HYDROGEOLOGIC FRAMEWORK OF THE MIDWESTERN BASINS AND ARCHES REGION IN PARTS OF INDIANA, OHIO, MICHIGAN, AND ILLINOIS

REGIONAL AQUIFER-SYSTEM ANALYSIS

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1423–B

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Hydrogeologic Framework of the Midwestern Basins and Arches Region in Parts of Indiana, Ohio, Michigan, and Illinois

By GEORGE D. CASEY

REGIONAL AQUIFER-SYSTEM ANALYSIS—MIDWESTERN BASINS AND ARCHES

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1423–B

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FOREWORD

THE REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM

The Regional Aquifer-System Analysis (RASA) Program was started in 1978 following a congressional mandate to develop quantitative appraisals of the major ground-water systems of the United States. The RASA Program represents a systematic effort to study a number of the Nation's most important aquifer systems, which in aggregate underlie much of the country and which represent an important component of the Nation's total water supply. In general, the boundaries of these studies are identified by the hydrologic extent of each system and accordingly transcend the political subdivisions to which investigations have often arbitrarily been limited in the past. The broad objective for each study is to assemble geologic, hydrologic, and geochemical information, to analyze and develop an understanding of the system, and to develop predictive capabilities that will contribute to the effective management of the system. The use of computer simulation is an important element of the RASA studies, both to develop an understanding of the natural, undisturbed hydrologic system and the changes brought about in it by human activities, and to provide a means of predicting the regional effects of future pumping or other stresses.

The final interpretive results of the RASA Program are presented in a series of U.S. Geological Survey Professional Papers that describe the geology, hydrology, and geochemistry of each regional aquifer system. Each study within the RASA Program is assigned a single Professional Paper number, and where the volume of interpretive material warrants, separate topical chapters that consider the principal elements of the investigation may be published. The series of RASA interpretive reports begins with Professional Paper 1400 and thereafter will continue in numerical sequence as the interpretive products of subsequent studies become available.

Gordon P. Eaton
Director

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[Plates are in pocket]

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CONVERSION FACTORS AND DATUM

Factors for converting inch-pound units to the International System (SI) of units are given below:

Multiply	*By*	*To obtain*
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
foot per day (ft/d)	0.3048	meter per day
foot squared per day[1] (ft^2/d)	0.0929	meter squared per day

[1]This unit is used to express transmissivity, the capacity of an aquifer to transmit water. Conceptually, transmissivity is cubic feet (of water) per day per square foot (of aquifer area) per foot (of aquifer thickness). In this report, the unit is reduced to its simplest form.

Sea Level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929) — a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

HYDROGEOLOGIC FRAMEWORK OF THE MIDWESTERN BASINS AND ARCHES REGION IN PARTS OF INDIANA, OHIO, MICHIGAN, AND ILLINOIS

By George D. Casey

ABSTRACT

This report is a product of an extensive U.S. Geological Survey Regional-Aquifer Systems Analysis study undertaken to define the hydrology, geochemistry, and geologic framework of the Silurian and Devonian carbonate-rock aquifer system. The aquifer system underlies a 90,000-square-mile area in western Ohio; northern, central, and southeastern Indiana; and adjacent States and consists of Silurian and Devonian carbonate rock. Regionally, the carbonate-rock aquifer consists dominantly of limestones, dolomites plus subordinate amounts of terrigenous clastic rocks, and evaporites. The carbonate-rock aquifer system is underlain by Ordovician shales and interbedded carbonate rocks of the Maquoketa Group and undifferentiated Cincinnatian rocks that are virtually impermeable and regionally extensive. These units collectively form a barrier to ground-water flow that effectively limits the transfer of significant quantities of water through the base of the Silurian and Devonian carbonate-rock aquifer. Near the edge of the study area, the carbonate-rock aquifer is confined above by Devonian and Mississippian shales and siltstones. Where the upper confining unit has been eroded away, the overlying glacial sediments partially confine the carbonate-rock aquifer. This relationship between the glacial sediments and the Silurian and Devonian carbonate rocks prevails throughout much of the study area, where the potentiometric surface of the Silurian and Devonian carbonate rocks is within the overlying glacial deposits.

Data for this study were collected and analyzed from July 1989 through June 1993. Natural-gamma and electric geophysical well-log data and stratigraphic test-well data were examined from more than 2,500 wells in the Midwestern Basins and Arches region. From these 2,500 wells, more than 1,700 were selected to determine the hydrologic framework on the basis of location, depth of geophysical log or core, and quality of the log. A series of maps, together with five hydrogeologic sections, depicts the geometry, lateral extent, and horizontal and vertical relationships between the carbonate-rock aquifer and confining units.

INTRODUCTION

The U.S. Geological Survey's (USGS) Regional Aquifer-System Analysis (RASA) Program, initiated in 1978, was designed to determine and assess the water resources of major aquifer systems on a regional scale (Sun, 1986; Sun and Johnston, 1994). In 1988, the USGS began an extensive regional investigation, as part of the RASA Program, to (1) define the hydrogeologic framework, (2) simulate current ground-water flow, and (3) define the water chemistry and the geochemical basis for that chemistry in the Midwestern Basins and Arches region (Bugliosi, 1990).

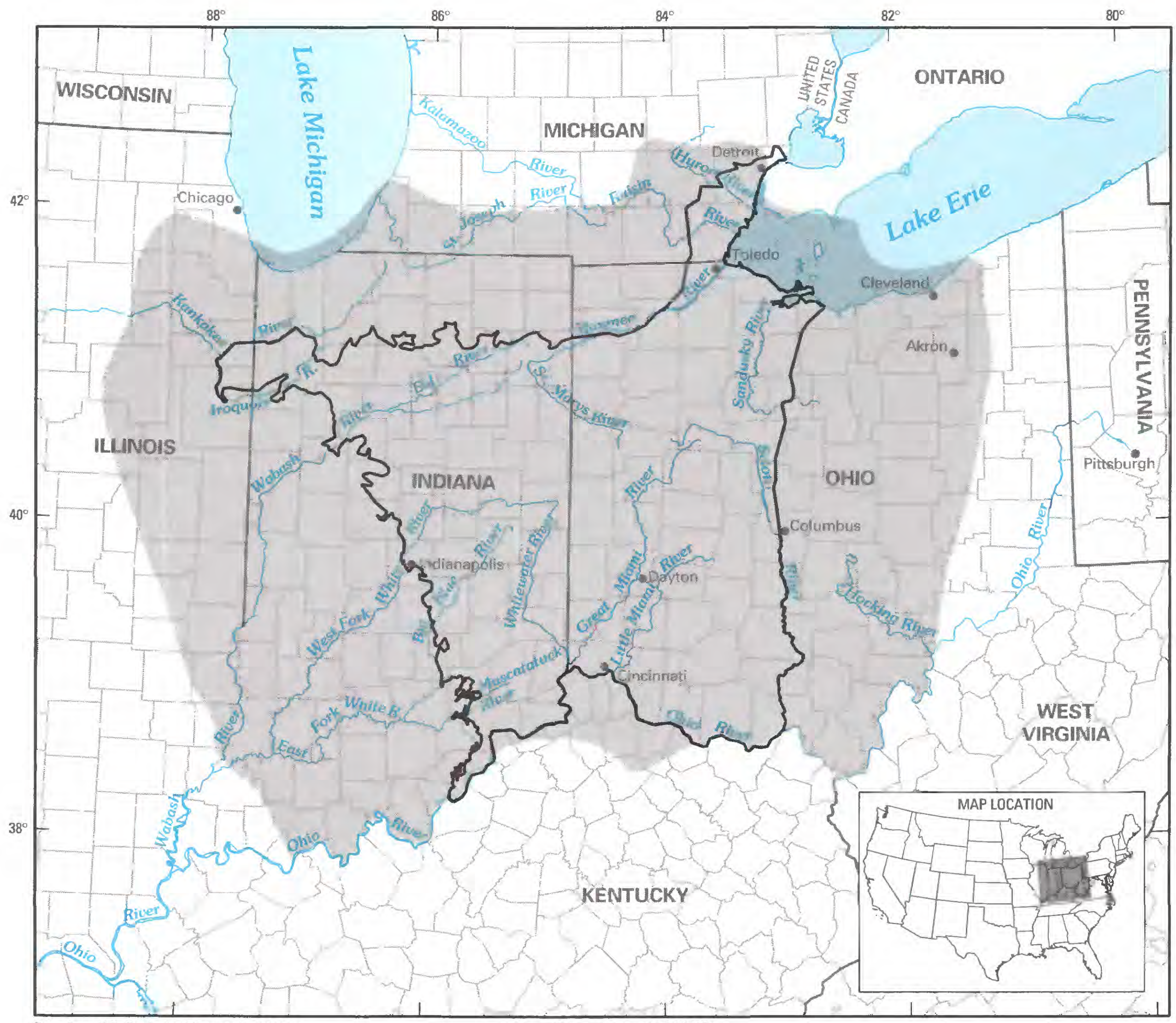
The Midwestern Basins and Arches RASA data-collection area spans approximately 90,000 mi^2 in parts of Indiana, Ohio, Michigan, Illinois, and Kentucky, as well as a small part of Canada (fig. 1). This area, which is approximately 380 miles wide and 230 miles long, straddles a regional arch complex (Kankakee, Cincinnati, and Findlay Arches) and extends into three structural basins (Appalachian, Michigan, and Illinois Basins). The study area is approximately 44,000 mi^2 and is contained within the data-collection area in parts of Indiana, Ohio, Michigan, and Illinois (fig. 1).

PURPOSE AND SCOPE

This report defines the regional extent and configuration of the hydrogeologic units (aquifers and confining units) that compose the regional aquifer system in the Midwestern Basins and Arches region in order to further the understanding of ground-water hydrology and subsurface geology there. The regional aquifer system is depicted in maps showing the altitude of the top of the hydrogeologic units and their thickness and extent, as well as hydrogeologic sections. The hydrogeologic units are described in terms of age, stratigraphic position, depositional environment, regional stratigraphic correlations, lithology, configuration, areal extent, and geophysical-log signatures.

PREVIOUS INVESTIGATIONS

Few reports of a regional scope have been published about the geology or ground-water resources of the Midwestern Basins and Arches region. Stratigraphic relations within this region have been compiled and documented by Shaver (1985). In Ohio, a comprehensive study of the limestones and dolomites of western Ohio was completed by Stout (1941). Shaver and others (1986) compiled a compendium of Paleozoic rock-unit stratigraphy in Indiana, and Hull (1990) proposed a generalized column of bedrock units in Ohio. Larsen (1991) researched and documented the development of Silurian and Devonian lithostratigraphy in northwestern Ohio, and Janssens (1970, 1977) discussed the Sil-



Base from U.S. Geological Survey digital data, 1:2,000,000, 1972

0 20 40 60 MILES

0 20 40 60 KILOMETERS

EXPLANATION

Data-collection area

Boundary of study area

FIGURE 1.—Location of data-collection and study areas in the Midwestern Basins and Arches region.

urian and Devonian rocks in the subsurface of northwestern Ohio. The paleogeography of the Midwestern Basins and Arches region has been described by Droste and others (1975) and Droste and Shaver (1983, 1987). The regional carbonate reef or bank-type deposits have been studied by Doheny and others (1975), Briggs and others (1978), Shaver and others (1978), and Ault and others (1992).

The hydrogeology of the Midwestern Basins and Arches region has not been previously addressed other than in several reports that have considered subregional areas. The occurrence of water in the Silurian and Devonian carbonate-rock aquifer in western Ohio was described by the Ohio Department of Natural Resources, Division of Water (Walker and others, 1970), as well as by Norris and Spieker (1961), Norris and Fidler (1971; 1973), and Norris (1979). Ground-water resources of the Whitewater River and Kankakee River basins were studied by the Indiana Department of Natural Resources (1988, 1990). A statewide survey of existing hydrogeologic data for Indiana was compiled by Geosciences Research Associates Inc. (1982). A ground-water atlas of the State of Indiana was compiled by Fenelon and others (1994).

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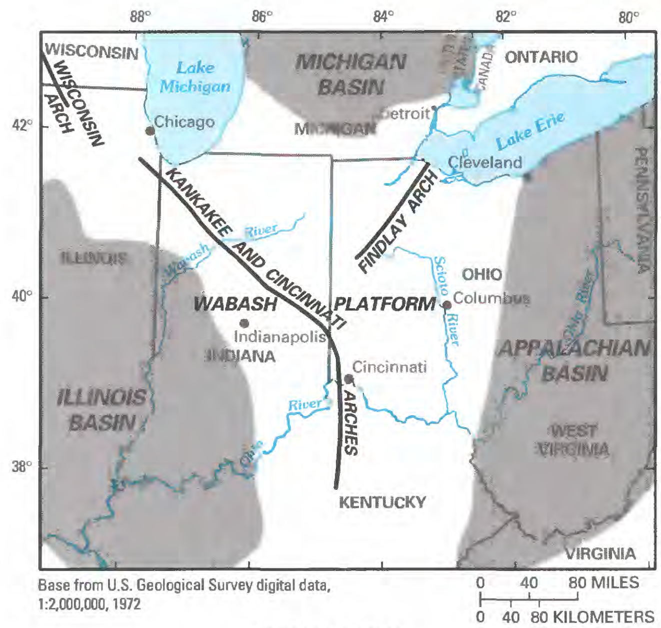
SUMMARY OF MIDWESTERN BASINS AND ARCHES CARBONATE AND GLACIAL GEOLOGY

REGIONAL SETTING

The Midwestern Basins and Arches region is in the Interior Lowlands of Eastern North America (P.B. King, 1977), which cover the central part of the North American craton and extend from the Appalachian Mountains system west to the Colorado Plateaus. The study area of the Midwestern Basins and Arches RASA is in western Ohio; northern, central, and southeastern Indiana; southeastern Michigan; and a small part of northeastern Illinois. This area spans the Kankakee, Cincinnati, and Findlay Arches (fig. 2). The axes of the Cincinnati and Kankakee Arches trend west-northwest to southeast, whereas the axis of the Findlay Arch trends southwest to north-northeast. This structurally positive feature has been described as the Wabash Platform because of the sedimentary deposition that took place in this area (Shaver and others, 1978). The study area is bounded on the north by the Michigan Basin, on the east by the Appalachian Basin, and on the west by the Illinois Basin (fig. 2).



EXPLANATION

Approximate location of basin

Approximate location of arch

FIGURE 2.—Structural elements in the Midwestern Basins and Arches region.

GENERALIZED REGIONAL GEOLOGY

The data-collection area is underlain by sedimentary rocks that range in age from Precambrian through Mississippian; however, only Ordovician (Cincinnatian) through Mississippian rocks crop out (fig. 3). The sedimentary rocks of primary interest range in age from Cincinnatian through Early Mississippian. These units dip away from the crests of the arches and thicken into the adjacent structural basins. The oldest sedimentary rocks are exposed along the crest of the Cincinnati Arch in southwestern Ohio and southeastern Indiana (figs. 2 and 3) and are overlain by younger strata toward the center of the basins.

RELATION OF STRATIGRAPHY AND HYDROGEOLOGIC UNITS

The basal confining unit of the carbonate-rock aquifer system in the Midwestern Basins and Arches region

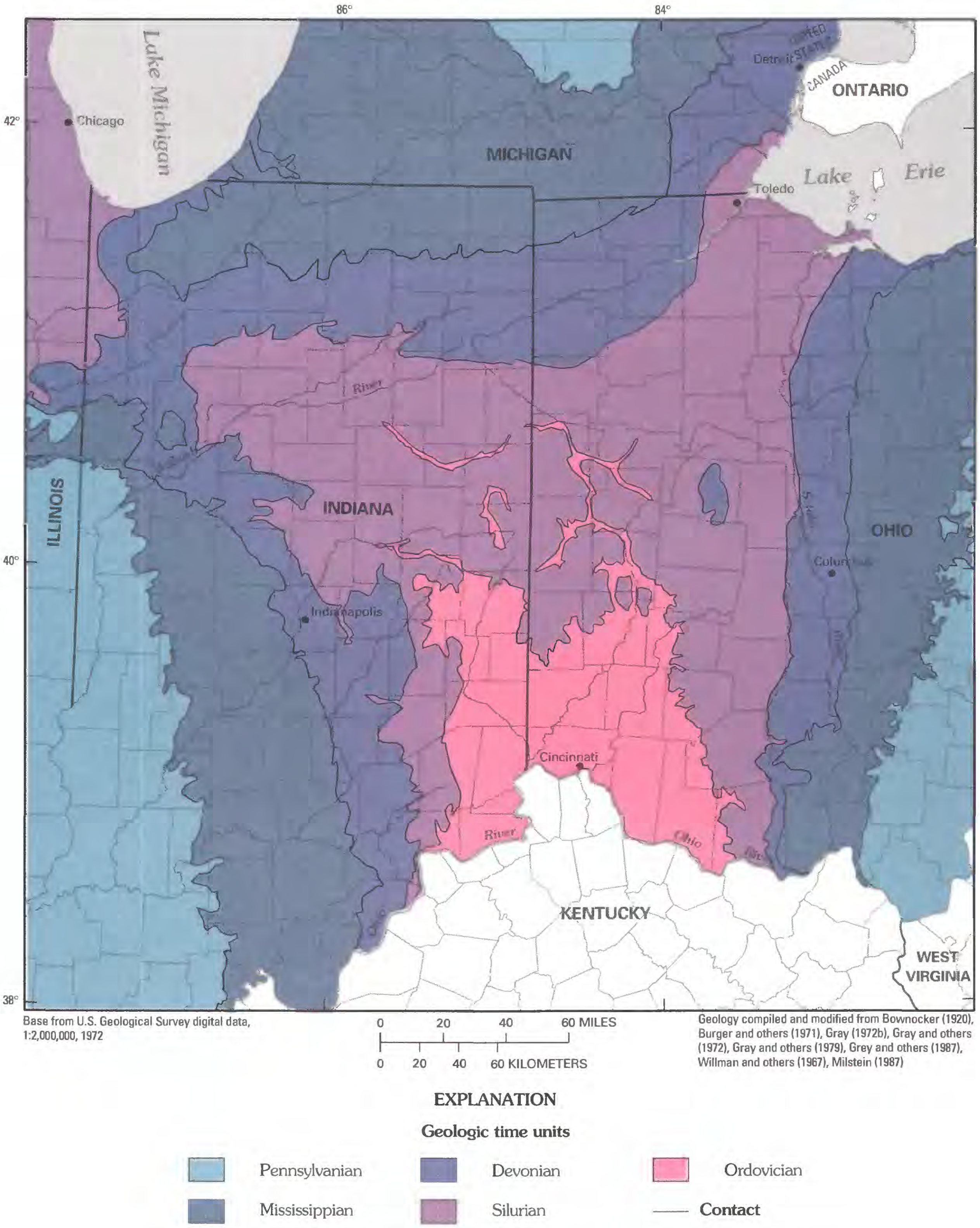


FIGURE 3.—Generalized bedrock geologic map of the Midwestern Basins and Arches region.

consists of shales and minor interbedded limestones of Ordovician age (fig. 4). The carbonate-rock aquifer consists of Silurian and Devonian limestones and dolomites. The rocks that compose the aquifer in Indiana can be grouped into four major stratigraphic units, whereas the equivalent rocks in Ohio have not been grouped into major stratigraphic units (fig. 4). The upper confining unit of the carbonate-rock aquifer system consists of upper Middle Devonian, Upper Devonian, and Lower Mississippian shales and siltstones (fig. 4). Where the shales and siltstones have been removed by erosion, the overlying glacial deposits function as a moderately permeable regional confining unit.

The basal confining unit thickens eastward from the western border of Indiana toward Ohio (pls. 1 and 2). The basal confining unit in Ohio gradually thickens as it dips into the Appalachian Basin (pl. 2). The basal confining unit thins where it crops out in southeastern Indiana and southwestern Ohio because of pre-Silurian erosion of the unit and post-Permian uplift and subsequent erosion along the crest of the Cincinnati Arch (pl. 2).

