AVAILABILITY OF WATER FROM LIMESTONE AND DOLOMITE AQUIFERS IN SOUTHWEST OHIO and the Relation of Water Quality to the Regional Flow System

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AVAILABILITY OF WATER FROM LIMESTONE AND DOLOMITE AQUIFERS IN SOUTHWEST OHIO AND THE RELATION OF WATER QUALITY TO THE REGIONAL FLOW SYSTEM

By Stanley E. Norris and Richard E. Fidler

ABSTRACT

The largest potential water supplies from the 150-to 450-foot thick carbonate-rock aquifer in southwest Ohio are available in a 2,800 square-mile area on the crest and east flank of the Cincinnati arch. The specific capacity of 26 test wells in this high-yield area ranged from 5.4 to 106 gallons per minute per foot of drawdown and averaged 30 gallons per minute per foot. The specific capacity of 23 test wells in the same rocks outside the high-yield area ranged from 0.5 to 5.0 gallons per minute per foot. Wells in the high-yield area produce mainly from the Newburg zone, a permeable stratum in the lower part of the Bass Islands Group, as used by the Ohio Division of Geological Survey. A structure contour map on the top of the Lockport Dolomite shows that the Newburg zone conforms to the configuration of the Cincinnati arch.

The chemical quality of the water in the consolidated-rock aquifers is intimately related to the regional flow system and undergoes a progressive change from a calcium bicarbonate type in recharge areas to a calcium sulfate type in areas of natural discharge.

INTRODUCTION

In 1970 the Ohio Department of Natural Resources, Division of Water, in cooperation with the U.S. Geological Survey, completed a 3-year investigation of the limestone and dolomite aquifers in northwest Ohio, in an area of about 9,000 square miles. The main part of the investigation was a comprehensive program involving the drilling, testing, and geophysical logging of 77 exploratory wells. Reports by Walker and others (1970) and Norris and Fidler (1971a, b) describe the physical framework, water-yielding properties, and water-quality characteristics of the principal carbonate-rock aquifer in this area. The investigation showed that additional large quantities of water of good chemical quality are available from the carbonate rock aquifer in northwest Ohio, in areas where geologic and hydrologic conditions are favorable. This widespread aquifer system presently is the source of approximately 35 mgd (million gallons per day) of water pumped by municipal and industrial wells.

Upon completion of the northwest Ohio investigation, the Ohio Division of Water and the U.S. Geological Survey began a similar cooperative study of the principal carbonate-rock aquifer in the southwest and central parts of the State, essentially covering the remainder of the outcrop area of the limestone and dolomite deposits in western Ohio. The investigation was made as part of the State's Southwest and Central Water Development Plans. These comprehensive plans are concerned not only with the carbonate-rock aquifers but with all water sources in the region, including sand and gravel aquifers and surface-water sources. The present report deals only with the principal carbonate-rock aquifer, the same aquifer system described previously in northwest Ohio. Reports by State personnel and private consultants employed by the State will cover other aspects of the water resources in the Southwest and Central project areas.

This investigation includes only those parts of the State's Southwest and Central project areas principally underlain by the chief carbonate-rock aquifer. (See fig. 9.) Covering most of the Southwest project area, but only the western half of the Central project area, the total study area includes approximately 12,210 square miles -- all or parts of 35 counties.

The present investigation of the carbonate-rock aquifer in southwest Ohio is similar to that made in northwest Ohio. Test wells in the limestone and dolomite were logged and tested by pumping for aquifer evaluation. Eighteen test wells were drilled in the State's Southwest project area, and 35 test wells were drilled in the Central project area. The wells ranged in depth from 200 to 425 feet; the average depth was about 315 feet.

Each of the test wells was cased to the limestone bedrock with 12-inch diameter steel casing. The remainder of the hole was uncased, except at two or three sites where an inside casing was installed to prevent caving or to test the lower part of the hole separately. The test wells were logged by personnel of the U.S. Geological Survey, who made natural gamma, single-point resistance, self-potential, and caliper logs with a portable hand-operated logger. Copies of the geophysical logs are contained in a series of open-file reports describing the drilling and testing of each of the test wells. The locations of the test wells are shown on the principal maps in the present report; those wells drilled as part of the Southwest project are prefixed SW; those drilled as part of the Central project are prefixed CP. Wells prefixed M and S relate to the northwest Ohio investigation (Norris and Fidler, 1971a).

The chief purpose of this report is to show that in southwest Ohio, as in the northwest part of the State, geologic structure played a key role in development of secondary permeability in the carbonate-rock aquifer. The high-yield area, in northwest Ohio, is extended into the present study area on the basis of recent test drilling. In addition, this report partly defines a zone of high permeability (the Newburg zone) that is a major source of water to wells drilled in the high-yield area.

As its secondary purpose, this report presents evidence showing that the chemical quality of water in the consolidated-rock aquifers is intimately related to the regional flow system. In the Northwest Ohio investigation (Norris and Fidler, 1971b), changes in the departure of the ground water from equilibrium with respect to calcite were used to delineate the principal areas of recharge to the aquifer. A somewhat different approach is used in the present work, which shows that a progressive change in chemical quality occurs as the water moves through the aquifer from recharge to discharge areas. Finally, this report describes the interpretation of the geophysical logs.

The authors are grateful for the assistance of Adriaan E. Janssens, geologist of the Division of Geological Survey, Ohio Department of Natural Resources, whose stratigraphic studies, based on examination of cuttings from the test wells, were extremely valuable in interpreting the geophysical logs. They also appreciate the assistance and cooperation of the staff geologists of the Division of Water, Ohio Department of Natural Resources, especially A. C. Walker, H. B. Eagon, Jr., J. J. Schmidt, D. E. Johe, R. B. Stein, and J. A. Noyes; and of the ground-water consultants employed by the State in the Southwest and Central projects, namely, J. M. Heckard and F. D. Bailly of Dames and Moore, and C. L. Simpson and D. R. Killius of F. H. Klaer, Jr. and Associates.

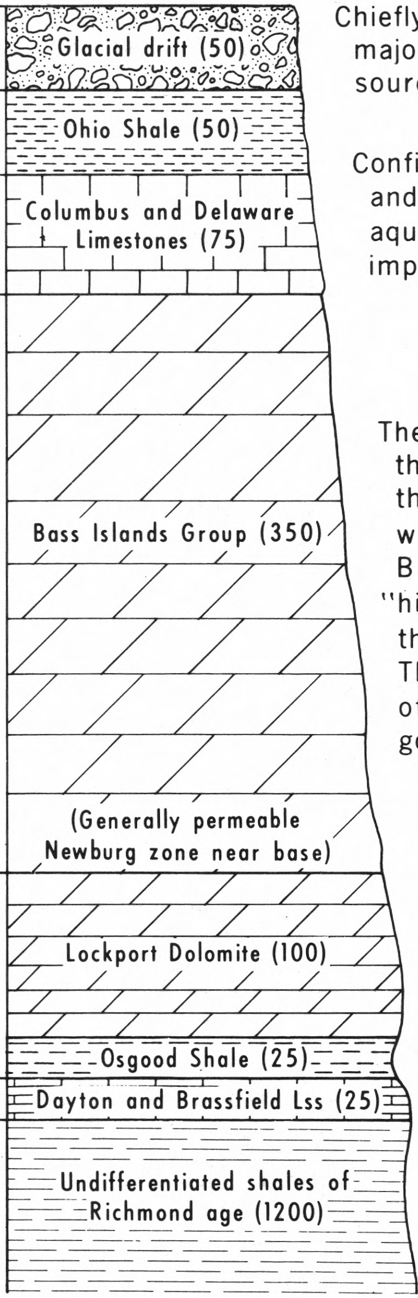
AQUIFER FRAMEWORK

The principal carbonate-rock aquifer in southwest Ohio is composed of hydraulically interconnected beds of limestone and dolomite, consisting primarily of the Lockport Dolomite of Middle Silurian age, and the overlying Bass Islands Group (chiefly dolomite) of Late Silurian age (fig. 1). These carbonate beds crop out or lie beneath glacial deposits with a wide range in thickness in about 10,000 square miles in the northern and east-central parts of the study area. (See figs. 2 and 9.)

The consolidated rocks in southwest Ohio were raised by tectonic forces early in geologic time to form the broad, low Cincinnati arch, a slightly northeast-tilted regional upwarping, whose long axis extends from southwest to northeast across western Ohio, from Cincinnati approximately through Dayton, Springfield, Urbana, and Kenton. (See fig. 9.) Erosion, in pace with uplift, reduced the consolidated rocks to a generally even plain, exposing progressively older beds along the top of the arch in a southwesterly direction. The carbonate beds that constitute the principal aquifer were removed by erosion in the southwestern quarter of the study area, in an area of approximately 3,700 square miles, leaving exposed, or thinly covered by glacial drift, a thick sequence of thinly bedded and, for all practical purposes, nonwater-bearing shale and shaly limestone beds of Ordovician age (see fig. 3).

Peripheral to this area of Ordovician rocks, the Lockport Dolomite constitutes the bedrock in an irregular band, underlying approximately 3,400 square miles in all or parts of 15 counties. The outcrop band is narrowest in the southern part of the study area, near the Ohio River in central Adams County, and widest in the northwest part of the study area, where it underlies virtually all of Darke, Mercer, and Shelby Counties and significant parts of adjacent counties (fig. 2).

As shown by the structure contour maps, figures 2 and 3, the carbonate beds are nearly flat lying on the top of the Cincinnati arch in Logan County and southeast Hardin County and dip away from the crest of the arch on both sides at low angles. In the northwest part of the study area, the dip of the Lockport Dolomite on the west side of the arch is to the north and northwest 5 to 10 feet per mile. On the east side of the arch, the regional dip on the Lockport is somewhat steeper, about 25 feet per mile along a line extending from east-central Champaign County into eastern Franklin County.



GEOLOGIC AGE	LITHOLOGY AND TYPICAL THICKNESS (FT)	DESCRIPTION
Pleistocene	Glacial drift (50)	Chiefly till (clay) on uplands, sand and gravel in major valleys. Sand and gravel is major water source in parts of southwest Ohio.
Upper Devonian	Ohio Shale (50)	Confined chiefly to eastern part of study area and not considered part of the carbonate-rock aquifer in this report. The limestone beds are important locally as sources of ground water.
Middle Devonian	Columbus and Delaware Limestones (75)	
Upper Silurian	Bass Islands Group (350) (Generally permeable Newburg zone near base)	The Bass Islands Group (chiefly dolomite) and the Lockport Dolomite together constitute the principal carbonate-rock aquifer in western Ohio. Highest yields are from the Bass Islands Group, from wells drilled in the "high yield" area, especially those drilled to the Newburg zone near the base of the unit. The Lockport Dolomite is also a good source of ground water where the unit has undergone weathering at or near the surface.
Middle Silurian	Lockport Dolomite (100)	
	Osgood Shale (25)	Not a source of ground water.
Lower Silurian	Dayton and Brassfield Lss (25)	Poor water source, especially where deeply buried.
Ordovician	Undifferentiated shales of Richmond age (1200)	Soft, calcareous shale, interbedded with thin, hard limestone layers. Called Cincinnati shale in old reports. Not generally a source of ground water.

Figure 1.--Generalized section of the consolidated rocks in southwest Ohio.

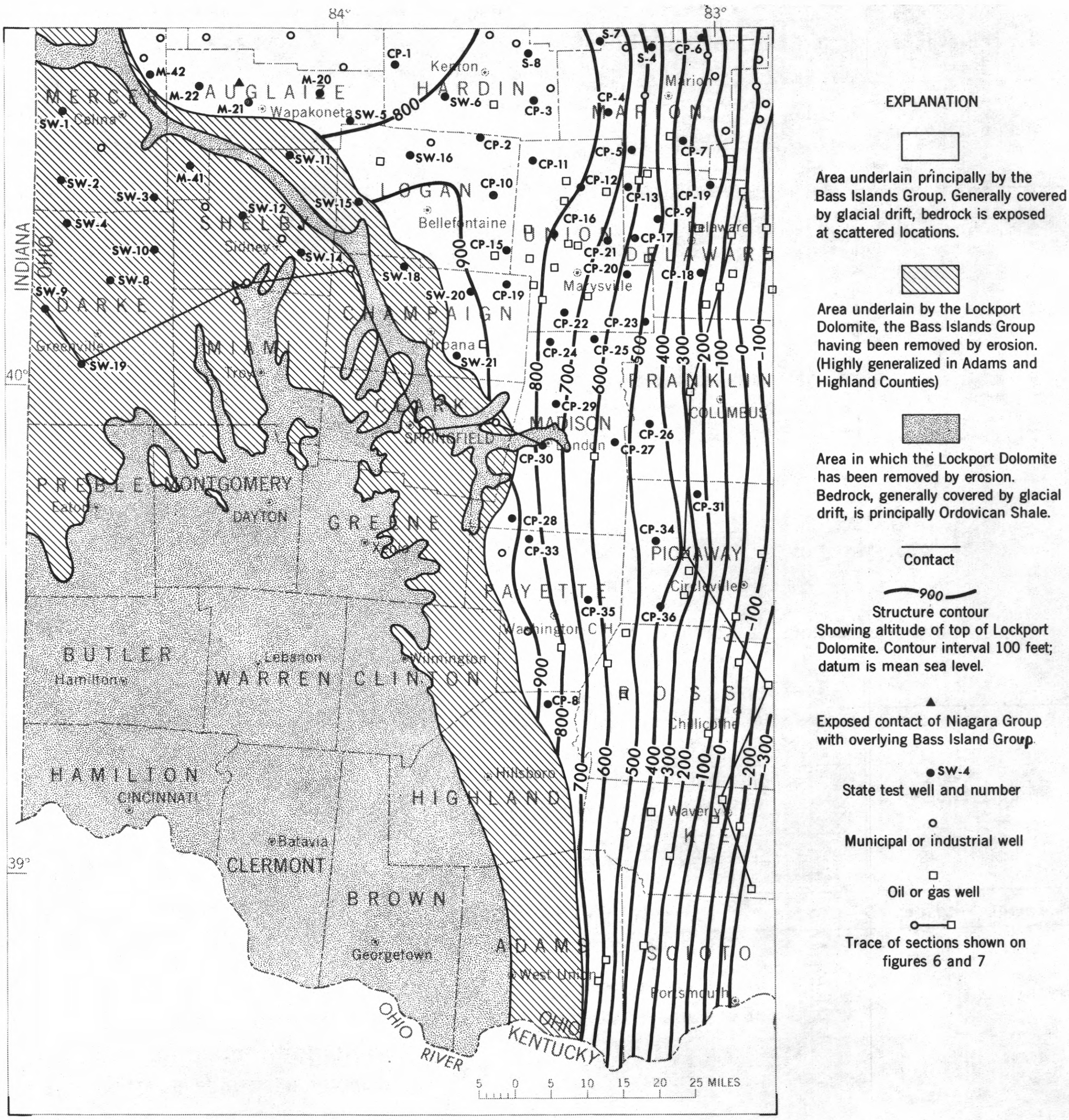


Figure 2.--Map of southwest Ohio showing approximate structure contours on the Lockport Dolomite.

