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In cooperation with the
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Water Quality in the Vicinity of Mosquito Creek Lake, Trumbull County, Ohio, in Relation to the Chemistry of Locally Occurring Oil, Natural Gas, and Brine

Water-Resources Investigations Report 98-4180

U.S. Department of the Interior
U.S. Geological Survey

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By Gary J. Barton, Robert C. Burruss, and Robert T. Ryder

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CONTENTS

ILLUSTRATIONS

TABLES

CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

Multiply	By	To obtain
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
cubic foot (ft^3)	0.02832	cubic meter
million gallons (Mgal)	3,785	cubic meter
pound per square inch (lb/in^2)	6.895	kilopascal

Temperature is given in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by use of the following equation:

°F = 1.8(°C) + 32

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.

Abbreviated prefixes for multiples: M, million; G, billion.

Abbreviated water-quality units used in this report: Chemical concentrations and water temperature are given in metric units. Chemical concentration is given in milligrams per liter (mg/L) or nanograms per liter (ng/L). Milligrams per liter is a unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water. For concentrations less than 7,000 mg/L, the numerical value is approximately the same as for concentrations in parts per million. One million nanograms per liter is equivalent to one milligram per liter.

Specific conductance of water is expressed in microsiemens per centimeter at 25 degrees Celsius (µS/cm). This unit is equivalent to micromhos per centimeter at 25 degrees Celsius (µmho/cm), formerly used by the U.S. Geological Survey.

Stable isotope ratios, indicated by use of the delta symbol (δ) and expressed in parts per thousand (per mil), represent the proportions of selected isotopes in a given sample as compared to proportions of the same isotopes in an established standard.

WATER QUALITY IN THE VICINITY OF MOSQUITO CREEK LAKE, TRUMBULL COUNTY, OHIO, IN RELATION TO THE CHEMISTRY OF LOCALLY OCCURRING OIL, NATURAL GAS, AND BRINE

By Gary J. Barton, Robert C. Burruss, and Robert T. Ryder

Abstract

Environmental samples collected in the Mosquito Creek Lake area were used to characterize water quality in relation to the chemistry of locally occurring oil, natural gas, and brine and to establish baseline water quality. Mosquito Creek Lake (a manmade reservoir) and the shallow bedrock aquifers near the lake are major sources of potable water in central Trumbull County. The city of Warren relies on the lake as a sole source of potable water. Some of the lake bottom may be in direct hydraulic connection with the underlying aquifers. The city of Cortland, along the southeastern shore of the lake, relies on the Cussewago Sandstone aquifer as a sole source of potable water. This aquifer subcrops beneath the glaciofluvial sediments that underlie the lake. Nearly all residential homes around the lake, with the exception of homes in the city of Cortland, rely on domestic supply wells as a source of potable water.

Oil and natural gas exploration and production have been ongoing in the Mosquito Creek Lake area since the discovery of the historic Mecca Oil Pool in the Mississippian Berea and Cussewago Sandstones in 1860. Since the late 1970's, the major drilling objective and zone of production is the Lower Silurian Clinton sandstone. The oil and natural gas resources of the Mosquito Creek Lake area, including reservoir pressure, production history, and engineering and abandonment practices are described in this report.

The chemical and isotopic characteristics of the historic Mecca oil and natural gas are very different than those of the Clinton sandstone oil and natural gas. Gas chromatograms show that Mecca oil samples are extensively altered by biodegradation, whereas Clinton sandstone oils are not. Extensive alteration of Mecca oil is consistent with their occurrence at very shallow depths (less than 100 ft below land surface) where microbial activity can affect their composition. Also, the carbon-isotope composition of dissolved methane gas from Berea and Cussewago Sandstone water samples indicates that the gas is microbially generated, whereas the Clinton sandstone gases are thermogenically generated.

Methane gas, in addition to crude oil, occurs naturally in the shallow Berea and Cussewago Sandstone aquifers in the Mosquito Creek Lake area and concentrations of dissolved methane are significant in the city of Cortland public-supply wells and in the domestic-supply wells near the southern shore of the lake. Water associated with oil and gas in the Clinton sandstone is a brine with high concentrations of chloride. Water from the Berea and Cussewago Sandstones, however, is fresh and potable. The contrasting geochemical characteristics are important for addressing water-

quality issues that relate to oil and natural gas development in the Mosquito Creek area.

A reexamination of the geologic framework and results of a subsurface-gas survey show that crude oil in the historic Mecca Oil Pool probably does not seep into Mosquito Creek Lake. Environmental samples show no evidence of any measurable release of oil, gas, or brine from the deeper Clinton sandstone oil and gas wells to the shallow aquifers, the lake, or lake tributaries. Brine is not associated with the hydrocarbons in the shallow Berea-Cussewago aquifer system and therefore cannot be a source of brine contamination. A mixing diagram constructed for dissolved bromide and chloride in surface water and water-supply wells shows no demonstrable mixing of these water resources with brine from the Clinton sandstone. There is some notable salinity in surface waters; however, the water is bromide poor, and a mixing diagram indicates that some local ground waters are influenced by halite solutions, presumably derived from leaching of road salt or from septic effluent.

Introduction

The Bureau of Land Management, in cooperation with the U.S. Army Corps of Engineers and the Ohio Department of Natural Resources (ODNR), is investigating whether to lease Federal mineral rights associated with Mosquito Creek Lake for the drilling of oil and natural gas wells. The drilling targets are in the Clinton sandstone[1], which underlies the lake at depths of 4,200 to 4,700 ft. Oil and natural gas wells tapping the Clinton sandstone must be drilled through the Berea Sandstone, Cussewago Sandstone, and other aquifers by vertical and directional drilling methods from sites near the lake. Optimum oil and gas resources in the Clinton sandstone appear to be limited to the southern two-thirds of the lake, and production of these resources has the potential for affecting water quality in the Mosquito Creek Lake area. Known sources of pollutants to Mosquito Creek Lake include refined oil and gasoline from watercraft, road salt, nutrients and sediment associated with urban and agricultural runoff, bacteria from residential sewage systems and waterfowl, and atmospheric deposition. The U.S. Geological Survey (USGS), in cooperation with the city of Warren and the ODNR, investigated the chemistry of water, oil, gas, and brine in the vicinity of Mosquito Creek Lake to document water quality in relation to past oil and natural gas drilling and production.

Mosquito Creek Lake, a manmade reservoir, and shallow bedrock aquifers near the lake are the major sources of potable water in central Trumbull County. The city of Warren, about 5 mi south of Mosquito Creek Lake, relies on the lake as the sole source of potable water. Some areas of the lake bottom may be in direct hydraulic connection with underlying aquifers. The city of Cortland, along the southeastern shore of the lake, relies on the Cussewago Sandstone aquifer as the sole source of potable water. Nearly all residential homes near the lake, with the exception of the city of Cortland, rely on domestic supply wells as a source of potable water. Many domestic supply wells have been drilled within 0.25 mi of the Mosquito Creek Lake shore and most of the wells are completed in the Berea Sandstone and the Cussewago Sandstone aquifers. Should leaks develop in casings of oil and gas wells in the Clinton sandstone, they may become pathways for natural gas and fluids to migrate upward from deep formations to shallow aquifers. This migration, however, would require mechanical failure of multiple casings and a sufficient driving mechanism, and improvements in drilling and production technology, along with stricter regulations, have reduced the potential negative effects of oil and natural gas drilling and production on water quality.

Prior to this investigation, surface water and ground water in the Mosquito Creek Lake area have been sampled and analyzed only on a very limited basis for constituents that may result from oil and natural gas drilling activities. Moreover, little information is available on baseline water quality in the area; without this baseline information, the effects of future oil and natural gas drilling and production activities will be unknown. Regulatory agencies need baseline chemical data on oil and natural gas samples from the historic Mecca Oil Pool, the Berea and Cussewago Sandstone aquifers, and the Clinton sandstone to allow differentiation between in-place formation hydrocar-

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[1] The terms "Clinton sandstone" and "Medina sand" (mentioned later in this report) are informal names coined by drillers in the 1860's. These units may not be equivalent to the Clinton Formation, Clinton Group, or Medina Group as formally recognized in northeastern Ohio and northwestern Pennsylvania.

bons and hydrocarbons migrating from other formations.

Purpose and scope

The purpose of this report is to describe current water quality and the chemistry of oil, natural gas, and brine in the Mosquito Creek Lake area. Additionally, these data are used to characterize water quality in the Mosquito Creek Lake area in relation to past oil and natural gas well drilling and production.

To meet the overall objective, several goals for this investigation were established. These include (1) collect water-quality and subsurface-gas data from shallow sediments and rock that can be used for future evaluation of possible effects of oil and natural gas well drilling and production on water supplies, (2) characterize current surface-water and ground-water quality as it relates to the natural occurrence and (or) release of oil, gas, and brine, (3) sample and chemically characterize the oil in the shallow Mecca Oil Pool, gas from the Berea and Cussewago Sandstone aquifers, and the oil, gas, and brine from the Clinton sandstone, and (4) identify areas where aquifers are vulnerable to contamination from surface spills at oil and natural gas drilling and production sites.

Acknowledgments

Thomas Repphun of TNT Water Company assisted USGS scientists by helping to locate homeowners interested in having water-quality samples collected from their domestic wells, and he provided the USGS access to samples of Mecca oil from domestic water wells as they were drilled.

Richard A. Liddle of Lomak Petroleum, Inc., and Loren Smith of Loma Enterprises, Inc., gave the USGS permission to collect oil, natural gas, and brine samples from the Clinton sandstone. John Frederick of Lomak Petroleum, Inc., and Bob Pettenati of Loma Enterprises, Inc., accompanied USGS scientists in the field and provided technical support necessary to collect oil, natural gas, and brine samples.

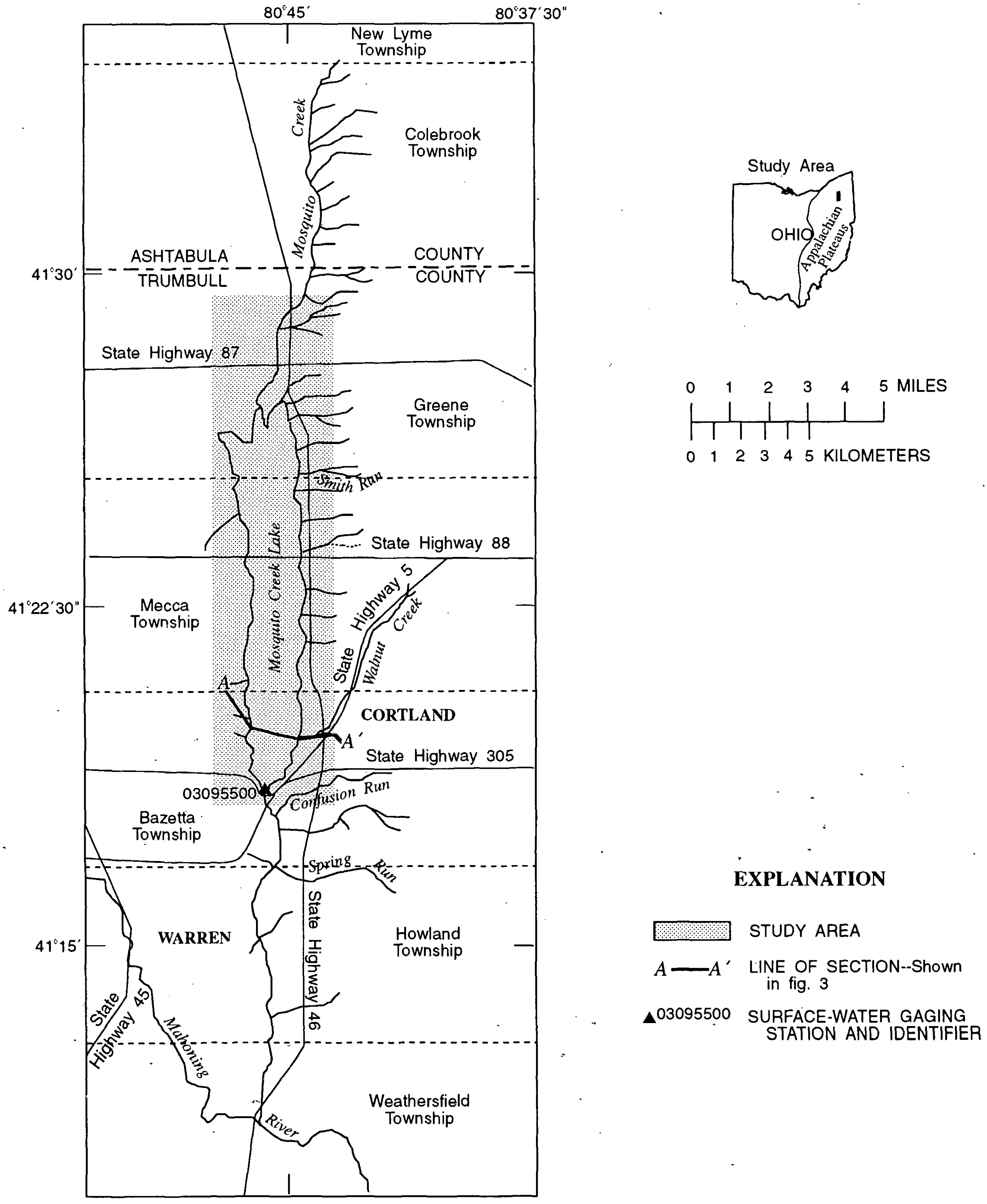
Description of the study area

The study area covers about 15 mi^2 in central Trumbull County in northeastern Ohio (fig. 1) and is part of the Appalachian Plateaus Physiographic Province. Precipitation averages about 36 in per year (Owenby and Ezell, 1992). The topography of Trumbull County, characterized by moderate relief and land-surface altitudes ranging from about 860 to 1,100 ft above sea level, is largely controlled by Pleistocene glacial deposits such as moraines, eskers, lacustrine sediments, and outwash (Hull, 1984). Several valleys in the county, including the one occupied by Mosquito Creek Lake, have been incised into bedrock by glacial and fluvial processes (Larsen, 1996a–c; Slucher and Larsen, 1996). The linear nature of these incised valleys, as well as the trellis and rectilinear drainage patterns of smaller tributary streams, suggest they are localized along fracture and fault zones. Glacial drift covers most of Trumbull County and ranges in thickness from 5 to 50 ft except in bedrock valleys where it is as much as 200 ft thick (White, 1971).

Approximately 9,000 ft of Paleozoic sedimentary rocks, from Late Cambrian to Early Pennsylvanian age, are preserved beneath a thin cover of glacial deposits (table 1, in the back of this report). These strata and underlying granitic basement rocks of Middle Proterozoic age constitute part of the northwestern margin of the Appalachian Basin. Only the uppermost 4,800 ft of the sedimentary record, including the glacial deposits, are relevant to this investigation. Geologic structure of the Paleozoic sequence in northeastern Ohio consists of a gentle homocline that dips less than 1 degree to the southeast.

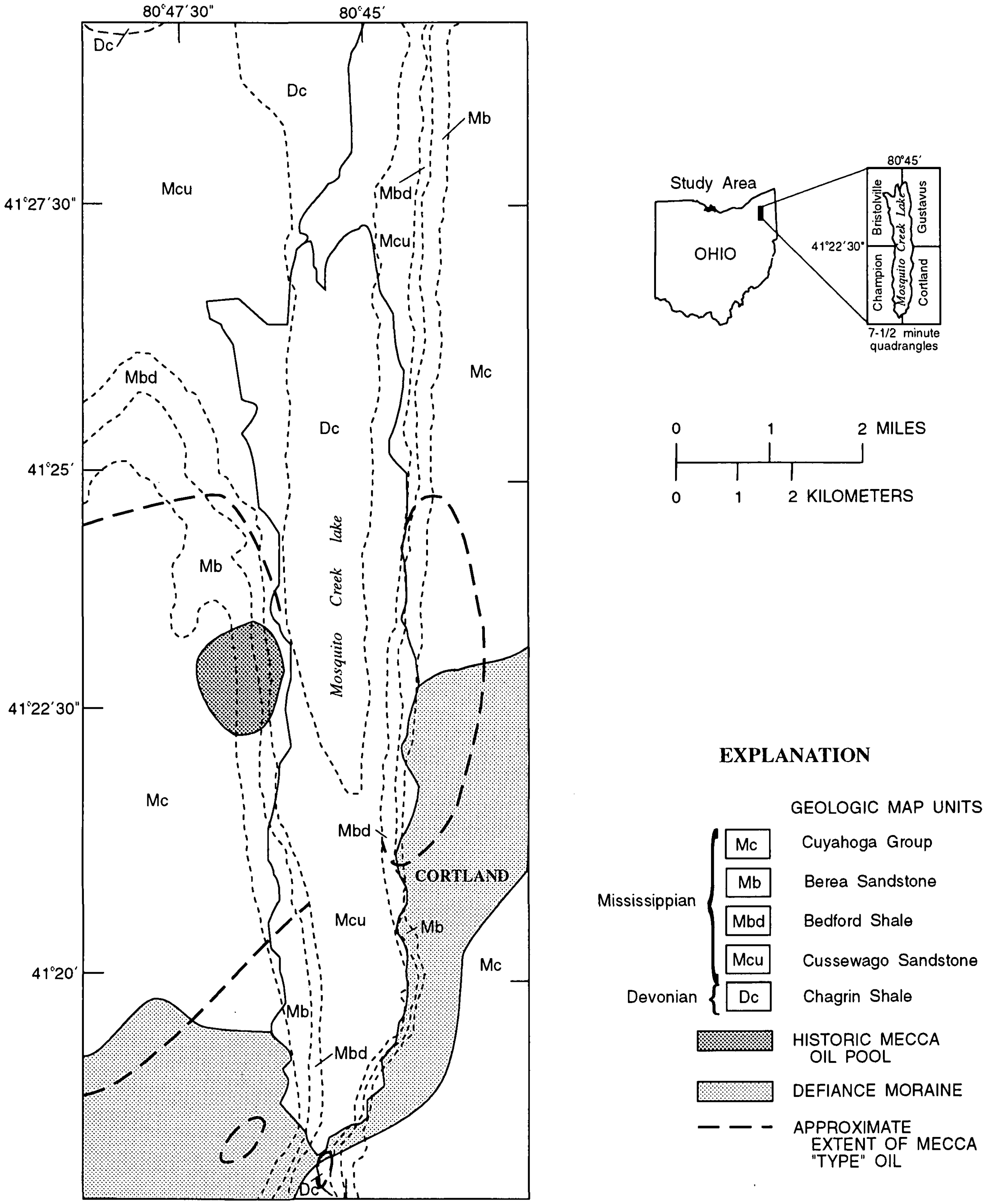
The cities of Warren and Cortland are the primary consumers of water in the study area. The city of Warren is the largest user of water for public supply in Trumbull County and is permitted to withdraw up to 16 Mgal/d from Mosquito Creek Lake. Water is obtained from three 36-in.-diameter intake ports at altitudes of 892, 886, and 876 ft at the southern end of the lake and is pumped to the city water-treatment plant below the lake impoundment. The city of Cortland is located along the southeastern shore of Mosquito Creek Lake and relies on six wells for potable water. These supply wells, drilled between 1937 and 1982, are completed in the Cussewago Sandstone aquifer (figs. 2 and 3). From 1991 through 1995, the combined average daily withdrawal for the supply wells was 556,500 gal/d.