In southeastern Indiana and southwestern Ohio, the Silurian and Devonian carbonate-rock aquifer increases in thickness from its contact with the underlying Ordovician shales (the updip edge of the carbonate-rock aquifer) as it is traced downdip into the various structural basins (pls. 1 and 2). Along the crests of the arches, in a structurally high position, the aquifer units crop out and have been subjected to several extensive periods of erosion. This erosion has resulted in the loss of entire sections of the carbonate-rock aquifer in the central part of the study area.

In Ohio and northern Indiana, the upper confining unit increases in thickness from its contact between the Middle Devonian carbonates and the updip edge of the Upper Devonian shales as it is followed downdip into the Appalachian and Michigan Basins (pls. 1 and 2). In central and southwestern Indiana, the upper confining unit increases in thickness from its contact between the Middle Devonian carbonates and the updip edge of the Middle and Upper Devonian shales as it is traced downdip toward the Illinois Basin (pls. 1 and 2).

Along the crests of the arches, in structurally high positions, the upper confining unit has been subjected to several extensive periods of erosion. This erosion has resulted in the loss of entire sections of the confining unit in the central part of the study area, with the exception of the so-called Bellefontaine outlier, which is approximately 50 miles northwest of Columbus, Ohio (figs. 5 and 6).

STRATIGRAPHY

ORDOVICIAN ROCKS

The nomenclature of the basal confining unit of the Silurian and Devonian carbonate-rock aquifer system depends largely on the geographic location. In Indiana, it is referred to as the Maquoketa Group, both in the subsurface and as a subcrop unit in southeastern Indiana near the Ordovician outcrop (Gray and others, 1985). In Ohio terminology, the names of outcrop units are used to describe the Upper Ordovician rocks in southwestern Ohio; however, in the subsurface in northwestern Ohio, the Upper Ordovician unit is described as undifferentiated Cincinnatian shale and limestone (Hull, 1990). In order to minimize confusion and to maintain uniformity with the usage of the various State geological surveys, this RASA study has adopted the names "Maquoketa Group" in Indiana and "undifferentiated Cincinnatian rocks" in Ohio (Shaver, 1985) (fig. 4). This naming convention follows the usage of the Ohio Geological Survey and the Indiana Geological Survey.

The Upper Ordovician units are present throughout the study area and unconformably overlie the Trenton Limestone in Indiana, except in southeastern Indiana where the Ordovician units conformably overlie the Kope Formation (Gray, 1972b; Droste and Shaver, 1985). In northwestern and central Ohio, the undifferentiated Cincinnatian rocks unconformably overlie the Trenton Limestone (Janssens, 1977). The Upper Ordovician units are overlain unconformably by either the Sexton Creek Limestone or Brassfield Limestone and the Cataract Formation of Silurian age (LaFerriere and others, 1986).

The Maquoketa Group or the undifferentiated Cincinnatian rocks are a clastic wedge that extends across the study area from the west. The shale that predominates in these units is generally gray and calcareous, but a brown carbonaceous shale (100–300 ft thick) is present in the lowermost part of the unit. Approximately 20 percent of the basal confining unit is composed of limestone, predominantly in the uppermost part of the unit (Gray, 1972b).

SILURIAN ROCKS

The Silurian rocks that compose the carbonate-rock aquifer in Indiana and northeastern Illinois can be grouped into three major stratigraphic units: the equivalent units consisting of the Brassfield Limestone, Sexton Creek Limestone, or the Cataract Formation; the Salamonie Dolomite; and the Salina Group (fig. 4). The stratigraphic units in Ohio and southern Michigan have

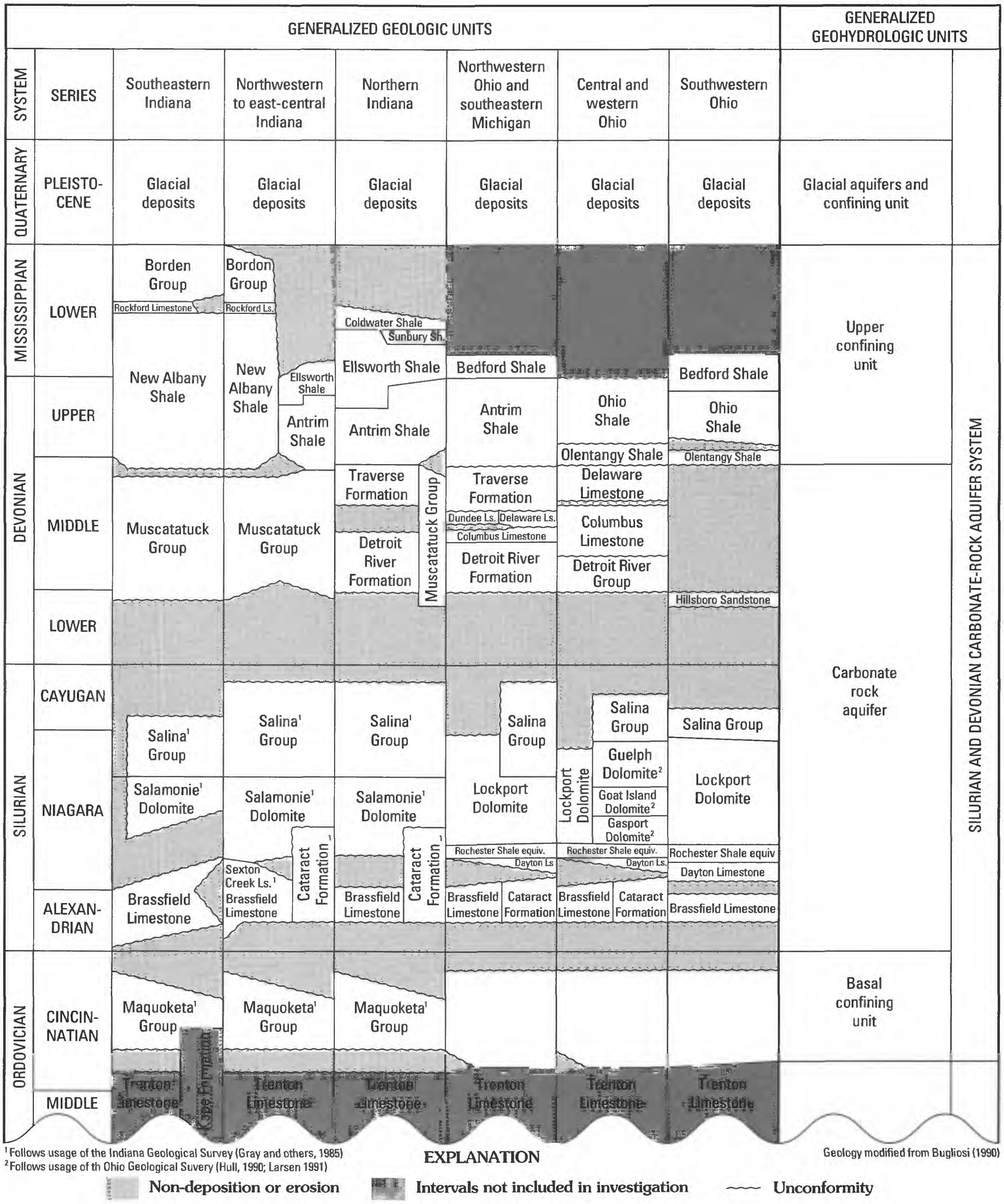


FIGURE 4.—Stratigraphic chart showing time- and rock-stratigraphic framework and nomenclature for the Midwestern Basins and Arches region.

been subdivided more than those in Indiana. In Ohio and southeastern Michigan, the Silurian rocks that compose the carbonate-rock aquifer are the Brassfield Limestone or the Cataract Formation, the Dayton Limestone, the Rochester Shale equivalent, the Lockport Dolomite and its equivalent units, and the Salina Group (fig. 4).

During Alexandrian and early Niagaran time, tectonic events in the Great Lakes region were continuing to be affected by the Taconic orogeny. In northwestern Ohio, northeastern Indiana, and southern Michigan, the accumulation of Alexandrian and lower Niagaran carbonates was affected by depositional environments that were restricted to the Michigan Basin. This resulted in the deposition of the Cataract Formation, which is mostly a dolomite in the lower one-third of the formation and an impure and argillaceous dolomite in the upper two-thirds (Shaver and others, 1986). The Cataract Formation is conformably overlain in the extreme northwestern part of Indiana by the Salamonie Dolomite, and in this area, the basal section of the Salamonie Dolomite is in a facies relation with the upper part of the Cataract Formation (Rexroad and Droste, 1982). In most of the region, the Cataract Formation is unconformably overlain by either the Salamonie Dolomite or the Dayton Limestone.

In southeastern Indiana and southwestern Ohio, carbonate-sediment accumulation during Alexandrian and early Niagaran time was affected by the depositional environments within the Illinois and Appalachian Basins. This resulted in the deposition of the Brassfield Limestone, a medium- to coarse-grained fossiliferous limestone that is locally dolomitized and contains thin, noncontinuous stringers of shale (Shaver and others, 1986; Stout, 1941). The Brassfield Limestone is unconformably overlain by either the Salamonie Dolomite or the Dayton Limestone.

In the western one-half of Indiana, the accumulation of Alexandrian and lower Niagaran carbonate sediments was affected by the depositional environments within the Illinois Basin, which resulted in the deposition of the Sexton Creek Limestone, a very cherty, impure limestone or dolomite. In northwestern Indiana and northeastern Illinois, the lowest section of this unit is an argillaceous dolomite or a dolomitic shale (Rexroad and Droste, 1982; Shaver and others, 1986). The Sexton Creek Limestone is unconformably overlain by the Salamonie Dolomite in the western one-half of Indiana, with the exception of a small part of northwestern Indiana where the Salamonie Dolomite conformably overlies the Sexton Creek Limestone (Rexroad and Droste, 1982).

During middle Niagaran time, the Great Lakes region underwent a period of relative tectonic quiescence, as compared to Alexandrian and early Niagaran time, and was accompanied by a marine transgression (Shaver and others, 1986). In western Ohio, this transgression resulted in the deposition of the Dayton Limestone and the Rochester Shale equivalent rocks. The Dayton Limestone is a saccharoidal, coarsely crystalline, medium-bedded dolomite (Stout, 1941; Ausich, 1987). The name Rochester Shale equivalent refers to several members that have been described as containing soft calcareous clay shale and thin layers of dolomite (Stout, 1941; Hull, 1990). These stratigraphic units are comparable in character to the lowest part of the Salamonie Dolomite in southeastern Indiana and the highest part of the Cataract Formation in northern and east-central Indiana (Shaver and others, 1986).

The Salamonie Dolomite consists of two distinct lithologies. The basal part generally is a fine-grained, impure, argillaceous limestone, dolomitic limestone, and shale (Shaver and others, 1986). This basal part is correlative to the Dayton Limestone and the Rochester Shale equivalent in Ohio as described above. The upper part of the Salamonie Dolomite is generally a uniform, pure, white to light-gray dolomite that has a coarse-grained, bioclastic, vuggy texture (Shaver and others, 1986). In Ohio, the correlative unit of the upper part of the Salamonie Dolomite is the lower and middle part of the Lockport Dolomite.

The Lockport Dolomite conformably overlies the Rochester Shale equivalent and is conformably overlain, with minor local unconformities near reef-bank facies (Shaver, 1991), by the Salina Group, where the Salina has not been eroded from above the Lockport Dolomite. In central and western Ohio, the Lockport Dolomite interval has been subdivided into the Gasport Dolomite, the Goat Island Dolomite, and the Guelph Dolomite (Janssens, 1977). The Gasport Dolomite is a microcrystalline to coarsely crystalline, medium- to dark-gray dolomite. The Goat Island Dolomite is a microcrystalline to finely crystalline, light-brown to light-gray-brown dolomite. The Guelph Dolomite is a fossiliferous, predominantly coarsely crystalline, vuggy, white to light-gray dolomite. The term "undifferentiated Lockport Dolomite" is used in Ohio only for areas where a distinct lithology cannot be determined for the Goat Island Dolomite; therefore, the Lockport Dolomite includes the Gasport and Goat Island Dolomite equivalent rocks and the Guelph Dolomite (Janssens, 1977).

Droste and Shaver (1976) described the Salamonie Dolomite as a laterally extensive, blanketlike deposit of carbonate rocks that covered the entire State of Indiana before the multiple post-Silurian periods of erosion. This description can be extended to the correlative Lockport Dolomite of Ohio. The pre-Devonian erosion resulted in the removal of not only the Salamonie and the Lockport

Dolomites but also the Silurian strata below these units in the south-central part of the study area.

During late Niagaran time, the Great Lakes region underwent a series of marine regressions and transgressions as the result of a combination of tectonic forces exerted by (1) deposition within the structural basins, (2) emplacement of an overthrust on the eastern margin of the North American Craton in the present-day Middle Atlantic States, and (3) possible eustatic sea-level changes (Beaumont and others, 1988; Shaver and

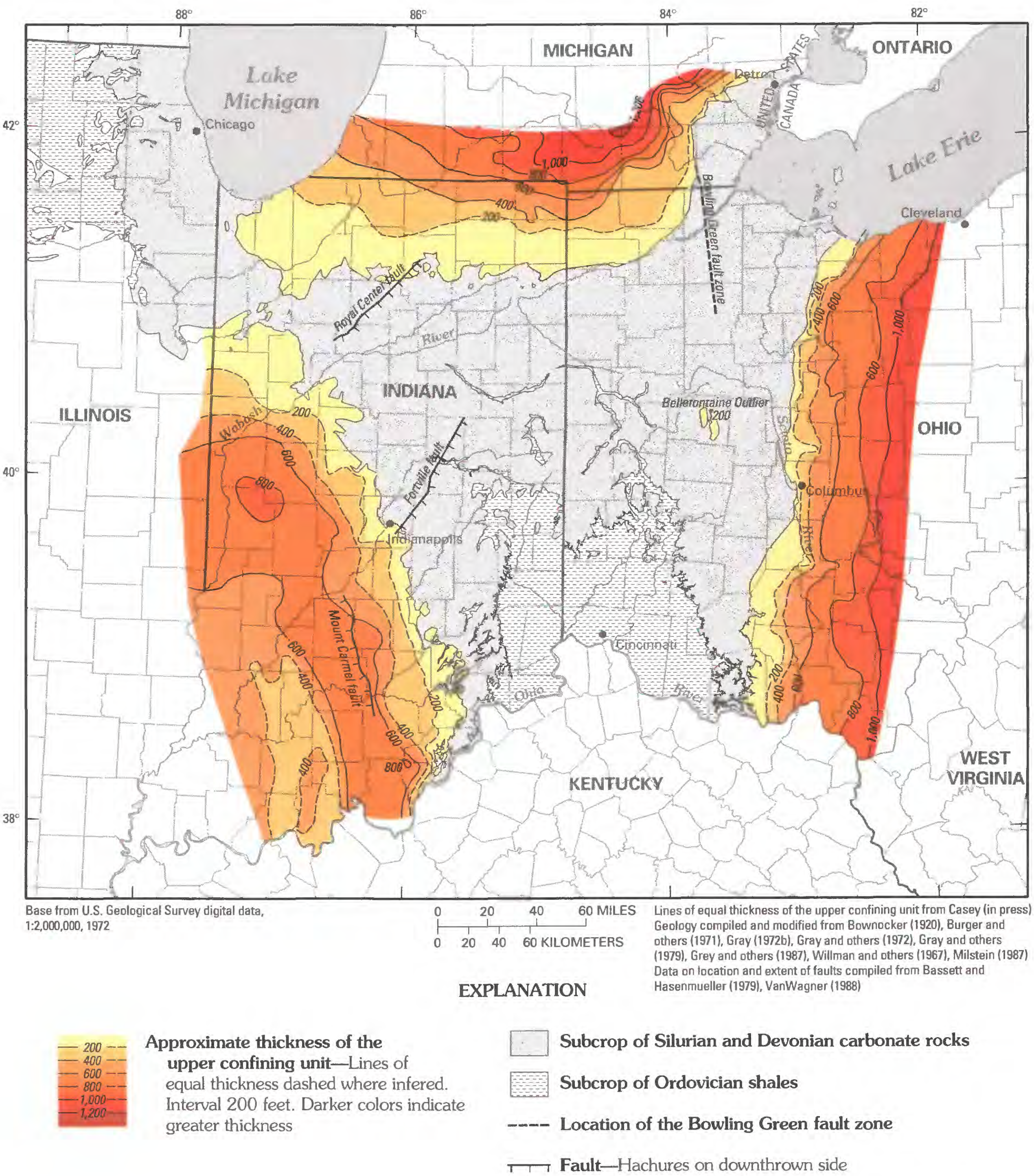


FIGURE 5.—Approximate thickness and extent of the upper confining unit of the Silurian and Devonian carbonate-rock aquifer system in the Midwestern Basins and Arches Region.

Sunderman, 1983; Onasch and Kahle, 1991). The Salina Group conformably and unconformably overlies the Salamonie Dolomite and the Lockport Dolomite. The unconformities are considered to be minor local unconformities near the reef-bank facies (Shaver, 1991). The upper contact of the Salina Group is a regionally extensive unconformity. The overlying Devonian rocks, where present, range in age from Early to Middle Devonian (Droste and Shaver, 1982; Hull, 1990).

In Indiana, the Salina Group includes a diverse assemblage of dominantly carbonate rocks that range from fine-grained argillaceous rocks to a pure carbonate mud. The Salina Group also includes a coarse-grained, bioclastic, vuggy, and fossiliferous facies that consist of reef-framework rocks (Shaver and others, 1986). In Indiana, south of a paleogeographic feature named the "Fort Wayne Bank" (fig. 7), the lower one-half of the Salina Group contains three distinct facies (Pinsak and Shaver, 1964). These facies consist of a micritic to fine-grained and sucrosic dolomite; an argillaceous to shaly, fine-grained, thin-bedded dolomite; and a reef facies. The reef facies grades from a fully mature reef rock to what has been described as an incipient reef rock (Shaver and others, 1986). North of the Fort Wayne Bank, the reef facies generally is absent. Instead, the dolomites that compose the lower one-half of the Salina Group north of the Fort Wayne Bank consist of a dark-brown, micritic to fine-grained, partially laminated dolomite and a lighter colored, granular, vuggy dolomite (Shaver and others, 1986).

The upper one-half of the Salina Group in Indiana was deposited during latest Niagaran to earliest Cayugan time. These rocks contain several lithologies that grade into one another across the western one-half of the study area (Shaver and others, 1986). The lithologies of these rocks include dense to fine-grained, calcareous, silty dolomite; dolomitic, silty limestone; fine-grained, light-colored limestone; dolomitic limestone; and dolomite. Also included are micritic to fine-grained, thinly laminated limestone; granular, vuggy dolomite; and carbonate mudstones that are contained within the bank, reef, reef-detrital, and biohermal deposits.

The upper part of the Salina Group has been subjected to post-Cayugan, pre-Middle Devonian subaerial exposure and erosion. This is apparent where the uppermost part of the Salina Group is exposed within quarries. At several locations in Indiana where the Cayugan carbonate rocks have not been removed by erosion, paleokarst features are evident. The paleokarst features consist of caves, grykes (solution-widened fissures), solution-widened bedding joints, and fractures derived from the settling of reef-flank deposits (Shaver, 1989). The paleokarst features are filled with a whitish quartz sand and a shaly material, which are cave breakdown that consists of the local host rock, and what appears to be pisolites. As evidence of the age of these features in relation to the overlying sediment, Shaver (1989) described a calcareous shaly material that fills a cave and contains Devonian conodonts.