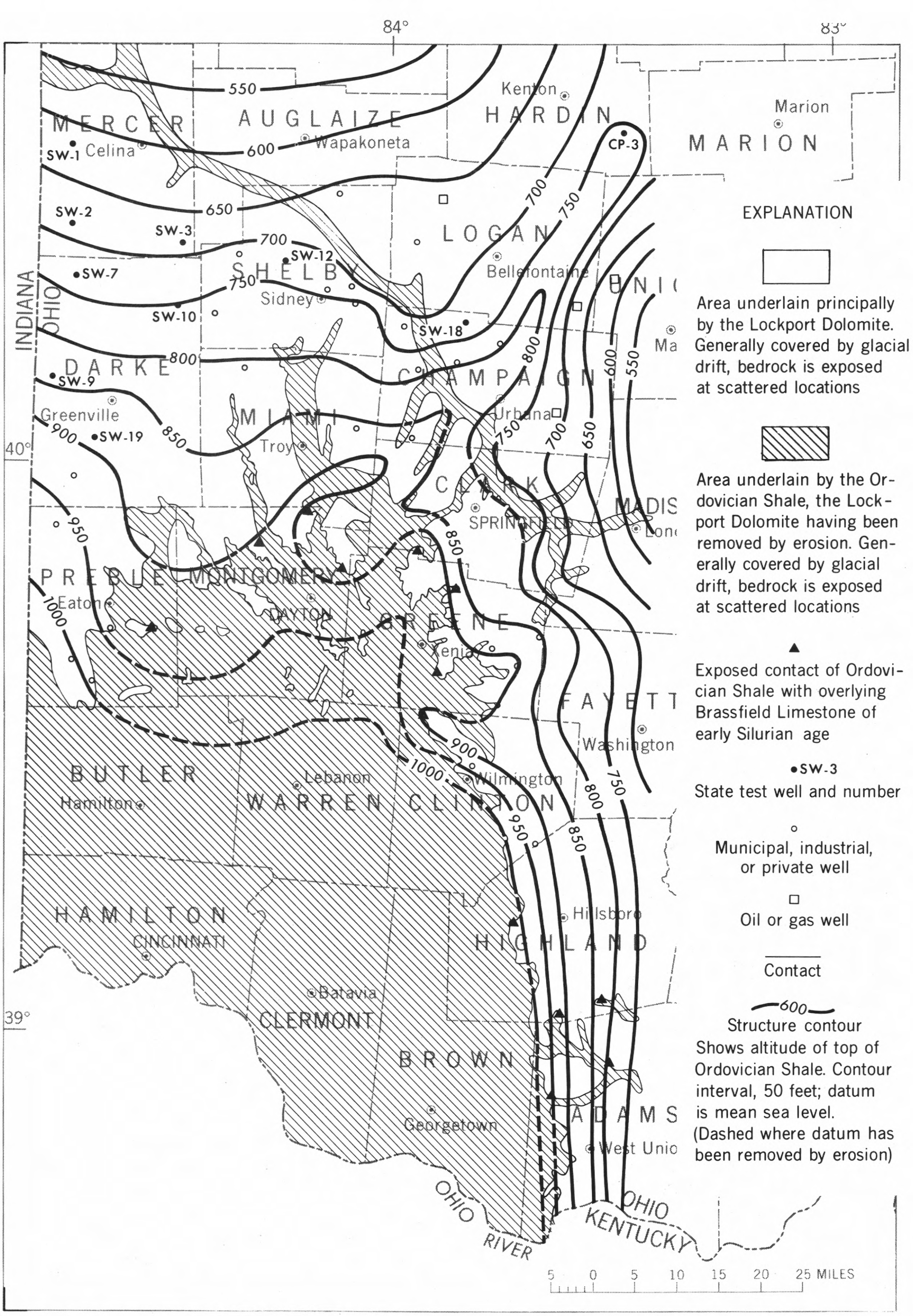


Figure 3.--Map of southwest Ohio showing approximate structure contours on the Ordovician shale.

The carbonate beds thicken on both sides of the arch in the direction of dip. The aggregate thickness of the entire carbonate sequence ranges from zero at the outcrop in western Ohio to (about) 600 feet at Columbus, where it includes approximately 130 feet of Columbus and Delaware Limestones. Typically, the carbonate aquifer is from 150 to 450 feet thick in most of the area where it is a principal source of ground water.

The Lockport Dolomite ranges in thickness from zero in the outcrop area, where it pinches out against the older rocks, to about 250 feet in the vicinity of Celina, in Mercer County. The unit thins southeastward, beneath a thickening cover of younger rocks, to about 65 feet near London, in Madison County, where the top of the stratum, at the site of test well CP-30, occurs at a depth of 261 feet. (See fig. 6.)

The Lockport is an exceptionally pure light-gray to white finely to coarsely crystalline dolomite, typically occurring in beds ranging in thickness from a foot to about 5 feet. Locally, it grades into reeflike masses, with little or no discernible bedding. The change from normal bedding to the reeflike phase is accompanied by a large increase in thickness; it is estimated that reefs characterize the unit wherever it is more than about 100 feet thick.

Overlying the Lockport Dolomite and constituting the bedrock in most of the eastern and northern parts of the study area, is a wedge-shaped sequence of carbonate beds of the Bass Islands Group. The Bass Islands rocks are generally more permeable than the Lockport Dolomite and are the principal source of ground water in the area of several hundred square miles adjacent to the Lockport outcrop. Locally in parts of Logan and Champaign Counties and more generally in counties along the eastern boundary of the study area, the Bass Islands Group is overlain by Middle Devonian limestones (Columbus and Delaware Limestones) and shale (fig. 1).

The Bass Islands Group, as used by the Ohio Division of Geological Survey, consists generally of a thinly bedded brown to drab crystalline to granular argillaceous dolomite. There is, however, much variation in lithology from place to place. Carman (1927, p. 485) states that although rocks fitting the general description of the Bass Islands Group can be found in all the constituent members, "each member also has one or more other types of stone within it. There are zones of massive permeable dolomite, of evenly bedded nonlaminated dolomite, of brecciated dolomite, of dolomitic shale, of limestone, and of gypsum."

One of the difficulties in correlating individual units in the Bass Islands Group stems from the fact that the outcrop area is generally covered by glacial drift, and exposures of the bedrock are typically small and scattered. In addition, the rocks contain few fossils, and it becomes nearly impossible to trace individual beds for any appreciable distance on the surface.

Most problems in correlation involve the upper part of the Bass Islands Group. The lower part comprises two generally recognized units, the Greenfield Dolomite at the base and the overlying Tymochtee Formation. In northwest Ohio, rocks above the Tymochtee Formation were called by Janssens (in Walker and others, 1970, table 1) the Raisin River Dolomite. However, in the southwest Ohio study area Janssens (oral commun., 1972) prefers to refer to these rocks as undifferentiated Salina, pending his completion of current stratigraphic studies. In this report, rocks above the Tymochtee Formation are referred to simply as the upper Bass Islands Group, as used by the Ohio Division of Geological Survey.

The Greenfield Dolomite, about 50 feet in average thickness, is described at the type locality in Highland County by Carman (1927, p. 486) as "a drab, fine-grained dolomite with carbonaceous partings and commonly in beds of 2-6 inches, although at places with thicker beds or massive ledges. This massive phase is rough textured and vesicular, with corals and stromatoperoids, and is a kind of reef rock which at places can be seen to pass laterally into the even-grained, bedded type." There are no known exposures in the southwest Ohio study area of the contact between the Greenfield Dolomite and the underlying Lockport Dolomite or between the Greenfield Dolomite and the overlying Tymochtee Formation. In northwest Ohio such contacts, where exposed, range from disconformable, in which there is a sharp and clearly evident break between beds of the respective units, to conformable and gradational, in which it is difficult to distinguish between the beds of a unit and those of the underlying or overlying unit.

The Tymochtee Formation, about 100 feet in average thickness, is more shaly than the remainder of the Bass Islands sequence. Carman (1927, p. 488) describes the Tymochtee Formation as a "drab, thin-bedded, laminated, argillaceous dolomite with much carbonaceous material as partings along the bedding planes. It is the most shaly member ... and at places contains distinct zones of shale."

Rocks of the upper Bass Islands Group, as used by the Ohio Division of Geological Survey, typically consist of drab to brown finely crystalline dolomite. Cuttings from scattered wells contain local evidence of carbonaceous material and traces of chert and gypsum.

The Dayton Limestone and the Brassfield Limestone, both of Early Silurian age, together make up a 15 to 50-foot thick stratum that underlies the Lockport Dolomite and is separated from the Lockport by 5 to 40 feet of Osgood Shale (fig. 1). The water-yielding properties of the Dayton and Brassfield Limestones were not systematically explored in this investigation. Although nearly 40 percent of the test wells were drilled deeply enough to reach these carbonate units, they did so only after penetrating considerable thicknesses -- 110 to 390 feet -- of overlying rocks. The wells were uncased and water was free to enter at all levels. No special tests were made to determine the quantity of water yielded by each of the contributing beds. In those drillers' logs in which mention is made of the depths at which water entered the well as it was being drilled, the notes indicate that very little of the total yield came from that part of the hole open to the Dayton and Brassfield Limestones. Neither high yields nor water of good quality would be expected from the Dayton and Brassfield Limestones where these units are deeply buried and separated from the overlying aquifers by the relatively impermeable Osgood Shale.

Permeability in the carbonate rocks in southwest Ohio is primarily the result of solution by water moving through joints and other openings, including intergranular openings, in the rocks. Most permeability developed in the geologic past in association with the erosional processes by which the beds were progressively removed from the top of the rising Cincinnati arch. For long intervals the arch area lay at or slightly above sea level, with only the structurally and topographically higher beds emergent and subject to ground-water circulation. The beds that underwent most solution and, consequently, those now having the highest permeability ring the arch in northwest Ohio (Norris and Fidler, 1971a). The permeable beds extend completely across the crest and partway down the flanks of the arch in the northern part of the southwest Ohio study area. Also, in southwest Ohio there is evidence of a zone of inherent permeability in the lower part of the Bass Islands Group, called the Newburg zone, the permeability of which has been increased by ground-water circulation and solution.

Circulation in the carbonate rocks is greatest at or a little below the water table. Thus, the zone of maximum permeability in southwest Ohio is determined to a large extent by the range in the position of the water table over geologic time. In the eons following the final emergence of the southwest Ohio land mass there no doubt occurred a certain amount of upward and downward shifting in the position of the water table, perhaps over a range of several tens of feet, as suggested by the extensive development of permeability vertically within the aquifer. A major readjustment of the water table occurred with the onset of glaciation. Before the Pleistocene the streams in western Ohio were deeply entrenched in the limestone. The master stream of the preglacial drainage system, the Teays River -- its valley now abandoned and deeply filled with glacial drift in much of western Ohio -- declined in altitude from 568 feet in south-central Madison County to 538 feet in southern Champaign County (Norris and Spicer, 1958, p. 218). By comparison, the altitude of the bed of the Great Miami River at Dayton is approximately 720 feet, and the altitude of the bed of the Scioto River at Columbus is about 680 feet. Thus, the water table in southwest Ohio just before glaciation was significantly lower than it is today, perhaps as much as 200 feet lower in some areas. Development of permeability was related to the position of this former base level, which in much of the study area is below the base of the carbonate aquifer. In the time required for establishment of this low base-level control, the water table moved through virtually the full thickness of the carbonate aquifer, resulting in the development and enlargement of solutional openings at all levels.