Oil and natural gas exploration and production have been more or less continuous in Trumbull County since the discovery of the historic Mecca Oil Pool in the Mississippian Berea Sandstone and Cussewago Sandstone in 1860. Since the late 1970's, the major drilling objectives and zones of production were



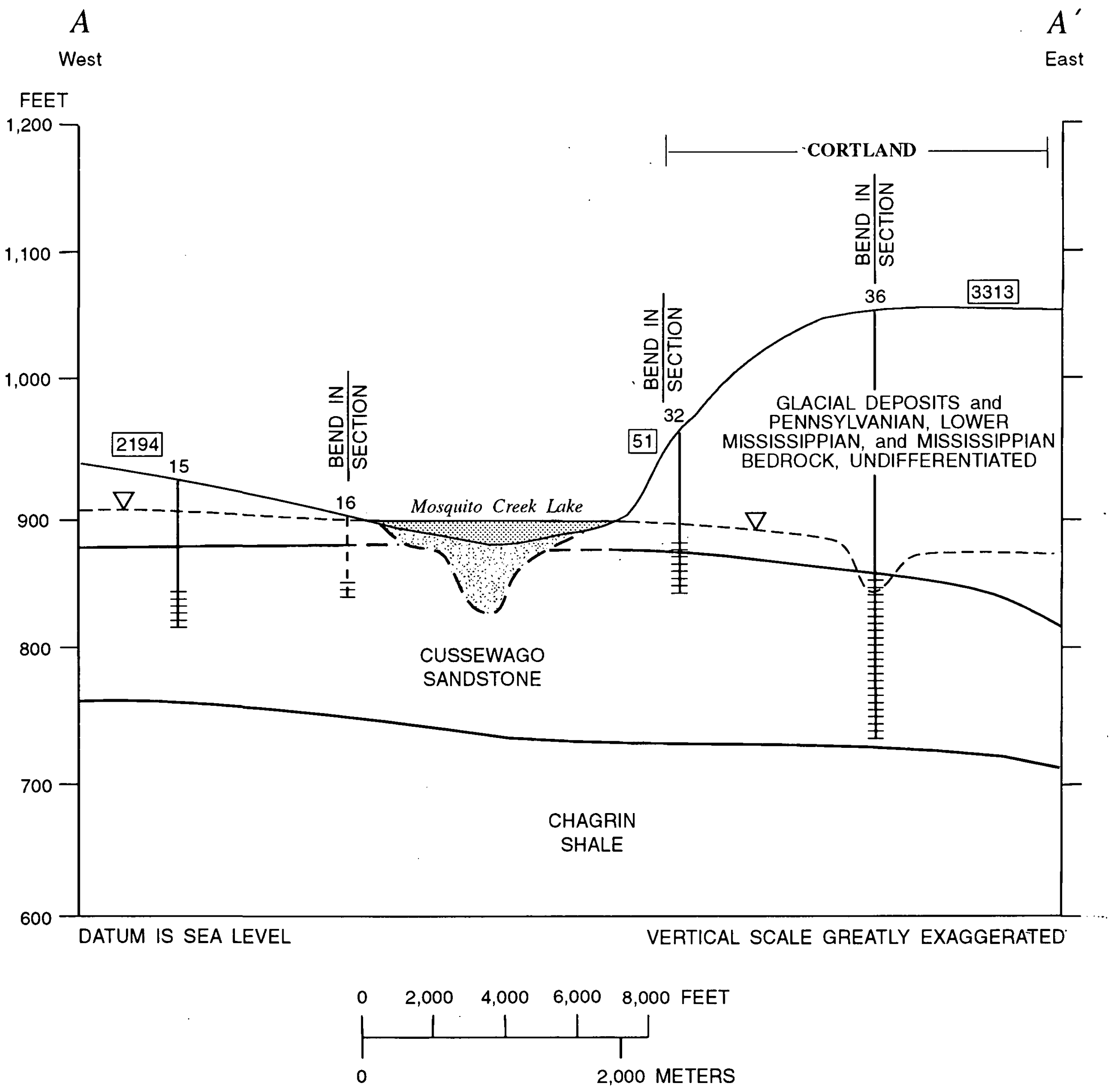
Base from U.S. Geological Survey
Cleveland 1:250,000, 1956, revised 1972

Figure 1. Mosquito Creek Lake and the study area, Trumbull County, Ohio.



Geologic map modified from: deWitt, W., Jr., unpub. geol. map, 1940; King, E.L., 1952; Larsen, G.E., 1996a, Champion 7 1/2 min. quad.; Larsen, G.E., 1996b, Bristolville 7 1/2 min. quad.; Larsen, G.E., 1996c, Gustavus 7 1/2 min. quad.; Slucher, E.R. and Larsen, G.E., 1996, Cortland 7 1/2 min. quad.; Barton, G.J. and Wright, P.R., 1997

Figure 2. Glacial and bedrock geology and the Mecca Oil Pool in the vicinity of Mosquito Creek Lake.



EXPLANATION

▨	GLACIOFLUVIAL SEDIMENTS
--▽--	POTENTIOMETRIC SURFACE--Shows altitude at which water level would rise in wells, September 1996
———	BOUNDARY BETWEEN GEOLOGIC FORMATIONS--Dashed where inferred
15	WATER WELL--Number is identifier with county prefix omitted. Dashed well has been projected onto section line
╪	INTERVAL OF WATER WELL THAT IS OPEN TO AQUIFER
55	GAS WELL AND IDENTIFIER NUMBER (OHIO PERMIT NUMBER)

Figure 3. Hydrogeologic section *A-A′* through Mosquito Creek Lake area, Trumbull County, Ohio. (Line of section shown in fig. 1; modified from Barton and Wright, 1997.)

Lower Silurian Clinton sandstone and Medina sand. Secondary drilling objectives include the Lower Devonian Oriskany Sandstone and an unnamed Upper Devonian black shale. In 1995, the first hole was drilled in Trumbull County to test the Cambrian-age Rose Run Sandstone and Knox Dolomite. This 6,800-ft deep well was dry and was abandoned.

Mosquito Creek Lake

Mosquito Creek Lake was constructed by the U.S. Army Corps of Engineers in the 1940's for flood control, streamflow augmentation, and municipal water supply. The lake covers an area of approximately 12.3 mi^2 and has 13.9 mi of shoreline. Mosquito Creek, Walnut Creek, and about 50 unnamed tributaries flow into the lake. South of State Highway 88, approximately 31 unnamed tributaries and drainage ditches flow into the lake. Because the residences around Mosquito Creek Lake are not connected to a sewer or wastewater treatment system, septic drainage is present in many of the unnamed tributaries.

Before the construction of Mosquito Creek Lake, the study area was dominated by farms with flowing artesian water wells. These flowing wells were located along Center Street, which is now inundated by the lake. During periods of very low lake levels, the casings of the artesian wells protrude above the lake level, and the wells continue to flow. During winter months, the lake typically freezes over; however, the lake does not freeze near the flowing wells (Thomas Kachur, local historian, Cortland, Ohio, oral commun., 1997). Drilling records are not available for these wells, thus well depths are not known.

The maximum storage in the lake is about 33.9 billion gal at a pool elevation of 904 ft above sea level (U.S. Army Corps of Engineers, 1992). At the maximum summer low-water regulation pool elevation of 901.4 ft, the lake has a capacity of 24.2 billion gal. The USGS stream gaging station No. 03095500 (fig. 1), located at the outlet of the lake, recorded a mean annual discharge of 89 ft^3/s during 1943-91. The maximum daily streamflow at the outlet was 1,280 ft^3/s on June 5, 1947. On average, about one lake volume of water passes through the lake outlet during a 1-year period.

Since 1954, the quality of Mosquito Creek Lake water has been monitored daily at the city of Warren supply intake. Water-sample collection and analytical methods for temperature, pH, and dissolved chloride have not changed during this period (Jim Sherwood, oral commun., City of Warren Water Department, Warren, Ohio, 1997). Additionally, dissolved oxygen and total dissolved solids have been measured since 1972. Since 1955, the average annual lake temperature has ranged from 11.6 to 13.7 degrees Celsius (fig. 4). The average annual pH has increased slightly from 7.2 in 1964 to 7.9 in 1992. From 1959 through 1980, the average annual concentration of dissolved chloride increased from 4.3 to 31 mg/L. These increases may be attributed to increasing use of road salt, septic discharge into the lake, and (or) storm-sewer runoff. Since 1988, the average annual concentration of dissolved chloride has fluctuated between 21 and 32 mg/L. Dissolved oxygen has ranged from about 6 to 9.2 mg/L from 1972 to the present.

Soils

Soils surveys were conducted before and after lake impoundment. During the early 1900's, Coffey and others (1916) mapped soils in the study area, including the area now occupied by Mosquito Creek Lake. Since that study, the soil classification system has been modified; however, the classification scheme still categorizes soils as poorly drained, somewhat poorly drained, somewhat well drained, and well drained. More recently, the U.S. Department of Agriculture, Soil Conservation Service (1992) identified about 25 types of soils within 0.25 mi of Mosquito Creek Lake south of State Highway 88.

In broad terms, the soils surveys show that, within 0.5 mi of the western lakeshore, soils are predominantly somewhat poorly drained, and soils within 0.5 mi of the eastern shore are predominately somewhat poorly drained to somewhat well drained. On the basis of soil descriptions from Coffey and others (1916) and results of this study, most areas of the lake are underlain by poorly or somewhat poorly drained soils with few exceptions.

Poorly drained soils, including the Canadice silty clay loam, Condit silt loam, Damascus loam, Holy silt loam, and Severing silt loam, are equally distributed along the eastern and western lakeshore; however, they represent less than 10 percent of the area (U.S. Department of Agriculture, Soil Conservation Service, 1992). Well drained soils, including the Chili loam, Lakin loamy fine sand, and Oshtemo sandy loam, are distributed along the eastern lakeshore. Coffey and others (1916) mapped isolated occurrences of well drained Chenenago sandy loam, which grades

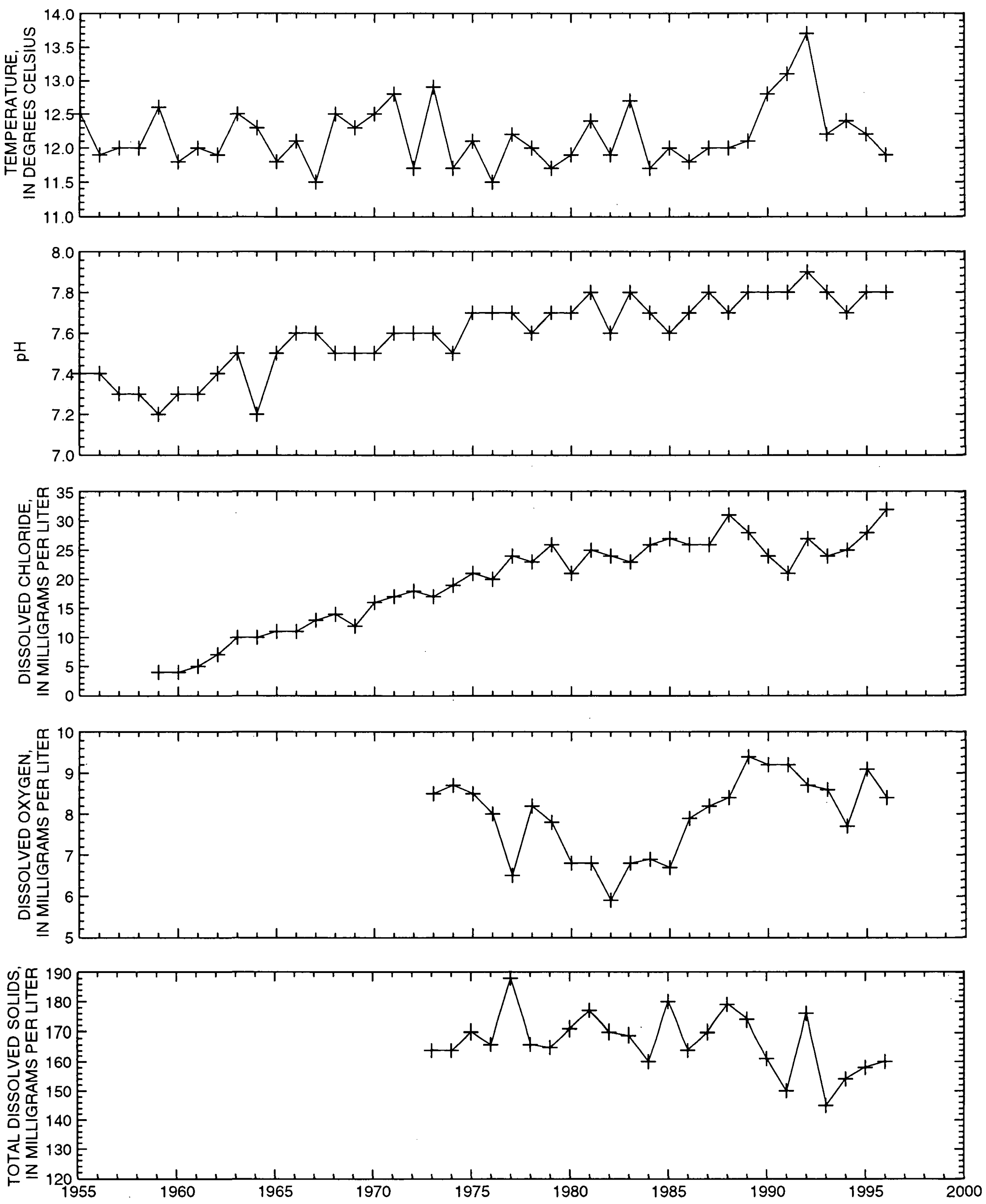


Figure 4. Average annual temperature, pH, and concentrations of dissolved chloride, dissolved oxygen, and total dissolved solids for raw water samples at the city of Warren water intake, Mosquito Creek Lake, Ohio, 1955-96.

into sand and gravel at depths of about 2 ft along the eastern lakeshore.

Ground-water resources

Glacial deposits cover the entire study area except for a few sandstone ledges that crop out locally on hillsides. Mosquito Creek and the Mosquito Creek Lake are underlain by a buried valley filled with unconsolidated glaciofluvial sediments (White, 1971; Larsen, 1996a; Slucher and Larsen, 1996). The glacial deposits are underlain by a series of Devonian and Mississippian sandstone aquifers and shale confining units (table 1). Bedrock dips gently towards the southeast (Pepper and others, 1954).

The Cussewago Sandstone is the primary aquifer and the Berea Sandstone is a secondary aquifer in the study area. Many domestic supply wells in the study area are open to multiple aquifers. In effect, a well completed in multiple aquifers functions as a pipeline that hydraulically connects the aquifers (Barton and Wright, 1997). Domestic-supply wells have steel or PVC casing extending from land surface to a depth of about 20 to 120 ft, and the wells are generally 40 to 200 ft deep. Water quality of the Berea Sandstone and Cussewago Sandstone aquifers is generally suitable for domestic uses in the Mosquito Creek Lake area, but some water wells drilled in the area adjacent to Mosquito Creek Lake have reportedly produced traces of oil and gas.

Buried bedrock valley and glaciofluvial deposits. A bedrock valley was eroded along the modern day Mosquito Creek by a south-flowing glacial stream and was later filled in by glaciofluvial sediments. The buried bedrock valley generally extends to about 100 ft below land surface and locally extends to more than 140 ft below land surface south of Mosquito Creek Lake (Barton and Wright, 1997). The depth of this buried bedrock valley beneath the lake is poorly defined by the few data available. Several well drillers' logs and soil-boring records (U.S. Army Corps of Engineers, Pittsburgh, Pa., archived records) show that the unconsolidated glaciofluvial sediments in the valley are typically fine grained and dominated by clay-rich till, with discontinuous layers of sand and gravel. A small number of domestic supply wells in the study area are completed in sand and gravel lenses in these glaciofluvial sediments.

Bedrock aquifers and confining units. The Berea Sandstone aquifer crops out in an irregularly shaped belt and is characterized by salients and sharp reentrants caused by glaciofluvial erosion (fig. 2; Barton and Wright, 1997; Rau, 1969; Pepper and others, 1954). The Berea Sandstone is unconformably overlain by the Cuyahoga Group. In the study area, the thickness of Berea Sandstone ranges from 0 to 59 ft but generally is less than 30 ft. The Berea Sandstone consists of gray, silty sandstone and intercalated beds of shale. Geologic mapping by Wallace deWitt (Pepper and others, 1954; unpublished 15 minute quadrangle maps), prior to the damming of Mosquito Creek, indicated that the Berea Sandstone is absent beneath most of the present-day lake.

The Bedford Shale unconformably underlies the Berea Sandstone aquifer and is composed of silty gray shale, silty gray mudstone, and thin, platy, gray siltstone. The Bedford Shale is a confining layer between the Berea Sandstone and Cussewago Sandstone aquifers. The Bedford Shale ranges from 0 to 29 ft in thickness at the water wells in the study area. The upper contact of the Bedford Shale is irregular because the overlying Berea Sandstone was deposited in channels that were scoured into the Bedford Shale. In places, the Bedford Shale was completely eroded away before the Berea Sandstone was deposited. Where the Bedford Shale is absent, the Berea Sandstone and Cussewago Sandstone are hydraulically connected (Barton and Wright, 1997). Additionally, glacial streams have eroded the Bedford shale from some parts of the buried valley.

The Cussewago Sandstone aquifer crops out in Mecca Township just west of Mosquito Creek Lake and subcrops beneath the glaciofluvial sediments in the lake and in the Mosquito Creek valley south of the lake. This aquifer is predominantly a white quartz sandstone that is silt free, well sorted, and poorly cemented. The thickness of the Cussewago Sandstone ranges from less than 20 ft to about 152 ft (Barton and Wright, 1997). Beneath the Mosquito Creek flood plain, the upper surface of the Cussewago Sandstone is eroded to form a buried bedrock valley (figs. 2 and 3). The glacial stream that created the bedrock valley incised into the Cussewago Sandstone, and in a few limited areas, the stream incised further into the underlying Chagrin Shale. The hydraulic properties of this aquifer are discussed further in Barton and Wright (1997). Throughout most of the study area, the Cussewago Sandstone is a confined aquifer. West of the lake, where the Cussewago Sandstone crops out (fig. 2), the aquifer is near land surface; thus, it is likely to be unconfined and to function as a water-table aquifer.

Wells in the Cussewago Sandstone commonly yield 50 to 100 gal/min, but the aquifer can sustain well yields of greater than 100 gal/min in most areas east of the lake. The production rates of the Cortland public-supply Cussewago Sandstone wells range from 70 to 250 gal/min.

Ground-water flow patterns. Near Mosquito Creek Lake, ground-water flow patterns in the Berea Sandstone have not been investigated. Barton and Wright (1997) measured water levels in Cussewago Sandstone wells throughout the study area and reported that the regional ground-water flow pattern in the aquifer is generally west to east. Water levels in Cussewago Sandstone wells range from a few feet to slightly more than 200 ft below land surface. East and south of the lake, the potentiometric surface of the Cussewago Sandstone aquifer is lower than the pool elevation in the lake (Barton and Wright, 1997). Potential exists for water to flow from the lake and recharge into the Cussewago Sandstone; however, flow may be impeded to some extent by poorly permeable sediments on the lake bottom. In addition, before the construction of the lake, some farms in the valley had flowing water wells, and some of these wells may still exist today. Thus, potential exists for water to flow from aquifers beneath the lake into the lake.

East and southeast of the Mosquito Creek Lake, there is a downward vertical hydraulic gradient between the Berea Sandstone and Cussewago Sandstone. Thus, in domestic supply wells that are open to both the Berea Sandstone and Cussewago Sandstone aquifers, water in the Berea Sandstone can enter the well, flow down the open borehole, and exit from the borehole into the Cussewago Sandstone (Barton and Wright, 1997).

Oil and Natural Gas Resources

Oil and gas resources have played a critical role in the historical development of the Mosquito Creek Lake area. Before 1860, native Americans collected oil from seeps along the Mosquito Creek valley in the vicinity of West Mecca. Early settlers found considerable quantities of oil while quarrying stone from the beds of the Berea grit in the streams to the east of Mosquito Creek (Read, 1873). Edward Orton (1888) estimated that 2,000 to 2,500 wells were drilled in the Mecca oil field at depths generally less than 50 ft. The most prolific development was in south-central Mecca Township, west of Mosquito Creek (Prosser, 1912). In the early development of the Mecca oil field, wells were drilled with a spring pole and were uncased (Bownocker, 1903). Initial development was interrupted by the Civil War (Bownocker, 1903). The field was largely abandoned by the 1880's. Most wells drilled in the 1800's are abandoned; however, a few wells still exist and may produce oil.

During the early 1920's, additional wells were drilled into the Berea and Cussewago Sandstones in the area of the abandoned Mecca oil field along the Bazetta-Mecca Township border and near Bazetta. In 1965, the Kashmir Oil Company initiated a project to enhance oil recovery by injecting steam in the oil-bearing sandstone near Klondike (Carl Heinrich, consultant, written commun., 1998). According to Heinrich, the pilot project was unsuccessful due to the large amount of water production. Commercial production of gas and, to a lesser extent, oil from the Clinton sandstone at depths of 4,200 to 4,500 ft began in the Mosquito Creek area in early 1974.

Hydrocarbon reservoirs

The Berea Sandstone and Cussewago Sandstone in the Mosquito Creek area are unusual because they are primary regional bedrock aquifers as well as oil and gas reservoirs. Orton (1888) reported that water wells dug by the early settlers often produced water that contained globules of oil. Numerous water well logs on file with the Ohio Department of Natural Resources, Division of Water, document the presence of crude oil and (or) natural gas in shallow sandstone aquifers for wells drilled prior to the advent of Clinton sandstone exploration. Thus, a thorough understanding of the distribution and occurrence of crude oil and natural gas in the sandstone aquifers in the Mecca area is warranted. The following discussion centers on hydrocarbon reservoirs and source rocks within the Berea Sandstone, the Cussewago Sandstone, the Lower Mississippian and Devonian black shales, and the Clinton sandstone.

Berea and Cussewago Sandstone. Pepper and others (1954) and DeBrosse and Vohwinkel (1974) regarded the Berea and underlying Cussewago Sandstones as the oil-producing reservoirs of the historic Mecca Oil Pool. Early authors, including Read (1873), Orton (1888), and Prosser (1912) treated these sandstones as part of a single stratigraphic unit known as the Berea grit. DeWitt (1951) recognized them as separate units including the Berea Sandstone, Bedford Shale, and Cussewago Sandstone (in descending order). The geology of the Berea Sandstone, Bedford Shale, and Cussewago Sandstone is described in greater detail in Pepper and others (1954), Rau (1969), Pashin and Ettensohn (1995), and Barton and Wright (1997).

