted to any one stratigraphic unit but occurs as a minor impurity throughout the Silurian and Devonian carbonate rocks of northwest Ohio. The solubility of this mineral is relatively high when compared to dolomite or calcite and solution is not dependent upon the presence of CO_2. Throughout large areas of the carbonate rock aquifer, calcium and sulfate constitute from 50 to 90 percent of the total mineral content in ground water. Such waters typically carry unusually high concentrations of dissolved solids, total hardness, and non-carbonate hardness.

The total dissolved solids in waters of the study area cover the wide range of 363 to 3440 mg/l. This extreme variation is the result of waters which have or have not been exposed to deposits of gypsum. Ground waters in contact with this soluble impurity often carry more than 1500 mg/l dissolved solids. Sulfate concentrations and total hardness are correspondingly high

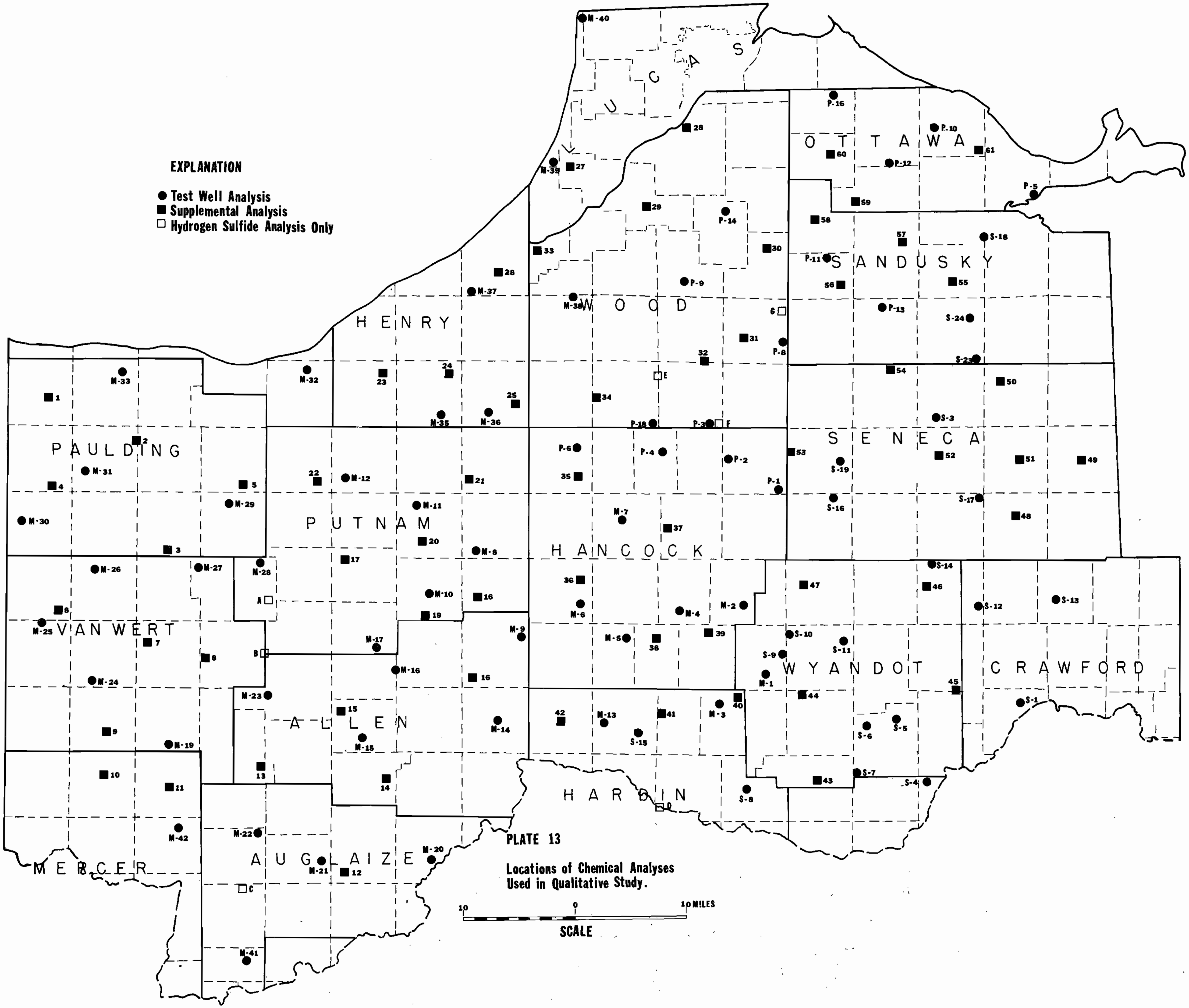


PLATE 13

Locations of Chemical Analyses Used in Qualitative Study.

and usually exceed 800 and 1000 mg/l, respectively. Major areas where waters display this high degree of mineralization are the eastern parts of Ottawa, Sandusky and Seneca counties, western Wood, southern Henry, central Wyandot, south-central Van Wert and northern Mercer counties. Such waters are bitter tasting, costly to treat and are generally classified as brackish.

Analyses in the lower range of dissolved solids display the typical characteristics of water from a true dolomite. Calcium and magnesium concentrations are nearly equivalent and bicarbonate is the principal anion. In western Sandusky, western Seneca, eastern Wood, western Paulding, southern Allen, eastern Auglaize and most of Lucas counties, total dissolved solids are commonly less than 600 mg/l. The hardness range in these areas is usually between 350 to 500 mg/l while sulfate concentrations seldom exceed 200 mg/l. In most of the remaining areas, concentrations fall within an intermediate range due to the mixing of bicarbonate waters with the more highly mineralized sulfate waters. Concentrations of dissolved solids and sulfates for all samples are indicated on plate 14.

Bicarbonate concentrations are in the normal range for waters from marine carbonate rocks and generally fall between 150 and 400 mg/l. The few extreme figures beyond this range are attributed to various chemical reactions related to the CO_2 content of water, the presence of organic matter and other factors. The bicarbonate buffer system, with few exceptions, acts to maintain the pH between 7.0 and 8.0.

Most minerals and compounds containing sodium and chloride readily dissolve in the presence of water. Although these constituents predominate in the connate brines which underlie much of Ohio and also from a significant part of industrial and human wastes, concentrations in fresh-water zones are substantially lower than bicarbonates and sulfates. In humid regions, these highly soluble components are rapidly leached from the surrounding rocks and soils and carried away as part of the hydrologic cycle. More than 90 percent of the chloride concentrations reported in the study area were below 50 mg/l. Sodium values commonly ranged upward to 100 mg/l. The excess sodium is derived from certain clay minerals associated with glacial till and shale. When exposed to percolating ground water containing calcium or magnesium, the sodium ions attached to clay are brought into solution through the process of natural ion exchange. The high extremes for both sodium and chloride were reported in well S-11 where concentrations exceeded 300 and 700 mg/l, respectively. These abnormal values may be attributed to the migration of deep-seated saline water into the shallower fresh-water zones.

Fluoride was reported in all of the samples and commonly in the range of 1.0 to 2.0 mg/l. The source of this constituent is the mineral fluorite (CaF_2) which occurs as a minor impurity in most carbonate rocks of marine origin. Four of the samples ranged from 2.6 to 4.2 mg/l which exceed the permissible limit in waters for human consumption. According to the U. S. Public Health Service Drinking Water Standards (1962), fluoride in these higher concentrations may cause dental fluorosis in children and constitute grounds for rejection of the supply.

Dissolved iron in some ground waters is an especially troublesome impurity, due to its staining effects, and necessitates the use of specialized iron-removal equipment in some cases. The concentrations from carbonate rocks, however, are substantially lower than from most other aquifers in Ohio. Iron is mostly derived from clays, other impurities in glacial drift, and various iron minerals in the carbonate rocks. Relatively high concentrations were noted in some of the shallower rock wells which receive direct recharge from the glacial material. Dissolved iron in the study area ranged from near zero to over 3.0 mg/l with a median value of 0.8 mg/l. Less than 20 percent of the samples exceeded 1.0 mg/l of iron. In a few wells, where waters were charged with hydrogen sulfide, iron values were considerably higher than the normal range of concentration. These higher figures are the result of a reaction between H_2S and metallic pump parts or well casings.

Over 70 percent of the samples contained varying concentrations of hydrogen sulfide. This soluble gas, with an obnoxious odor resembling rotten eggs, is primarily derived from numerous sulfur-bearing impurities within the aquifer. In an environment devoid of oxygen, H_2S may evolve through various reactions where metallic sulfides, organic matter and dissolved sulfate ions are chemically reduced. Sulfate reduction occurs in the presence of organic matter and is the result of a bio-chemical process involving anaerobic bacteria. Concentrations of hydrogen sulfide in the study area generally increase with depth and distance from recharge areas. The "black sulfur" waters noted in some areas are the result of a reaction between H_2S and iron-bearing water or metallic pump parts. The coloring is due to finely divided iron sulfide carried in suspension.

In the outcrop areas of the Lockport dolomite H_2S concentrations ranged from near zero to around 2.0 mg/l with a significant number of samples free of the gas. Concentrations steadily increase in the areas west of the Bowling Green fault and north of a line through Van Wert and Lima. Within the outcrop areas of the Raisin River and middle Devonian rocks, objectionable levels of H_2S were noted from all formations and ranged upward to 10, or more, mg/l. Concentrations exceeding 3.0 mg/l were also reported in central Ottawa County. Hydrogen sulfide values for all wells are indicated on plate 15.

Nearly all of the samples in the study area contained moderate to very low concentrations of silica, manganese and potassium. These substances are locally derived from clay and igneous fragments in the overburden or various trace minerals in the bedrock. In the normal range of concentrations they are of little or no significance to most users. Nitrate is likewise a minor constituent

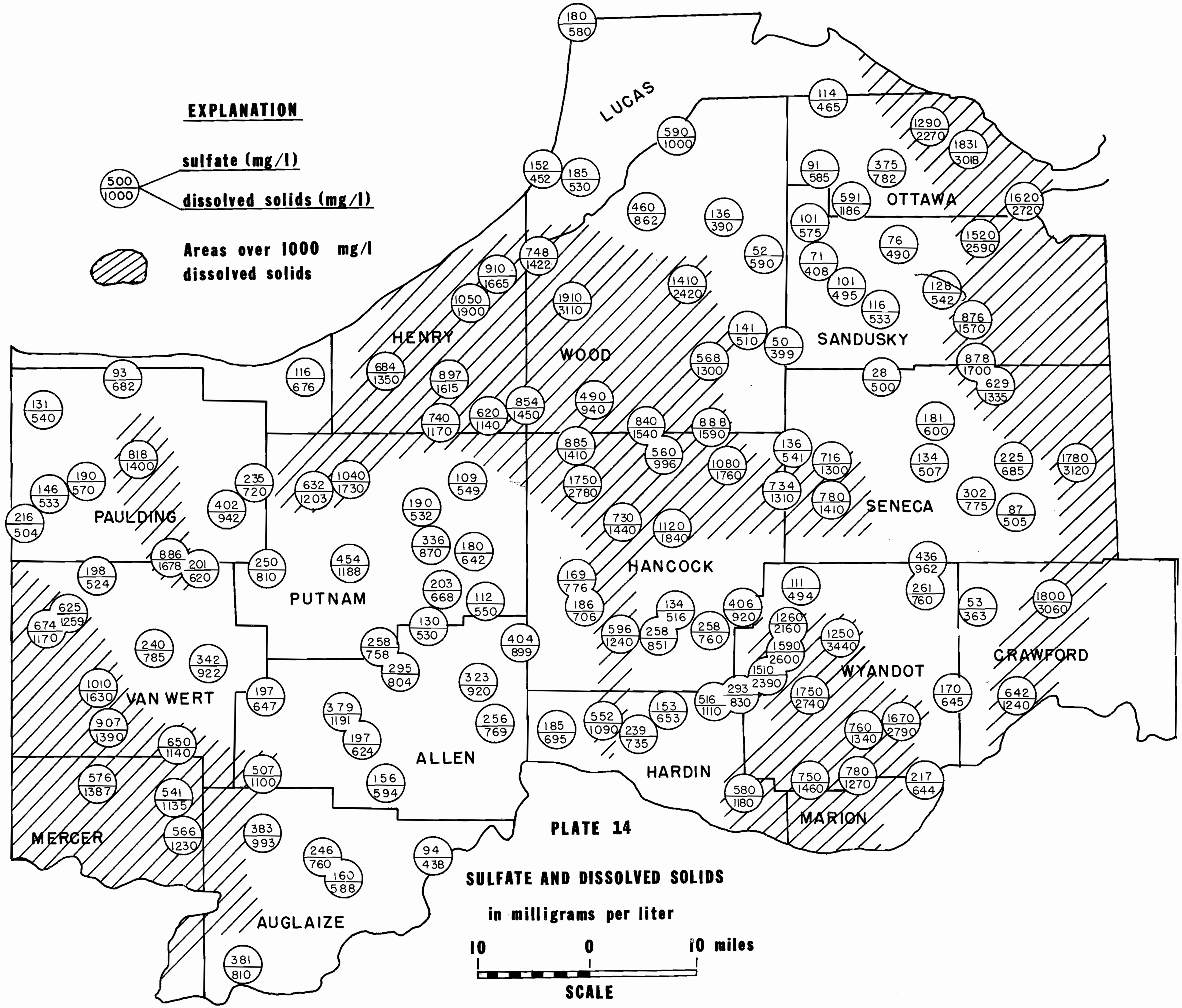


PLATE 14

SULFATE AND DISSOLVED SOLIDS

in milligrams per liter

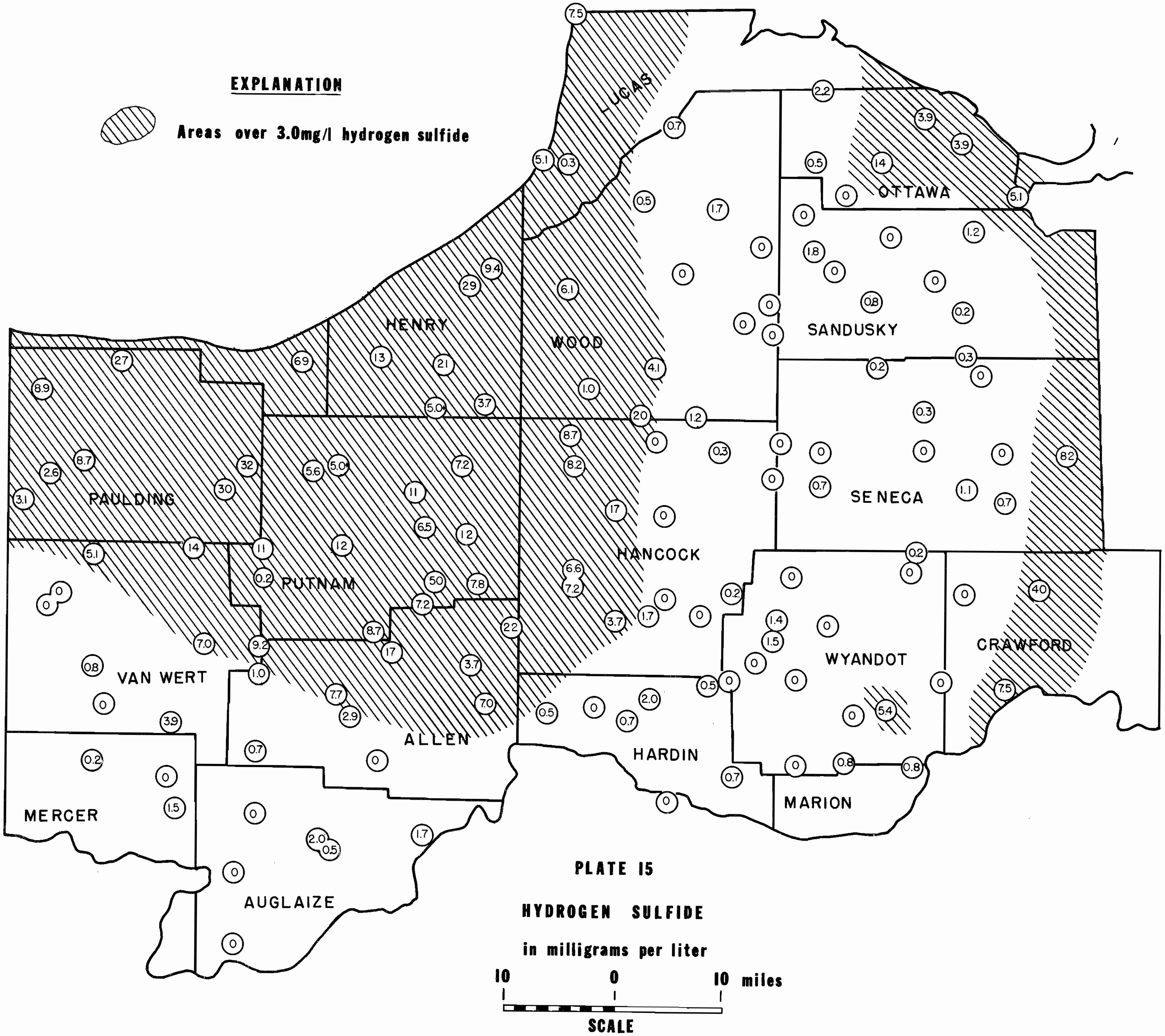


PLATE 15

HYDROGEN SULFIDE

in milligrams per liter

in ground water and is the final oxidation product of nitrogenous organic matter. Nearly 90 percent of the analyses contained less than 1.0 mg/l. Higher concentrations are found in a few local areas but are usually confined to shallow producing zones. A maximum concentration of 21 mg/l was noted from a municipal well at Carey and is attributed to direct recharge of surface waters into the relatively shallow cavernous bedrock. A study of this area conducted by Stein (1966), revealed numerous private wells with excessive nitrates and concluded that the principal source were domestic sewage, animal wastes and chemical fertilizers.

Quality Problems

Throughout much of northwest Ohio, the most objectionable water quality characteristics from the carbonate aquifers are the relatively high hardness and sulfate derived from the solution of gypsum, and the widespread occurrence of hydrogen sulfide. Iron concentrations are in the troublesome range in only a few local areas but will cause severe maintenance problems in municipal water systems unless proper treatment is applied. The high chlorides noted in some of the deeper wells may be attributed to past oil and gas drilling activity but can usually be prevented by limiting well depths or sealing off bottom zones contaminated with salt water. Elimination of high nitrate waters in some shallow cavernous areas can usually be accomplished by extending well casings below the contaminated zones and grouting the annular space.

Calcium Sulfate Waters:

Sulfate concentrations in the study area exceeded the Federal Drinking Water Standard of 250 mg/l in more than 60 percent of the samples analyzed. Nearly 40 percent of the analyses contained over twice the recommended concentration and ranged upward to more than 1800 mg/l. The limit for sulfate, as prescribed by the U. S. Public Health Service, has been adopted primarily for taste considerations and a slight cathartic effect experienced by some individuals. In spite of the detrimental qualities, most people apparently become accustomed to sulfate waters and develop a tolerance for somewhat higher concentrations. This is evidenced by the fact that numerous towns and cities in Ohio (28 in the study area) use waters which exceed the recommended limit where no better quality water can be delivered economically. Based primarily upon the taste factor, it would appear that sulfates are not particularly objectionable unless concentrations are above 500 to 600 mg/l.

Hardness exceeded 300 mg/l in all but three of the samples analyzed At that level and above, softening is highly desirable for domestic water use although not necessarily economical in the higher ranges. In the shaded areas of plate 14, where calcium sulfate waters prevail, hardness usually exceeds 750 mg/l. Municipal softening in these areas is a rather expensive undertaking especially for the smaller communities. Of the 16 municipalities which are currently using these highly mineralized waters, only four have installed softening plants. Due to the high percentage of non-carbonate hardness (contributed by calcium sulfate) all of the four utilize the zeolite process which is less costly than lime-soda ash treatment. In the remaining towns and in rural areas, private softeners are widely employed on an individual home basis. A pronounced disadvantage in the use of high sulfate waters is the fact that the sulfate content is not reduced by conventional softening methods and, in the higher ranges of 600 mg/l or more, an undesirable bitter taste is noticeable to most people. Nevertheless, these mineralized ground waters are still widely utilized in some areas for lack of an available raw water source of better quality.

In the unshaded areas of plate 14, sulfate concentrations are normally below 500 mg/l while hardness is in the range of 300 to 750 mg/l. Sixteen of the 43 municipalities in these areas operate softening plants with nine using zeolite softening and seven lime-soda ash treatment. Treatment costs for municipal softening are moderate to relatively high depending upon the degree of hardness but, for the most part, the cost of providing finished water to the consumer compares favorably to public supplies in other regions of Ohio.

Hydrogen Sulfide:

Within the shaded pattern of plate 15 which includes nearly half of the study area, ground waters usually carry more than 3.0 mg/l of hydrogen sulfide. Although this obnoxious gas is highly undesirable in water from an esthetic standpoint, the most serious objection to these waters is their corrosive tendency toward metals. At the levels of concentration that prevail in these areas, water systems and pump parts may be damaged beyond repair in a few years. Removal of H_2S is not only widely practiced but is often deemed highly essential as a preventive maintenance measure.

Effective sulfide removal is based on the premise that the gas is unstable under atmospheric conditions and will readily oxidize to free sulfur on exposure to air. Most towns and industries utilize simple aerators for reducing H_2S which consist of a series of alternating wood slats or coke-filled trays arranged in a baffle-type structure. Raw water is allowed to cascade or trickle downward through the unit by the force of gravity where much of the gas is dissipated. In the more sophisticated forced draft units, compressed air is sometimes forced upward through a column of raw water providing longer contact time and an even greater reduction in the gas.

Sixteen municipal supplies in the study area contain from 3 to 10 mg/l H_2S. Higher values are noted at Hamler, Holgate, Kalida, and Oakwood where concentrations are in the range of 12 to 32 mg/l. All of these towns utilize aeration systems of various designs which provide a sharp reduction in the gas content. Complete removal, however, is seldom accomplished by aeration alone. Any residual is usually oxidized by a follow-up chemical treatment. Automatic chlorination is widely used in municipal systems and, in Ohio, is a required treatment for disinfection purposes. Chlorine treatment is also employed on the majority of individual private supplies containing H_2S.

A properly operated aeration system, followed by continuous chlorination, has proven to be a simple and economical means for eliminating hydrogen sulfide This type of treatment offers the advantages of small investment in equipment, relatively low costs for chemicals and effective removal in the great majority of cases. In some instances, however, where concentrations are in the range of 10 mg/l or more, follow-up filtration is highly desirable for removing precipitated sulfur. In parts of a closed water system, where circulation is slow or restricted, free sulfur may revert back to the gaseous state and create serious corrosion problems or foul odors in the finished water. These problems are sometimes noted in softening beds, standpipes and deadend lines of municipal systems. If a backwash-type filter immediately follows the aeration process, nearly all traces of sulfur can be eliminated from the water supply.

Treatment of H_2S by the methods described is sometimes complicated by changes in concentration of the raw-water sources during the pumping cycle. Automatic chlorinators must be pre-set for a specific dosage of chlorine based upon the results of a raw-water analysis. Changes in the sulfide content cause considerable difficulty in maintaining the proper chlorine residual in the finished water of municipal systems. Under these circumstances, the design of an effective treatment plant requires a complete understanding of the wells' hydraulic properties as well as a thorough knowledge of the raw water chemistry. Each water source offers a different set of conditions which necessitate special design criteria on an individual basis.

Although effective sulfide removal will reduce corrosion damage in water systems and conditioning equipment, a major problem in the use of sulfurous waters is the lack of down-the-hole protection of metallic surfaces. High maintenance costs are incurred in municipal as well as private supplies due to the frequent replacement or repair of pump columns, turbine bowls and well casings. A solution to this corrosion problem lies in the development and use of corrosion-resistant materials in well and pump installations. In one instance, corrosion due to H_2S has been substantially reduced in a municipal supply through special well construction. Ottoville in Putnam County is situated in a known area of highly sulfurous ground waters. In 1965, the major production well for that village was double-cased to a depth of 160 feet in an effort to seal off shallow zones of hydrogen sulfide. A recent analysis of this raw water source revealed a sulfide concentration of only 0.2 mg/l.