In Ohio, the Salina Group consists of a diverse assemblage of carbonate and evaporate deposits. This group ranges from an argillaceous, microcrystalline dolomite, which includes a stromatolitic dolomite representing a biohermal facies, to a saccharoidal, medium-grained dolomite and bedded evaporate deposits (Janssens, 1977).

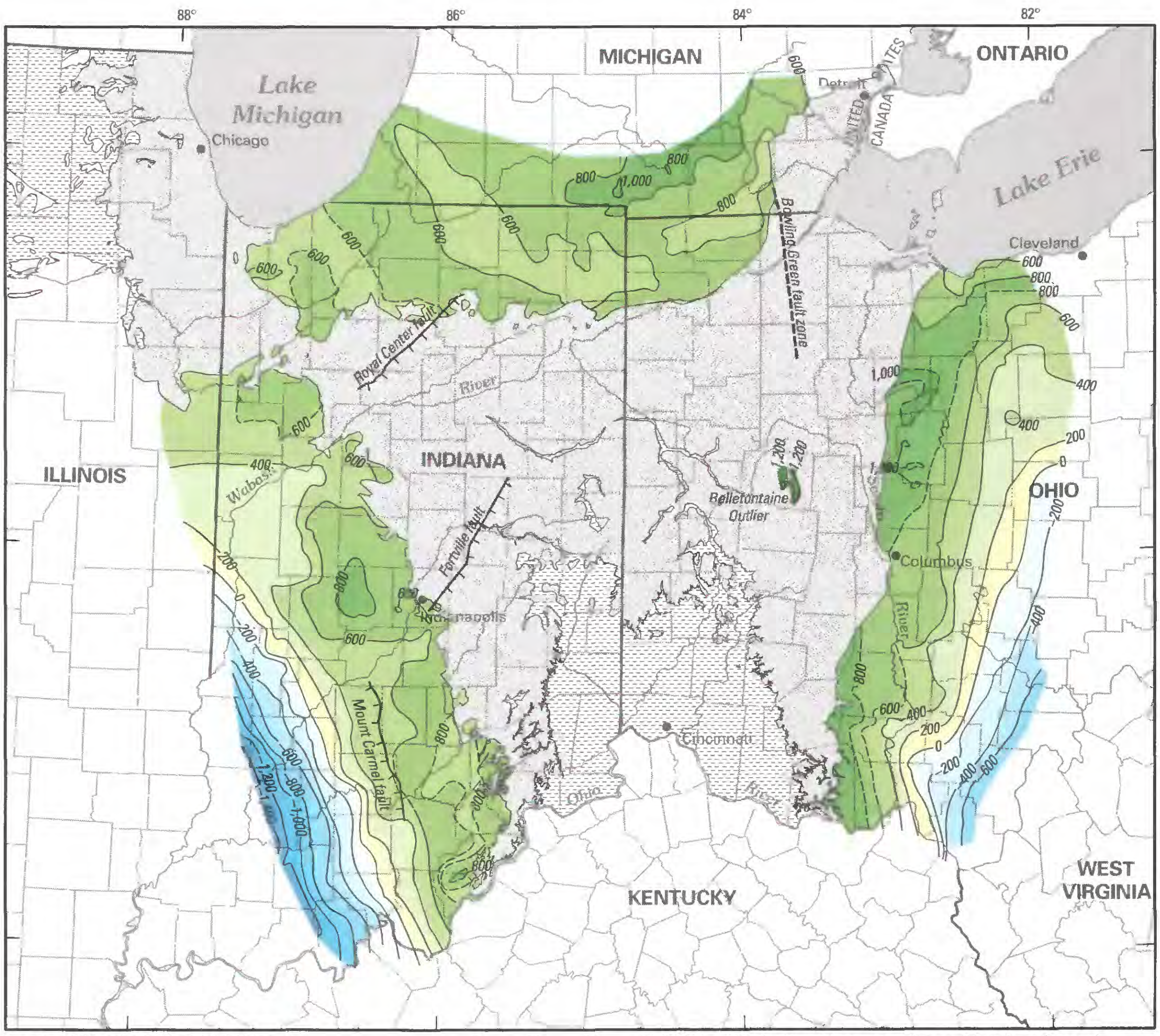
In northwestern Ohio, the Salina Group contains lithologies that also vary with the location. In the western one-half of northwestern Ohio, the Salina Group contains the following dominant lithologies: (1) a stromatolitic brown dolomite, (2) a partly argillaceous, silty, microcrystalline dolomite that contains some shale, (3) a microcrystalline dolomite that is partially laminated, argillaceous, and pelletal and that locally contains secondarily deposited gypsum (Janssens, 1977), and (4) a karst facies that contains mud cracks, as well as caverns that are believed to contain secondary fillings of Devonian sediments (G.E. Larsen, Ohio Geological Survey, oral commun., 1992).

A facies change has been noted within the Salina Group of northwestern Ohio east of the Bowling Green Fault Zone (fig. 5), where it contains dolomite, bedded anhydrite, very argillaceous dolomite, and shale. Janssens (1977, p. 23) described it as "an important updip facies of the salt-bearing Salina rocks of eastern Ohio". This facies change in northwestern Ohio could be the result of several periods of movement along the Bowling Green Fault Zone and their effect on depositional environments, coupled with subsidence in the Michigan Basin during this depositional episode (Onasch and Kahle, 1991).

In southwestern Ohio, the Salina Group has been subjected to a greater amount of post-Cayugan, pre-Middle Devonian erosion than in northwestern Ohio. Ulteig (1964, p. 34) suggested that the "Upper Silurian units under cover of the Devonian carbonates are truncated in a southwesterly direction". This erosion of the upper section of the Salina Group in southwestern Ohio leaves only the basal section, which consists of a pure crystalline dolomite that exhibits medium to massive bedding and has a sucrosic texture; an argillaceous to shaly dolomite; and a dolomite that has a reeflike character (Stout, 1941).

DEVONIAN ROCKS

The Devonian rocks that compose the carbonate-rock aquifer in Indiana can be grouped into two major stratigraphic units, the Detroit River and Traverse Formations, which together make up the Muscatatuck Group (fig. 4). The stratigraphic units in Ohio and southeastern Michigan have been subdivided more than those in Indiana. In Ohio and southeastern Michigan, the Devonian rocks that compose the carbonate-rock aquifer are the Hillsboro Sandstone, the Detroit River Group or Formation, the Columbus Limestone, the Delaware Limestone or the Dundee Limestone, and the Traverse Formation (fig. 4).

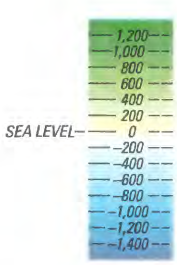


Base from U.S. Geological Survey digital data, 1:2,000,000, 1972

0 20 40 60 MILES
0 20 40 60 KILOMETERS

Altitude of top of the upper confining unit from Casey (in press)
Geology compiled and modified from Bownocker (1920), Burger and others (1971), Gray (1972b), Gray and others (1972), Gray and others (1979), Grey and others (1987), Willman and others (1967), Milstein (1987)
Data on location and extent of faults compiled from Bassett and Hasenmueller (1979), VanWagner (1988)

EXPLANATION



Approximate altitude of the top of the upper confining unit—Contour interval 200 feet. Dashed where inferred. Datum is sea level. Darker greens indicate greater elevation above sea level; darker blues indicate greater depth below sea level

Subcrop of Silurian and Devonian carbonate rocks

Subcrop of Ordovician shales

---- **Location of the Bowling Green fault zone**

Fault—Hachures on downthrown side

FIGURE 6.—Approximate altitude of the top of the upper confining unit of the Silurian and Devonian carbonate-rock aquifer system in the Midwestern Basins and Arches region.

The Antrim Shale and the Ellsworth Shale are the upper Middle Devonian and Upper Devonian shales that make up the upper confining unit of the Silurian and Devonian carbonate-rock aquifer system north of the Kankakee and Findlay Arches in northern Indiana, southeastern Michigan, and northwestern Ohio. South and west of the Kankakee and Cincinnati Arches in southeastern, northwestern, and east-central Indiana, the equivalent lithologic unit to the Antrim Shale is the New Albany Shale (fig. 4) (Lineback, 1970; Shaver and others, 1986). East of the Cincinnati Arch and south of the Findlay Arch in central-western and southwestern Ohio, the equivalent lithologic unit is the Olentangy Shale, Ohio Shale, and the lower part of the Bedford Shale (fig. 4).

After the post-Cayugan, pre-Middle Devonian erosional event, the Great Lakes region was again a site of carbonate and evaporite deposition. The controlling tectonic forces of this depositional event were the Acadian orogeny and a major subsidence episode in the Michigan and Illinois Basins (Droste and Shaver, 1983; Beaumont and others, 1988). The late Niagaran and Cayugan Fort Wayne Bank (fig. 7) also is thought to have played a large role in the deposition of the Middle Devonian carbonate rocks. As a resistant carbonate reef-bank facies, it may have functioned as a barrier or a sill during the early deposition of the Detroit River Group or the Detroit River Formation of the Muscatatuck Group (Doheny and others, 1975). Some investigators (Doheny and others, 1975; Briggs and others, 1978) have proposed that the Fort Wayne Bank was a continuous feature that extended from northwestern Indiana to northwestern Ohio (fig. 7). The Fort Wayne Bank, in conjunction with another carbonate bank in southern Michigan (proposed by Briggs, 1959), formed a restricted evaporite basin in northern Indiana, northwestern Ohio, and southern Michigan (Mesolella and others, 1974).

In northern Indiana, northwestern Ohio, and southern Michigan, the Detroit River Formation was deposited during late Early Devonian and Middle Devonian time. This stratigraphic unit unconformably overlies rocks of the Salina Group that become progressively younger from the Wabash Platform into the Michigan Basin. In northern Indiana, the Detroit River Formation is unconformably overlain by the Traverse Formation. In northwestern Ohio, the Detroit River Formation is conformably overlain by a thin section of the Columbus Limestone. The Detroit River Formation was described by Janssens (1970) and Shaver and others (1986) as having several distinct facies. The basal unit consists of a sandy dolomicrite that grades to a fine- to medium-grained sandstone, which is cemented by dolomite and contains thin lenses of dolomicrite. This basal unit grades upward into a fine-grained, laminated dolomite, dolomicrite, and dolosiltite that contains anhydrite and gypsum nodules (Janssens, 1970; Shaver and others, 1986).

In central and western Ohio, southeast of the eastern extension of the Fort Wayne Bank, the Detroit River Group was described by Stout (1941) as a true dolomite that grades into a calcareous dolomite. This limy dolomite is finely crystalline, light to brownish gray, and finely banded and contains no evaporites. The absence of evaporites can be explained by the presence of a more open, nonrestricted depositional environment south and east of the eastern extension of the Fort Wayne Bank in central and western Ohio (fig. 7).

The carbonate rocks that are present in southwestern Ohio were subjected to a large amount of erosion after early Cayugan and during Middle Devonian time. Locally, where it has not been eroded, the Hillsboro Sandstone unconformably overlies the Salina Group and is unconformably overlain by the Olentangy Shale, which makes up the lowest part of the upper confining unit. The Hillsboro Sandstone is said to be a clean, very pure, well-sorted, angular silicious sand (Orton, 1888).

In northwestern, east-central, and southeastern Indiana, the entire Middle Devonian carbonate-rock sequence is classified as the Muscatatuck Group (Shaver, 1974). The Muscatatuck Group unconformably overlies the Salina Group strata that become progressively younger from the Kankakee Arch into the Illinois Basin. In southeastern Indiana, the Muscatatuck Group is unconformably overlain by the New Albany Shale, which makes up the upper confining unit. In northwestern and east-central Indiana, the New Albany or Antrim Shale contact with the Muscatatuck Group generally is unconformable, but in places, the contact is conformable (fig. 4) (Shaver and others, 1986).

In northern Indiana, the Muscatatuck Group is divided into the Detroit River and Traverse Formations (Shaver and others, 1986). Several dominant carbonate lithologies are present in the Muscatatuck Group. The lowest part consists of a sandy, fine-grained, quartz-rich dolomite or a dolomitic quartz sandstone overlain by a granular, vuggy dolomite. These basal units are overlain by shaly to pure, granular limestone and dense, lithographic to fine-grained, typically laminated dolomites and dolomitic limestones (Becker, 1974; Shaver and others, 1986). Certain coarsely granular and fibrous anhydrite and gypsum deposits within the Muscatatuck Group correlate with the Detroit River Formation in northern Indiana (Becker, 1974; Shaver and others, 1986).

In central and western Ohio, the Columbus Limestone unconformably overlies the Detroit River Group (where the Detroit River Group is recognized) and is unconformably overlain by the Delaware Limestone (Hall and Alkire, 1956; Dow, 1962; Hull, 1990; Larsen, 1991). The Columbus Limestone consists of a basal brown, highly crystalline and porous dolomite or dolomitic limestone overlain by a massive, gray, fossiliferous limestone that locally contains some chert (Westgate, 1926; Stout, 1941; Hall and Alkire, 1956).

In northwestern Ohio, the Detroit River Formation is conformably overlain by a thin section of the Columbus Limestone (Shaver, 1985). The Columbus Limestone is unconformably overlain by the Dundee and Delaware Limestones (fig. 4), which are laterally equivalent. The Dundee Limestone is a saccharoidal, sandy, fine- and medium-grained crystalline dolomitic limestone or dolomite that contains nodular chert (Janssens, 1970). The Delaware Limestone is a fine-grained, argillaceous and fossiliferous limestone (Janssens, 1968). The Dundee and Delaware Limestones are unconformably overlain by the Traverse Formation (fig. 4).

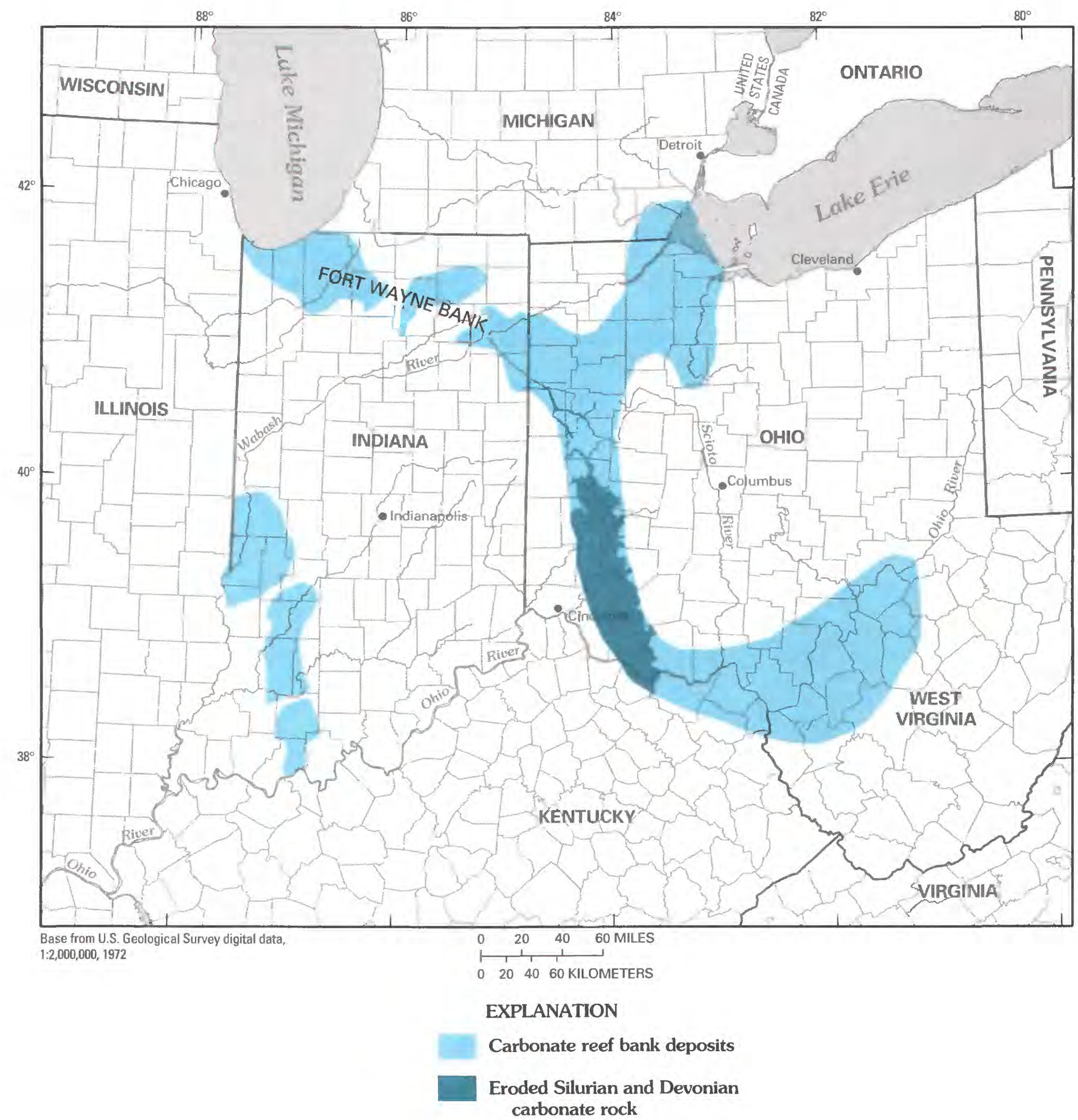


FIGURE 7.—Location of Fort Wayne Bank and other contemporaneous bank-type deposits in the Midwestern Basins and Arches region.

The Traverse Formation in northwestern Ohio contains two major lithologies. The basal part of the Traverse is a fine- to coarse-grained, argillaceous and fossiliferous limestone interbedded with calcareous shale. The upper part consists of a dense to medium-grained crystalline dolomite that contains lenticular and nodular chert and minor interbedded shaly dolomite and shale (Janssens, 1970). The Traverse Formation unconformably overlies the Dundee and Delaware Limestones and is unconformably overlain by the Antrim Shale (Janssens, 1970; Hull, 1990; Larsen, 1991). The Antrim Shale makes up the lowest part of the upper confining unit of the Silurian and Devonian carbonate-rock aquifer system in northwestern Ohio.

The Traverse Formation in northern Indiana is lithologically similar to the strata of the same name in Ohio. In Indiana, the Traverse Formation contains the following distinct lithologies: (1) a basal dense, micritic, fossiliferous limestone; (2) a highly fossiliferous, lithographic and sublithographic limestone that grades from northwestern to northeastern Indiana into a fossiliferous calcareous shale and an argillaceous limestone; and (3) a cherty, dense to medium-grained dolomite that overlies both of these units (Shaver and others, 1986). The Traverse Formation unconformably overlies the Detroit River Formation. The Traverse Formation overlies progressively younger parts of the Detroit River Formation updip from the Michigan Basin onto the Wabash Platform (Shaver and others, 1986). The Traverse Formation is overlain conformably and unconformably by the Antrim Shale (Shaver and others, 1986). In northern Indiana, the Antrim Shale is the lowest part of the upper confining unit of the carbonate-rock aquifer system.

In central and western Ohio, the Delaware Limestone unconformably overlies the Columbus Limestone and is unconformably overlain by the Olentangy Shale (Shaver, 1985; Hull, 1990; Larsen, 1991). The Olentangy Shale is the basal part of the upper confining unit of the Silurian and Devonian carbonate-rock aquifer system in central and western Ohio. The Delaware Limestone consists of a basal section of thinly bedded limestone that contains nodules of chert and thin layers of shale. This basal section grades into an argillaceous limestone, which contains beds of chert, and a massive limestone unit (Hall and Alkire, 1956; Dow, 1962; Janssens, 1968).