Some disagreement exists regarding the distribution of hydrocarbons in the Berea and Cussewago Sandstones in the Mecca area. In part, differences arise from slightly varying interpretations of stratigraphic information. Given the lack of oil well records, production data, and well-location information for wells drilled before 1900, it may not be possible to conclusively determine whether the Berea Sandstone or Cussewago Sandstone was the primary reservoir.

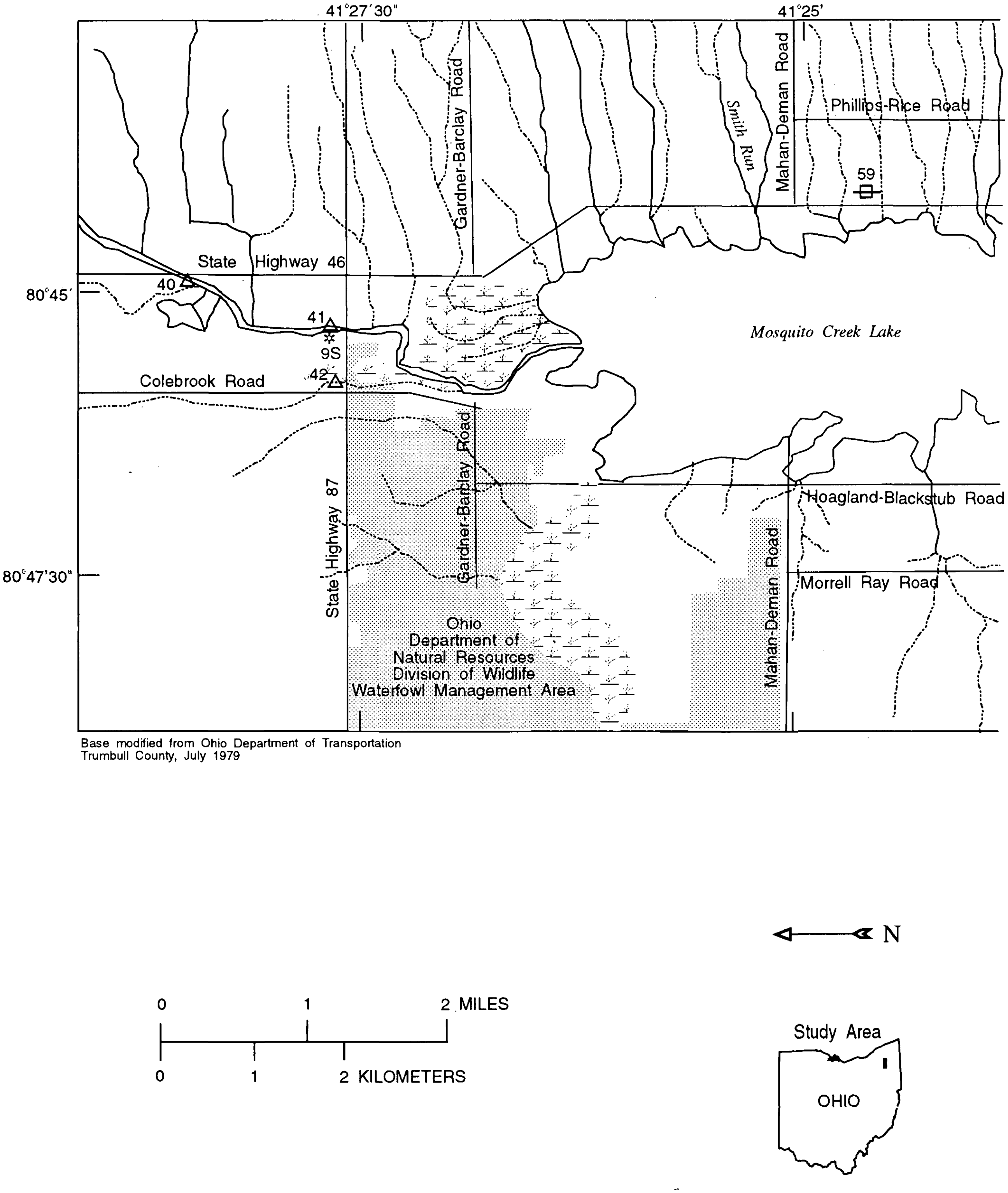
Pepper and others (1954) and DeBrosse and Vohwinkel (1974) reported that oil was produced from both the Berea Sandstone and Cussewago Sandstone in the Mecca oil field. Beneath Mosquito Creek Lake, where the Berea Sandstone has been removed by erosion, the Cussewago Sandstone is the sole reservoir of Mecca "type" oil. Mychkovsky (1998) and Scott Kell (oral commun., Ohio Department of Natural Resources, Division of Oil and Gas, 1998) concur with this interpretation. Based on examination of Ohio Geological Survey stratigraphic section descriptions, oil and gas well geophysical logs, reservoir properties, and historic literature describing the depth of oil occurrence, Mychkovsky and Kell believe that oil was produced from both the Berea and Cussewago Sandstones in the Mecca oil field. Read (1873), Orton (1888), and Pepper and others (1954) located the main part of the historic Mecca Oil Pool west of Mosquito Creek Lake in western and southwestern Mecca Township (fig. 2). Here, oil and trace amounts of natural gas were produced from as many as 2,500 wells. On the basis of a small gas pool in the Cussewago Sandstone about 2 mi north of the city of Cortland, Pepper and others (1954) mapped the historic Mecca Oil Pool to include an area east of Mosquito Creek Lake (fig. 2).

The configuration and boundary of the historic Mecca Oil Pool well field and the occurrence of Mecca "type" oil has been slightly modified as a result of USGS field work in the Mosquito Creek Lake area during 1996-97 and in response to oral accounts by local residents. The historic Mecca Oil Pool, limited to the Berea and Cussewago Sandstones, lies west and east of Mosquito Creek Lake and likely did not encompass the area now occupied by Mosquito Creek Lake. The Mecca "type" oil encompasses the southern half of Mecca township and the northern part of Bazetta Township.

During the course of this study, USGS scientists made observations that may help to refine the location of historic Mecca Oil Pool hydrocarbon reserves. Local accounts of oil drilling and production activity prior to the construction of Mosquito Creek Lake were provided to the USGS by Thomas Kachur, a long-time resident and historian for the Mosquito Creek Lake area (Kachur, 1972); Joseph Letwen, who was raised on a farm on Center Street (now submerged beneath the lake); and Thomas Repphun, a local water-well driller. According to Thomas Kachur and Joseph Letwen (oral commun., Cortland, Ohio, 1997), Mecca "type" oil has never been produced in the area now occupied by the lake. The bulk of the historic Mecca Oil Pool well field was located just west of Hoagland-Blackstub Road in Mecca Township. One local water-well driller reported that Mecca "type" oil is commonly found only in the Berea Sandstone (Thomas Repphun, TNT Water Company, Inc., oral commun., Cortland, Ohio, 1996).

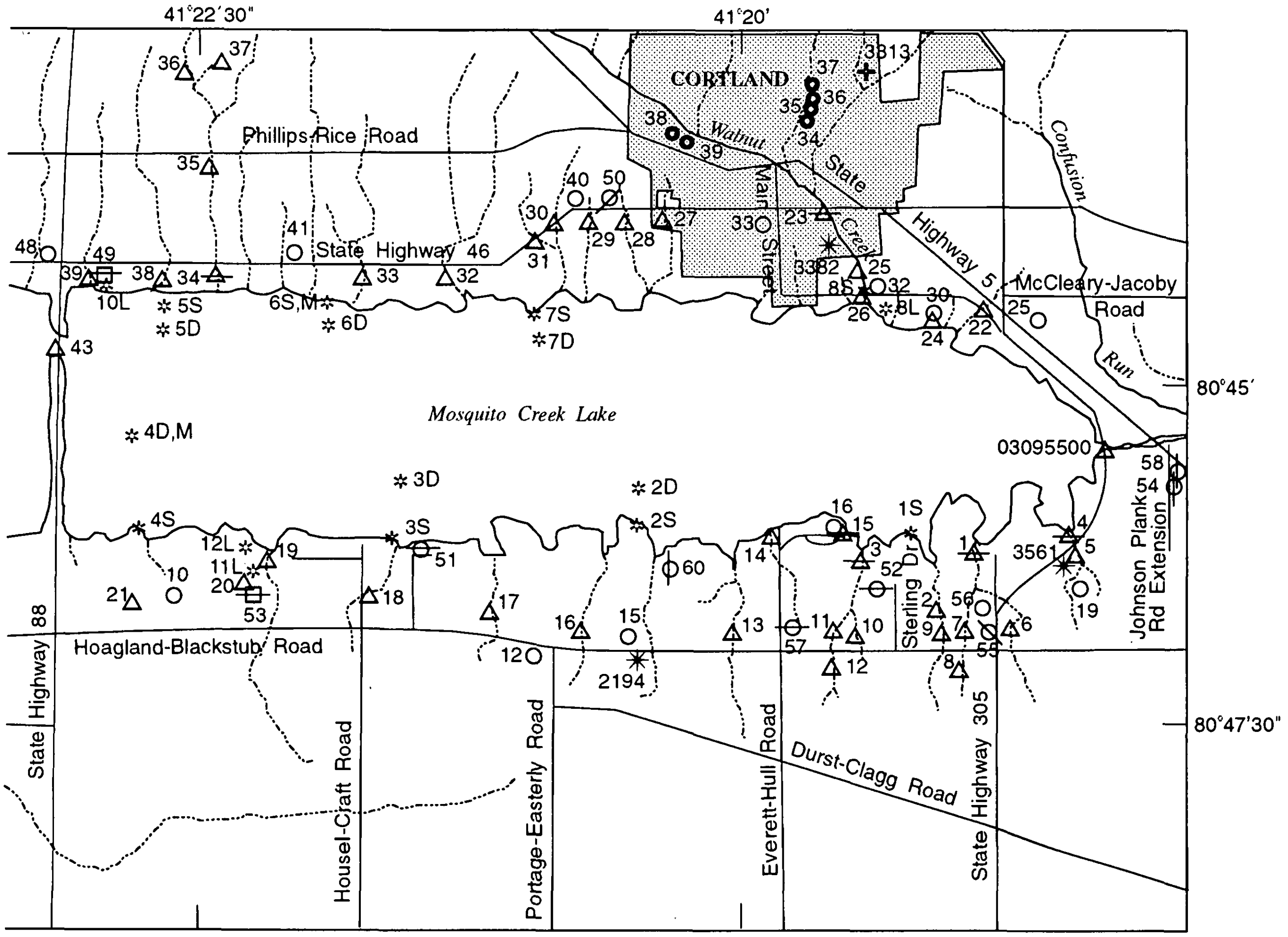
USGS water-level measurements made in numerous supply wells completed in the Cussewago Sandstone aquifer on both sides of the lake south of State Highway 88 have not yielded oil stains on water-depth measuring tapes, except for three wells located in the historic Mecca Oil Pool. During the drilling of a Cussewago Sandstone domestic-supply well at test hole T-49 (fig. 5), Mecca "type" oil was found in the Berea Sandstone but not the Cussewago Sandstone. Mecca "type" oil was also found in the Berea Sandstone at well T-53 (fig. 5). Driller's logs for domestic-supply wells frequently report oil shows only in the Berea Sandstone and not in the Cussewago Sandstone. An important consideration is that any Mecca "type" oil that existed in the Berea Sandstone and Cussewago Sandstone in the area now occupied by the lake could have been removed during the fluvial and glacial erosion that formed the Mosquito Creek valley. A geologic section of Trumbull County by Read (1873) shows that the Mecca oil reservoir was eroded and replaced with glaciofluvial sediments within the Mosquito Creek valley. The erosion of the Berea Sandstone and Cussewago Sandstone is associated with the downcutting by the relic Mosquito Creek and glaciation and likely split the Mecca Oil field into two separate oil pools (fig. 2).

Mecca "type" oil and gas probably migrated from an underlying Devonian black shale source in



Base modified from Ohio Department of Transportation
Trumbull County, July 1979

Figure 5. Data-collection sites in the Mosquito Creek Lake area.



EXPLANATION

▨ WETLANDS

△20 SURFACE-WATER-QUALITY AND STREAMFLOW MEASUREMENT SITE--Location and identification number, county prefix omitted.

○12 GROUND-WATER-QUALITY MEASUREMENT SITE--Well location and identification number, county prefix omitted. Wells are completed in the Cussewago Sandstone unless indicated otherwise.

- ⌽ Well is completed in Pleistocene sand and gravel
- Ø Well is completed in Cuyahoga Group
- ⦰ Well is completed in the Berea Sandstone and Cussewago Sandstone
- ⊖ Well is completed in the Berea Sandstone
- □ Mecca oil sampling sites--oil taken from well or exploratory borehole for chemical and isotopic analysis
- ● Public-supply well

✳3561 CLINTON NATURAL GAS AND OIL WELL-SAMPLING SITE--Ohio Department of Natural Resources identifier. Natural gas, oil, and brine samples taken for chemical and isotopic analysis. Gamma-ray log available for most wells

+3313 GAS WELL FOR WHICH GAMMA-RAY LOG IS AVAILABLE--Ohio Department of Natural Resources identifier

✲3D SUBSURFACE-GAS MEASUREMENT SITE--location and identification number. The letter D indicates the site located in waters usually greater than 3 feet deep

- S Site located nearshore in waters less than 2 feet deep
- L Site located on land
- M Sampler missing after installation

western Pennsylvania in late Paleozoic time. Given the relatively simple structure at the top of the Berea Sandstone and Cussewago Sandstone in central Trumbull County, entrapment of hydrocarbons at the historic Mecca Oil Pool and nearby pools is controlled by depositional and (or) diagenetic factors. Pepper and others (1954) suggest that much of the oil and gas in the Berea Sandstone in northeastern Ohio was localized in zones of better grain sorting caused by wave and current reworking. The historic Mecca Oil Pool and nearby oil and gas accumulations in the Berea and Cussewago Sandstones may be remnants of a once larger hydrocarbon accumulation that was depleted by postemplacement uplift and erosion and by circulation of meteoric water.

Lower Mississippian and Devonian black shale. One or more of the following organic carbon-rich black shale units may be a reservoir for Devonian-shale natural gas in Trumbull County: the Lower Mississippian Sunbury Member of the Orangeville Shale; the Upper Devonian Huron Member of the Ohio Shale, the Pipe Creek Shale Member of the Java Formation, and the Rhinestreet Shale Member of the West Falls Formation; and the Middle Devonian Marcellus Shale (table 1). The Upper Devonian and Lower Mississippian black shale units have moderately high total organic carbon content (average of 1.5 to 2 weight percent) and their moderate thermal maturity (percent R_o = 0.55 to 0.60) make them a probable source and reservoir for gas and possibly oil (Schmoker, 1993; Boswell, 1996). Charpentier and others (1993) assessed the potential for Devonian-shale gas in eastern and northeastern Ohio as moderate.

The potential for shale gas in Trumbull County is somewhat diminished given that the black shale units only reached levels of thermal maturity that are marginally mature for oil generation and immature for gas generation. Gas present in these shales may be a mixture of gases from biogenic processes and migrated, thermogenic gas similar to gas in the Antrim Shale in Michigan (Martini and others, 1996).

Clinton sandstone. The Lower Silurian Clinton sandstone and to a lesser extent the Medina sand are the major reservoirs for natural gas and oil in Trumbull County. Small amounts of brine are also produced from these sandstone reservoirs.

The Clinton sandstone consists of discontinuous sandstone lenses as much as 30 ft thick. The Clinton sandstone and Medina sand are very fine- to fine-grained quartzose sandstones with interstitial clay and silica cement (Suphasin, 1979). Because of their relatively low porosity and permeability, Clinton sandstone and Medina sand reservoirs require hydrofracturing to release oil, gas, and brine to the wellbore. The absence of structural closure or abrupt changes in dip and the lenticularity of the sandstone reservoirs indicate that gas accumulations in the Clinton sandstone and Medina sand are trapped by depositional and (or) diagenetic facies variations (Ryder and others, 1996).

Production history

Oil and natural gas exploration and production in Trumbull County began in 1860 with the discovery of the historic Mecca Oil Pool (Orton, 1888; Kachur, 1972). This accumulation produced heavy 27-29^{o} American Petroleum Institute (API) gravity oil from the Berea Sandstone and minor amounts from the Cussewago Sandstone, at depths of 60 ft or less. Of the estimated 2,000 to 2,500 wells drilled in the historic Mecca Oil Pool, several are reported to have a cumulative production of 3,000 bbl of oil. Commonly, large amounts of fresh water were produced with the oil (Orton, 1888). An estimated 890, 000 bbl were produced from the pool in the primary phase of production. Attempts to mine oil from shafts dug into the historic Mecca Oil Pool in 1884 (Orton, 1888) and to produce oil by steam flooding in the 1960's were largely unsuccessful.

Devonian shale gas was reported in subcommercial quantities from several wells in southern and western Trumbull County (Janssens, 1975; Gearheart and Grapes, 1977). No production data are available for these shale gas wells, but the initial production for two wells in the southern part of the county ranged from 50,000 to 200,000 ft^3 of natural gas per day (Janssens, 1975).

Natural gas and oil have been produced from the Clinton sandstone and Medina sand in Trumbull County and adjoining counties since about 1960 (DeBrosse and Vohwinkel, 1974). Drilling depths to the Clinton sandstone in Trumbull County range from 3,900 to 4,900 ft (Keighin and Hettinger, 1997). Numerous wells drilled in the late 1970's and throughout the 1980's succeeded in producing gas and oil and resulted in the rapid development of the Clinton sandstone gas and oil accumulation throughout most of Trumbull County (Wandrey and others, 1997). In 1995, 25 successful Clinton wells were drilled in the county (Ohio Department of Natural Resources, Division of Oil and Gas, 1996). The Clinton sandstone produces oil and natural gas along approximately two-thirds of the southern shoreline of Mosquito Creek Lake. Most of the wells produce gas, with some producing low volumes of oil. One well produces oil with little or no associated gas (Jeff Nolder, Bureau of Land Management, written commun., 1998).

From 1984 through 1996, approximately 15 Gft^3 (billion cubic feet) of natural gas and 135,000 bbl of oil have been produced from 175 wells in Bazetta and Mecca Townships of Trumbull County (Ohio Department of Natural Resources, Division of Oil and Gas, 1997). Most of this gas and associated oil have been produced from Bazetta Township (157 wells produced 14.8 Gft^3 of gas and 117,500 bbl of oil). Gas production for each of 112 wells in Bazetta Township that have been in operation for 8 to 12 years ranges from 3 to 408 Mft^3 (million cubic feet) with a median of 93 Mft^3. Because the majority of the wells in the Clinton sandstone stay in production for an average of 15 years, the well-production values represent a minimum estimated ultimate recovery (EUR) per well. The true median EUR for the group of 112 wells in Bazetta Township is probably between 110 to 125 Mft^3. Alternatively, the median EUR in Lordstown Township in southern Trumbull County is 170 Mft^3 (McCormac and others, 1996). For reasons not yet understood, EUR values per well for Clinton sandstone production in Mecca Township are less than 20 percent of those in Bazetta Township.

Engineering practices and abandonment of oil and natural gas wells in the Clinton sandstone

The drilling of a Clinton oil and natural gas well typically begins with drilling a borehole to a depth of about 350 ft and installing a steel surface casing. Most wells are drilled with compressed air to circulate drill cuttings; however, local water, including water from Mosquito Creek Lake, also may be used during drilling of the surface hole and for preparing cement or grout. The outside of the surface casing is bonded to bedrock and unconsolidated surficial deposits with cement. Drilling continues within the surface casing from land surface to near the total depth of the well, about 50 to 200 ft beneath the Clinton sandstone reservoir. A second, smaller-diameter steel casing (production casing) is set inside the surface casing. The smaller-diameter casing is bonded with cement to bedrock from the total depth of the well to about 700 ft above the Clinton sandstone. This casing and cement bond is perforated at the Clinton sandstone. Production tubing is hung inside the small-diameter casing and extends from land surface to near the top of the perforated zone. Natural gas and fluids associated with the gas (oil and brine) are produced through the production tubing. During each production cycle, natural gas, oil, and brine are removed from the tubing by a plunger ("rabbit") that travels uphole inside the tubing. The plunger falls back to the bottom of the tubing at the end of each cycle. If installed properly, this production arrangement isolates the gas, oil, and brine in the Clinton sandstone from shallow aquifers.

Abandoned Clinton sandstone wells are required by the ODNR to be sealed with cement that is circulated across a variety of zones including at land surface and at the bottom of the hole. Most wells that are sealed using this technique have not caused problems with contamination or leakage.