VII. CONCLUSIONS

Well planned development of the carbonate rock aquifers, based upon reliable hydrogeologic data, should encourage the growth of northwestern Ohio. It is not the purpose of this report to suggest ground water as a panacea, but rather to provide guidance in planning so that ground-water resources may be considered where they can economically compete with inland surface water supplies. Complete utilization of all water sources is needed for the full regional development potential of northwestern Ohio. Communities of moderate size, light to medium industry, and private water users will continue to use ground-water sources throughout the area. Larger communities and most large industries must rely upon surface water supplies.

Major growth, in terms of new industries using 2 to 5 mgd, has been predicted, by the Ohio Water Commission (1967). Such supplies can be developed over broad areas from the carbonate rock aquifer (see table 4 and plate 10). Well fields yielding as much as one mgd can be reasonably anticipated in 65 percent of the study region. Since specific locations of industrial development cannot be predicted, judgements as to the feasibility of using ground water must be made as growth occurs.

When requirements are known for specific locations, accurate assessments can be made. Table 6 lists the communities within the study area and the projected demands for public water supply as given by the Ohio Water Commission (1967). Ground water is available in sufficient quantity to meet the projected demands of nearly 75 percent of these communities. Supplies are potentially available for 33 of the 58 municipalities currently relying on wells. An additional 10 of these communities listed as questionable, are borderline cases where additional data or testing would be required before ground water should be eliminated as an alternative.

Although hydrogen sulfide is widespread and ground water in almost one-half of the area contains more than 3.0 mg/l (plate 15), this is not a deterrent to ground-water use and development. In general, the areas with the greatest quantity potential produce water within lower hydrogen sulfide ranges. Concentrations of less than 10 mg/l can be removed by the relatively simple and inexpensive processes of aeration and chlorination. Higher concentrations may require filtration also.

The other major quality considerations are high hardness and sulfates. Due to the nature of the carbonate aquifer, softening is recommended throughout the study area. The sulfate limit of 250 mg/l, prescribed by the U. S. Public Health Service is unrealistic. As sulfates are not particularly objectionable in concentrations of less than 500 to 600 mg/l, this more reasonable limit should be considered in ground-water planning. Plate 14 indicates, by shading, areas in which treatment costs may restrict ground-water development. Nearly

TABLE 6

AVAILABILITY OF GROUND WATER TO MEET PROJECTED DEMANDS FOR PUBLIC WATER SUPPLY

Municipality	(a) Type supply(1)	(b) Treatment(2)	(c) 1965 Average demand, mgd	(d) 1969 Average demand, mgd	(e) Present capacity, mgd	(f) 2006 Accelerated projection, mgd	(g) 2006 Peak demand, mgd	(h) Net mgd required	(i) Available from wells	(j) Ground-water cost(7)	(k) Reservoir cost(8)	(l) Closest test well
MAUMEE RIVER BASIN												
Ada	W	HDFKRS(6)	0.241	0.260(6)	1.73	1.08	1.62	----	Yes	No cost		M-13
Antwerp	W	AD	0.400	0.605	0.65	0.95	1.43	0.78	No			M-31
Arlington	W	IADFK	0.070	0.070	0.22	0.29	0.44	0.22	Yes	$ 44,000	494,000	M-5
Beaverdam	W	HADFz	0.027	0.035	0.03	0.16	0.24	0.21	Yes	24,000	353,000	M-14
Bluffton	W	ADKS	0.340	0.350	1.01	1.19	1.79	0.78	No			M-9
Bowling Green	IS	HCDFKMRSTV	1.807	2.400	5.00	8.01	----	----	No			P-9
Columbus Grove	W	AD	0.350	0.250	1.15	1.14	1.71	0.56	Questionable	27,000	1,100,000	M-10
Continental	W	None	0.075	0.057	0.32	0.36	0.48	0.16	Yes	50,000	544,000	M-12
Convoy	W	None	0.100	0.125	0.48	0.33	0.49	0.01	Yes	17,000	555,000	M-25
Cridersville	W	IADF	0.100	0.130	0.29	0.47	0.71	0.42	Yes	(4)		M-21
Delphos	W	AD	0.780	1.000	0.94	3.48	4.50	3.56	No			M-23
Deshler	W	HIADFK	0.195	0.145	0.72	0.61	0.85	0.13	Yes	20,000	735,000	M-36
Dunkirk	W	ADK(6)	0.060	0.065(6)	0.32	0.14	0.21	----	Yes	No cost		S-15
Elida	W	AD	0.108	0.130	0.72	0.67	1.00	0.28	Yes	26,000	712,000	M-15
Findlay	IS	HCDFKMRSTV	5.300	6.650	3.50	16.08	18.87	----	No			M-7
	W		-----	-----	1.00	----	----	----				
Forest	W	HDFS(6)	0.096	0.110(6)	0.72	0.22	0.33	----	Yes	No cost		M-3
Grand Rapids	IS	PCDFMST	0.082	0.077	0.44	0.35	0.53	0.09	Yes	(5)		M-38
Hamler	W	HIADF	0.020	0.040	0.28	0.10	0.15	----	Yes	No cost		M-35
Holgate	W	HIADF	0.095	0.095	0.72(3)	0.43	0.65	(3)	Questionable	(4)		M-34
Kalida	W	IADF	0.080	0.060	0.14	0.29	0.44	0.30	Yes	49,000	531,000	M-28
Leipsic	W	HACFMS	0.120	0.280	0.74	0.52	0.78	0.04	Yes	13,000	(4)	M-11
Lima	IS	HCDFKMRST	11.281	13.000	9.80	33.31	----	----	No			M-15
McClure	W	IADF	0.020	0.025	0.11	0.10	0.14	0.03	Yes	19,000	264,000	M-37
Mendon	W	IADFK	0.045	0.050	0.61	0.22	0.33	----	Yes	No cost		M-42
Middlepoint	W	HIAFFz	0.055	0.025	0.06	0.20	0.35	0.29	Yes	19,000	388,000	M-23
Mt. Blanchard	W	DK	0.080	0.045	0.29	0.23	0.35	0.06	Yes	22,000	475,000	M-4
New Bremen	W	HDFzK	0.199	0.200	1.67(3)	0.76	1.14	(3)	Questionable	(4)		M-41
Oakwood	W	AD	0.075	0.085	0.22	0.17	0.26	0.04	Yes	21,000	401,000	M-29
Ohio City	W	K	0.100	0.100	0.40	0.34	0.51	0.11	Yes	48,000	650,000	M-24
Ottawa	W	AD	0.390	0.850	1.68(3)	1.44	2.16	0.48	No			M-8
Ottoville	W	ADK	0.144	0.090	0.34	0.41	0.62	0.28	Yes	30,000	512,000	M-28
Pandora	W	AD	0.080	0.175	0.50	0.27	0.41	----	Yes	No cost		M-10
Paulding	IS	HCDFKMRST	-----	0.300	1.03	0.84	1.26	----	No			M-31
	W		0.250	-----	0.30	----	----	----				
Payne	W	HADFFzK	0.200	0.120	0.58	0.53	0.72	0.14	Yes	19,000	664,000	M-30
Rawson	W	A	0.040	0.060	0.08	0.14	0.21	0.13	Yes	24,000	370,000	M-6
Rockford	W	D	0.090	0.140	0.87	0.43	0.65	----	Yes	No cost		M-42
Spencerville	W	AD	0.370	0.500	1.20	1.26	2.39	1.19	Questionable	57,000	1,132,000	M-22
St Marys	W	HCDFKMRS	1.034	0.900	1.30	3.24	4.86	3.56	Yes	398,000	1,759,000	M-42
Sylvania	W		0.672	0.740	1.47	2.77	4.15	----	No			M-40
Toledo	LE	HCDFKMRSTV	72.516	77.000	160.00	181.38	----	----	No			----
VanWert	IS	HCDFMRST	1.069	1.490	1.94	4.84	----	----	No			M-24
Wapakoneta	W	HIADFz	0.700	0.800	2.52	2.35	3.52	1.00	Questionable	69,000	1,576,000	M-21
Waterville	IS	PCDFMSTV	0.139	0.265	0.40	0.57	0.86	0.46	Yes	(5)		M-39
Weston	IS	HCDFMST	0.076	0.070	0.03	0.39	0.59	----	Yes	(5)		M-38
Whitehouse	W	None	0.058	0.070	0.96	0.30	0.45	----	Yes	No cost		M-39
Willshire	IS	HCDFMS	0.031	0.035	0.21	0.16	0.24	0.03	Yes	(4)		M-24

TABLE 6 (Continued)

AVAILABILITY OF GROUND WATER TO MEET PROJECTED DEMANDS FOR PUBLIC WATER SUPPLY

Municipality	(a) Type supply(1)	(b) Treatment(2)	(c) 1965 Average demand, mgd	(d) 1969 Average demand, mgd	(e) Present capacity, mgd	(f) 2006 Accelerated projection, mgd	(g) 2006 Peak demand, mgd	(h) Net mgd required	(i) Available from wells	(j) Ground-water cost(7)	(k) Reservoir cost(8)	(l) Closest test well
PORTAGE RIVER BASIN												
Bloomdale	W	AD	0.040	0.065	0.13	0.24	0.36	0.23	No			P-3
Bradner	W	D	0.060	0.065	0.43	0.36	0.54	0.11	Questionable	$ 25,000	$ 572,000	P-8
Cygnet	W	HADFzK	0.040	0.045	0.30	0.22	0.33	0.03	Questionable	30,000	487,000	P-18
Elmore	W	HADFzK	0.092	0.095	0.34	0.57	0.86	0.52	No			P-12
Fostoria	IS	HCDFKMRST	2.981	2.800	3.34	6.74	----	----	No			P-2
	W				0.40							
Genoa	W	HADFzK	0.189	0.190	0.47	1.06	1.59	1.12	No			P-12
Gibsonburg	W	AD	0.197	0.245	0.86	0.80	1.20	0.34	No			P-11
Lindsey	W	None	0.060	0.060	0.14	0.23	0.35	0.21	Questionable	55,000	385,000	P-13
McComb	IS	HCDFMST	0.085	0.092	0.06	0.33	0.49	0.43	Yes	(5)		P-6
N. Baltimore	W	HADFzK	0.230	0.285	0.30	1.13	1.69	1.39	No			P-18
Oregon	LE	HCDFKMRSTV	2.360	3.100	20.00	11.29	----	----	No			P-16
Pemberville	W	HDFzK	0.070	0.120	0.60	0.42	0.63	0.03	No			P-11
Put-in-Bay	LE	D	0.035	0.150	----	0.18	0.27	----	Yes	(4)		----
Wayne	W	HDFzK	0.048	0.050	0.26	0.32	0.48	0.22	Questionable	30,000	526,000	P-8
Woodville	W	HCDFKMRS	0.185	0.190	0.64	0.67	1.00	0.36	No			P-11
SANDUSKY RIVER BASIN												
Attica	IS	PCDFKMST	0.098	0.100	0.04	0.30	0.45	----	No			----
Bettsville	W	D	0.060	0.110	0.20	0.19	0.29	0.09	Yes	20,000	601,000	S-3
Bloomville	W	D	0.063	0.045	0.55	0.20	0.30	----	Yes	No cost		S-17
Bucyrus	IS	HCDFKMRST	1.580	1.700	1.35	4.85	----	----	No			----
Carey	W	None	0.291	0.340	2.88	0.69	1.04	----	Yes	No cost		----
Clyde	IS	HCDFKMST	0.785	0.910	0.63	2.46	3.69	----	Yes	(5)		S-24
Crestline	W	DK	1.261	1.200	3.65(3)	3.14	4.71	1.06	Questionable			----
Fremont	IS	HCDFKMRST	2.743	3.400	5.10	10.02	----	----	No			S-24
Green Springs	W	HDFzK	0.076	0.095	0.50	0.32	0.48	----	Yes	No cost		S-23
Kellys Island	LE	D	0.040	-----	----	0.12	0.18	----	Yes	(4)		----
Lakeside	LE	PCDFMS	0.258	0.325	0.39	0.85	1.27	----	Yes	(4)		----
Marblehead	LE	PCDFKMS	0.074	0.085	0.28	0.53	0.79	----	Yes	(4)		----
New Washington	IS	HCDFKMST	0.063	0.075	0.06	0.32	0.48	----	No			----
Nevada	W	IF	0.040	0.040	0.16	0.13	0.20	0.04	Yes	16,000	409,000	S-5
Port Clinton	LE	PCDFKMST	1.304	1.560	6.20	7.04	----	----	No			----
Republic	W	D	0.040	0.040	0.70	0.15	0.23	----	Yes	No cost		S-17
Sycamore	W	HCDFKMRS	0.100	0.120	0.43	0.21	0.32	----	Yes	No cost		S-14
Tiffin	IS	PCDFKMSTV	1.837	1.825	5.18	5.59	----	----	No			S-3
Upper Sandusky	IS	HCDFKMRSTV	0.820	0.900	0.22	1.51	2.26	----	No			S-6

Columns (a, c, e, f, j, k), Ohio Water Commission (1967).
Columns (g, h), same as above supplemented by raw data, Burgess and Nipple, Ltd.
Columns (b, d), Ohio Department of Health (1969).
Columns (i, l), Ohio Division of Water.

(1) LE - Lake Erie; W - Wells; IS - Inland Surface.
(2) P - purification; H - hardness reduction; I - iron and manganese removal; A - aeration; C - chemical dosage for coagulation or softening; D - disinfection; F - filtration; Fz - ion exchange; K - chemical stabilization; M - mixing device; R - recarbonation; S - sedimentation; T - chemical taste and odor control; V - fluoride adjustment.
(3) Evaluation of present capacity considered to be in error.
(4) Cost comparison not available in Ohio Water Commission (1967).
(5) Ground-water quality is undesirable.
(6) 1967 data.
(7) Cost of additional development required to meet projected demand.
(8) Cost of development of an individual community supply with capacity to meet projected demand.

one-half of the high-yielding areas shown on plate 10 fall within this category. Improved water treatment methods, and more sophisticated methods of double casing to eliminate poor quality zones, could eliminate many of these quality problem areas.

It is estimated that, even with the present limitations imposed by quality considerations, an additional 215 mgd of usable ground water is available in the carbonate rock aquifer of northwestern Ohio. This is approximately 6.5 times the presently developed ground-water use. Well fields supplying water which is treatable by standard practices can be developed in 45 percent of the area. Thirty-five percent of the region will produce this type of water in quantities greater than one mgd.

The areas where both good quality and large quantity can be anticipated, although not well defined, lie in five general regions. The largest of these is in the buried-valley complex throughout most of the southern portion of the Maumee Basin. Conditions are also favorable in most of Lucas County and in two smaller areas in the vicinity of Carey and Fremont. Finally, in the Sandusky Basin, a broad area exists in eastern Wyandot and western Crawford counties, and the south-central portion of Seneca County. It is interesting to note that this area is relatively undeveloped.

Recommendations

(1) This report represents the most complete and comprehensive ground-water investigation in northwest Ohio to date. Although projections given are straightforward, estimation of ground-water potential must be a continuing process as additional data becomes available. It is recommended that water planners and developers work closely with the technical staff of the Division of Water as development of the area continues.

(2) This inventory of ground-water resources was not available during the evolution of The Northwest Ohio Water Development Plan. It is recommended that plans and priorities be reviewed in light of information presented in this report, specifically table 6. For example, projected demands for public supplies are available from ground water in five, and perhaps eight, communities which have been allocated reservoir withdrawals. Conversely, three municipalities scheduled for well field expansion are in areas where projected demands cannot be readily developed.

(3) The ground-water potential in northwest Ohio is dependent on recharge to the carbonate aquifer. It is recommended that evaluation of recharge rates be initiated as outlined herein, which includes the installation of monitoring devices within some major pumping centers. This will also provide continuous evaluation of the effects of development.

(4) In parts of northwest Ohio where ground waters carry high concentrations of dissolved solids or hydrogen sulfide, double-casing provides an opportunity to improve the raw water source by eliminating zones of poor quality water. The obvious result of this technique is a substantial reduction in water treatment costs and a savings in water system maintenance.

At the present time, quality changes with depth have been identified in only a few local areas. Additional testing through the use of inflatable packers and under a variety of hydrologic and geologic conditions is needed in order to provide a backlog of precise quality data and a sound basis for quality improvement techniques.

(5) Highly mineralized sulfate waters are encountered in a few areas. These waters carry from 1500 to 2000, or more, mg/l dissolved solids and are in the brackish to slightly saline category. Until such time that sulfate removal can be provided at a reasonable cost, other water sources for municipal supply should be considered for future development in these areas. Technological advances in the field of desalinization are progressing at a rapid pace. Processes such as reverse osmosis and electrodialysis have proven to be effective in the treatment of saline waters and offer much promise in greater utilization of this resource. These presently undesirable waters should therefore be protected for future use.

(6) Industrial development, which may be encouraged by the presence of ample ground-water supplies, can also result in industrial waste disposal problems. The carbonate aquifers are highly susceptible to pollution by industrial wastes, particularly where lagooning is used. Careful consideration of proper waste disposal methods is recommended for all industrial development plans in order to protect ground-water resources.

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APPENDIX

TABLE 7A

TEST WELL DATA

Well number	Depth of well (feet)	Depth to bedrock (feet)	Non-pumping level (feet)	Rate (gpm)	Drawdown (feet)	Specific capacity, 24 hour (gpm/ft)	Specific capacity per foot of penetration (gpm/ft^2)	Transmissivity T (gpd/ft)	Well loss constant C (sec^2/ft^5)	24 hour specific capacity (gpm/ft) corrected for well loss	Critical pumping level (feet)	Yield for 180 days (gpm)	Remarks
M-1	240	35	3	250	33.00	7.36	.0370	32,000	76.0	26.4	100	250	
M-2	220	12	4	100	71.00	1.41	.0042	7,200	----	----	130	80	
M-3	210	63	40	350	47.00	7.45	.0510	34,000	34.5	13.2	125	400	
M-4	320	13	10	300	108.00	2.78	.0105	18,800	----	----	160	150	
M-5	280	8	5	300	32.30	10.78	.0396	37,600	31.8	18.9	110	400	
M-6	320	6	7	500	11.88	42.00	.1360	60,000	7.5	208.0	30	600	
M-7	330	17	12	350	67.28	5.25	.0168	14,000	52.4	10.1	165	400	
M-8	450	12	16	200	191.90	1.04	.0024	6,600	374.0	1.7	280	230	
M-9	260	5	31	100	72.54	1.38	.0054	8,250	----	----	110	75	
M-10	320	10	8	149	209.20	.71	.0023	5,300	----	----	250	100	
M-11	420	56	41	100	180.90	.55	.0015	3,200	760.0	.7	260	100	
M-12	400	43	20	---	-----	----	-----	-----	----	----	---	20	No test, yield estimated
M-13	220	28	5	400	22.26	17.90	.0930	32,000	8.0	25.1	150	800	
M-14	360	5	flows	190	67.71	2.80	.0079	20,600	----	----	140	200	
M-15	370	15	25	175	145.00	1.21	.0036	7,000	447.0	2.2	200	175	
M-16	300	15	7	500	57.79	8.75	.0304	25,800	36.6	43.9	75	500	
M-17	300	9	3	250	130.50	1.90	.0065	26,000	400.0	35.7	185	250	
M-19	360	50	7	200	117.50	1.70	.0056	16,500	215.0	2.6	175	240	
M-20	350	45	11	500	25.59	19.58	.0768	27,600	8.0	32.4	55	500	
M-21	280	55	17	250	113.40	2.20	.0098	18,000	267.0	8.2	175	275	
M-22	227	26	18	400	11.89	33.70	.1680	26,000	2.0	39.1	80	800	
M-23	360	10	6	191	185.30	1.03	.0029	6,600	----	----	220	150	
M-24	340	147	7	400	131.00	3.05	.0158	12,000	46.8	4.2	165	400	
M-25	280	34	12	450	66.96	6.73	.0274	12,000	36.0	14.5	115	450	
M-26	258	7	6	500	42.81	11.70	.0460	20,000	6.0	14.1	120	850	
M-27	260	18	5	500	68.72	7.28	.0310	10,000	22.6	12.8	115	500	
M-28	370	27	10	170	205.30	.83	.0024	5,600	452.0	1.2	210	130	
M-29	370	34	21	240	145.70	1.65	.0049	13,000	316.0	4.3	200	250	
M-30	330	37	10	500	38.84	12.80	.0437	25,400	7.0	16.6	150	900	
M-31	360	18	4	96	109.90	.87	.0026	8,350	1360.0	2.0	140	100	
M-32	580	78	60	80	180.00	.45	.0009	530	----	----	---	75	Pumped by air lift method
M-33	385	46	flows	---	-----	----	-----	-----	----	----	---	40	No test, yield estimated
M-34	405	74	40	---	-----	----	-----	-----	----	----	---	20	No test, yield estimated
M-35	350	70	--	---	-----	----	-----	-----	----	----	---	5	No test, yield estimated
M-36	220	74	46	503	38.69	13.00	.0890	27,800	7.7	----	80	300	
M-37	300	42	22	150	79.40	1.60	.0064	2,600	168.0	2.0	110	80	
M-38	500	65	8	125	112.70	1.08	.0120	10,000	----	----	---	---	
M-39	250	66	42	500	24.56	20.40	.1110	106,900	12.8	56.0	110	800	
M-40	335	47	57	500	16.46	30.40	.1565	186,000	7.2	67.0	240	1000	
M-41	260	74	--	---	-----	----	-----	-----	----	----	---	50	No test, yield estimated
M-42	280	30	10	500	18.15	27.60	.1110	94,000	9.4	78.1	125	1000	
P-1	220	36	20	---	-----	----	-----	-----	----	----	80	25	Not pumped
P-2	220	41	flows	150	68.80	2.18	.0123	2,800	170.0	3.0	85	100	
P-3	230	20	11	---	-----	----	-----	-----	----	----	---	20	No test, yield estimated
P-4	230	60	18	---	-----	----	-----	-----	----	----	---	30	No test, yield estimated
P-5	350	68	5	250	104.60	2.49	.0147	6,400	94.0	3.3	175	300	
P-6	420	80	28	402	41.61	8.70	.0256	16,500	19.0	15.2	125	500	
P-8	260	28	9	503	157.80	3.19	.0138	9,600	72.6	7.6	165	460	
P-9	235	22	9	80	18.40	3.08	.0144	1,500	136.0	3.7	30	25	Pumped only 8 hours
P-10	300	50	5	176	102.20	1.05	.0058	7,200	246.0	2.7	120	160	
P-11	250	19	7	160	136.70	1.17	.0051	2,900	208.0	1.4	170	150	
P-12	360	38	24	99	99.80	1.01	.0028	3,600	717.0	1.5	160	100	
P-13	280	19	5	121	129.70	.93	.0036	4,000	----	----	125	100	
P-14	250	48	5	121	149.90	.81	.0040	1,800	450.0	1.0	170	100	
P-16	360	24	15	500	71.33	7.02	.0209	24,000	22.3	11.5	125	600	
P-18	300	25	31	76	49.90	1.53	.0056	5,000	694.0	2.5	90	50	
S-1	285	24	53	503	5.41	93.10	.3600	49,900	1.0	120.6	81	1000	
S-3	355	54	36	60	126.30	.47	.0016	1,750	----	----	250	50	
S-4	310	77	7	503	17.44	28.80	.1240	34,600	3.1	38.0	90	1000	
S-5	320	10	2	450	99.15	4.54	.0154	20,000	66.0	13.6	160	500	
S-6	300	72	24	150	88.32	1.70	.0091	6,900	293.0	2.6	115	130	
S-7	298	80	12	500	25.48	19.60	.1110	40,000	7.2	30.3	80	800	
S-8	330	41	flows	76	113.60	.66	.0047	3,085	----	----	100	60	
S-9	220	47	3	88	107.30	.91	.0054	3,870	2014.0	3.0	107	65	
S-10	200	32	flows	110	89.02	1.24	.0076	6,400	----	----	90	85	
S-11	180	35	1	---	-----	----	-----	-----	----	----	100	40	No test, yield estimated
S-12	330	19	18	500	17.00	29.40	.0945	58,500	1.2	32.2	120	1000	
S-13	350	74	--	---	-----	----	-----	-----	----	----	---	400	No test, well plugged
S-14	120	60	0	500	19.39	25.80	.4450	69,500	2.2	30.0	64	750	
S-15	250	18	5	350	47.80	7.33	.0320	28,400	10.3	8.4	100	250	
S-16	310	45	12	128	27.19	4.71	.0178	9,000	62.0	5.8	100	250	
S-17	395	115	52	454	45.75	9.90	.0354	43,000	16.0	15.5	115	500	
S-18	340	70	8	503	160.10	3.14	.0196	22,270	60.0	5.9	175	475	
S-19	375	32	7	300	60.66	4.95	.0145	10,000	21.4	5.8	150	300	
S-23	108	95	11	503	13.02	38.60	1.8400	65,150	2.9	54.1	95	900	
S-24	163	92	18	503	11.53	43.60	.6140	103,000	5.6	111.0	100	1000	