During late Middle Devonian and Late Devonian time, the Acadian orogeny caused the formation of the Catskill delta complex, which spread from the northeastern Appalachian Basin south along the trend of the basin and west onto contiguous sections of the craton. The Acadian Mountains were uplifted along the eastern margin of the craton and were a source area for the sediments that were shed into the Appalachian Basin (Ettensohn and Barron, 1981). The Catskill delta complex had a widespread distribution that ranged from the source area near the cratonic margin, across the Appalachian Basin onto the Cincinnati, Findlay, and Kankakee Arches, and into the east- and north-central midcontinent area of Illinois and eastern Iowa to the northwest (Ettensohn and Barron, 1981; Devera and Hasenmueller, 1991).

In central and western Ohio, the Olentangy Shale unconformably overlies the Delaware Limestone and is unconformably overlain by the Ohio Shale (Hoover, 1960; Larsen, 1991). In southwestern Ohio, the Olentangy Shale unconformably overlies the Hillsboro Sandstone (Devonian) and is unconformably overlain by the Ohio Shale (Hull, 1990; Larsen, 1991). The Olentangy shale is a bluish-gray to greenish-gray, clay-rich shale that has black, fissile shale beds in the upper part of the unit; these black shale beds are more numerous in southwestern Ohio (Hoover, 1960).

The Ohio Shale in central, western, and southwestern Ohio unconformably overlies the Olentangy Shale. The Ohio Shale crops out beneath glacial sediments in central and western Ohio, and the Ohio Shale is conformably overlain by the Bedford Shale in southwestern Ohio. The Ohio Shale is a grayish-black, fissile shale that contains some gray argillaceous layers, thin sheets of micaceous sandstone, and pyrite (Hoover, 1960). The Ohio Shale and its equivalents constitute a carbon-rich or petroliferous shale sequence that has produced moderate quantities of natural gas (Janssens and de Witt, 1976). The Ohio Shale in central, western, and southwestern Ohio is equivalent to the Antrim Shale in northwestern Ohio and northern and northwestern Indiana, north of the Findlay and Kankakee Arches (Shaver, 1985).

DEVONIAN AND MISSISSIPPIAN ROCKS

The Antrim Shale in northwestern Ohio and southeastern Michigan unconformably overlies the Traverse Formation and is conformably overlain by the Bedford Shale; it is buried by glacial sediments where it crops out at the bedrock surface (fig. 4) (Shaver, 1985; Hull, 1990; Larsen, 1991). The Antrim Shale was described by Janssens (1970) as a black and dark-brown, fissile shale, of which the basal 30 ft is interbedded with minor dark-brown dolomitic layers.

North of the Kankakee Arch, in northern and northwestern Indiana, the Antrim Shale paraconformably overlies the Traverse Formation (Muscatatuck Group) and is laterally equivalent to parts of the Ellsworth Shale (fig. 4) (Shaver and others, 1986; Gutschick and Sandberg, 1991). The Antrim Shale was described by Lineback (1970) as a mostly brownish black shale that includes a greenish-gray shale in the basal section of the unit.

South and west of the Kankakee and Cincinnati Arches in southeastern, northwestern, and east-central Indiana, the lithologic unit equivalent to the Antrim Shale is the New Albany Shale (Lineback, 1970; Shaver and others, 1986). The New Albany Shale is a brownish-black, carbon-rich shale and a greenish-gray shale containing minor dolomite and dolomitic quartz sandstone layers (Lineback, 1970). The New Albany Shale unconformably overlies the Muscatatuck Group. Locally, the New Albany Shale is conformably overlain by the Rockford Limestone, which represents a thin Mississippian limestone interval (less than 10 ft thick); in places, the New Albany Shale is unconformably overlain by the Borden Group, a Mississippian shale and siltstone.

The Bedford Shale in southwestern Ohio conformably overlies the Ohio Shale and is conformably overlain by Mississippian sandstone that was not considered within the scope of this study. The Bedford Shale grades from a soft, clay-rich shale in the lower part of the formation to a siltstone containing gray, silty shale layers in the upper part of the formation (Hoover, 1960). North of the Findlay Arch in northwestern Ohio and southeastern Michigan, the Bedford Shale is a soft to hard siliceous shale (J.M. King, 1977). The Bedford Shale conformably overlies the Antrim Shale and is conformably overlain by a Mississippian sandstone that was not considered within the scope of this study.

North of the Kankakee Arch in northern, northwestern, and east-central Indiana, the Ellsworth Shale conformably overlies the Antrim Shale. In northern Indiana, the Ellsworth Shale is laterally equivalent to the Sunbury Shale and is conformably overlain by the Coldwater Shale (Shaver and others, 1986). The Ellsworth Shale crops out at the bedrock surface in northern Indiana, where it is covered by glacial deposits. The Ellsworth Shale consists of alternating beds of gray-green shale and brownish-black shale in the lower part and grayish-green shale in the upper part (Hasenmueller and Woodard, 1981).

MISSISSIPPIAN ROCKS

In northern Indiana, the Sunbury Shale conformably overlies and is laterally equivalent to the Ellsworth Shale (Shaver and others, 1986) (fig. 4). Hasenmueller and Woodard (1981) describe the Sunbury Shale as a brownish-black, carbonaceous shale. The Sunbury and Ellsworth Shales are conformably overlain by the Coldwater Shale (fig. 4) (Shaver and others, 1986), which crops out at the bedrock surface in northern Indiana, where it is deeply buried by glacial deposits (Johnson and Keller, 1972). Shaver and others (1986) describe the Coldwater Shale as a gray to greenish-gray, silty shale that has red stringers in the lower part of the unit.

South and west of the Kankakee and Cincinnati Arches in parts of southeastern, northwestern, and central Indiana, the Borden Group conformably overlies the Rockford Limestone, which represents a thin Mississippian limestone interval (less than 10 ft thick); in other areas, the Borden Group unconformably overlies the New Albany Shale (fig. 4). The Borden Group is described as a dominantly gray, argillaceous siltstone and shale that contains some fine-grained sandstone and interbedded, discontinuous limestone lenses (Shaver and others, 1986).

GLACIAL DEPOSITS

Approximately 80 percent of the study area is covered by Pleistocene deposits (fig. 8); most are of Wisconsinan age and represent three major stages: early, middle, and late Wisconsinan. Advances by the late Wisconsinan Laurentide Ice Sheet removed evidence of earlier glaciations in most places by eroding the surficial materials and incorporating older deposits with those transported by the glacier. In many places, the ice sheets overrode and deposited sediments on top of older deposits (Mickelson and others, 1983). The resulting landforms are a composite of unconsolidated deposits from multiple glacial advances and retreats.

The composition of till in the glacial deposits depends on glacial-flow paths and local geology. Most of the mineral composition of a till is representative of the local bedrock (Strobel and Faure, 1987). Many of the till units in the study area are rich in clay because of the composition of the bedrock (the Devonian and Mississippian shales) and its low resistance to glacial erosion. In addition, the Wisconsinan glacial deposits have a till composition that is determined by the inclusion of older glacial and interstadial material during the final ice advance. The direction of flow, as determined from erosional and depositional features, indicates that ice advances during late Wisconsinan time crossed the Lake Erie basin and other interstadial lakes (Whillans, 1985). These lakes provided clay-rich lacustrine sediments that have been included in the upper Wisconsinan tills as well.

A system of buried river valleys, filled with various lacustrine, alluvial, and glacial deposits, is present throughout the Silurian and Devonian carbonate-rock aquifer system. These buried river valleys have been referred to by several different names based on location and origin, but in this report they are referred to as the "Teays–Mahomet bedrock valley system" (fig. 9). These valleys were formed as a result of several continental

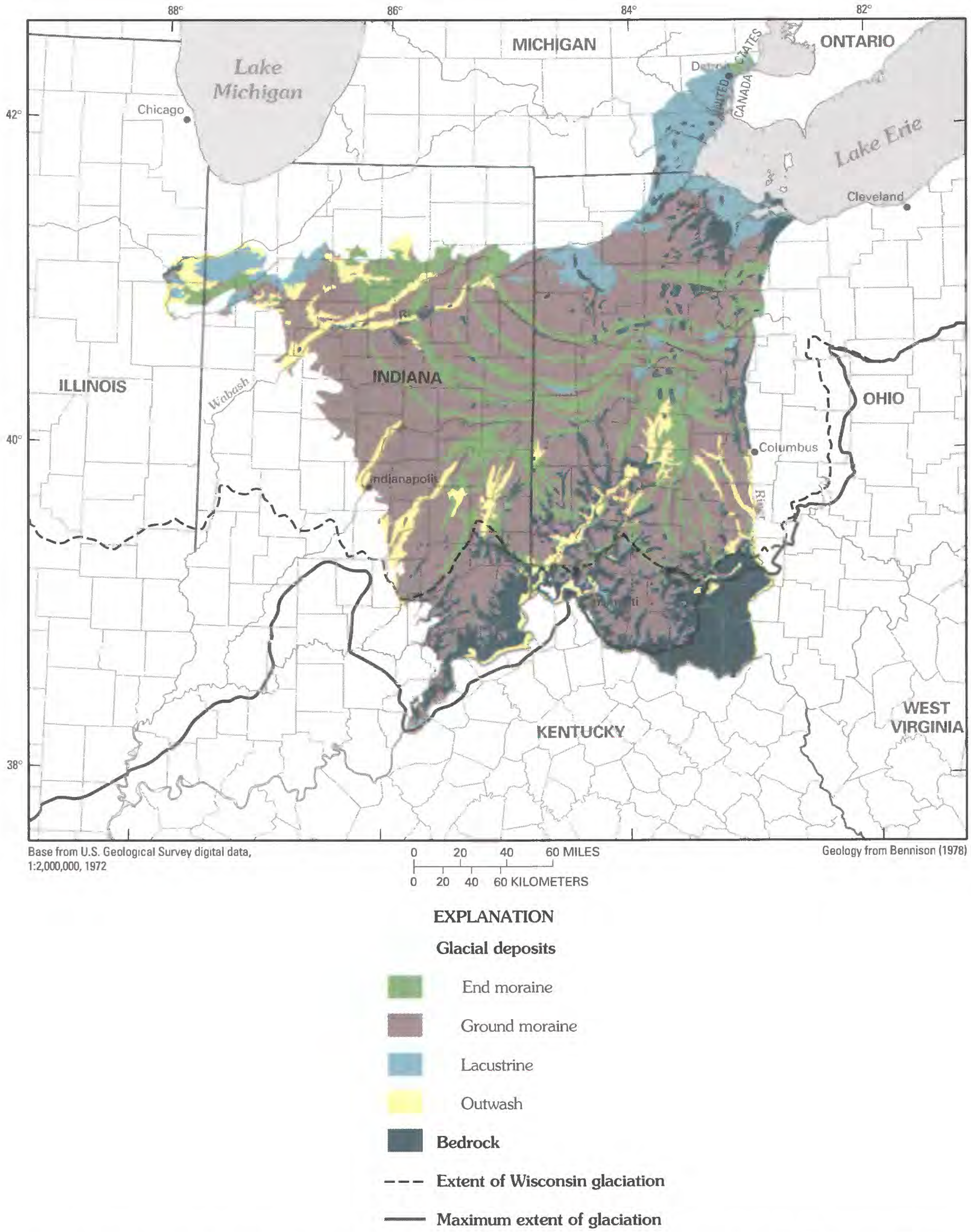


FIGURE 8.—Generalized glacial deposits and location of Wisconsinan and maximum glacial limits in the Midwestern Basins and Arches region.

glaciations that took place during the Pleistocene Epoch, although evidence exists that a preglacial river system followed a similar course (Fullerton, 1986; Goldthwait, 1991). As the ice margin retreated northward, sediment-laden rivers incised the bedrock of western Ohio and eastern Indiana, altering the preglacial valleys and later depositing valley-fill material (Gray, 1991). The hydrologic characteristics of these buried valleys vary with the type of materials deposited in them and the depth of incision into the bedrock.

HYDROGEOLOGIC FRAMEWORK

The correlation of the hydrogeologic units was based primarily on the interpretation of natural-gamma logs, drill-core descriptions, and a small number of electric logs and drillers' logs. Regional subsurface nomenclature and geologic mapping in the Midwestern Basins and Arches region was based on the Ohio and Indiana State Geological Surveys' formal geologic (rock-stratigraphic) and chronologic (time-stratigraphic) units. These units have been defined by location, lithology, and biostratigraphy from well cuttings, drill cores, and outcrop locations. The description and correlation of the various stratigraphic units that compose the Silurian and Devonian carbonate-rock aquifer system in this area are necessary because different names are used for

Base from U.S. Geological Survey digital data, 1:2,000,000, 1972

Modified from Goldthwait (1991)

0 40 80 MILES
0 40 80 KILOMETERS

EXPLANATION

—— Trace of Teays-Mahomet bedrock valley system

Figure 9.—Generalized location of the Teays–Mahomet bedrock valley system in the Midwestern Basins and Arches region.

similar stratigraphic units in the various States. The geologic nomenclature and stratigraphic relations and the hydrogeologic nomenclature used by the Midwestern Basins and Arches RASA project are shown in figure 4.

Geophysical logs, descriptions of drill core, and geologists' or drillers' logs for more than 1,000 sites were considered for use in the delineation of the hydrogeologic sections. Of these sites, 221 were selected for evaluation on the basis of their location, the quality and length of the geophysical log, and the availability of drill core or drillers logs (table 1, on p. 32). Natural-gamma logs were used because they exhibit distinctive patterns, or signatures, that correspond to geologic contacts between the aquifer units and the confining units.

The typical response of natural-gamma-ray and spontaneous-potential electric logs to different lithologies in the Midwestern Basins and Arches region is illustrated in figure 10. Natural-gamma logs are obtained by lowering an instrument and recording the resulting response at the surface from a detector that measures the natural radioactive properties of the rock (Keys, 1990). The natural-gamma log can be run on a borehole that has been cased or uncased, and the presence of fluid in the borehole is not required. The type of electric log used in this report was the spontaneous-potential (SP or self-potential) curve. The electric log is obtained by lowering an electrode into an uncased, fluid-filled borehole and recording the resulting electrical response at the surface (Telford and others, 1976).

A natural-gamma log is a plot of the changes that take place with depth in the natural-gamma radiation emitted from the strata that are penetrated by the borehole. These naturally occurring emissions of gamma rays are products of small amounts of uranium, thorium, and potassium contained within the strata (Telford and others, 1976). Carbonate rock, sandstone, and unconsolidated deposits that have a low clay content all have a low natural-gamma-ray activity. This low activity results in a deflection to the left on a natural-gamma log trace, which indicates a decrease in natural-gamma radiation. Shale, siltstone, and unconsolidated deposits that have a high clay content all have a high natural-gamma activity because of the presence of small amounts of naturally occurring uranium, thorium, and potassium in the clay. These radioactive elements are concentrated by way of ion exchange and adsorption by the clay minerals. This concentration of natural-gamma-ray emitters results in a deflection to the right on a natural-gamma-log trace, which indicates an increase of natural-gamma radiation.

The spontaneous-potential curve is a plot of small changes in voltage that vary with depth between the fluid in the borehole and the strata penetrated by the

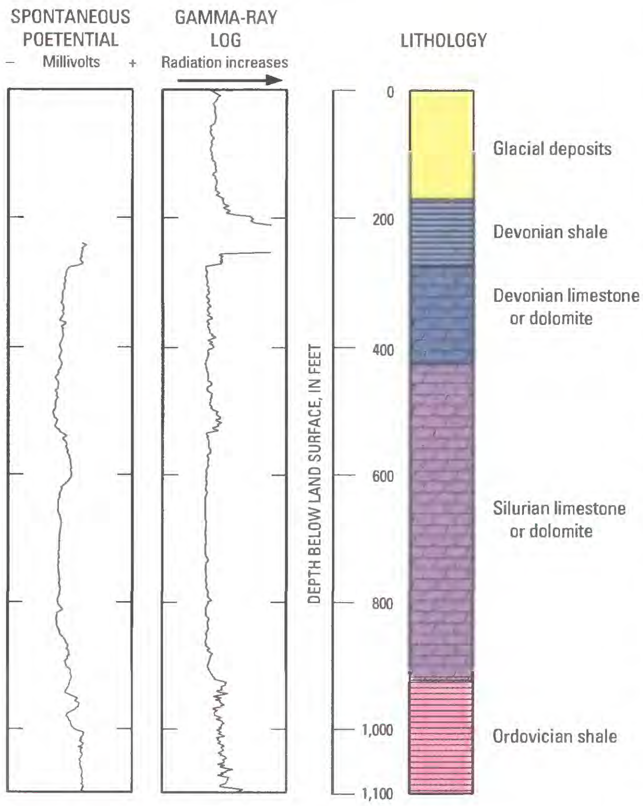


FIGURE 10.—Graph showing generalized responses of natural gamma-ray and spontaneous-potential electric logs to rock units in the Midwestern Basins and Arches region.

borehole, measured in ohms (Keys, 1990). These naturally occurring, spontaneous potentials are caused by electrochemical reactions between the fluid in the borehole and the surrounding strata (Telford and others, 1976). In general, carbonate, sandstone, and unconsolidated deposits that have a low clay content are more resistant to the flow of an electrical current and cause a negative deflection of the spontaneous potential to the left. Shale, siltstone, and unconsolidated deposits that have a high clay content are less resistant to the flow of an electrical current and cause a positive deflection to the right. Where water in the borehole is more saline than water in the formation, the deflection is reversed (Keys, 1990).

The composition of the strata that constitute the carbonate-rock aquifer system in the Midwestern Basins and Arches region makes the use of electric and natural-gamma logs ideal for lithologic correlation. The use of the geophysical logs combined with the drill cores, drill-hole sample cuttings, and drillers' logs allow for a reasonable amount of certainty when making correlations across such a large area. Detailed information about borehole geophysics can be found in Telford and others (1976); information on the application of borehole geophysics to a water-resources investigation can be found in Keys (1990).

GLACIAL DEPOSITS

The thickness of the glacial deposits in the Midwestern Basins and Arches region ranges from 100 ft near the limit of glaciation to more than 400 ft in northeastern Indiana and along the course of the ancient Teays–Mahomet bedrock valley system (figs. 11 and 9). In northwestern Ohio, the glacial deposits generally are less than 100 ft thick, except for the northwesternmost part of the State where thicknesses increase to more than 300 ft. The increase in the thickness of the glacial deposits in this part of Ohio is due to the area's interlobate position during the Wisconsinan glaciation (Soller, 1986). In central Ohio near the eastern limit of glaciation, the glacial deposits thicken to approximately 200 ft and then abruptly thin near the limit of glaciation. Soller (1986) describes this increase in thickness east of Columbus, Ohio, to be a result of the concentration of glacial materials between a glacial lobe and bedrock uplands (fig. 8).

Glacial deposits range from 200 to more than 400 ft thick in northeastern Indiana, north of the Eel River. The northeastern part of Indiana was between two glacial lobes and was covered by large quantities of glacial materials (Wayne, 1956). In northeastern Indiana, the glacial deposits range in thickness from less than 100 ft to more than 300 ft; the increases in thickness of the glacial deposits were controlled by the location and depth of preglacial bedrock valleys (Wayne, 1956). In central Indiana, south of the Iroquois, Wabash, and Eel Rivers, the thickness of the glacial deposits ranges from less than 100 ft to more than 400 ft. Generally, the thickness of the glacial deposits is less than 200 ft, except where the ancient Teays–Mahomet bedrock valley system (fig. 9) deeply incised the bedrock and controlled the thickness of the glacial deposits.

The major feature that affects the thickness of the glacial deposits in the Midwestern Basins and Arches region is the ancient Teays–Mahomet bedrock valley system (fig. 9). The system entered the study area from near the confluence of the Scioto River and the Ohio River, then trended northward from the Ohio River, flowed northwestward just south of Columbus, Ohio, toward Indiana, and crossed the Ohio–Indiana State line in an east-west orientation (Goldthwait, 1991). The ancient Teays–Mahomet bedrock valley system flowed westward across Indiana in a sinuous channel and left the study area, crossing the Indiana–Illinois State line from the west-central part of Indiana (Burns and others, 1985a, b, c; Bleuer, 1991; Gray, 1991).