Reservoir pressures

Most oil and natural gas reservoirs in the Appalachian Basin, of which the Mosquito Creek Lake area is a part, have abnormally low fluid pressures (Russell, 1972). These abnormally low fluid pressures greatly reduce the risk of a blowout during drilling of a well. Bottom-hole pressure and pressure-to-depth ratios for the Clinton sandstone reservoir in northeastern Ohio range from about 1,500 to 1,600 lb/in^2 and 0.27 to 0.37 $(lb/in^2)/ft$, respectively (Thomas, 1993). Fifteen Clinton sandstone wells in Bazetta Township have comparable bottom-hole pressures that range from 1,250 to 1,500 lb/in^2 and pressure-to-depth ratios that range from 0.29 to 0.35 $(lb/in^2)/ft$. These bottom-hole fluid pressures are derived from initial shut-in pressures at the wellhead using calculations described by Thomas (1993). Equivalent freshwater heads supported by these bottom-hole pressures in the Clinton sandstone wells in Bazetta Township range from about 850 to 1,475 ft below land surface. Equivalent saltwater heads for these same wells, where total dissolved solids are approximately 200,000 mg/L, range from about 1,325 to 1,850 ft below land surface.

Berea Sandstone pressure-to-depth ratios in northeastern Ohio have about the same range as those for the Clinton sandstone (Thomas, 1993). In the study area, where the Berea Sandstone and underlying Cussewago Sandstone are near-surface aquifers, they are associated with a normal hydrostatic pressure of about 10 to 100 lb/in^2. Equivalent freshwater heads supported by the pressures in the Cussewago Sandstone range from land surface to 200 ft below land surface (Barton and Wright, 1997).

Problems in a Clinton oil and gas well, such as ruptured casing or poor well-construction techniques, could conceivably allow formational gas and (or) fluids to leak and migrate upward around the outside of the steel production casing into the annulus between the surface and production casings. Assuming existing subnormal bottom-hole pressures, gas could rise within the borehole far enough to mix with fresh water in the Berea and Cussewago Sandstone aquifers. However, for gas to leak into near-surface aquifers, the casings and cemented zones must lose their integrity and annular pressures (greater than aquifer hydrostatic pressures) must be high enough to drive the gas from the annulus into the aquifer. Brine consisting of 200,000 mg/L total dissolved solids could rise uphole from the Clinton sandstone only to within 1,325 to 1,850 ft of land surface. Brine coproduced with the Clinton oil would prevent the oil from rising uphole much more than 1,000 ft from land surface. Any near-surface freshwater that seeps down along the outside of poorly cemented casing would further reduce the pressure available to support an oil column. Therefore, brine and associated oil cannot contaminate even the deepest water wells developed in the Cussewago Sandstone aquifer.

Source, migration, and evolution of oil and natural gas

The origin and evolution of petroleum in Paleozoic reservoirs of the northwestern margin of the Appalachian Basin were studied by a number of workers (Cole and others, 1987; Ryder and others, 1998). Rocks rich in organic matter capable of generating petroleum occur within the Mississippian Sunbury Shale, the Devonian Ohio Shale, Olentangy Shale (Java and West Falls Formations of this report) and Marcellus Shale and the Middle Ordovician Utica Shale (Point Pleasant Formation of Cole and others, 1987). Devonian shales are the dominant source of oil in Silurian and younger reservoirs in eastern Ohio (Cole and others, 1987), whereas the Ordovician Utica Shale is the dominant source of oil in Lower Silurian and older reservoirs (Drozd and Cole, 1994; Ryder and others, 1998).

In conventional accumulations of crude oil and natural gas, petroleum is trapped in subsurface structures or stratigraphic features that are sealed by rocks with capillary entry pressures greater than buoyancy or hydrodynamic forces. This type of accumulation occurs in the Berea and Cussewago Sandstones of Trumbull County. Gas accumulation in the Clinton sandstone is classified as an unconventional or continuous-type petroleum accumulation (Ryder and others, 1996). Although the gas and minor amounts of oil in the Clinton sandstone are subjected to the same type of buoyancy and hydrodynamic forces that affect conventional accumulations, the trapping mechanism that maintains the accumulation is poorly understood.

Once a petroleum accumulation forms, the composition of the oil and natural gas can change over time if geologic conditions change. For example, if source rocks and reservoirs are buried under additional sediments, increasing temperatures may break down the organic matter and oil to form natural gas, causing the relative amount of gas to increase. If the trap is deformed by faulting or the seal is breached by erosion, natural gas and low-molecular-weight oil components will escape, leaving a heavy oil or tar accumulation. Oils in relatively shallow reservoirs can also be exposed to ground water that recharges in the vicinity of the oil accumulation. Active ground-water flow can alter the oil and natural gas by removing the most water-soluble compounds in the oil or by introducing bacteria capable of biodegrading the oil and oxidizing the natural gas. In some cases, subsurface microbial ecosystems can biodegrade oil and generate gas through metabolic processes. These processes of water washing and biodegradation are of particular importance to shallow oil occurrences in the historic Mecca Oil Pool.

Study Methods

During this study, several types of environmental samples were collected. Sample collection methods, quality assurance (QA) procedures, laboratory chemical analysis, and data archival are discussed below.

Sediment augering

Shallow unconsolidated sediments were hand augered at 10 sites on land and 8 sites in Mosquito Creek Lake as close as possible to a subsurface-gas survey site (fig. 5). In Mosquito Creek Lake, sediment cores were collected by augering in water less than 4 ft deep. Water depth limitations on the augering determined how close a boring could be made to subsurface-gas survey sites. Augering depths ranged from 0.2 ft to about 8.0 ft and were limited by the presence of bedrock near land surface. The cores were described by an onsite geologist and disposed of in the field.

Subsurface-gas survey

During the summer of 1997, a subsurface-gas survey was conducted using a passive-gas detection system. This system provided a rapid method for locating petroleum residues in shallow subsurface sediments and rock. The primary component of this passive-gas detection system is an activated carbon absorbent cartridge. The method may detect petroleum residues in the subsurface at distances possibly greater than 100 ft from the sampling point at ultra low concentrations (Harry O'Neil, EMFLUX, Inc., written commun., 1997).

Subsurface-gas samplers were installed at 18 sites south of State Highway 88 (fig. 5) and one site upgradient from the lake in Mosquito Creek at State Highway 87. Four subsurface-gas samplers were installed on land, one on Walnut Creek, and 14 in the bottom sediments of Mosquito Creek Lake. The installations in the lake consisted of seven shallow installations in water about 1.5 ft deep and seven deep installations in water with depth ranging from 8 to 12 ft. At each survey site, subsurface-gas samples were collected during a 72-hour period of maximum earth gravitational tides—the period of theoretical maximum soil-gas emissions—to increase the likelihood of detecting petroleum residues. The subsurface-gas samples were analyzed by Quadrel Service, Inc., for low-molecular-weight hydrocarbons associated with crude oil, including benzene, toluene, ethylbenzene, xylene (collectively known as BTEX compounds), trimethylbenzene, and naphthalene. The head space in a sample vial of one Mecca Oil sample also was analyzed for these compounds.

Collection of water samples

Water samples were collected to characterize surface- and ground-water quality as it relates to the occurrence or release of oil, natural gas, and (or) brine. The physical properties of water, including temperature, pH, specific conductance, and dissolved oxygen, were measured at the time of sample collection to provide background data to aid in interpreting other chemical data.

Samples were analyzed for dissolved bromide and chloride to chemically differentiate between the sources of salinity in surface water and ground water. Bromide-chloride concentration ratios (Br:Cl) are useful for identifying oil and gas brines for several reasons. First, oil and gas brines have some of the highest Br:Cl ratios of natural waters, with values typically greater than approximately 10^{-3}, whereas halite-solutions have ratios of less than 10^{-4} (Richter and Kreitler, 1993; Breen and others, 1984). Differences in this ratio between end members of mixtures with freshwater are generally large enough to allow identification or differentiation of the respective source(s). Second, although other anions and cations can be used to distinguish between different salinity sources, most of these ion ratios are subject to error because of ion-exchange processes, mineral precipitation, or oxidation-reduction reactions. Bromide and chloride generally are the two most conservative constituents in natural ground waters (Whittemore, 1995). Consequently, Br:Cl ratios are not susceptible to the same source of error as techniques based on other ion pairs.

Surface water. During the summer and fall of 1997, measurements of water quality and stream discharge were made during low-flow conditions at 44 surface-water stations on or near Mosquito Creek Lake (fig. 5). The network included one station on Mosquito Creek above the lake, stations near the lake south of State Highway 88, stations close to the lake but not in backwater, and stations on public lands or right-of-way for easy access. Stream-discharge measurements were made during water sampling using a pygmy current meter, volumetric measurement, or visual estimation.

During September 7-8, 1997, a synoptic water-quality reconnaissance was conducted at 42 stations on 23 tributaries of Mosquito Creek Lake, at 4 ponds south of State Route 88, at 2 stations on Mosquito Creek above Mosquito Creek Lake, and in Mosquito Creek Lake (fig. 5). This reconnaissance consisted of field measurements of water temperature, pH, specific conductance, and concentration of dissolved oxygen. Streamflow was visually estimated.

Ground water. During the summer and fall of 1997, water-quality measurements were made on water samples from 27 domestic- and public-supply wells near Mosquito Creek Lake (fig. 5). Criteria for the design of the network of domestic supply wells included collection of samples in primary aquifers south of State Highway 88 near the lake, and samples from wells in the southern third of the study area, where oil and natural gas drilling is most likely to occur. All wells were on private property except for city of Cortland supply wells. Field measurements for water temperature, pH, specific conductance, and concentrations of dissolved oxygen were made at most wells. Samples for analysis of dissolved methane, ethane, and propane were collected by submerging a sample vial in a cleaned basin filled with the well water and allowing water from the discharge tube to fill the vial without making contact with the atmosphere. The submerged and filled vial was then sealed, labeled, and shipped to the laboratory for analysis.

Only raw, untreated water was sampled from domestic wells. Prior to sampling a domestic well, the standing water in the well was evacuated and was monitored for temperature, pH, specific conductance, and dissolved oxygen to ensure that stagnant water from within the well casing was evacuated. Water samples were collected from a spigot on the water storage tank before the water flowed through any water softening and filtration system. During evacuation and sampling, one to three household spigots were opened. The decline in water pressure within the pressure tank caused the pump to operate continuously; thus, water flowing from the spigot was derived from the aquifer instead of the pressure tank. Cortland Public supply wells were sampled at a spigot near the wellhead inside of pump houses.

Samples of ground water from beneath the historic Mecca Oil Pool were collected at well 59 (fig. 5) by lowering a drill-rig bailer into the open borehole. A sample of water beneath the oil pool was collected at wells 49 and 53 by lowering a submersible pump into the borehole to a depth of about 12 ft below the oil.

Sampling oil- and gas-associated brine from the Clinton sandstone

Brine samples were collected from brine holding tanks at three Clinton gas-oil wells (fig. 5). The pH of each brine sample was measured in the field. Brine samples were sent to the USGS National Water Quality Laboratory in Arvada, Colo., for measurement of specific conductance and determination of dissolved bromide and chloride.

Sampling oil and natural gas for chemical and stable isotope analysis

Chemical and stable isotope composition of oil and natural gas provides information on origin, migration, accumulation, and degree of alteration. Individual compounds in the oil and gas samples were analyzed for stable isotopes of carbon and hydrogen. The relative concentration of naturally occurring stable isotopes of carbon (carbon-13) and hydrogen (deuterium) is an indicator of the source and thermal maturity of the individual components of gas and oils.

Six samples of oil were collected in the vicinity of Mosquito Creek Lake. Three Mecca oil samples were collected from wells in the Berea Sandstone aquifer (T-49, T-53, and T-59) by lowering a bailer into the well. Additional samples were obtained from three Clinton sandstone gas wells (permits 2194, 3561, and 3382). These oil samples were collected at the oil, gas, and brine separator near the wellhead.

Samples of natural gas were collected from three shallow wells penetrating aquifers. Gas was sampled from wells using a vacuum pump to remove the gas in each well bore and was collected in 1-liter, helium purged and evacuated Tedlar bags. Gas was sampled from well T-34 by collecting a ground-water sample in a 1-liter, helium purged and evacuated Tedlar bag. Water in this gas sample exhibited a significant amount of degassing as noted by the presence of bubbles. Samples of gas also were collected from Clinton sandstone wells (permits 2194, 3561, and 3382) in a solvent-cleaned, baked, and evacuated stainless steel cylinder. Sampling cylinders were attached to the wellhead, and gas in the well was allowed to flow into the cylinder.

Chemical analysis and data archival

Water-quality data used in the study are stored and archived in USGS data bases. Specific conductance, bromide, and chloride analyses on water and brine samples were performed by the USGS National Water Quality Laboratory in Arvada, Colo. Chemical analysis of soil-gas samples were performed by Quadrel Service, Inc., Clarksburg, Md. Dissolved methane, ethane, and propane samples were analyzed by the Pennsylvania Department of Environmental Protection Bureau of Laboratories, Harrisburg, Pa. Chemical and stable-isotope analysis of subsurface-gas samples was performed by ISOTECH Laboratories, Champaign, Ill.

Quality assurance

To ensure accurate measurement of pH, specific conductance, and dissolved oxygen of water at each field station, the meters were calibrated at the beginning and end of each field day. About 15 percent of the chloride, bromide, and dissolved methane, ethane, and propane water samples were quality-assurance samples in the form of field replicates and blanks. The relative percent difference (RPD) was calculated for constituents found in concentrations greater than the analytical minimum reporting level.

Trip blanks accompanied the subsurface-gas samplers during shipment, deployment, and collection. Trip blanks were not exposed to atmospheric conditions during shipment or sampling and were analyzed with the regular samples. Ambient-air control samples were collected at three sites to identify organic compounds present in the air during deployment and retrieval of passive gas samplers. Also, a chain-of-custody form accompanied the subsurface-gas samples and natural gas stable isotope samples during shipping and sampling.

Water Quality

Concentrations and other values for properties and constituents of water were determined by means of field measurements and laboratory analyses. Water-quality data are presented in tables 2, 3, and 4 in the back of this report. Descriptive statistical summaries of water-quality data are given in tables 5 and 6 in the back of this report.

pH

During July and September 1997, the pH of water at the dam at Mosquito Creek Lake (station 03905500) was 7.5 and 8.3, respectively (table 2). These values indicate slightly alkaline water and are similar to historical values presented in fig. 4. During the surface-water quality reconnaissance (September 7-8, 1997), the pH of water in tributaries flowing into Mosquito Creek Lake ranged from 7.1 to 10.1 with a median of 7.9. Tributaries containing septic drainage had a grayish color and had the highest pH in the study area.

The pH of water sampled from supply wells ranges from 6.8 to 8.1 (table 3). The median pH for water samples collected from the Berea Sandstone was 7.2 and for Cussewago Sandstone was 7.6 (table 5). Although the pH's of ground water in the Berea Sandstone and Cussewago Sandstone aquifers are similar, ground water tends to become increasingly alkaline with increasing depth. City of Cortland public-supply wells (fig. 5) are the deepest wells in the study area—water samples had the highest pH for the study area, ranging from 7.8 to 8.1. In contrast, the pH's of the three Clinton oil and gas brine samples were significantly lower, ranging from 3.7 to 4.5.

Dissolved oxygen

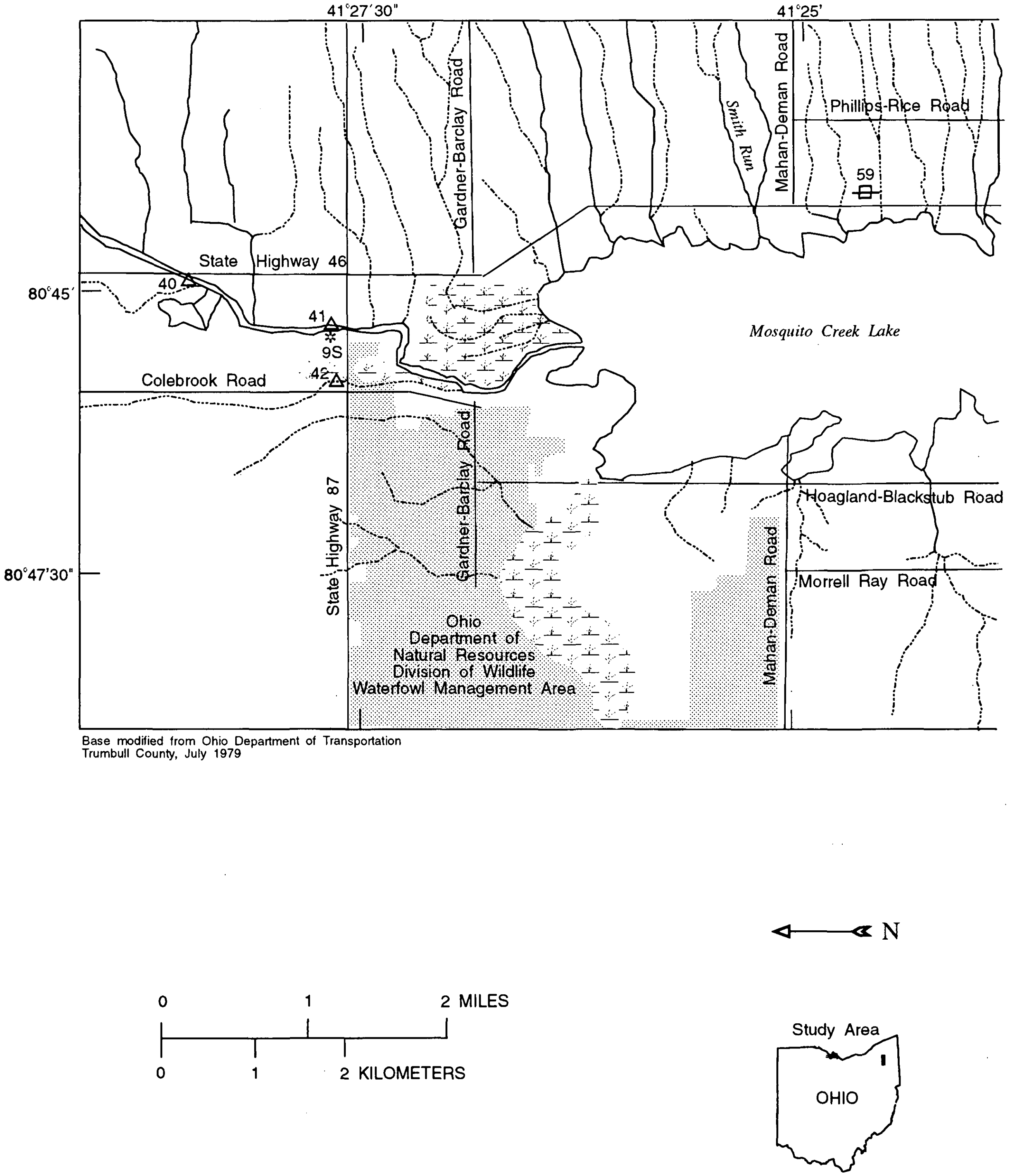
During July and September 1997, measurements of dissolved oxygen in water at the Mosquito Creek Lake dam (station 03905500) were 7.0 to 8.6 mg/L, respectively (table 2). These values are similar to historical values given in fig. 4. During the surface-water quality reconnaissance, the concentration of dissolved oxygen in water in tributaries flowing into Mosquito Creek Lake ranged from 0.1 to 15.5 mg/L with a median of 4.3 mg/L (table 5). Samples from unnamed tributaries at stations 9, 18, 19, 38, 39, and 42 had concentrations of dissolved oxygen less than 1.0 mg/L (table 2), and samples from nine other stations had concentrations ranging from 1.0 to 3.0 mg/L. Low concentrations of dissolved oxygen are an indicator of surface-water-quality degradation, which can be attributed to excessive microbiological activity resulting from water affected by septic discharge.

Concentrations of dissolved oxygen in water collected from domestic- and public-supply wells were less than 1.0 mg/L (table 3). Although oxygen is supplied to ground water through recharge, low concentrations of dissolved oxygen in ground water are common because microbial activity in the unsaturated zone rapidly depletes dissolved oxygen in infiltrating waters.