Water in the carbonate aquifer occurs under both confined (artesian) and unconfined (nonartesian) conditions. The former is the more common, owing to the widespread blanket of poorly permeable glacial till that generally overlies the bedrock. Also, the dip of the carbonate beds away from major recharge areas along the top of the Cincinnati arch results in the progressive deepening of the zones of highest permeability away from the crest. As the water moves through the carbonate rocks towards points of discharge along the major streams, it becomes increasingly confined beneath this thickening cover of less permeable rock. The water level in relatively deep wells drilled in topographically low areas typically rises above the water table, as indicated by the water level in shallow wells. In some areas the regional potentiometric head is sufficient to raise the water to the surface and produce free-flowing artesian wells from the deeper beds.

INTERPRETATION OF THE GEOPHYSICAL LOGS

The geologic structure maps, figures 2 and 3, which show contours on the top of the Lockport Dolomite and the Ordovician shale, respectively, are based largely on data from gamma logs. These logs were made by the U.S. Geological Survey in the State test wells and in a scattering of public and private wells and were supplemented by gamma logs of oil and gas wells made by commercial logging companies and available from the files of the Ohio Department of Natural Resources, Division of Geological Survey.

A gamma log reveals differences in lithology by showing variations in natural gamma radiation with depth. Representative gamma logs of test wells CP-12 and CP-24 (figures 4 and 5) show the contrast in radiation between the Lockport Dolomite and the underlying and overlying beds. A relatively pure carbonate rock, the Lockport has low radiation properties. On the typical gamma log the section corresponding to the Lockport is relatively featureless, especially in the upper part, and distinctly different than the log sections above and below. However, despite differences in the respective log sections, the contact of the Lockport Dolomite with the overlying Bass Islands rocks is difficult to determine with confidence on some logs. The authors' method of picking the contact in northwestern Ohio was to compare a given log with sections previously made in quarry shotholes, which were located near enough to the exposed contact to relate its position to the logs accurately (Norris and Fidler, 1969, p. B159). In the southwest Ohio study area no similar opportunities were found for studying the Lockport Dolomite and Bass Islands contact, and the criteria used in the northwest Ohio study were arbitrarily extended into this part of the State. No doubt some error was introduced because of regional differences in the lithology of the Lockport Dolomite, but such errors are probably small on a regional scale. Contacts picked by this method check closely in most instances with those determined by Adriaan Janssens from a study of sample cuttings from the wells.

One notable difference between gamma logs made of the Lockport Dolomite in northwest Ohio and similar logs made in southwest Ohio is the relative prominence on many of the latter logs of the section corresponding to the middle beds of the Lockport. Identified by Janssens as belonging to the Goat Island Member of Howell and Sanford, 1947, the prominence of these beds on the southwest Ohio logs can be misleading if too strict a comparison is made between these logs and many of the logs made in the northwest Ohio study.

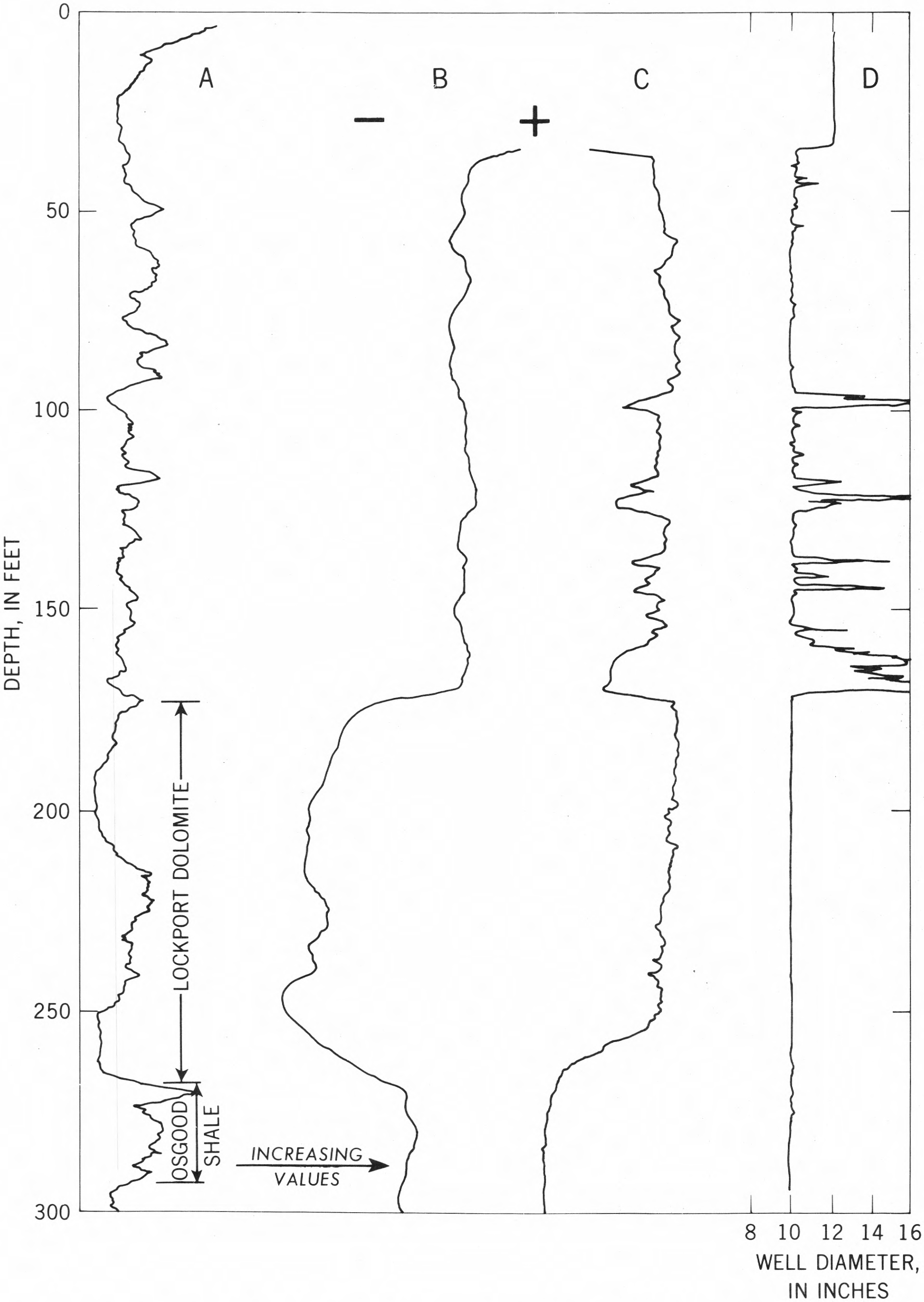


Figure 4.--Geophysical logs of well CP-12 showing: A, gamma; B, self-potential; C, single-point resistance; and D, caliper types.

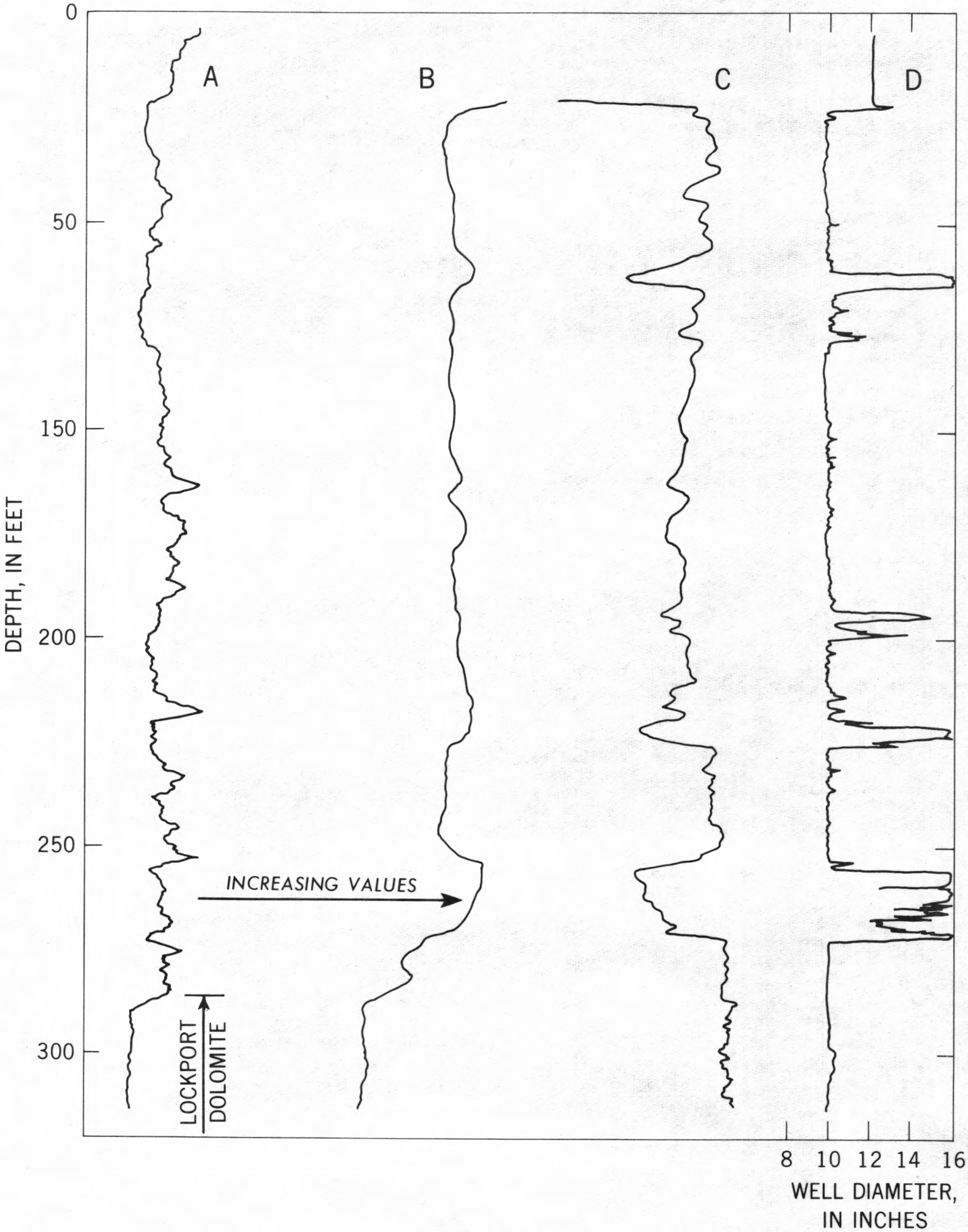


Figure 5.--Geophysical logs of well CP-24 showing: A, gamma; B self-potential; C, single-point resistance; and D, caliper types.

Compared with the Lockport-Bass Islands contact, the contact between the Lockport Dolomite and the underlying Osgood Shale is relatively easy to pick from the gamma log. Shale is more radioactive than dolomite, and the difference in the respective log sections is typically sharp and unmistakable. The log of test well CP-12, figure 4, shows an example of the Lockport Dolomite-Osgood Shale contact.

Figure 6 is an east-west lithologic profile based on gamma logs made by the U.S. Geological Survey in seven wells in southwest Ohio. (Locations shown on figure 2.) Wells SW-9, SW-19, and CP-30 are State test wells; wells SH-21, CH-22, and CL-21 are private wells, CH-22 being an abandoned gas test well. Well CL-22 is a municipal well at the village of South Vienna. Only one of the logs, that made in well CP-30, shows the contact of the Lockport Dolomite with the overlying Bass Islands Group. At all other sites the Bass Islands rocks were removed by erosion before deposition of the glacial cover. As shown in fig. 6, the Osgood Shale and the Dayton and Brassfield Limestones thicken slightly from west to east.

Figure 7 shows a north-south lithologic profile approximately parallel with the Scioto River. This profile is based on gamma logs made by commercial logging companies in oil and gas test wells, whose locations are also shown on figure 2. The scale factors for these logs are not the same as those for the logs made by the U.S. Geological Survey, and the respective logs are not directly comparable. The commercial logs are presented to show their general character and the differences between log sections upon which identification of the respective lithologic units was based.

The logging equipment used by the U.S. Geological Survey in the southwest Ohio study had the capability of making caliper logs and self-potential and single-point resistance (or resistivity) logs in addition to gamma logs. As shown by the examples of logs made in wells CP-12 and CP-24 (figs. 4 and 5, respectively), the caliper logs measures hole size, or roughness, and thus gives a record of the location of cracks, crevices, and other openings. The caliper probe is an electro-mechanical device employing spring-loaded movable arms, which maintain physical contact with the sides of the bore hole as the probe is being raised. The arms are electrically coupled to the recorder, thus providing a continuous record of hole diameter. The caliper logs are discussed further in this report in the section dealing with the high-yield area.

