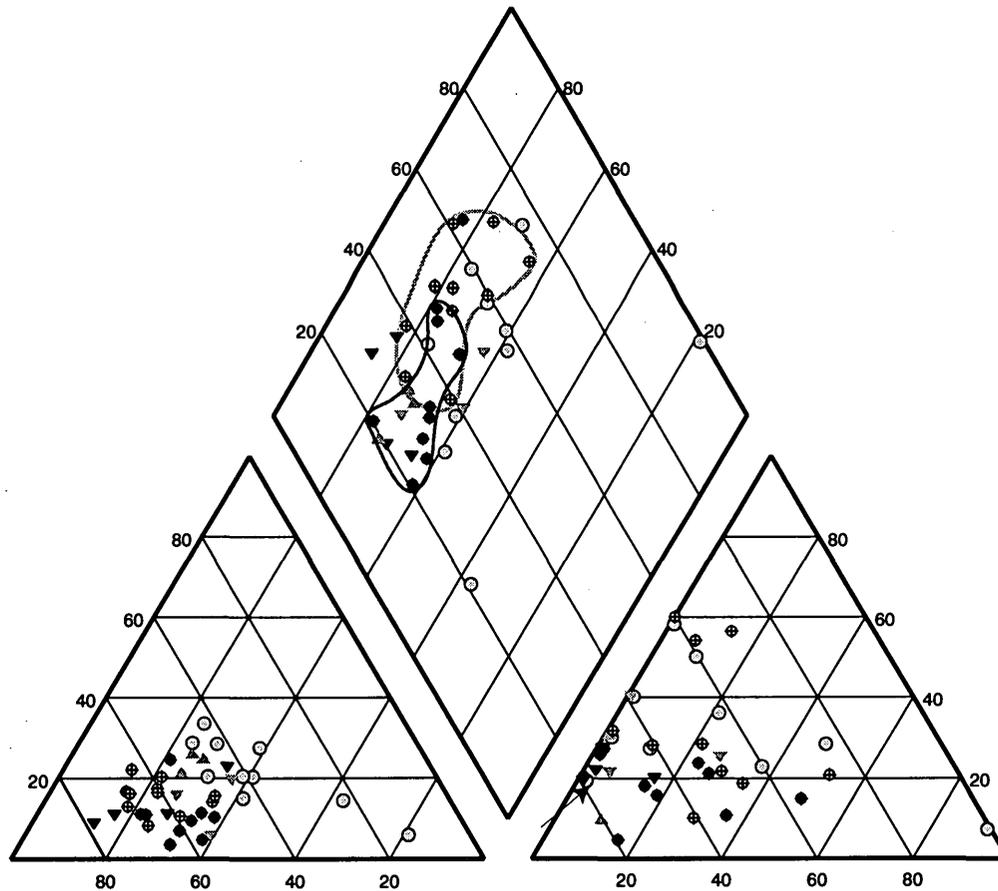




Arsenic Concentrations in Bedrock Wells in Colchester, East Hampton, and Woodstock, Connecticut

Water-Resources Investigations Report 02-4135



Prepared in cooperation with the
Connecticut Department of Public Health

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

Cover: Piper diagram showing geochemical differences among ground-water samples in bedrock wells in the Colchester and Woodstock areas (modified from fig. 6).

U.S. Department of the Interior
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By Craig J. Brown and Stewart K. Chute

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**East Hartford, Connecticut
2002**

U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
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CONVERSION FACTORS, ABBREVIATIONS AND VERTICAL DATUM

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi ²)	2.590	square kilometer
	Flow	
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per day (ft/d)	0.0003527	centimeter per second (cm/s)
gallon per minute (gal/min)	3.785	liter per minute (L/s)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$^{\circ}\text{C} = (^{\circ}\text{F} - 32) / 1.8$$

Sea level, as used in this report, 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.

Concentrations of chemical constituents are given in milligrams per liter (mg/L), micrograms per liter (µg/L), millimoles per liter (mmol/L), microcuries (µCi), and milligrams per kilogram (mg/kg).

Other abbreviations used:

- <, less than
- >, greater than
- ‰, per mil
- δ, delta
- µM, micron

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ABSTRACT

Arsenic concentrations in water from bedrock wells differed considerably between two areas in eastern Connecticut, where water samples were collected to evaluate the relative importance of bedrock type and redox chemistry on the occurrence and mobility of arsenic in ground water. Arsenic concentrations were low (less than 10 $\mu\text{g/L}$) in samples from wells in the Colchester area, and showed little or no difference in samples from wells in the Hebron Formation—known to have a high occurrence of arsenic in supply wells in northeastern Connecticut—and the Brimfield Schist, which is sulfidic and is more likely to contain arsenic. Concentrations of dissolved oxygen were lower and concentrations of dissolved iron and manganese were higher in samples from the Brimfield Schist than in samples from the Hebron Formation. In the Woodstock area, where arsenic concentrations in water from bedrock wells historically have been high, water samples from eight wells had dissolved arsenic concentrations greater than the detection limits from two laboratories. Six of these wells are in the Hebron Formation in southeastern Woodstock. Samples from two of these wells had dissolved arsenic concentrations that exceeded the new (2001) U.S. Environmental Protection Agency arsenic standard of 10 $\mu\text{g/L}$.