Specific conductance

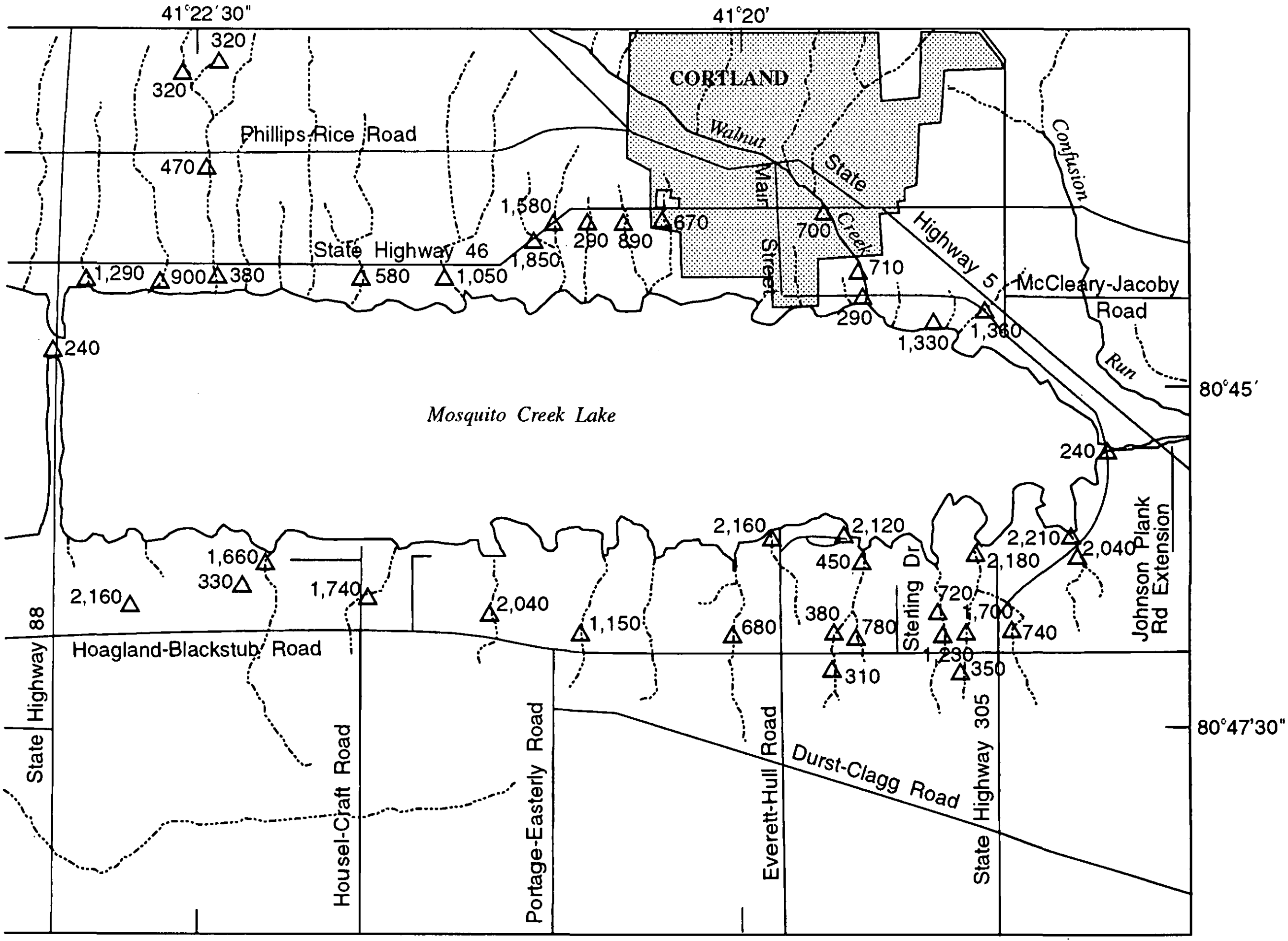
In July 1997, the specific conductance of water sampled below the dam at Mosquito Creek Lake (station 03905500) was 220 μS/cm, and water sampled from Mosquito Creek above the lake at station 40 was 400 μS/cm. These data are typical for the summer of 1997, when the surface water and the shallow ground water entering Mosquito Creek Lake had a higher specific conductance than that of water flowing out of the lake through the dam. Sources of water with a lower specific conductance entering the lake include precipitation falling directly on the lake, spring-melt runoff, and storm runoff.

During the surface-water quality reconnaissance, the specific conductance of water in tributaries flowing into Mosquito Creek Lake ranged from 240 to 2,210 μS/cm with a median of 670 μS/cm (fig. 6). Tributaries containing septic drainage had some of the highest specific conductance in the study area. Runoff



Base modified from Ohio Department of Transportation
Trumbull County, July 1979

Figure 6. Specific conductance of water samples collected from surface water.



EXPLANATION

▭ WETLANDS

△900 SPECIFIC CONDUCTANCE OF SURFACE WATER SITES--in microsiemens per centimeter at 25 degrees celsius. Water-quality and stream-flow measurement site location and identification number provided in fig. 5

from cattle feedlots and agricultural fields also may contribute to the high specific conductance of surface-water inflow to the lake.

Specific conductance measurements for ground water in glaciofluvial sediments were limited to two wells because very few wells are completed in glaciofluvial sediments within the study area. These wells (T-54 and T-58) are located west-southwest of the Mosquito Creek Lake dam (fig. 5). Specific conductance of water samples collected from wells T-54 and T-58 was 1,420 and 1,110 μS/cm, respectively; 1,420 μS/cm (well T-54) was the highest measurement for all ground-water wells sampled in the study area. An abandoned water well (ODNR log number 156401) was within 30 ft of well T-54; however, the USGS could not obtain permission to sample the well. The drillers' log reported 126 ft of unconsolidated glacial sediments and saline water in the Chagrin Shale at 227 ft below land surface.

Specific conductance of water samples collected from the Berea Sandstone ranged from 360 μS/cm at well T-59 to 1,170 μS/cm at well T-57. Specific conductance of water samples collected from Cussewago Sandstone wells ranged from 550 μS/cm at well T-48 to 1,050 μS/cm at well T-34 with a median of 820 μS/cm (table 5). Specific conductance is generally higher in deeper wells, in particular, wells in the southeastern part of the study area. The Cussewago Sandstone aquifer is deeper from the surface in the southeastern part of the study area and ground-water residence time is probably greater there than in shallow parts of the aquifer. As one would expect, the specific conductance of brine samples collected at three oil and gas wells in the Clinton sandstone were several orders of magnitude greater than other fresh ground-water samples and ranged from 186,000 to 200,000 μS/cm (table 5).

Bromide and chloride

Dissolved bromide and chloride were analyzed in 32 samples of ground water, surface water, and brine to determine possible mixing and sources of these elements in the Mosquito Creek Lake area. Results of the analyses are listed in tables 2 and 3.

Twenty-three ground-water samples from five different aquifers were analyzed as part of this study. Overall, bromide and chloride concentrations increase with depth: concentrations in the shallow glacial aquifers, the Cuyahoga Group, and the Berea Sandstone are generally less than those in the Cussewago Sandstone. Median bromide concentration in the shallow aquifers is 0.064 mg/L, whereas median concentration in the Cussewago Sandstone is 0.21 mg/L. Similarly, median chloride concentration for the shallow aquifers is 14 mg/L, whereas median concentrations for the Cussewago Sandstone is 36 mg/L. The range of bromide concentrations was relatively small in the upper aquifers: <0.01 mg/L from the Berea Sandstone (well T-49) to 0.66 mg/L in the Cussewago Sandstone (well T-34). The range of chloride concentrations, however, indicates that the maximum chloride concentration was found in a Berea Sandstone and Cussewago Sandstone well (148 mg/L in well T-55) and the minimum concentration was in a Cussewago Sandstone well (1.3 mg/L in well T-16), which was contrary to the overall trend in median concentrations with depth.

Water-quality samples were collected at nine surface-water sites from July through November 1997. Station 03095500, at the outfall of the Mosquito Creek Lake dam, had the lowest bromide concentration of all sampling sites (less than the detection limit of 0.01 mg/L); however, the chloride concentration in the same sample was 23 mg/L. Six surface-water sites on tributaries flowing into Mosquito Creek Lake had bromide concentrations that ranged from 0.024 to 0.15 mg/L, with a median of 0.071 mg/L (results for two bromide analyses are not reported because of analytical interference). Chloride concentrations from the surface-water sites ranged from 27 to 430 mg/L and had a median of 189 mg/L (tables 2 and 5).

Three brine samples from the Clinton sandstone had significantly higher bromide and chloride concentrations than those in shallow ground water. Bromide concentration ranged from 1,710 to 2,460 mg/L, whereas chloride ranged from 137,000 to 178,000 mg/L.

Quality-assurance samples

All water-quality and subsurface-gas samples met U.S. Environmental Protection Agency recommended holding-time criteria (U.S. Environmental Protection Agency, 1986). The RPD between concentrations of dissolved chloride in regular ground-water, surface-water, and Clinton brine samples and replicate samples (table 7) ranged from 0.0 to 4.3 percent, and the median RPD was 1.3 percent. The RPD between the concentrations of dissolved bromide in the regular and replicate ground-water, surface-water, and brine samples (table 7) ranged from 2.3 to 34 percent. The RPD between concentrations of dissolved methane in regular ground-water samples and replicates samples (table 7) ranged from 0.0 to 40.1 percent.

The variability in chloride concentrations was within expected reporting levels supplied by the laboratory. Bromide concentrations varied significantly, presumably due to interference from other dissolved constituents (bromide results for two other regular sample analyses were inconclusive because of interference reported by the laboratory). Variability in replicate dissolved methane concentrations is reasonable because significant degassing may have occurred in sampling lines and in the sample bottle. Additionally, methane not in solution could be lost during sample analysis. All concentrations of dissolved ethane and propane in regular water samples and in the replicate samples were less than the reporting level (table 3).

Trip blanks for subsurface gas survey samples did not contain measurable concentrations of BTEX compounds (table 8). Ambient air control sample B detected contamination during the deployment or retrieval of the passive gas sampler at station 4S (fig. 5). Ambient air control sample B had 228 ng/L of 1,2,4 trimethylbenzene and 110 ng/L of 1,3,5 trimethylbenzene (table 8). These concentrations are more than 3 orders of magnitude greater than concentrations detected in the passive-gas sample at station 4S. No corrective action was taken because contamination of this sample was likely from the gas tank on board the sampling vehicle, and no other trip blank showed concentrations of BTEX compounds above the detection limit.

Chemical Characteristics of Crude Oil, Natural Gas, and Brine and their relation to ground-water and surface-water quality

The chemical characteristics of crude oil in the historic Mecca Oil Pool and Clinton sandstone and natural gas in the historic Mecca Oil Pool, Devonian shales, and Clinton sandstone are described below. Results of the subsurface-gas survey, which was designed to determine whether crude oil residues lie within the shallow sediments beneath and adjacent to Mosquito Creek Lake, also are discussed.

Crude oil residue in shallow sediments beneath and adjacent to Mosquito Creek Lake

Concentrations of BTEX compounds were used as indicators of crude oil contamination and were measured in soils near Mosquito Creek Lake (including the survey sites over the historic Mecca Oil Pool), in the water column of the lake, and in bottom sediments of the lake (table 4).

The maximum concentrations for BTEX compounds are summarized in table 6. These concentrations are several orders of magnitude less than the U.S. Environmental Protection Agency enforceable maximum contaminant level (MCL; U.S. Environmental Protection Agency, 1998). About 50 percent of the BTEX analytical data presented in table 4 have concentrations less than the "ultra low" reporting levels of less than 1 ng/L. Concentrations of benzene, toluene, xylene, 1,2,4 trimethylbenzene, and 1,3,5 trimethylbenzene in the historic Mecca oil sample are 2 to 3 orders of magnitude higher than the maximum concentrations detected in soils and lake-bottom sediments; however, these concentrations are also less than the MCL.

During field work, only one intermittent Mecca oil seep was identified. This seep is about 1,000 ft east of well T-53 (fig. 5) and is not near a tributary to the lake. Brine is not associated with the historic Mecca Oil Pool; however, low concentrations of BTEX compounds could be leached from Mecca oil into the adjacent ground water and could discharge to the lake. Whether this is occurring is not known because water in Berea Sandstone wells was not sampled or analyzed for BTEX compounds, and lake sediments indicate only trace amounts of BTEX compounds.

Mecca oil is commonly observed in domestic supply wells open to the Berea Sandstone; however, none of the three oil samples collected from the Berea Sandstone showed evidence of Clinton oil seeping into shallow ground-water resources. As previously mentioned, the Clinton sandstone is underpressured, and pressure is insufficient to force Clinton oil to land surface in the event a well or borehole develops a breach. Because the subsurface-gas survey did not detect significant concentrations of BTEX compounds, these data do not provide any evidence of Clinton oil released into the lake near any subsurface-gas survey site. This conclusion is based on the fact that Clinton oils contain abundant low-molecular-weight compounds, including BTEX compounds, and release of Clinton oils into the lake would likely result in measurable concentrations of BTEX compounds in the shallow sediments.

Crude oil in the historic Mecca Oil Pool and Clinton sandstone

The chemical and stable-isotope characteristics of the historic Mecca oil and the Clinton oil near Mosquito Creek Lake are distinctly different from each other (table 9). All Mecca oil samples were extensively altered by biodegradation, whereas Clinton oils have not undergone extensive biodegradation. Extensive alteration of the historic Mecca oils is consistent with their occurrence at very shallow depths (less than 100 ft below land surface) where microbial activity can affect their composition. In contrast, the Clinton oils occur in deeper reservoirs where microorganisms are not present in great numbers, and no evidence for alteration has been observed. These findings are in agreement with previous characterizations of oils in eastern Ohio (Cole and others, 1987; Drozd and Cole, 1994).

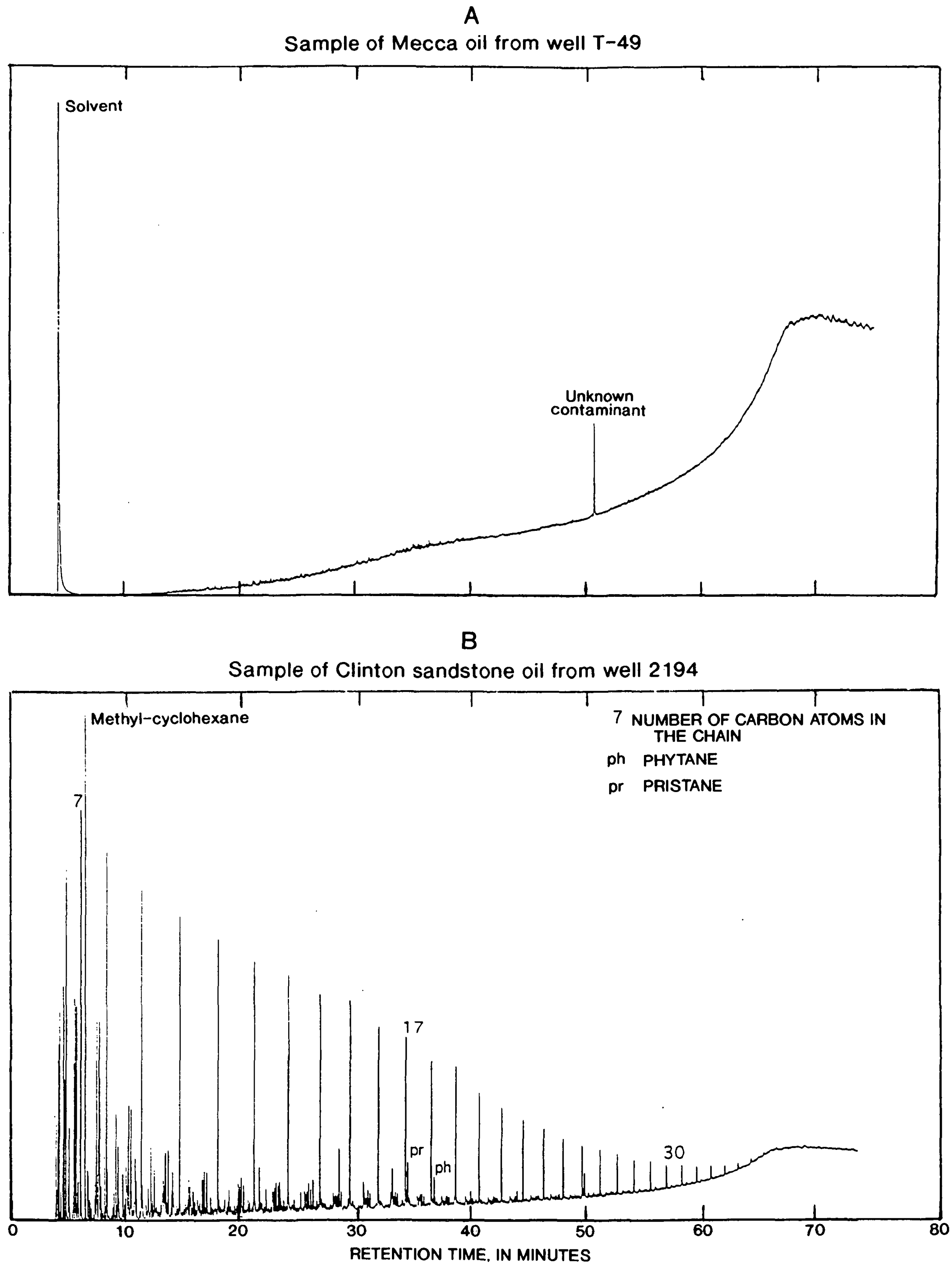
Gas chromatograms for the Mecca oil sample collected from well T-49 and the Clinton sandstone oil sample collected from well 2194 are shown in figure 7. The historic Mecca oil sample has a smooth chromatographic trace (fig. 7a) that is distinct from the regularly spaced peaks in the Clinton oil chromatogram (fig. 7b). Prominent sharp peaks on the chromatogram for the Clinton oil sample represent alkane hydrocarbons. Although the concentration of low-molecular-weight BTEX compounds were not determined for Clinton oils, the numerous peaks on the chromatogram near a retention time of 10.0 indicate that these compounds are present in measurable concentrations. Other Mecca oil samples collected from wells T-53 and T-59 and Clinton oil samples collected from wells 3382 and 3561 have chromatograms almost identical to examples shown in figure 7. Biodegradation has removed most or all alkanes and branched alkanes in the three samples of Mecca oil. This interpretation is consistent with the low weight percent of saturated hydrocarbons reported in the Mecca oils in comparison to the Clinton oils. The degree of biodegradation is so extensive that compounds commonly used to characterize crude oils, such as the isoprenoid hydrocarbons pristane and phytane, are missing. Also, low-molecular-weight BTEX hydrocarbons are missing from chromatograms of the Mecca oil samples. However, the subsurface-gas survey analysis of a Mecca oil sample from well T-53 detected low concentrations of BTEX compounds in the head space.

Natural gas in the historic Mecca Oil Pool, Devonian Shale, and Clinton sandstone

Samples of gas produced from three wells completed in the Berea and Cussewago Sandstone aquifers have a range of chemical and isotopic compositions that are distinctly different from samples of gas produced from the Clinton sandstone wells. Berea and Cussewago Sandstone samples are heterogeneous, whereas Clinton sandstone samples have a homogeneous chemical and isotopic composition (table 10).

The carbon isotope composition of methane from samples collected from the Berea Sandstone exploratory borehole T-53 and the Cortland public-supply well T-34 completed in the Cussewago Sandstone is less than -70 per mil, and the hydrogen isotopic composition is less than -240 per mil. These isotopic values indicate that the methane was microbially generated. Both of the gas samples contain more than 50 percent nitrogen and no other hydrocarbon gases (other than a trace of ethane in the sample collected from well T-34). The sample from well T-55, completed in the Berea and Cussewago Sandstone aquifers, is rich in methane and other hydrocarbons, low in nitrogen, and rich in carbon dioxide (this sample contains the highest amount of carbon dioxide of all the gas samples). The carbon isotopic composition of methane in this sample is about -49 per mil, a value traditionally interpreted as indicating thermogenic origin (Jenden and others, 1993). Recent work on gases produced from Devonian shales at shallow depths in the Michigan basin, however, demonstrate that this value, in a sample with carbon dioxide enriched in ^{13}C, is consistent with microbial generation of methane (Martini and others, 1996). Despite the range of isotopic and molecular compositions of these gases produced from Berea Sandstone and Cussewago Sandstone water wells, an integrated interpretation of all the geochemical variables demonstrates that they are generated by microbial processes. The microbial processes are the same as those that take place in modern and ancient marine and lake sediments (Whiticar and others, 1986), landfills (Coleman and others, 1995), and fractured, organic-rich shales (Martini and others, 1996).

The molecular and isotopic composition of gases from wells producing from the Clinton sandstone are virtually identical (table 10). Clinton gas contains roughly 90 percent methane, 5 percent ethane, and 1.5 percent propane by volume. These measurements identify them as gases generated by the



A
Sample of Mecca oil from well T-49

B
Sample of Clinton sandstone oil from well 2194

Figure 7. Chromatograms of representative samples of crude oil from (A) the Mecca oil pool and (B) the Clinton sanstone, Trumbull County, Ohio.

thermal breakdown of organic matter in deeply buried sediments (Jenden and others, 1993). The compositions are also very similar to gases from wells in the same sedimentary horizon in New York and Pennsylvania, (Jenden and others, 1993; Laughrey and Baldassare, 1998). The dissolved gas in the shallow ground-water system is composed of methane but contains no measurable amounts of ethane or propane (table 3). The Mecca "type" oil and accompanying microbial activity are the probable source of this naturally occurring methane. Early thermogenic gas generated from the Chagrin, Bedford, and Sunbury Shales could be a secondary source of methane. Gas from the shallow wells is of biogenic origin and is not representative of Clinton gas. The absence of dissolved ethane and propane in any ground-water sample indicates that the gas source is other than "Clinton."

