U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

PREPARED IN COOPERATION WITH THE
U.S. DEPARTMENT OF THE NAVY, SOUTHERN DIVISION,
NAVAL FACILITIES ENGINEERING COMMAND

WATER-RESOURCES INVESTIGATIONS REPORT 02-4123
SHEET 1 of 3
Taylor, C.J., and Hostettler, F.D., 2002, Hydrogeologic Framework and Geochemistry of Ground Water and Petroleum in the Silurian-Devonian Carbonate Aquifer, South-Central Louisville, Kentucky

INTRODUCTION

Previously published investigations concerning the ground-water resources of the city of Louisville and Jefferson County, Kentucky, have mostly focused on the highly productive Ohio River alluvial aquifer (Rorabaugh, 1956; Walker, 1957; Bell, 1966; Unthank and others, 1995). In contrast, relatively little attention has been given to the Ordovician and Silurian-Devonian carbonate aquifers that underlie much of the Louisville and Jefferson County area (fig. 1) because of their limited potential for water-supply development (Palmquist and Hall, 1960). However, detailed information about the ground-water quality and hydrogeology of the carbonate aquifers is needed by State and Federal environmental regulators and private consultants for planning and conducting local environmental site assessments and ground-water remediation. The Silurian-Devonian carbonate aquifer is of particular interest because it underlies much of the urbanized and industrialized areas of the city of Louisville, exhibits moderately well-developed karst, and is potentially vulnerable to human-induced contamination.

During 1999–2001, the U.S. Geological Survey (USGS), in cooperation with the U.S. Department of the Navy (Navy), conducted a multidisciplinary investigation of the Silurian-Devonian carbonate aquifer in a 52 mi^2 study area (fig. 2) in south-central Louisville, Kentucky. The purpose of the investigation was to provide information about the hydrogeologic and geochemical framework of the aquifer, ambient ground-water quality, and the source of petroleum hydrocarbons occurring in bedrock strata in the study area. This information was needed by the Navy to assist environmental-characterization work being done at the former Naval Ordnance Station Louisville (NOSL) site. The NOSL site was designated for closure under the Base Realignment and Closure Act (BRAC) in 1995, and ownership of the 144-acre property is being transferred to the Louisville/Jefferson County Redevelopment Authority. Federal and State environmental requirements must be satisfied as part of the transfer process.

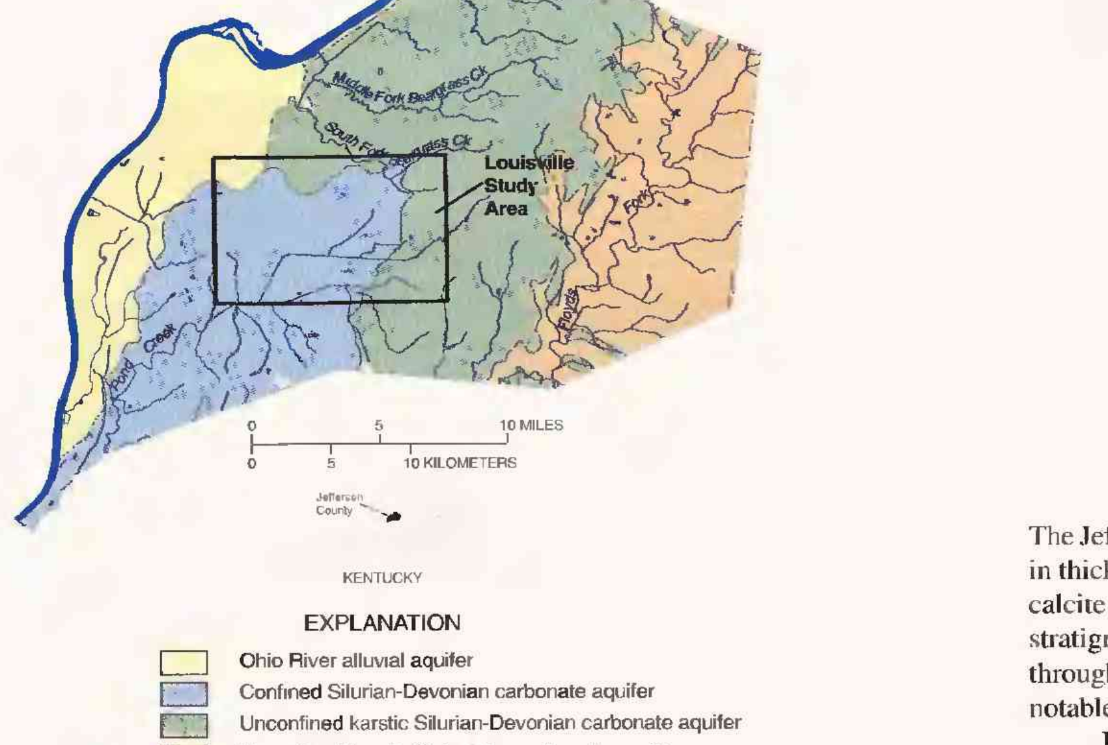


Figure 1. Subregional aquifer systems within Jefferson County, Kentucky.

Purpose and Scope

This report presents the results of the multidisciplinary investigation conducted by the USGS during 1999–2001, and describes the hydrogeologic framework of the Silurian-Devonian carbonate aquifer and geochemistry of ground water and petroleum in the aquifer in south-central Louisville, Kentucky. The approach used in the investigation is similar to the one described by Zanini and others (2000). Data obtained from water-level measurements, aquifer tests, borehole-geophysical and heat-pulse flowmeter logs, and petrographic analyses of rock cores were used to characterize the physical hydrogeologic framework of the carbonate aquifer—hydrostratigraphic units, porosity and permeability, contributing (water-bearing) fracture zones, hydraulic heads, and aquifer thickness. The major-ion and isotopic composition of ground-water samples collected from open-borehole observation wells and a karst spring were used to characterize the geochemistry of ground water in the aquifer—the spatial differences in ground-water chemistry that relate to changes in transmissivity, recharge, ground-water flow patterns, and mixing in the aquifer. In addition, ground-water isotopic data are used to investigate the potential sources of recharge to the aquifer and to qualitatively assess ground-water residence time.

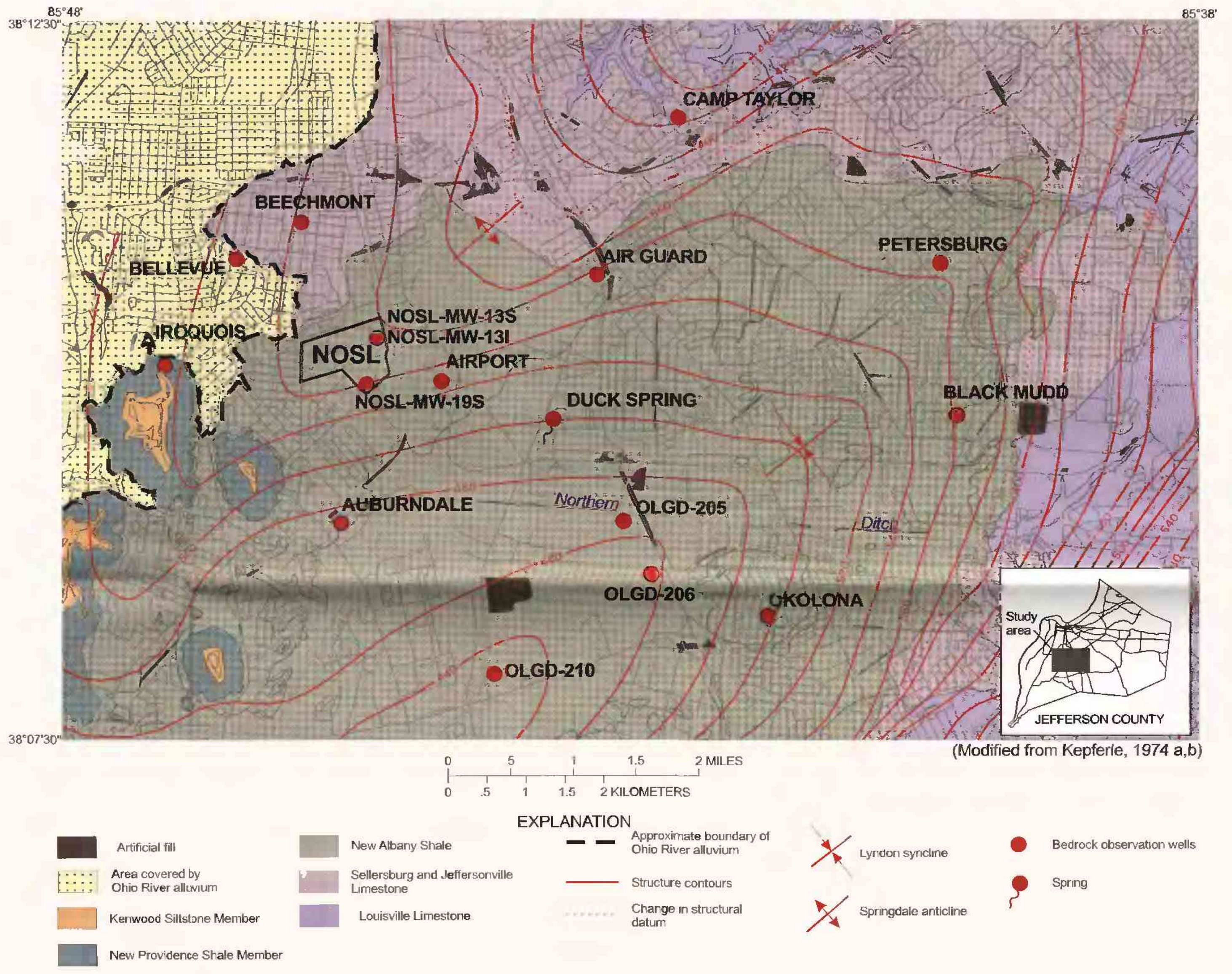
Petroleum is not usually considered a naturally occurring chemical constituent of ground water; however, its presence as a secondary fluid in the Silurian-Devonian carbonate rocks in the study area required that its occurrence and geochemical characteristics also be investigated. Therefore, hydrocarbon-fingerprinting techniques and identification of organic geochemical biomarkers were used to characterize the aromatic and aliphatic hydrocarbon fractions of representative petroleum samples and to identify possible oil-oil and oil-source rock correlations.

Geologic Setting

Bedrock strata that crop out at or near the surface in the study area are illustrated on the geologic map shown in figure 2. The Sellersburg, Jeffersonville, and Louisville Limestone Formations (listed youngest to oldest, respectively) form the stratigraphic framework for the Silurian-Devonian carbonate aquifer. In the central and southwestern parts of the study area, these three limestone formations are overlain by the Devonian New Albany Shale. There the carbonate aquifer is confined by the shale and exhibits little visible karstification. To the north and east, outside the shale outcrop boundary, the carbonate aquifer is unconfined and exhibits moderately well-developed karstification. A more detailed lithologic description of these strata is provided below.

The New Albany Shale is a carbonaceous, olive to black, laminated shale that ranges from less than 12 to more than 85 ft in thickness in the study area (Kepferle, 1974a, and b). Pyrite nodules and bands are scattered throughout the formation and a prominent 1- to 2-in. thick pyrite band is common at its base. Significant concentrations of trace metals-uranium, zinc, molybdenum, cadmium, vanadium, lead, nickel, and copper-may be present in some bedding units (Leininger, 1981). In weathered outcrop exposures, the shale appears to be fissile and well jointed; however, in core samples and unweathered exposures, the bedding units of the shale typically appear unfractured and very competent. Where relatively thick and unfractured, the shale is assumed to be an effective confining unit (Palmquist and Hall, 1960). Matrix permeabilities of unweathered core samples from the shale reportedly range from 2.5 x 10^{-6} to 1.9 millidarcies (7.9 x 10^{-14} to 6x 10^{-8} ft/s) (Hamilton-Smith, 1993).

The Sellersburg and Jeffersonville Limestone Formations are similar in overall lithologic properties and are undifferentiated on the geologic maps of the study area (Kepferle, 1974a and b). The Sellersburg Limestone is a coarsely crystalline, white to greenish-gray, fossil-fragmental, dolomitic limestone that ranges from about 2 to 15 ft in thickness. The Sellersburg can sometimes be subdivided into two units: the Beechwood Limestone Member, characterized by abundant crinoid fragments and well-developed moldic porosity; and the Silver Creek Limestone Member, characterized by sparsely fossiliferous, layered, argillaceous dolostone (Freeman, 1951). The contact with the underlying Jeffersonville Limestone is disconformable and marked by phosphatic pebbles, pyrite, quartz sand, and glauconite.



(Modified from Kepferle, 1974 a,b)

Figure 2. Bedrock geology and structure and ground-water sampling sites, south-central Louisville, Kentucky.

The Jeffersonville Limestone is also a coarse-grained limestone, ranging up to 40 ft in thickness, having abundant whole and fragmented fossils bound in a sparry calcite or dolomitic mudstone matrix. Vuggy porosity is present in isolated stratigraphic intervals and stylolites (pressure-solution seams) are conspicuous throughout much of the unit. The lower part of the Jeffersonville Limestone is notable for abundant whole corals.

In contrast to the Sellersburg and Jeffersonville Limestones, the Louisville Limestone is a fine-grained, thin to thickly bedded, dolomitic limestone ranging up to 85 ft in thickness (Kepferle, 1974a and b). The base of the Louisville Limestone is not exposed in the study area, and its contact with the overlying Jeffersonville Limestone is disconformable and rather sharply delineated by an abrupt change from coarse-grained, massively bedded limestone to fine-grained, wavy-bedded dolomitic limestone.