Detected arsenic concentrations in ground water were not restricted to reducing conditions. Arsenic concentrations were highest in ground water with low concentrations of dissolved iron and manganese, and the water with the highest total arsenic concentration and the second highest dissolved arsenic concentration was oxic. Wells in the Hebron Formation in the Woodstock area with detected concentrations of dissolved sulfide

(0.13, 0.007, and 0.008 mg/L), also had detected concentrations of dissolved arsenic (6 $\mu\text{g/L}$, 5.6 $\mu\text{g/L}$, and 2.9 $\mu\text{g/L}$); these detections could indicate that arsenic was either desorbed from mineral surfaces or reduced from ferric hydroxides or manganous oxides under reducing conditions.

Water from six of the eight wells with the highest arsenic concentrations were in the Woodstock area with pH levels greater than 7.7; these pH levels could indicate that arsenic occurrences are related to the desorption of arsenate at high pH. The higher pH in water samples from wells in the Hebron Formation in the Woodstock area, compared to those in the Hebron Formation in the Colchester area, could result from higher concentrations of calcite or more extensive weathering of silicate minerals in the Woodstock bedrock. Small pegmatite intrusions and vein-filled fractures are common throughout the Hebron Formation and may be a source of arsenic-bearing minerals. Further study would be necessary to determine whether the high frequency of arsenic occurrences in the Woodstock area is from arsenic either within the Hebron Formation, from overlying stratified glacial deposits, or from anthropogenic contamination.

INTRODUCTION

Moderate to high concentrations of arsenic (>10 $\mu\text{g/L}$) have been detected in bedrock wells throughout the United States (Welch and others, 2000), the New England States (Boudette and others, 1985; Ayotte and others, 1999; Peters and others, 1999), and Connecticut (Agency for Toxic Substances and Disease Registry, 1999). Arsenic concentrations in wells are affected by many factors, including natural bedrock sources, anthropogenic sources, and the redox chemistry and pH of the contributing ground water. Anthro-

pogenic sources of arsenic to soils and ground water include fertilizer and pesticide application to orchard/potato crops, runoff from sulfide-rich mine tailings, and chemicals used in leather tanning and wood preservative (copper chromium arsenate) (Wall and Stratton, 1994). Determining arsenic sources and pathways is complex because (1) both natural and anthropogenic sources commonly are present at bedrock well sites, (2) arsenate was used widely as a pesticide from the early 1900s to the early 1970s and detailed records are not available, and (3) arsenic mobility is dependent on the redox environment, which controls whether arsenic is trivalent (arsenite or As(III)) or pentavalent (arsenate or As(V)), and on the pH. The U.S. Environmental Protection Agency (USEPA) recently (2001) has lowered the maximum acceptable level of arsenic in drinking water to 10 µg/L and considers arsenic to be a known human carcinogen (National Research Council, 2001).

Arsenic has an estimated average concentration in the Earth's upper crust of 1.5 mg/kg (Taylor and McLennan, 1985). Arsenic is found at high concentrations in primary sulfide minerals (for example, pyrite, pyrrhotite, orpiment, realgar, and tennantite) and substitutes for trace elements in some silicate rock-forming minerals (Onken and Hossner, 1996). Arsenic compounds are least soluble in the pentavalent (As(V)) form, which commonly sorbs to or coprecipitates with iron and manganese oxyhydroxides. The anion-exchange dynamics of arsenate (H_2AsO_4^-) are similar to those of phosphate (H_2PO_4^-), with competition for exchange sites favoring phosphate over arsenate (Peryea and Kammereck, 1997).

Detectable arsenic concentrations have been associated with high (>7.5) pH in bedrock wells in New England (Brown and Chute, 2001; Ayotte and others, 2001). Arsenic commonly is dissolved and (or) desorbed from arsenic-bearing iron oxides under reducing conditions in unconsolidated aquifers (Nickson and others, 1998) or bedrock fractures. Microbial activity is thought to be responsible for arsenate reduction to arsenite in soils and sediments (Onken and Hossner, 1996) but arsenate can be reduced abiotically by reductants such as dissolved sulfide (Rochette and others, 2000). Arsenic also can be weathered from arsenic-bearing sulfide minerals (for example, arsenopyrite) under oxidizing conditions through oxidative dissolution; however, the arsenic likely will oxidize to the pentavalent state under these conditions and (or) sorb to oxide grain coatings. Arsenic mobility can be facilitated by association with inorganic colloids (Puls and Powell, 1992), organic

acids (D.A. Vroblecky, U.S. Geological Survey, written commun., 1999), or by methylation of As (III) to neutral complexes (Holm and others, 1979).