TABLE 7B

SUPPLEMENTAL WELL DATA

Number	Owner	Date	Depth of well (feet)	Diameter of well (inches)	Depth to bedrock (feet)	Non-pumping level (feet)	Test Data: Rate (gpm)	Test Data: Drawdown (feet)	Time (hours)	Specific capacity (gpm/ft)	Specific capacity per foot of penetration (gpm/ft^2)	Remarks
						Allen County						
1	City of Bluffton	1968	212	12	15	30	325	28	8	11.6	.0605	
2	Central Power	1949	328	10	5	9	325	---	7	----	-----	Cased to 77 feet
3	Village of Cairo	1966	78	6	22	27	54	2	24	27.0	.4900	City park well
4	Beaverdam	1962	305	8	32	12	193	29	24	6.7	.0248	
5	Beaverdam	1964	310	8	34	14	190	24	24	7.9	.0280	
6	Village of Elida	1965	327	10	24	45	182	25	24	7.3	.0245	
7	Village of Elida	1947	124	8	18	20	200	55	24	3.6	.0343	
8	Lima State Hospital	1955	150	--	15	10	229	15	24	15.8	.1170	Pump test on file
9	Lima State Hospital	1956	150	--	32	39	259	26	24	9.9	.0839	Pump test on file
10	American Mall Co.	1965	396	10	282	100	250	10	24	25.0	.1290	
11	Lima State Hospital	1962	200	10	28	131	200	6	8	33.3	.1950	
12	Pepsi Cola Co.	1965	169	8	86	47	300	25	8	12.0	.1450	
13	Spencerville	1950	250	12	31	31	435	29	8	15.0	.0685	Cased to 50 feet
14	Indian Hills	1969	103	8	50	34	230	55	12	4.2	.0836	
15	Standard Oil	1948	397	12	66	102	160	73	8	2.2	.0066	Solar refinery
16	Sohio Chemical	1965	390	12	132	135	700	24	37	29.2	.1340	
17	Sohio Chemical	1965	383	12	123	126	700	15	26	46.6	.2100	
						Auglaize County						
1	Fisher Dairy	1949	311	8	120	--	200	120	10	1.7	.0087	
2	Wapakoneta	1948	304	10	126	8	110	98	24	1.1	.0064	
3	Wapakoneta	----	---	--	--	--	---	--	--	8.2	-----	Average of 4 wells
4	Church of Nazarene	1948	288	8	116	38	94	120	13	.8	.0046	
5	Goodyear Rubber	1947	356	8	108	20	535	17	24	31.5	.1270	
6	City of St. Marys	1968	279	12	98	28	800	10	8	76.2	.4210	
7	City of St. Marys	1967	284	12	75	27	800	11	15	76.0	.3640	Pump test on file
8	Goodyear Rubber	1957	360	10	155	22	500	30	8	16.7	.0082	
9	Weston Paper Co.	1964	325	12	130	35	300	14	8	23.2	.1160	
						Hancock County						
1	Village of McComb	1935	156	10	65	35	170	48	36	3.6	.0389	
2	Kay Meat Packers	1949	230	8	95	60	70	100	10	.7	.0052	Location questionable
3	Burdett Oxygen	1956	192	8	30	30	40	110	12	.4	.0023	
4	Remington Arms	1969	200	10	12	30	73	150	24	.5	.0028	
5	City of Findlay	1946	180	12	18	20	140	50	12	2.8	.0173	
6	City of Findlay	1946	70	12	29	25	265	35	12	7.5	.1840	
7	Mt. Blanchard	1950	90	10	22	23	100	4	24	25.0	.3845	
						Hardin County						
1	Village of Ada	----	150	7	--	--	158	--	1 mo	45.0	.3750	Pump test on file
						Henry County						
1	Village of McClure	1947	85	8	40	29	26	40	24	.7	.0149	
2	Village of McClure	----	60	8	35	45	75	27	24	2.8	.2310	
3	Village of Hamler	1945	53	12	48	31	60	19	24	3.2	.6320	
						Lucas County						
1	Toledo Hospital	1957	350	10	70	76	250	55	12	4.6	.0190	Cased to 110 feet
2	DiSalle Plating	1960	555	6	88	107	250	20	24	12.5	.0269	Cased to 90 feet
3	Mr. McKelvey	1968	352	8	62	47	170	263	8	.6	.0023	
4	Libby Owens Ford	1946	528	12	69	--	286	56	24	5.1	.0111	Pump test on file
5	Libby Owens Ford	1947	526	12	--	--	315	71	24	4.5	.0161	Pump test on file
6	Wayne High School	1968	410	8	74	62	200	100	24	2.0	.0060	Cased to 78 feet

TABLE 7B (Continued)

SUPPLEMENTAL WELL DATA

Number	Owner	Date	Depth of well (feet)	Diameter of well (inches)	Depth to bedrock (feet)	Non-pumping level (feet)	Test Data		Time (hours)	Specific capacity (gpm/ft)	Specific capacity per foot of penetration (gpm/ft^2)	Remarks
							Rate (gpm)	Drawdown (feet)				
	Mercer County											
1	Rockford	1959	308	10	59	13	130	117	8	1.1	.0045	
2	Mendon	1947	200	8	42	18	230	28	48	8.2	.0555	
3	Mendon	1948	292	8	51	12	125	60	48	2.1	.0087	
	Ottawa County											
1	Stokely Foods	1952	351	10	61	32	250	60	12	4.2	.0144	
2	State of Ohio	1968	110	6	55	1	70	17	24	4.1	.0876	
3	Genoa	----	436	10	22	18	125	128	30	.9	.0024	
4	Perma Glass Inc.	1961	265	8	6	17	130	60	12	2.2	.0092	
5	Brush Beryllium	1956	338	10	12	20	220	265	24	.8	.0030	
6	Brush Beryllium	1960	415	10	28	50	135	220	12	.6	.0016	
7	Brush Beryllium	1961	410	10	27	50	140	140	12	1.0	.0028	
8	Elmore	1928	381	--	30	--	200	97	144	2.1	.0059	
	Paulding County											
1	Antwerp	1950	100	--	38	18	32	--	7	---	-----	Test well
	Putnam County											
1	Continental	1947	167	8	48	40	32	65	24	.5	.0042	
2	Ottawa	1966	510	8	44	60	325	70	24	4.6	.0101	Location not accurate
3	Ottawa	1966	510	8	87	60	300	100	24	3.0	.0072	Location not accurate
4	Ottawa	1949	150	8	51	49	120	45	24	2.6	.0270	
5	Ottawa	1949	200	8	53	50	85	45	24	1.8	.0128	
6	Ottawa	1952	149	8	49	46	125	20	24	6.3	.0625	
7	Ottawa	1955	525	8	45	45	200	15	24	13.3	.0279	On Rectine farm
8	Ottawa	1949	215	10	51	29	80	56	24	1.4	.0087	On Rectine farm
9	Ottawa	1952	141	8	53	45	60	40	24	1.5	.0171	
10	Ottawa	1967	510	8	37	40	225	200	8	1.1	.0024	Location not accurate
11	Kalida	1946	120	10	27	20	80	75	24	1.1	.0115	
12	Pandora	1960	110	8	11	11	150	10	8	15.0	.1530	
13	Pandora	1947	114	8	11	5	220	50	24	4.4	.0430	
14	Ottoville	1954	244	10	12	10	80	130	24	.6	.0027	
15	Ottoville	1947	152	10	22	12	35	73	24	.4	.0037	
16	Columbus Grove	1949	451	10	30	7	390	162	8	2.4	.0057	Step test on file
17	Columbus Grove	1950	168	10	37	17	425	17	26	27.9	.2140	Location unknown
18	Columbus Grove	1952	167	10	31	18	400	18	24	22.2	.1630	Location unknown
	Sandusky County											
1	Woodville	1950	260	10	28	--	80	110	36	.7	.0035	
2	Woodville	1950	255	10	29	20	90	100	48	.9	.0040	
3	Lindsey	1948	405	8	20	8	62	160	24	.3	.0011	
4	Holiday Inn	1967	107	6	62	21	140	70	8	2.0	.0513	Well No. II
5	Holiday Inn	1967	104	6	63	23	68	70	8	.9	.0270	Well No. I
6	Rockwell Trout	1964	125	8	72	5	60	17	48	3.5	.0720	
7	Peter Ekrich	1965	389	12	18	45	400	84	44	4.8	.0129	
8	Fremont School	1963	225	8	18	20	58	80	48	.7	.0045	
9	Havenshire Dairy	----	160	6	17	58	36	9	16	4.0	.0298	
10	Clyde	1965	304	8	60	35	425	35	10	12.1	.0359	
11	Willard Fry	1949	108	6	89	70	30	5	24	6.0	.3160	

TABLE 7B (Continued)

SUPPLEMENTAL WELL DATA

Number	Owner	Date	Depth of well (feet)	Diameter of well (inches)	Depth to bedrock (feet)	Non-pumping level (feet)	Test Data: Rate (gpm)	Test Data: Drawdown (feet)	Time (hours)	Specific capacity (gpm/ft)	Specific capacity per foot of penetration (gpm/ft^2)	Remarks
						Seneca County						
1	Bettsville	1960	230	8	6	2	125	140	24	.9	.0043	
2	Bettsville	1951	250	8	5	--	80	138	24	.6	.0027	
3	Bettsville	1949	230	8	6	2	125	140	24	.9	.0042	
4	George Charles	1948	171	6	4	120	30	10	12	3.0	.0184	
5	Jerome Wolfe	1949	183	6	3	90	30	80	12	.3	.0022	
6	Harold Boyer	1948	114	6	20	75	40	6	12	6.6	.0758	
7	Flatrock	1949	150	6	7	90	25	30	24	.8	.0060	
8	Tiffin Hospital	1968	342	8	14	15	100	117	24	.8	.0026	Pump test on file
						VanWert County						
1	Convoy	1959	301	8	34	16	130	60	24	2.2	.0083	
2	Convoy	1962	252	10	28	14	210	81	8	2.6	.0118	
3	Chrysler Corporation	1969	412	10	47	37	400	85	12	4.7	.1300	
4	Van Wert Corporation	1947	410	8	30	106	100	5	8	20.0	.0526	
5	Van Wert	1946	351	8	44	31	170	65	10	2.6	.0085	
6	Delphos	1946	294	10	12	26	325	34	24	9.6	.0339	
7	Delphos	1946	300	10	10	24	350	16	24	21.9	.0755	
8	Delphos	1946	320	10	16	23	250	112	24	2.2	.0073	
9	Delphos	1967	350	10	13	71	375	114	24	3.3	.0102	
10	Delphos	1967	350	10	13	71	290	109	24	2.6	.0081	
11	Delphos Grain	1962	404	10	25	120	160	70	27	2.3	.0061	
12	Edge Creek Golf	1962	255	10	26	9	205	96	8	2.1	.0097	
13	Ohio City	1962	300	10	55	35	265	50	8	5.3	.0228	
14	Ohio City	1950	300	20	55	22	240	20	8	12.0	.0490	
15	Ohio City	1950	335	20	55	21	260	40	8	6.5	.0232	
16	Ohio City	1956	121	10	70	27	207	30	24	6.9	.1350	
						Wood County						
1	Chrysler Corporation	1966	343	6	71	27	170	93	8	1.8	.0059	
2	Tontopany	1953	104	10	92	14	75	75	24	1.0	.0770	
3	Pemberville	1949	150	10	14	4	66	146	8	.4	.0036	
4	Bowling Green Univ.	1964	236	8	10	6	60	180	24	.3	.0015	Cased to 21 feet
5	Bradner	1968	315	8	3	10	100	75	10	1.3	.0050	Cased to 48 feet
6	Wayne	1954	250	10	40	27	125	90	30	1.3	.0066	
7	Ohio Agri. Research	1967	260	6	55	15	253	29	22	8.7	.0416	44 feet of slotted pipe
8	North Baltimore	1949	260	10	33	28	160	15	24	10.7	.0482	Pump test on file
						Wyandot County						
1	Carey	1947	130	12	25	32	650	15	24	43.3	.4130	
2	Dayton Mal. Iron Co.	1966	130	12	34	35	500	6	8	77.0	.8020	Location not accurate
3	Sycamore	1946	175	8	134	32	110	4	8	27.5	.6700	
4	John Ergestone	1954	305	10	34	53	704	20	24	35.0	.1295	
5	State of Ohio	1969	172	6	62	9	55	1	24	55.0	.5140	

TABLE 8A

WATER ANALYSES OF TEST WELLS

Well number	County	Date analyzed (month, year)	Depth of well (feet)	Water-bearing units	Milligrams per liter: Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (residue at 180°C.)	Hardness $CaCO_3$: Total	Hardness $CaCO_3$: Noncarbonate	Hydrogen Sulfide (H_2S)	pH	Remarks
M-1	Wyandot	12-68	240	G L	22	4.0	.03	527	82	50	4.9	224	1510	12	1.8	.1	2390	1650	1470	0	7.1	
M-2	Hancock	12-68	220	G L	17	1.7	.02	176	62	32	3.9	400	406	22	1.6	.3	920	695	366	.2	7.3	
M-3	Hardin	1-69	220	T G L	17	.96	0	195	85	32	4.0	446	516	8.0	1.6	.1	1110	837	471	.5	7.3	
M-4	Hancock	5-70	320	T G L	16	.71	.05	113	42	13	3.0	388	134	13	1.2	.5	516	455	137	0	7.3	Not pumped
M-5	Hancock	12-68	275	R T G L	12	.25	.02	211	98	34	3.9	416	596	30	1.5	.1	1240	930	589	3.7	7.1	
M-6	Hancock	11-68	320	R T G L	14	.18	.02	132	58	26	3.6	446	186	40	1.4	.1	706	568	203	7.2	7.2	
M-7	Hancock	11-68	330	R T G L	12	.20	.01	311	70	37	4.5	340	730	96	.9	.2	1440	1060	786	17.	7.7	
M-8	Putnam	9-68	450	R T G L	10	.23	0	121	43	29	4.6	380	180	44	1.5	0	642	479	168	12.	7.5	
M-9	Allen	7-68	260	R T G L	8.6	2.3	.04	156	66	29	5.2	333	404	32	1.6	.1	899	661	388	22.	7.2	Plugged back from 280'
M-10	Putnam	8-68	320	R T G L	11	.30	.01	109	56	30	5.7	392	203	10	1.9	0	668	503	182	50.	7.3	
M-11	Putnam	9-68	420	R T G L	8.3	.38	.08	83	23	60	4.4	202	190	48	1.7	0	532	302	136	11.	7.4	
M-12	Putnam	5-70	400	R T G	13	.44	.07	245	120	89	9.1	282	1040	19	1.8	0	1730	1100	874	----	7.4	Not pumped. H_2S present
M-13	Hardin	7-68	220	R T G L	11	.36	.02	175	77	44	3.2	290	552	12	2.0	.3	1090	754	516	0	7.4	
M-14	Allen	7-68	360	R T G L	13	.43	.02	139	59	29	4.0	415	256	28	1.4	.2	769	590	250	7.	7.2	
M-15	Allen	10-68	370	T G L	14	.44	0	108	47	31	3.8	350	197	30	1.4	.2	624	463	176	2.9	7.4	
M-16	Allen	11-68	300	R T G L	12	.18	.01	136	60	33	4.9	394	295	28	1.6	.2	804	587	264	17.	7.3	
M-17	Putnam	8-68	300	R T G L	12	.18	.01	123	62	35	6.3	390	258	35	1.8	0	758	562	243	8.7	7.2	
M-19	VanWert	6-70	360	T G L	13	.57	.05	181	68	65	4.2	248	650	18	1.9	0	1140	732	528	3.9	7.4	
M-20	Auglaize	4-69	300	R T G L	16	.74	.01	81	36	20	2.0	352	94	4.0	1.9	0	438	350	62	1.7	7.6	
M-21	Auglaize	10-68	280	G L	16	1.1	.01	128	57	37	3.4	384	246	48	1.1	.8	760	554	240	2.0	7.4	
M-22	Auglaize	3-68	229	G L	18	3.1	.03	169	85	29	3.5	510	383	8.0	1.5	0	993	772	353	0	7.2	
M-23	Allen	2-69	360	T G L	11	1.6	.13	109	50	38	4.8	354	197	44	1.0	.1	647	478	188	1.0	7.6	
M-24	VanWert	3-69	340	L	11	.97	.02	229	96	93	2.8	120	1010	13	.9	.2	1630	967	869	.8	7.6	
M-25	VanWert	3-69	280	L	12	.85	.02	167	60	80	2.6	140	674	12	1.4	0	1170	664	550	0	7.7	
M-26	VanWert	3-69	258	R G L	13	.10	0	90	39	32	2.6	254	198	30	1.6	.1	524	385	177	5.1	7.6	
M-27	VanWert	4-69	260	R T G L	11	.14	.02	102	48	31	5.0	304	201	46	1.5	.1	620	452	203	14.	7.4	
M-28	Putnam	10-68	370	R T G L	11	.85	.02	105	58	50	4.4	288	250	80	1.8	.1	810	501	265	11.	7.4	
M-29	Paulding	10-68	370	R T G L	10	.31	.04	130	79	44	5.0	310	402	34	1.8	.1	942	650	396	30.	7.1	
M-30	Paulding	4-69	330	R G L	9.5	.03	0	59	48	36	2.8	172	216	37	1.9	0	504	345	204	3.1	7.6	
M-31	Paulding	2-69	360	D R T	12	.18	.03	106	43	21	2.8	328	190	18	1.6	.1	570	442	173	8.7	7.3	

Water-bearing units: D - Devonian System; R - Raisin River Formation; T - Tymochtee Formation; G - Greenfield Formation; L - Lockport Group

TABLE 8A (Continued)

WATER ANALYSES OF TEST WELLS

Well number	County	Date analyzed (month, year)	Depth of well (feet)	Water-bearing units	Milligrams per liter: Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved Solids (residue at 180°C.)	Hardness $CaCO_3$: Total	Hardness $CaCO_3$: Noncarbonate	Hydrogen Sulfide (H_2S)	pH	Remarks
S-7	Wyandot	5-70	290	T G L	15	4.5	.02	240	83	41	4.0	246	780	14	1.6	.1	1270	941	740	.8	7.4	
S-8	Hardin	4-70	330	G L	8.9	1.4	0	179	78	55	4.4	285	580	34	1.7	.2	1180	768	534	.7	7.4	
S-9	Wyandot	2-70	220	G L	17	2.4	.01	533	93	67	5.8	188	1590	23	2.0	.7	2600	1710	1560	1.5	7.0	
S-10	Wyandot	2-70	200	G L	18	3.5	.05	429	91	48	6.4	246	1260	18	1.8	0	2160	1440	1240	1.4	6.8	
S-11	Wyandot	2-70	180	G L	10	---	---	420	195	368	24	230	1250	780	1.3	0	3440	1850	1660	0	7.4	Not pumped
S-12	Crawford	3-70	330	D R	14	.64	0	94	22	3.6	1.8	338	53	1.0	1.1	.1	363	325	48	0	7.1	
S-13	Crawford	2-70	340	D R	10	3.4	1.2	641	141	47	6.8	376	1800	62	1.8	.1	3060	2180	1870	40	7.3	Not pumped. Sample turbid.
S-14	Wyandot	2-70	120	R	17	1.2	0	193	64	6.3	2.7	324	436	1.5	1.6	.1	962	745	479	.2	7.0	Plugged back from 200'
S-15	Hardin	4-70	250	R T G L	15	3.4	.04	150	53	21	2.2	480	239	4.3	1.4	0	735	592	199	.7	7.5	
S-16	Seneca	1-70	310	G L	13	2.3	.08	250	58	65	3.8	170	780	15	.9	0	1410	863	748	.7	7.1	
S-17	Seneca	2-70	395	T G L	14	.88	.03	156	56	12	4.1	386	302	7.0	1.4	0	775	620	303	1.1	6.9	
S-18	Sandusky	10-69	340	T G L	12	.37	.02	484	156	24	3.9	267	1520	39	1.5	.2	2590	1850	1630	1.2	7.2	Double-cased to 180'
S-19	Seneca	1-70	375	L	13	1.6	.07	215	60	64	4.6	152	716	16	.9	.2	1300	784	660	0	7.2	
S-23	Sandusky	11-69	108	T G	19	2.2	.05	375	71	15	2.6	416	878	5.0	1.0	0	1700	1230	887	.3	7.2	
S-24	Sandusky	10-69	163	T G	16	1.3	.03	282	91	35	2.8	232	876	12	1.5	.1	1570	1080	888	.2	7.3	

Water-bearing units: D - Devonian System; R - Raisin River Formation; T - Tymochtee Formation; G - Greenfield Formation; L - Lockport Group

TABLE 8A (Continued)