Structurally, the rocks in the study area are part of an arcuate belt of Silurian-Devonian strata that crop out along the western flank of the Cincinnati arch (fig. 3), a major structural upwarp beneath the eastern midcontinental United States (McDowell, 1986). In general, bedrock strata dip west off the arch at 20 to 70 ft/mi toward the Illinois Basin, a major structural downwarp located beneath much of west-central Kentucky, Indiana, and Illinois. Locally superimposed on the regional dip are two adjacent, northeast-trending, structural features identified by Kepferle (1974a and b) as the Springdale anticline and Lyndon syncline (fig. 2). Bedrock strata dip to the north and south relative to the axial trends of these structures. No mapped faults are present within the study area; however, Bell (1966) reports the presence of a prominent joint set that trends N30°E.

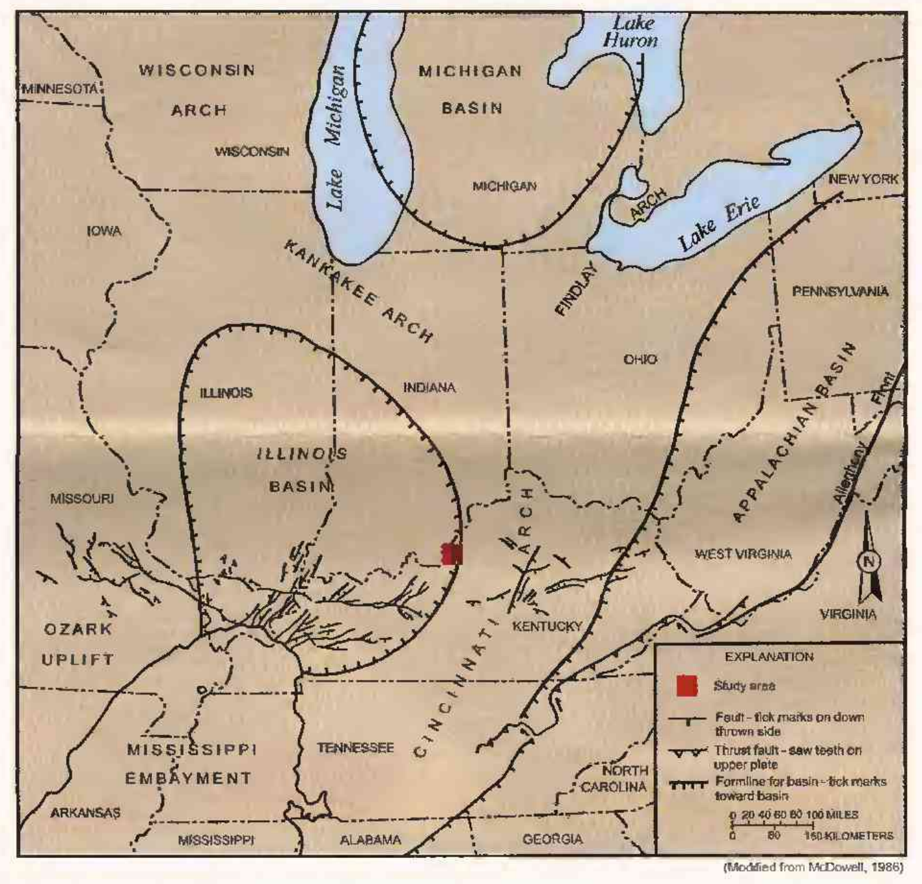
Though not shown on the map in figure 2, much of the area within the Lyndon syncline is overlain by approximately 10 to 25 ft of unconsolidated Quaternary sediments, which include lacustrine clay, glacial outwash, and loess deposits. These deposits are variably saturated and may contain a seasonal water table perched upon the New Albany Shale. Surface drainage in most of the study area is within the Pond Creek watershed (fig. 1). Base flow to Pond Creek is provided by ground water discharging from the Quaternary sediments and from springs or seeps discharging from the New Albany Shale or the carbonate rocks.

Ground-Water Sampling Sites

A well inventory done in 1999 indicated that few wells are present in the study area that are completed within the carbonate aquifer and accessible for sampling. Nine open-borehole wells (fig. 2) were drilled by the USGS in October 1999 and February 2000 to facilitate hydraulic testing, water-level measurements, and ground-water sampling. The nine well locations are identified on figure 2 as follows: Air Guard (Kentucky Air National Guard Annex); Airport (Louisville International Airport); Auburndale; Beechmont (Beechmont Community Center); Bellevue (Bellevue Park); Black Mudd (Black Mudd Park); Camp Taylor (Camp Taylor Park); Iroquois (Iroquois Park); Okolona (Okolona Park); and Petersburg (Petersburg Park). Later in the investigation, access was obtained to seven additional ground-water sampling sites, including three monitoring wells at the Outer Loop Landfill (OLGD-205 OLGD-206, and OLGD-210); three monitoring wells at the NOSL site (MW-13S, MW-13I, and MW-19S); and Duck Spring. Duck Spring is an artesian karst spring located near the center of the study area (fig. 2) that discharges from a solutional conduit located below land surface, near the contact between the Sellersburg/Jeffersonville Limestone and New Albany Shale. According to unpublished historical data on file at the USGS office in Louisville, Kentucky, the discharge of the spring typically ranges from 0.13 to 0.68 ft^3/s. The recharge area for the spring has not been delineated.

Acknowledgments

The authors express appreciation to all those who contributed to the completion of the investigation and publication of this report. The Kentucky Air National Guard, Louisville International Airport Authority, Louisville Metropolitan Parks Department, and Louisville Gas and Electric Energy Corporation graciously provided access to property needed for the drilling and construction of ground-water observation wells. The United Parcel Service and Waste Management Incorporated of Kentucky granted the USGS access to several additional existing ground-water sampling sites. David Morse, Illinois State Geological Survey, provided organic geochemical data that was useful in evaluating the results of petroleum hydrocarbon fingerprinting done during the investigation. Jonathan J. Kolak, USGS, assisted with the organic geochemical analyses conducted on petroleum samples, and Hugh L. Nelson Jr. and Bonnie Stich Fink, USGS, assisted in preparing the illustrations and manuscript for publication.



(Modified from McDowell, 1986)

Figure 3. Major regional structural features near south-central Louisville, Kentucky.

HYDROGEOLOGIC FRAMEWORK OF THE CARBONATE AQUIFER

Little published information is available regarding the occurrence, flow, and quality of ground water in the carbonate rocks in the study area. Bell (1966) described the hydraulic behavior of wells completed in Silurian-Devonian limestones beneath the Ohio River alluvium, approximately 3 mi to the north of the study area; however, the hydrogeologic setting of these wells is not comparable to that of the present study area. A general summary of the lithologic and water-bearing characteristics of carbonate rocks throughout Jefferson County is provided by Palmquist and Hall (1960). The Silurian-Devonian carbonates are described as yielding highly variable amounts of water to wells and, with the exception of karst springs, producing ground water of poor quality because of high concentrations of chloride, hydrogen sulfide, iron, and other dissolved solids. A statewide hydrogeologic-sensitivity map prepared by Ray and others (1994) depicts bedrock aquifers in the study area as likely to have low-to-moderate permeability, diffuse or limited concentrated recharge (depending on sinkhole occurrence and density), and relatively slow ground-water-flow velocities.

During this investigation, data obtained by use of a caliper borehole logging tool (borehole diameter), acoustic televiewer, heat-pulse flowmeter, and hydraulic tests indicated that ground-water occurrence and flow is largely controlled by horizontal fractures within the stratigraphic interval between the Sellersburg Limestone and upper Louisville Limestone. Composite borehole logs for the Iroquois, Beechmont, Air Guard, and Petersburg wells (figs. 4a-d) illustrate the relation between fractures, contributing zones, and hydraulic conductivity in the aquifer. Fractures identified on the caliper and acoustic televiewer logs are small in aperture (width), nearly horizontal in attitude (dip), and are of unknown lateral extent and interconnectivity. The heat-pulse flowmeter data indicate that few fractures within the Sellersburg–Upper Louisville Limestone stratigraphic interval were hydraulically active and contributed water to the open-borehole wells. At the Beechmont and Air Guard sites, more than 60 percent of the water contributed to the borehole during testing was obtained from a single horizontal fracture in the Jeffersonville Limestone (figs. 4b and c). At the Petersburg location, more than 80 percent of the water was obtained from a single horizontal fracture near the contact between the Jeffersonville and Louisville Limestones (fig. 4d). Other minor contributing zones were associated with stylolites (pressure-solution seams) and narrow intervals of moldic porosity in the Sellersburg or Jeffersonville Limestone. The thickness of the carbonate aquifer, as defined by the stratigraphic interval containing contributing fractures, ranged from about 10 to 45 ft. Contributing fractures were not detected more than 10 to 15 ft below the top of the Louisville Limestone, indicating that the lower part of the limestone may act as a confining unit.

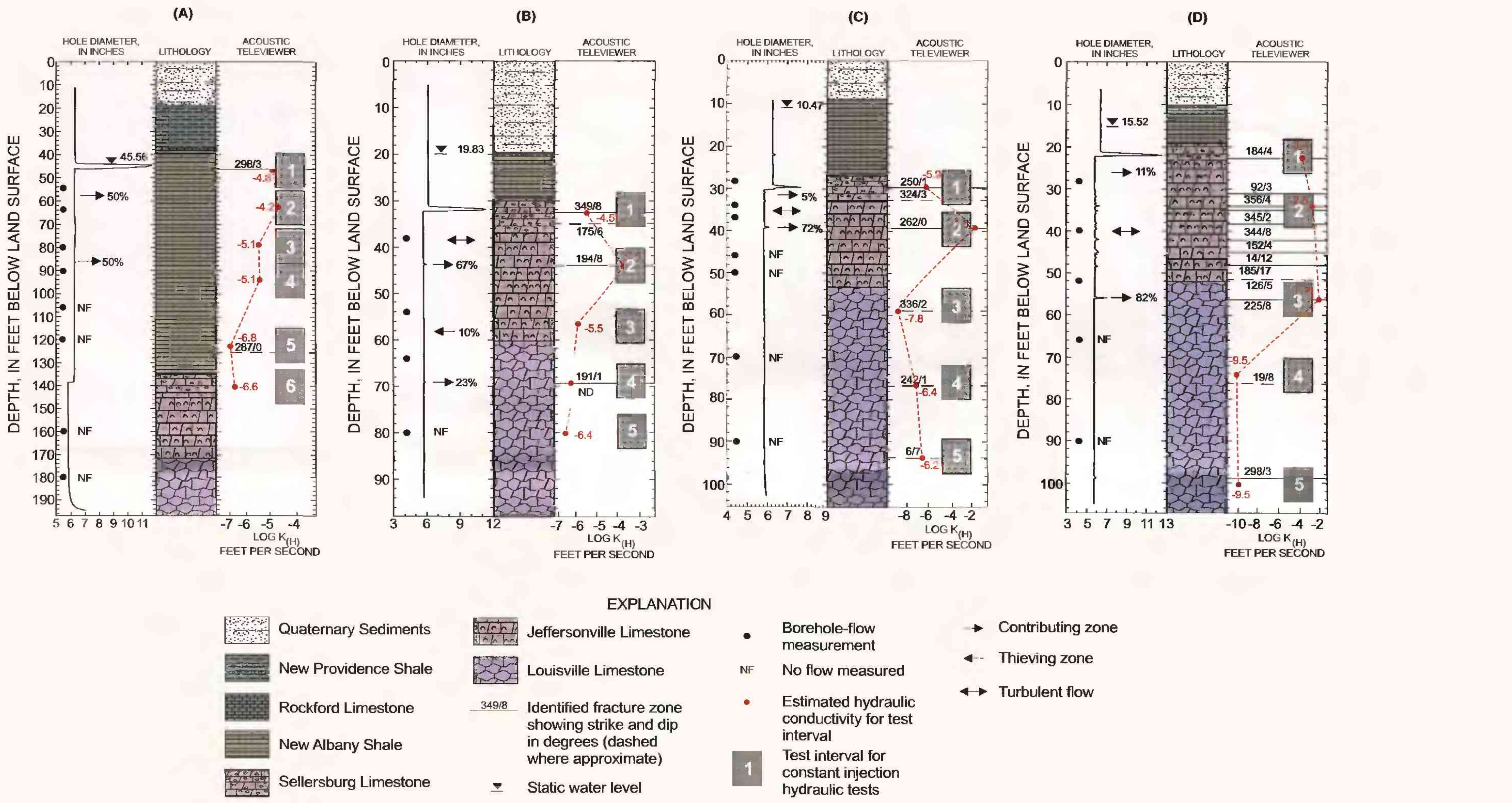


Figure 4. Composite borehole logs for (A) Iroquois, (B) Beechmont, (C) Air Guard, and (D) Petersburg wells.

Hydraulic Conductivity

The vertical distribution of permeability was evaluated in selected boreholes by conducting constant-head fluid injection tests to obtain estimates of horizontal hydraulic conductivity. Inflatable packer equipment was used to isolate narrow (7.5-ft long) stratigraphic intervals, most containing contributing fractures, for hydraulic testing. The water-inflow rate and maximum change in pressure (hydraulic head) recorded during each test were used to calculate the transmissivity of the test interval using the Thiem equation (Batu, 1998). The calculated transmissivity was then divided by the length of the test interval to obtain an average horizontal hydraulic conductivity.

The results of the constant-head injection tests are summarized in table 1 and illustrated graphically on the acoustic televiewer logs in figure 4. The apparent magnitude of change in hydraulic conductivity in vertical profile is depicted by the trend line inferred from the logarithmic values of hydraulic conductivity (log $K_{(H)}$) measured in each test interval. In general, the test results indicate that the overall hydraulic conductivity of the carbonate aquifer is low except where contributing fractures are present. Estimates of hydraulic conductivity ranged from 10^{-10} to 10^{-3} ft/s but a few fractures had hydraulic conductivities that exceeded the upper test limits (>10^{-2} ft/s).