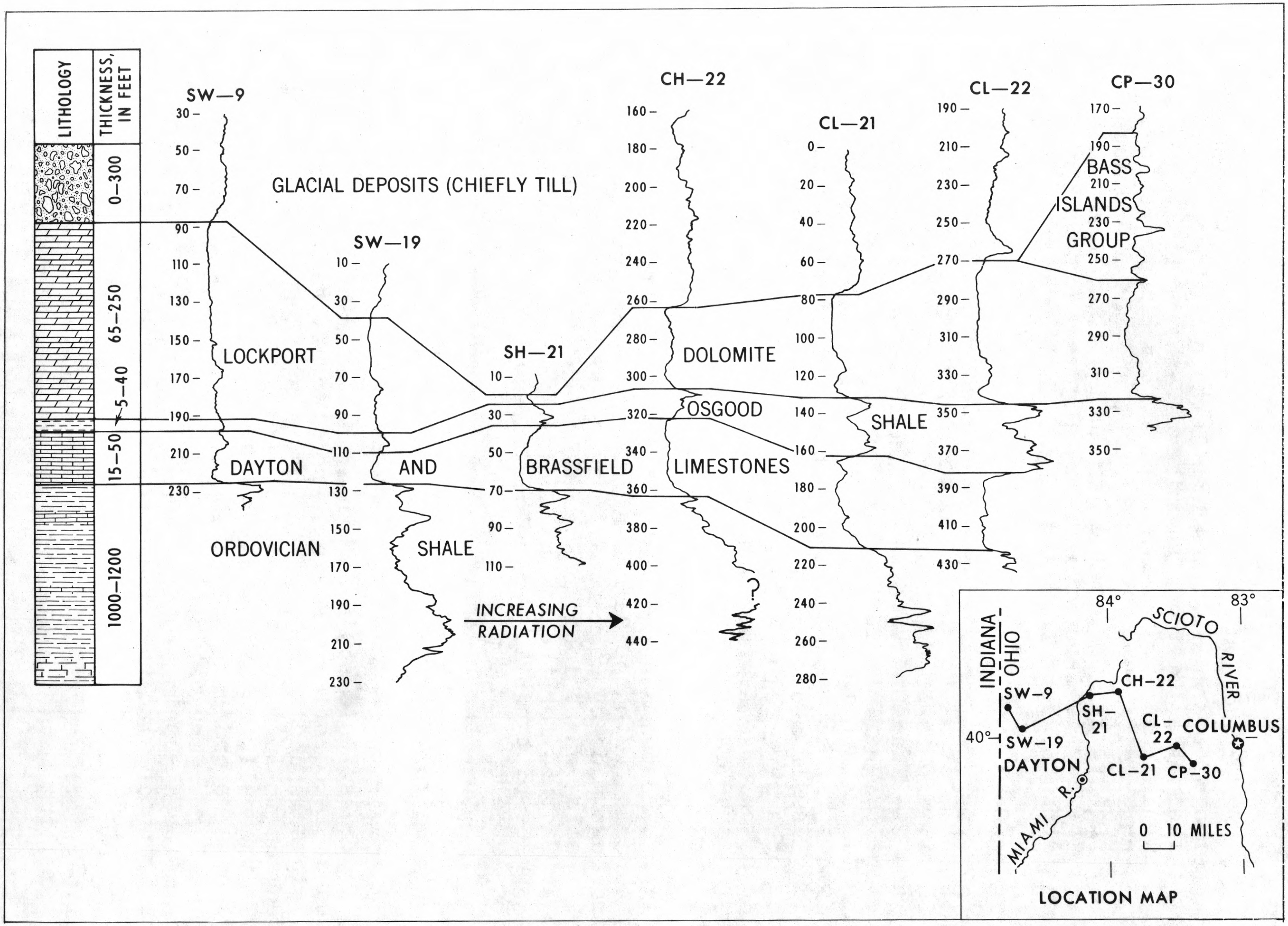


Figure 6.--Lithologic profile in western Ohio showing characteristic gamma logs of wells penetrating the consolidated-rock aquifers. (Numbers alongside logs give depth below land surface in feet; location of section shown inset and in fig. 2.)

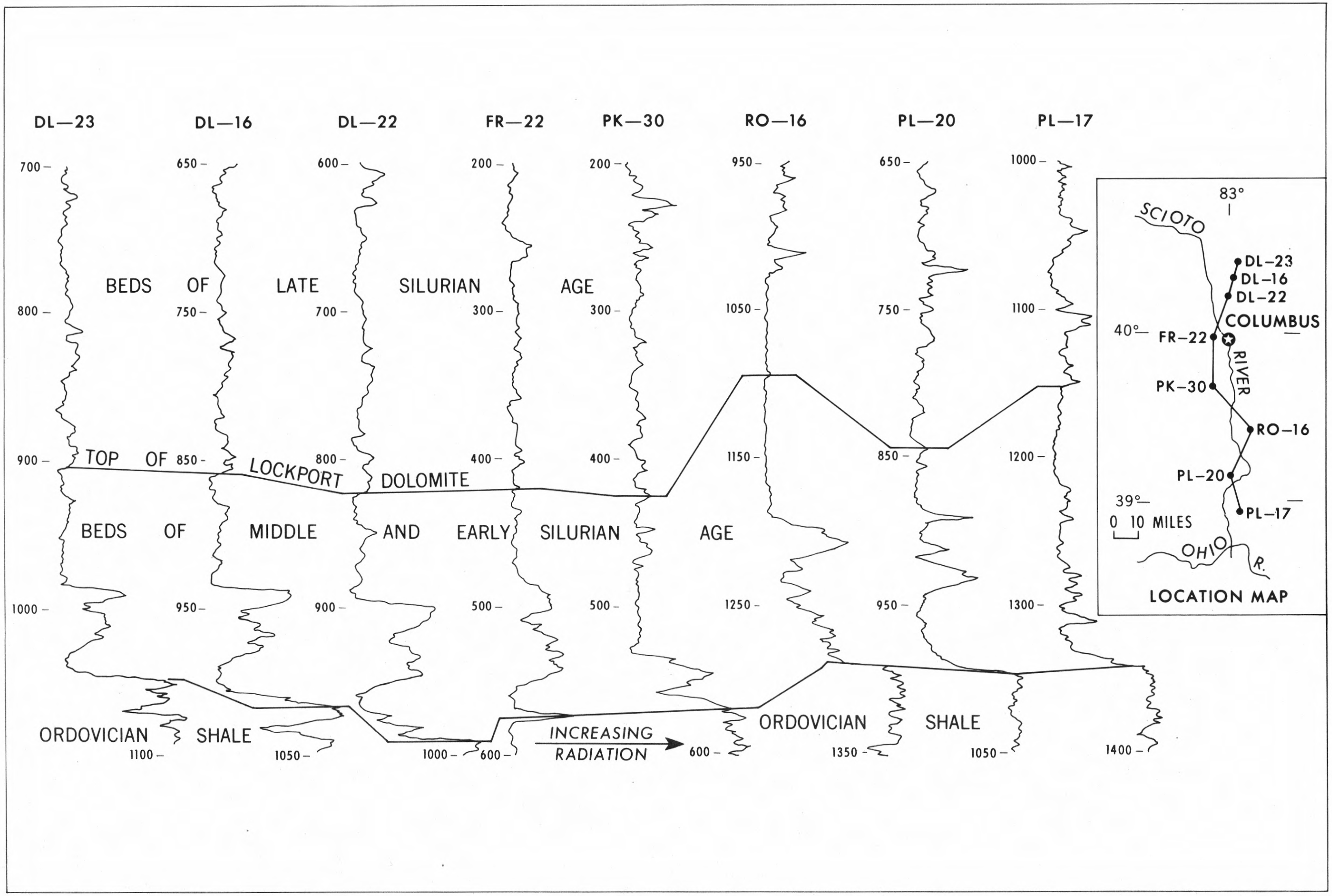


Figure 7.--Lithologic profile in central Ohio showing commerical gamma logs of wells penetrating the consolidated-rock aquifers. (Numbers alongside logs give depth below land surface in feet; location of section shown inset and in fig. 2; logs courtesy of Division of Geological Survey, Ohio Department of Natural Resources.)

The self-potential and resistance logs, commonly referred to as E logs or electric logs, measure the electrical properties of the earth in the vicinity of the borehole. Electrical current flows through mineralized water in the rocks; dry rocks do not conduct electricity. The flow of current in a well is affected by changes in water quality with depth and by the physical properties of the rocks, including the geometry of the well bore and associated cracks and crevices. The self-potential and resistance logs have proved useful in this investigation, primarily as adjuncts to the gamma and caliper logs, respectively. As shown by figures 4 and 5, the self-potential logs of wells CP-12 and CP-24 show significant differences between the section corresponding to the Lockport Dolomite and the section corresponding to the other rock units. In these examples, identification of the Lockport Dolomite can be made from the self-potential logs with nearly as much confidence as from the gamma logs. Assuming there was little change in the chemical properties of the water from top to bottom in these wells when they were logged, the relatively low electrical values of the self-potential logs of the Lockport section probably reflect the lack of open space in the rocks and, hence, the logs indicate a lower permeability for the Lockport than for rocks of the overlying Bass Islands Group. A different interpretation is suggested, however, for the marked increase in that part of the self-potential curve of well CP-12 corresponding to the beds beneath the Lockport Dolomite. Although the pre-Lockport beds are known to be poorly permeable, the water in these deeper beds is typically more mineralized than the water from shallower sources. An increase in mineralization of the water probably accounts for the higher self-potential values in this part of the log.

The resistance log is typically a mirror image of the self-potential log, and where one curve shows an increase in value the other shows a decrease. However, the resistance logs made in this investigation are much more sensitive to differences in hole diameter than the self-potential logs. As strikingly shown by the examples in figures 4 and 5, the resistance log shows differences in hole diameter in nearly as much detail as the caliper log. This property of the resistance log to reveal cavities and other openings in a well bore can be important, as most small, hand-operated loggers of the type likely to be used by water-well contractors do not have the capability for making caliper logs. In such instances a resistance log might prove a valuable guide in well construction or well-stimulation problems.

DISTRIBUTION AND WATER-YIELDING PROPERTIES OF THE AREA OF HIGH-YIELD WELLS

In the recently concluded investigation of the carbonate-rock aquifer in northwest Ohio, aquifer-test data plus caliper log and other evidence revealed the existence of a regionally extensive zone of relatively high permeability in the carbonate-rock aquifer, occurring as a long striplike area paralleling the crest of the Cincinnati arch (Norris and Fidler, 1971a). Most wells of relatively high yield, defined as those whose 25-hour specific capacities were greater than 5 gpm per ft (gallons per minute per foot of drawdown), are confined to this strip, 7 to 18 miles in width, which extends from Marion County, near the southern boundary of the northwest Ohio study area, northward along the east flank of the arch to the southern shore of Lake Erie in Ottawa and Lucas Counties. From the lake shore the strip curves westward around the nose of the arch and continues back southward along its west flank (Norris and Fidler, 1971a, fig. 3). The specific capacity of 26 test wells drilled in the high-yield area in northwest Ohio ranged from 5.1 to 93 gpm per ft, and averaged 31 gpm per ft. In contrast, the specific capacity of 36 test wells drilled into the same aquifer outside the high-yield area averaged only 1.8 gpm per ft, and the estimated yield of seven other such wells was so low that specific-capacity tests were not made. Identification of the high-yield area and knowledge of its water-yielding properties in northwest Ohio are of obvious importance. Equally important, the present investigation showed that the high-yield area extends also into the northern part of the present study area, where it constitutes a major source of ground water in an area of approximately 2,800 square miles, including parts of 17 counties.

As shown in figure 8, the area of high-yielding wells extends southward from Hardin and Marion Counties to form an irregularly shaped area in the northern half of the present study area, underlying virtually all of Union County and significant parts of adjacent counties. The high-yield area extends southward as far as northern Clark, central Madison, and northern Pickaway Counties; a small outlying area of high-yielding wells also occurs farther west, in western Shelby and eastern Darke Counties.