WATER ANALYSES OF TEST WELLS

Well number	County	Date analyzed (month, year)	Depth of well (feet)	Water-bearing units	Milligrams per liter: Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (residue at 180°C.)	Hardness $CaCO_3$: Total	Hardness $CaCO_3$: Noncarbonate	Hydrogen Sulfide (H_2S)	pH	Remarks
M-32	Defiance	4-68	580	D R	7.7	6.8	.07	69	56	94	15	389	116	120	2.2	.1	676	403	76	69.	7.5	Sample turbid
M-33	Paulding	8-69	385	D R	14	12	.05	98	53	69	8.7	426	93	115	2.3	.7	682	463	114	27.	7.4	Sample turbid
M-35	Henry	5-70	340	R T	13	.74	.08	130	47	160	2.2	86	740	11	1.2	.1	1170	518	448	---	7.7	Not pumped. H_2S present
M-36	Henry	7-69	220	R	20	.18	0	159	56	102	2.8	144	620	53	1.3	0	1140	628	510	3.7	7.8	Plugged back from 265'
M-37	Henry	6-69	300	D R	11	.42	.03	283	133	72	5.6	240	1050	107	1.9	.1	1900	1250	1060	29.	7.4	
M-38	Wood	10-69	500	R T	8.2	.32	.08	552	180	62	3.8	180	1910	48	1.7	0	3110	2120	1970	6.1	7.3	Double-cased to 410'
M-39	Lucas	6-69	250	D	8.6	.22	.03	67	27	38	2.7	247	152	6.0	2.3	0	452	278	76	5.1	7.6	
M-40	Lucas	8-69	335	D	11	---	---	114	33	13	2.2	330	180	4.5	1.8	.1	580	420	150	7.5	7.5	
M-41	Auglaize	5-70	260	L	16	2.2	.05	141	47	56	3.6	264	381	24	1.2	2.7	810	546	329	0	7.9	Not pumped
M-42	Mercer	4-69	280	G L	16	2.9	.04	189	100	39	4.3	430	566	8.0	1.2	0	1230	884	531	1.5	7.2	
P-1	Hancock	12-69	220	L	17	---	---	186	90	72	3.4	188	734	14	.8	0	1310	835	680	0	7.7	Not pumped
P-2	Hancock	12-69	220	L	18	---	---	295	86	84	3.8	132	1080	20	1.6	.3	1760	1090	982	.3	7.5	
P-3	Wood	11-69	230	L	9.7	1.6	.05	227	95	91	6.0	150	888	63	2.1	0	1590	958	835	---	7.8	Not pumped
P-4	Hancock	5-70	230	L	10	16	.05	132	57	96	3.6	146	560	30	1.3	.1	996	564	445	0	7.4	Not pumped. Sample turbid
P-5	Ottawa	10-69	350	T G L	13	.30	0	577	130	21	3.6	284	1620	38	1.4	0	2720	1980	1740	5.1	7.2	Double-cased to 180'
P-6	Hancock	6-69	420	R T G L	11	.57	.02	236	79	92	4.2	180	885	20	1.3	0	1410	915	767	8.7	7.1	
P-8	Wood	11-69	260	L	16	.36	.02	94	31	7.1	1.6	370	50	8.7	.7	.1	399	362	59	0	7.4	
P-9	Wood	11-69	235	G L	22	3.1	.05	480	136	23	4.1	305	1410	18	1.6	0	2420	1760	1510	0	7.2	
P-10	Ottawa	9-69	300	G L	12	.90	0	400	146	22	3.2	198	1290	47	1.7	.03	2270	1600	1440	3.9	7.2	Double-cased to 120'
P-11	Sandusky	8-69	250	L	14	.73	0	87	31	8.8	1.9	332	71	10	.6	0	408	345	72	1.8	7.6	
P-12	Ottawa	9-69	360	G L	8.9	.79	0	104	55	42	2.4	190	375	18	1.4	.03	782	486	330	14	7.1	
P-13	Sandusky	11-69	280	L	15	.79	0	105	45	7.5	1.8	398	116	8.0	1.6	0	533	447	121	.8	7.3	
P-14	Wood	8-69	250	L	11	1.3	.03	67	23	24	1.7	186	136	12	1.0	.1	390	262	109	1.7	7.7	
P-16	Ottawa	8-69	360	L	9.2	.25	.01	108	32	5.0	1.4	354	114	1.0	1.9	0	465	401	111	2.2	7.4	
P-18	Wood	5-69	300	G L	16	.41	.03	203	116	63	4.8	258	840	25	1.0	0	1540	984	773	20.	7.1	
S-1	Crawford	4-70	285	D R	13	.12	0	248	74	24	5.3	362	642	6.0	1.5	0	1240	924	628	7.5	7.1	
S-3	Seneca	11-69	360	G L	16	.86	.04	103	49	14	2.0	345	181	6.0	1.5	0	600	459	176	.3	7.5	
S-4	Marion	5-70	320	R T G	15	.34	0	146	38	9.7	2.5	371	217	1.0	1.6	0	644	520	216	.8	7.7	
S-5	Wyandot	3-70	320	T G L	9.4	.35	.08	553	146	33	3.8	304	1670	55	1.8	1.6	2790	1980	1730	5.4	6.8	
S-6	Wyandot	3-70	300	T G L	12	1.3	.08	247	70	49	3.4	230	760	20	1.8	0	1340	905	716	0	7.8	

Water-bearing units: D - Devonian System; R - Raisin River Formation; T - Tymochtee Formation; G - Greenfield Formation; L - Lockport Group

TABLE 8B

WATER ANALYSES OF SUPPLEMENTAL WELLS

Number	County	Location	Date analyzed (month, year)	Depth of well (feet)	Water-bearing units	Milligrams per liter: Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (residue at 180°C.)	Hardness $CaCO_3$: Total	Hardness $CaCO_3$: Noncarbonate	Hydrogen Sulfide (H_2S) [b]	pH	Remarks
1	Paulding	Antwerp	12-62	280	D R	.20	0	79	37	39	268	131a	52	2.2	1.3	540	350	130	8.9	7.8	c
2	Paulding	Paulding, 1 mi E	6-63	90	D	1.5	0	148	130	54	86	818	5.0	.5	2.0	1400	904	752	----	7.6	H_2S present
3	Paulding	Scott, 5 mi E	4-53	50	R	1.8	.09	276	129	27	426	886	5.0	.9	.5	1678	1320	971	----	6.4	H_2S present
4	Paulding	Payne	10-63	225	R T	.60	.10	112	36	18	348	146a	21	.8	0	533	428	143	2.6	7.2	c
5	Paulding	Oakwood	12-62	206	R	.10	0	102	48	45	301	235a	40	1.8	1.3	720	450	203	32	8.1	c
6	VanWert	Convoy	7-68	252	L	1.3	0	200	61	116	156	625	15	1.1	.5	1259	744	616	0	7.7	c
7	VanWert	VanWert, 1 mi E	2-61	400	T G L	.20	0	112	63	24	415	240a	0	.9	---	785	540	200	----	7.0	c H_2S present
8	VanWert	Middlepoint	1-60	144	T G	3.2	0	158	66	23	414	342a	14	1.1	0	922	666	326	7.0	7.2	c
9	VanWert	Ohio City	1-60	335	L	.30	.10	264	58	74	130	907a	4.0	1.5	0	1390	780	673	0	7.6	c
10	Mercer	Rockford	11-60	150	SG/ L	1.5	.10	214	58	72	211	576a	15	1.4	.4	1387	774	601	.2	7.5	c
11	Mercer	Mendon	9-63	292	G L	1.4	.10	197	53	55	307	541a	8.0	1.4	2.5	1135	710	458	0	7.8	c
12	Auglaize	Wapakoneta	5-67	268	G L	1.6	0	107	44	30	386	160	16	1.2	1.9	588	448	132	.5	7.5	
13	Allen	Spencerville	1-63	250	T G L	.70	0	136	83	35	262	507a	8.0	1.6	1.0	1100	680	465	.7	8.0	c
14	Allen	Fort Shawnee	9-64	276	T G L	2.3	.03	106	50	23	408	156	8.0	1.7	1.2	594	470	136	0	8.1	
15	Allen	Elida	10-57	124	R T	.85	.08	188	81	28	488	379a	47	1.1	3.2	1191	802	402	7.7	7.0	c
16	Allen	Beaverdam	9-70	305	R T G L	.88	.04	152	74	36	450	323	34	1.5	1.0	920	684	315	3.7	7.3	
17	Putnam	Kalida	9-65	120	R	.10	0	203	66	45	400	454a	52	1.2	2.0	1188	780	452	12.	7.1	c
18	Putnam	Pandora	8-62	125	R T	.30	0	100	39	15	372	112a	14	1.3	.9	550	410	105	7.8	7.1	c
19	Putnam	Columbus Grove	11-62	167	R T	.40	0	91	47	11	366	130a	6.0	1.0	.4	530	420	120	7.2	7.3	c
20	Putnam	Ottawa	8-62	510	R T G L	.15	0	114	54	55	286	336a	28	1.4	.4	870	510	275	6.5	7.5	c
21	Putnam	Leipsic	10-59	500	R T G L	.05	.05	72	28	66	262	109a	75	2.6	0	549	296	81	7.2	8.1	c
22	Putnam	Continental	3-58	167	R	.15	.05	142	60	100	171	632a	14	1.6	.9	1203	604	464	5.6	8.1	c
23	Henry	Holgate	3-62	310	D R	2.3	.10	153	65	84	115	684a	18	1.2	0	1350	650	556	13.	7.6	c
24	Henry	Hamler	3-62	54	D R	.70	.05	200	97	78	154	897a	4.0	1.6	1.3	1615	900	774	21.	7.4	c
25	Henry	Deshler	5-67	167	R	1.0	0	200	72	113	129	854	32	1.5	1.4	1450	796	690	----	7.6	H_2S present

a -- SO_4 calculated
b -- H_2S analyzed, 1969-70
c -- Analysis by Ohio Department of Health

Water-bearing units: SG - Sand and gravel; D - Devonian System; R - Raisin River Formation; T - Tymochtee Formation; G - Greenfield Formation; L - Lockport Group

TABLE 8B (Continued)

WATER ANALYSES OF SUPPLEMENTAL WELLS

Number	County	Location	Date analyzed (month, year)	Depth of well (feet)	Water-bearing units	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (residue at 180°C.)	Hardness $CaCO_3$ Total	Hardness $CaCO_3$ Noncarbonate	Hydrogen Sulfide (H_2S) [b]	pH	Remarks
						Milligrams per liter															
26	Henry	McClure	3-62	60	D	.25	0	275	100	69	213	910a	89	1.6	0	1665	1100	925	9.4	7.5	c
27	Lucas	Whitehouse	1-62	140	D	1.1	0	97	31	6.0	220	185a	5.0	1.1	3.5	530	370	189	.3	7.5	c
28	Wood	Perrysburg	9-70	352	G L	.11	.01	137	59	71	140	590	18	4.2	1.8	1000	585	470	.7	7.4	
29	Wood	Haskins, 2 mi E	9-70	193	G L	.27	.02	133	58	45	200	460	33	3.2	.3	862	571	407	.5	7.6	
30	Wood	Pemberville	2-62	150	L	.30	0	103	32	51	365	52a	105	.4	.4	590	390	90	0	7.7	c
31	Wood	Wayne	1-62	258	G L	.05	0	86	38	19	305	141a	10	1.4	0	510	370	120	0	7.4	c
32	Wood	Jerry City, 2 mi E	4-62	290	G L	.40	0	183	90	34	342	568a	20	1.6	---	1300	830	550	---	7.9	c
33	Wood	Grand Rapids	4-53	45	D	3.9	0	192	119	52	352	748	10	1.6	.2	1422	970	681	---	7.2	
34	Wood	Hoytville, 2 mi N	9-70	260	R T	.19	0	135	61	57	220	490	20	1.4	0	940	588	408	1.0	7.9	
35	Hancock	McComb	9-70	156	R	.28	.02	464	131	91	140	1750	14	2.6	0	2780	1700	1580	8.2	7.2	
36	Hancock	Rawson	3-64	64	R T	----	.10	126	49	20	406	169	20	1.3	0	776	516	183	6.6	7.8	c
37	Hancock	Findlay, 1 mi E	9-70	135	L	1.4	.03	195	162	92	270	1120	10	1.6	0	1840	1150	933	0	7.5	
38	Hancock	Arlington	12-67	90	T	.10	0	200	33	18	420	258a	8.0	1.6	.8	851	632	287	1.7	7.7	c
39	Hancock	Mount Blanchard	6-61	90	G	2.2	.05	138	43	30	372	258a	9.0	1.4	0	760	520	215	0	7.1	c
40	Hardin	Forest	4-62	200	T G L	.30	0	126	64	25	396	293a	1.0	1.6	0	830	580	255	0	7.3	c
41	Hardin	Dunkirk	11-62	200	R	.20	0	108	48	15	377	153a	22	1.4	0	653	466	157	2.0	8.0	c
42	Hardin	Ada	8-61	157	R T G L	.80	0	129	51	21	457	185a	7.0	1.3	0	695	530	155	.5	7.3	c
43	Wyandot	Marseilles	11-61	60	G	2.5	.09	218	112	59	392	750	30	1.6	.3	1460	1000	684	0	7.3	
44	Wyandot	Kirby	11-61	58	G	2.5	.11	556	100	67	188	1750	9.0	1.9	.3	2740	1800	1640	0	7.1	
45	Wyandot	Nevada	12-62	93	D R	.30	0	126	38	9.0	378	170a	2.0	1.0	0	645	470	160	0	7.7	c
46	Wyandot	Sycamore	12-62	175	R	1.0	0	141	51	16	396	261a	0	1.4	0	760	560	235	0	7.8	c
47	Wyandot	Carey	3-60	127	G L	.30	0	98	40	4.0	341	111a	5.0	.3	21.	494	410	130	0	7.8	c
48	Seneca	Bloomville	9-62	308'	D R T	.10	0	105	31	13	378	87a	12	1.2	1.3	505	390	80	.7	7.5	c
49	Seneca	Reedtown, 2 mi W	7-64	200	D R	0	----	470	203	146	440	1780	50	1.9	.1	3120	2010	1650	82.	7.2	
50	Seneca	Green Springs	11-58	96	T	.10	.05	286	48	20	362	629a	3.0	1.0	0	1335	912	615	0	7.5	c

a -- SO_4 calculated
b -- H_2S analyzed, 1969-70
c -- Analysis by Ohio Department of Health

Water-bearing units: D - Devonian System; R - Raisin River Formation; T - Tymochtee Formation; G - Greenfield Formation; L - Lockport Group

TABLE 8B (Continued)

WATER ANALYSES OF SUPPLEMENTAL WELLS

Number	County	Location	Date analyzed (month, year)	Depth of well (feet)	Water-bearing units	Milligrams per liter: Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (residue at 180°C.)	Hardness $CaCO_3$		Hydrogen Sulfide (H_2S) [b]	pH	Remarks
																	Total	Noncarbonate			
51	Seneca	Republic	9-62	123	R	.40	0	114	50	9.0	335	225a	1.0	.6	.4	685	490	215	0	7.6	c
52	Seneca	Tiffin	5-62	150	L	.98	.11	102	36	16	354	134	8.0	1.3	.2	507	403	113	0	6.8	
53	Seneca	Fostoria, 1 mi S	5-63	153	L	2.9	.04	115	34	18	352	136	28	.2	.3	541	427	139	0	8.0	
54	Seneca	Bettsville	5-66	230	G L	.40	0	116	31	8.0	461	28	19	1.6	0	500	414	36	.2	8.1	c
55	Sandusky	Fremont	11-65	389	G L	1.0	.18	109	46	7.0	410	128	9.0	1.2	.4	542	461	125	0	7.4	
56	Sandusky	Gibsonburg	4-63	301	L	0	0	102	33	5.0	348	101a	8.0	.6	0	495	390	105	0	8.2	c
57	Sandusky	Lindsey	8-62	315	G L	.10	0	100	29	5.0	366	76a	0	.9	.4	490	370	70	0	7.4	c
58	Sandusky	Woodville	10-62	225	L	.05	0	104	39	8.0	378	101a	17	.3	0	575	420	110	0	7.9	c
59	Ottawa	Elmore	1-68	375	L	.20	0	236	72	22	340	591	28	1.6	.7	1186	878	599	0	7.7	c
60	Ottawa	Genoa	6-69	350	L	.10	0	138	21	7.0	381	91	17	.7	0	585	432	120	.5	7.2	c
61	Ottawa	Oak Harbor, 3 mi E	8-54	137	T G	.05	----	544	177	26	246	1831	46	1.8	0	3018	2090	1884	3.9	7.2	
A	Putnam	Ottoville	10-69	450	G L	----	----	---	---	----	---	-----	----	---	---	----	----	----	0.2	---	Double-cased to 160'
B	Allen	Delphos	2-70	450	R T G L														9.2		North well field
C	Auglaize	St. Marys	2-70	270	L														0		New well field
D	Hardin	Kenton	11-69	358	T G L														0		
E	Wood	Cygnet	10-69	170	G L														4.1		
F	Wood	Bloomdale	10-69	181	L														1.2		
G	Wood	Bradner	9-69	315	L														0		

a -- SO_4 calculated
b -- H_2S analyzed, 1969-70
c -- Analysis by Ohio Department of Health

Water-bearing units: R - Raisin River Formation; T - Tymochtee Formation; G - Greenfield Formation; L - Lockport Group

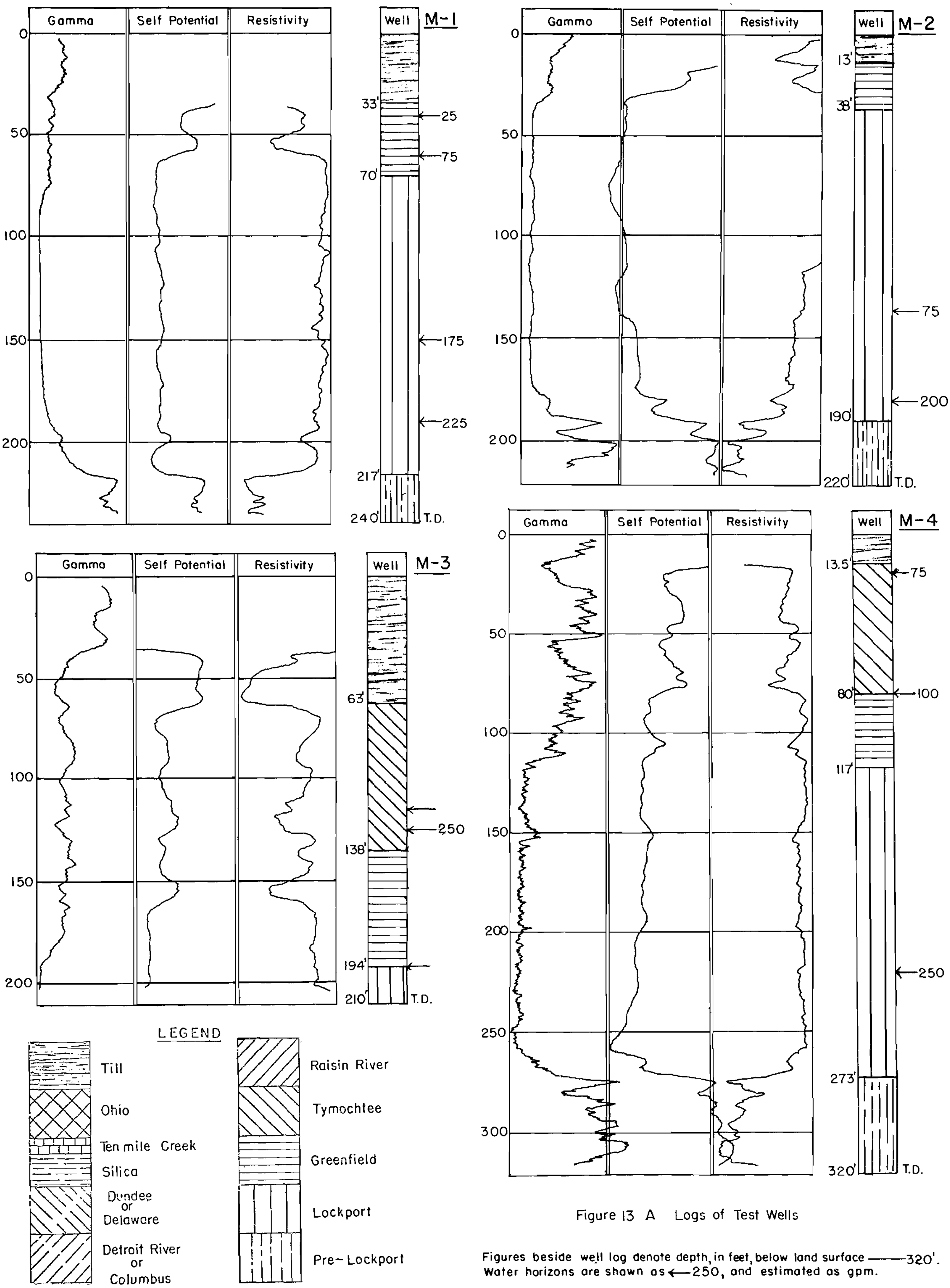


Figure 13 A Logs of Test Wells

Figures beside well log denote depth, in feet, below land surface ———320'.
Water horizons are shown as ←—250, and estimated as gpm.

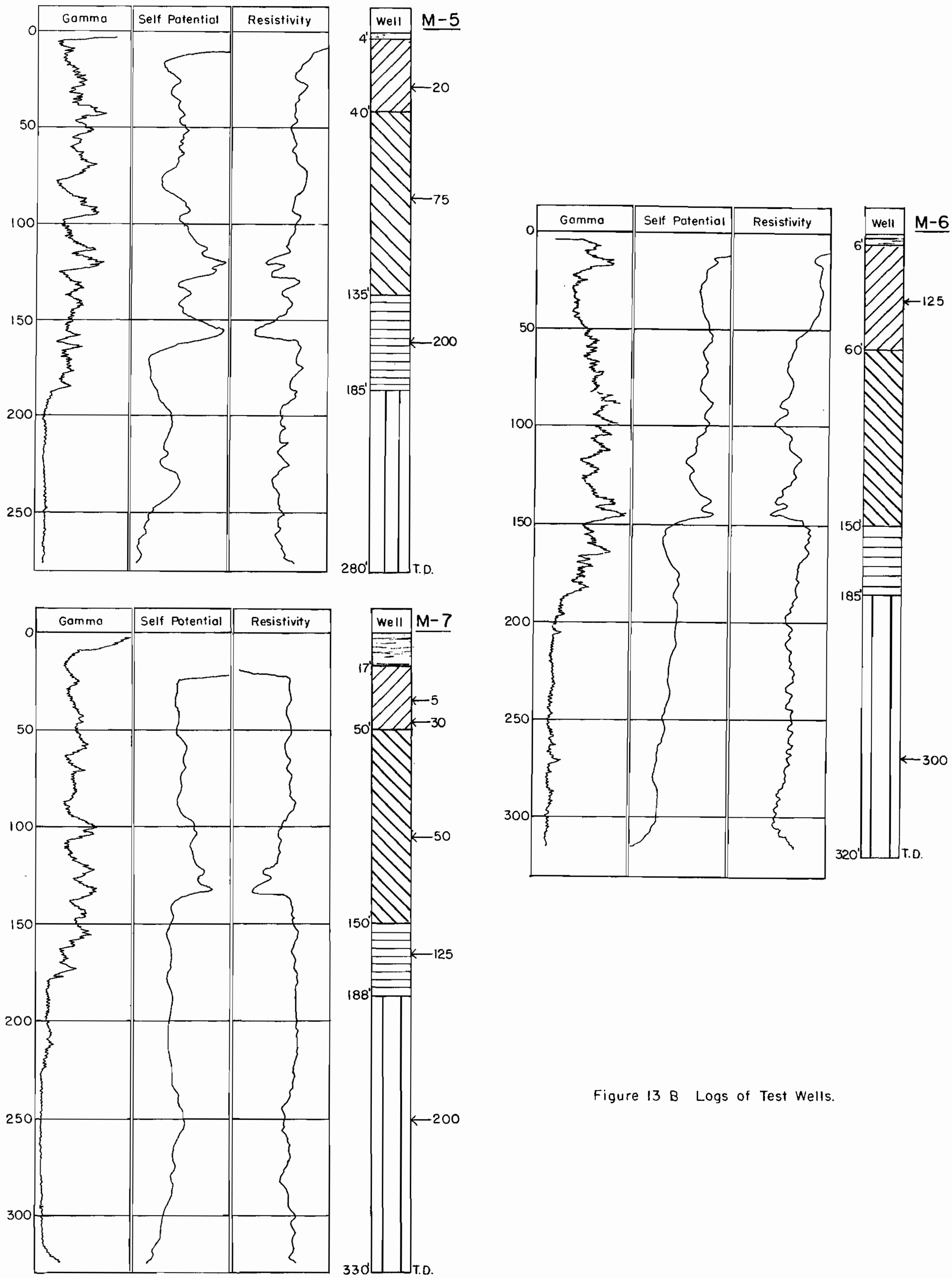


Figure 13 B Logs of Test Wells.