Some bedrock types in Connecticut are sulfidic, and, therefore, potentially high in arsenic content; this arsenic content may contribute to arsenic concentrations in ground water. Arsenic is likely to be present in some sulfidic bedrock formations in Connecticut, including the Brimfield Schist (Peper and others, 1975) and the Shuttle Meadow and East Berlin Formations (Robinson and Sears, 1988; Gray, 1988). Arsenic has been detected at concentrations greater than 5 µg/L in 4 public supply wells (Agency for Toxic Substances and Disease Registry, 1999; J.D. Ayotte, U.S. Geological Survey, written commun., 2000), domestic wells (Brown and Chute, 2001), and observations wells (Focazio and others, 1999) in Connecticut. Arsenic from anthropogenic sources can complicate the delineation of bedrock sources. Arsenic concentrations in wells in the New England area, for example, have been correlated with certain bedrock types, but the correlations were complicated by additional correlations between rock types and land use (Ayotte and others, 1999). The extent and magnitude of naturally occurring arsenic in Connecticut ground water are not adequately known.

In 2000, the U.S. Geological Survey (USGS), in cooperation with the Connecticut Department of Public Health (CDPH), began a study to assess the effect of redox chemistry and bedrock type on the extent and origin of arsenic contamination in private bedrock wells. The study focused on sampling water from private bedrock wells along transects in two areas where bedrock is likely to contain arsenic-bearing minerals or where concentrations of arsenic have exceeded 10 µg/L in bedrock public-supply wells. Water samples also were collected from wells in adjacent bedrock types that were not expected to contain detectable arsenic concentrations, including the Eastford Gneiss phase of the Canterbury Gneiss (Dixon, 1982), the Bigelow Brook Formation, and the Southbridge Formation (Pease, 1972).

Purpose and Scope

This report describes the relative importance of redox chemistry, pH, and bedrock type on the occurrence and mobility of arsenic in Connecticut bedrock aquifers. The report also examines whether (1) arsenic is present in water from wells drilled in certain bedrock types that are likely to be high in arsenic, and

(2) arsenic is more mobile under reducing conditions than under oxidizing conditions. The term “high arsenic concentration” in this report is used to describe concentrations greater than 10 µg/L. Arsenic, redox-sensitive constituents, and other major ions were analyzed in 40 ground-water samples from bedrock wells to help determine the sources and pathways of arsenic. The two areas sampled are in east-central and northeastern Connecticut. Each sampled area includes 20 private wells in an area of about 20 mi².

Acknowledgments

The authors thank the East Hampton Department of Health, the Colchester Department of Health, and the Northeast District Department of Health for providing assistance with contacting private well owners and for other information. Ralph Lewis with the Connecticut Department of Environmental Protection and student interns Sam Frank and Sasha Warzesha are thanked for providing assistance with ground-water sampling. The authors also thank the well owners in the study area who allowed access to their property for sampling. Appreciation is extended to Brian Toal at the CDPH Toxic Hazards Section for assistance in locating domestic wells to sample and to Stephen Gudernatch at the CDPH Laboratory for sample analysis.

DESCRIPTION OF STUDY AREA

The study sites include the towns of Colchester and East Hampton, Conn. (Colchester area) in east-central Connecticut, and the town of Woodstock, Conn. (Woodstock area) in northeastern Connecticut (fig. 1). Natural sources of arsenic and the intrinsic aquifer geochemistry can affect the mobilization and concentration of arsenic in wells; therefore, the bedrock geology is discussed here in some detail. Land use and associated human influences also can affect arsenic concentrations in ground water and are discussed in this section.

Geology

On a regional scale, bedrock in the central part of eastern Connecticut is part of the southern limit of the Merrimack synclinorium, which extends northward through Massachusetts and into New Hampshire. The synclinorium is bordered on the west by rocks of the

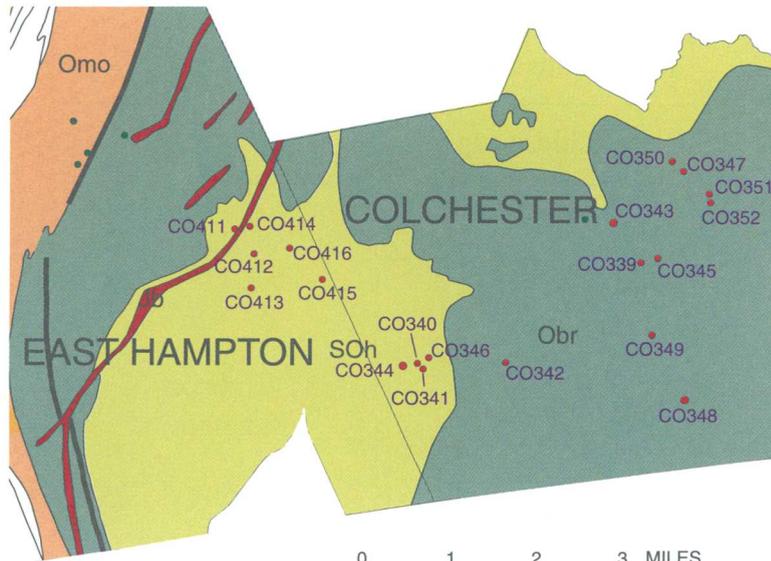
Bronson Hill anticlinorium, and on the south and east by the Honey Hill-Lake Char thrust fault (Dixon, 1968). The subsurface in this area generally consists of fractured metasedimentary rocks (gneiss, schist, granofels), overlain by stratified glacial deposits and (or) glacial till (Rodgers, 1985; Stone and others, 1992).