Lying chiefly on the east flank of the Cincinnati arch, and overlapping the crest of the arch in Champaign, Logan, and Hardin Counties, the high-yield area in southwest Ohio is a continuation of the high-yield area described in northwest Ohio (fig. 9). Moreover, the water-yielding characteristics

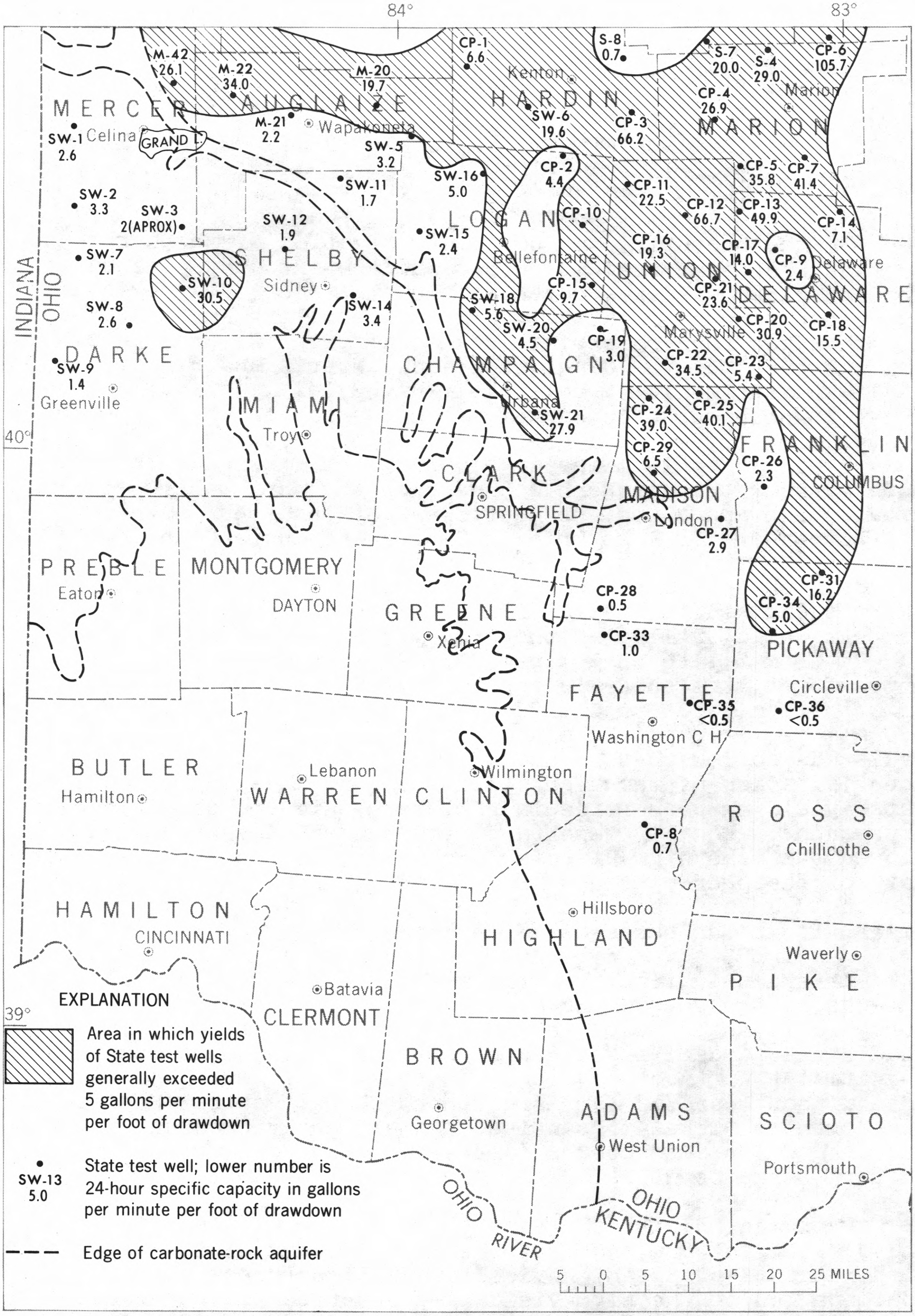


Figure 8.--Map of southwest Ohio showing area of high-yielding wells drilled in the carbonate-rock aquifer.

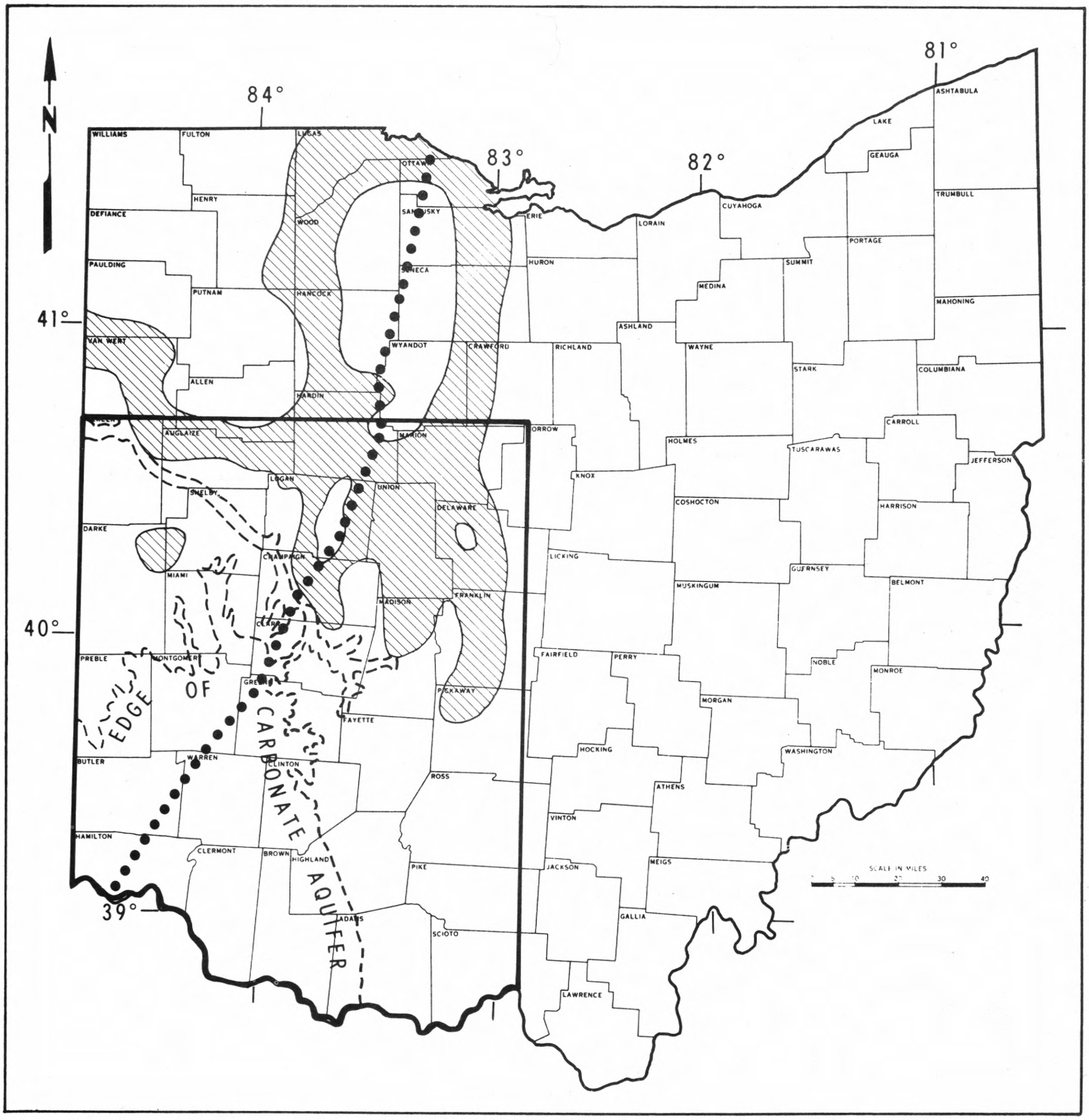


Figure 9.--County outline map of Ohio showing location of area of high-yielding wells (shaded) in the carbonate-rock aquifer. Heavy lines bound present study area; dots mark axis of Cincinnati arch.

of the high-yield area in southwest Ohio, based on aquifer-test data, are remarkably similar to those of the high-yield area in northwest Ohio. In the southwest Ohio counties, the specific capacity of 26 test wells drilled in the high-yield area ranged from 5.4 to 106 gpm per ft and averaged 30 gpm per ft, nearly identical to the figures reported for a like number of test wells drilled in the high-yield area in northwest Ohio. The specific capacity of 23 test wells drilled in areas outside the high-yield area in southwest Ohio ranged from 0.5 to 5.0 gpm per ft and averaged 2.6 gpm per ft, the average being somewhat higher than the 1.8 gpm per foot figure reported for 36 test wells drilled outside the high-yield area in northwest Ohio. Pumping rates during the aquifer tests also were slightly higher in the southwest Ohio investigation, averaging 665 gpm for wells in the high-yield area and 260 gpm for the test wells drilled outside the high-yield area. Comparable figures for the northwest Ohio investigation are 450 gpm and 160 gpm, respectively.

Geologic and hydrologic evidence indicates a common origin for the high-yield area in all of western Ohio. The high-yielding strata resulted primarily from ground-water solution in the carbonate rocks and extensive development of secondary permeability in favored areas. As postulated in the report on the northwest Ohio investigation, solution was most active in the beds constituting structurally higher areas that periodically emerged above sea level in the geologic past. The carbonate rocks remained above sea level for varying intervals of time, during which they were subject to ground-water circulation and solution. Erosion, subsequent to the final emergence of the region, removed the beds from the tops of the structurally and formerly topographically higher areas, leaving remnants of the permeable beds in peripheral areas as a linear zone of high productivity (Norris and Fidler, 1971a, p. B234-B235).

The high-yield area in southwest Ohio was developed in much the same way as it was in the northwest part of the State, primarily as a result of ground-water solution in the geologic past. Here, too, solution was largely confined to the structurally and topographically higher beds that were, and are, key components in the regional flow system. However, erosion of the beds along the top of the arch did not progress as far in southwest Ohio as in the northwest, and the permeable beds extend across the top of the arch in a large area in west-central Ohio.

Another important element also played a leading part in the development of the high-yield area in southwest Ohio. Evidence shows that a discrete zone, or stratum, of unusually high permeability occurs in the carbonate-rock aquifer in western Ohio at a specific position in the stratigraphic column. Wells typically penetrate this highly productive stratum in the lower part of the Bass Islands Group, near the top of the Lockport Dolomite. At some sites the water is under sufficient artesian pressure to cause the wells to flow at the surface. This permeable stratum, which present evidence shows is widespread in western Ohio, was previously identified in west-central Ohio by the senior author from records of eight relatively deep wells, of which five were drilled many years ago in search of oil or gas (Norris, 1956). In the drillers' records of these wells, some of which are reported in early geologic reports, reference is made to prominent water zones, or to cavities and fissures in the rocks, penetrated at depths that become progressively lower in altitude from west to east, consistent with the regional dip of the strata. Some of the wells flowed or were pumped at relatively high rates. For example, two wells drilled in 1889 in search of oil or gas at Plain City, about 15 miles northwest of Columbus, penetrated a prominent water-yielding zone at a depth of about 400 feet, from which the water rose 18 feet above land surface. The combined flow from these wells was estimated at 2 million gallons per day (Orton, 1899). From reports such as this, plus evidence from other drilling sites at Columbus and nearby towns, the author inferred the existence of a widespread zone of high permeability in the carbonate rocks, at or near the top of the Niagara Group (Lockport Dolomite). He tentatively correlated this zone with the horizon of the Newburg sand of drillers.

The Newburg, named for a local gas-producing stratum near Cleveland, is recognized throughout much of eastern Ohio, where the carbonate rocks that crop out in the western part of the State are deeply buried, as being correlative with a prominent water zone. According to Stout (1935, p. 307), the Newburg zone is the source of what the oil-and-gas-well driller terms the "big water" or sometimes "second water" in the "big lime." It seems logical that a unique stratum of such widespread occurrence would be traceable to the outcrop area of the carbonate rocks. Norris (1956, p. 95) states:

> "It is significant that the Newburg, which lies under deep cover in the eastern part of the State, is generally noted for its water-bearing properties. Judging by its widespread occurrence, the high permeability of this 'sand' seems to be of inherent

nature and evidently is characteristic of the stratum, generally. For this reason the Newburg sand (?) zone of drillers should be traceable as a water-bearing stratum over much wider areas than those in which it is now recognized, perhaps to its outcrop area in western Ohio. Data are few, unfortunately, in the area intervening between the oil and gas fields of eastern Ohio and the outcrop area of the Niagara group, and the general continuity of the Newburg as a zone of high permeability cannot be established with certainty on the basis of the present evidence. However, the evidence points to the probability that it is continuous."

Based on the eight west-central Ohio area wells, Norris (1956, fig. 1) contoured the Newburg zone and the potentiometric surface in western Franklin and eastern Madison Counties. Both sets of contours are similar to those in figures 2 and 11 of this report, which show, respectively, structure on the Lockport Dolomite and the regional potentiometric surface.

To ascertain the character, thickness, and stratigraphic position of the Newburg zone in southwest Ohio, an analysis was made of drillers' records, geologists' logs, and geophysical logs of the State-owned test wells. Data from 20 test wells drilled into the carbonate-rock aquifers were pertinent to the analysis. The caliper logs made by the U.S. Geological Survey proved especially helpful, as did the descriptive logs made from sample studies by Adriaan Janssens (1972, unpublished data) of the Ohio Division of Geological Survey. On-site reports of the field geologists representing the ground-water consultants employed by the State in its Central Project investigation also were useful in the analysis.

Figure 10 shows caliper logs of six wells drilled in the high-yield area, showing prominent cavities in the rocks immediately above the Lockport Dolomite. The cavities were probably caused by ground-water solution and are typical of wells drilled in the high-yield area. By contrast, wells drilled outside the high-yield area show little if any cavities on the caliper logs. These conditions are similar to those reported previously in the northwest Ohio investigation (Norris and Fidler, 1971a, p. B234; fig. 4).