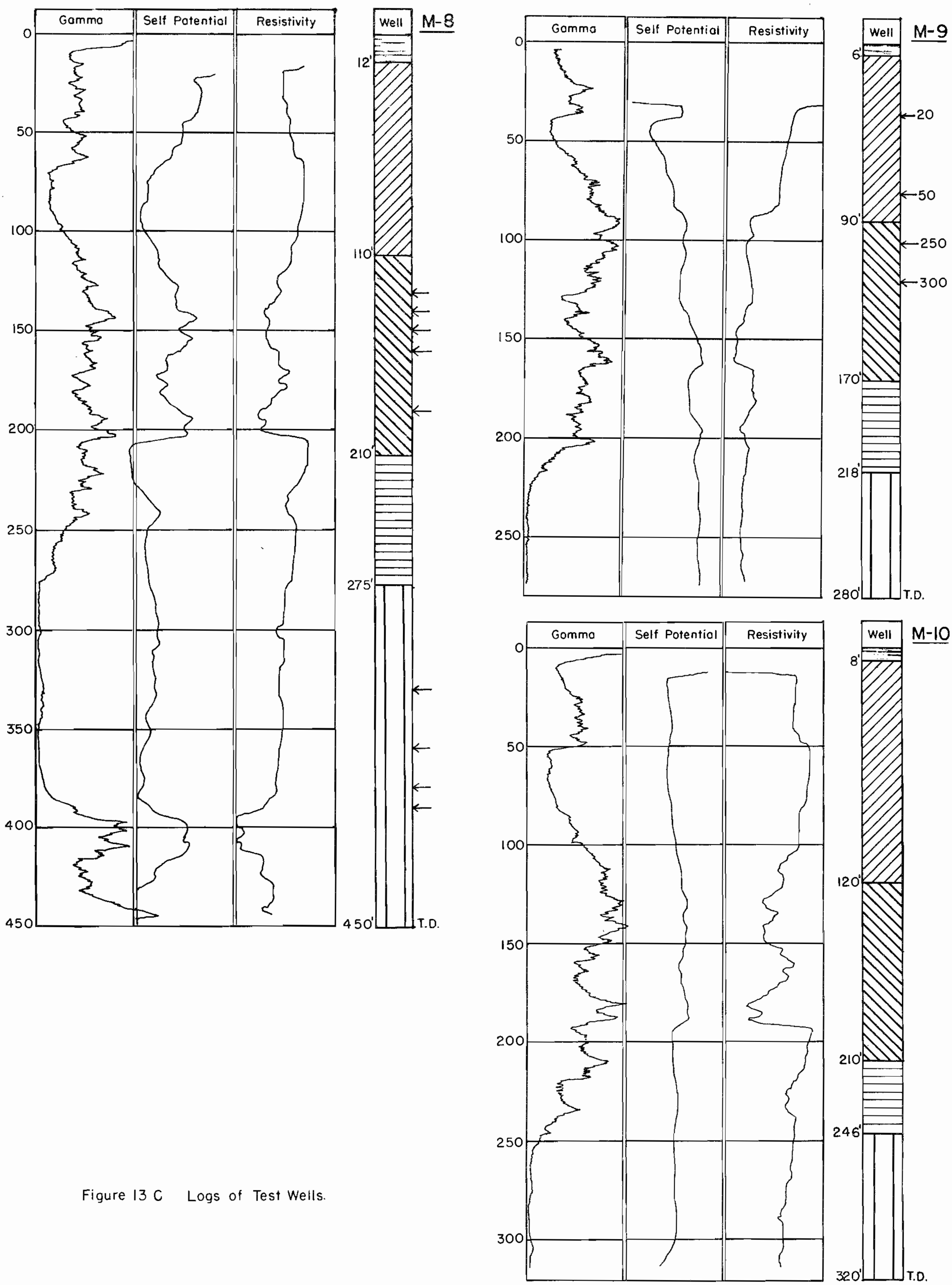


Figure 13 C Logs of Test Wells.

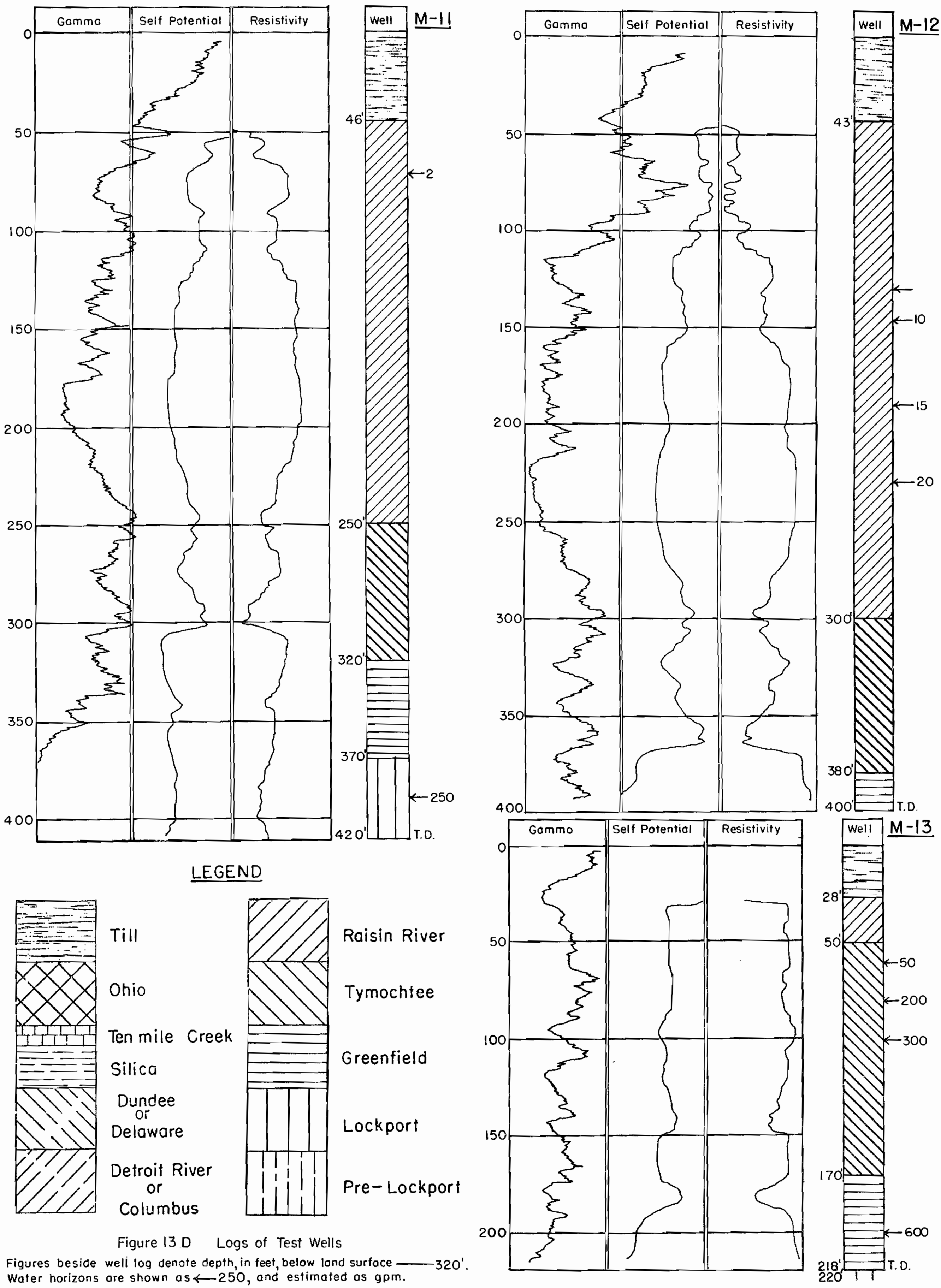
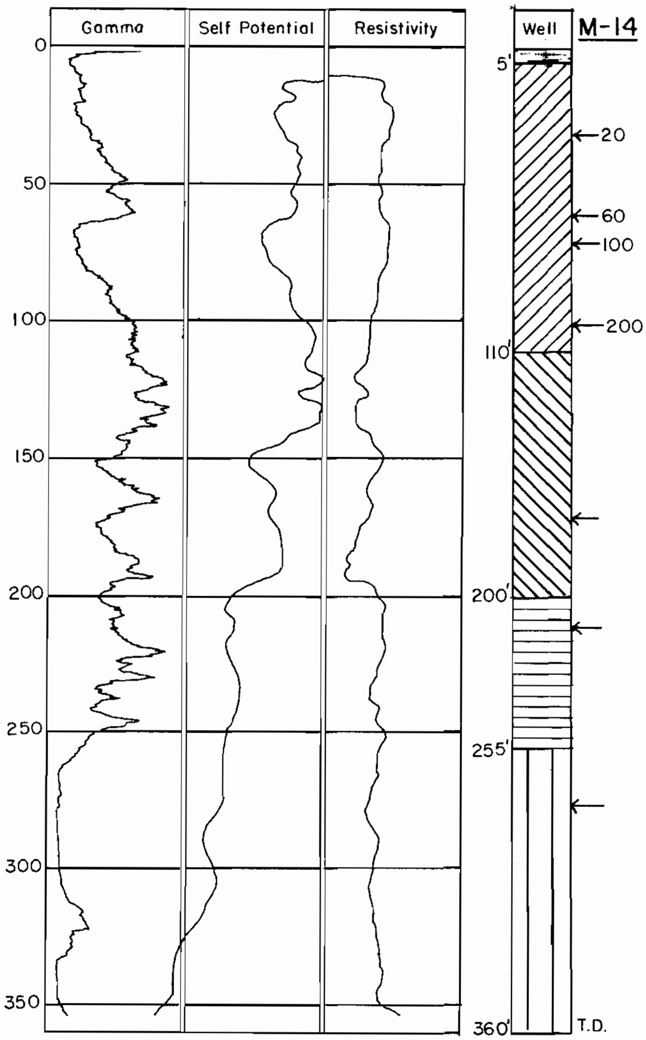


Figure 13.D Logs of Test Wells

Figures beside well log denote depth, in feet, below land surface ——320'.
Water horizons are shown as ←—250, and estimated as gpm.



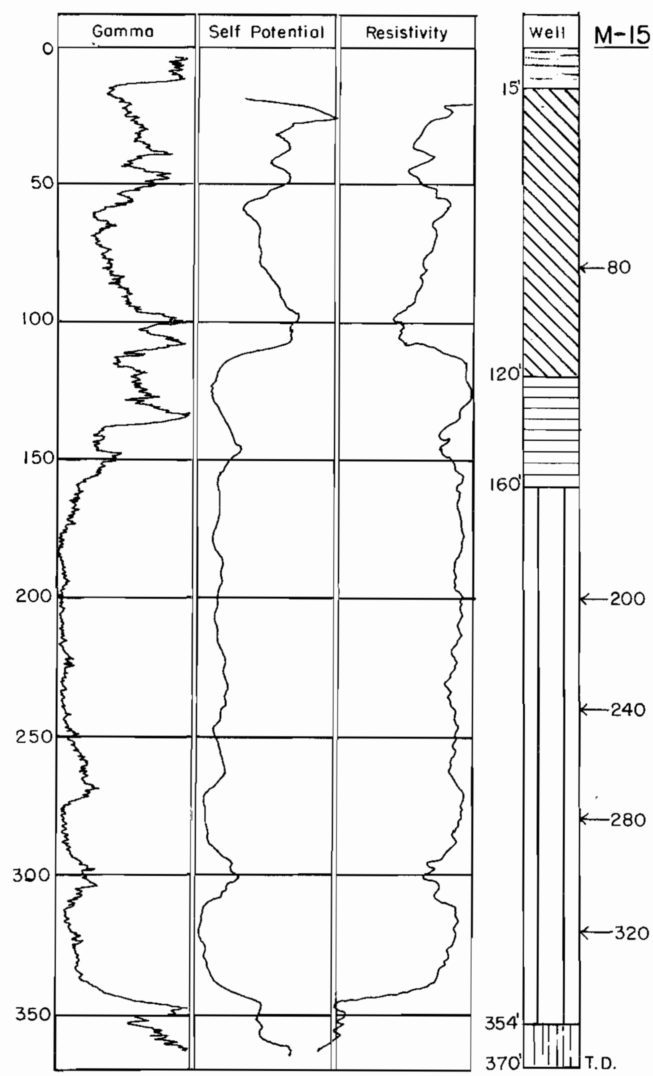


Figure 13E Logs of Test Wells.

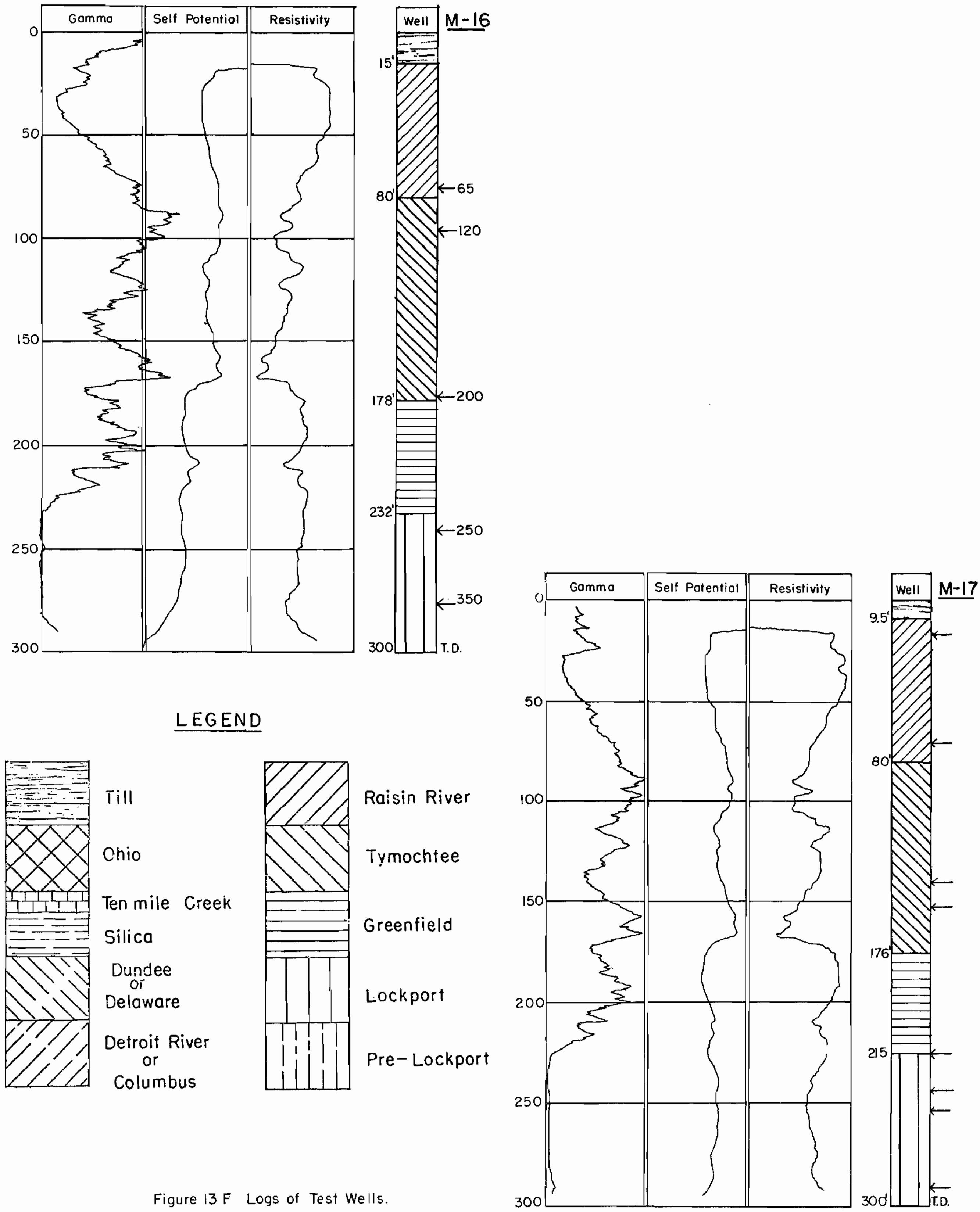


Figure 13 F Logs of Test Wells.

Figures beside well log denote depth, in feet, below land surface ——320'.
Water horizons are shown as ←—250, and estimated as gpm.

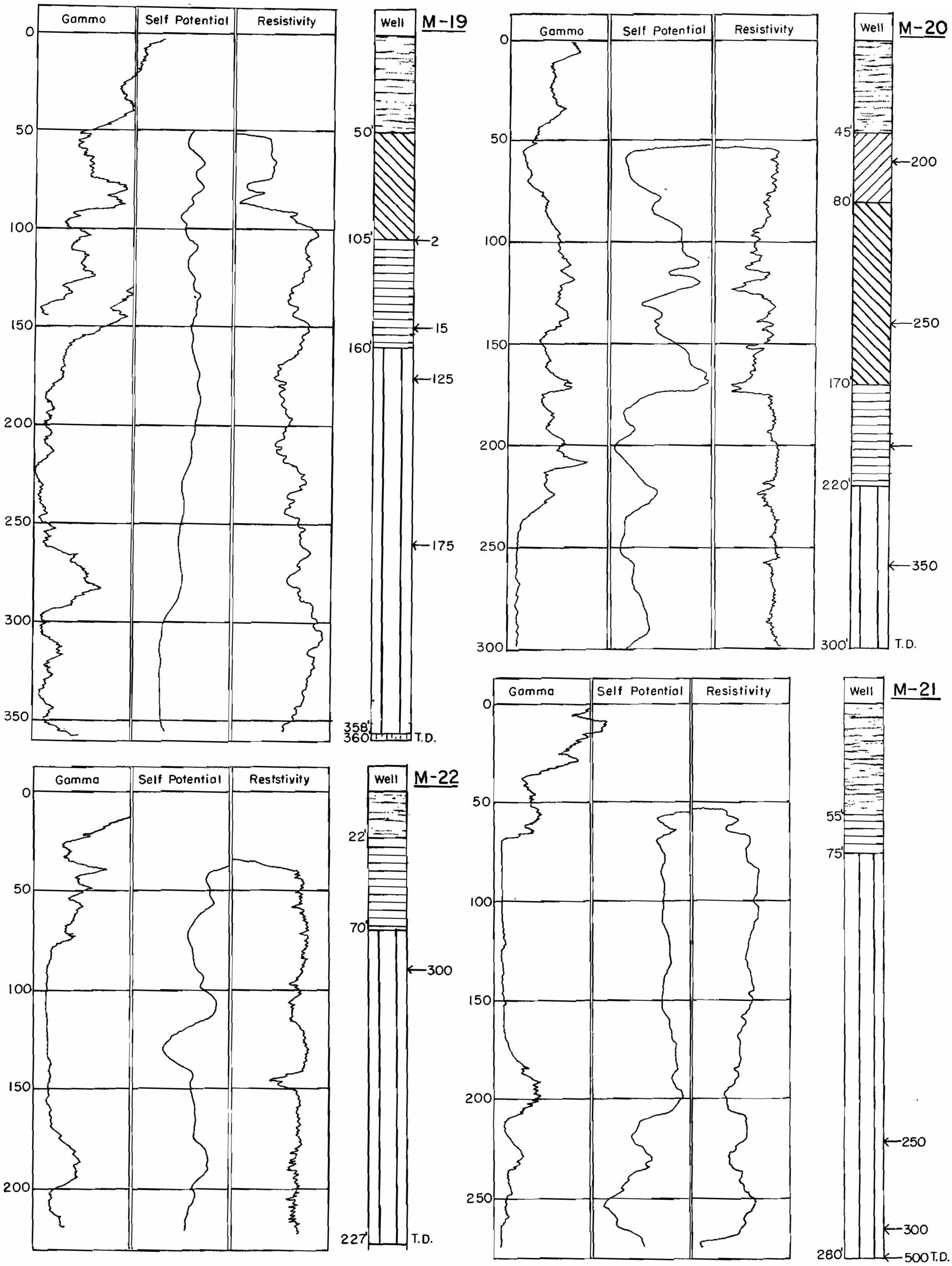


Figure 13 G Logs of Test Wells.

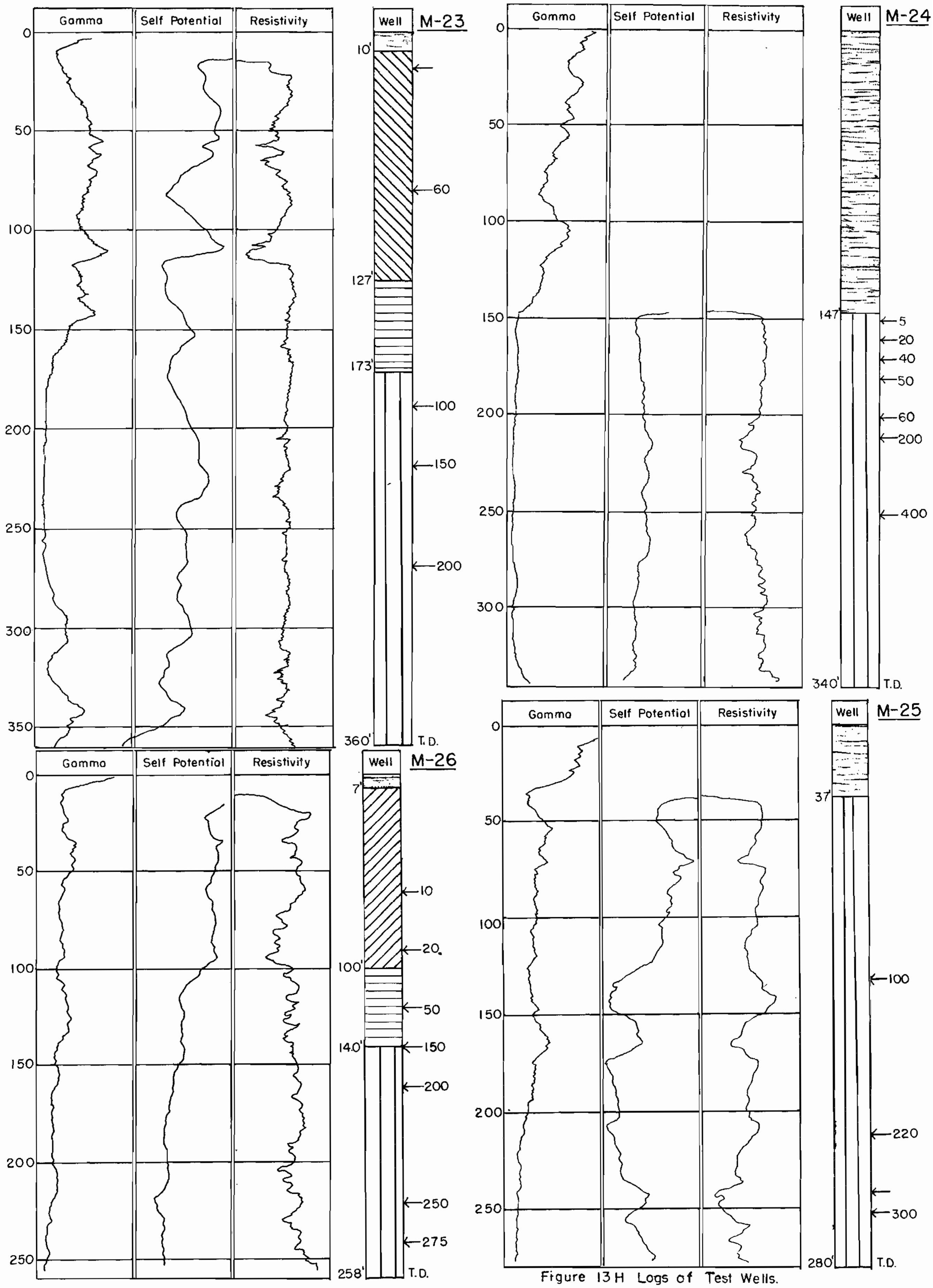


Figure 13 H Logs of Test Wells.