Geologic units that are pertinent to this study were compiled from statewide geologic quadrangle maps by Rodgers (1985) and are shown in figure 2. The geologic units were revised by Pease (1989) and are shown in figure 3. More detailed geologic data used in this report were compiled from previous studies, including bedrock geologic maps of the Moodus and Colchester quadrangles (Lundgren and others, 1971) for the Colchester area, and the Putnam (Dixon, 1982) and Eastford (Pease, 1972) quadrangle maps for the Woodstock area. The primary bedrock units discussed in this report are the Hebron Formation and the Brimfield Schist. The Hebron Formation and Brimfield Schist generally have been described as Ordovician (?)¹ to Devonian (?) metasedimentary rocks that extend northeastward into Massachusetts (Peper and others, 1975; Pease, 1989).

In the Colchester area, the Hebron Formation forms an almost complete ring around the central area of the overlying, gently dipping Brimfield Schist in what is known as the Colchester basin (fig. 1; Lundgren and others, 1971). The Hebron Formation in the Colchester area consists of layers of quartz-biotite schist and calc-silicate granofels, with layers of muscovite-biotite schist present locally (figs. 2A and 4A). The muscovite-biotite schist forms layers that are up to a few feet thick and are different mineralogically from the dominant rock types; the opaque accessory minerals include graphite, pyrrhotite, and possibly pyrite (Lundgren and others, 1971). The Brimfield Schist is a coarse-grained biotite-muscovite schist unit that is chemically and physically unstable upon exposure (fig. 4B). The muscovite schist contains red garnets and traces of iron oxide (magnetite-ilmenite), graphite, and iron sulfide (pyrite or pyrrhotite); quartz and plagioclase are present in augen-like aggregates (Lundgren and others, 1971). Pegmatite and small masses of finer grained granitic rock form lenses, layers, and dikes in the layered units.

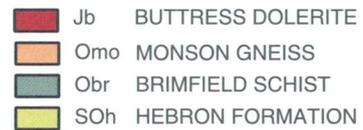
¹(?) indicates that the ages assigned were based on assumed stratigraphic correlations and not on direct age dating.