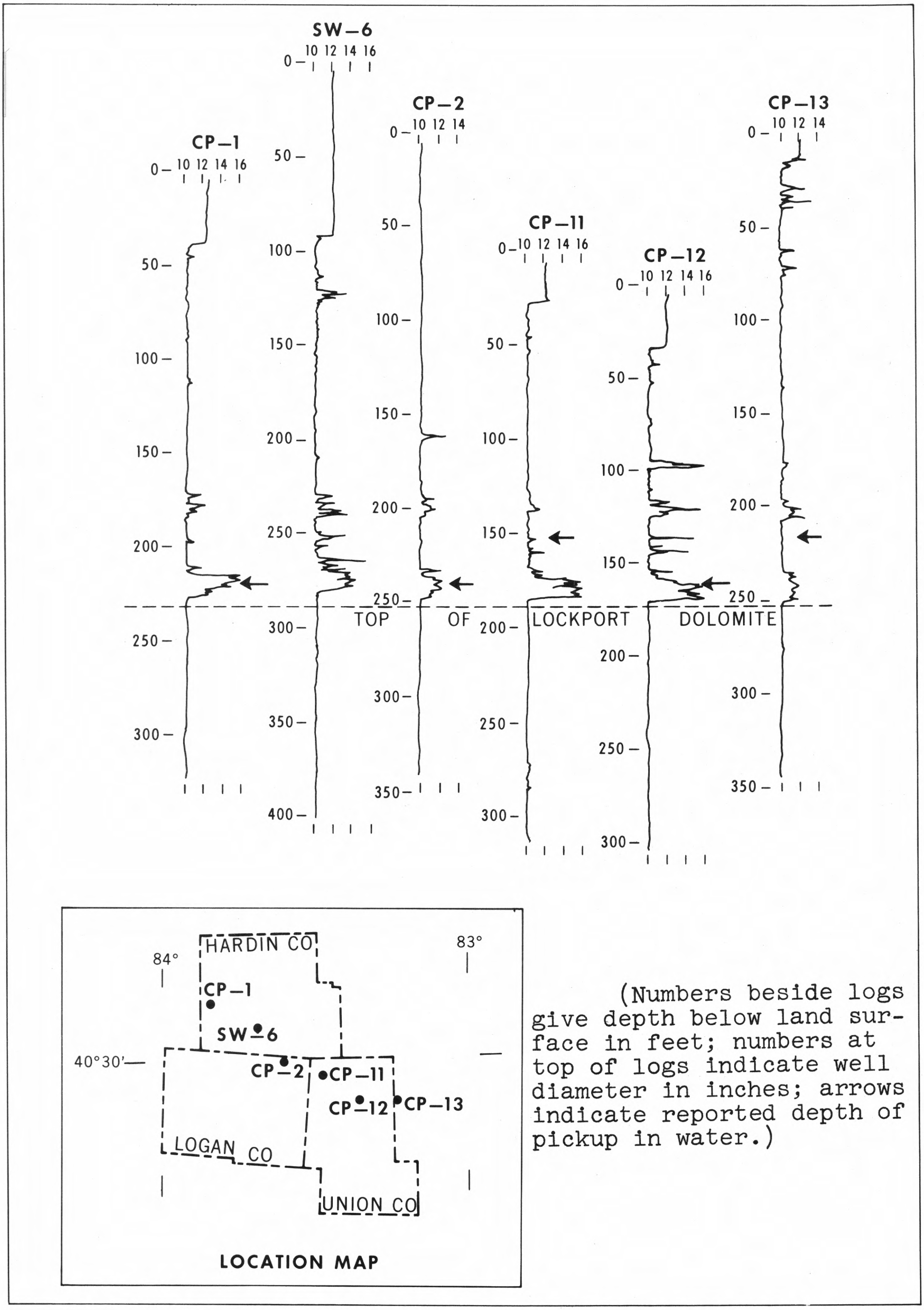


Figure 10.--Caliper logs of selected wells in western Ohio showing cavity zone (Newburg) above the Lockport Dolomite. Datum is top of Lockport Dolomite.

The six logs in figure 10 show that the cavities are essentially confined to the beds that overlie the Lockport Dolomite and are especially prominent in a zone about 15 feet thick, the base of which lies from 2 to 7 feet above the Lockport. The authors believe this stratum represents the Newburg zone. Caliper logs of nine other test wells drilled in the southwest Ohio investigation, namely CP-3, CP-4, CP-5, CP-15, CP-16, CP-17, CP-19, CP-21, and CP-24, whose locations are shown on figure 2, also show this prominent zone of cavities at the same stratigraphic horizon. The thickness of the zone, based on inspection of the 15 logs in which it is prominently revealed, ranges from 10 to 15 feet; the base of the cavity zone typically ranges from 3 to 5 feet above the Lockport Dolomite.

If this cavity zone represents the Newburg, what clues does the evidence afford as to its character and origin? Examination of the geologists' logs reveals no radical difference in lithology between the rocks in this interval and those above and below. The permeable beds are largely confined to the lower part of the Greenfield Dolomite, a 50-foot thick unit, described by Janssens (in Walker and others, 1970, table 1) in northwest Ohio as a medium bedded finely crystalline brown dolomite. In describing the Greenfield Dolomite from drill cuttings from the southwest Ohio test wells, Janssens typically notes a light-colored dolomite in the interval corresponding to the cavity zone, which he describes either as "light brown," "light gray," "light gray-brown," or sometimes "yellowish." Janssens also makes frequent reference in describing this interval to sucrosic, or sugary appearing, porous dolomite. In some logs he notes the presence of secondary limestone, or recrystallized calcite. Secondary mineralization is indicative of ground-water circulation and the precipitation of minerals in openings in the rocks. Janssens also reports traces of shale and sand in some of the samples, as did the field geologists who observed the drilling of the test wells. The clay and shale particles may have been carried into the cavity zone by circulating ground water. Or, this argillaceous material may be indicative of a widespread facies change in which, in a restricted zone, clastic sediments were deposited along with the carbonate sediments. The latter interpretation is suggested by Stout's description (1935, p. 307) of the Newburg sand in the oil and gas fields of eastern Ohio:

"...the so-called sand is generally impure, porous dolomite, varying from light gray to pink in color. Locally the horizon containes thin lenses of sandstone, evidently deposits left along a line of disconformity. The position of the Newburg sandstone is variable, but commonly it is found 150-200 feet above the base of the 'Big lime.' Stratigraphically, the deposits are interpreted to lie near the contact between the Salina Formation and the underlying Guelph dolomite. The thickness of the Newburg sand ranges from 1 to 30 feet..."

Whatever its genesis, the existence in the carbonate rocks in western Ohio of a widespread zone of generally high permeability has been established. The evidence suggests strongly that this zone is correlative and probably continuous with the Newburg sand of eastern Ohio. Although generally a source of water, the Newburg may not be highly productive except where the permeability has been increased by ground-water solution, as in parts of southwest Ohio, where the Newburg is an integral part of the high-yield area. The Newburg zone probably exists also as a discrete water-yielding stratum in parts of northwest Ohio, though specific evidence for its existence was not developed in the investigation of that area.

Commonly, in records of wells drilled to the Newburg zone, drillers report an abrupt pickup in water from the Newburg, or the beds immediately above the Newburg, as the well is being deepened. (See fig. 10.) In some places water is encountered only after the well has penetrated a considerable thickness of unproductive strata. However, in parts of southwest Ohio there has been much solution of the rocks and extensive development of permeability, both laterally and vertically. In such areas drillers may report a more or less continuous pickup in water and water from several depth intervals, as the well is being deepened. Usually, the highest increments of yield from these wells are from the Newburg zone or beds close to the Newburg.

Examples also have been reported where the Newburg zone is a poor source of water. In such examples the voids in the rocks appear to have been filled with primary or secondary minerals, reducing the inherent permeability of the aquifer. Norris (1956, p. 97) cites as an example a relatively unproductive well drilled on property of the Battelle Memorial Institute in Columbus, in which little water was reported and the rocks in the interval corresponding to the Newburg zone contained a high percentage of gypsum and anhydrite.

The quality of water from the Newburg zone in the high-yield area in southwest Ohio is comparable with that from the overlying carbonate rocks and is within the common range of waters from a limestone region. Where the Newburg is deeply buried, the quality deteriorates, and in parts of central Ohio and in eastern Ohio the water is mineralized to the extent that it is unfit for most purposes. Norris (1956, p. 98-99) reports that water from the Newburg, from wells 400 feet deep at Harrisburg and Plain City, in western Franklin County, was typical of that from a limestone region. By contrast, water from the Newburg zone at Grove City, in west-central Franklin County only a few miles downdip from the Harrisburg well, had a dissolved solids content of 2,230 mg/l (milligrams per liter) and was considered unsuitable as a source of municipal supply. Despite its limitations, locally, resulting either from poor water quality or a reduction in permeability caused by deposition of secondary minerals in the rock openings, the Newburg zone is a major source of water generally in southwest Ohio. This permeable stratum will be a key factor in large-scale water development projects in the future. Its stratigraphic position near the top of the Lockport Dolomite makes the Newburg an easily identifiable horizon, the altitude of which can readily be determined from the structure contours shown on figure 2. The yields available from the Newburg zone in the high-yield area are sufficient for large-scale municipal and industrial use at many places in southwest Ohio.

EFFECT OF REGIONAL FLOW ON THE QUALITY OF GROUND WATER

In a typical drainage basin in Ohio, water may enter into or be discharged from the ground-water body, or saturated zone, at virtually any point within the basin. Whether or not water is entering or leaving the ground-water body at any given time and place depends in part upon climatic factors, such as distribution and intensity of rainfall, the season of the year, and plant cover. It also depends upon the prevailing ground-water flow system.

Water that reaches the water table and enters the saturated zone moves slowly through the ground from points of higher to points of lower elevation under the influence of gravity. Ultimately, the water is discharged from the ground-water reservoir, perhaps temporarily, only to reenter the saturated zone farther downgradient. Although simple in principle, ground-water flow can be highly complex and difficult to determine. Configuration of the flow field depends upon the altitude, slope, and roughness of the terrain, the character of and permeability distribution in the geologic materials through which the water moves, location of intake and discharge areas, and other hydrologic factors.

Toth (1962) defined three types of ground-water flow systems -- local, intermediate, and regional -- that can occur in a typical small drainage basin. Although important in many hydrologic problems, local and intermediate flow systems will not be considered in the present context, in which an effort will be made to show a relation between ground-water quality and the regional flow system. In a regional flow system, ground water moves in long arcuate paths from the highest to lowest parts of the basin; generally from the principal drainage divides, which function as recharge areas to discharge areas in and along the major streams.

Figure 11 shows approximate contours on the regional potentiometric surface in southwest Ohio, based on the altitude of ground-water levels reported or measured in selected deep wells, drilled in the consolidated-rock aquifers. The wells include those drilled by the State in this investigation, supplemented by wells drilled for municipal, industrial, or domestic use for which records are available in the files of the Ohio Division of Water. The common range in depth of these wells is 80 to 250 feet; depths of relatively few of the wells are outside this range. The water level in most of the wells sensibly represents the regional potentiometric surface, as here conceived, that is, of a flow system where distances between recharge and discharge areas are measured in a few miles or, at most, a few tens of miles. Typically, this regional potentiometric surface is not the same as the head represented

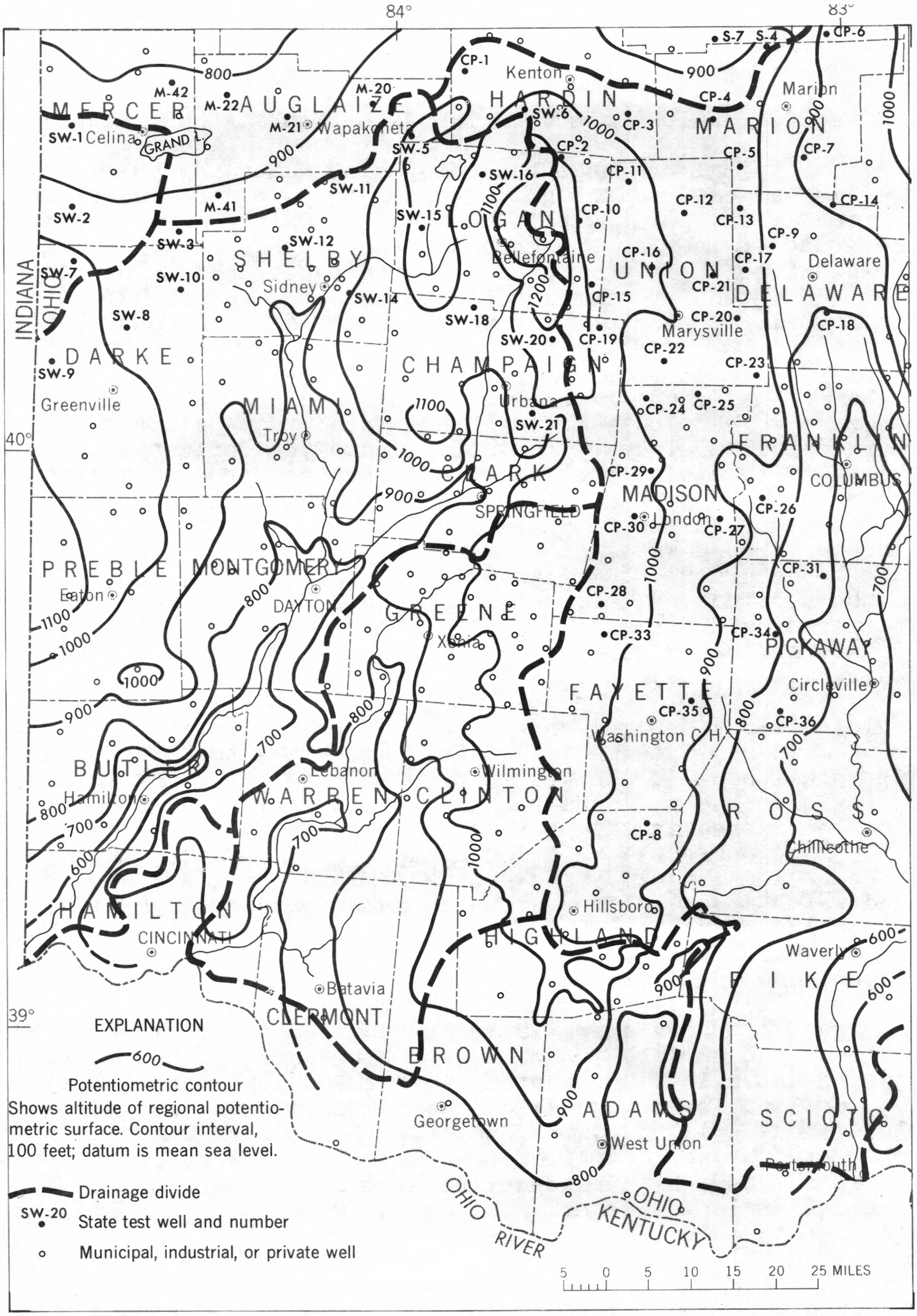


Figure 11.--Map of southwest Ohio showing approximate contours on the regional potentiometric surface, based on data from selected deep wells drilled in the consolidated-rock aquifers

by the water level in relatively shallow wells, of which some either tap a local artesian flow system or indicate the position of the water table in an unconfined system. However, this difference in head is not large, as ground-water levels in nonpumping wells in southwest Ohio are not far from the surface whether they represent the regional flow system or some local or intermediate system. The depth to water in a typical well is between 10 and 20 feet in most areas, and the common range in ground-water levels is from about 40 feet below the surface to a foot or two above the surface. The water level in comparatively few wells is outside this range.