Table 1. Summary of hydraulic conductivity data obtained by use of constant-head injection tests at selected open-borehole wells in south-central Louisville, Kentucky
[BLS, below land surface datum; >, greater than indicated value; ND, value could not be determined because of leakage around packer; <, less than indicated value]

Location (fig. 2)	Test	Open interval (feet BLS)	Average hydraulic conductivity (feet per second)	Stratigraphic unit
Air Guard	1	25-32.5	1.2 x 10^{-6}	Sellersburg Limestone
	2	35.5-43	>3.3 x 10^{-2}	Jeffersonville Limestone
	3	54-61.5	1.5 x 10^{-8}	Louisville Limestone
	4	72-79.5	3.6 x 10^{-7}	Louisville Limestone
	5	89-96.5	5.6 x 10^{-7}	Louisville Limestone
Beechmont	1	28-35.5	2.9 x 10^{-5}	Sellersburg Limestone
	2	40-47.5	7.2 x 10^{-4}	Jeffersonville Limestone
	3	53-60.5	3.3 x 10^{-6}	Jeffersonville Limestone
	4	65-72.5	ND	Louisville Limestone
	5	76-83.5	3.9 x 10^{-7}	Louisville Limestone
Iroquois	1	44-51.5	1.5 x 10^{-5}	New Albany Shale
	2	60-67.5	6.8 x 10^{-5}	New Albany Shale
	3	80-87.5	8.2 x 10^{-6}	New Albany Shale
	4	90-97.5	8.2 x 10^{-6}	New Albany Shale
	5	121-128.5	1.6 x 10^{-7}	New Albany Shale
	6	138-145.5	2.7 x 10^{-7}	Sellersburg/Jeffersonville Limestone
Petersburg	1	18-25.5	4.3 x 10^{-4}	Sellersburg/Jeffersonville Limestone
	2	31-38.5	1.5 x 10^{-3}	Jeffersonville Limestone
	3	52-59.5	>3.3 x 10^{-2}	Louisville Limestone
	4	70-77.5	<3.3 x 10^{-10}	Louisville Limestone
	5	96-103.5	<3.3 x 10^{-10}	Louisville Limestone

At the Iroquois site, the carbonate rocks are overlain by more than 100 ft of New Albany Shale. No ground water is contributed to the open-borehole well from the carbonate rocks. Contributing zones were identified in the upper half of the shale (fig. 4a), although no specific fractures could be identified on the caliper or acoustic televiewer logs. The hydraulic conductivity measurements obtained from four test intervals in the shale ranged from 10^{-5} to 10^{-7} ft/s. Although no contributing zones were identified in the Sellersburg and Jeffersonville Limestones, a hydraulic conductivity estimate of 10^{-7} ft/s was obtained for Test Interval 6 (fig. 4a), which included the stratigraphic contact between these two units.

Hydraulic conductivity and transmissivity estimates were also determined by pneumatic (air) slug tests conducted on the Air Guard, Beechmont, and Petersburg wells, and three additional wells (Auburndale, Bellevue, and Camp Taylor) that were not suitable for testing with packers because of borehole roughness. The tests were done in the manner described by Greene (1993) and test data were evaluated using the analytical solutions of Cooper and others (1967) or Ferris and others (1962). Estimates of the hydraulic conductivity obtained by the slug test method are averaged over the entire open-borehole interval of each well. These data are shown in table 2 for comparison with the estimates obtained by the constant-head injection tests.

Table 2. Summary of hydraulic conductivity data obtained by use of air slug tests at selected open-borehole wells in south-central Louisville, Kentucky
[BLS, below land surface datum; <, less than indicated value; ND, not determined]

Location (fig. 2)	Open interval (feet BLS)	Transmissivity (square feet per second)	Average hydraulic conductivity (feet per second)
Air Guard	27-106	7.1 x 10^{-2}	9.0 x 10^{-4}
Auburndale	41-116	8.0 x 10^{-4}	1.1 x 10^{-5}
Beechmont	30-98	1.2 x 10^{-1}	7.1 x 10^{-2}
Bellevue	51-102	1.2 x 10^{-4}	2.4 x 10^{-6}
Black Mudd	19-101	2.4 x 10^{-1}	2.9 x 10^{-3}
Camp Taylor	14-97	<1 x 10^{-5}	ND
Petersburg	19-107	2.9 x 10^{-1}	3.3 x 10^{-3}

The highest values for transmissivity were obtained for the Air Guard, Beechmont, and Petersburg wells, all of which are located near the outcrop boundary of the New Albany Shale confining unit. Lower values of transmissivity were obtained for the Auburndale well, which is the farthest downgradient from the outcrop boundary of the shale confining unit, and for the Bellevue well, which is completed in the Jeffersonville and Louisville Limestone. Transmissivity was estimated at 1.2 x 10^{-4} ft^2/s in the Bellevue well, which is about 3 orders of magnitude lower than that determined for most of the other wells near the boundary of the shale confining unit. The transmissivity of the Camp Taylor well, completed in the Louisville Limestone beyond the boundary of the shale confining unit, could not be estimated because it was outside the lower quantification limit of 10^{-5} ft^2/s.

Moldic, Vuggy Porosity and Permeability

Microscopic thin-section analysis of core samples from the Sellersburg and Jeffersonville Limestones revealed that the moldic, vuggy porosity often present in these strata is caused by the replacement of the original fossil grains by the carbonate mineral dolomite. The prominent skeletal molds indicate that the original fossil grains consisted of pelmatozoan echinoderms, coral fragments, gastropods, algal material, and bivalves. Molds of crinoid stems and plates dominate the thin sections of the Sellersburg Limestone, and subtle wavy bedding is visible in the form of micrite interbeds and layered dolomitic crystals. The horizontal microstylolites indicate that significant mechanical compaction and pressure dissolution occurred early in the diagenetic history of the carbonate sediments.

The secondary dolomite in the thin sections of the Sellersburg and Jeffersonville Limestone is fine-to-coarsely crystalline, with crystal size ranging from 0.015 to 0.3 millimeters. Well-formed rhombohedral crystals line the larger moldic vugs (figs. 5a and b), and pore spaces between the crystals appear to be poorly interconnected. Secondary minerals other than dolomite exist in trace amounts, and contribute to the limited interconnectivity between pores. Larger pores and vugs are often lined with microcrystalline clay, pyrite, iron oxide, and bitumen (asphaltic residue or crude oil). In the thin section of the Jeffersonville Limestone, microcrystalline pyrite and quartz are more abundant (than in the thin section of the Sellersburg Limestone), and conspicuous kaolinite plates are common.

Figure 5. Photomicrographs of moldic, vuggy porosity in the Sellersburg Limestone Formation: (A) scanning electron microscope image (125x magnification); (B) stained thin section under plane-polarized light (pore spaces indicated by pink areas) (40x magnification).

Hydraulic tests were performed in the laboratory on the core samples to quantify porosity and three-dimensional permeability of the vuggy, moldic porosity zones. These data are summarized in table 3. Porosity ranged from about 8 to 18 percent and was greater than 10 percent in 6 of 9 samples. Gas permeameter tests were used to obtain values for vertical hydraulic conductivity (Kv); the maximum hydraulic conductivity parallel to bedding (Kmax); and hydraulic conductivity at 90° to the maximum (K90). The results of these tests confirm that pore spaces are poorly interconnected, with the average maximum hydraulic conductivity values at or below 10^{-6} ft/s. Hydraulic conductivity values of this order of magnitude indicate that vuggy, moldic porosity zones are relatively impermeable and that ground-water flow through these zones is insignificant compared to that through the contributing fractures identified in the boreholes.

Table 3. Summary of porosity and hydraulic conductivity measurements for rock core samples collected at open-borehole well locations, south-central Louisville, Kentucky
[BLS, below land surface datum; K(max), maximum horizontal hydraulic conductivity; K(90), horizontal hydraulic conductivity measured 90 degrees to K(max); K(v), vertical hydraulic conductivity]

Location (fig. 2)	Sample depth (feet BLS)	Porosity (percent)	Hydraulic conductivity: K(max) (feet per second)	Hydraulic conductivity: K(90) (feet per second)	Hydraulic conductivity: K(v) (feet per second)	Stratigraphic unit
Air Guard	29	18.5	3.3 x 10^{-6}	2.0 x 10^{-6}	1.5 x 10^{-8}	Sellersburg Limestone
Auburndale	42	13.2	3.3 x 10^{-8}	3.0 x 10^{-8}	3.4 x 10^{-9}	Sellersburg Limestone
Beechmont	30	6.9	7.8 x 10^{-9}	2.3 x 10^{-9}	1.0 x 10^{-9}	Sellersburg Limestone
Iroquois	138	9.3	1.1 x 10^{-7}	6.7 x 10^{-8}	1.7 x 10^{-9}	Sellersburg Limestone
Okolona	103	8.6	1.3 x 10^{-7}	1.3 x 10^{-7}	2.6 x 10^{-8}	Jeffersonville Limestone
Okolona	117	16.2	4.2 x 10^{-7}	2.5 x 10^{-7}	3.7 x 10^{-9}	Jeffersonville Limestone
Petersburg	37	14.3	6.2 x 10^{-6}	2.0 x 10^{-6}	1.6 x 10^{-6}	Jeffersonville Limestone
Petersburg	67	17.6	7.9 x 10^{-6}	5.9 x 10^{-6}	2.1 x 10^{-7}	Jeffersonville Limestone
Petersburg	51	10.7	8.2 x 10^{-7}	6.1 x 10^{-7}	4.2 x 10^{-7}	Jeffersonville Limestone

Hydrogeologic Framework and Geochemistry of Ground Water and Petroleum in the Silurian-Devonian Carbonate Aquifer, South-Central Louisville, Kentucky

By Charles J. Taylor and Frances D. Hostettler

2002

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

PREPARED IN COOPERATION WITH THE
U.S. DEPARTMENT OF THE NAVY, SOUTHERN DIVISION,
NAVAL FACILITIES ENGINEERING COMMAND

WATER-RESOURCES INVESTIGATIONS REPORT 02-4123
SHEET 2 of 3
Taylor, C.J., and Hostettler, F.D., 2002, Hydrogeologic Framework and Geochemistry of Ground Water
and Petroleum in the Silurian-Devonian Carbonate Aquifer, South-Central Louisville, Kentucky

Ground-Water Flow

Water-level measurements collected during September 2000 were used to map the potentiometric surface of the carbonate aquifer (fig. 6). Artesian conditions existed in all wells except Camp Taylor, with water levels ranging from about 3 ft above the top of the Sellersburg Limestone at the Black Mudd and Petersburg sites to more than 45 ft above the top of the limestone at the Bellevue site. Hydraulic heads in the aquifer ranged from approximately 450 to 500 ft above mean sea level, were highest to the north and east, and were lowest to the west and southwest. The contoured potentiometric surface mimicked the bedrock structure contours (fig. 2), indicating that ground-water flow in the carbonate aquifer is structurally controlled.

A major ground-water-flow divide was inferred at or near the NOSL site that was approximately coincident with the mapped axis of the Springdale anticline (fig. 2). North of the divide, ground-water flow was to the west. South of the divide, ground-water flow was to the south-southwest, generally following the structural trends of the Lyndon syncline (fig. 2). Hydraulic gradients were steepest near the ground-water divide and ranged from 20 to 30 ft/mi. A major ground-water trough was inferred within the area of the Lyndon syncline, where hydraulic gradients decreased significantly and ranged from 10 to less than 5 ft/mi. Relatively sluggish ground-water-flow velocities and long ground-water residence time may be anticipated to occur in most parts of the carbonate aquifer.

GEOCHEMISTRY OF GROUND WATER IN THE CARBONATE AQUIFER

An initial round of ground-water samples were collected during July 1999 from the Airport, Air Guard, Auburndale, Beechmont, Bellevue, Black Mudd, Camp Taylor, Iroquois, and Petersburg wells. These samples were analyzed for inorganic constituents, stable isotope composition, tritium content, and were screened for dissolved organic chemical compounds. A second round of ground-water samples was collected in September 2000 from these same wells; from three wells at the NOSL site (MW-13S, MW-13I, and MW-19S); two wells at the Outer Loop Landfill (OLGD-206 and OLGD-210); and Duck Spring. The second round of samples was analyzed for selected inorganic constituents, stable isotope composition, and tritium content. Analytical results for inorganic constituents, stable isotopes, and tritium obtained from both ground-water sampling rounds are provided in table 4.

Water samples for major dissolved species and trace elements were collected using standard techniques described by Koterba and others (1995) and Wilde and others (1998). Wells were purged and sampled using a submersible pump and Teflon® tubing at discharge rates of 1.0 gal/min or less. Field water-quality parameters—specific conductance, dissolved oxygen, pH, and temperature—were measured while purging using a flow-through chamber to prevent contact between the water sample and the atmosphere. All water samples were collected after the equilibration of the field water-quality parameters and preserved using USGS protocols (Wilde and others, 1998; Wilde and Radtke, 1998). Water samples also were collected and titrated with acid in the field to determine concentrations of carbonate and bicarbonate.

Field Water-Quality Parameters

Specific conductance of ground-water samples ranged from 762 to 26,745 µS/cm at 25°C and is greater than 1,000 µS/cm at 25°C in most wells (table 4). Concentrations of dissolved oxygen were at or near the detection limit (±0.2 mg/L) for the field probe and indicated that anaerobic conditions were present throughout most of the aquifer. The pH of samples ranged from near neutral to slightly alkaline (6.18 to 7.36). Alkalinity ranged from 300 to 528 mg/L as $CaCO_3$. Alkalinity values obtained for water samples collected from some wells, particularly the Airport and Auburndale sites, were anomalously high, and may have been biased by organic acids associated with petroleum (Hem, 1989).