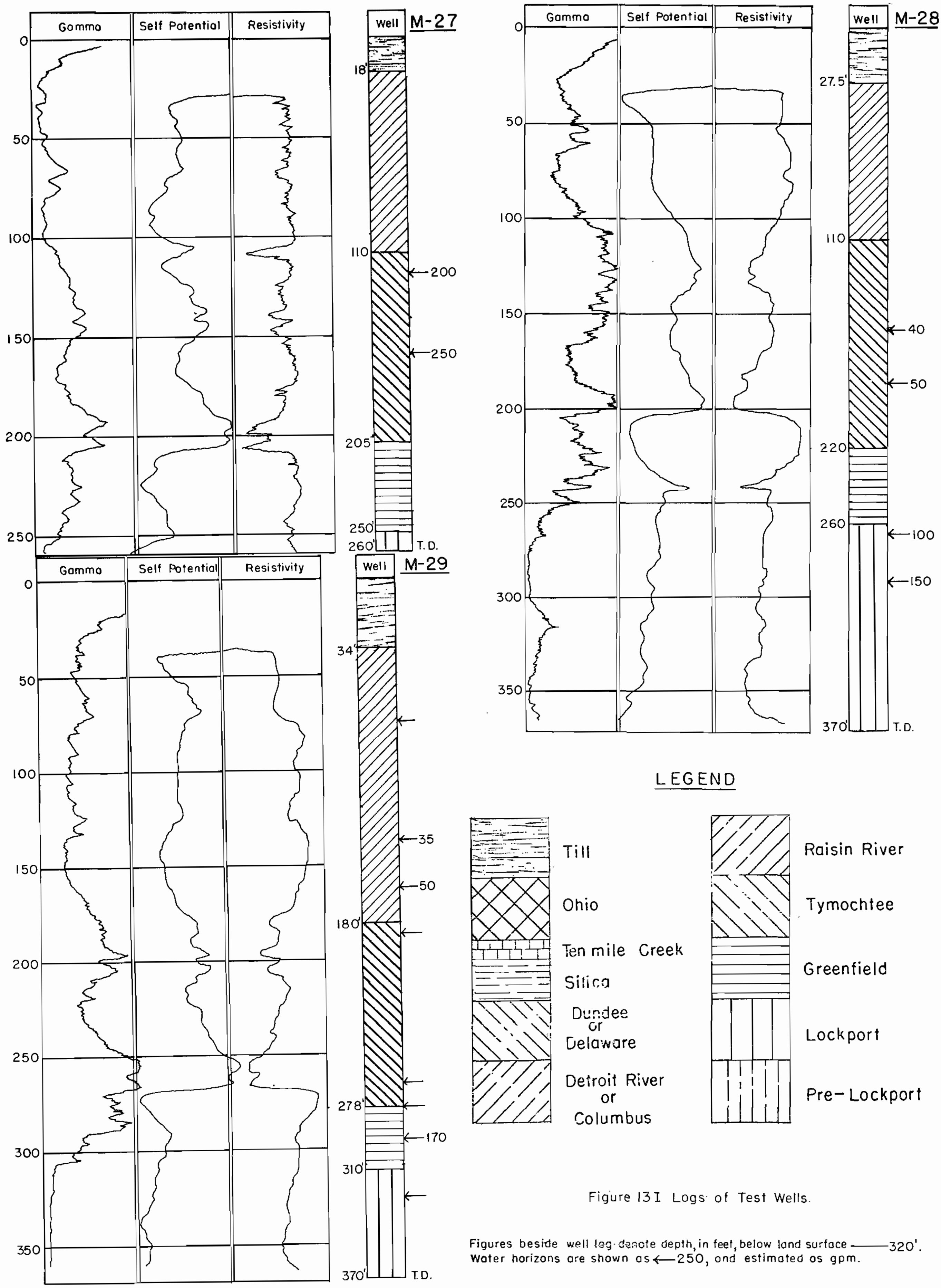
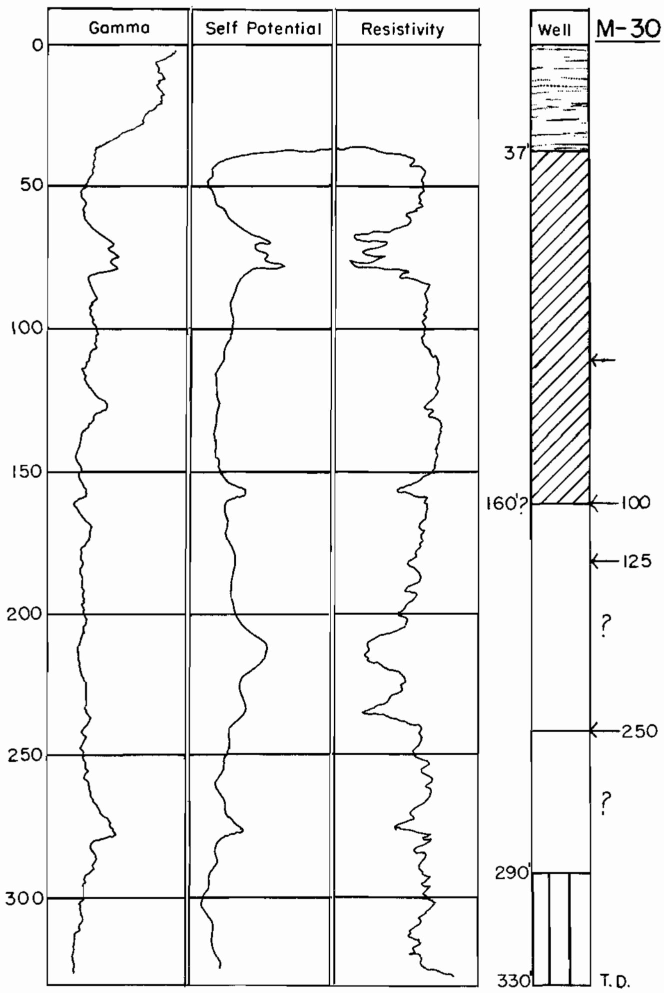


Figure 131 Logs of Test Wells.

Figures beside well log denote depth, in feet, below land surface ——320'.
Water horizons are shown as ←250, and estimated as gpm.



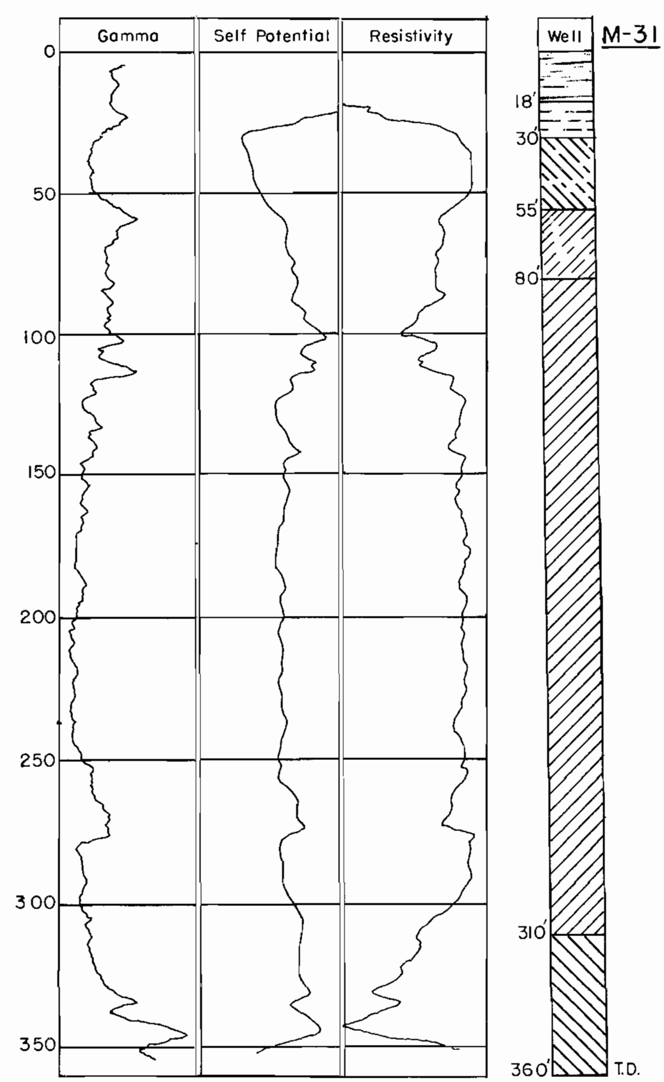
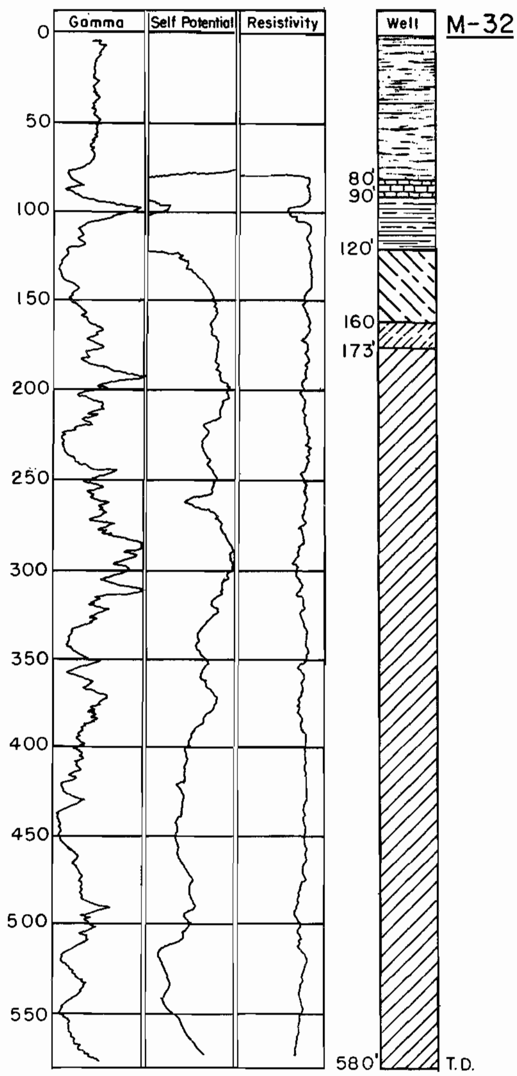
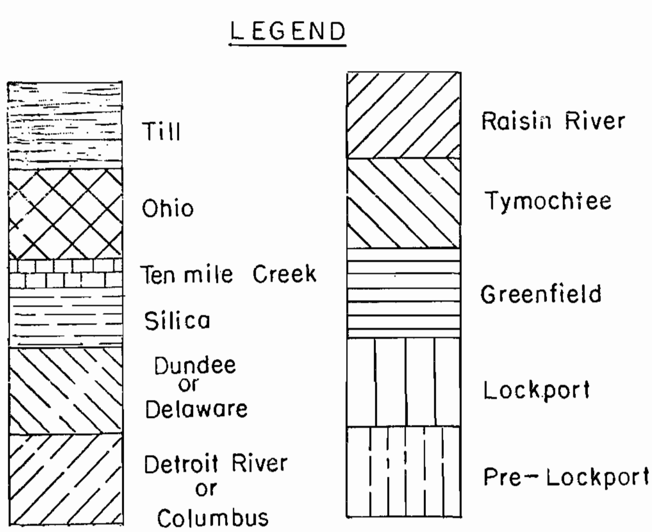


Figure 13 J Logs of Test Wells.





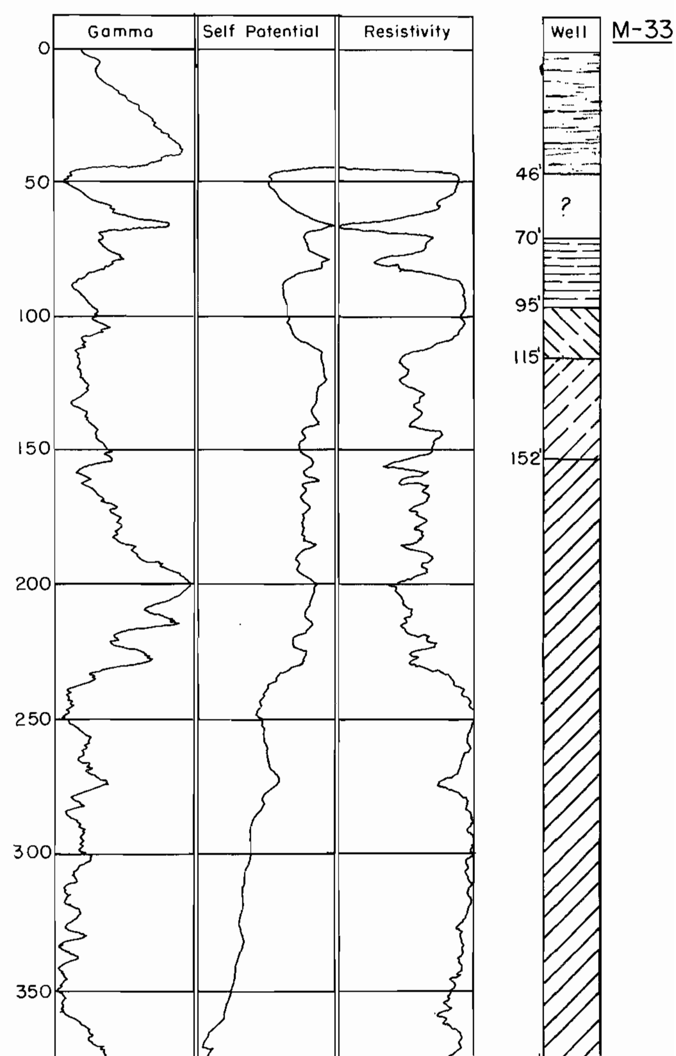
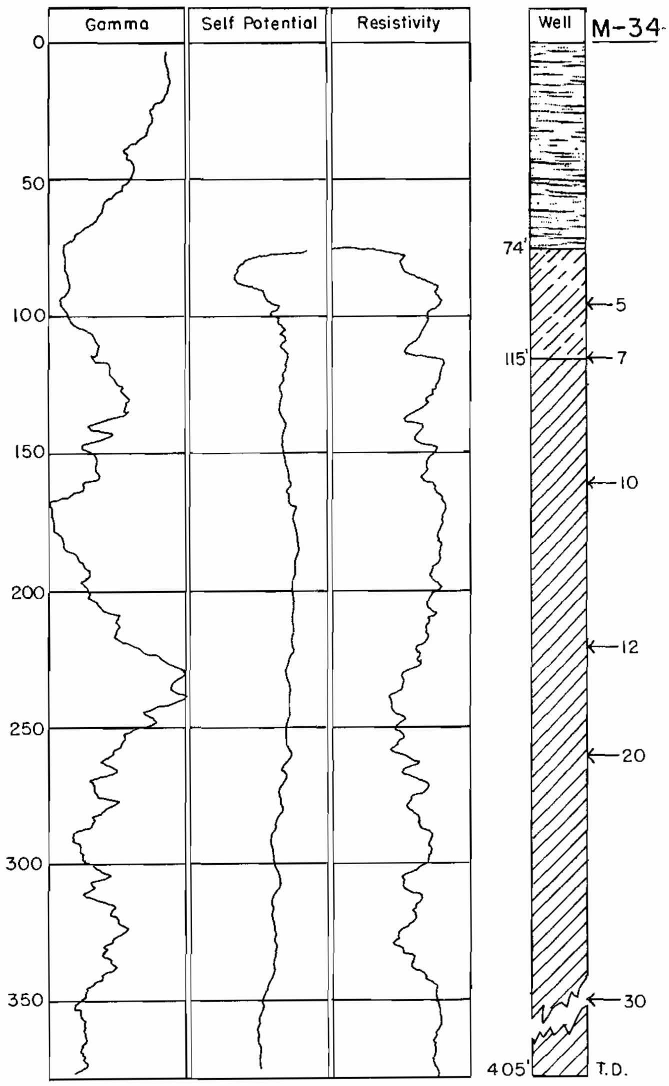


Figure 13 K Logs of Test Wells.



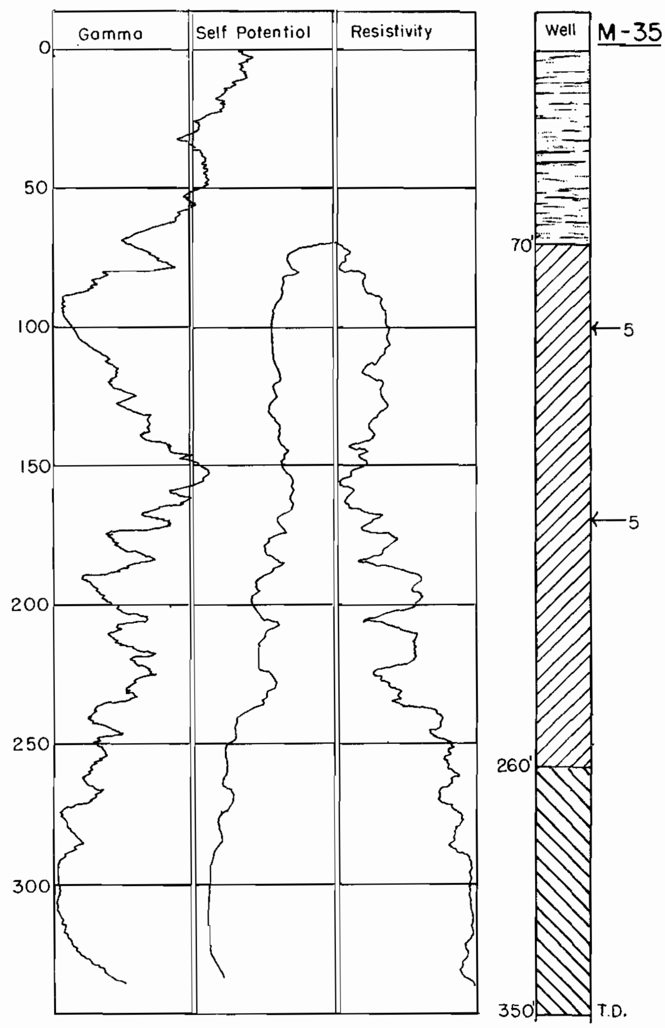


Figure 13 L Logs of Test Wells.

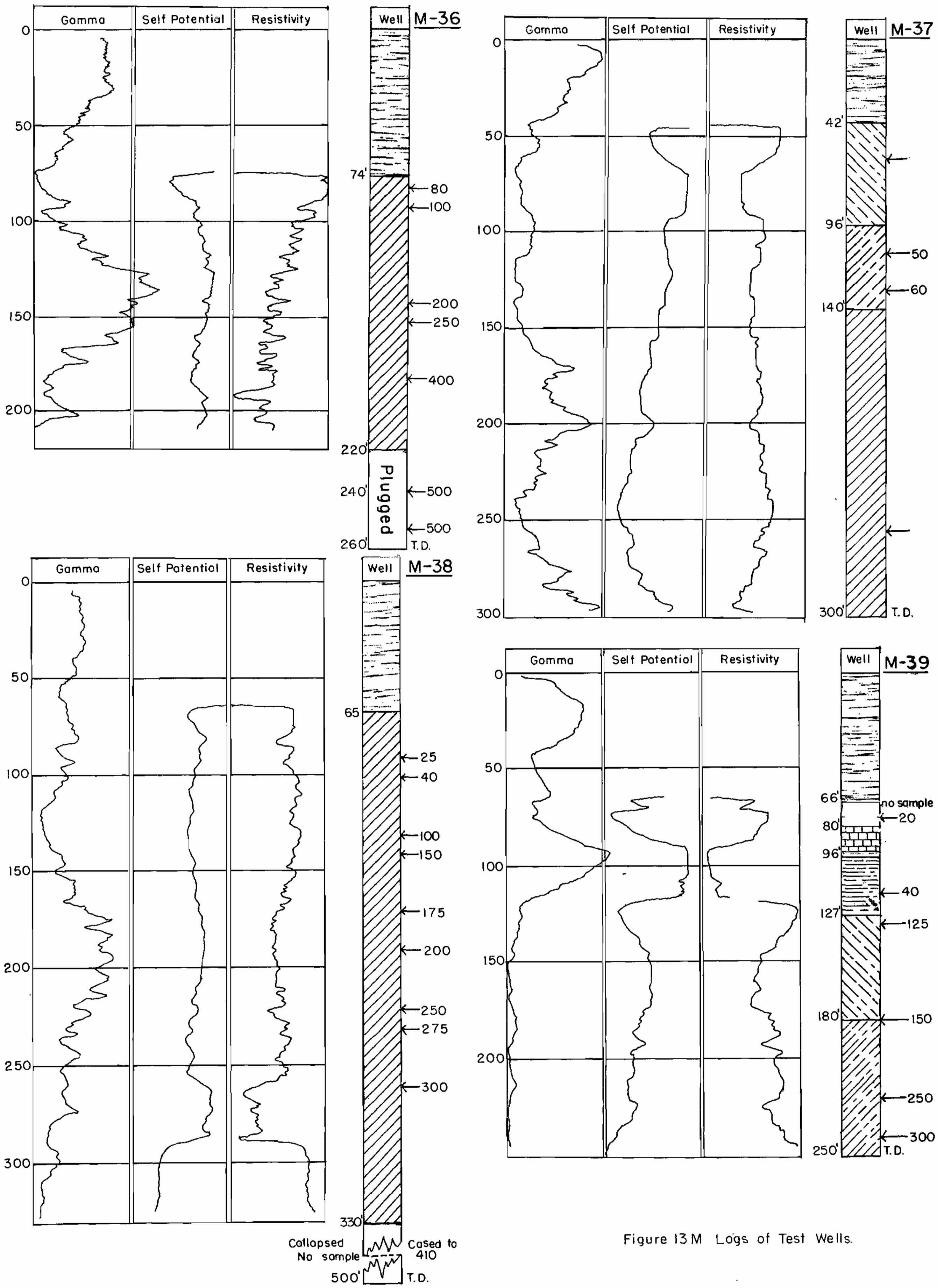


Figure 13 M Logs of Test Wells.

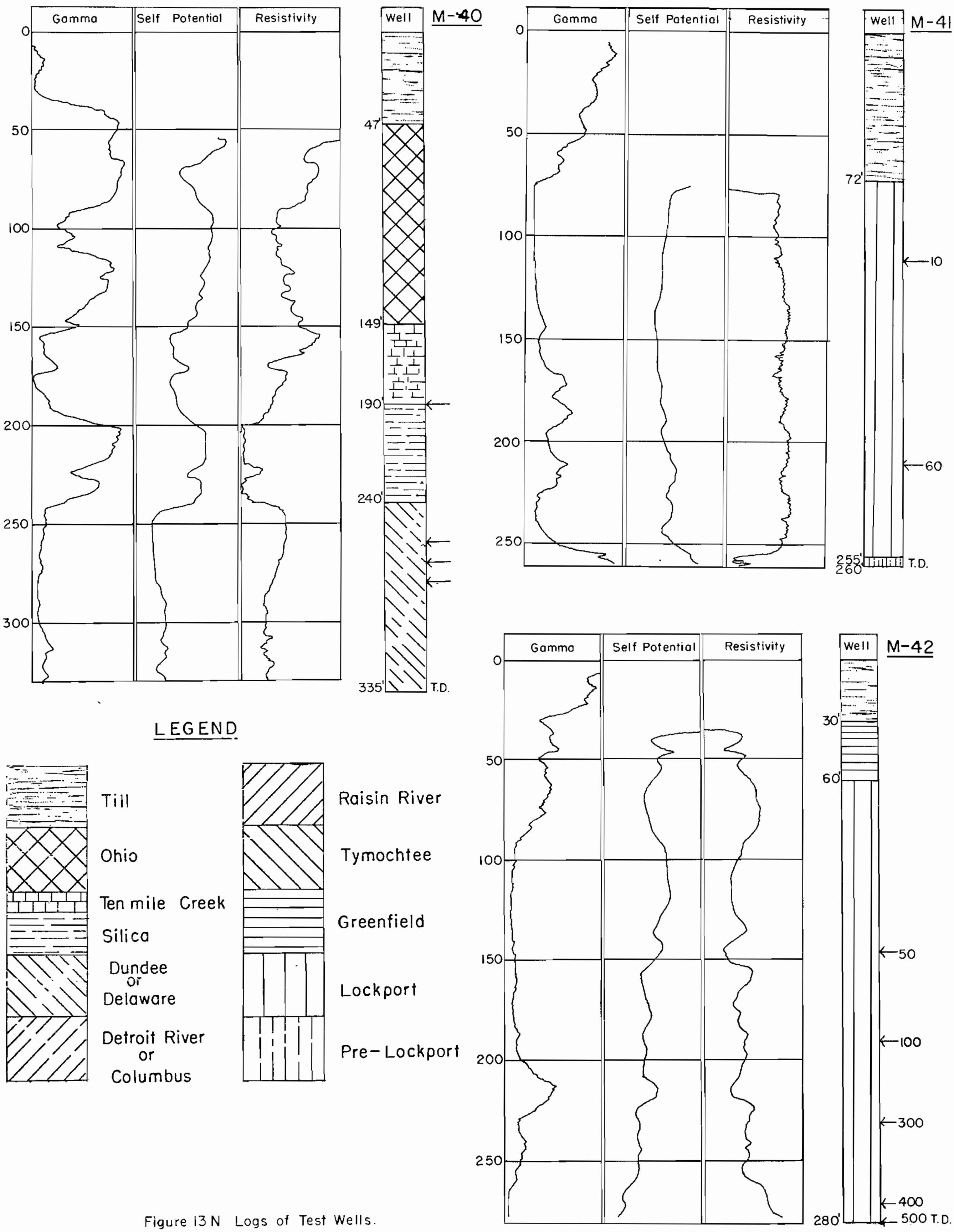


Figure 13 N Logs of Test Wells.