A. Colchester Area

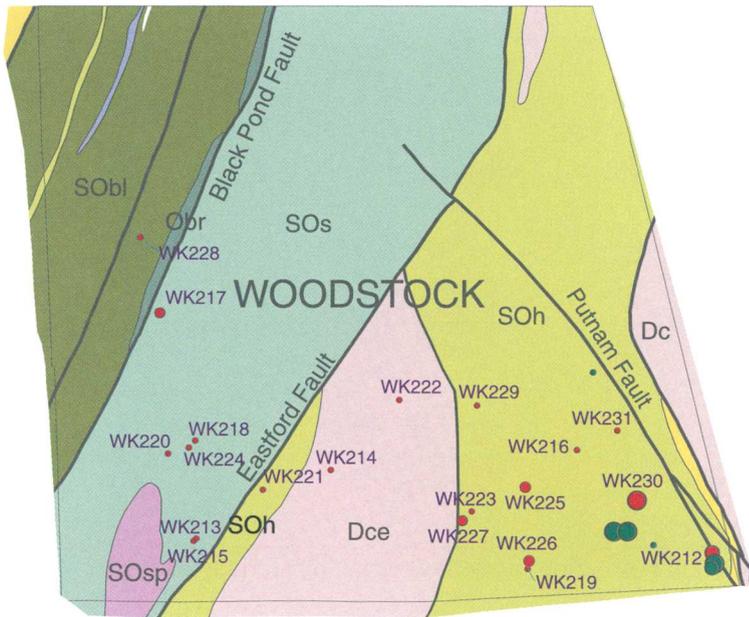


EXPLANATION

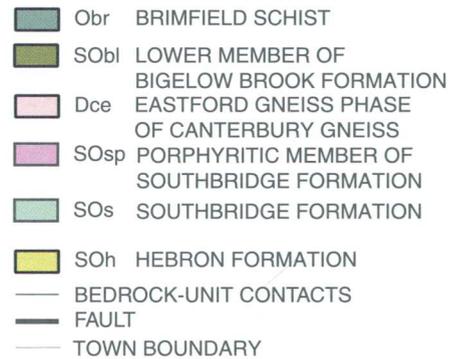
BEDROCK UNITS



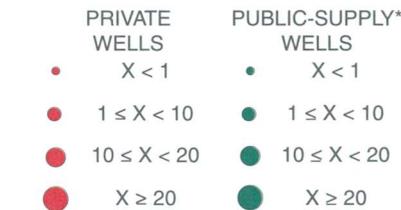
B. Woodstock Area



BEDROCK UNITS



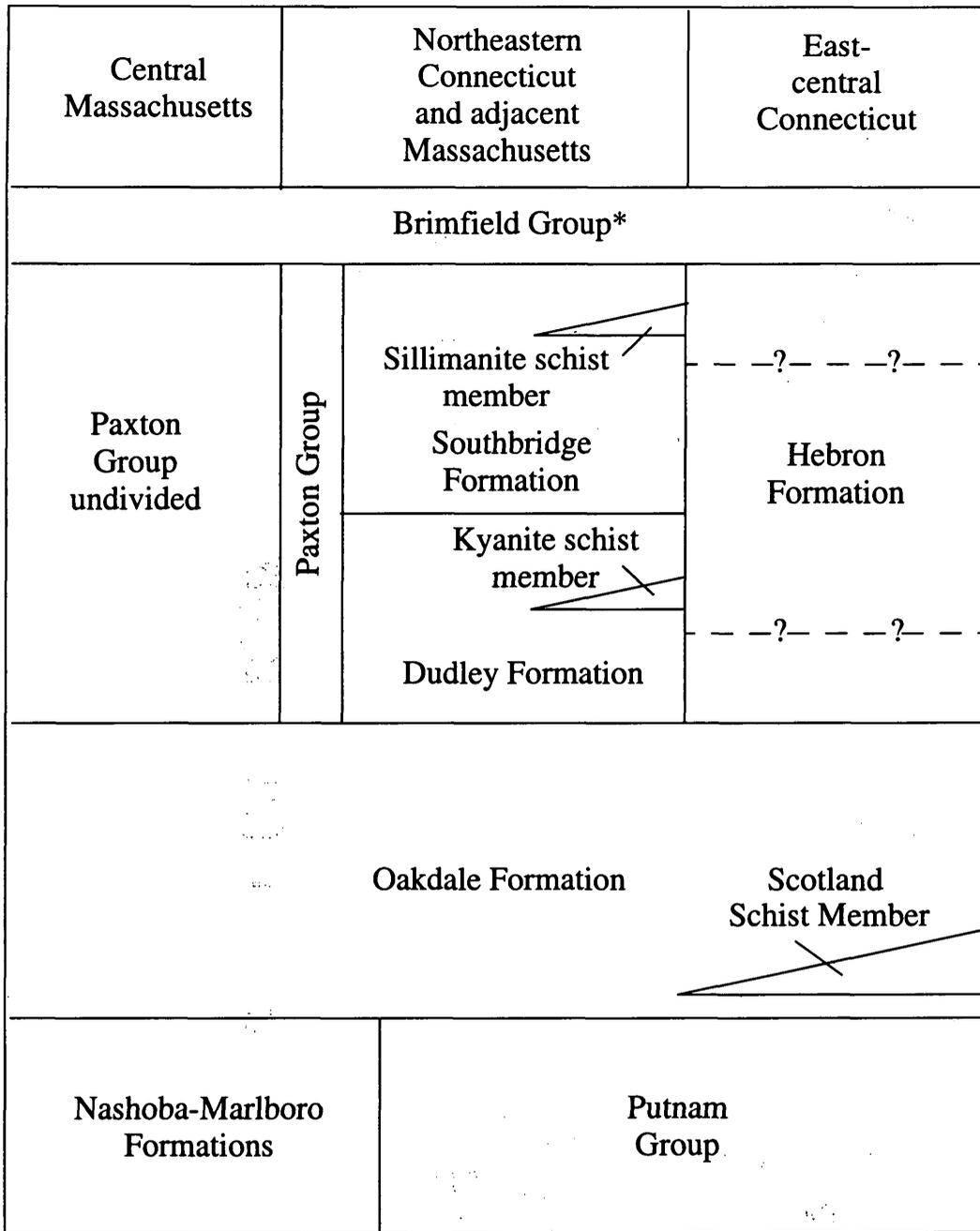
ARSENIC CONCENTRATION, IN MILLIGRAMS PER LITER



WK212 WELL ID
 <, less than; >, more than
 ≤, less than or equal to
 ≥, more than or equal to

*Data from J.D. Ayotte, U.S. Geological Survey, written commun., 2000

Figure 2. Arsenic concentrations in private wells and public-supply wells, and their host bedrock units in (A) Colchester and East Hampton, Conn. (Colchester area), and (B) Woodstock, Conn. (Woodstock area). [Geology compiled by Pease, 1989; Rodgers, 1985.]



* Includes the Bigelow Brook Formation in northeastern Connecticut and adjacent Massachusetts.

Figure 3. Stratigraphic and structural relations of selected bedrock geologic units, Connecticut and Massachusetts. [Modified from Pease, 1989.]