Inorganic Constituents

Inorganic constituents detected at the highest concentrations included ionic species associated with the dissolution of carbonate minerals and with residual brine (often termed "connate" or "formation" waters) (table 4). These include bicarbonate, calcium, chloride, magnesium, potassium, sodium, and sulfate. The ground-water samples can be subdivided by major-ion composition into two dominant water types: (1) a "saline" or sodium-chloride dominated water, and (2) a "fresh" or calcium-magnesium-bicarbonate dominated water (fig. 7). In addition to these, two "mixed" water types are also distinguishable, differing by the relative amount of chloride and varying proportions of major cations contributed by the saline and freshwater end-members. Chloride concentrations in the saline water samples ranged from 1,000 to more than 17,000 mg/L. Significant concentrations of the trace elements barium, boron, bromide, lithium, and strontium were also detected in these samples. These constituents are often associated with the dissolution of evaporite minerals or with residual brines in sedimentary basins (Hem, 1989).

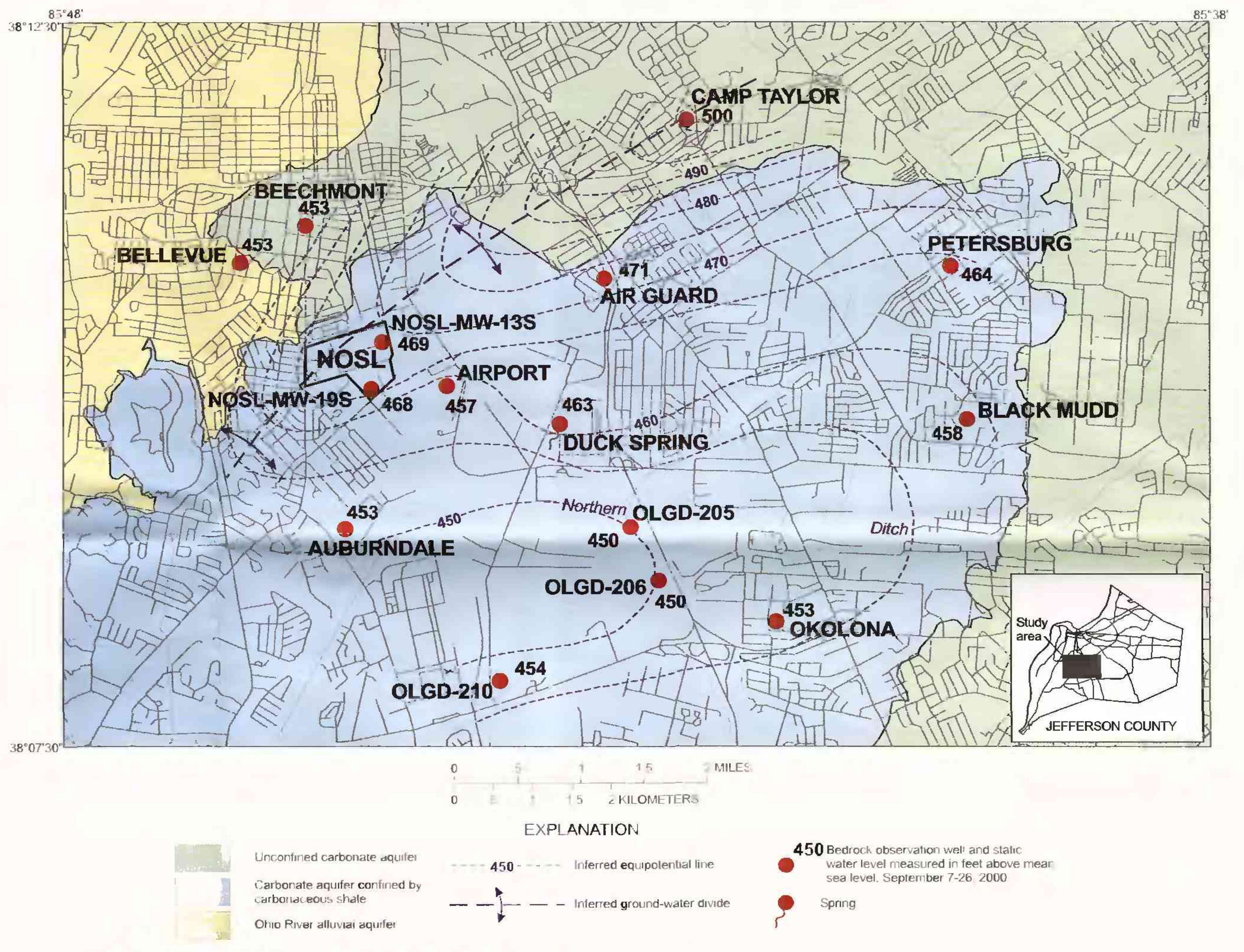


Figure 6. Potentiometric surface map for the Silurian-Devonian carbonate aquifer, south-central Louisville, Kentucky.

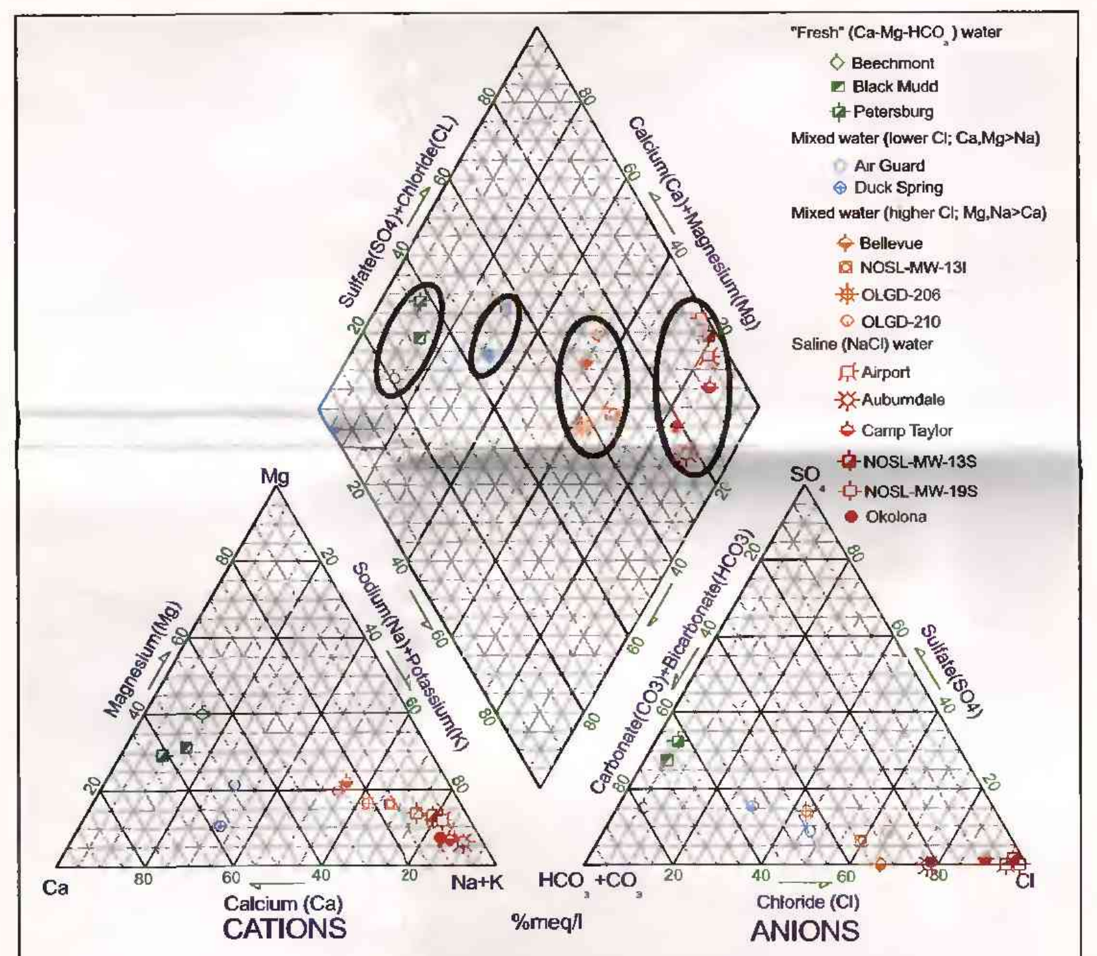


Figure 7. Major-ion composition of ground-water samples collected in September 2000, south-central Louisville, Kentucky.

Concentrations of most inorganic constituents detected in those wells that were sampled twice exhibited little temporal variation. The Bellevue well, located where the fractured Jeffersonville Limestone is overlain by alluvial sediments, is an exception in that the concentrations of most inorganic constituents were considerably lower in samples collected in September 2000 compared to July 1999. The lower concentrations of dissolved constituents detected in ground-water samples from this well in September 2000 may be related to better development of sediment-choked fractures during the second round of well purging.

Organic Compounds

Dissolved organic compounds detected in ground-water samples (table 5) are associated with petroleum hydrocarbons in the carbonate aquifer. Aromatic hydrocarbon compounds—ethylbenzene, toluene, and xylene—were detected at low concentrations in ground-water samples collected from the Airport and Auburndale wells, and from the Iroquois well, which is recharged only by the New Albany Shale. Concentrations of aromatic hydrocarbons in samples from all other wells were at or below minimum detection limits. Several semivolatile organic compounds—napthalene, phenanthrene, chrysene, fluorene, and phenol—also were detected at low concentrations in samples from the Airport and Auburndale wells. Chlorinated hydrocarbons, which are common ground-water contaminants in urbanized or industrialized areas, were not detected above the minimum quantification limits in any of the samples collected from the carbonate aquifer.

Table 5. Dissolved organic compounds detected in ground-water samples from selected open-borehole wells in south-central Louisville, Kentucky

[All concentrations reported in micrograms per liter (µg/L); ND, concentration below minimum detection limit]

Constituent	Location (fig. 2)		
	Airport	Auburndale	Iroquois
Benzene	116	22	2
Ethylbenzene	62.2	14.7	1.2
Xylene	94.9	93.7	1.6
Toluene	193	96	2.2
Napthalene	7.7	13.8	1
Phenanthrene	7	6	ND
Chrysene	2	1	ND
Fluorene	1	3	ND
Phenol	454	158	ND

Stable Isotopes and Tritium

The concentrations of deuterium (δ^2H) and oxygen-18 ($\delta^{18}O$) shown in table 4 are measured as the ratio of the heavy isotope relative to the lighter, more abundant isotope (δ^1H and $\delta^{16}O$, respectively) normalized to the Vienna Standard Mean Ocean Water (VSMOW). Analyses of δ^2H and $\delta^{18}O$ were determined by use of hydrogen equilibration techniques and are reported in parts per thousand (per mil, or o/oo). Negative values indicate the depletion of the heavy isotope relative to the lighter, more common isotope in the water sample. Concentrations of δ^2H detected in ground-water samples ranged from -30.7 to -42.6 per mil. Concentrations of $\delta^{18}O$ detected in the samples ranged from -5.3 to -6.9 per mil. The stable isotope composition of all water samples collected in September 2000 plots near the global meteoric water line of Craig (1961) (fig. 8), indicating that ground water in the aquifer is derived from the infiltration of modern precipitation.

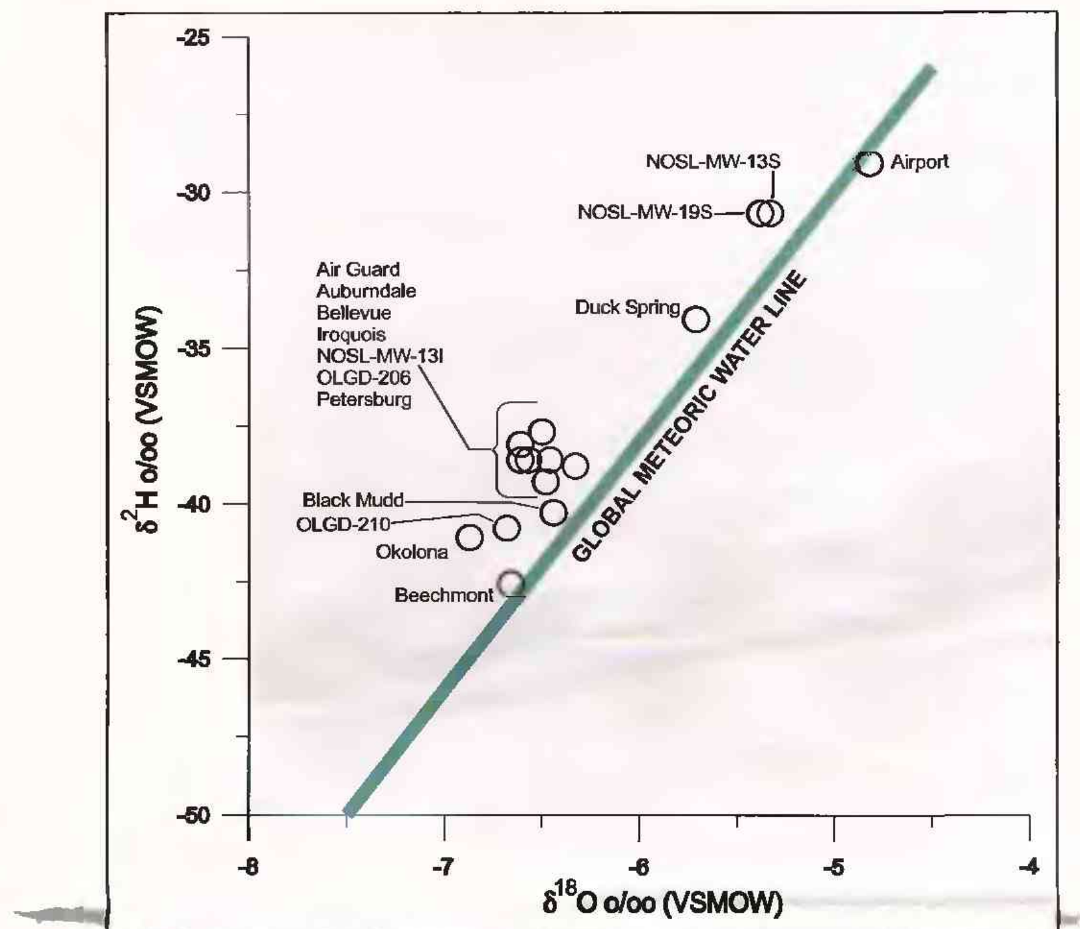


Figure 8. Stable isotope composition of ground-water samples collected in September 2000, south-central Louisville, Kentucky.