Hydrologic data for the glacial deposits in the Midwestern Basins and Arches region have been compiled by Joseph and Eberts (1994). Transmissivities reported for the glacial deposits, as determined from aquifer tests, range from 1.5 to 69,700 ft^2/d; storage coefficients range from 0.00002 to 0.2 (Joseph and Eberts, 1994). Where the upper confining unit has been eroded, the overlying glacial sediments partially confine the carbon-

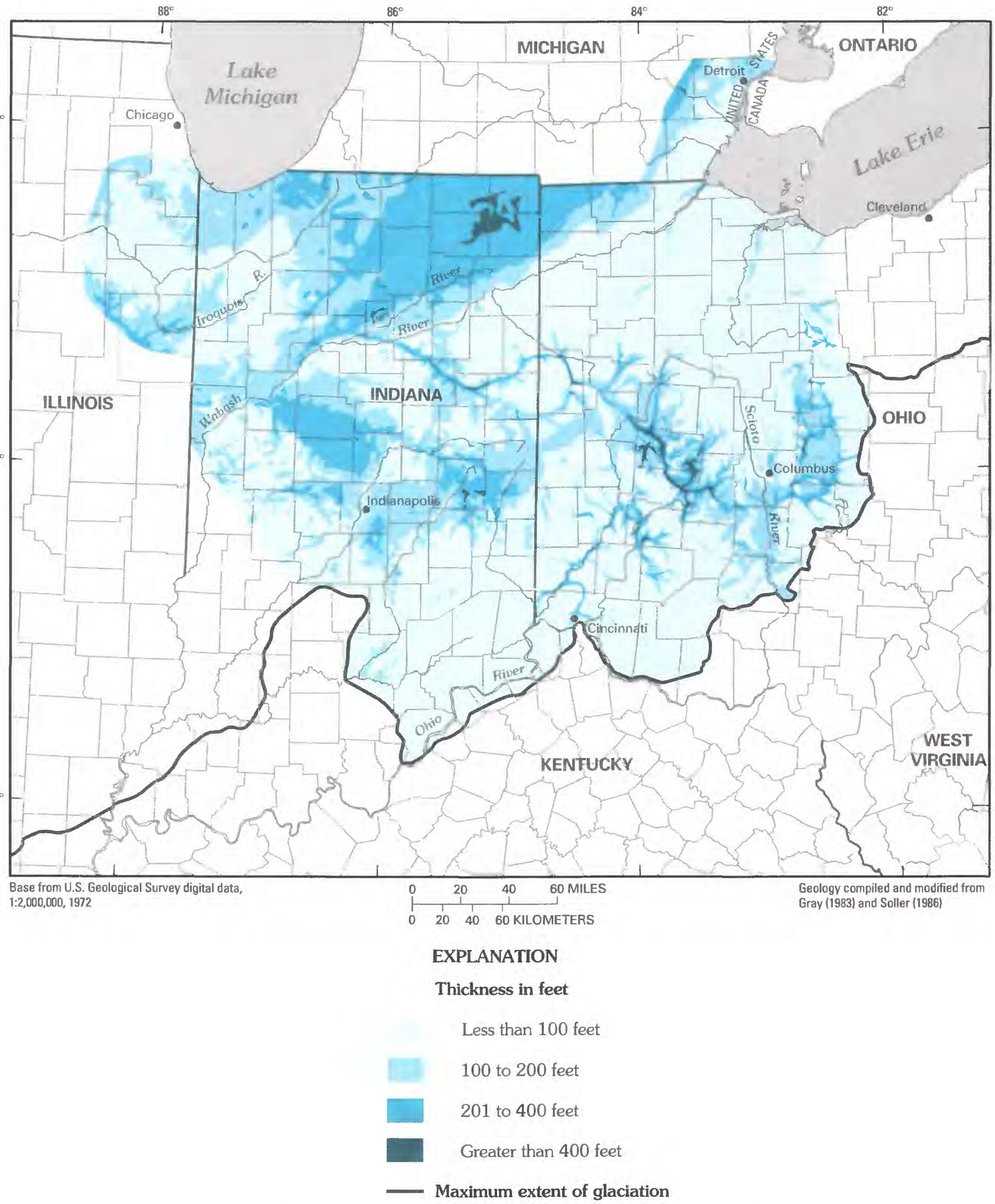


FIGURE 11.—Generalized thickness of glacial deposits in the Midwestern Basins and Arches region.

ate-rock aquifer (S.M. Eberts, U.S. Geological Survey, written commun., 1992).

BEDROCK AQUIFER AND CONFINING UNITS

Data used to compute the thickness and altitude of the top of the carbonate-rock aquifer and the confining units were obtained primarily from the Indiana and the Ohio Geological Surveys in the form of geophysical logs and drillers logs. Supplemental information on the thickness and altitude of the carbonate-rock aquifer and the confining units was obtained from the Petroleum Information Corporation's data base, and deep-test-well data were obtained from the USGS's Ground-Water Site Inventory (GWSI) data base.

UPPER CONFINING UNIT

In Ohio and Indiana, the upper confining unit has been subjected to several extensive periods of erosion. This erosion has resulted in the removal of the upper confining unit in the central part of the study area. The only exception is the Bellefontaine outlier, which is approximately 50 mi northwest of Columbus, Ohio (fig. 5).

In Ohio and northern Indiana, the upper confining unit increases in thickness from the contact between the Devonian carbonate rocks and the updip edge of the Devonian shales as it is followed downdip into the Appalachian and Michigan Basins (figs. 2 and 5). The approximate thickness of the upper confining unit ranges from zero at the contact with the Devonian carbonate rocks to more than 1,000 ft on the western flank of the Appalachian Basin and the southern flank of the Michigan Basin (Casey, in press, b). In central and southwestern Indiana, the upper confining unit increases in thickness from zero at the contact between the Devonian carbonate rocks and the updip edge of the Devonian shales to more than 600 ft downdip into the Illinois Basin; however, in southwestern Indiana, the upper confining unit thins to less than 400 ft because of its proximity to the edge of the Catskill delta, which was described in the section on "Devonian Rocks" (Kammer and others, 1983).

The upper confining unit is cut by one major fault in Indiana, the Mt. Carmel Fault (fig. 5). This fault is located along the eastern edge of the Illinois Basin and is thought to represent movement during Mississippian and Pennsylvanian time (Melhorn and Smith, 1959; Shaver and Austin, 1972). Vertical displacement on this fault is generally thought to be less than 200 ft; therefore, the confining unit does not appear to be completely offset along the Mt. Carmel Fault.

The approximate altitude and configuration of the top of the upper confining unit are shown in figure 6. Along the eastern flank of the Cincinnati and Findlay Arches, the slope (the change in altitude over distance) of the top of the upper confining unit is fairly flat (less than 10 ft/mi) near the updip edge of the Devonian shales. The slope increases (to greater than 20 ft/mi) as the distance from the updip edge of the Devonian shales increases because of the effects of the erosional thinning of outcrops of the upper confining unit and the downwarping of the crust in the Appalachian Basin. A similar configuration is found along the Michigan and Illinois Basins, again because of (a) the relative position of the updip edge of the Devonian shales, (b) erosion, and (c) downwarping of the crust in the basins.

Hydrologic data for the upper confining unit of the carbonate-rock aquifer system are sparse, but some vertical and horizontal hydraulic conductivities have been determined from analysis of cores collected from the upper confining unit in Ohio. Horizontal and vertical matrix permeabilities determined for cores from two wells drilled into the Ohio Shale ranged from 10^{-5} to 10^{-7} ft/d (unpublished data maintained in the files of the USGS, Columbus, Ohio), and are similar to those reported for shales by Heath (1983). Hydraulic conductivities in the upper confining unit are three to five orders of magnitude lower than the calculated hydraulic conductivities (10^{-2} to $5x10^{2}$ ft/d) for the Silurian and Devonian carbonate-rock aquifer (Casey, 1992). In Ohio and Indiana, the Devonian and Mississippian shales and siltstones have been described as having a very low effective porosity (Bailey and Imbrigiotta, 1982; Coen, 1989). Yields of water wells completed in the shales and siltstones of the upper confining unit typically are low (less than 2 gal/min), and dry holes are common (Smith and Schmidt, 1953; Walker and Schmidt, 1953; Walker, 1953; Schmidt, 1954; Hartke and others, 1980; Bailey and Imbrigiotta, 1982).

CARBONATE-ROCK AQUIFER

In southeastern Indiana and southwestern Ohio, the thickness of the Silurian and Devonian carbonate-rock aquifer increases from its contact with the underlying Ordovician shales (the updip edge of the carbonate-rock aquifer) downdip into the various structural basins (figs. 12 and 2). The thickness of the carbonate-rock aquifer ranges from zero at its contact with the Ordovician shales to a maximum of nearly 2,500 ft in southeastern Michigan. Along the crests of the Cincinnati, Findlay, and Kankakee Arches, in a structurally high position, the aquifer units crop out and have been subjected to several extensive episodes of erosion. This erosion has resulted in the loss of entire sections of the carbonate-rock aquifer in the central part of the study area (fig. 12).

In Ohio, near the edge of the Appalachian Basin along the eastern limit of the study area, the carbonate-rock aquifer ranges in thickness from about 500 ft in the south to nearly 1,300 ft in the north. In northern Indiana and northwestern Ohio, where the study area borders the southern edge of the Michigan Basin, the thickness of the carbonate-rock aquifer ranges from 600 ft in northwestern Indiana to 800 ft in northwestern Ohio near the Indiana–Ohio State line to nearly 2,500 ft in southeastern Michigan. Along the western limit of the data-collection area, near the northeastern edge of the Illinois Basin, the thickness of the carbonate-rock aquifer ranges from about 100 ft in southeastern Indiana to 600 ft in northwestern Indiana.

In Indiana, the carbonate-rock aquifer is cut by the following major faults: the Royal Center, the Fortville, and the Mt. Carmel (fig. 12). These faults, located along the northeastern and eastern edge of the Illinois Basin (fig. 2), are thought to represent movement during Mississippian and Pennsylvanian time (Melhorn and Smith, 1959; Shaver and Austin, 1972). Vertical displacement along these faults is generally thought to be less than 200 ft. The altitude of the Silurian and Devonian carbonate-rock aquifer near the Mt. Carmel and Royal Center Faults was determined by Bassett and Hasenmueller (1979).

In Ohio, the Silurian and Devonian carbonate-rock aquifer is displaced by faults within the Bowling Green Fault Zone (fig. 12). A large number of multiple faults have been mapped within this fault zone (VanWagner, 1988), which extends north from northwestern Ohio along the western edge of the Appalachian Basin into southeastern Michigan. Movement along this feature may have taken place during early Paleozoic time but could have happened as recently as Mesozoic or possibly Cenozoic time (Onasch and Kahle, 1991). Vertical displacement along the Bowling Green Fault Zone ranges from 90 to 300 ft (VanWagner, 1988).

The effects of the ancient Teays–Mahomet bedrock valley system (fig. 9) on the thickness of the carbonate-rock aquifer are evident in the map in figure 13. The Ordovician shales of the basal confining unit crop out beneath the unconsolidated sediments within the buried valley in areas where glaciofluvial erosion has cut down through the carbonate-rock aquifer.

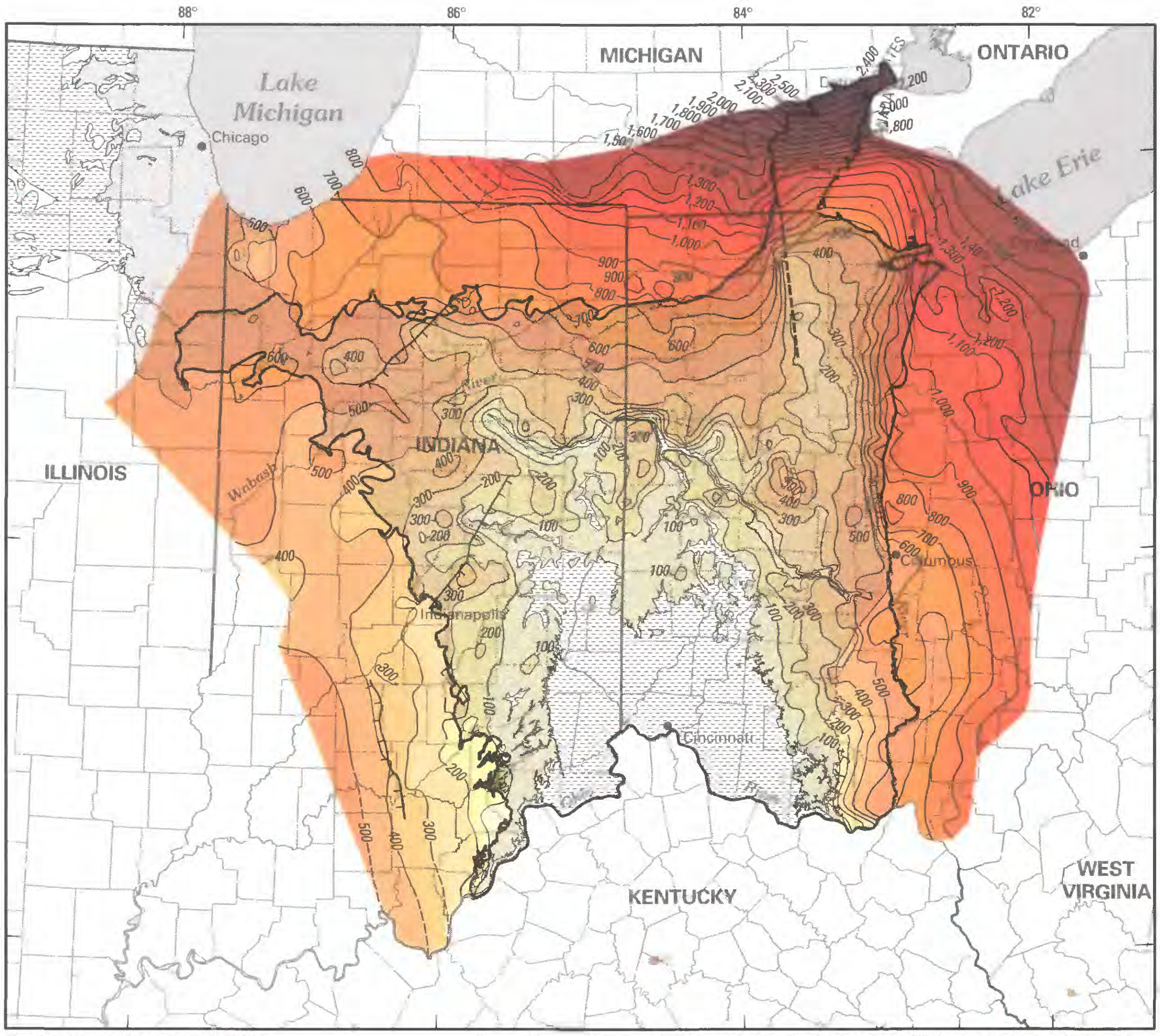
The altitude and configuration of the top of the carbonate-rock aquifer are shown in figure 13. Within the subcrop area of the Silurian and Devonian carbonate rocks, the top of the aquifer is the bedrock surface. A broad area of low relief is depicted on the top of the carbonate-rock aquifer along the southern edge of the Michigan Basin. Where the aquifer units dip beneath overlying strata into the Michigan Basin, the slope of this surface is noticeably less steep (approximately 10 ft/mi) than it is where the aquifer units dip into the Illinois Basin (approximately 15 ft/mi) and the Appalachian Basin (approximately 20 ft/mi).

The permeability of a carbonate rock is the result both of primary openings that form when the carbonate sediment is deposited or precipitated and of secondary openings that form after the sediment has been lithified. The carbonate rocks that form the Silurian and Devonian carbonate-rock aquifer have been affected by many processes that control the ability of the various geologic units to transmit water. These processes include cementation, recrystallization, micritization, solution, dolomitization, uplifting, faulting, unloading, and weathering (Brahana and others, 1988). Many of these processes can either increase or decrease the ability of carbonate rocks to transmit water.

In the Silurian and Devonian carbonate-rock aquifer, certain facies have a porous and vuggy texture (noted in the section "Stratigraphy"). This texture can be the result of various diagenetic processes that can increase the porosity and permeability of the carbonate-rock aquifer in the facies affected. Throughout the carbonate-rock aquifer, rocks that have this porous and vuggy texture can be laterally equivalent to dense rocks that do not have this texture. These relations are present throughout the carbonate-rock aquifer. At a regional scale, the areas of diagenetically controlled increases or decreases in permeability are not mappable.

Data from 10 wells within the study area were examined in order to determine the variation in the matrix porosity and permeability in the carbonate-rock aquifer (figs. 1 and. The data were analyzed by using several nonparametric statistical methods (Casey, 1994a, b). The porosity and permeability data were tested by various groupings, and in all but one case, the groups of data had identical distributions, except where the data were grouped by composition (limestone or dolomite). In a regional study, like the RASA Program, the mapping of the compositional variation of the carbonate-rock aquifer is impractical because of the large study area, the variation of the composition of the carbonate rocks that compose the aquifer, and the changes in composition of laterally equivalent rocks over small distances (tens of miles). These results indicate that the matrix porosities and permeabilities of the Silurian and Devonian carbonate rocks are statistically similar and that variation between the groups is small. Only the compositional grouping can be used to define a difference in matrix porosity and permeability of the carbonate-rock aquifer (Casey, 1994a, b).