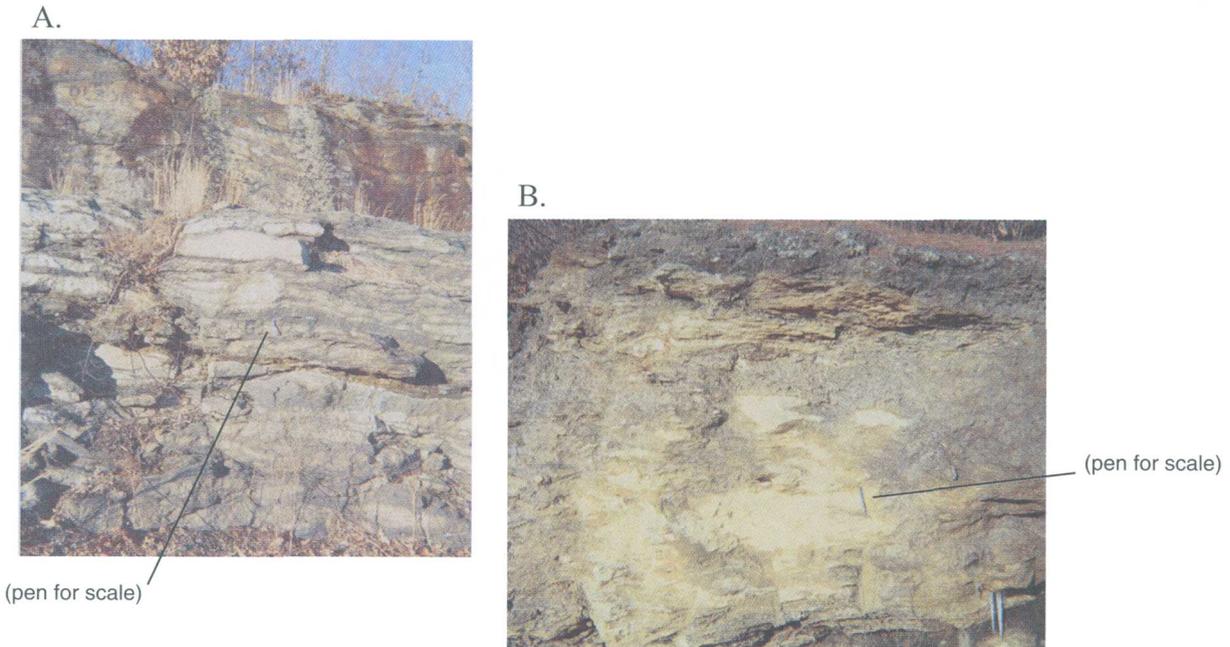


Figure 4. Outcrops of (A) the Hebron Formation (on westbound Route 2, southeast of the Mill Road overpass) showing interlayered quartz-biotite schist and calc-silicate gneiss, and (B) the Brimfield Schist (on westbound Route 2, west of Route 149), showing weathered, rust-stained, muscovitic schist, Colchester, Conn. [The blue pen in each photo is 5.5 inches in length.]

In the Woodstock area, the Hebron Formation is present east of the northeast-trending Eastford fault and underlies the Southbridge Formation, which is northwest of the fault (fig. 2B; Pease, 1989). The Brimfield Schist lies further to the west and structurally overlies the Southbridge Formation. The Hebron Formation was classified as the Dudley Formation of the Paxton Group by Pease (1989) and is described as a biotite schist, commonly containing hornblende and diopside in the Eastford quadrangle in the western part of the study area (Pease, 1972) and as a biotite-quartz-andesine schist in the Putnam quadrangle in the eastern part of the study area (Dixon, 1982). The Hebron Formation is intruded by numerous pegmatitic and granitic sills and dikes (Dixon, 1982). The Eastford gneiss, which is a phase of the Canterbury Gneiss, appears to have intruded the Hebron Formation beneath the kyanite schist member (Pease, 1989). The Eastford gneiss is a gneissoid quartz-monzonite composed mostly of oligoclase-potassium feldspar and quartz with black biotite and accessory minerals

(Pease, 1972). Pease (1972) divided the Southbridge Formation (SOs) in the Eastford quadrangle into a lower and an upper member. The uppermost member of the Southbridge contains local interlayers of sillimanite schist, sulfidic schist, and amphibolite; the lower member is less well layered and more uniform than the upper member and is characterized by the presence of potassium feldspar megacrysts (Barosh and Moore, 1988). The overlying Bigelow Brook Formation, which is the lower unit of the Brimfield Group, consists mostly of quartzo-feldspathic schist and gneiss that contain biotite, garnet, and sparse sillimanite (Peper and others, 1975). In the Eastford quadrangle, the Bigelow Brook Formation is described as a biotite-sillimanite-garnet schist and gneiss; interlayered graphitic gneiss and schists are sulfidic (Pease, 1972).

Although discussion in this report uses terminology from the geologic quadrangle maps and from Rodgers (1985), more recent regional interpretations are discussed briefly here to provide a regional

perspective of the geologic units. These recent interpretations have resulted in a revised classification that facilitates correlation of the Paxton Group and Oakdale Formation of Massachusetts with the Hebron Formation and Scotland Schist Member in northeastern Connecticut (Barosh and Moore, 1988; Pease, 1989, fig. 3). In the revised classification, the Paxton Group in northeastern Connecticut and southeastern Massachusetts, formerly mapped as the Hebron Formation in Connecticut, was divided into the Dudley and Southbridge Formations (Pease, 1989). The Hebron Formation and Scotland Schist of east-central Connecticut (Colchester area), which were not included in the Paxton Group (Lundgren and others, 1971), extend into northeastern Connecticut (Woodstock area) and Massachusetts where they are mapped as the Paxton Group and Oakdale Formation (Pease, 1989). The Oakdale Formation has been traced into Connecticut, where it adjoins eastern exposures of rocks previously mapped as the Hebron Formation; furthermore, the Scotland Schist, formerly mapped as a separate formation younger than the Hebron, was shown to be a member of the Oakdale Formation (fig. 3).