Figures beside well log denote depth, in feet, below land surface ——320'.
Water horizons are shown as ←—250, and estimated as gpm.

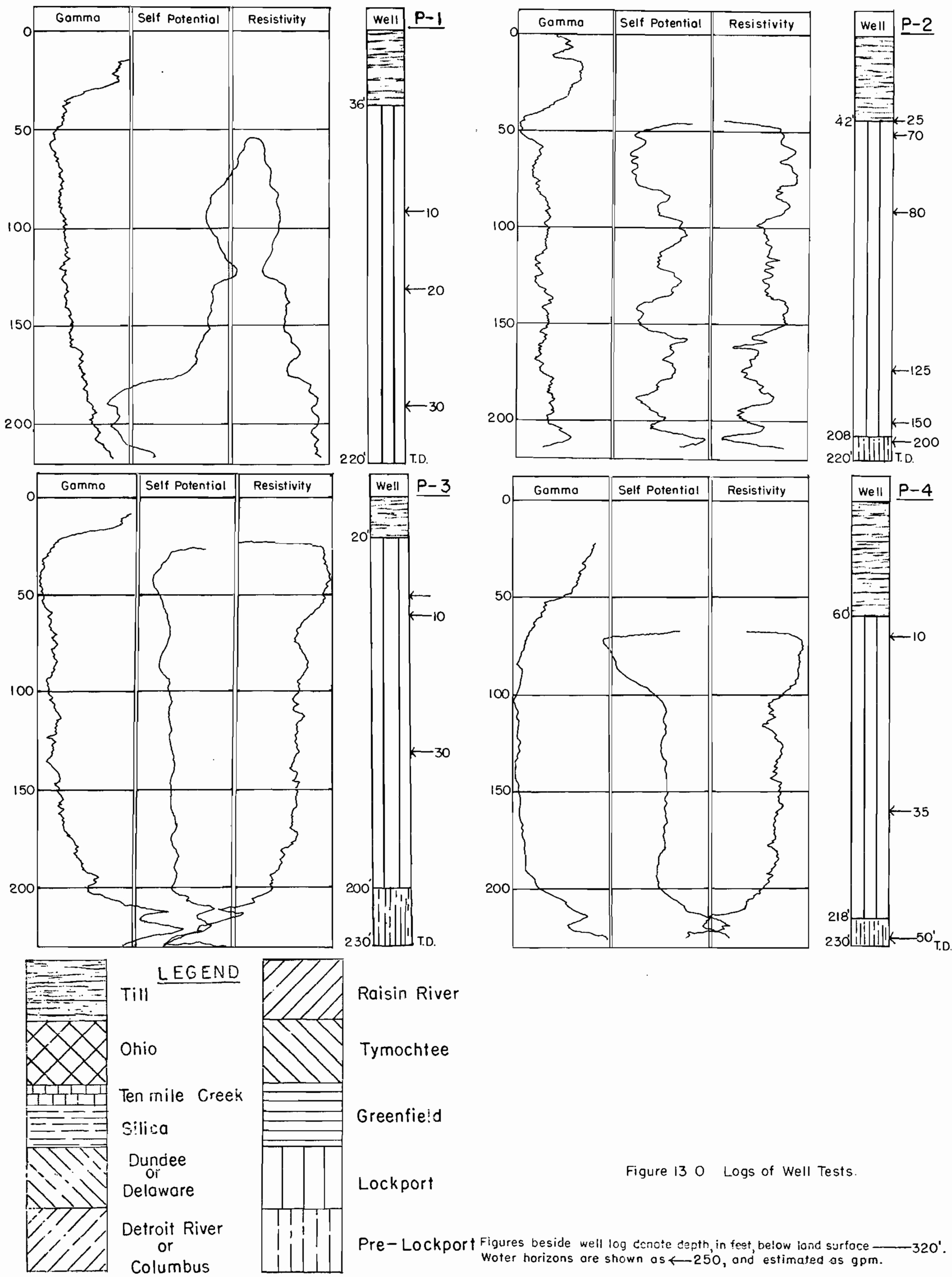


Figure 13 O Logs of Well Tests.

Figures beside well log denote depth, in feet, below land surface ——320'.
Water horizons are shown as ←250, and estimated as gpm.

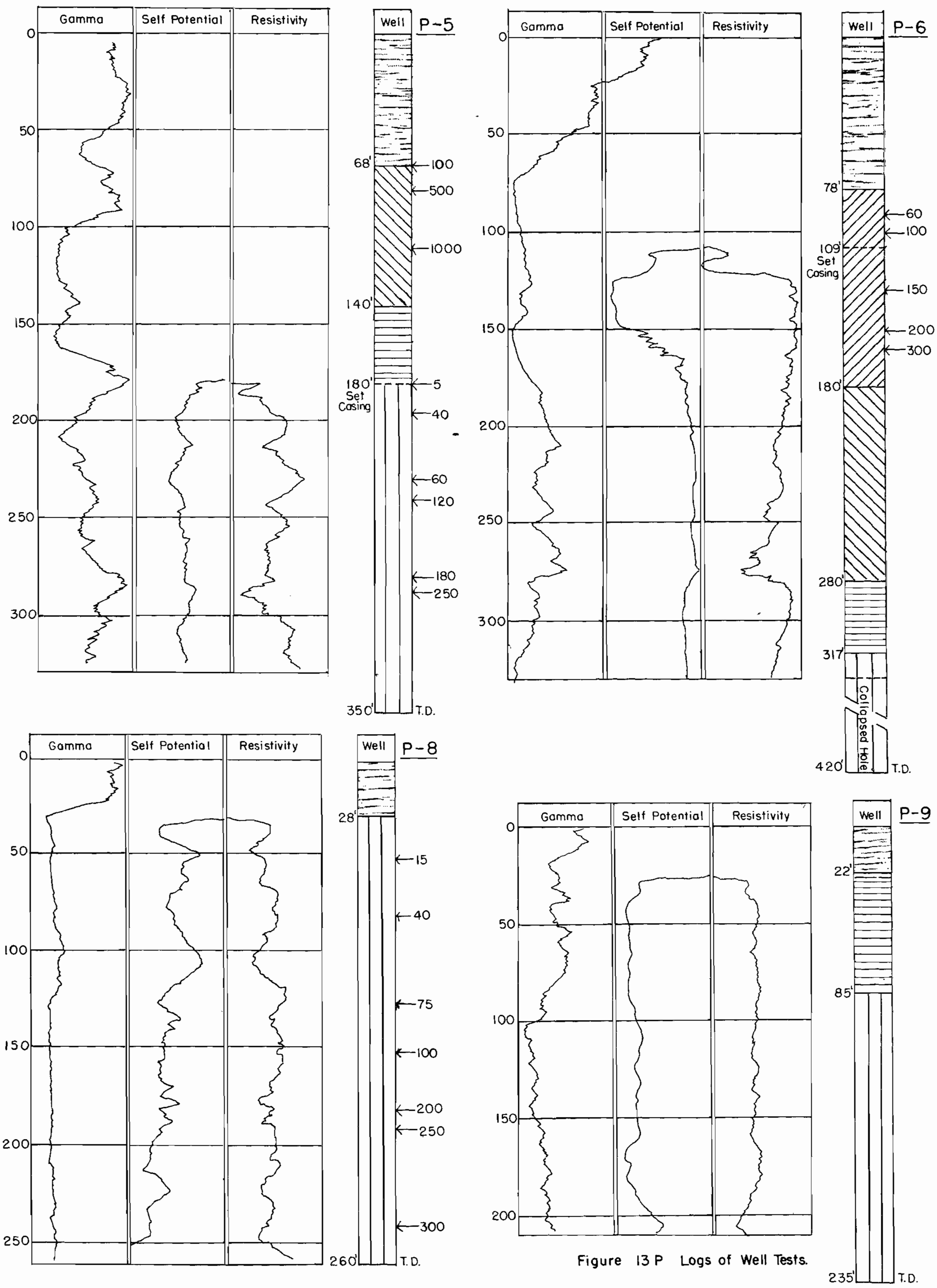
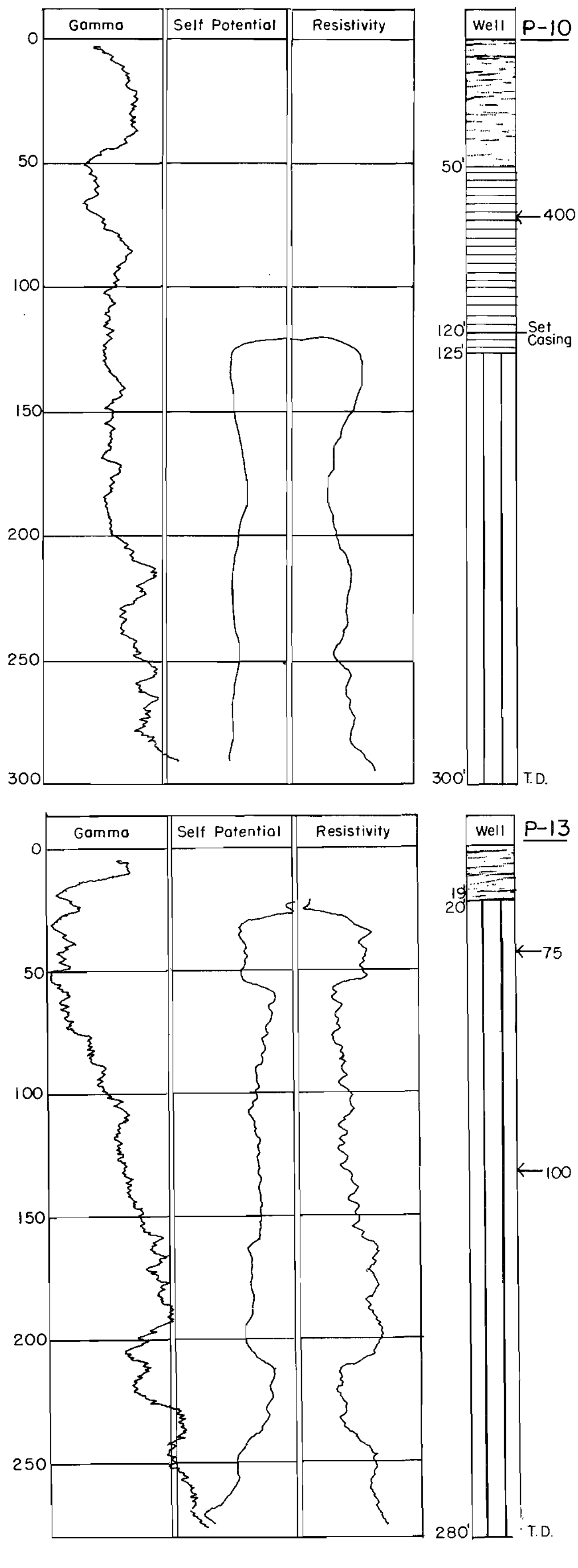


Figure 13 P Logs of Well Tests.



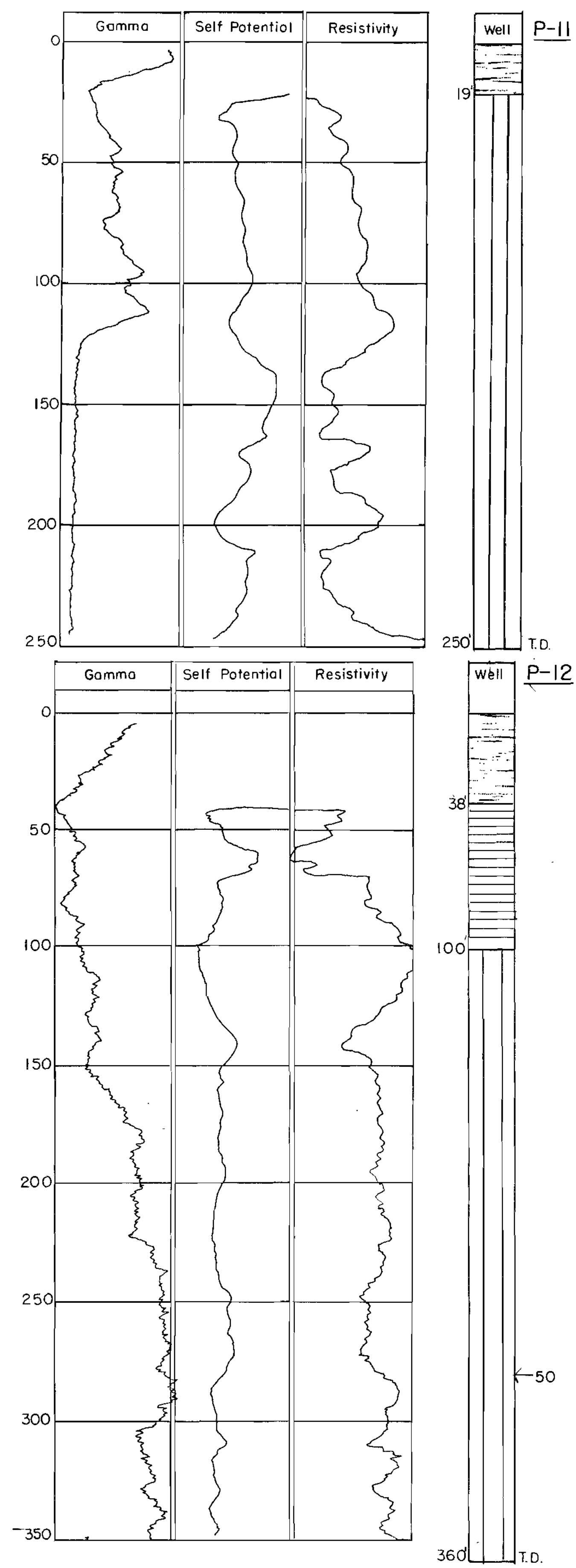


Figure 13 Q Logs of Test Wells.

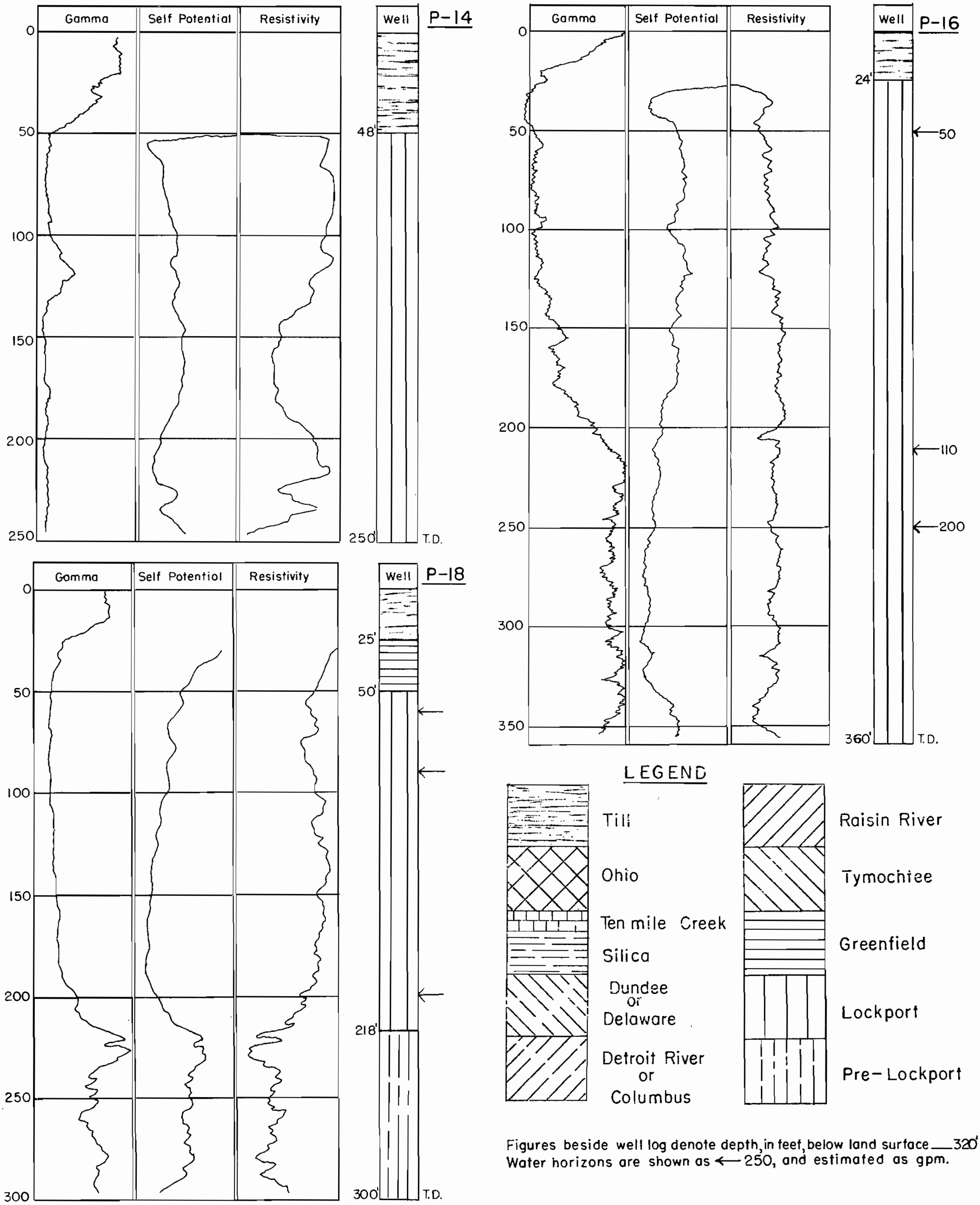


Figure 13 R Logs of Test Wells.

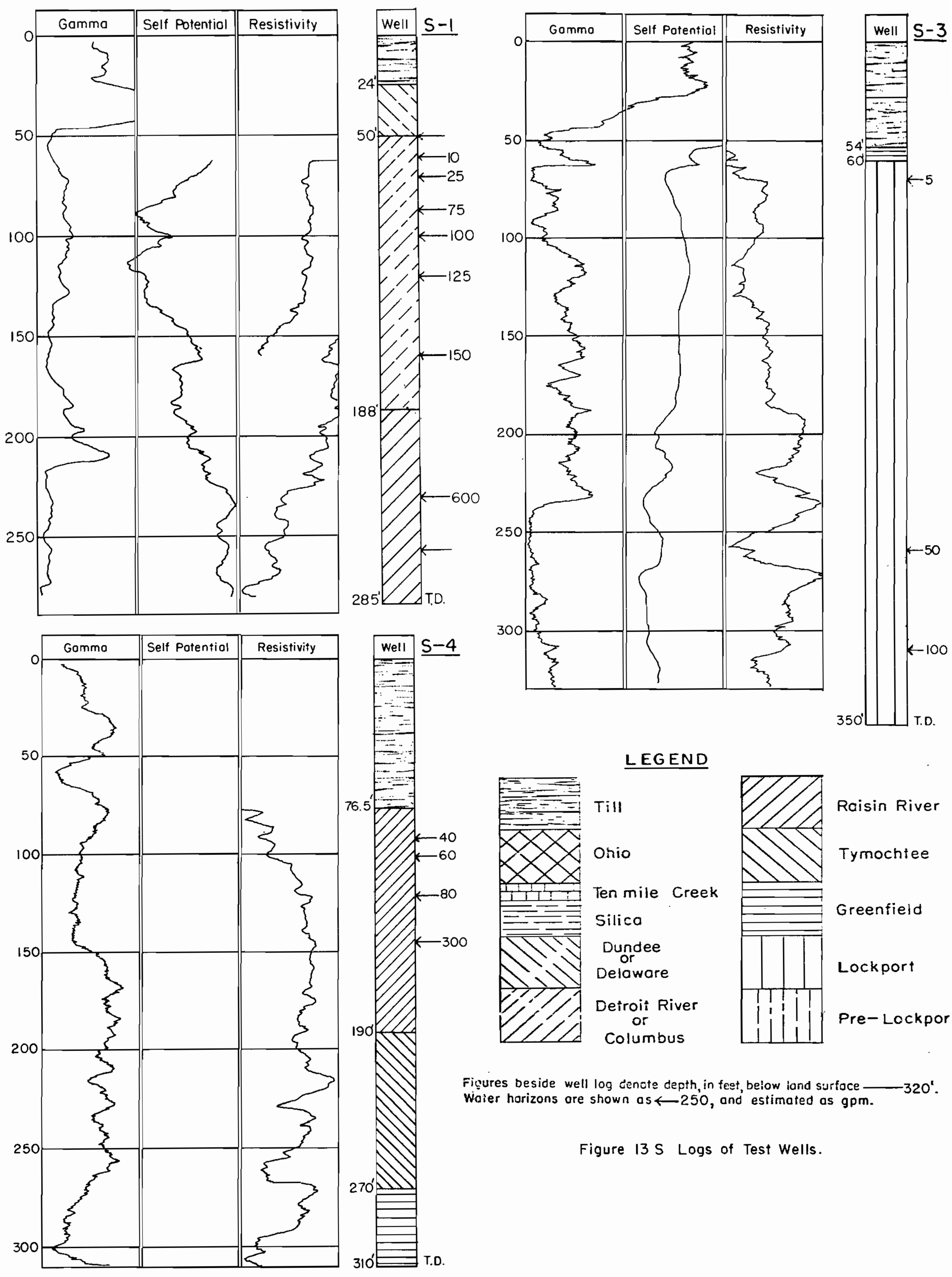
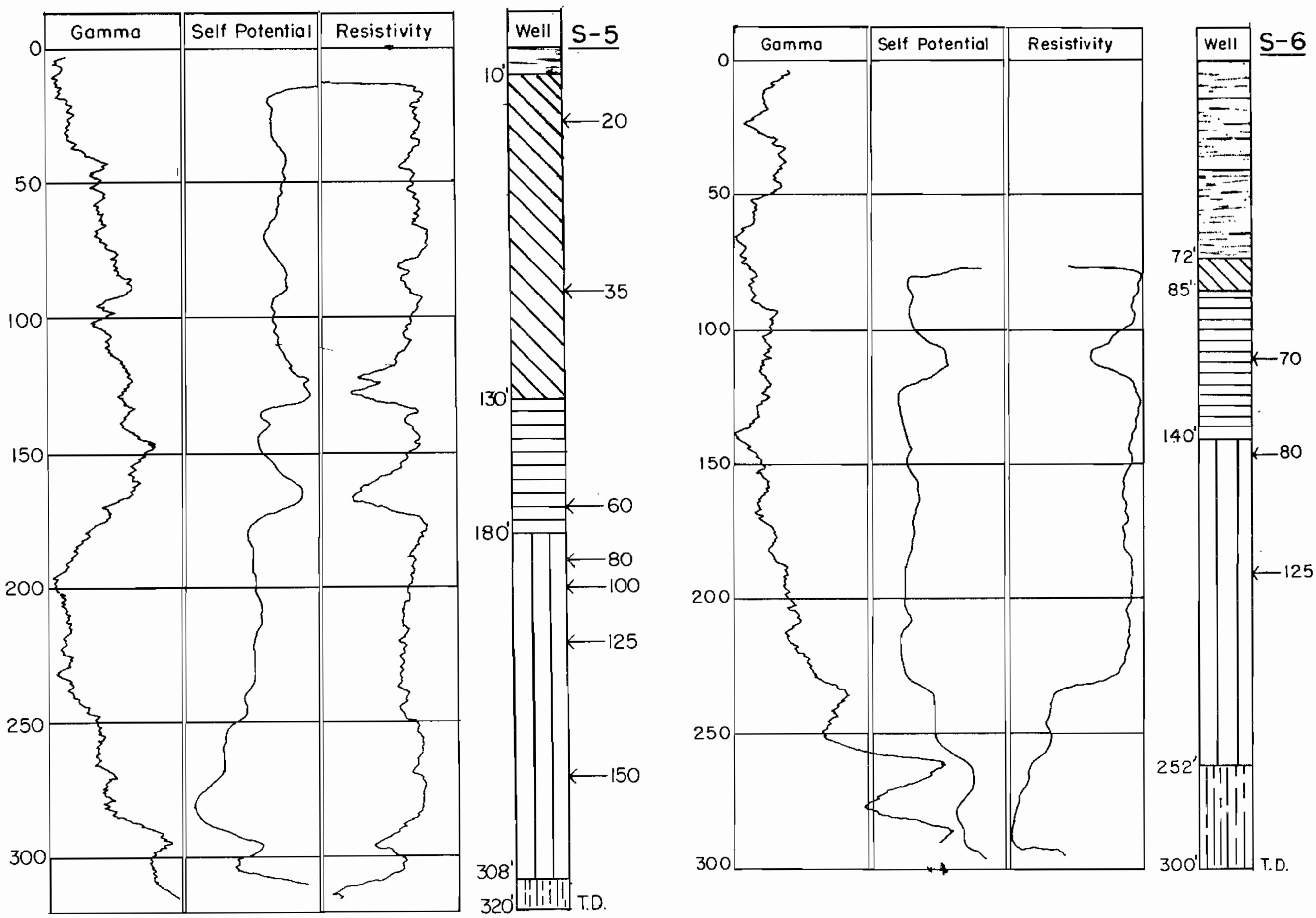


Figure 13 S Logs of Test Wells.