Concentrations of dissolved methane in water samples from several water-supply wells were greater than the analytical reporting level of 0.0313 mg/L in 24 of 25 wells sampled in the study area (table 3), whereas concentrations of dissolved ethane and propane in all ground-water samples were less than this reporting level. The concentration of dissolved methane in the Berea Sandstone wells was low; the median concentration was 1.74 mg/L and the maximum concentration was 2.37 mg/L in well T-51 (table 3). Concentrations of dissolved methane were, in general, much higher in the Cussewago Sandstone: the 'adjusted' median concentration was 4.96 mg/L and the maximum concentration was 28.7 mg/L in well T-56 (table 5). (In this context, the 'adjusted' median methane concentration for Cussewago wells is defined as a single, averaged concentration of dissolved methane for all samples collected from the city of Cortland well field). Areas of greatest gas accumulation in the aquifer system occur near the southwestern terminus of Mosquito Creek Lake and beneath the city of Cortland (fig. 8). Well T-55, located on a farm near the southwest terminus of the lake, was used during the 1950's and 60's as a supply of gas and potable water for domestic purposes. Usage of gas for domestic purposes predated the drilling of Clinton sandstone gas wells on the farm.

The U.S. Environmental Protection Agency and the Ohio Environmental Protection Agency do not have a drinking water standard for dissolved methane, ethane, or propane. Methane, however, is flammable at concentrations greater than 15 percent in air, and is considered an explosive and lethal hazard. The concentration of methane in water-supply well T-55 is greater than 15 percent methane in air and was ignited at a gas spigot by USGS scientists during sampling.

Oil- and gas-associated brine

The results of this study indicate that the Berea and Cussewago Sandstone aquifers in the Mosquito Creek Lake area do not appear to contain saline water: the historic Mecca Oil Pool in the Berea Sandstone is underlain by fresh potable water and the Cussewago Sandstone contains fresh potable water. These findings are noticeably different than those of Haiker (1996) who reported that many Cussewago wells near Mosquito Creek Lake encounter brackish or salt water and oil and gas residue and that ground water may not be potable.

On the basis of analyses of water samples collected in the study area, the surface water and ground water is alkaline compared to the Clinton brine. Because the Clinton brine is a concentrated solution, any significant surficial or subsurface release of brine should lower the pH of the water and raise dissolved solids concentrations for some duration. The specific conductance and chloride concentration of Clinton brine are approximately 3 orders of magnitude greater than those of ground water in the shallow glaciofluvial and bedrock aquifers and surface water in the study area. The large contrast in water quality between the surface- and ground-water samples and the brine samples is not indicative of leaking or spills of Clinton brine.

A Br:Cl mixing diagram (fig. 9) was constructed to distinguish between different sources of salinity, including gas- and oil-associated brine and halite-solution road salt in surface and ground waters. The mixing diagram is based, in part, on curves prepared by Eberts and others (1990, fig. 25) using methods described by Whittemore (1984, 1988, and 1995). Bromide to chloride weight ratios were calculated for surface-water and ground-water samples and were plotted with measured chloride concentrations. The end-members of mixing plotted on the diagram include (A′) fresh (meteoric) water, (B′) gas- and oil-associated brine, and (C′) halite-solution water. The mixing diagram shows hypothetical boundaries of various mixtures of uncontaminated water, gas- and oil-associated brine, and halite-solution water. The curves delineate four mixing zones: zone 1, which represents the local fresh water; zone 2, which represents a mixture of local waters and oil- and gas-associated brine; zone 3, which represents a mixture of local waters with halite solution; and zone 4, which represents a mixture of local waters and local oil- and gas-associated brine and halite solution or other fluids. Comparison of figure 9 and the figure presented in Eberts and others (1990) reveals that the Clinton sandstone oil- and gas-associated brine end member plots nearly identical in both figures.

The Br:Cl mixing curves for the study area show that Br:Cl weight ratios decrease with increasing chloride concentrations. This trend may be caused by dissolution of halite, which is chloride rich and bromide poor. Most of the water samples plot within the local freshwater zone 1. Surface-water sampling station 03095500, located at the lake impoundment, plots in zone 1. The city of Cortland public supply well number 5 (T-38) is completed in the Cussewago Sandstone and is the only water sample to plot in zone 2. The bromide and chloride data for T-38 may indicate mixing of local fresh waters with Clinton sandstone oil-and gas-associated brine. However, this point also plots close to zone 1, so it is not possible to develop a definitive interpretation about the mixing relations based on these data alone. The water in well T-34, the Cortland number 1 public-supply well (also completed in the Cussewago Sandstone), is the only well to plot within zone 4. The source of salinity in well T-34 is not known.

Seven surface-water sites, the Berea Sandstone well T-57, and the Cussewago Sandstone wells T-30 and T-41 plot within zone 3 and indicate a mixture of local ground water and halite-solution brine. The surface-water samples were collected during the summer and early fall, when most road salt probably had already moved through these tributaries and into Mosquito Creek Lake. During collection of surface-water samples, septic drainage was observed upgradient from the sampling sites. The source of salinity to the wells (T-30, T-41, and T-57) is not known, but may represent mixing of fresh water with halite solutions derived from road salt and (or) septic effluent.

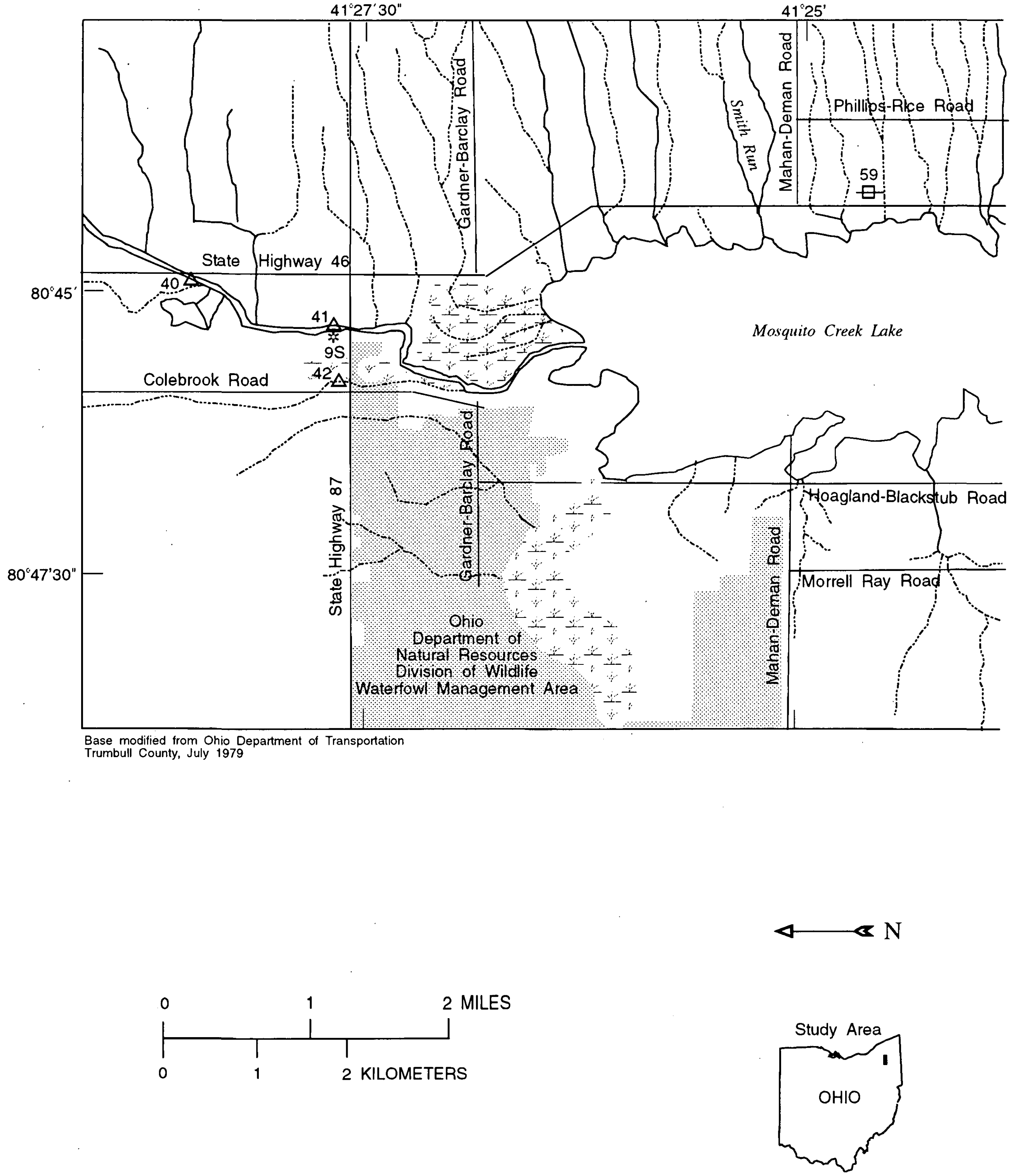
Susceptibility of Aquifers to Surface Spills

Hydrocarbons, including oil and gas, occur naturally in the shallow aquifer system in the Mosquito Creek Lake area. Detectable amounts of Mecca "type" oil, however, were not found in the lake. Brine has not been shown to be associated with the shallow aquifer system, the lake, or its tributaries. Additionally, there were no detectable releases of Clinton oil, gas, or brine to the freshwater aquifer or surface water. The release of oil, gas, or brine from an oil or gas well could, however, go undetected if a leaky well or surface spill was not located near the water-quality sampling network or if the release was very small. Nevertheless, there is no evidence of any widespread release of Clinton sandstone oil, gas, or brine to the water resources of the area. The only indication of shallow saline water is indirect evidence from a driller's well log (ODNR permit 156401) for an abandoned well adjacent to well T-54. This driller's log reports saltwater in the uppermost beds of the Chagrin Shale. The source of saltwater could not be determined because the USGS could not obtain permission to collect a water sample from this well.

In the event of a brine spill at an oil and gas well or brine injection well, brine and water-soluble components of oil (such as BTEX compounds) could infiltrate from land surface into a shallow, unconfined aquifer. Areas where shallow aquifers are the least susceptible and most susceptible to contamination from a surface spill can be identified by (1) soils data, (2) lithologic descriptions in well-driller logs, (3) lithologic descriptions from sediment augering at or near subsurface-gas sampling sites, and (4) hydrogeologic data.

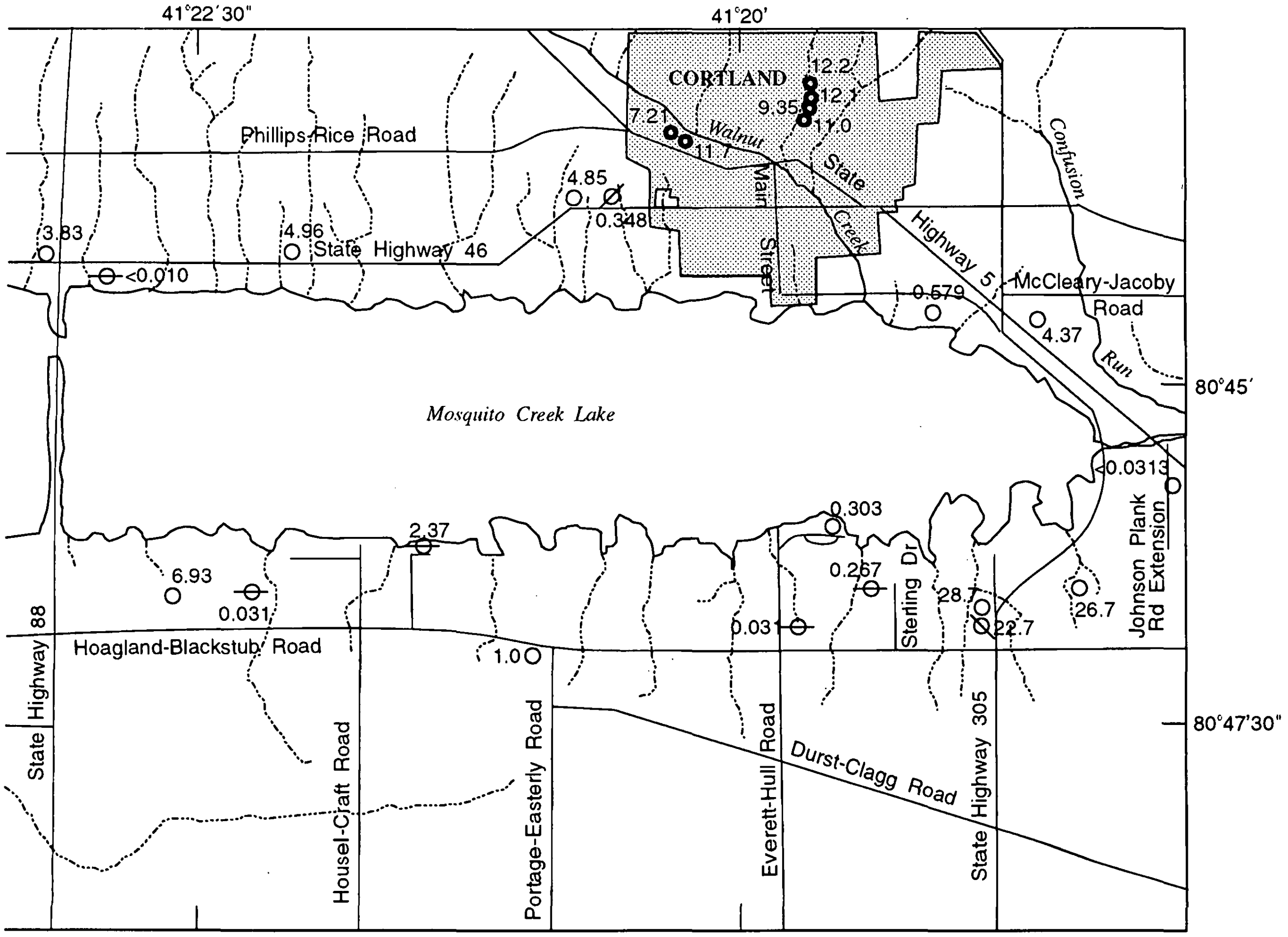
The location of poorly-drained and well-drained soils is an important criterion in addressing the susceptibility of the bedrock aquifers to surface spills. USGS sediment augering near subsurface-gas survey sites in and along the shore of Mosquito Creek Lake shows a dense clay within 2 ft of land surface or the lake bottom. In the general vicinity of the confluence of Walnut Run and Mosquito Creek Lake, however, the soil and glacial sediments that mantle the Berea and Cussewago Sandstones are only a few feet thick and, in places, the bedrock is jointed, fractured, and exposed at the surface. Here, the bedrock aquifers may be very susceptible to contamination from surface spills.

The Berea Sandstone is generally closer to land surface than the Cussewago, and thus is more susceptible to contamination from surface spills. Clay and clay-rich till extends from the soil horizon to depths of 8 ft at well T-30 to 56 ft at T-19 (Hull, 1984; Barton and Wright, 1997). The thickness of this shallow clay layer is another important criterion in addressing susceptibility at specific locations. Throughout most of the study area, shale overlies and confines the Cussewago Sandstone aquifer. The degree to which aquifer confinement reduces susceptibility is best illustrated by the absence of detectable concentrations of tritium



Base modified from Ohio Department of Transportation
Trumbull County, July 1979

Figure 8. Concentration of dissolved methane in water collected from domestic and public-supply wells.

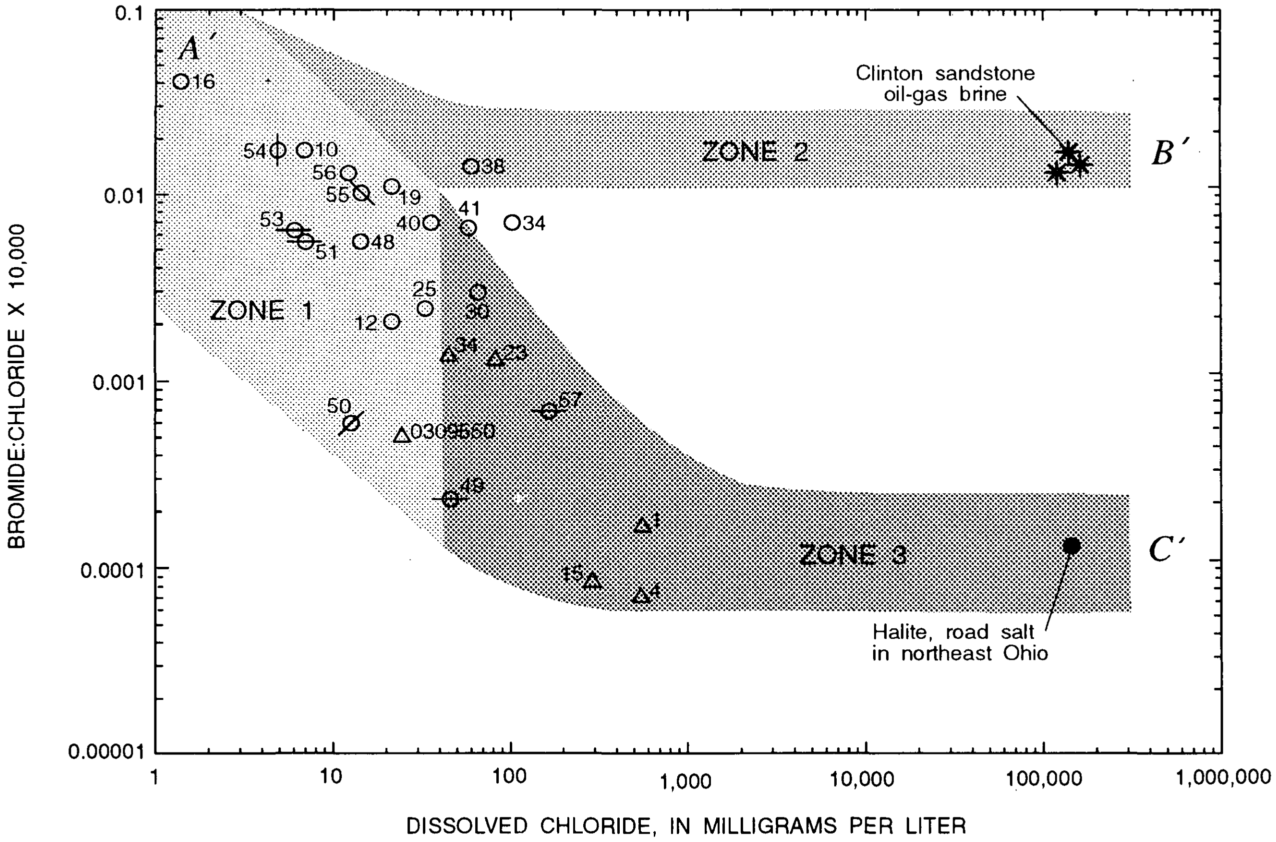


EXPLANATION

▨ WETLANDS

○ 4.85 CONCENTRATION OF DISSOLVED METHANE IN WATER SAMPLED FROM WELLS--in milligrams per liter. Well location and identification number provided in fig. 5. Concentrations of dissolved ethane and propane below the reporting level of 0.0313 milligrams per liter. Wells are completed in Cussewago Sandstone unless indicated otherwise

- ϕ Well is completed in Pleistocene sand and gravel
- Ø Well is completed in Cuyahoga Group
- ⊘ Well is completed in the Berea Sandstone and Cussewago Sandstone
- ⊖ Well is completed in the Berea Sandstone
- ● Public-water supply well



EXPLANATION

ZONE 1	LOCAL WATER
ZONE 2	MIXTURE OF LOCAL WATERS WITH LOCAL CLINTON OIL-GAS BRINE
ZONE 3	MIXTURE OF LOCAL WATERS WITH LOCAL HALITE SOLUTIONS
ZONE 4	MIXTURE OF LOCAL WATERS WITH LOCAL OIL-GAS BRINE AND LOCAL HALITE SOLUTIONS OR OTHER FLUIDS
△48	SURFACE-WATER SAMPLE AND IDENTIFICATION NUMBER
○12	GROUND-WATER SAMPLE AND IDENTIFICATION NUMBER--county prefix omitted. Wells are completed in the Cussewago Sandstone unless indicated otherwise.
ϕ	Well is completed in Pleistocene sand and gravel
∅	Well is completed in Cuyahoga Group
⦸	Well is completed in the Berea Sandstone and Cussewago Sandstone
-θ-	Well is completed in the Berea Sandstone
✳	Well is completed in Clinton sandstone
A′	POINTS DISCUSSED IN TEXT

Figure 9. Relation between dissolved bromide and dissolved chloride concentration ratios and dissolved chloride concentrations for all water samples and Clinton sandstone brine samples.

in water samples from Cussewago Sandstone wells in the city of Cortland (Barton and Wright, 1997). This confinement helps protect the water in the aquifer from contamination associated with a surface spill. West of the lake, in areas where the Cussewago Sandstone crops out (fig. 2 and 3), the aquifer is near land surface and is likely to be unconfined and to function as a water-table aquifer; here, the aquifer may be more susceptible to contamination from surface spills.