Water samples also were analyzed for the radioisotope tritium (δ^3H), according to methods described by Michel (1989). Concentrations of tritium were determined by liquid scintillation with a reproducibility of 3.2 to 4.5 tritium units (TU's). Detectable concentrations of tritium were present in all samples except well NOSL MW-19S, and ranged from 1.8 to 16.2 TU's. Concentrations of tritium declined slightly from July 1999 to September 2000 in wells that were sampled twice. Concentrations of tritium can be used to qualitatively evaluate the residence time of ground water in well-mixed aquifers in fractured rock or in karstic aquifers (Clark and Fritz, 1997). In general, ground water with less than 5 TU's in shallow aquifers is a mixture of water recharged prior to 1952 and more recent recharge, and water having 5 to 15 TU's is a mixture of modern water recharged from about 1985 to the present (Clark and Fritz, 1997). The apparent significance of spatial trends in the tritium concentration data will be explained further in the following section of the report.

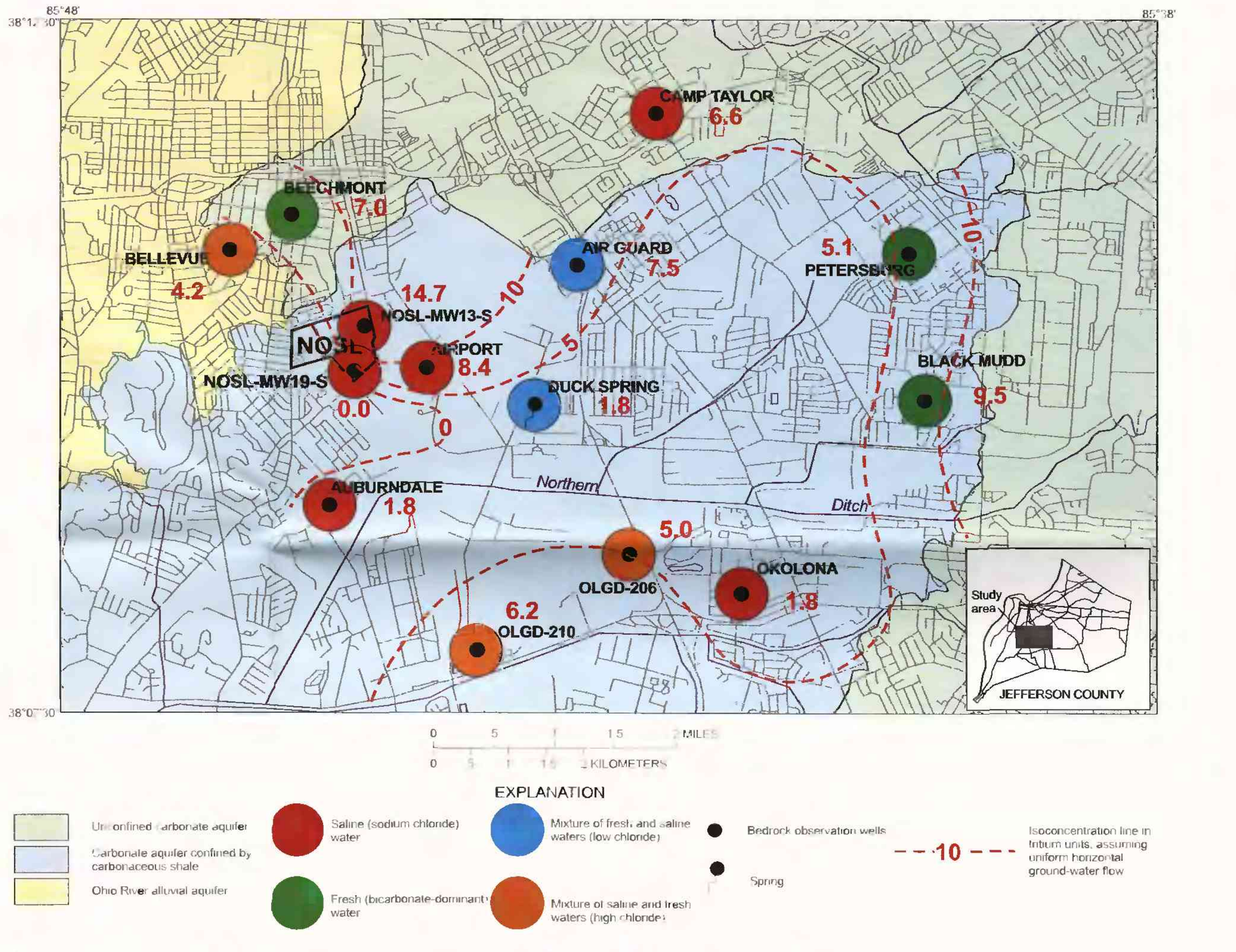


Figure 9. Major-ion composition and tritium in ground-water samples collected in September 2000, south-central Louisville, Kentucky.

Use of Geochemistry to Further Define the Ground-Water Flow System

Spatial trends in the major ion, stable isotope, and tritium composition of ground-water samples were evaluated to obtain further insights about ground-water flow patterns and the effects of the hydrogeologic framework of the aquifer system on ground-water chemistry, recharge, and mixing.

In general, wells that exhibited bicarbonate-dominated water and higher concentrations of tritium (greater than 5 TU's) are hydraulically upgradient and nearest to the outcrop boundary of the shale confining unit (fig. 9). This stratigraphic boundary also marks the transitional boundary between the unconfined and confined aquifer zones, and is the apparent recharge boundary for the confined aquifer zone. The results of slug and constant-head injection tests indicated that transmissivity and hydraulic conductivity are higher in wells in this part of the aquifer. It is therefore inferred that fracture and dissolution permeability are more enhanced and that the major ion and tritium composition of ground water is related to the greater infiltration and circulation of fresh meteoric recharge and shorter ground-water residence times.

In contrast, wells that exhibited saline water and lower concentrations of tritium (less than 5 TU's) are hydraulically downgradient and farther from the shale outcrop/aquifer recharge boundary. The results of slug tests and constant-head injection test data on saline water/lower tritium wells indicated that transmissivity and hydraulic conductivity are low. It is therefore inferred that both fracture and dissolution permeability are less well developed in these parts of the confined aquifer and that the major ion and tritium composition of ground water is related to residual brine, greatly restricted infiltration and circulation of fresh meteoric recharge, and longer ground-water residence times.

An exception to these two generalizations occurs where the fracture permeability of the shale confining unit is locally enhanced, but the large-scale transmissivity of the carbonate aquifer is not. This seems to best explain the high concentrations of tritium in saline water detected at the NOSL MW-13S well, the Airport well, and the OLGD-206 and 210 wells. At these locations, vertical infiltration through the shale must allow a fraction of younger recharge water to enter the carbonate aquifer. However, the transmissivity of the carbonate aquifer must be too low in these locations to allow the saline water to be completely flushed or significantly diluted by the influx of fresh meteoric recharge.

Duck Spring is a special case in that its water chemistry is affected by changes in the proportion of water contributed by the rapid-flow and slow-flow components of the spring recharge. The presence of bicarbonate water indicates that dissolution of carbonate minerals is occurring and fresh meteoric water is providing recharge to the spring. However, the mixed bicarbonate and saline water type exhibited by the spring and the low concentration of tritium detected in the September 2000 sample (1.8 TU's) indicates that the spring's recharge at the time of sample collection was dominated by older, highly mineralized water contributed from storage in fractures, smaller conduits, or the overlying alluvium.

The indication that large-scale variations in transmissivity in the aquifer act either to enhance or restrict the flushing or dilution of residual brines is supported by analysis of the conservative natural tracers chloride and $\delta^{18}O$. Brines in sedimentary basins are typically enriched with respect to $\delta^{18}O$ and δ^2H (Clark and Fritz, 1997) and any ground-water samples that represent diluted brine might be expected to retain some trace of that isotopic signature—plotting to the right of the global meteoric water line shown in figure 8. Although the plot of isotopic composition for the ground-water samples from the study area is not shifted to the right of the global meteoric water line, the samples obtained from NOSL MW-13S, NOSL MW-19S, and the Airport well seem to be slightly enriched in $\delta^{18}O$ and δ^2H relative to the others. This apparent difference in water composition is clarified by plotting the concentration of chloride relative to $\delta^{18}O$ for all ground-water samples (fig. 10). On this plot, the ground-water samples cluster into three distinctive groups: (1) a low chloride and depleted $\delta^{18}O$ group, (2) a moderate chloride and depleted $\delta^{18}O$ group, and (3) a high chloride and less depleted $\delta^{18}O$ group.

The low chloride/depleted $\delta^{18}O$ group is defined by samples from three wells that are located near the recharge boundary for the confined aquifer zone (Beechmont, Black Mudd, and Petersburg), and represent an end-member dominated by fresh meteoric recharge. The high chloride/less depleted $\delta^{18}O$ group is defined by the samples from NOSL MW-13S, NOSL MW-19S, and the Airport well, is enriched in $\delta^{18}O$ and chloride, and represents another end-member that may be closest in chemical composition to the residual brine.

Most of the ground-water samples plotted on figure 10 cluster within the moderate chloride/depleted $\delta^{18}O$ group. This group represents ground water derived from the mixing of fresh meteoric water (the low chloride/depleted $\delta^{18}O$ group) with residual brine (the high chloride/less depleted $\delta^{18}O$ group) in different proportions. Overall, the water chemistry of this intermediate (mixed) group is much closer in composition to that of the fresh meteoric water even where chloride concentrations are high. This can be demonstrated using the geochemical modeling program NETPATH (Plummer and others, 1994) to determine hypothetical mixing ratios between water from the low chloride/depleted $\delta^{18}O$ group and water from the high chloride/less depleted $\delta^{18}O$ group. These water types are represented by the Petersburg and NOSL MW-19S wells, respectively.

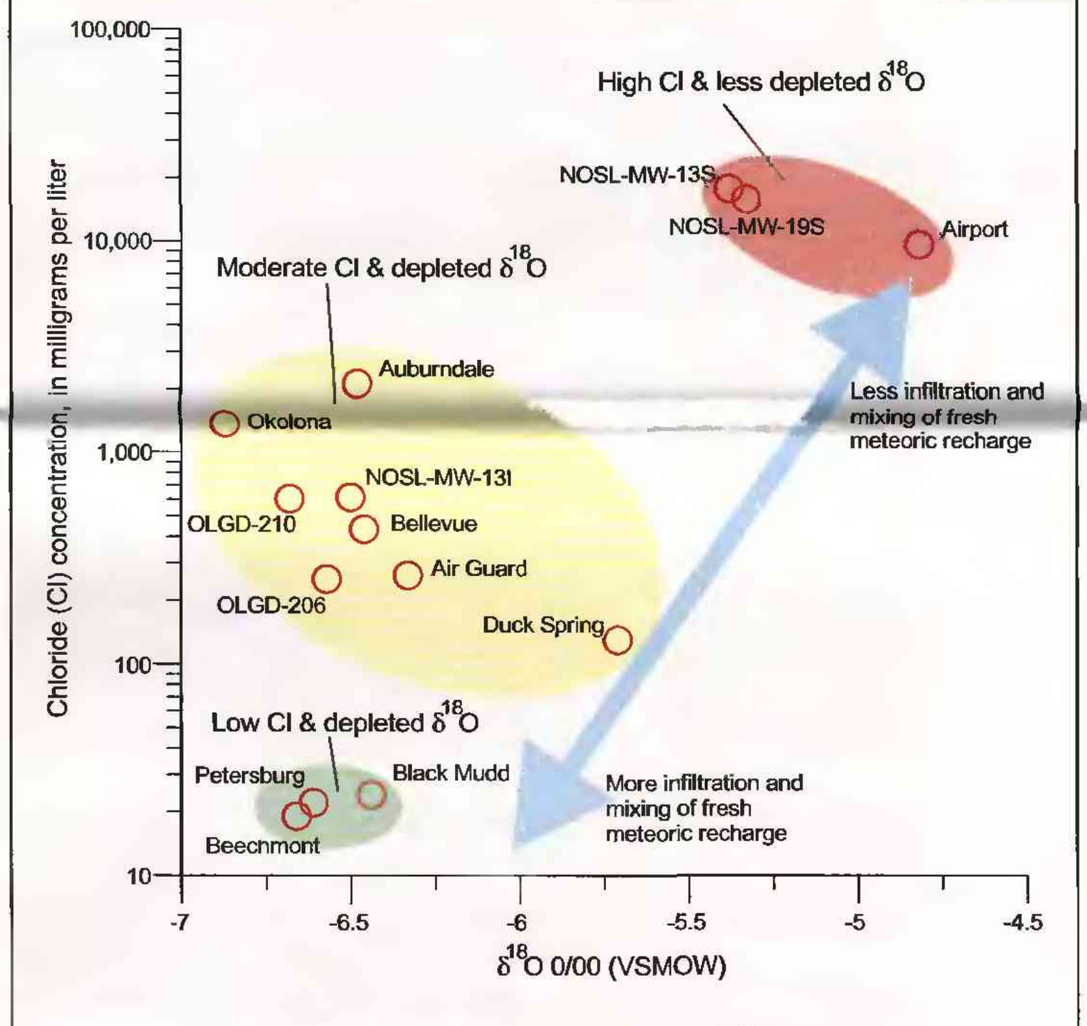


Figure 10. Ground-water subtypes determined by chloride and $\delta^{18}O$ composition, and their relation to the relative amount of infiltration and mixing of fresh meteoric recharge in the carbonate aquifer system, south-central Louisville, Kentucky.