The flow and storage of ground water within the carbonate-rock aquifer are primarily within those zones of



Base from U.S. Geological Survey digital data, 1:2,000,000, 1972

0 20 40 60 MILES
0 20 40 60 KILOMETERS

Lines of equal thickness of the Silurian and Devonian carbonate-rock aquifer from Casey (in press)
Geology compiled and modified from Bownocker (1920), Burger and others (1971), Gray (1972b), Gray and others (1972), Gray and others (1979), Grey and others (1987), Willman and others (1967), Milstein (1987)
Data on location and extent of faults compiled from Bassett and Hasenmueller (1979), VanWagner (1988)

EXPLANATION

Approximate thickness of the Silurian and Devonian carbonate-rock aquifer—Lines of equal thickness dashed where infered. Interval 100 feet. Darker colors indicate greater thickness

Subcrop of Silurian and Devonian carbonate rocks

Subcrop of Ordovician shales

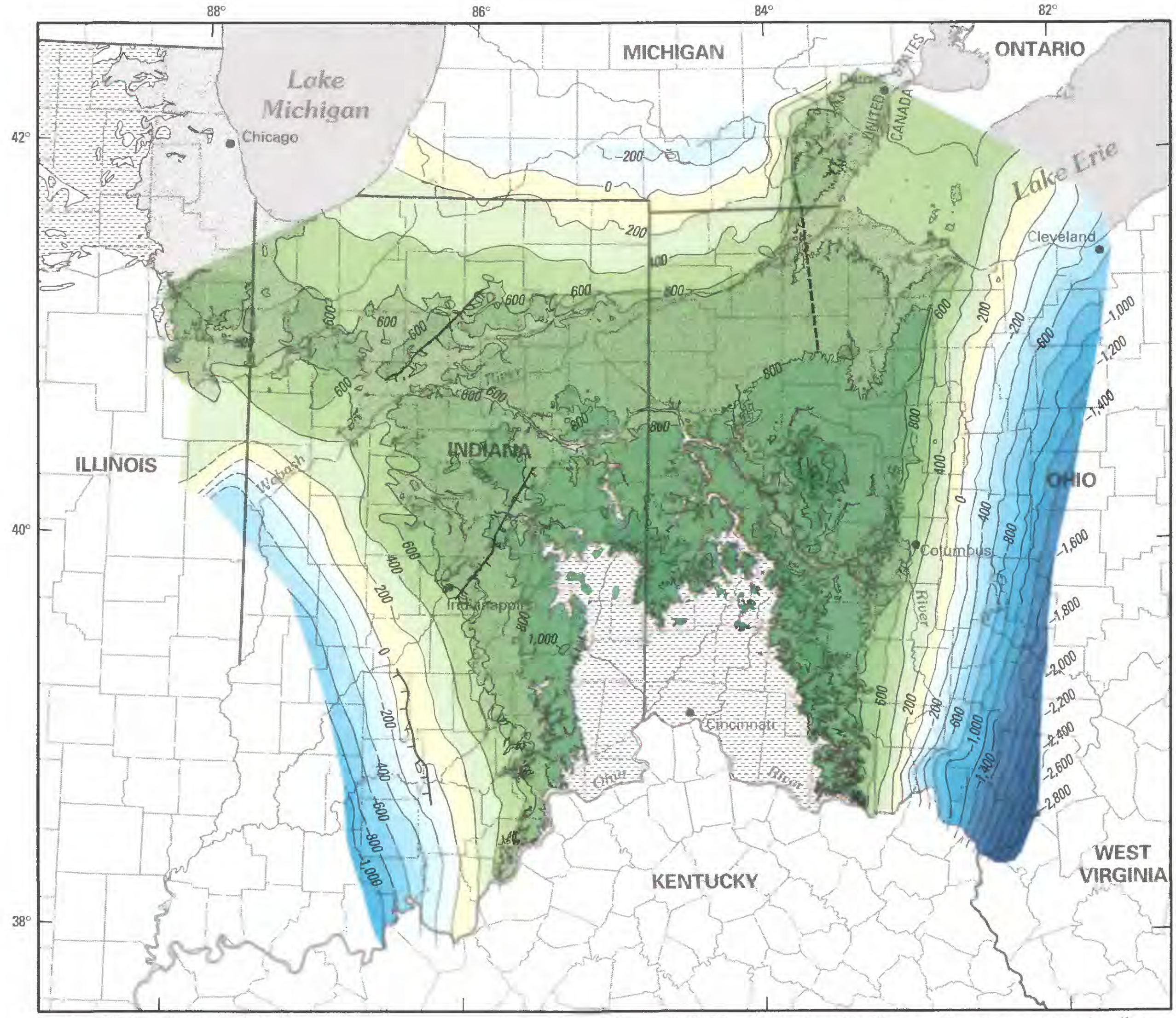
Limit of the principal hydrologic investigation area

Location of the Bowling Green fault zone

Fault—Hachures on downthrown side

Figure 12.—Approximate thickness and extent of the Silurian and Devonian carbonate-rock aquifer in the Midwestern Basins and Arches region.

rock that contain openings along joints, fractures, and bedding planes (secondary permeability). Some of these openings have been enlarged by dissolution as the ground water flowed through them. The magnitude and degree of interconnection among these openings determine the ability of the rock to transmit and yield wa-

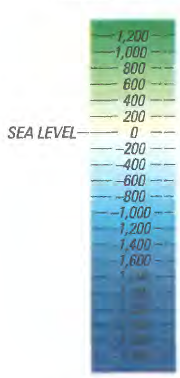


Base from U.S. Geological Survey digital data, 1:2,000,000, 1972

0 20 40 60 MILES
0 20 40 60 KILOMETERS

Altitude of top of the Silurian and Devonian carbonate-rock aquifer from Casey (in press)
Geology compiled and modified from Bownocker (1920), Burger and others (1971), Gray (1972b), Gray and others (1972), Gray and others (1979), Grey and others (1987), Willman and others (1967), Milstein (1987)
Data on location and extent of faults compiled from Bassett and Hasenmueller (1979), VanWagner (1988)

EXPLANATION



Approximate altitude of the top of the Silurian and Devonian carbonate-rock aquifer—Contour interval 200 feet Dashed where inferred. Datum is sea level. Darker greens indicate greater elevation above sea level; darker blues indicate greater depth below sea level

Subcrop of Silurian and Devonian carbonate rocks

Subcrop of Ordovician shales

---- **Location of the Bowling Green fault zone**

Fault—Hachures on downthrown side

FIGURE 13.—Approximate altitude of the top of the Silurian and Devonian carbonate-rock aquifer in the Midwestern Basins and Arches region.

ter. The matrix of the carbonate rocks also contains water that contributes to the ground-water flow system (primary and secondary permeability), but this water is assumed to be insignificant when compared to the quantity of water that moves through the joints, fractures, and bedding planes (L.D. Arihood, USGS, written commun., 1992). Results of a series of aquifer tests in northwestern Indiana showed that "almost all of the transmissivity is derived from horizontal fracturing; however, only a few fractures present in the carbonate are transmissive" (L.D. Arihood, USGS, written commun., 1992). Transmissivities determined from aquifer tests in northwestern Indiana ranged from 300 to 27,000 ft^2/d.

The upper zone is the most highly fractured zone of the Silurian and Devonian carbonate-rock aquifer (the strata at or near the bedrock surface regardless of the lithologic unit), as compared to the more deeply buried zones, and generally contains the greatest number of fractures and solution-enlarged openings. This preva-

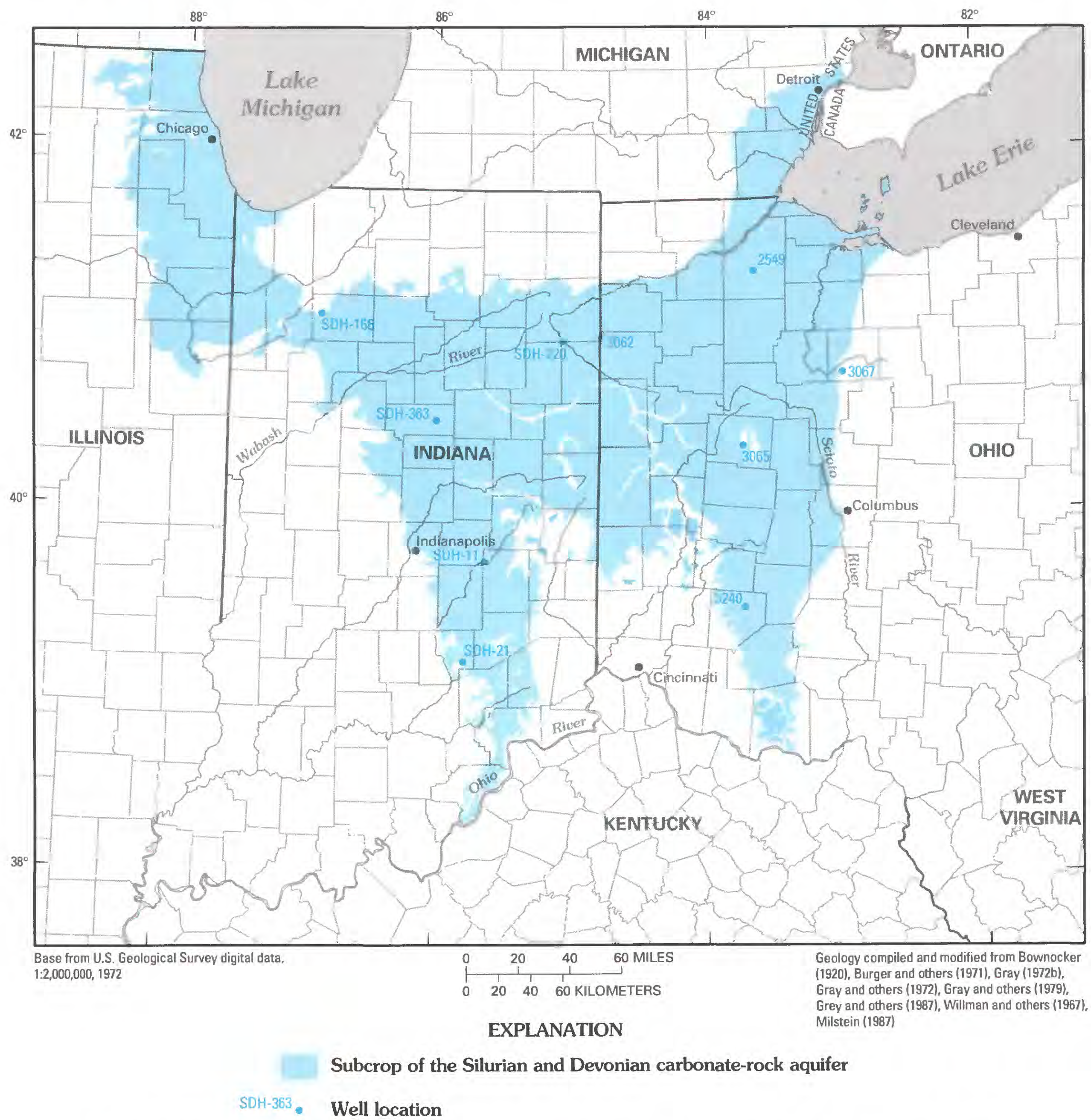


FIGURE 14.—Location of wells used to determine matrix permeability and porosity in the Midwestern Basins and Arches region.

lence of fractures and solution-enlarged openings is a result of the weathering of the bedrock, unloading, and dissolution of the carbonate rock by ground-water flow. At depths greater than 250 to 300 ft below the land surface, however, these fractures generally are not thought to be capable of transmitting water because the weight of the overlying strata limits the fracturing related to unloading, and the secondary mineralization of the fractures limits the size of the openings between the fracture walls. The Great Lakes region has been glaciated several times, and some investigators (Beaumont and others, 1988) have postulated that a thick sequence of sedimentary rock was deposited on top of the carbonate-rock aquifer and has since been removed from the study area. The removal of the overlying strata, coupled with the multiple glacial advances and retreats, allowed the joints related to unloading to form preferentially at preexisting points of weakness in the Silurian and Devonian carbonate rocks (Kappel and Tepper, 1993).

Some zones below the upper fractured zone within the carbonate-rock aquifer have an increased transmissive capability compared to the rest of the carbonate-rock aquifer. The "Newburg Zone," which is a term used by the oil and gas industry in eastern Ohio for one of these zones, was documented by Norris and Fidler (1971). This zone is in the carbonate strata overlying the Lockport Dolomite in the lower part of the Salina Group (Norris and Fidler, 1971). The Newburg Zone is not contiguous within the study area, and other permeable zones have been noted in a broader stratigraphic section than that described by Norris and Fidler (1971). These zones of increased tranmissive capability can be associated with local unconformities that have been texturally described as near-reef and bank-type deposits. Strobel and Bugliosi (1991) proposed that the Newburg Zone could be the result of multiple, diachronous processes. Because of the lack of evidence that this zone is laterally extensive, it is probably not regionally important as a water-bearing zone, but it could be significant locally.

The carbonate rocks at and above a regionally extensive erosional surface (the Silurian-Devonian unconformity) can yield continuously large quantities of water from seeps within quarries and outcrops (Shaver, 1989). This feature has been eroded in the central part of the study area where even older rocks crop out; however, the unconformity and a zone above the unconformity appear to be a less resistant path for ground-water flow than zones either above or below it. A clastic-rich zone that is contained within the lower part of the Middle Devonian Detroit River Formation, directly above the unconformity (described in the section "Stratigraphy"), transmits ground water effectively. The underlying Silurian rock is a massive carbonate rock, whereas the rock within the clastic-rich zone is fine-grained sandstone and sandy dolomite that are overlain by alternating units of argillaceous to pure bioclastic, vuggy, nonfossiliferous dolomite (Shaver, 1989). Additionally, surficial iron staining of carbonate rock below this zone indicates that water moves preferentially within this zone as a result of the change in hydrologic character between the overlying Devonian carbonate rock and the underlying Silurian carbonate rock. This staining results from the flow of ground water out of the more transmissive zone and down the quarry face below.

Faulting of carbonate rocks can affect ground-water flow in various ways. It can increase an aquifer's ability to transmit water along the fractures. This increased ground-water flow aids the dissolution of the carbonate rock and consequently enlarges the original fractures. Faulting also can restrict ground-water flow where a relatively impermeable unit is displaced along the fault and comes in contact with a more permeable unit.

Of the four major faults that affect the Silurian and Devonian carbonate-rock aquifer, only the Bowling Green Fault Zone has been studied with respect to its hydrologic effects. VanWagner (1988) described the variation of specific capacity (which was termed "transmissivity factor") across sections of the fault zone. He noted that the largest specific capacities were found along fracture trends but that a number of unproductive wells were located within several hundred feet of wells that had large specific capacities. This example demonstrates that hydrologic characteristics can differ widely over short distances within a feature such as the Bowling Green Fault Zone.

Transmissivities for the carbonate-rock aquifer, determined from aquifer tests, ranged from 70 to 28,000 ft^2/d, and storage coefficients ranged from 0.00001 to 0.01 (Joseph and Eberts, 1994). These transmissivities are three to five orders of magnitude greater than those reported for the Ordovician shales of the basal confining unit of the carbonate-rock aquifer and for the Upper Devonian and Lower Mississippian shales and siltstones that compose the upper confining unit of the aquifer system (Droste and Vitaliano, 1976).

BASAL CONFINING UNIT

The Maquoketa Group thickens eastward from the western border of Indiana toward Ohio. It ranges in thickness from about 200 ft in northwestern Indiana to nearly 900 ft at the Ohio–Indiana State line. The undifferentiated Cincinnatian rocks in Ohio gradually thicken as they dip into the Appalachian Basin. These units thin where they crop out in southeastern Indiana and southwestern Ohio because of the pre-Silurian erosion of the group and the post-Permian uplift and subsequent erosion along the crest of the Cincinnati Arch (fig. 15).

In Indiana, the basal confining unit of the carbonate-rock aquifer is cut by the Royal Center, Fortville, and Mount Carmel Faults (fig. 15). These faults, which are located along the northeastern and eastern edge of the Illinois Basin, are thought to represent movement during Mississippian and Pennsylvanian time (Melhorn and Smith, 1959; Shaver and Austin, 1972). Vertical

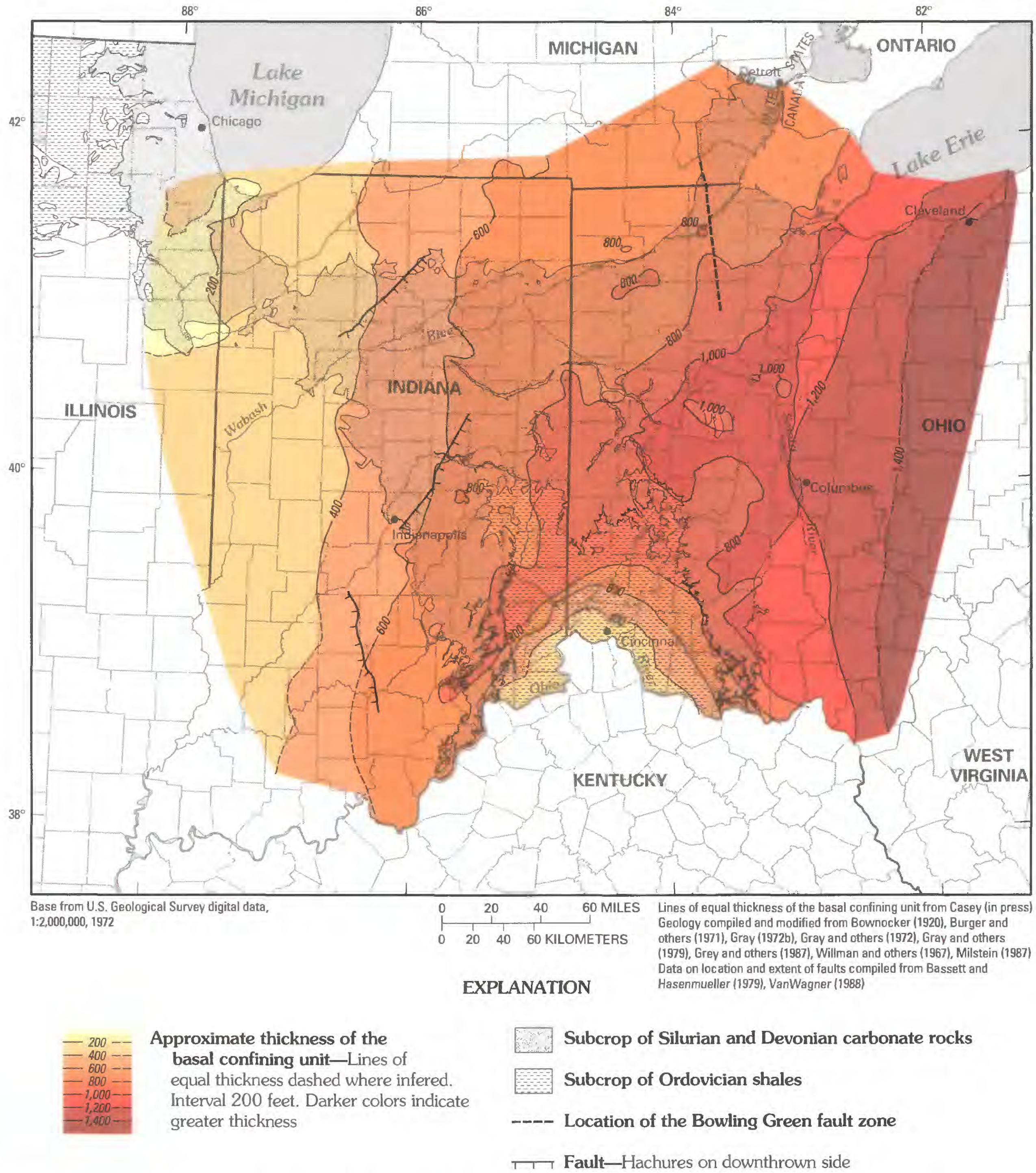


FIGURE 15.—Approximate thickness and extent of the basal confining unit of the Silurian and Devonian carbonate-rock aquifer system in the Midwestern Basins and Arches region.

displacement on these faults is less than 200 ft; therefore, the basal confining unit does not appear to be completely offset along any of the faults.

In Ohio, the basal confining unit is displaced by faults within the Bowling Green Fault Zone, where a large number of multiple faults have been mapped (VanWagner, 1988). Movement along this feature may have taken place during early Paleozoic time but could have happened as recently as Mesozoic or even Cenozoic time (Onasch and Kahle, 1991). Because the vertical displacement along the Bowling Green Fault Zone ranges from 90 to 300 ft (VanWagner, 1988), the basal confining unit is not completely offset (pl. 2).

The altitude and configuration of the top of the basal confining unit are shown in figure 16. The altitude ranges from 1,000 ft above sea level in the south-central part of the study area to less than –1,600 ft below sea level in the structural basins. Along the eastern flank of the Cincinnati and Findlay Arches, the slope of the top of the basal confining unit is fairly flat near the crests of the arches (less than 10 ft/mi); however, the slope increases as the distance from the crests increases (approximately 40 ft/mi) because of the effects of downwarping of the crust in the Appalachian Basin. A similar configuration is found along the Michigan and Illinois Basins, again because of the relative positions of the crests of the arches and downwarping of the crust in the basins.

Hydrologic data for the Upper Ordovician rocks are scanty, but some vertical and horizontal hydraulic conductivities have been determined from analysis of core collected from the upper sections of the undifferentiated Cincinnatian rocks in southwestern Ohio. Vertical and horizontal hydraulic conductivities ranged from 10^{-5} to 10^{-7} ft/d (Lawrence Wickstrom, Ohio Geological Survey, written commun., 1991). Comparisons of the hydraulic conductivities calculated for the carbonate-rock aquifer indicate that the hydraulic conductivities measured in the basal confining unit are three to five orders of magnitude lower than the calculated hydraulic conductivities for the carbonate-rock aquifer. Data from an inventory of drillers' logs in southwestern Ohio and southeastern Indiana indicate that far fewer wells are completed in the Ordovician bedrock than in the overlying Silurian carbonate bedrock. Wells that are completed in the Ordovician bedrock typically have small yields (less than 2 gal/min) or are dry.