Summary and Conclusions

Several types of environmental measurements were made in the Mosquito Creek Lake area to characterize current surface- and ground-water quality as it relates to locally occurring oil and natural gas and to the drilling and production of hydrocarbons and brine in the Clinton sandstone. Samples of oil and natural gas were collected from shallow water wells, and oil, gas, and brine were collected from Clinton oil and gas wells. Chemical and isotopic analyses of these samples provided data to help characterize the hydrocarbons and brine.

The surface water and ground water in the study area is dilute and alkaline compared to the concentrated and acidic Clinton brine. The chemical and stable-isotope characteristics of oil in the historic Mecca Oil Pool within the Berea and Cussewago Sandstones and the Clinton oil near Mosquito Creek Lake are distinctly different. The shallow Mecca oil is extensively altered by biodegradation, whereas Clinton oils have not undergone biodegradation. Samples of gas produced from wells completed in the Berea and Cussewago Sandstone aquifers have heterogeneous chemical and isotopic compositions, in contrast to samples of gas produced from the Clinton sandstone wells, which are chemically and isotopically homogeneous. The carbon isotopic composition of methane from Berea and Cussewago Sandstone samples indicates that these gases are microbially generated, whereas Clinton gases are thermogenically generated.

Petroleum, as crude oil and methane-rich gas, occurs naturally in the shallow Berea and Cussewago Sandstone aquifers in the Mosquito Creek Lake area. Concentrations of methane were frequently detected in samples from water-supply wells, and concentrations are significant in the city of Cortland public supply wells and domestic wells along the southern shore of the lake. The historic Mecca Oil Pool, adjoining small oil and gas accumulations, and accompanying microbial activity are the probable sources of this naturally occurring methane. Also, microbial and (or) early thermogenic gas generated from the Chagrin, Bedford, and Sunbury Shales (Devonian and Mississippian in age) could be a secondary source of the naturally occurring methane.

A reexamination of the geologic framework, combined with results from a subsurface gas survey, show that crude oil in the Mecca Oil Pool does not likely seep into Mosquito Creek Lake at detectable concentrations. Brine is not associated with the hydrocarbons in the shallow aquifer system, unlike the much deeper hydrocarbons in the Clinton sands. A mixing diagram constructed for samples collected from water-supply wells and surface-water sites show no demonstrable mixing of these water resources with Clinton brine. The only notable source of salinity in the surface waters may be bromide-poor road-salt solution or septic drainage. There is no evidence of any release of oil, gas, or brine from deep Clinton sandstone wells to the shallow aquifers, to the lake, or to lake tributaries.

Areas where aquifers are most and least vulnerable to contamination from a surface spill at oil and natural gas drilling and production sites are delineated on the basis of soil drainage characteristics, sediment augering data, and type and proximity of the aquifer to land surface. On the basis of these criteria, the Berea Sandstone aquifer, which is generally closer to land surface than the Cussewago Sandstone aquifer, is more susceptible to contamination from surface spills. The vicinity of the confluence of Walnut Run and Mosquito Creek Lake, and a narrow belt west of the lake that extends about one mile south of State Highway 88, where the Cussewago Sandstone crops out, appear to be vulnerable to surface spills.

References

Barton, G.J., and Wright, P.R., 1997, Ground-water resources in the vicinity of Cortland, Trumbull County, Ohio: U.S. Geological Survey Water-Resources Investigations Report 97–4130, 20 p.

Boswell, R., 1996, Play Uds—Upper Devonian black shales, *in* Roen, J.B., and Walker, B.J., eds., The atlas of major Appalachian gas plays: West Virginia Geological and Economic Survey Publication V–25, p. 93–99.

Bownocker, J.A., 1903, The occurrence and exploitation of petroleum and natural gas in Ohio: Geological Survey of Ohio Fourth Series, Bulletin No. 1, 325 p.

Breen, K.J., Angelo, C.G., and Sedam, A.C., 1984, Chemical and isotopic characteristics of brines from three oil- and gas-producing sandstones in eastern Ohio, with applications to the geochemical tracing of brine sources: U.S. Geological Survey Water-Resources Investigations Report 84–4314, 58 p.

Charpentier, R.R., deWitt, W., Jr., Claypool, G.E., Harris, L.D., Mast, R.F., Megeath, J.D., Roen, J.B., and Schmoker, J.W., 1993, Estimates of unconventional natural gas resources of the Devonian shales of the Appalachian basin, *in* Roen, J.B., and Kepferle, R.C., eds., Petroleum geology of the Devonian and Mississippian black shale of eastern North America: U.S. Geological Survey Bulletin 1909, p. N1–N20.

Coffey, G.N., Woodward, John, and Snyder, J.M., 1916, Soil survey of Trumbull County, Ohio: U.S. Department of Agriculture, 53 p.

Cole, G.A., Drozd, R.J., Sedivy, R.A., and Halpern, H.I., 1987, Organic geochemistry and oil-source correlations, Paleozoic of Ohio: American Association of Petroleum Geologists Bulletin, v. 71, no. 7, p. 788–809.

Coleman, D.D., Liu, C.L., Hackley, K.C., and Pelphrey, S.R., 1995, Isotopic identification of landfill methane: Environmental Geosciences, v. 2, p. 95–103.

DeBrosse, T.A., and Vohwinkel, J.A., 1974, Oil and gas fields of Ohio: Ohio Division of Geological Survey, Map 3, scale 1:500,000.

deWitt, W., Jr., 1951, Stratigraphy of the Berea Sandstone and associated rocks in northeastern Ohio and northwestern Pennsylvania: Geological Society of America Bulletin, v. 62, p. 1347–1370.

Drozd, R.J., and Cole, G.A., 1994, Point Pleasant-Brassfield(!) petroleum system, Appalachian Basin, U.S.A., *in* Magoon, L.B., and Dow, W.G., eds., The petroleum system—From source to trap: Tulsa, Okla., American Association of Petroleum Geologists, p. 387–398.

Eberts, S.M., Bair, E.S., and de Roche, J.T., 1990, Geohydrology, ground-water quality, and simulated ground-water flow, Geauga County, Ohio: U.S. Geological Survey Water-Resources Investigations Report 90–4026, 117 p.

Gearheart, L.C., and Grapes, C.R., 1977, Gas and oil shows in the Ohio Shale in eastern Ohio: Ohio Division of Geological Survey Open-File Map 101, 2 sheets.

Haiker, K.S., 1996, Ground-water resources of Trumbull County: Ohio Department of Natural Resources Division of Water, 1 plate, scale 1:62,500.

Hull, D.N., 1984, Sand and gravel resources of Trumbull County, Ohio: Ohio Department of Natural Resources Division of Geological Survey, 1 plate, scale 1:62,500.

Jagucki, M.L., and Lesney, L.L., 1995, Ground-water levels and directions of flow in Geauga County, Ohio, September 1994, and changes in ground-water levels, 1986-94: U.S. Geological Survey Water-Resources Investigations Report 95–4194, 26 p.

Janssens, Adriaan, 1975, Wells producing from the Ohio Shale in eastern Ohio: Ohio Division of Geological Survey Open-File Map 77, 1 sheet.

Jenden, P.D., Drozan, D.J., and Kaplin, I.R., 1993, Mixing of thermogenic natural gases in northern Appalachian basin: American Association of Petroleum Geologists Bulletin, v. 77, p. 980–998.

Kachur, Thomas, 1972, Mecca: Cortland, Ohio, 130 p.

Keighin, C.W., and Hettinger, R.D., 1997, Depositional dip-oriented cross-section through the Lower Silurian Clinton sandstone and Medina Group in northeastern Ohio and western Pennsylvania (abs.): American Association of Petroleum Geologists Bulletin, v. 81, no. 9, p. 1555.

Larsen, G.E., 1996a, Reconnaissance bedrock geology of the Champion, Ohio quadrangle: Ohio Division of Geological Survey Open-File Map BG–D1C7, 1 sheet, scale 1:24,000.

——— 1996b, Reconnaissance bedrock geology of the Bristolville, Ohio quadrangle: Ohio Division of Geological Survey Open-File Map BG–D1D7, 1 sheet, scale 1:24,000.

——— 1996c, Reconnaissance bedrock geology of the Gustavus, Ohio quadrangle: Ohio Division of Geological Survey Open-File Map BG–D1D6, 1 sheet, scale 1:24,000.

Laughrey, C.D., and Baldassare, F.J., 1998, Geochemistry and origin of some natural gases in the Plateau province of the central Appalachian basin, Pennsylvania and Ohio: American Association of Petroleum Geologists Bulletin, v. 82., p. 317–335.

Martini, A.M., Budai, J.M., Walter, L.M., and Schoell, M., 1996, Microbial generation of economic accumulations of methane within a shallow organic-rich shale: Nature, v. 383, p. 155–158.

McCormac, M.P., Mychkovsky, G.O., Opritza, S.T., Riley, R.A., Wolfe, M.E., Larsen, G.E., and Baranoski, M.T., 1996, Play Scm—Lower Silurian Cataract/Medina Group (Clinton) sandstone play, *in* Roen, J.B., and

Walker, B.J., eds., The atlas of major Appalachian gas plays: West Virginia Geological and Economic Survey Publication V-25, p. 156–163.

Mychkovsky, G.O., 1998, Mosquito Creek Reservoir hydrogeology: *in* Mosquito Creek Lake Draft Planning Analysis/Environmental Assessment, U.S. Department of Interior, Bureau of Land Management, Appendix C1-27.

Ohio Department of Natural Resources, Division of Oil and Gas, 1996, 1995 Division of Oil and Gas annual report: 56 p.

——— 1997, "What's available on line to view?" Available at URL http://www.dnr.oh.us/odnr/oil+gas/view.html.

Orton, Edward, 1888, The Berea grit as a source of oil and gas in Ohio, chapter 4, *in* Report of the Geological Survey of Ohio, v. 6, Economic Geology: Columbus, Ohio, p. 311–409.

Owenby, J.R., and Ezell, D.F., 1992, Monthly station normals of temperature, precipitation, and heating and cooling degree days, 1961–1990, Ohio: Ashville, N.C., National Oceanic and Atmospheric Administration Climatography of the United States no. 81, [variously paginated].

Pashin, J.C., and Ettensohn, F.R., 1995, Reevaluation of the Bedford-Berea sequence in Ohio and adjacent states—Forced regression in a foreland basin: Boulder, Colo., Geological Society of America Special Paper 298, 68 p.

Pepper, J.F., deWitt, W., Jr., and deMarest, D.F., 1954, Geology of the Bedford Shale and Berea Sandstone in the Appalachian Basin: U.S. Geological Survey Professional Paper 259, 111 p.

Prosser, C.S., 1912, The Devonian and Mississippian formations of northeastern Ohio: Ohio Geological Survey Bulletin 15, 4th ser., 574 p.

Rau, J.L., 1969, Hydrology of the Berea and Cussewago Sandstones in northeastern Ohio: U.S. Geological Survey Hydrologic Atlas HA–341, 2 sheets.

Read, M.C., 1873, Geology of Trumbull County, chapter 18, *in* Report of the Geological Survey of Ohio, v. 1, Geology and Paleontology: Columbus, Ohio, Nevin and Myers, State Printers, p. 493–509.

Richter, B.C., and Kreitler, C.W., 1993, Geochemical techniques for identifying sources of ground-water salinization: Boca Raton, Fla., CRC Press, 258 p.

Russell, W.L., 1972, Pressure-depth relations in Appalachian region: American Association of Petroleum Geologists Bulletin, v. 56, no. 3, p. 528–536.

Ryder, R.T., Kerry, L.A., Hettinger, R.D., Law, B.E., Miller, J.J., Nuccio, V.F., Perry, Jr., W.J., Prensky, S.E., SanFilipo, J.R., and Wandrey, C.J., 1996, Possible continuous-type (unconventional) gas accumulation in the Lower Silurian Clinton sands, Medina Group, and Tuscarora Sandstone in the Appalachian basin—A progress report of 1995 project activities: U.S. Geological Survey Open-File Report 96–42, 82 p.

Ryder, R.T., Burruss, R.C., and Hatch, J.R., 1998, Black shale source rocks and oil generation in the Cambrian and Ordovician of the Central Appalachian basin, USA: American Association of Petroleum Geologists Bulletin, v. 82. p. 412–441.

Schmoker, J. W., 1993, Use of formation-density logs to determine organic-carbon content in Devonian shales of the western Appalachian basin and an additional example based on the Bakken Formation of the Williston Basin, *in* Roen, J.B., and Kepferle, R.C., eds., Petroleum geology of the Devonian and Mississippian black shale of eastern North America: U.S. Geological Survey Bulletin 1909, p. J1–J14.

Slucher, E.R., and Larsen, G.E., 1996, Reconnaissance bedrock geology of the Cortland, Ohio quadrangle: Ohio Division of Geological Survey Open-File Map BG–D1C7, 1 sheet, scale 1:24,000.

Suphasin, C., 1979, The subsurface geology of the Grimsby Clinton Sandstone of Trumbull County, northeastern Ohio: Kent, Ohio, Kent State University, M.S. thesis, 59 p., 7 plates.

Thomas, M.A., 1993, Subnormal fluid pressures in the Clinton sandstone of eastern Ohio: Kent, Ohio, Kent State University, Ph.D. dissertation, 111 p.

U.S. Army Corps of Engineers, 1992, Drought contingency plan for Mosquito Creek Ohio [variously paginated].

U.S. Department of Agriculture, Soil Conservation Service, 1992, Soil survey of Trumbull County: 256 p. plus maps.

U.S. Environmental Protection Agency, 1986, Quality criteria for water, 1986: Washington, D.C., U.S. Government Printing Office, 256 p.

——— 1998, Drinking water regulations and health advisories: at URL http://www.epa.gov/OST/Tools/dwstds.html. Accessed July, 1998.

Wandrey, C.J., Ryder, R.T., Nuccio, V.F., and Aggen, K.L., 1997, The areal extent of continuous type gas accumulations in Lower Silurian Clinton sands and Medina Group sandstones of the Appalachian basin and the environments affected by their development: U.S. Geological Survey Open-File Report 97–272, 2 sheets, scale 1:500,000.

White, G.W., 1971, Glacial geology of Trumbull County, Ohio: Ohio Department of Natural Resources Division of Geological Survey Report of Investigations 80, 1 plate.

Whiticar, M.J., Faber, E., and Schoell, M., 1986, Biogenic methane formation in marine and freshwater environments, CO_2 reduction vs. acetate fermentation—Isotope evidence: Geochimica et Cosmochimica Acta, v. 50, p. 693–709.

Whittemore, D.O., 1995, Geochemical differentiation of oil and gas brine from other saltwater sources contaminating water resources—Case studies from Kansas and Oklahoma: Environmental Geosciences, v. 2, no. 1, p. 15–31.

——— 1988, Bromide as a tracer in ground-water studies—Geochemistry and analytical determination, *In* Proceedings, Association of Ground Water Scientists and Engineers, Denver, Colo. 1988 Dublin, Ohio: National Water Well Association, p. 339–359.

——— 1984, Geochemical identification of the source of salinity in groundwaters of southeastern Seward County: Kansas Geological Survey Open File Report 84-3, 15 p.

DATA TABLES

Table 1. Summary of rock units and associated water-bearing and oil- and gas-bearing properties in the vicinity of Mosquito Creek Lake, Ohio

[Modified from Jagucki and Lesney (1995). Shaded areas include rocks that function as confining units. Unconformities are shown as thick lines. >, greater than; Fm, Formation; G, major gas-producing unit; O, major oil-producing unit; O*, oil produced with gas; o, minor oil; g, minor gas; SR, oil and gas source rock]

Series	System	Geologic unit		Approximate thickness (in feet)	Character of deposits	Water-bearing properties	Oil-gas reservoir	Oil-gas source rock
Pleistocene	Quaternary	Glacial deposits		0 - 140	Clay, silt, sand, and gravel; till and valley fill	Few domestic wells; wells in coarse gravel may yield 100 gallons per minute		
Lower	Pennsylvanian	Sharon Conglomerate Member of Pottsville Fm		0 - >70	Sandstone containing local channels of conglomerate and sandy shale	Wells yield 10 to 25 gallons per minute or more in the southeast part of the study area		
Lower	Mississippian	Cuyahoga Group		0 - 176	Interbedded shales and sandstones, fine-grained			
		Sunbury Member of the Orangeville Shale		0 - 20	Black shale		g	SR
		Berea Sandstone		0 - 59	Fine gray sandstone to siltstone, relatively well sorted, with local lenses of shale	Wells yield 25 to 50 gallons per minute; wells may yield up to 100 gallons per minute	O, g	
		Bedford Shale		0 - 29	Interbedded shales and siltstones; discontinuous		o, g	
		Cussewago Sandstone		0 - 152	White quartz sandstone; relatively well sorted, poorly cemented	Wells yield 50 to 100 gallons per minute; sustainable yields of greater than 100 gallons per minute possible	o,g	
Upper	Devonian	Chagrin Shale Huron Member of Ohio Shale Pipe Creek Shale Member of the Java Fm. Rhinestreet Shale Member of the West Falls Fm.		2,300 -2,500	Chagrin Shale, Java Fm., West Falls Fm., and Hamilton Group-gray shale and siltstone; Huron, Pipe Creek and Rhinestreet Shale-Black Shale	Not a source of water to wells. Likely to contain brackish water or brine water	g g g	SR
		Hamilton Group						
Middle	Devonian	Marcellus Shale		20 - 30	Black Shale		g	SR
		Onondaga Limestone (Columbus Limestone)	Driller's Big Lime	250 - 270	Limestone	Brine		
Lower		Oriskany Sandstone		10 - 15	White quartzose sandstone	Brine	o?, g?	
		Helderberg Limestone		200 - 220	Limestone			

Table 1. Summary of rock units and associated water-bearing and oil- and gas-bearing properties in the vicinity of Mosquito Creek Lake, Ohio —Continued

[Modified from Jagucki and Lesney (1995). Shaded areas include rocks that function as confining units. Unconformities are shown as thick lines. >, greater than; Fm, Formation; G, major gas-producing unit; O, major oil-producing unit; O*, oil produced with gas; o, minor oil; g, minor gas; SR, oil and gas source rock]

Series	System	Geologic unit		Approximate thickness (in feet)	Character of deposits	Water-bearing properties	Oil-gas reservoir	Oil-gas source rock
Upper	Silurian	Bass Island Dolomite	Driller's Big Lime	80 - 100	Dolomite			
		Salina Group		560 - 600	Dolomite, anhydrite, and halite			
		Lockport Dolomite Newburg of drillers		300 - 350 10 - 20	Dolomite	Brine	g?	
Lower		Rochester Shale		100 - 120	Gray shale and thin limestone and dolomit beds			
		Packer Shell of drillers		25 - 30	Limestone and dolomite			
		Clinton sandstone		190 - 210	Quartzose sandstone	Brine produced with gas and oil at 0.5 to 5 barrels per day	G, O*	
		Cobot Head Shale			Gray shale			
		Medina sand			Quartzose sandstone		g?, o?	
Upper	Ordovician	Queenston Shale		750-800	Red shale and siltstone			

Table 2. Physical properties of and dissolved chloride and bromide concentrations in water samples from Mosquito Creek Lake and tributaries, July through November 1997

[Unless otherwise noted, discharge was visually estimated. d m s, degrees, minutes, seconds; deg. C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L milligrams per liter; ft^3/s, cubic feet per second; --, data not collected; int., analysis inconclusive because of interference; NF, no flow]