Table 4. Physical properties, inorganic constituents, and isotopes in ground-water samples collected from selected wells and a spring in the carbonate aquifer in south-central Louisville, Kentucky

[All values reported in milligrams per liter (mg/L) unless otherwise indicated; °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; --, no data; δ18O, oxygen-18 isotope; o/oo, parts per thousand; δ2H, deuterium; δ3H, tritium; TU, tritium units; <, less than stated value]

Location (fig. 2)	Date sampled	Water temperature (°C)	Specific conductance (µS/cm)	pH	Dissolved oxygen	Dissolved solids	Alkalinity (mg/L as $CaCO_3$)	Bicarbonate (mg/L as $CaCO_3$)	Calcium	Magnesium	Potassium	Sodium	Chloride	Silica	Sulfate	Barium	Boron	Bromide	Dissolved organic carbon	Fluoride	Iron	Manganese	Lithium	Strontium	$\delta^{18}O$ (o/oo)	δ^2H (o/oo)	δ^3H (TU)
Air Guard	07/99	16.4	1,383	6.89	0.1	991	375	458	127	35.8	6.22	91.8	190	13	67.3	0.48	0.1	--	2.0	--	0.04	0.28	0.01	0.54	-6.3	-40.5	5.6
	09/00	21.7	1,530	6.48	.3	1,071	353	430	151	39.9	5.64	102	262	13.2	67.3	.5	.08	0.19	--	0.22	.05	.3	.01	.62	-6.3	-38.8	7.5
Airport	07/99	19.4	26,745	7.1	2.14	16,213	[1]675	[1]824	357	412	173	5,228	9,705	6.75	8.92	5.8	1.9	--	13	--	.44	.01	4.43	18.7	-6.3	-38.5	1.8
	09/00	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	8.4
Auburndale	07/99	16.9	7,085	7.23	1.75	4,146	[1]981	[1]1,196	74.4	51.3	108	1,373	1,918	7.61	17.1	3.9	1.65	--	2.9	--	.04	.01	1.36	5.16	-6.6	-40.6	1.8
	09/00	17.2	7,932	6.59	.09	4,873	[1]878	[1]1,054	67	54.7	122	1,445	2,120	9.1	1.1	3.87	1.66	12.4	--	1.18	.13	.02	1.52	6.18	-6.5	-39.3	1.8
Beechmont	07/99	17.6	790	6.9	.13	712	374	456	85.4	43.7	18	21.9	21.2	12.6	70.7	.23	.13	--	2.1	--	.31	.15	.02	1.2	-6.6	-41.7	6.6
	09/00	18.8	762	6.29	.09	691	359	438	84.6	43.6	1.69	26.1	18.8	13	65.5	.23	.15	.09	--	.42	.03	.15	.02	1.26	-6.7	-42.6	7
Bellevue	07/99	17.4	--	7.36	.11	11,549	354	432	398	228	30.9	3,677	6,725	10.4	37.6	83	.7	--	2	--	.39	.02	2.55	39.4	-5.9	-35.2	1.8
	09/00	17.7	1,970	6.88	.1	1,181	300	366	86.5	49.4	2.95	272	432	11.8	43	.42	.14	1.99	--	.44	.6	.03	.17	2.9	-6.5	-38.6	4.2
Black Mudd	07/99	15.4	1,232	6.77	.13	1,060	465	568	143	46.8	4.86	55.4	29.7	19.1	192	.1	.35	--	2.7	--	.18	.39	.05	.79	-6.4	-41.4	16.2
	09/00	17.6	1,173	6.25	.07	1,057	476	581	148	50.6	3.19	41.4	24.4	22.1	187	.02	.2	.3	--	.54	.02	.58	.04	.38	-6.5	-40.3	9.5
Camp Taylor	07/99	16.2	7,948	7.23	.18	4,437	313	382	108	62.4	16	1,491	2,319	12.3	46.6	2.79	1.17	--	8	--	.09	<.01	1.35	6.89	-6.7	-40.5	1.8
	09/00	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	6.6
Duck Spring	09/00	20	1,194	6.55	4.01	879	328	400	140	15.6	3.65	87.1	130	13.9	89.2	.06	.07	.11	--	.16	.01	.01	<.01	.19	-5.7	-34.1	1.8
NOSL-MW13-I	09/00	25.3	3,170	6.96	.12	1,907	496	605	93.4	35.4	10.9	433	610	12.3	87.1	.56	1.16	3.81	--	.65	.3	.04	.28	4.46	-6.5	-33.7	4.8
NOSL-MW13-S	09/00	23.5	4,180	6.29	.2	26,679	516	630	719	707	541	7,812	15,887	9.82	373	1.54	1.79	86.8	--	.35	.66	.1	6.09	101	-5.3	-30.7	14.7
NOSL-MW19-S	09/00	22.7	--	6.18	.72	28,938	380	464	1,124	845	68.2	8,623	17,790	9.11	3.9	33.8	2.46	102	--	.24	1.17	.15	6.3	112	-5.4	-30.7	0
Okolona	09/00	15.7	5,332	6.39	.03	3,085	528	644	84.9	43.2	11.9	909	1,369	8.12	15.5	6.82	1.2	8.84	--	.95	.05	.08	.91	3.68	-6.9	-41.1	1.8
OLGD-206	09/00	20.3	1,590	6.96	.21	1,837	352	429	213	100	6.51	712	251	13.7	112	.15	4.12	1.35	--	.91	.02	.06	.42	6.26	-6.6	-38.6	5
OLGD-210	09/00	16.9	2,590	6.74	.08	1,688	362	443	135	60.4	7.86	309	610	13	111	.21	.31	3.41	--	.79	.04	.14	.24	3.7	-6.7	-40.8	6.2
Petersburg	07/99	16.4	1,126	6.77	.01	977	385	470	151	45.1	3.73	27.6	39.3	18.7	221	.08	.06	--	2.6	--	.8	.46	.02	.23	-6.6	-40.3	8.6
	09/00	17.1	1,095	6.44	.2	916	383	467	148	43.1	2.96	24.1	21.6	19.3	190	.07	.06	.22	--	.32	.65	.4	.01	.22	-6.6	-38.1	5.1

[1] Titrated alkalinity and bicarbonate values likely affected by organic acids associated with petroleum hydrocarbons.

Hydrogeologic Framework and Geochemistry of Ground Water and Petroleum in the Silurian-Devonian Carbonate Aquifer, South-Central Louisville, Kentucky

By Charles J. Taylor and Frances D. Hostettler

2002

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

PREPARED IN COOPERATION WITH THE
U.S. DEPARTMENT OF THE NAVY, SOUTHERN DIVISION,
NAVAL FACILITIES ENGINEERING COMMAND

WATER-RESOURCES INVESTIGATIONS REPORT 02-4123
SHEET 3 of 3
Taylor, C.J., and Hostettler, F.D., 2002, Hydrogeologic Framework and Geochemistry of Ground Water and Petroleum in the Silurian-Devonian Carbonate Aquifer, South-Central Louisville, Kentucky

NETPATH was used to calculate the proportions of fresh (Petersburg) water and saline (NOSL MW-19S) water needed to generate a final mixed water having a chloride composition similar to three wells from the moderate chloride/depleted $\delta^{18}O$ group—Auburndale, OLGD-210, and Air Guard. Each of these wells represents a different water subtype plotted on the Piper diagram in figure 7, with chloride concentrations decreasing respectively from the former to the later. The calculated mixing ratios are as follows:

(1) 89 percent Petersburg well water (fresh) + 11 percent NOSL MW-19S well water (saline) ➞ Auburndale water.

(2) 97 percent Petersburg well water (fresh) + 3 percent NOSL MW-19S well water (saline) ➞ OLGD-210 water.

(3) 99 percent Petersburg well water (fresh) + 1 percent NOSL MW-19S well water (saline) ➞ Air Guard water.

One interpretation of these mixing model results is that chloride concentrations decrease as the proportion of fresh, bicarbonate-dominated water in the aquifer increases. In the context of the hydrogeologic framework, this interpretation supports the conclusion that saline water (representing residual brine) is restricted to locations in the aquifer where large-scale transmissivity is very low and that fresher recharge water circulating through the more transmissive parts of the aquifer is diluting the residual brine or flushing it from the aquifer. Another conclusion, given the positions of the three wells representing the final mixed water types relative to the outcrop boundary of the shale confining unit and the hydraulic gradient, is that recharge from the unconfined, more karstified part of the aquifer is freshening the water in the confined part of the aquifer.

Mixing ratios using $\delta^{18}O$ as a tracer also were evaluated using NETPATH; however, a mixing model could only be obtained for the Petersburg well water + NOSL MW-19S well water ➞ Air Guard water scenario, with calculated mixing ratios of 82 and 18 percent, respectively. Although this mixing ratio is considerably different from the one obtained using chloride, it also indicates that a greater proportion of fresh meteoric water is providing recharge to the aquifer at this location. Mixing models could not be obtained for the two other hypothetical mixing scenarios using $\delta^{18}O$ as a tracer. A possible explanation for these results is that the $\delta^{18}O$ composition is more directly affected by the isotopic signature of meteoric recharge than chloride is, and because of increasing homogenization as meteoric water contributed by different recharge events migrates downgradient and mixes within the aquifer.

GEOCHEMISTRY OF PETROLEUM IN THE CARBONATE AQUIFER

Petroleum, in the form of crude oil and natural gas, is common in Silurian-Devonian rocks throughout the Illinois Basin, including the Sellersburg and Jeffersonville Limestones (Barrows and Cluff, 1984). Although shows of oil and natural gas are often encountered in exploratory boreholes, no commercially productive oil or gas pools have been identified in Jefferson County, Kentucky (Wilson and Sutton, 1973). The principal source of the petroleum in the Illinois Basin is kerogen in the organic-rich sediments of the New Albany Shale (Barrows and Cluff, 1984; Hamilton-Smith, 1993). The petroleum most likely migrated from the center of the basin where it was generated and thermally matured after the basin sediments were fully compacted, and in response to a northward flow system established in the late Paleozoic and Mesozoic during regional tectonic uplift (Bethke and others, 1991).

Methods of Analysis

Petroleum entrained in moldic pores and hairline fractures in cores of the Sellersburg and Jeffersonville Limestones (figs. 11a and b), and occurring as a floating layer of immiscible oil in the Airport and Auburndale wells, was sampled and sent to a USGS research laboratory in Menlo Park, California, for analysis of organic geochemical constituents. Bitumen (or kerogen) extracted from fresh representative samples of the New Albany Shale also was collected for analysis. Sample preparation was done in the manner described by Hostettler and others (1999). Oil-laden rock was pulverized to coarse sediment, which was ground further to pass a 32-mesh screen, and petroleum samples suitable for analysis were obtained from the sediment by microwave extraction. Liquid-oil samples were prepared for analysis by dissolution in dichloromethane solvent. All petroleum samples were treated with acid-activated copper to remove sulfur and were fractionated on aluminum-silica gel columns to separate the aromatic and aliphatic hydrocarbon fractions.

Figure 11. Petroleum staining in (A) moldic porosity zone in the Sellersburg Limestone and (B) nearly vertical fractures in the Jeffersonville Limestone.

The two hydrocarbon fractions obtained for each petroleum sample were analyzed by gas chromatography and mass spectroscopy (GC/MS) in full-scan and selected-ion-monitoring (SIM) modes. Full-scan GC/MS analysis of the aromatic and aliphatic fractions and total-ion chromatograms (TIC's) were used for a semi-quantitative comparison of napthalenes, phenanthrenes, chrysenes, and triaromatic steranes. SIM chromatograms were used to identify and calculate the ratios of weathering-invariant aliphatic hopane and sterane biomarkers. Biomarkers are organic compounds having molecular carbon structures that are related to biologic precursors, petrogenic source or depositional environment, and petroleum maturity (Peters and Moldowan, 1993; Kvenvolden and others, 1995). The evaluation of biomarker ratios is ideal for semi-quantitative comparisons of the similarities and differences between oils, or between oils and source rocks (Peters and Moldowan, 1993; Hunt, 1996; Hostettler and others, 1999).

Organic Geochemistry and Biomarkers

Petroleum samples from the study area had organic geochemical characteristics very similar to those of Devonian crude oils characterized by Hatch and others (1991). TIC's of the aliphatic hydrocarbon fractions were dominated by *n*-alkanes (paraffins), in a typical crude-oil envelope, had chromatographic peaks that ranged from about C_{11} to C_{37} with maximum peaks around C_{21}, and isoprenoids, which are regularly branched hydrocarbons, that were dominated by pristane (C_{19}) and phytane (C_{20}) (fig. 12a). TIC's of the aromatic hydrocarbon fractions indicated the presence of several groups of hydrocarbon constituents, including napthalenes, phenanthrenes, chrysenes, and triaromatic steranes (fig. 12b). A typical fresh crude-oil sample is often dominated by C1 to C4 alkylated naphthalenes and phenanthrenes. Although these compounds were present in the samples, they were not the dominant hydrocarbon constituents, especially in petroleum samples obtained from the Sellersburg Limestone. Instead, these samples were dominated by a suite of C_{10} to C_{23}, and higher, monomer aryl isoprenoids, also known as 2-alkyl-1,3,4-trimethylbenzenes (fig. 12b).