The low hydraulic conductivity of the Ordovician shale units makes them favorable repositories for underground storage of liquefied natural gas. A room-and-pillar storage facility constructed in south-central Indiana in the Maquoketa Group was found to be impermeable (Droste and Vitaliano, 1976). Additional evidence of the low hydraulic conductivity of the Ordovician shale units is provided by the fact that the shale units have functioned as a barrier to the migration of oil and gas reserves and the associated highly concentrated brines within the Trenton Limestone. This stratigraphic trap is created by the low permeability of the Ordovician shale units that were upwarped during the post-Ordovician uplift that formed the Cincinnati Arch (Keller and Abdulkareem, 1980).

SUMMARY

The Silurian and Devonian carbonate-rock aquifer system of the Midwestern Basins and Arches region consists primarily of dolomite and limestone plus subordinate amounts of terrigenous clastic rocks and evaporites. The carbonate-rock aquifer is underlain by the Maquoketa Group and undifferentiated Cincinnatian rocks, which constitute the basal confining unit and are virtually impermeable and regionally extensive. These units collectively form a barrier to ground-water flow across the Ordovician–Silurian boundary, and this effectively limits the transfer of significant quantities of water through the base of the Silurian and Devonian carbonate-rock aquifer. The carbonate-rock aquifer is overlain by an upper confining unit on the margins of the study area that consists of Upper Devonian and Lower Mississippian shales and siltstones that are virtually impermeable; therefore, these units, where present, collectively form a barrier to ground-water flow that effectively limits the transfer of significant quantities of water to and from the underlying carbonate-rock aquifer. Where the upper confining unit is absent, the carbonate-rock aquifer is confined by the moderately permeable, overlying glacial sediments.

The locations of the primary water-bearing zones in the Silurian and Devonian carbonate-rock aquifer are related to the degree of fracturing and dissolution, depth below land surface, and lithologic variation within the aquifer. At shallow depths (less than 300 ft below land surface), the upper part of the aquifer contains the most fractures and generally has the greatest number of solution-enlarged openings. Clastic-rich dolomite at and directly above the unconformable contact between the Silurian and Devonian carbonate rocks forms a regional water-bearing zone. Other locally significant water-bearing zones are found in the carbonate-rock aquifer. These water-bearing zones have been associated with local unconformities that have been described as being near-reef and bank-type deposits. An example of this type of water-bearing zone is the Newburg Zone.

The thickness of the Silurian and Devonian carbonate-rock aquifer ranges from zero at its contact with the underlying Ordovician shales (the updip edge of the aquifer) to a maximum of nearly 2,500 ft in southeast-

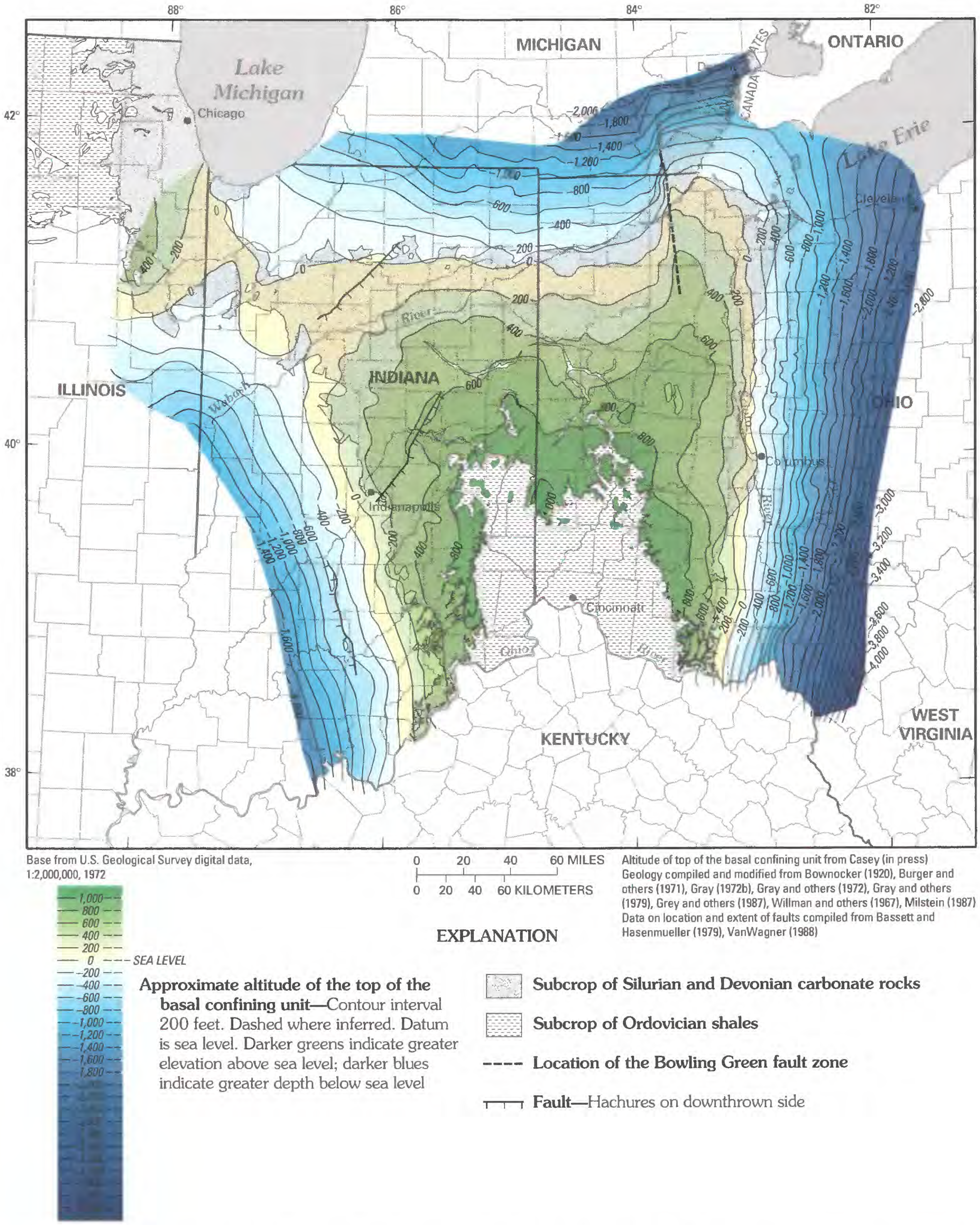


FIGURE 16.—Approximate altitude of the top of the basal confining unit of the Silurian and Devonian carbonate-rock aquifer system in the Midwestern Basins and Arches region.

ern Michigan. Along the crests of the various arches (the Cincinnati, Findlay, and Kankakee Arches), in a structurally high position, the aquifer units crop out and have been subjected to several extensive episodes of erosion. This erosion has resulted in the loss of entire sections of the carbonate-rock aquifer in the central part of the study area.

The carbonate-rock aquifer has been completely eroded in places by the ancient Teays–Mahomet bedrock valley system. The downcutting of this valley system has caused the basal confining unit to crop out beneath the unconsolidated sediments that today fill the buried valley. The downcutting also has thinned the aquifer along the course of the ancient Teays–Mahomet bedrock valley system.

The Silurian and Devonian carbonate-rock aquifer is overlain and confined on the margins of the study area by Upper Devonian and Lower Mississippian shales and siltstones where the aquifer units dip into the various basins (Appalachian, Michigan, and Illinois Basins) surrounding the study area. Elsewhere, the carbonate-rock aquifer is overlain and confined by moderately permeable, unconsolidated glacial deposits.

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TABLE 1.—*Descriptions of wells used in construction of hydrogeologic sections of the Midwestern Basins and Arches region*

Well identifier used for this project	Well or drill-hole designation	Site identification [1]	Latitude	Longitude	Altitude of land surface (feet above sea level)	Depth logged (feet)	Type of log	Hydrogeologic sections (see pls. 1 and 2)
A1	SDH 350	403342087220701	40° 33′42″	87° 22′07″	790	425	Core	A–A′
A2	NEVA WEALING 1	404021087131801	40° 40′21″	87° 13′18″	750	1,600	Geologist	A–A′
A3	JAS 7	404424087091001	40° 44′24″	87° 09′10″	740	192	Core	A–A′
A4	BEN TRACHSEL 2	404631087055001	40° 46′31″	87° 05′50″	717	1,030	Driller, geologist, caliper, neutron, gamma	A–A′
A5	517475495640	404836087030601	40° 48′36″	87° 03′06″	700	228	Driller	A–A′
A6	523920497175	405204087020001	40° 52′04″	87° 02′00″	685	27	Driller	A–A′
A7	WILLIAM MOSLEY 1	405440086555401	40° 54′40″	86° 55′54″	675	1,640	Driller, geologist	A–A′
A8	INPU–9	405712086533101	40° 57′12″	86° 53′31″	682	160	Driller	A–A′
A9	PUL 1	405924086524801	40° 59′24″	86° 52′48″	675	200	Core	A–A′
A10	ORVILLE WHITE SDH–166	410425086512601	41° 04′25″	86° 51′26″	686	720	Driller, geologist, electric	A–A′
A11	L. BOWEN 1	410829086393501	41° 08′29″	86° 39′35″	712	1,480	Driller, gamma, neutron, lateral	A–A′, B–B′
A12	CHARLES KENNEDY 1	411700086363501	41° 17′00″	86° 36′35″	710	1,160	Driller	A–A′
A13	CONTINENTAL OIL CO. 1	411558086214801	41° 15′58″	86° 21′48″	763	1,690	Driller, gamma, neutron, lateral	A–A′
A14	HELEN AMES 1	412237086111101	41°22′37″	86°11′11″	803	4,080	Driller, gamma, neutron, induction, caliper, microlateral	A–A′

TABLE 1.—*Descriptions of wells used in construction of hydrogeologic sections of the Midwestern Basins and Arches region—Continued*

Well identifier used for this project	Well or drill-hole designation	Site identification [1]	Latitude	Longitude	Altitude of land surface (feet above sea level)	Depth logged (feet)	Type of log	Hydrogeologic sections (see pls. 1 and 2)
A15	INEH–03	412803086033701	41°28′03″	86°03′37″	870	1,750	Lateral, gamma,	A–A′
A16	INEH–02	413629085590001	41°36′29″	85°59′00″	865	1,880	Gamma,	A–A′
B1	INLAND STEEL CO. 2	413934087254001	41°39′34″	87°25′40″	596	4,380	Gamma, caliper, neutron, lateral	B–B′
B2	MIDWEST STEEL WD–1	413746087102101	41°37′46″	87°10′21″	603	4,310	Gamma, neutron, induction, sonic	B–B′
B3	PFIZER INJECT. WELL 2	412850087000601	41°28′50″	87°00′06″	774	4,530	Gamma, neutron, induction, caliper, gamma-gamma	B–B′
B4	N. AMER. EXPL. 3	412133086592901	41°21′33″	86°59′29″	698	224	Driller	B–B′
B5	N. AMER. EXPL. 2	411739086575701	41°17′39″	86°57′57″	677	211	Driller	B–B′
B6	INLP–01	411747086510601	41°17′47″	86°51′06″	670	1,120	Electric	B–B′
B7	B.N. SEGHETTI 1	411245086434601	41°12′45″	86°43′46″	712	1,520	Driller, gamma, neutron, lateral	B–B′
B8	PUL 6	410636086360501	41°06′36″	86°36′05″	715	163	Driller	B–B′
B9	PUL503	410408086361401	41°04′08″	86°36′14″	710	238	Driller	B–B′
B10	PETERS 1	410336086310501	41°03′36″	86°31′05″	718	1,500	Driller, gamma, neutron, lateral	B–B′
B11	MARION GOHNN 1	410303086155301	41°03′03″	86°15′53″	763	1,510	Driller, gamma, neutron, fluid conduct	B–B′

TABLE 1.—*Descriptions of wells used in construction of hydrogeologic sections of the Midwestern Basins and Arches region—Continued*

Well identifier used for this project	Well or drill-hole designation	Site identification [1]	Latitude	Longitude	Altitude of land surface (feet above sea level)	Depth logged (feet)	Type of log	Hydrogeologic sections (see pls. 1 and 2)
B12	CLAIR & FREIDA GOOD 1	405802086064801	40°58′02″	86°06′48″	850	1,800	Driller, gamma, neutron,electric, caliper,gamma-gamma	B–B′
B13	MIA501	405513086044201	40°55′13″	86°04′42″	870	362	Driller	B–B′
B14	INMI–7	405246086033201	40°52′46″	86°03′32″	785	225	Driller	B–B′
B15	MIA504	405112085591501	40°51′12″	85°59′15″	750	254	Driller	B–B′
B16	L.H. SCHMALZRIED 1	405044085592301	40°50′44″	85°59′23″	767	1,190	Driller, gamma, neutron, gamma–gamma, caliper	B–B′
B17	MIA505	404817085591701	40°48′17″	85°59′17″	780	119	Driller	B–B′
B18	IRENE RICHARDSON 1	404824085571001	40°48′24″	85°57′10″	784	1,600	Driller, gamma, neutron, electric	B–B′
B19	WAB 15	404632085553501	40°46′32″	85°55′35″	655	854	Driller	B–B′
B20	H. & H. WHITESEL 1	404312085545401	40°43′12″	85°54′54″	793	997	Driller	B–B′
B21	WAB502	404228085543001	40°42′28″	85°54′30″	800	83	Driller	B–B′
B22	WAB 8	404010085494902	40°40′10″	85°49′49″	790	153	Driller	B–B′
B23	A. & F. TROYER 1	403925085452701	40°39′25″	85°45′27″	746	937	Driller	B–B′
B24	INGT–14	403522085384801	40°35′22″	85°38′48″	870	168	Driller	B–B′
B25	LOSURE FARMS INC 1	403515085344201	40°35′15″	85°34′42″	865	1,540	Driller, gamma, neutron, caliper, induction	B–B′

Well identifier used for this project	Well or drill-hole designation	Site identification [1]	Latitude	Longitude	Altitude of land surface (feet above sea level)	Depth logged (feet)	Type of log	Hydrogeologic sections (see pls. 1 and 2)
B26	M. & S. OLYNGER 1	402951085300401	40°29′51″	85°30′04″	874	1,260	Driller, electric,	B–B′
B27	GEORGE HEINLEIN 1	402633085295601	40°26′33″	85°29′56″	911	1,520	Driller, gamma, neutron caliper, induction	B–B′
B28	NORMAN & DEB LIGHT 2	402305085262301	40°23′05″	85°26′23″	868	1,760	Driller, caliper, gamma, neutron, laterlal	B–B′
B29	INDW–6	402146085241201	40°21′46″	85°24′12″	930	127	Driller	B–B′
B30	DEL 2	402023085204501	40°20′23″	85°20′45″	920	206	Driller	B–B′
B31	WF–11	401641085195201	40°16′41″	85°19′52″	940	121	Driller	B–B′
B32	INDW–9	401547085193701	40°15′47″	85°19′37″	960	102	Driller	B–B′
B33	TERRY SHREVE 1	401419085194301	40°14′19″	85°19′43″	958	1,280	Driller, gamma, neutron	B–B′
B34	WF–13	401310085182301	40°13′10″	85°18′23″	981	101	Driller	B–B′
B35	ROBERT DRAGOO 1	401220085155301	40°12′20″	85°15′53″	1,001	1,240	Driller, gamma, neutron	B–B′
B36	WF–6	401135085111101	40°11′35″	85°11′11″	1025	139	Driller	B–B′
B37	WF–333	401015085070101	40°10′15″	85°07′01″	1,025	91	Driller	B–B′
B38	RAN501	401055085073501	40°10′55″	85°07′35″	1,030	58	Driller	B–B′
B39	JONAS MILLS 1	400930085064701	40°09′30″	85°06′47″	1,038	1,370	Driller	B–B′
B40	JOHN CULLISON 9T13	400712085045801	40°07′12″	85°04′58″	1,099	1,570	Driller, gamma, neutron, dip meter	B–B′, C–C′
B41	437165672545	400408084583601	40°04′08″	84°58′36″	1,160	181	Driller	B–B′
B42	433415678680	400202084542101	40°02′02″	84°54′21″	1,220	217	Driller	B–B′

TABLE 1.—*Descriptions of wells used in construction of hydrogeologic sections of the Midwestern Basins and Arches region—Continued*

Well identifier used for this project	Well or drill-hole designation	Site identification [1]	Latitude	Longitude	Altitude of land surface (feet above sea level)	Depth logged (feet)	Type of log	Hydrogeologic sections (see pls. 1 and 2)
B43	D–14	400227084401800	40°02′27″	84°40′18″	1,025	400	Driller, caliper, electric	B–B′ D–D′
B44	D–60	400418084262000	40°04′18″	84°26′20″	997	57	Driller	B–B′
B45	MI–1059	400353084230500	40°03′53″	84°23′05″	970	76	Driller	B–B′
B46	MI–1050	400338084154200	40°03′38″	84°15′42″	937	68	Driller	B–B′
B47	MI–38	400352084050500	40°03′52″	84°05′05″	1,030	3,510	Geologist, gamma	B–B′
B48	CL–200	400111084010400	40°01′11″	84°01′04″	1,095	68	Driller	B–B′
B49	CL–131	395926083570500	39°59′26″	83°57′05″	1,095	74	Driller	B–B′
B50	CL–203	395830083552200	39°58′30″	83°55′22″	1,080	75	Driller	B–B′
B51	CL–229	395623083510100	39°56′23″	83°51′01″	900	106	Driller	B–B′
B52	CL–21	395446083471500	39°54′46″	83°47′15″	1,020	1,010	Driller, gamma	B–B′
B53	CL–224	395338083455400	39°53′38″	83°45′54″	1,030	79	Driller	B–B′
B54	CL–223	395237083434100	39°52′37″	83°43′41″	1,090	130	Driller	B–B′
B55	CL–234	395059083414800	39°50′59″	83°41′48″	1,080	249	Driller	B–B′
B56	CL–122	394946083393300	39°49′46″	83°39′33″	1,087	127	Driller	B–B′
B57	M–74	394445083364400	39°44′45″	83°36′44″	1,122	172	Driller	B–B′
B58	M–18	394358083323400	39°43′58″	83°32′34″	1,055	225	Driller, caliper, electric, gamma	B–B′
B59	FA–15	394105083295400	39°41′05″	83°29′54″	1,035	245	Driller, caliper, electric, gamma	B–B′
B60	FA–109	394103083253800	39°41′03″	83°25′38″	1,005	58	Driller	B–B′

TABLE 1.—*Descriptions of wells used in construction of hydrogeologic sections of the Midwestern Basins and Arches region—Continued*

Well identifier used for this project	Well or drill-hole designation	Site identification [1]	Latitude	Longitude	Altitude of land surface (feet above sea level)	Depth logged (feet)	Type of log	Hydrogeologic sections (see pls. 1 and 24)
B61	FA–126	394047083171900	39°40′47″	83°17′19″	897	3,540	Gamma, neutron	B–B′
B62	PK–205	394011083100300	39°40′11″	83°10′03″	840	98	Driller	B–B′
B63	PK–30	393933083053100	39°39′33″	83°05′31″	785	3,730	Gamma, neutron	B–B′
B64	PK–31	393940082540000	39°39′40″	82°54′00″	820	3,270	Gamma, neutron	B–B′
B65	F–25	393636082463000	39°36′36″	82°46′30″	1,090	3,770	Geologist, neutron, gamma	B–B′
C1	BRO 1	391426086143401	39°14′26″	86°14′34″	720	800	Driller	C–C′
C2	WILBER HIATT ET AL 1	391525086115201	39°15′25″	86°11′52″	756	1,510	Driller, geologist	C–C′
C3	GEORGE I WHITE 1	392244086060601	39°22′44″	86°06′06″	785	1,890	Driller, geologist	C–C′
C4	BILL OLIVER SDH–20	392357086000301	39°23′57″	86°00′03″	671	409	Driller, geologist, electric	C–C′
C5	SHE506	392917085555201	39°29′17″	85°55′52″	735	150	Driller	C–C′
C6	HAROLD LAUTENBACH 1	393110085571201	39°31′10″	85°57′12″	712	1,140	Driller, gamma, neutron, caliper, lateral	C–C′
C7	GENERAL ELEC. CO. 1	393114085444401	39°31′14″	85°44′44″	790	1,590	Driller, gamma, neutron, caliper	C–C′
C8	GLEN & ALTA BURTON 1	393415085400801	39°34′15″	85°40′08″	856	884	Driller	C–C′