USGS identifier	Latitude (d m s)	Longitude (d m s)	Date	Time	Temperature (deg. C)	Specific conductance (µS/cm)	pH	Dissolved oxygen (mg/L)	Discharge (ft^3/s)	Chloride (mg/L)	Bromide (mg/L)
03095500[a]	41 17 59	80 45 31	07/16	1830	25.0	220	7.5	7.0	--	23	<0.010
03095500[a]	41 17 59	80 45 31	09/08	1435	22.3	240	8.3	8.6	--	--	--
03095500[b]	41 17 59	80 45 31	07/16	--	24.4	--	7.6	--	--	--	--
03095500[b]	41 17 59	80 45 31	09/80	--	23.3	--	8.0	--	--	--	--
1	41 18 31	80 46 12	09/07	1125	17.7	2,180	8.1	8.0	>0.002	430	.071
2	41 18 53	80 46 21	09/07	1145	18.9	720	7.9	7.6	>.001	--	--
3	41 19 06	80 46 24	09/07	1210	22.3	450	7.8	9.3	>.001	27	int.
4	41 18 13	80 46 08	09/07	1245	18.4	2,210	8.0	1.7	.003	409	.026
5	41 18 12	80 46 19	09/07	1320	21.6	2,040	8.3	4.3	.002	--	--
6	41 18 27	80 46 45	09/07	1400	19.1	740	7.3	3.0	.003	--	--
7	41 18 36	80 46 45	09/07	1430	20.1	1,700	8.0	4.8	.002	--	--
8	41 18 37	80 46 49	09/07	1445	27.3	350	8.2	9.0	NF	--	--
9	41 18 52	80 46 45	09/07	1515	18.5	1,230	7.9	.5	>.003	--	--
10	41 19 11	80 46 45	09/07	1540	23.6	780	8.6	14.2	>.001	--	--
11	41 19 22	80 46 45	09/07	1550	21.1	380	8.5	8.2	.005	--	--
12	41 19 21	80 46 49	09/07	1600	24.8	310	8.6	8.4	NF	--	--
13	41 19 57	80 46 46	09/07	1615	17.8	680	8.3	9.1	>.002	--	--
14	41 19 46	80 46 05	09/07	1630	19.6	2,160	7.7	1.5	.001	--	--
15	41 19 25	80 46 01	09/07	1640	19.8	2,120	10.1	2.7	.007	285	.024
16	41 20 46	80 46 46	09/07	1700	18.9	1,150	7.4	1.7	NF	--	--
17	41 21 11	80 46 42	09/07	1730	19.1	2,040	7.3	2.5	>.002	--	--
18	41 21 51	80 46 28	09/07	1735	19.3	1,740	7.7	0.2	>.002	--	--
19	41 22 11	80 46 19	09/07	1815	19.2	1,660	9.2	0.1	>.001	--	--
20	41 22 11	80 46 20	09/07	1825	23.5	330	8.3	7.7	NF	--	--
21	41 2258	80 46 36	09/07	1835	18.0	2,160	7.9	2.7	>.001	--	--
22	41 17 57	80 45 29	09/08	1500	27.1	1,360	7.9	8.2	>.005	--	--
22	41 17 57	80 45 29	11/03	1730	22.0	1,070	7.8	--	>.005	193	.15
23	41 19 25	80 43 54	07/16	1900	26.0	760	7.6	9.9	2.6[c]	83	.096
23	41 19 25	80 43 54	09/08	1415	19.1	700	8.0	10.0	3.4[c]	--	--

Table 2. Physical properties of and dissolved chloride and bromide concentrations in water samples from Mosquito Creek Lake and tributaries, July through November 1997 —Continued

[Unless otherwise noted, discharge was visually estimated. d m s, degrees, minutes, seconds; deg. C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L milligrams per liter; ft^3/s, cubic feet per second; --, data not collected; int., analysis inconclusive because of interference; NF, no flow]

USGS identifier	Latitude (d m s)	Longitude (d m s)	Date	Time	Temperature (deg. C)	Specific conductance (µS/cm)	pH	Dissolved oxygen (mg/L)	Discharge (ft^3/s)	Chloride (mg/L)	Bromide (mg/L)
24	41 18 57	80 44 30	09/08	1525	19.4	1,330	7.8	5.9	>0.005	--	--
25	41 19 15	80 44 28	09/08	1530	20.1	710	8.3	12.0	--	--	--
26	41 19 16	80 44 29	09/08	1540	25.2	290	8.5	9.8	--	--	--
27	41 20 24	80 43 53	09/08	1614	19.2	670	7.7	6.6	.003	--	--
28	41 20 38	80 43 54	09/08	1620	18.4	890	7.6	2.5	>.002	--	--
29	41 20 45	80 43 55	09/08	1631	21.9	290	8.0	6.9	NF	--	--
30	41 20 58	80 44 02	09/08	1637	21.9	1,580	8.1	3.2	>.002	--	--
31	41 21 04	80 44 05	09/08	1640	19.0	1,850	7.8	4.1	NF	--	--
32	41 21 27	80 44 14	09/08	1713	17.9	1,050	7.9	2.5	.003	--	--
33	41 21 46	80 44 13	09/08	1722	21.8	580	8.3	15.5	NF	--	--
34	41 22 40	80 44 12	09/08	1735	17.7	380	8.1	8.8	.003	43.68	.06
35	41 22 37	80 43 26	09/08	1751	17.9	470	7.8	7.0	.009	--	--
36	41 22 37	80 43 17	09/08	1806	23.0	320	8.7	10.8	NF	--	--
37	41 22 28	80 43 12	09/08	1829	23.0	320	8.7	10.8	NF	--	--
38	41 22 51	80 44 13	09/08	1842	18.5	900	7.9	.5	.003	--	--
39	41 23 14	80 44 13	09/08	1845	19.0	1,290	7.6	0.3	.007	--	--
40	41 28 09	80 44 48	07/15	1700	28.9	400	8.1	--	1.410[d]	31.13	int.
40	41 28 09	80 44 48	09/08	1858	20.9	550	8.1	9.0	--	--	--
41	41 27 42	80 45 15	09/08	1915	19.6	530	7.8	7.5	--	--	--
42	41 27 43	80 45 39	09/08	1920	18.6	480	7.1	.3	NF	--	--
43	41 23 23	80 45 00	08/21	1545	21.0	240	8.6	9.2	--	--	--

[a] Period of record, 1926–29 station published as "near Cortland". 1943 to 1991, discharge; 1991 to current year, stage only. Prior to Aug. 1943 nonrecording gage, and Aug. 23, 1943, to Feb. 14, 1951, water-stage recorder at site 900 ft downstream.

[b] Sample of raw water from water intake collected by city of Warren (James Sherwood, City of Warren, written commun., 1997).

[c] Volumetric measurement.

[d] Measurement made with pygmy meter.

Table 3. Physical properties of and concentrations of dissolved chloride, bromide, methane, ethane, and propane in ground-water samples from the Mosquito Creek Lake area, Ohio, July through November 1997

[ODNR, Ohio Department of Natural Resources; deg. C, degrees Celsius; µS/cm; microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter]

USGS identifier or ODNR permit	Site identifier	Date	Time	Temper-ature (deg. C)	Specific conduct-ance (µS/cm)	pH	Dissolved oxygen (mg/L)	Chloride (mg/L)	Bromide (mg/L)	Methane (mg/L)	Ethane (mg/L)	Propane (mg/L)
Glaciofluvial sediments												
T-54	411735080454200	08/22	1830	12.9	1,420	7.3	<0.1	4.8	0.084	<0.0313	<0.0313	<0.0313
T-58	411733080454700	--	1945	11.7	1,110	7.4	.2	--	--	--	--	--
Cuyahoga Group												
T-50	412026080435400	08/22	1600	12.2	570	7.7	<.1	13	.062	.348	<.0313	<.0313
Berea Sandstone												
T-49	412310080441500	07/15	1557	12.4	560	7.1	<.1	44	<.010	--	--	--
T-51	412138080461100	08/23	1620	12.2	550	7.1	<.1	6.7	.032	2.37	<.0313	<.0313
T-52	411907080462300	08/24	1815	12.5	740	7.2	<.1	14	.075	.267	<.0313	<.0313
T-53	412214080462700	09/06	1030	11.5	610	7.4	.4	5.9	.031	1.74	<.0313	<.0313
T-57	411946080463500	09/12	1035	12.4	1,170	7.0	.1	14	.089	.031	<.0313	<.0313
T-59	412348080441000	06/11	1030	--	360	--	<.1	--	--	--	--	--
Berea Sandstone and Cussewago Sandstone												
T-55	411829080464400	09/09	1750	12.1	910	6.8	<.1	148	.13	22.7	<.0313	<.0313
Cussewago Sandstone												
T-10	412238080463501	08/24	1115	11.6	620	7.2	.1	6.7	.047	6.93	<.0313	<.0313
T-12	412058080465101	08/23	1130	11.8	690	7.3	<.1	21	.039	1.00	<.0313	<.0313
T-16	411925080460301	08/23	1340	12.3	660	7.2	<.1	1.3	.048	.303	<.0313	<.0313
T-19	411812080461701	08/21	1730	11.29	951	7.2	<.1	21	.21	26.7	<.0313	<.0313
T-25	411812080443501	08/22	1200	11.31	580	7.7	<.1	34	.071	4.37	<.0313	<.0313
T-30	411857080443701	09/11	1753	11.74	820	7.5	<.1	78	.25	.579	<.0313	<.0313
T-33	411951080440201	08/21	1010	11.71	610	7.6	<.1	--	--	13.9	<.0313	<.0313
T-34	411946080431601	09/12	1515	12.62	980	7.8	<.1	95	.66	11.3	<.0313	<.0313
T-34	411946080431601	11/03	1045	13.24	1,050	7.9	<.1	--	--	11.0	<.0313	<.0313
T-35	411946080431101	11/03	1220	11.63	1,000	7.9	.1	--	--	9.35	<.0313	<.0313
T-36	411943080430801	11/03	1325	11.38	1,010	8.0	.2	--	--	12.1	<.0313	<.0313
T-37	411945080430301	11/03	1530	11.27	1,000	8.1	<.1	--	--	12.2	<.0313	<.0313
T-38	412015080432001	11/03	1620	11.38	960	8.1	.2	64	.44	7.21	<.0313	<.0313
T-39	412013080431900	11/03	1715	11.13	960	8.1	.1	--	--	11.7	<.0313	<.0313
T-40	412039080435401	08/22	1800	11.71	790	7.9	<.1	.36	.25	4.85	<.0313	<.0313

Table 3. Physical properties of and concentrations of dissolved chloride, bromide, methane, ethane, and propane in ground-water samples from the Mosquito Creek Lake area, Ohio, July through November 1997 —Continued

[ODNR, Ohio Department of Natural Resources; deg. C, degrees Celsius; µS/cm; microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter]

USGS identifier or ODNR permit	Site identifier	Date	Time	Temperature (deg. C)	Specific conductance (µS/cm)	pH	Dissolved oxygen (mg/L)	Chloride (mg/L)	Bromide (mg/L)	Methane (mg/L)	Ethane (mg/L)	Propane (mg/L)
T-41	412215080441201	08/21	1400	12.88	780	7.6	<0.1	51	0.35	4.96	<0.0313	<.0313
T-48	412323080441101	08/21	1510	12.20	550	7.5	<.1	14	.066	3.83	<.0313	<.0313
T-56	411829080463500	09/12	1035	12.38	900	7.0	<.1	12	.14	28.7	<.0313	<.0313
					Clinton sandstone							
2194	412032080465100	09/09	1000	--	200,000	3.7	--	178,000	2,460	--	--	--
3561	411817080462300	09/09	1050	--	186,000	4.5	--	137,000	1,710	--	--	--
3382	411928080441100	09/08	1130	--	198,000	3.7	--	161,000	2,450	--	--	--

Table 4. Concentration of selected organic compounds in soil near Mosquito Creek Lake and in bottom sediment of Mosquito Creek Lake, Ohio, July through September 1997

[d m s, degrees, minutes, seconds; all concentrations are in nanograms per liter; L, lake; S, shallow (water depth approximately 1.5 feet); D, deep (water depth approximately 6 to 10 ft); <, less than]

Identifier	Latitude (d m s)	Longitude (d m s)	Benzene	Toluene	Ethylbenzene	Xylene	Naphthalene	1,2,4-Trimethylbenzene	1,3,5-Trimethylbenzene
Unsaturated sediments near Mosquito Creek Lake									
8L	41 18 50	80 44 32	<0.58	<0.40	<0.33	<0.12	<8.49	1.02	<0.45
10-1L	41 22 17	80 46 25	<.58	.26	<.33	19.02	<8.49	<0.11	<.45
11-2L	41 22 14	80 46 15	<.58	<.40	<.33	.43	<8.49	<.11	.22
12-3L	41 22 14	80 45 55	<.58	<.40	<.33	.34	<8.49	.91	.25
Shallow-water sampling sites									
1S	41 18 51	40 45 49	.84	3.34	<.33	<.46	<8.49	<.45	4.12
2S	41 20 27	80 45 53	.75	1.16	.43	<.46	<8.49	.49	5.38
3S	41 21 47	80 45 47	.49	3.38	<.33	<.46	1.19	<.45	2.67
4S	41 23 02	80 45 49	<.58	3.09	<.33	<.46	16.41	<.45	.80
5S	41 22 58	80 44 33	.75	3.74	<.33	11.25	9.62	2.92	3.70
7S	41 20 55	80 44 32	<.58	2.07	<.33	<.46	<8.49	<.45	4.16
8S	41 19 17	80 44 28	<.58	3.85	<.33	<.46	<8.49	<.45	5.15
9S	41 27 42	80 45 15	<.58	<.40	<.33	<.46	<8.49	<.45	<.11
Deep-water sampling sites									
2D	41 20 27	80 45 42	.68	5.78	<.33	<.12	<.15	<.11	<.11
3D	41 21 46	80 45 42	<.60	<3.21	<.33	<.12	<.15	<.11	<.11
5D	41 22 59	80 44 34	.70	<3.21	<.33	<.12	<.15	<.11	<.11
6D	41 21 59	80 44 39	.88	35.31	<.33	<.12	<.15	<.11	<.11
7D	41 20 57	80 44 44	.98	5.35	<.33	<.12	<.15	<.11	<.11

Table 5. Statistical summary of chemical data for surface water, ground water, and brine in the Mosquito Creek Lake area, Ohio, July through November 1997

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; --, data not collected]

Location or value	pH	Specific conductance (µS/cm)	Dissolved oxygen (mg/L)	Chloride (mg/L)	Bromide (mg/L)	Methane (mg/L)	Ethane (mg/L)	Propane (mg/L)
Mosquito Creek Lake								
Dam	7.5	220	7.0	22	<0.010	--	--	--
Causeway bridge	8.6	240	9.2	--	--	--	--	--
Tributaries flowing into Mosquito Creek Lake								
Minimum	7.3	380	.1	27	.024	--	--	--
Maximum	10.1	2,210	12.0	430	.15	--	--	--
Median	7.9	1,150	3.2	189	.071	--	--	--
Berea Sandstone wells								
Minimum	7.0	360	<.1	5.9	<.010	.0313	<0.0313	<0.0313
Maximum	7.4	1,170	.4	148	.089	2.37	<.0313	<.0313
Median	7.2	610	<.1	14	.032	1.74	<.0313	<.0313
Cussewago Sandstone wells								
Minimum	7.0	550	<.1	1.3	.039	.303	<.0313	<.0313
Maximum	8.08	1,050	.2	95	.66	28.7	<.0313	<.0313
Median	7.6	820	<.1	34	.20	4.96	<.0313	<.0313
Clinton sandstone oil- and gas-associated brine								
Minimum	3.7	186,000	--	137,000	1,710	--	--	--
Maximum	4.5	204,000	--	185,000	2,460	--	--	--

Table 8. Quality-assurance data for selected organic compounds in soil and lake-bottom sediments from the Mosquito Creek Lake area, Ohio

[All concentrations are in nanograms per liter; <, less than]

Identifier	Date	Site	Benzene	Toluene	Ethylbenzene	Xylene	Naphthalene	1,2,4 Trimethylbenzene	1,3,5-Trimethylbenzene
Trip blank-1	7/14/97	--	<30	<30	<30	<30	<30	<30	<30
Trip blank-2	9/10/97	--	<30	<30	<30	<30	<30	<30	<30
Ambient air sample-A	7/14/97	6S	<30	<30	<30	<30	<30	<30	<30
Ambient air sample-B	7/14/97	4S	<30	<30	<30	<30	<30	228	110
Ambient air sample-C	9/10/97	9S	<30	<30	<30	<30	<30	<30	<30

Table 9. Chemical and isotopic data for Mecca and Clinton oil samples from wells near Mosquito Creek Lake, Ohio 1997

[HC, hydrocarbons; NOS, total nitrogen plus oxygen plus sulfur]

Well number	Petroleum fraction (weight percent)				Saturated HC characteristics (weight percent)			Isotopic composition (per mil)	
	Saturated HC	Aromatic HC	NOS	Asphaltines	Pristane/phytane	Pristane/n-C_{17}	Phytane/n-C_{18}	Saturated HC $\delta^{13}C$	Aromatic HC $\delta^{13}C$
				Berea Sandstone Mecca oil samples					
T-59	79.7	17.7	2.6	0.0	--	--	--	-29.32	-29.48
T-49	79.2	18.4	2.5	.0	--	--	--	-29.35	-29.45
T-53	84.0	13.6	2.2	.2	--	--	--	-29.42	-29.22
				Clinton sandstone oil samples					
3561	89.3	7.6	1.8	1.3	1.35	0.38	0.33	-29.80	-28.96
3382	86.7	8.6	3.2	1.6	1.57	.41	.33	-29.61	-29.08
2194	87.3	8.5	3.4	.8	1.63	.40	.31	-29.66	-28.86

Table 6. Maximum concentrations of selected organic compounds in soil and lake-bottom sediments and concentrations in the Mecca oil, July and September 1997

[all concentrations are in nanograms per liter; <, less than; --, goal has not been established]

Benzene	Toluene	Ethylbenzene	Xylene	Naphthalene	1,2,4-Trimethyl-benzene	1,3,5-Trimethyl-benzene
Unsaturated soils near Mosquito Creek Lake						
<0.58	0.26	<0 .33	19.02	< 8.49	10.02	0.25
Bottom sediments of Mosquito Creek Lake						
.98	35.3	.43	11.25	16.41	2.92	5.38
Mecca oil sample from exploratory well T-53						
153	3,070	<.33	19,900	< 8.49	3,860	3,250
U.S. Environmental Protection Agency maximum contaminant level goal						
5,000	1,000,000	700,000	10,000,000	--	--	--

Table 7. Quality-assurance data for dissolved chloride, dissolved bromide, and methane in samples of water and brine from the Mosquito Creek Lake area, Ohio

[mg/L, milligrams per liter; RPD, relative percent difference (calculated as ((S-D) / [(S+D) / 2]) x 100, where S = concentration of constituent in regular sample and D = concentration of constituent in duplicate sample); --, no data]

Identifier	Date	Chloride			Bromide			Methane		
		Regular sample (mg/L)	Duplicate sample (mg/L)	RPD	Regular sample (mg/L)	Duplicate sample (mg/L)	RPD	Regular sample (mg/L)	Duplicate sample (mg/L)	RPD
T-30	9/11/97	78	77	1.3	0.25	0.29	15	0.579	0.869	40.1
T-34	11/3/97	--	--	--	--	--	--	11.0	11.7	6.2
T-38	11/3/97	64	64	0.0	.44	.43	2.3	7.21	7.21	0.0
T-51	8/23/97	6.7	6.7	.0	.032	.045	34	2.37	2.43	2.5
SW-22	11/3/97	193	190	1.6	.15	.16	6.5	--	--	--
2194	9/9/97	177,590	185,365	4.3	2,464	2,407	2.3	--	--	--

Table 10. Chemical and isotopic data for natural gas samples from wells near Mosquito Creek Lake, Ohio 1997

[All values are in weight percent unless otherwise noted; nd, not detected; --, not analyzed]

Well number	Methane	Ethane	Ethylene	Propane	iso-Butane	n-Butane	iso-Pentane	n-Pentane	Hexanes +	Helium	Hydrogen	Argon	Nitrogen	Carbon dioxide	$\delta^{13}C$, methane (per mil)	δD (per mil)	$\delta^{13}C$, ethane (per mil)	$\delta^{13}C$, propane (per mil)	$\delta^{13}C$ carbon dioxide (per mil)
Berea Sandstone																			
T-55	87.308	0.008	nd	0.002	nd	0.008	nd	nd	0.001	nd	nd	0.010	0.281	12.382	-48.97	-274.0	nd	nd	-23.96
T-53	3.542	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	1.006	91.911	3.542	-91.23	-281.5	nd	nd	-24.33
Cussewago Sandstone																			
T-34	39.284	.005	nd	nd	nd	nd	nd	nd	nd	nd	nd	.992	58.640	1.079	-72.75	-241.1	nd	nd	--
Clinton sandstone																			
3561	89.340	5.110	nd	1.650	0.220	0.400	0.110	0.110	.120	0.091	0.001	nd	2.840	0.010	-37.49	-168.5	-35.29	-30.94	--
3382	90.330	4.640	nd	1.470	.200	.380	.110	.130	.140	.089	.002	nd	2.500	.010	-37.20	-166.6	-34.88	-30.58	na
2194	90.640	4.480	nd	1.320	.180	.310	.085	.096	.120	.099	nd	nd	2.670	nd	-37.4	-165.7	-34.67	-30.4	na

Barton and others-Water Quality in the Vicinity of Mosquito Creek Lake, Trumbull County, Ohio, in Relation to the Chemistry of Locally Occurring Oil, Natural Gas, and Brine-WRIR 96-4106