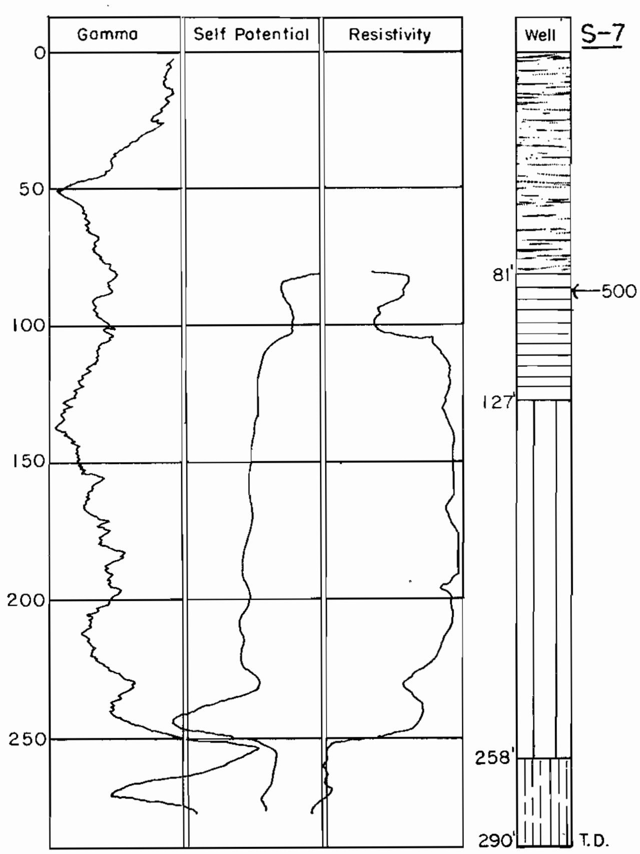


Figure 13T Logs of Test Wells.

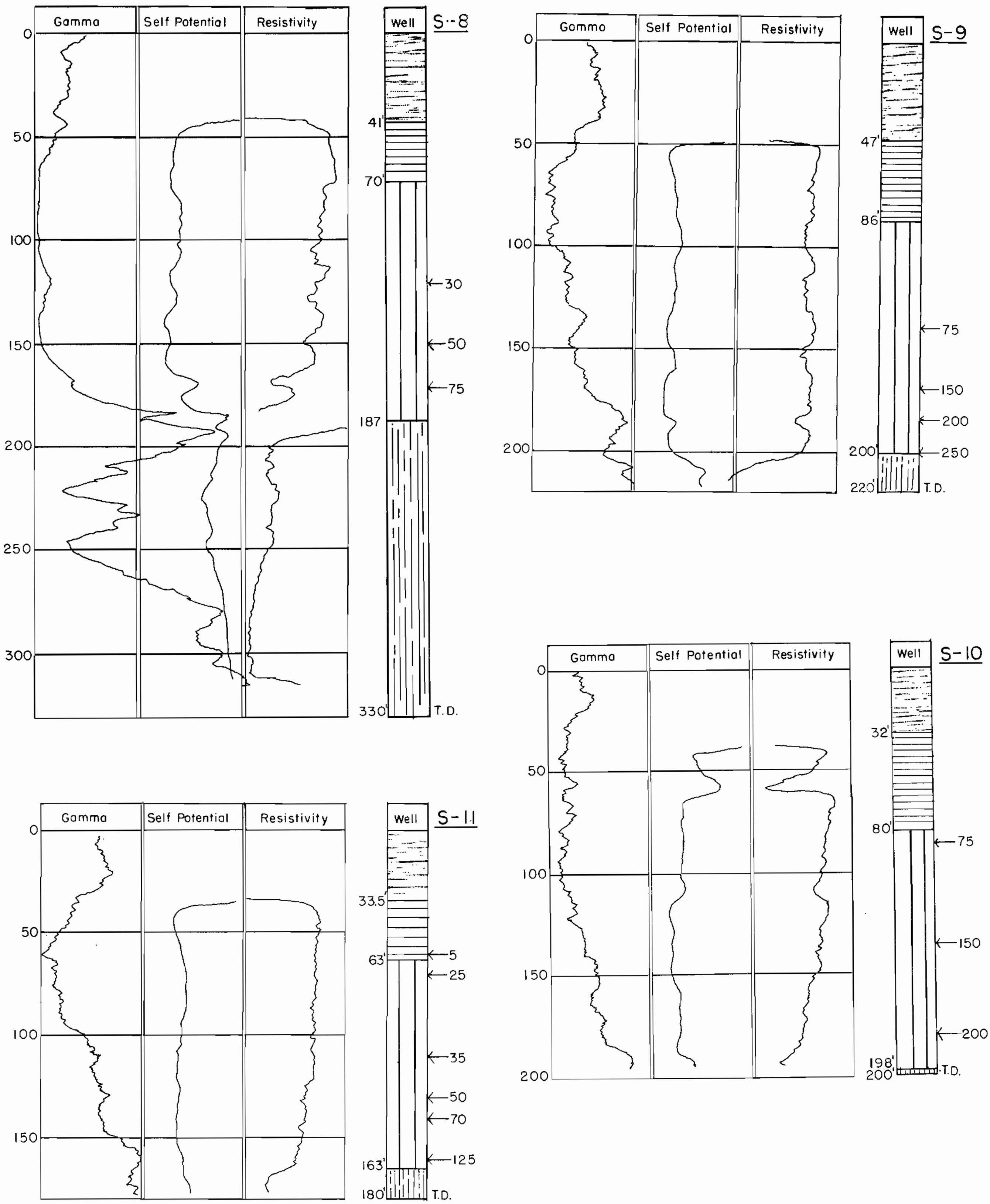


Figure 13 U Logs of Test Wells.

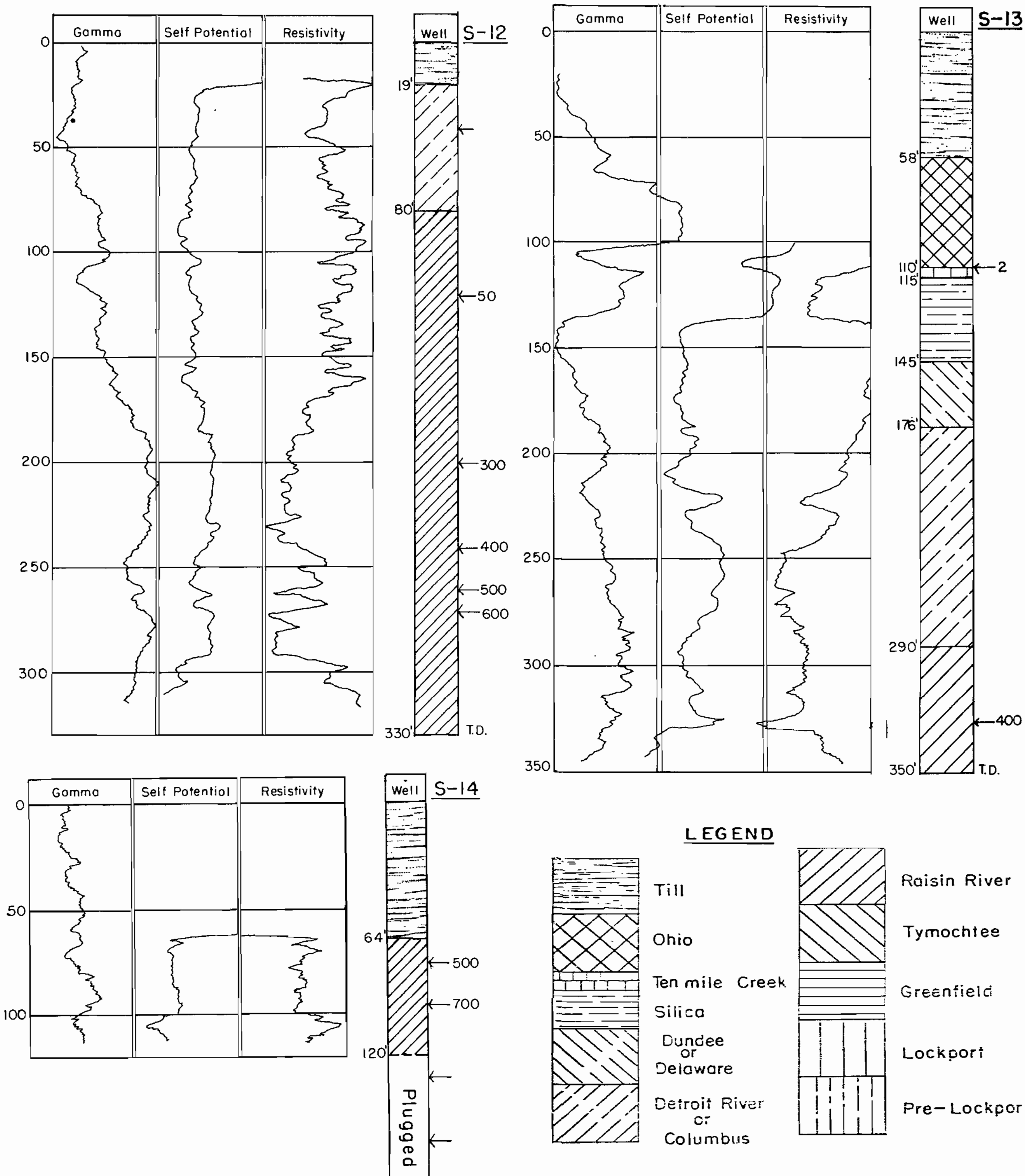
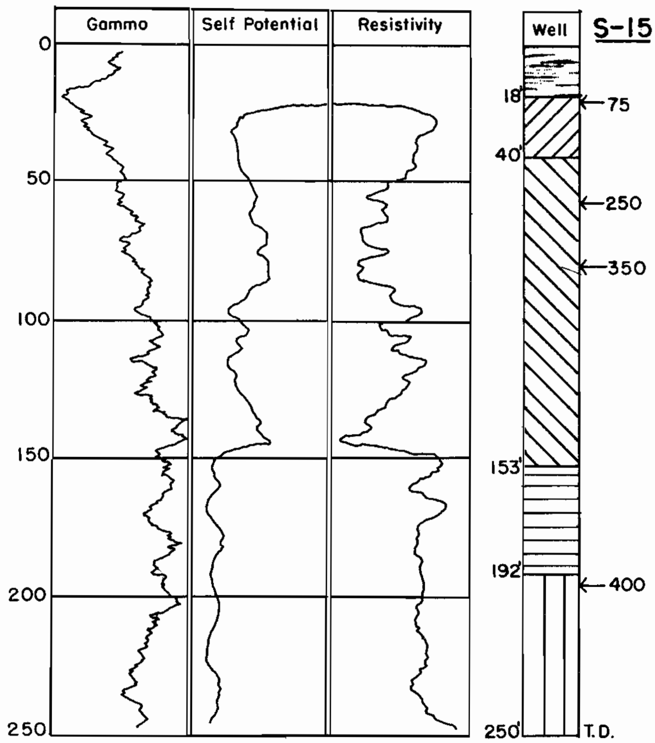


Figure 13 V Logs of Test Wells.

Figures beside well log denote depth, in feet, below land surface ——320'.
Water horizons are shown as ←—250, and estimated as gpm.



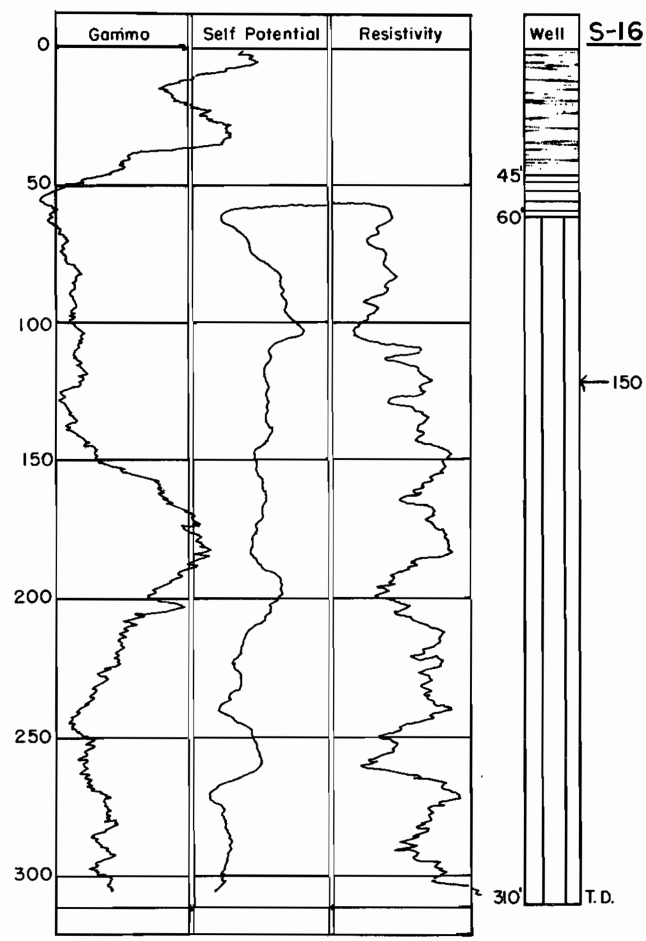


Figure 13 W Logs of Test Wells.

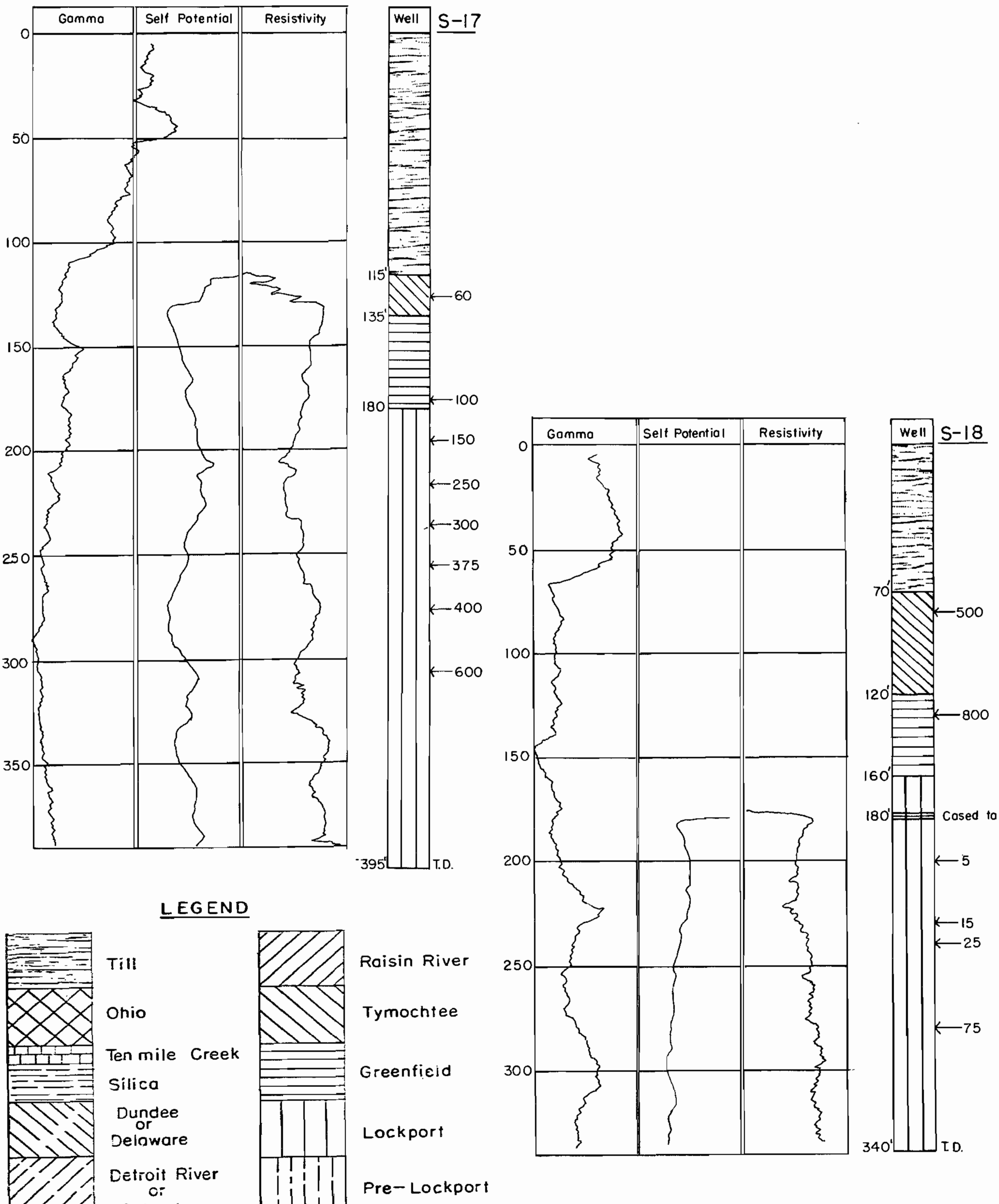


Figure 13 X Logs of Test Wells.

Figures beside well log denote depth, in feet, below land surface ———320'.
Water horizons are shown as ←—250, and estimated as gpm.

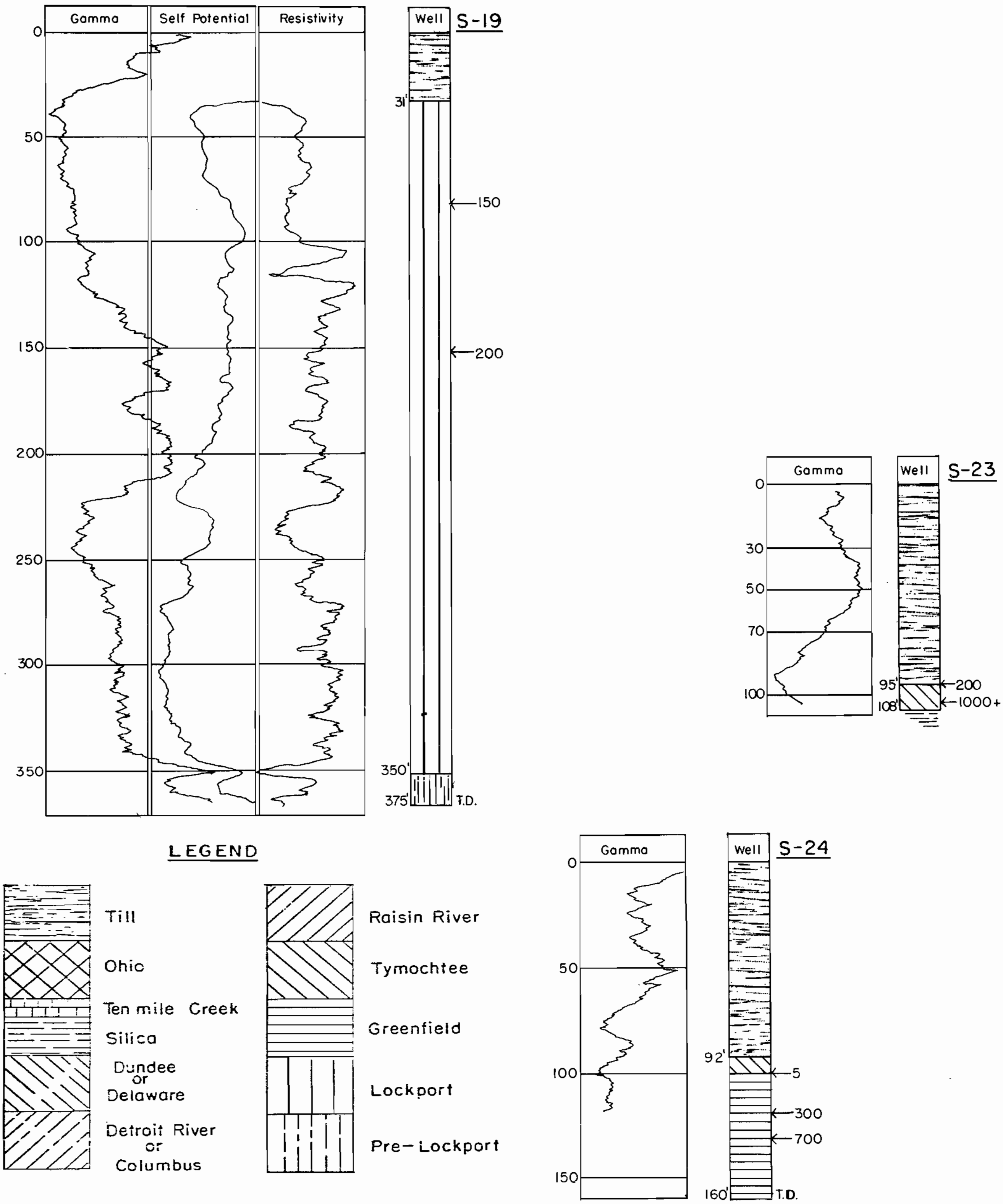


Figure 13 Y Logs of Test Wells.

Figures beside well log denote depth, in feet, below land surface ——320'.
Water horizons are shown as ←—250, and estimated as gpm.