Hydrology

Bedrock aquifers are an important source of water for domestic well users and commonly are tapped for public drinking-water supplies in the study area. These crystalline bedrock aquifers have little or no primary porosity and a secondary porosity that generally is low relative to overlying stratified glacial

deposits. Bedrock aquifers are recharged by infiltration through overlying stratified glacial deposits, and water is stored and transmitted primarily through intersecting fractures. Hydraulic conductivities in fractured crystalline bedrock in New England range from 2.8×10^{-4} to 26 ft/d (Randall and others, 1988; Paillet and Kapucu, 1989; Harte, 1992; Hsieh and others, 1993). Residence times vary widely, depending on the local or regional nature of a particular flowpath and the degree of interconnections of fractures in an aquifer underlying the study area. Well yields commonly range from 2 to more than 30 gal/min in fractured crystalline bedrock aquifers and from 10 to 1,500 gal/min in stratified drift (Hansen and Simcox, 1994; Moore and others, 1994; Olcott, 1995).

Land Use

Land use in the study areas generally consists of mixed forested and agricultural areas with some low-density residential areas (fig. 5). Generalized land-use and land-cover information was determined from LANDSAT Thematic Mapper (TM) images by the Multi-Resolution Land Characterization (MRLC) Consortium. These data, known as the National Land Cover Data (NLCD) set, consist of a 21-class, land-cover classification scheme derived from early to mid-1990s LANDSAT TM data applied consistently over the United States (Vogelmann and others, 1998). Both study areas mostly are forested, but the Woodstock area contains more agricultural land (20 percent) and less urban land (4 percent) than does the Colchester area (10 percent and 8 percent, respectively).

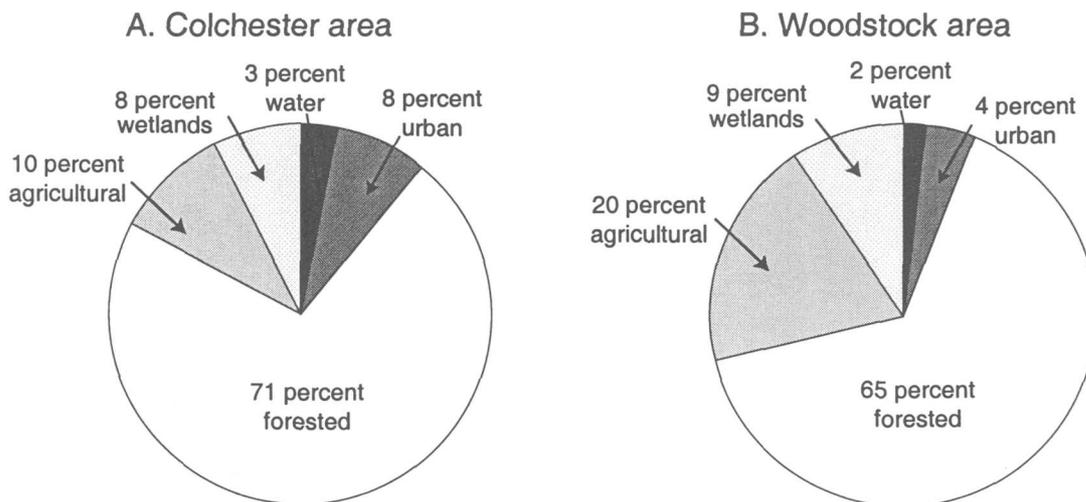


Figure 5. Land-use and land-cover percentages in the (A) Colchester area and (B) Woodstock area, Conn.

DATA COLLECTION AND ANALYSIS

Water was sampled from 20 domestic bedrock wells in each of two areas (fig. 2). The Colchester area includes two adjacent bedrock units: the Brimfield Schist, which commonly contains iron-sulfide minerals (Lundgren and others, 1971), and the Hebron Formation. The Woodstock area includes four bedrock units: the Hebron Formation, in which arsenic concentrations in various bedrock wells have been greater than or equal to 10 µg/L, and three other units (the Southbridge Formation, the Eastford Gneiss phase of the Canterbury Gneiss, and the lower member of the Bigelow Brook Formation) with no known concerns related to arsenic in the water. Wells were selected to ensure their suitability for obtaining ground-water samples that represent the bedrock of interest. Selection of wells generally was based on well-completion reports, including depth and the presence of surface casing, and onsite examination of sampling access (accessible prior to treatment systems). The host bedrock unit at each well site was identified by overlaying the latitude and longitude coordinates for the well onto the bedrock geologic map of Connecticut (Rodgers, 1985). Identification of bedrock units could not be verified at the well sites for this study.