The SIM chromatograms for the aliphatic fractions of all samples indicated typical crude-oil constituents in the hopane (mass/charge ratio = 191) and sterane (mass/charge ratio = 217) groups (figs. 13a and b). Biomarker parameters calculated from these groups and used to correlate or differentiate between the samples are listed in table 6 and include the following:

(1) **Pr/Ph**—the pristane and phytane ratio—a common source indicator used to characterize oil source (Hunt, 1996).

(2) **Triplet**—the ratio of the sum of C_{26} tricyclic terpanes to C_{24} tetracyclic terpanes—a source parameter first noticed in a study of North Slope crude oil discharged during the Exxon Valdez spill (Kvenvolden and others, 1995).

(3) **Tm/Ts**—the ratio between 17α-22,29,30-trisnorhopane and 18α-22,29,30-trisnorhopane—a source and maturity indicator (Peters and Moldowan, 1993).[1]

(4) **C_{30}/C_{29}**—the ratio between 17α,21β(H)-hopane and 17α,21β(H)-30-norhopane—a source-rock indicator (Peters and Moldowan, 1993).[1]

(5) **C_{31} S/S+R**—the ratio between 17α,21β(H)-homohopane (22S) and 17α,21β(H)-homohopane (22S) + (22R)—a terpane-maturity indicator used extensively in petroleum geochemistry (Peters and Moldowan, 1993).[1, 2]

(6) **C_{29} S/S+R**—the ratio between 24-ethyl-5α,14α,17α(H)-cholestane (20S) and 24-ethyl-5α,14α,17α(H)-cholestane (20S) + (20R)—a sterane-maturity indicator (Hostettler and others, 1999).[1, 2]

(7) **GI**—the gammacerane index—an indicator of the salinity of the depositional environment (Hunt, 1996).

(8) **RI**—the refractory index—determined by the ratio of triaromatic sterane to methyl chrysene refractory constituents, used as a source indicator (Hostettler and others, 1999).

Evaluated collectively, these biomarker parameters indicate that the petroleum samples from the Sellersburg and Jeffersonville Limestones in the study area represent a mature crude oil, derived from Type II kerogen, originally deposited in a saline-to-hypersaline, mixed carbonate and clastic environment. The hopane and sterane profiles for the sample from the Jeffersonville Limestone at Petersburg Park (sample number KD7) are significantly different from all the samples from the Sellersburg Limestone (KD1, KD4, and KD5). The Jeffersonville Limestone sample is much more weathered than the other samples, with the effects of weathering seen in the prominence of pristane and phytane over the *n*-alkanes; however, weathering is not advanced enough to affect the evaluated biomarker parameter ratios.

Oil-source rock correlations are more problematic than oil-oil correlations because of fractionation processes that occur as the oil is generated and migrates from the rock (Hunt, 1996). Compositional differences between a sampled oil and any particular source rock may be observed because the oil found within large, structurally complex, sedimentary basins is typically a mixture of petroleum fluids generated from different source rocks or different locations in the same source rock (Hunt, 1996). The Jeffersonville Limestone petroleum sample may represent an oil related to, but derived from different source rock than that for the Sellersburg Limestone samples; a different fractionation of the oil derived from the same source rocks as the petroleum in the Sellersburg Limestone; or a mixture of the two. Biomarker parameters calculated for kerogen samples from the New Albany Shale (KD2, KD3, and KD6 on table 6) are similar but distinctively different from those for the petroleum samples from the Sellersburg and Jeffersonville Limestones. In particular, the kerogen samples were less mature as seen in the higher Tm/Ts values (2.3 to 2.6 compared to 1.1 to 1.2); the lower sterane C_{29} S/(S+R) values (0.35 to 0.41 compared to 0.45 to 0.46); and the sterane distribution where the shales were dominated by the ααα C_{29} R component with a lower relative level of diasteranes. This difference in maturity is compatible with the interpretation that the New Albany Shale is a potential source rock, and the petroleum in the limestone is an expelled oil.

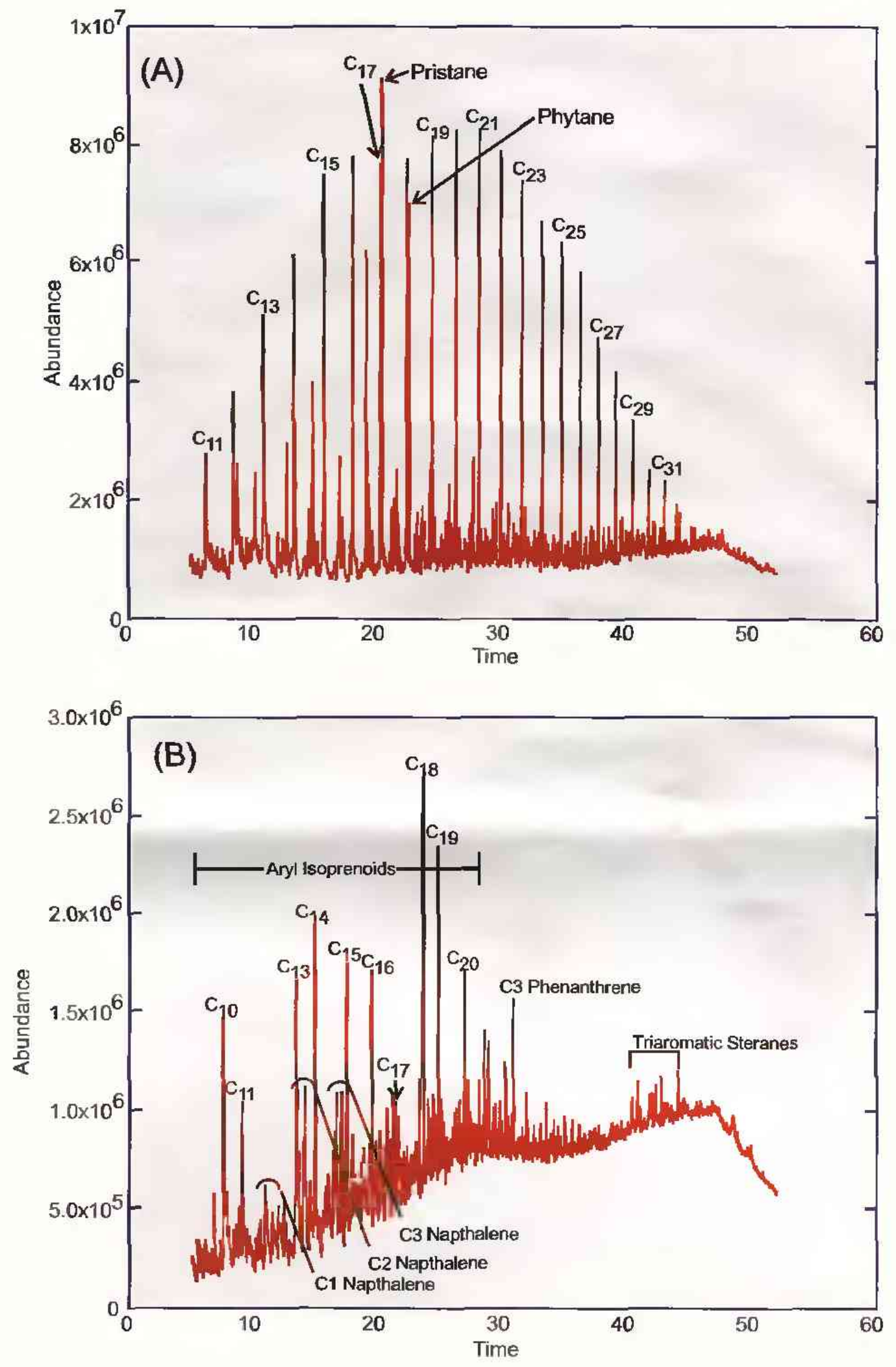


Figure 12. Chromatograms showing organic geochemical constituents in the (A) Aliphatic and (B) Aromatic Hydrocarbon fractions of a petroleum sample from the Louisville International Airport corehole site.

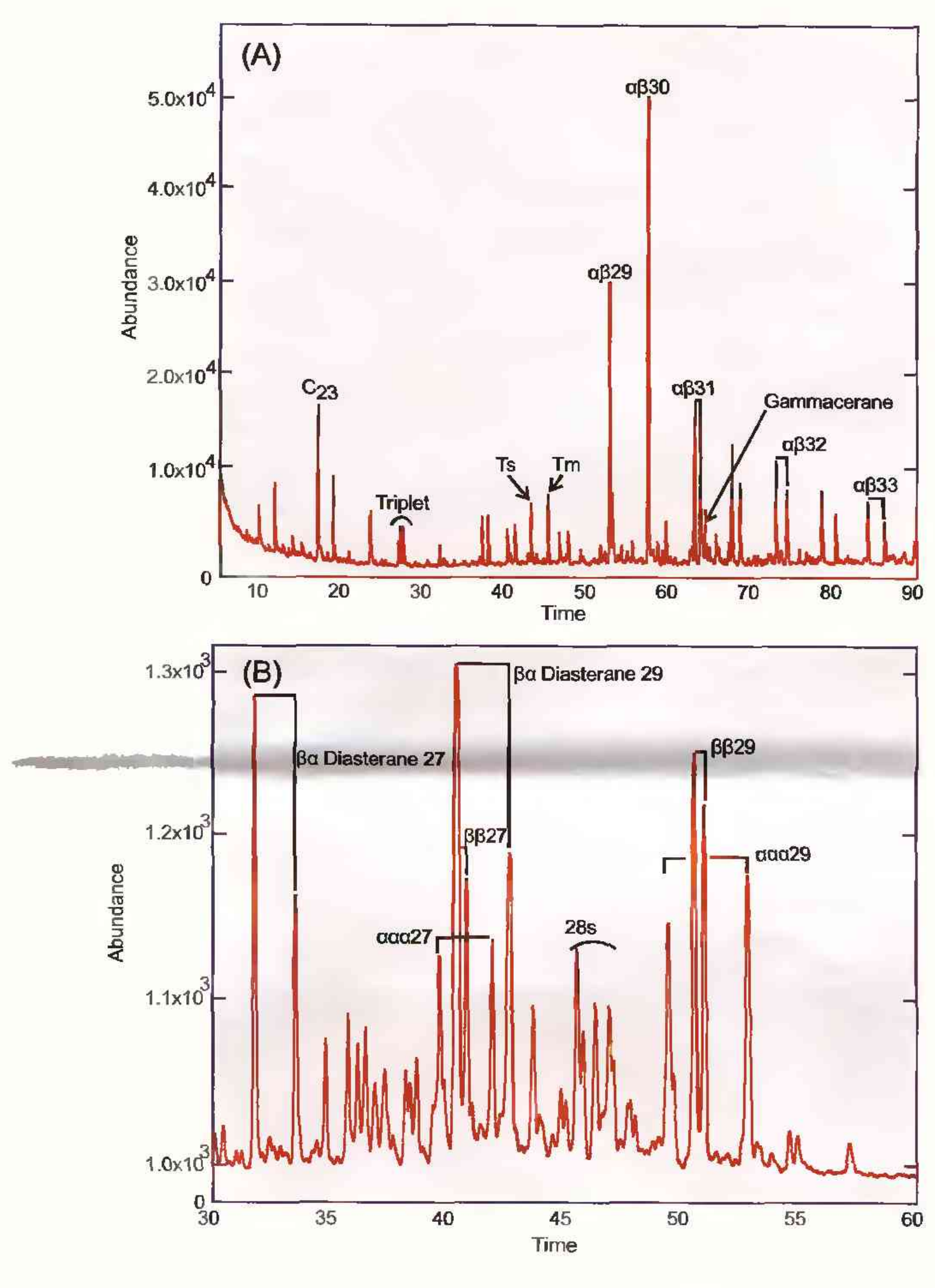


Figure 13. Chromatograms showing (A) Hopane and (B) Sterane (Diasterane) biomarkers identified in petroleum sample from the Louisville International Airport corehole site.

Table 6. Organic geochemistry and biomarkers for petroleum samples from selected open-borehole wells in south-central Louisville, Kentucky
[See text for explanation of biomarker abbreviations; m/z, mass/charge ratio; ND, not determined; NA, not applicable]

					m/z 191					m/z 217		
Sample number	Location (fig. 2)	Sample media	TOC	Pr/Ph	Triplet	Tm/Ts	C_{30}/C_{29}	C_{31} S/S+R	GI	C_{29} S/S+R	Sterane distribution	RI
KD1	Beechmont	Sellersburg Limestone	0.6	1.4	3.2	1.2	1.7	0.59	0.07	0.45	29βαD, ββ>27; low 28s	10
KD2	Beechmont	New Albany Shale	16.1	1.7	2.7	2.5	1.6	.59	.19	.41	ααα29>27; low 28s	4.6
KD3	Air Guard	New Albany Shale	8.5	1.6	2.2	2.3	1.2	.59	.27	.4	same as KD2	3.9
KD4	Air Guard	Sellersburg Limestone	1.2	1.1	3.1	1.2	1.6	.59	.07	.46	same as KD1	6.6
KD5	Auburndale	Sellersburg Limestone	1.5	1.2	3.4	1.1	1.5	.6	.07	.46	same as KD1	6.9
KD6	Okolona	New Albany Shale	14.6	1.6	2.5	2.6	1.5	.58	.26	35	same as KD2	35
KD7	Petersburg	Jeffersonville Limestone	.8	1.4	1	2	.15	.28	2.8	ND	βαD29>βαD27>other	99
KD8	Auburndale	liquid (oil)	NA	1.3	3.3	1.1	1.6	6	.07	.46	same as KD1	6.6
KD9	Airport	liquid (oil)	NA	1.4	3.1	1.2	1.7	.59	.08	.45	same as KD1	7.3

The most compelling correlation, however, is the dominance of 2-alkyl-1,3,4-trimethylbenzenes in the aromatic fractions of the kerogen samples from the New Albany Shale and in all the petroleum samples from the limestone. This suite of organic compounds is a particularly distinctive characteristic of Devonian oils in the Illinois Basin (Hatch and others, 1991) and the Williston Basin in the western United States and Canada (Requejo and others, 1992) and is interpreted as derived from kerogen precursors in the *Chlorobiaceae* family of photosynthetic sulfur bacteria. Their presence is indicative of prolific anaerobic bacterial growth in stratified water at and below the oxic-anoxic boundary layer in tropical to subtropical marine environments (Requejo and others, 1992). It is this type of depositional environment that is postulated for the generation and preservation of the kerogen-rich sediments that formed the New Albany Shale (Barrows and Cluff, 1984; Hamilton-Smith, 1993).