TABLE 1.—*Descriptions of wells used in construction of hydrogeologic sections of the Midwestern Basins and Arches region—Continued*

Well identifier used for this project	Well or drill-hole designation	Site identification [1]	Latitude	Longitude	Altitude of land surface (feet above sea level)	Depth logged (feet)	Type of log	Hydrogeologic sections (see pls. 1 and 2)
C9	RUS506	393444085303101	39°34′44″	85°30′31″	975	110	Driller	C–C′
C10	R. B. ANDERSON 1	393502085272701	39°35′02″	85°27′27″	958	1,520	Driller, lateral, gamma, caliper, sonic	C–C′
C11	RUS 5	393716085270201	39°37′16″	85°27′02″	970	50	Driller	C–C′
C12	W. G. WAGGONER 2	394023085242101	39°40′23″	85°24′21″	968	1,500	Driller, gamma, caliper, sonic, lateral	C–C′
C13	W. G. WAGGONER 1	394247085250001	39°42′47″	85°25′00″	1,022	1,260	Driller	C–C′
C14	RUS512	394440085262701	39°44′40″	85°26′27″	1,015	123	Driller	C–C′
C15	T.F. NUGEN 1 (ST 3)	394854085220001	39°48′54″	85°22′00″	1,081	1,560	Driller, lateral, sonic, gamma, caliper	C–C′
C16	MUSE– HARRIS–BRIAR 1	394923085121201	39°49′23″	85°12′12″	1,019	1,730	Driller, caliper, gamma, induction	C–C′
C17	CHARLES CAIN 1	395409085090701	39°54′09″	85°09′07″	997	887	Driller	C–C′
C18	MARGARET BILIHEIMER 1	395835085110701	39°58′35″	85°11′07″	1,062	2,020	Driller	C–C′
C19	RAN510	400453085094101	40°04′53″	85°09′41″	1,130	266	Driller	C–C′
C20	LLOYD WELCH 1	400738084525501	40°07′38″	84°52′55″	1,162	1,870	Driller, gamma, neutron	C–C′, D–D′
C21	INRA–6	401201084501701	40°12′01″	84°50′17″	1,100	221	Driller	C–C′, D–D′
C22	RAN 14	401300084482301	40°13′00″	84°48′23″	1,075	300	Driller	C–C′

TABLE 1.—*Descriptions of wells used in construction of hydrogeologic sections of the Midwestern Basins and Arches region—Continued*

Well identifier used for this project	Well or drill-hole designation	Site identification [1]	Latitude	Longitude	Altitude of land surface (feet above sea level)	Depth logged (feet)	Type of log	Hydrogeologic sections (see pls. 1 and 2)
C23	D–78	401554084471500	40°15′54″	84°47′15″	1,040	1,800	Driller,Gamma	C–C′ D–D′
C24	D–10	401925084424900	40°19′25″	84°42′49″	1,060	340	Driller, caliper, electric, gamma	C–C′, D–D′
C25	D–50	402011084374700	40°20′11″	84°37′47″	995	137	Driller	C–C′
C26	MR–72	402448084351900	40°24′48″	84°35′19″	931	1,200	Driller, gamma	C–C′
C27	MR–77	402706084352400	40°27′06″	84°35′24″	920	1,220	Driller, gamma	C–C′
C28	MR–53	402758084341300	40°27′58″	84°34′13″	900	242	Driller	C–C′
C29	AU–21	403128084250500	40°31′28″	84°25′05″	860	240	Driller, gamma, caliper	C–C′
C30	AU–14	403149084231600	40°31′49″	84°23′16″	860	355	Gamma	C–C′
C31	AU–46	403344084224600	40°33′44″	84°22′46″	874	1,250	Driller, gamma	C–C′
C32	AU–12	403706084211100	40°37′06″	84°21′11″	835	228	Electric, caliper, gamma	C–C′
C33	AU–29	403849084203200	40°38′49″	84°20′32″	830	70.6	Driller	C–C′
C34	AL–3	404246084210200	40°42′46″	84°21′02″	825	320	Electric, gamma	C–C′
C35	AL–48	404525084172100	40°45′25″	84°17′21″	806	1,330	Gamma	C–C′
C36	AL–32	404619084090500	40°46′19″	84°09′05″	825	72	Driller	C–C′
C37	AL–22	404836084070100	40°48′36″	84°07′01″	785	60	Driller	C–C′

TABLE 1.—*Descriptions of wells used in construction of hydrogeologic sections of the Midwestern Basins and Arches region—Continued*

Well identifier used for this project	Well or drill-hole designation	Site identification [1]	Latitude	Longitude	Altitude of land surface (feet above sea level)	Depth logged (feet)	Type of log	Hydrogeologic sections (see pls. 1 and 2)
C38	PU–12	405203084080300	40°52′03″	84°08′03″	770	300	Electric, caliper, gamma	C–C′
C39	PU–19	405456084035300	40°54′56″	84°03′53″	775	161	Electric, gamma	C–C′
C40	PU–15	405630084013900	40°56′30″	84°01′39″	755	320	Electric, gamma	C–C′
C41	PU–43	405845083554600	40°58′45″	83°55′46″	760	1,330	Gamma, neutron	C–C′
C42	HA–46	405954083441500	40°59′54″	83°44′15″	795	100	Driller	C–C′
C43	HA–27	410101083433000	41°01′01″	83°43′30″	785	2,050	Gamma	C–C′
C44	HA–13	410239083424800	41°02′39″	83°42′48″	765	330	Electric, gamma	C–C′
C45	HA–44	410412083411700	41°04′12″	83°41′17″	787	84	Driller	C–C′
C46	HA–10	410815083404700	41°08′15″	83°40′47″	750	621	Gamma	C–C′
C47	WO–11	411007083401600	41°10′07″	83°40′16″	725	300	Electric, gamma	C–C′
C48	WO–219–H11	411336083411200	41°13′36″	83°41′12″	705	58	Driller	C–C′
C49	WO–18	411518083394000	41°15′18″	83°39′40″	689	2,770	Gamma	C–C′
C50	WO–254–PO9	411841083363900	41°18′41″	83°36′39″	677	46	Driller	C–C′
C51	WO–23 NWOH TEST–STEWART	412140083352700	41°21′40″	83°35′27″	670	235	Electric, caliper, gamma	C–C′
C52	WO–269–F20 (CONTRIES)	412237083301800	41°22′37″	83°30′18″	685	82	Driller	C–C′
C53	S–183–M18	412318083244600	41°23′18″	83°24′46″	695	92	Driller	C–C′

TABLE 1.—*Descriptions of wells used in construction of hydrogeologic sections of the Midwestern Basins and Arches region—Continued*

Well identifier used for this project	Well or drill-hole designation	Site identification [1]	Latitude	Longitude	Altitude of land surface (feet above sea level)	Depth logged (feet)	Type of log	Hydrogeologic sections (see pls. 1 and 2)
C54	S–11 NWOH TEST–ACKERMAN	412356083212600	41°23′56″	83°21′26″	650	250	Electric, gamma,	C–C′
C55	S–187–WO2	412539083193700	41°25′39″	83°19′37″	645	100	Driller	C–C′
C56	S–20	412615083185900	41°26′15″	83°18′59″	640	2,780	Gamma	C–C′
C57	O–41	412745083140500	41°27′45″	83°14′05″	606	1,710	Driller, gamma, neutron	C–C′
C58	O–29	412932083143700	41°29′32″	83°14′37″	602	75	Driller	C–C′
C59	O–38	413057083124900	41°30′57″	83°12′49″	596	1,710	Driller, gamma, neutron	C–C′ E–E′
C60	O–12	413438083092800	41°34′38″	83°09′28″	575	300	Caliper, electric, gamma	C–C′
C61	O–40	413509083090300	41°35′09″	83°09′03″	575	2,290	Driller, gamma, neutron	C–C′
C62	O–15	413536083083800	41°35′36″	83°08′38″	575	1,720	Gamma	C–C′
C63	EX–10	414953082520100	41°49′53″	82°52′01″	597	2,350	Geologist	C–C′
C64	EX–7	415700082500700	41°57′00″	82°50′07″	591	2,600	Geologist	C–C′
D1	WILLIAM LOSEKAMP 1	392212084525401	39°22′12″	84°52′54″	986	1,800	Driller, induction	D–D′
D2	363610686255	392413084501201	39°24′13″	84°50′12″	930	70	Gamma	D–D′
D3	WALTER H. CLAWSON 1	393024084595701	39°30′24″	84°59′57″	700	704	Driller	D–D′
D4	INUN–1	393323084565101	39°33′23″	84°56′51″	920	120	Driller	D–D′
D5	JOHN SHEETS 1	393448084552001	39°34′48″	84°55′20″	997	2,760	Driller, gamma, neutron	D–D′

TABLE 1.—*Descriptions of wells used in construction of hydrogeologic sections of the Midwestern Basins and Arches region—Continued*

Well identifier used for this project	Well or drill-hole designation	Site identification [1]	Latitude	Longitude	Altitude of land surface (feet above sea level)	Depth logged (feet)	Type of log	Hydrogeologic sections (see pls. 1 and 2)
D6	UNI 2	393643084571901	39°36′43″	84°57′19″	945	41	Driller	D–D′
D7	HARRISON LAFUZE 1	394016084550801	39°40′16″	84°55′08″	958	1430	Driller	D–D′
D8	FREDERICK TAYLOR 1	394649084514601	39°46′49″	84°51′46″	1,030	3,330	Driller, geologist	D–D′
D9	PR–39	395257084475500	39°52′57″	84°47′55″	1,180	220	Driller	D–D′
D10	LESLIE COOK SDH–57	395343084494901	39°53′43″	84°49′49″	1,028	1,080	Driller, geologist, electric	D–D′
D11	418800684560	395403084502801	39°54′03″	84°50′28″	1,085	100	Driller	D–D′
D12	INWE–7	395553084485101	39°55′53″	84°48′51″	1,075	121	Driller	D–D′
D13	D–65	395931084401000	39°59′31″	84°40′10″	1,110	85	Driller	D–D′
D14	D–54	400139084394900	40°01′39″	84°39′49″	1,035	49	Driller	D–D′
D15	INRA–4	400528084510401	40°05′28″	84°51′04″	1,160	181	Driller	D–D′
D16	WF–30	400838084540301	40°08′38″	84°54′03″	1,144	160	Driller	D–D′
D17	RAN516	401515084492301	40°15′15″	84°49′23″	1,045	103	Driller	D–D′
D18	D–82	402058084441500	40°20′58″	84°44′15″	1,060	1,260	Driller	D–D′
D19	RALPH MAY 1–26	402457084492801	40°24′57″	84°49′28″	935	1,690	Driller, gamma, neutron, caliper, induction	D–D′
D20	MR–61	403008084475700	40°30′08″	84°47′57″	895	182	Driller	D–D′
D21	JAY504	403019084505301	40°30′19″	84°50′53″	885	80	Driller	D–D′
D22	JAY503	403233084564601	40°33′00″	84°56′51″	870	159	Driller	D–D′

TABLE 1.—*Descriptions of wells used in construction of hydrogeologic sections of the Midwestern Basins and Arches region—Continued*

Well identifier used for this project	Well or drill-hole designation	Site identification [1]	Latitude	Longitude	Altitude of land surface (feet above sea level)	Depth logged (feet)	Type of log	Hydrogeologic sections (see pls. 1 and 2)
D23	ROYCE E. WALL 1	403354084543201	40°33′54″	84°54′32″	854	1,030	Driller, gamma, neutron	D–D′
D24	INAD–3	403521084505601	40°35′21″	84°50′56″	867	161	Driller	D–D′
D25	BLAINE BAILEY 1	403805084491901	40°38′05″	84°49′19″	841	1,760	Driller, lateral, gamma, caliper	D–D′
D26	MR–74	404032084410500	40°40′32″	84°41′05″	816	1,890	Gamma, neutron	D–D′
D27	MR–50	404147084361100	40°41′47″	84°36′11″	807	199	Driller	D–D′
D28	VW–40	404532084373900	40°45′32″	84°37′39″	824	1,840	Driller. gamma	D–D′
D29	VW–13	404626084371200	40°46′26″	84°37′12″	820	318	Electric, gamma	D–D′
D30	VW–23	404845084384900	40°48′45″	84°38′49″	807	122	Driller	D–D′
D31	VW–14	404915084385300	40°49′15″	84°38′53″	795	340	Electric, gamma,	D–D′
D32	VW–11	405448084424300	40°54′48″	84°42′43″	785	301	Driller, gamma	D–D′
D33	ALL 36	405543084514001	40°55′43″	84°51′40″	810	95	Driller	D–D′
D34	ALL 35	405728084514501	40°57′28″	84°51′45″	790	91	Driller	D–D′
D35	BETTY LEUENBERGER 1	405751084541201	40°57′51″	84°54′12″	797	3,670	Driller, gamma, caliper	D–D′
D36	ALL 34	410026084522301	41°00′26″	84°52′23″	775	80	Driller	D–D′
D37	P–12	410234084463200	41°02′34″	84°46′32″	755	330	Electric, gamma	D–D′

TABLE 1.—*Descriptions of wells used in construction of hydrogeologic sections of the Midwestern Basins and Arches region—Continued*

Well identifier used for this project	Well or drill-holedesignation	Site identification [1]	Latitude	Longitude	Altitude of land surface (feet above sea level)	Depth logged (feet)	Type of log	Hydrogeologic sections (see pls. 2,3 and 4)
D38	MU–85	410431084485401	41°04′31″	84°48′54″	755	74	Driller	D–D′
D39	ALL 52	410726084494601	41°07′26″	84°49′46″	750	64	Driller	D–D′
D40	CARL ROEMKE 2	410851084492101	41°08′51″	84°49′21″	745	1,600	Driller, gamma, neutron	D–D′
D41	ALL 65	411115084485801	41°11′15″	84°48′58″	745	74	Driller	D–D′
D42	MATHEW FOOTE 1	411215084491001	41°12′15″	84°49′10″	742	1,850	Driller, electric	D–D′
D43	P–34	411415084480400	41°14′15″	84°48′04″	740	94	Driller	D–D′
D44	WARREN SMITH 1	411614084513801	41°16′14″	84°51′38″	839	575	Driller, electric	D–D′
D45	DE–13	411953084375500	41°19′53″	84°37′55″	730	1,830	Driller, gamma	D–D′
D46	DE–12	412125084390100	41°21′25″	84°39′01″	740	3,200	Geologist	D–D′
D47	WM–16	412801084450900	41°28′01″	84°45′09″	845	2,220	Gamma	D–D′
D48	ARCHIE BURKHART 1	413147084492701	41°31′47″	84°49′27″	908	2,550	Driller	D–D′
D49	WM–110	413410084463700	41°34′10″	84°46′37″	905	3,000	Gamma, sonic, caliper,	D–D′
D50	INSB–07	414427084551701	41°44′27″	84°55′17″	1,050	3,340	Driller, neutron	D–D′
E1	MILN–6	420254083545801	42°02′54″	83°54′58″	872	4,050	Driller, gamma, neutron	E–E′
E2	MILN–4	415355083505501	41°53′55″	83°50′55″	683	3,250	Driller, gamma, neutron	E–E′

TABLE 1.—*Descriptions of wells used in construction of hydrogeologic sections of the Midwestern Basins and Arches region—Continued*

Well identifier used for this project	Well or drill-hole designation	Site identification [1]	Latitude	Longitude	Altitude of land surface (feet above sea level)	Depth logged (feet)	Type of log	Hydrogeologic sections (see pls. 1 and 2)
E3	MILN–10	414402083443701	41°44′02″	83°44′37″	695	2,580	Driller, gamma, neutron	E–E′
E4	LU–102–SY16	414132083423300	41°41′32″	83°42′33″	672	104	Driller	E–E′
E5	LU– 13–T TOLEDO AG CENTER	414007083403100	41°40′07″	83°40′31″	630	400	Gamma, electric, caliper	E–E′
E6	LU–126 INVERNESS G.C.NO 3 AT TOLEDO OH	413905083385300	41°39′05″	83°38′53″	625	155	Driller	E–E′
E7	LU–1 STATE OF OHIO	413704083362200	41°37′04″	83°36′22″	620	525	Electric, gamma	E–E′
E8	WO–313–R LOF 2 AT ROSSFORD OH	413658083332900	41°36′58″	83°33′29″	615	541	Driller	E–E′
E9	WO–110	413608083303400	41°36′08″	83°30′34″	618	120	Geologist	E–E′
E10	WO–316–LK4 BILLINGS AT WALBRIDGE OH	413542083282700	41°35′42″	83°28′27″	615	149	Driller	E–E′
E11	WO–321–LK12 TRAVER AT EAST LAWN OH	413455083260400	41°34′55″	83°26′04″	610	115	Driller	E–E′
E12	O–44	413458083210300	41°34′58″	83°21′03″	601	1,710	Driller, gamma, neutron,	E–E′
E13	O–42	413121083134200	41°31′21″	83°13′42″	602	1,720	Driller, gamma.	E–E′
E14	O–28	412952083085200	41°29′52″	83°08′52″	562	58	Driller	E–E′
E15	O–43	412935083080500	41°29′35″	83°08′05″	583	1,730	Driller, gamma, neutron	E–E′
E16	S–18 NWOH–TEST	412537083040100	41°25′37″	83°04′01″	575	340	Driller, gamma, electric	E–E′

TABLE 1.—*Descriptions of wells used in construction of hydrogeologic sections of the Midwestern Basins and Arches region—Continued*

Well identifier used for this project	Well or drill-hole designation	Site identification [1]	Latitude	Longitude	Altitude of land surface (feet above sea level)	Depth logged (feet)	Type of log	Hydrogeologic sections (see pls. 1 and 2)
E17	S–15	412445083025100	41°24′45″	83°02′51″	580	2,400	Gamma, neutron	E–E′
E18	S–236–RL23 GRIFFAW NR VICKERY OH	412252082582600	41°22′52″	82°58′26″	597	62	Driller	E–E′
E19	S–21	412134082550800	41°21′34″	82°55′08″	640	2,690	Gamma	E–E′
E20	S–132–Y1 GROVES N OF BELLEVUE OH	412026082505000	41°20′26″	82°50′50″	735	150	Driller	E–E′
E21	E–222	411929082434600	41°19′29″	82°43′46″	715	3,650	Driller, gamma, neutron	E–E′
E22	E–212	411803082424900	41°18′03″	82°42′49″	662	58	Driller	E–E′
E23	HU–24	411230082403200	41°12′30″	82°40′32″	752	3,220	Gamma, neutron	E–E′
E24	HU–25	411112082372300	41°11′12″	82°37′23″	803	3,460	Gamma, neutron	E–E′
E25	HU–23	410539082345400	41°05′39″	82°34′54″	963	935	Gamma, neutron	E–E′
E26	HU–27	410107082342000	41°01′07″	82°34′20″	1,035	3,940	Gamma, neutron	E–E′

[1] Site Identification refers to a unique identifier used in the U.S. Geological Survey's Ground-Water Site Inventory data base.