The potentiometric contours on figure 11 are highly generalized, either because water levels on which the map is based do not truly represent the regional flow system or because of a scarcity of data in some areas. The principal problem stems from the fact that most wells open in the consolidated-rock aquifers are cased only to the top of the bedrock and are drilled as an open hole for the remainder of their depth. The water level in such a well represents an integration of the heads in the different water-yielding zones that contribute to the well. The resultant head, as reported on the driller's record or measured in the field, may not be the same as the head that would occur if the well were open only at the bottom and tightly cased throughout the remainder of its depth. The magnitude of any errors introduced in this way could not be determined, but they are probably small enough not to appreciably affect the overall accuracy of the map. Regrettably there was also a lack of comparative water-level data of the type that would have permitted the water level in a relatively deep well, cased to the bottom, to be compared with the water level in a nearby shallow well. The absence of such data ruled out an accurate determination of the extent of the principal recharge and discharge areas. Recharge areas are assumed to coincide generally with areas of elevated potentiometric levels, as shown on figure 11, and discharge areas are assumed to conform to generally low levels.

In considering the accuracy of the contours in figure 11, note that data are sparse in areas where most wells tap the unconsolidated deposits at shallow depth and few wells are drilled into the bedrock. Moreover, in wide areas in southern Ohio where shale bedrock is at or near the surface and the unconsolidated-rock aquifers are relatively unproductive, it is doubtful that a regional flow system exists within the common depths of wells. Distortions of the regional flow system and anomalous ground-water levels are also caused by the presence of local flow systems and variation in the permeability of the aquifers. Wells were selected to eliminate such local anomalies whenever they were detected.

Regional flow is generally downward in the recharge areas, upward in the discharge areas, and lateral in the intermediate areas. In recharge areas the regional potentiometric surface is typically lower than the water table, indicating the movement of water downward into the regional system. The water level in a well being drilled becomes progressively lower as the well is deepened, reflecting the decline in head with depth. In discharge areas the reverse is true; the regional potentiometric surface is generally higher than the water table, indicating upward flow in response to the regional gradient. Along the major streams in southwest Ohio, it is not uncommon for the potentiometric head in the deeper wells to cause the water level to rise above the land surface, resulting in free-flowing wells. In discharge areas, the water level in a relatively deep well progressively rises as the well is deepened.

In southwest Ohio water enters the regional flow system primarily in the divide areas in the higher parts of the basins and moves down the slope of the potentiometric surface to principal discharge areas, either in the bottom lands along and beneath the major streams, or on the lower slopes of the valleys. Much recharge to the regional flow system occurs in that broad upland area lying between the Great Miami and the Scioto River systems, principally covering Clark, Champaign, and Logan Counties. Much of this upland is composed of hummocky to hilly glacial moraine, consisting of deposits -- 200 to 300 feet thick -- of till, interbedded or associated with extensive beds of permeable sand and gravel. This morainal complex, where it overlies the bedrock outlier centering in Logan County, includes the highest terrain in the State. The highest point, 1,549 feet above mean sea level, is a hilltop near Bellefontaine. Water moves from this upland area to discharge areas principally along the upper reaches of the Great Miami River and Scioto River systems, at altitudes of about 900 feet or lower.

The present regional flow system is generally similar to that which may have prevailed over much of past geologic time in southwest Ohio. As previously explained, the high-yield area, which underlies virtually all of Union County and extends into parts of adjacent counties (fig. 8), was produced by a ground-water flow system that predated the present system by millions of years. That region, situated on and near the crest of the Cincinnati arch, was a positive element throughout much of geologic time. The regional flow system, then as now, derived its energy from water entering this higher ground, whence it began its slow movement down the hydraulic slope towards the principal streams. An important consequence of the regional movement of ground water in southwest Ohio is the effect of this movement on the chemical quality of the water in the principal aquifers.

In a regional system, ground-water-quality characteristics are basically dependent upon the geologic framework and change both laterally and vertically in response to length and direction of the flow paths taken by the water and its residence time within the aquifer (Back and Hanshaw, 1971, p. 1009). In a geochemical study of a small drainage basin in Minnesota, Maclay and Winter (1967) identified five basic water types that were related both to the ground-water flow systems and the character of the rocks within the basin. They found, for example, that calcium bicarbonate type water occurred in recharge areas and that concentrations of all ions except bicarbonate increased in the direction of ground-water flow. Maclay and Winter concluded that changes in water chemistry indicate the direction of ground-water movement in the basin, and these changes agree with the direction of flow as determined by the slope of the potentiometric surface.

Geochemical evidence in southwest Ohio agrees with certain of the conditions described by Maclay and Winter. Wells drilled in the consolidated-rock aquifers, and tapping the regional flow system, yield calcium bicarbonate type water in and near areas of recharge. The water becomes progressively more mineralized as it moves down the potentiometric gradient, and it changes to a calcium sulfate type in the principal discharge areas. This regional change in water chemistry is indicated by the map, figure 12, which shows the change in the ratio of the bicarbonate ion to the total anions in representative samples from the deeper wells. Comparison of figure 12 with the potentiometric map, figure 11, shows that the bicarbonate ratio contours conform generally to the regional flow system. Higher bicarbonate percentages occur in areas where the potentiometric surface is relatively high, and lower values -- indicating a corresponding increase in the sulfate ion -- occur in areas where the potentiometric surface is relatively low. The bicarbonate ratio exceeds 80 percent in

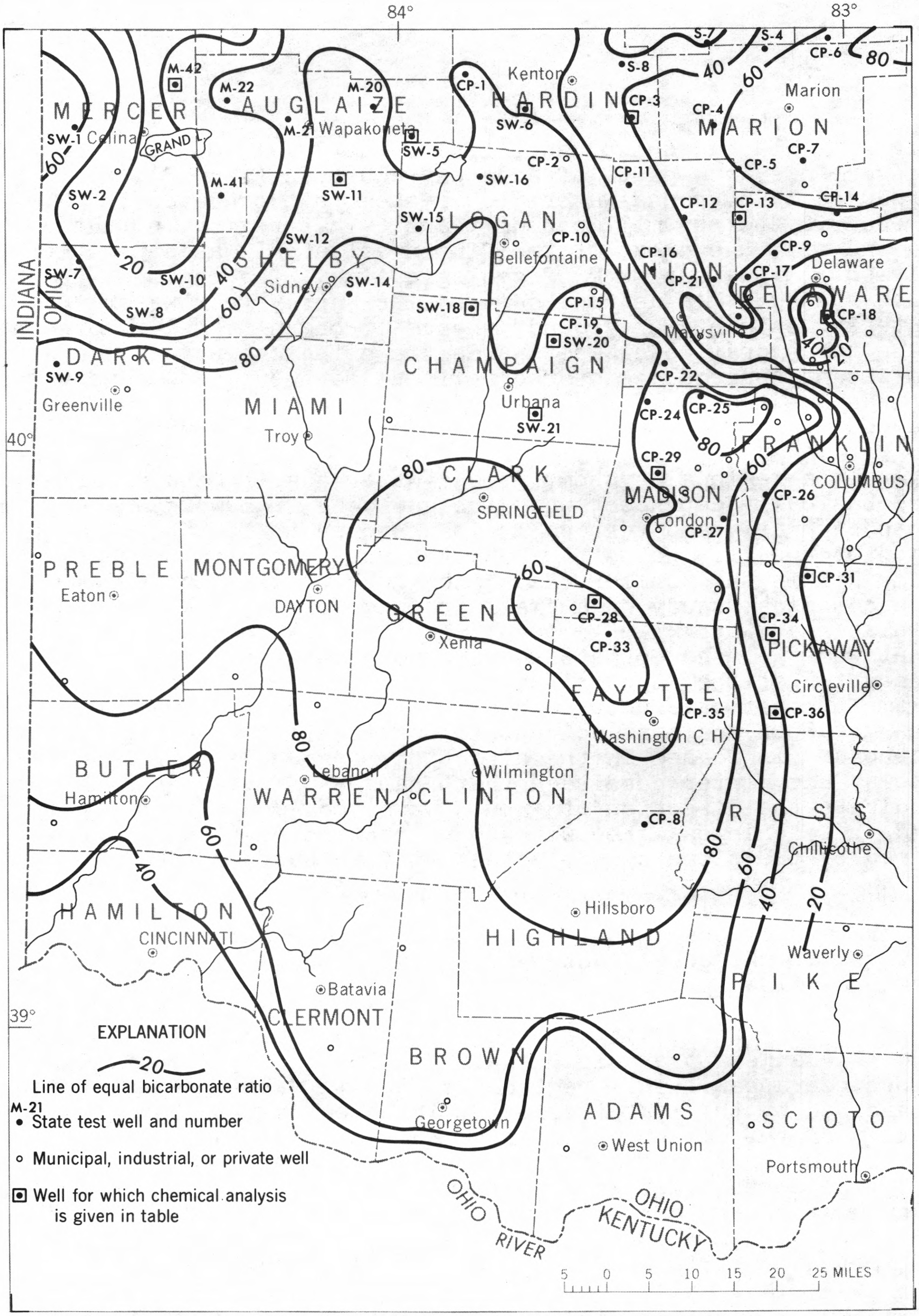


Figure 12.--Map of southwest Ohio showing ratio in percent of bicarbonate ion concentration (me/l) to total anions in water from the consolidated-rock aquifers.

much of the central part of the study area, which includes the principal areas of recharge, and drops below 50 percent along the lower reaches of the major streams and in other discharge areas.

Areas of relatively low bicarbonate ratio include most of Mercer County and parts of adjacent counties and a trough-shaped area extending from the Scioto Valley in Franklin and Delaware Counties northwestward through central Union and Hardin Counties. The potentiometric levels are relatively low in these areas, which are presumed to be discharge areas. Wells drilled into the limestone aquifers in Mercer County, notably in the vicinity of Lake St. Marys, typically flow. Free-flowing wells and generally high ground-water levels also occur in the Union-Hardin County area. This area is adjacent to the higher terrain centering in Logan County, from which the flowing wells probably derive their head.

The discharge area in Union and Hardin Counties includes a large part of the high-yield area. This is noteworthy in light of a special chemical-quality study made in northwest Ohio to determine the degree of saturation of the ground water with respect to calcium carbonate. The study showed that in northwest Ohio the high-yield area is the major area of recharge to the carbonate-rock aquifer (Norris and Fidler, 1971b). Depending on the terrain and its location with respect to the major streams, the high-yield area may be associated with different parts of the flow system. In southwest Ohio the high-yield area is extensive and constitutes parts of all elements of the regional flow system, including recharge, intermediate, and discharge areas.

The relation between ground-water quality and the regional flow system in southwest Ohio is further indicated by the comparative data in table 1, which lists the chemical constituents in 15 samples of water from selected State-drilled test wells. Five of the wells were drilled in regional recharge areas, five in discharge areas, and five in intermediate areas. Locations of wells for which the analyses are given are shown on figure 12. Comparison of the three groups of analyses shows a general change in the chemical character of the water as it moves from areas of recharge through intermediate areas to areas of discharge. It is interesting to review the changes in selected constituents. For the five wells drilled in recharge areas, calcium averages 88 mg/l (milligrams per liter); the five-well average rises to 125 mg/l for wells in intermediate areas, and to 323 mg/l for wells in discharge areas. For dissolved solids, the five-well averages from the respective areas are 435, 715, and 1,826 mg/l; for chloride, 5, 9, and 28 mg/l, respectively, and for sulfate 69, 256, and 981 mg/l. The increases in constituents reflect the progressive mineralization of the water as it moves through the regional flow system. Interestingly, the total bicarbonate content drops slightly as the water moves through the system, the average for five wells dropping from 425 mg/l in recharge areas to 375 mg/l in intermediate areas and to 360 mg/l in discharge areas.