SUMMARY AND CONCLUSIONS

The results of this multidisciplinary investigation help to provide a better conceptual understanding of the hydrogeologic framework and geochemistry of ground water and petroleum in the Silurian-Devonian carbonate aquifer in south-central Louisville, Kentucky. The physical hydrogeologic framework of the carbonate aquifer—hydrostratigraphic units, porosity and permeability, contributing (water-bearing) fracture zones, hydraulic heads, and aquifer thickness—was characterized using data obtained from water-level measurements, aquifer tests, borehole-geophysical and heat-pulse flowmeter logs, and petrographic analyses of rock cores collected from open-borehole observation wells. The geochemistry of ground water in the aquifer—the spatial differences in ground-water chemistry that relate to changes in transmissivity, recharge, ground-water flow patterns, and mixing—was characterized using the major-ion and isotopic composition of ground-water samples collected from open-borehole observation wells and a karst spring. Isotopic data also were useful in investigating the sources of recharge to the aquifer and in qualitatively assessing ground-water residence time. The information provided by the investigation was needed by the U.S. Department of the Navy to help evaluate ground-water occurrence and quality at the former Naval Ordnance Station Louisville (NOSL) site, but also will be useful to other hydrogeologic investigations, environmental site assessments, and ground-water remediation projects being conducted in the study area.

The northern part of the carbonate aquifer is unconfined and exhibits moderately well-developed karstification. The southern part of the aquifer is confined by carbonaceous shale and exhibits little or no visible evidence of karstification, with the exception of Duck Spring. The transitional boundary between the unconfined and confined aquifer zones is delineated by the outcrop boundary of the New Albany Shale. This outcrop boundary also defines the recharge boundary for the confined aquifer zone. Ground-water flow in the carbonate aquifer is structurally controlled and mostly occurs through a few highly transmissive horizontal fractures within a narrow (10-45 ft) stratigraphic interval between the Sellersburg Limestone and upper Louisville Limestone Formation. Below this interval, the number and hydraulic conductivity of fractures decrease, and the carbonate rocks may act as a lower confining unit.

Recharge from the unconfined karstified part of the aquifer is freshening the water in the confined part of the aquifer. Spatial trends in the major ion, tritium, and stable isotope composition of ground water indicate distinct zones where the transmissivity of the aquifer and the infiltration and circulation of fresh meteoric recharge are either relatively enhanced or restricted. Younger, bicarbonate-dominated water occurs where transmissivity is highest and the infiltration and circulation of fresh meteoric recharge are greatest. Older, saline water occurs where transmissivity is low, infiltration and circulation of fresh meteoric recharge is restricted, and residual brine has not been flushed from the aquifer. Mixed bicarbonate and saline water occurs where the transmissivity is sufficiently high to allow some influx and circulation of fresh meteoric recharge but it is not high enough to allow complete flushing of the saline water from the aquifer.

Ground-water quality of the carbonate aquifer is affected by high concentrations of total dissolved solids, chloride, sodium, and other dissolved inorganic constituents typically associated with the dissolution of evaporite minerals or with residual brines in sedimentary basins. In some locations, ground-water quality is also degraded by dissolved organic hydrocarbons associated with petroleum (crude oil) in the Sellersburg and Jeffersonville Limestones. The petroleum exhibits close geochemical affinities with other Devonian-age crude oils, particularly those from the Illinois Basin. Biomarker parameters identified in the petroleum are consistent with the interpretation that the petroleum is probably derived from kerogen contained in the New Albany Shale.

---

[1] The symbols "α" and "β" refer to isomers of hydrocarbon chain molecules. The hydrogen atom (H) or methyl group (CH_3) is in the α position if it is attached below the rings of a straight or branched hydrocarbon chain and in the β position if it is attached above the rings.

[2] Differences in the three-dimensional structures of hydrocarbon ring structures occur at the 20-carbon position for steranes and at the 22-carbon position for hopanes. The symbols "S" and "R" refer (respectively) to left-handed and right-handed spatial orientations in the ring structures of the isomers in these groups.

REFERENCES CITED

Barrows, M.H., and Cluff, R.M., 1984, New Albany Shale Group (Devonian-Mississippian) source rocks and hydrocarbon generation in the Illinois Basin, *in* Demaison, G., and Murris, R.J., eds., Petroleum geochemistry and basin evaluation: American Association of Petroleum Geologists, Memoir 35, p. 111-137.

Batu, V., 1998, Aquifer hydraulics—a comprehensive guide to hydrogeologic data analysis: New York, Wiley, 727 p.

Bell, E.A, 1966, Summary of hydrologic conditions of the Louisville area Kentucky: U.S. Geological Survey Water- Supply Paper 1819-C, 36 p., 6 pl.

Bethke, C.M., Reed, J.D., and Oltz, D.F., 1991, Long-range petroleum migration in the Illinois Basin: American Association of Petroleum Geologists Bulletin, v. 75, no. 5, p. 925-945.

Clark, I.D., and Fritz, P., 1997, Environmental isotopes in hydrogeology: Lewis Publishers, 328 p.

Craig, H., 1961, Isotopic variations in meteoric waters: Science, v. 133, p. 1,702-1,703.

Cooper, H.H., Jr., Bredehoeft, J.D., and Papadopulos, I.S., 1967, Response of a finite-diameter well to an instantaneous charge of water: Water Resources Research, v. 3, no. 1, p. 263-269.

Ferris, J.G., Knowles, D.B., Brown, R.H., and Stallman, R.W, 1962, Theory of aquifer tests: U.S. Geological Survey Water-Supply Paper 1536-E, 173 p.

Freeman, L.B, 1951, Regional aspects of Silurian and Devonian subsurface stratigraphy in Kentucky: American Association of Petroleum Geologists Bulletin, v. 35, no. 1, p. 1-61.

Greene, E.A., 1993, Hydraulic properties of the Madison Aquifer System in the western Rapid City area, South Dakota: U.S. Geological Survey Water-Resources Investigations Report 93-4008, 56 p.

Hamilton-Smith, T., 1993, Gas exploration in the Devonian shales of Kentucky: Lexington, Ky., Kentucky Geological Survey Bulletin 4, ser. 11, 31 p.

Hatch, J.R., Risatti, J.B., and King, J.D., 1991, Geochemistry of Illinois Basin oils and hydrocarbon source rocks, *in* Leighton, M.W., Kolata, D.R., Oltz, D.F., and Eidel, J.J., eds., Interior Cratonic Basins: American Association of Petroleum Geologists Memoir 51, p. 403-423.

Hem, J.D., 1989, Study and interpretation of the chemical characteristics of natural water (3d ed.): U.S. Geological Survey Water-Supply Paper 2254, 263 p.

Hostettler, F.D., Kvenvolden, K.A., Rosenbauer, R.J., and Short, J.W., 1999, Aspects of the Exxon Valdez oil spill—a forensic study and a toxics controversy, *in* Morganwalp, D.W, and Buxton, H.T., eds., U.S. Geological Survey Toxic Substances Hydrology Program—Proceedings of the Technical Meeting, Charleston, South Carolina, March 8-12, 1999, volume 2 of 3, Contamination of hydrologic systems and related ecosystems: U.S. Geological Survey Water-Resources Investigations Report 99-4018A, p. 135-145.

Hunt, J.M., 1996, Petroleum geochemistry and geology (2d ed.): New York, W.H. Freeman and Company, 743 p.

Kepferle, R.C., 1974a, Louisville West and Lanesville Quadrangles, Kentucky: U.S. Geological Survey Geologic Quadrangle Map GQ-1202, scale 1:24,000.

———1974b, Louisville East Quadrangle, Kentucky: U.S. Geological Survey Geologic Quadrangle Map GQ-1203, scale 1:24,000.

Koterba, M.T., Wilde, F.D., and Lapham, W.W., 1995, Ground-water data collection protocols and procedures for the National Water-Quality Assessment Program—collection and documentation of water-quality samples and related data: U.S. Geological Survey Open-File Report 95-399, 113 p.

Kvenvolden, K.A., Hostettler, F.D., Carlson, P.R., Rapp, J.B., Threlkeld, C.N., and Warden, A., 1995, Ubiquitous tar balls with a California-source signature on the shorelines of Prince William Sound: Environmental Science and Technology, v. 29, p. 2,684-2,694.

Leininger, R.K., 1981, Inorganic geochemistry, *in* Hasenmueller, N.R., and Woodard, G.S., eds., Studies of the New Albany Shale (Devonian and Mississippian) and equivalent strata in Indiana: State of Indiana, Department of Natural Resources, Geological Survey, 100 p.

McDowell, R.C., 1986, Structural geology, *in* McDowell, R.C., ed., The geology of Kentucky—a text to accompany the geologic map of Kentucky: U.S. Geological Survey Professional Paper 1151-H, p. 53-59.

Michel, R.L., 1989, Tritium deposition over the Continental United States, 1953-1983: Oxfordshire, U.K., Atmospheric Deposition, International Association of Hydrological Sciences, p. 109-115.

Palmquist, W.N., Jr., and Hall, F.R., 1960, Availability of ground water in Bullitt, Jefferson, and Oldham Counties, Kentucky: U.S. Geological Survey Hydrologic Investigations Atlas HA-22, 3 sheets, scale 1:25,000.

Peters, K.E., and Moldowan, J.M, 1993, The biomarker guide: Englewood Cliffs, N.J., Prentice-Hall, 363 p.

Plummer, L.N., Prestemon, E.C., and Parkhurst, D.L., 1994, An interactive code (NETPATH) for modeling NET geochemical reactions along a flow PATH (ver. 2.0): U.S. Geological Survey Water-Resources Investigations Report 94-4169, 130 p.

Ray, J.A., Webb, J., and O'Dell, P., 1994, Groundwater sensitivity regions of Kentucky: Frankfort, Ky., Natural Resources and Environmental Protection Cabinet, Department of Environmental Protection, Division of Water, 1 sheet.

Requejo, A.G., Allan, J., Creaney, S., Gray, N.R., and Cole, K.S., 1992, Aryl isoprenoids and diaromatic carotenoids in Paleozoic source rocks and oils from the Western Canada and Williston Basins: Advances in Organic Geochemistry, v. 19, p. 245-264.

Rorabaugh, M.I., 1956, Ground water in northeastern Louisville, Kentucky, with reference to induced infiltration: U.S. Geological Survey Water-Supply Paper 1360-B, 169 p., 18 pl.

Unthank, M.D., Stevens, C.L., Nelson, H.L., Jr., and Poole, J.M., 1995, Ground-water levels in and pumpage from the alluvial aquifer at Louisville, Kentucky, May 1989–May 1991: U.S. Geological Survey Water-Resources Investigations Report 94-4099, 2 sheets.

Walker, E.H., 1957, The deep channel and alluvial deposits of the Ohio Valley in Kentucky: U.S. Geological Survey Water-Supply Paper 1411, 25 p., 6 pl.

Wilde, F.D., and Radtke, D.B., 1998, National field manual for the collection of water-quality data: U.S. Geological Survey Techniques of Water-Resources Investigations Report book 9, chap. A6 [variously paged].

Wilde, F.D., Radtke, D.B., Gibs, J., and Iwatsubo, R.T, eds., 1998, National field manual for the collection of water-quality data: U.S. Geological Survey Techniques of Water-Resources Investigations Report book 9, chap. A1-A5 [variously paged].

Wilson, E.N., and Sutton, D.G., 1973, Oil and gas map of Kentucky, sheet 3, east-central part: Lexington, Ky., Kentucky Geological Survey, ser. X, 1 sheet.

Zanini, L., Novakowski, K.S., Lapcevic, P., Bickerton, G.S., Voralek, J., and Talbot, C., 2000, Ground water flow in a fractured carbonate aquifer inferred from combined hydrogeological and geochemical measurements: Ground Water, v. 38, no. 3, p. 350-360.

CONVERSION FACTORS AND VERTICAL DATUM

CONVERSION FACTORS

Multiply	By	To obtain
acre	0.004047	square kilometer
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
foot per second (ft/s)	0.3048	meter per second
square foot per second (ft^2/s)	0.09290	square meter per second
foot per mile (ft/mi)	0.1894	meter per kilometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon per minute (gal/min)	0.06309	liter per second
square mile (mi^2)	2.590	square kilometer
millidarcy	3.15×10^{-8}	foot per second
millimeter	0.03937	inch

Degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) by use of the following equation:

$$°F = (9/5)(°C) + 32$$

VERTICAL DATUM

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.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Concentrations of inorganic and organic chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

For additional information write to:

District Chief, Kentucky District
U.S. Geological Survey
9818 Bluegrass Parkway
Louisville, KY 40299–1906

Website - http://ky.water.usgs.gov

Copies of this report can be obtained from:

U.S. Geological Survey
Information Services
Box 25286
Denver, CO 80225–0286

Printed on recycled paper

Hydrogeologic Framework and Geochemistry of Ground Water and Petroleum in the Silurian-Devonian Carbonate Aquifer, South-Central Louisville, Kentucky

By Charles J. Taylor *and* Frances D. Hostettler

2002