Another method of comparing regional water characteristics is by plotting on a graph the concentrations of dominant ions for wells in different parts of the flow system. This is done in figure 13 for 10 of the wells listed in table 1. Five of the wells are in recharge areas and five are in discharge areas. The difference in concentration of the ions is readily apparent on the graph; for instance, note the relatively higher sulfate concentration in the waters from wells in discharge areas.

In comparing or studying analyses from individual wells, it must again be brought to mind that each of the wells listed in table 1 was drilled as an open hole in the limestone bedrock. Some mixing of waters from different flow systems undoubtedly occurred during pumping and sampling. However, the consistency of the results, as shown by progressive changes in chemical quality as the water moves down the potentiometric gradient, indicate that most relatively deep wells in southwest Ohio, drilled into the consolidated-rock aquifers, tap a recognizable regional flow system. In moving through this system the ground water undergoes orderly chemical change, upon which predictions can logically be made in advance of drilling of the water quality to be expected at a given site.

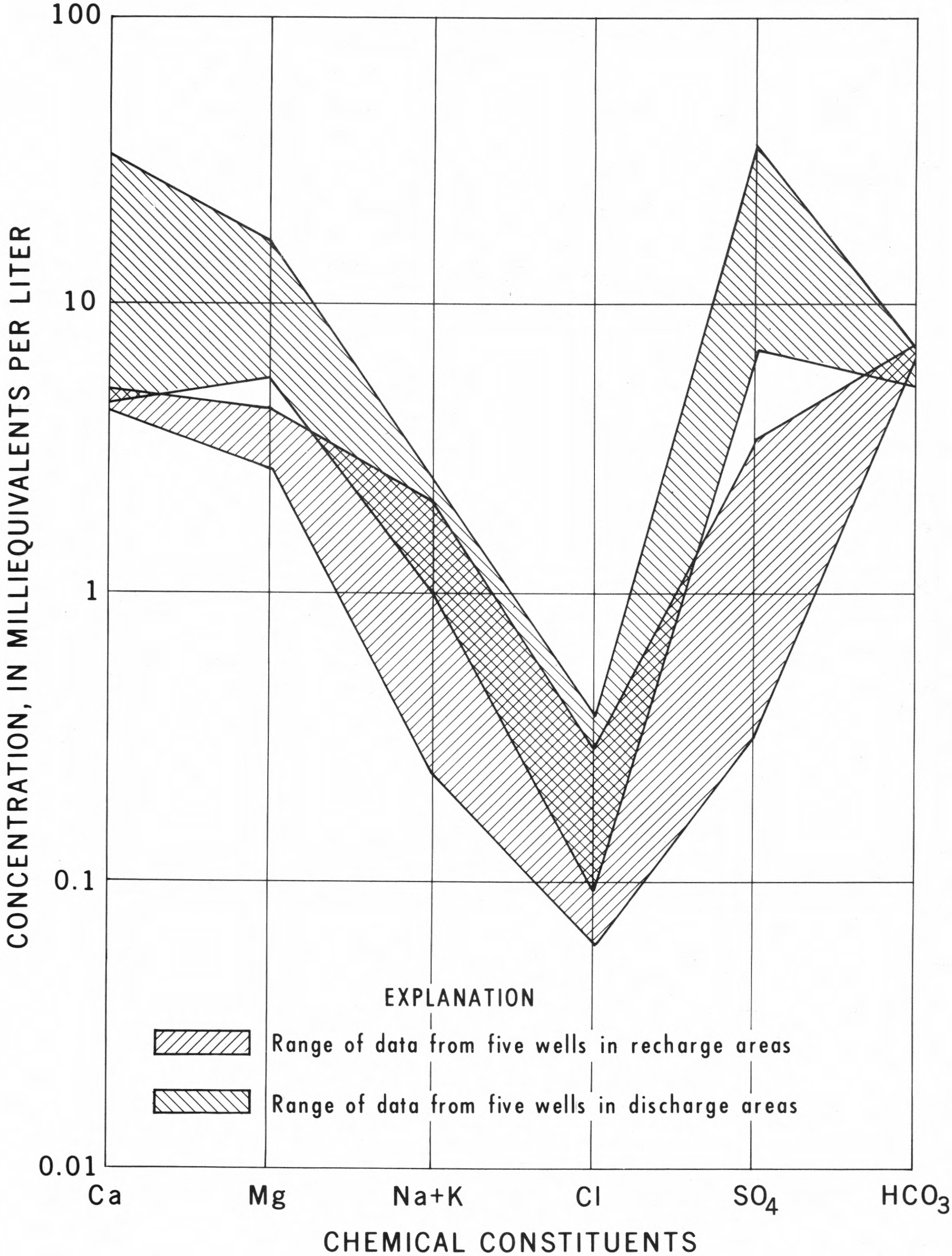


Figure 13.--Comparison of Regional water characteristics for wells in recharge areas against wells in discharge areas.

Table 1.--Analyses of water from selected wells drilled into the consolidated-rock aquifers in southwest Ohio, showing relation between chemical characteristics and regional hydrologic environment. (Analyses by U.S. Geological Survey)

Well No.	Regional hydrologic environment (R-recharge area; I-intermediate area; D-discharge area)	Depth (ft)	Depth to bedrock (ft)	Date of sampling	Yield (gpm)	Non-pumping water level (ft below land surface)	Temperature °C during pumping	Chemical constituents (Results in milligrams per liter except as indicated): Silica (SiO_2)		Iron (Fe)		Manganese (Mn)		Calcium (Ca)		Magnesium (Mg)		Sodium (Na)		Potassium (K)		Total cations
								mg/l	me/l	mg/l	me/l	mg/l	me/l	mg/l	me/l	mg/l	me/l	mg/l	me/l	mg/l	me/l	me/l
CP-29	R	290	138	8-11-71	600	9	12.0	11	--	1.1	--	0.110	--	98	4.89	52	4.28	28	1.22	3.0	0.08	10.47
SW-18	R	360	235	5- 1-71	500	8	----	18	--	1.40	--	.040	--	86	4.29	34	2.80	6.1	.26	1.5	.04	7.39
SW-20	R	420	92	5- 7-71	275	91	----	16	--	3.3	--	.14	--	89	4.44	39	3.21	4.8	.21	1.3	.03	7.89
SW-21	R	310	116	5-13-71	500	6	----	17	--	.59	--	.060	--	82	4.09	33	2.71	7.9	.34	1.8	.05	7.19
SW-11	R	415	185	8-26-71	125	37	11.0	18	--	1.2	--	.055	--	88	4.39	49	4.03	24	1.04	2.7	.07	9.53
CP-28	I	225	40	9-10-71	70	Flows	13.5	12	--	.53	--	.22	--	140	6.99	44	3.62	56	2.44	3.5	.09	13.14
CP-3	I	200	25	2- 5-71	500	Flows	11.0	19	--	2.6	--	.046	--	140	6.99	56	4.61	27	1.17	3.7	.09	12.86
CP-13	I	350	12	4- 2-71	1,000	Flows	11.0	15	--	5.8	--	.027	--	140	6.99	48	3.95	21	.91	2.5	.06	11.91
SW-5	I	380	52	5-28-71	480	12	----	16	--	.2	--	.055	--	110	5.49	43	3.54	27	1.17	4.1	.10	10.30
SW-6	I	410	92	5-20-71	450	58	----	16	--	.26	--	.10	--	94	4.69	47	3.87	42	1.83	3.7	.09	10.48
CP-34	D	300	65	9-17-71	450	14	----	9.8	--	1.2	--	.093	--	200	9.98	68	5.59	45	1.96	4.9	.12	17.65
CP-31	D	345	115	9-23-71	1,000	3	12.0	12	--	.3	--	.040	--	640	31.94	140	11.52	47	2.04	8.9	.23	45.73
CP-36	D	320	170	9- 1-71	2	35	11.0	4.2	--	.28	--	.051	--	89	4.44	84	6.91	46	2.00	14	.36	13.71
M-42	D	280	35	4-29-69	500	9	----	16	--	2.9	--	.04	--	189	9.43	100	8.23	39	1.70	4.3	.11	19.47
CP-18	D	[a]395	12	9- 2-71	-----	[b]137	11.0	6.7	--	29.0	--	.800	--	500	24.95	200	16.45	20	.87	4.7	.12	42.39

Well No.	Dissolved solids: Calculated	Dissolved solids: Residue on evaporation at 180° C	Hardness: As $CaCO_3$	Hardness: Non-carbonate	Chemical constituents (Results in milligrams per liter except as indicated): Bicarbonate (HCO_3)		Carbonate (CO_3)		Sulfate (SO_4)		Chloride (Cl)		Fluoride (F)		Nitrate (NO_3)		Total anions	Bicarbonate: total anion ratio	Specific conductance (micromhos at 25°C)	pH	Color
	mg/l	mg/l	mg/l	mg/l	mg/l	me/l	mg/l	me/l	mg/l	me/l	mg/l	me/l	mg/l	me/l	mg/l	me/l	me/l				
CP-29	570	580	460	130	404	6.62	0	0	170	3.54	6.0	0.17	1.4	0.07	0.0	0.00	10.40	64	886	7.5	2
SW-18	378	349	350	0	428	7.01	0	0	18	.37	3.0	.08	.5	.03	.0	.00	7.49	93	646	7.5	10
SW-20	398	373	380	8	454	7.44	0	0	22	.46	2.0	.06	.5	.03	.1	.02	8.01	93	677	7.5	5
SW-21	368	354	340	0	420	6.88	0	0	16	.33	3.0	.08	.6	.03	.0	.00	7.32	94	634	7.5	5
SW-11	522	520	420	74	422	6.92	0	0	120	2.50	10	.28	1.1	.06	.1	.00	9.76	71	827	7.5	5
CP-28	761	802	530	190	420	6.88	0	0	290	6.04	8.0	.22	.5	.03	.1	.00	13.17	52	1,120	7.3	5
CP-3	741	775	580	260	388	6.36	0	0	290	6.04	10	.28	2.0	.10	.0	.00	12.78	50	1,080	7.6	5
CP-13	684	710	550	240	384	6.29	0	0	250	5.20	17	.48	1.2	.06	.0	.00	12.03	52	1,000	7.7	5
SW-5	605	678	450	190	320	5.24	0	0	240	5.00	6.0	.17	1.1	.06	.2	.00	10.47	50	964	7.4	5
SW-6	598	612	430	130	366	6.00	0	0	210	4.37	3.0	.08	1.7	.09	.1	.00	10.54	57	910	7.4	5
CP-34	1,060	1,120	780	480	366	6.00	0	0	550	11.45	4.0	.11	1.1	.06	.2	.00	17.62	34	1,450	7.5	3
CP-31	2,850	3,070	2,200	1,900	335	5.49	0	0	1,750	36.44	85	2.40	2.2	.12	.1	.00	44.45	12	3,060	6.7	5
CP-36	777	840	570	290	337	5.52	0	0	340	7.08	32	.90	1.1	.06	.0	,00	13.56	41	1,190	7.8	0
M-42	1,140	1,230	884	531	430	7.05	0	0	566	11.78	8,0	.22	1.2	.06	.0	.00	19.11	37	1,560	7.2	3
CP-18	2,640	2,870	2,100	1,800	332	5.44	0	0	1,700	35.39	13	.37	1.9	.10	.1	.00	41.30	13	2,860	6.9	1

[a] Limestone aquifer overlain by shale.
[b] Well cased to 340 feet.

CONCLUSIONS

The most important result of this investigation of the carbonate-rock aquifer has been the identification and mapping of the high-yield area in southwest Ohio. In the northwest Ohio investigation, in which the high-yield area was originally described and related to geologic structure, it was stated that the high-yield area could be expected to extend into southwest Ohio and to occur also in other areas where geologic conditions were favorable. This statement has proved true with respect to southwest Ohio, where the high-yield area is now shown to underlie large areas on the crest and east flank of the Cincinnati arch. In addition, important new evidence also shows that within the high-yield area in southwest Ohio yields to wells are augmented by water from the Newburg zone, a permeable stratum in the lower part of the Bass Islands Group, near the top of the Lockport Dolomite. This investigation has gone far toward establishing the continuity of the Newburg zone as a generally permeable stratum extending from its outcrop area in western Ohio into the oil and gas regions of eastern Ohio. The depth to the Newburg zone in western Ohio can readily be determined from a structure-contour map drawn on the top of the Lockport Dolomite. Underscoring the importance of geophysical logging in regional hydrologic studies is the fact that data for the structure map were based largely on interpretation of the logs made in this investigation.

In southwest Ohio, as predicted earlier for northwest Ohio, it seems inevitable that future large-scale ground-water developments will be drawn to the high-yield area. The high-yield area will commend itself as a source of ground water to industry seeking to decentralize and move from the larger cities. Its potential productivity will favor expansion of those municipalities it underlies, especially those municipalities not favorably located with respect to alternative water sources. To these the high-yield area will offer an economic advantage denied to those upland communities beneath which the carbonate-rock aquifer is nonexistent or poorly productive.

The second most important result of this investigation is the relating of the chemical quality of water in the consolidated-rock aquifers to the regional flow system. The evidence shows that a general change in quality occurs as the water moves from areas of recharge through intermediate areas to areas of discharge. Increases that occur in selected constituents, as the water moves through the regional flow system, are, in a measure, predictable. This knowledge represents an important step forward in defining the water-quality characteristics in a large area of the State; it will be highly significant in future problems involving development of ground-water supplies and perhaps also in the consideration of underground waste-injection projects.

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