Wells were sampled according to USGS ground-water-sampling protocols (Wilde and others, 1998). Wells were purged, and field measurements of specific conductance, pH, temperature, and dissolved oxygen were monitored until stable. Colorimetric procedures (Hach Company, 1993) were used onsite to measure concentrations of total dissolved sulfide (H_2S and HS^-) and low levels of dissolved oxygen; a dissolved oxygen meter and the revised Winkler method were used to measure dissolved oxygen concentrations above 0.8 mg/L. Wells were sampled from a valve at the pressure tank to avoid filtration systems. Where possible, samples were collected using sampling equipment constructed entirely of stainless steel and Teflon. Samples were filtered with a 0.45-µm inline filter, with the exception of samples for total arsenic and alkalinity. All ground-water samples were measured for alkalinity by incremental titration 4 to 6 hours after sample collection.

Samples were stored on ice until the CDPH samples were brought to the CDPH for processing and analysis or the USGS samples were sent to the USGS National Water-Quality Laboratory (NWQL) in Denver, Colo., for analysis. The CDPH samples

collected for total arsenic (unfiltered) were preserved onsite; samples for dissolved constituents, including arsenic and cations, were filtered onsite but preserved in the laboratory according to standard CDPH procedure. Dissolved constituents reported by the CDPH, therefore, could have been affected by precipitation or sorption to the inside of the sample container. Water samples were analyzed for major dissolved constituents, nutrients, iron, manganese, and total and dissolved arsenic by CDPH using segmented flow analysis with an ion analyzer, colorimetry, and atomic absorption spectrometry with a graphic furnace. Replicates were collected at 10 percent of the sites and shipped to the USGS NWQL for quality assurance. Dissolved, acidified replicates of all samples also were sent to the USGS NWQL for analysis of dissolved arsenic, iron, and silica. Major and trace elements were measured by inductively coupled plasma mass spectrometry and ion chromatography, with the exception of nutrients and silica, which were analyzed by colorimetry.

In 1999, the detection limit for arsenic used by the NWQL was decreased from 0.9 to 0.18 µg/L; only two USGS samples (CO 339 and EHM 411) were analyzed using the older (0.9-µg/L) detection limit. Dissolved arsenic concentrations analyzed by the USGS used a lower detection limit (<0.18 or <0.9 µg/L) than that of the CDPH Laboratory (<3 µg/L); therefore, USGS NWQL-derived dissolved arsenic concentrations are used in this report in most cases. Concentrations of constituents in samples analyzed by the CDPH generally were consistent with those in replicate samples analyzed by the USGS for arsenic, although agreement was poor between results for two USGS and CDPH samples analyzed for dissolved arsenic concentrations (samples WK 225 and WK 226). These two samples were reanalyzed by the USGS NWQL and showed a nearly identical result; furthermore, an assessment of the quality-control practices used by both laboratories indicated that the analyses were acceptable. Both the NWQL and the CDPH Laboratory are routinely evaluated by how closely their analytical results approximate the most probable value of the blind QC samples and standard reference samples. The analytical results for the blind QC samples, the standard reference samples, and blanks (all of which were run with the regular samples) for both the CDPH and the USGS are considered acceptable. The analytical uncertainty of arsenic analyses for the methods used by the CDPH Laboratory and the

USGS NWQL was about 10 percent. Because the CDPH obtained the same analytical results for both total and dissolved arsenic samples at each site, the CDPH dissolved arsenic values were used in place of those analyzed by the USGS for WK 225 and WK 226 (table 1). These two sets of samples for dissolved arsenic were collected on the same day and it is possible that a preservative was not added to samples sent to the USGS laboratory.

For four wells, water samples for sulfate analysis were collected on an anion-exchange resin column for sulfur-isotope analysis and analyzed for BaSO₄ precipitates by the USGS using procedures described in Carmody and others (1998). Sulfur-isotope analyses of water samples were conducted at the USGS Geochemistry Laboratory in Reston, Va.; results are reported in per mil (‰) relative to the Vienna Canyon Diablo Troilite (VCDT) standard. The uncertainty associated with δ³⁴S values is ± 0.2 ‰.

GROUND-WATER GEOCHEMISTRY

Ground water from 40 private bedrock wells (fig. 2) was sampled and analyzed for major ions, trace metals, and selected redox-active constituents (table 1). Four samples were analyzed for δ³⁴S of sulfate. The composition of ground water at the study sites depends on the type of bedrock and overlying sediments through which the water flows. The major ion chemistry of water samples from wells varied spatially and among the different bedrock types (table 1).

Major Ion Concentrations

Major ion concentrations in samples from wells in the Hebron Formation differed between the two sites, as shown in the Piper diagram (fig. 6). A Piper diagram consists of two ternary diagrams that describe the compositions of cations and anions, and a diamond-shaped diagram that combines the compositions of cations and anions; the data points from the cation and anion triangles are transferred to the diamond diagram by drawing lines parallel to the outer boundary until they unite in the diamond (Appelo and Postma, 1993). These diagrams can be used to determine the rock-type origins as well as the different mechanisms of rock weathering. Geochemical differences were apparent among samples from wells in the Hebron Formation and those in the Brimfield Schist; the Brimfield Schist contains less calcium and bicarbonate than the Hebron Formation (fig. 6). Ground water in the Hebron Forma-

tion in the Woodstock area plots closer to a Ca, Mg-HCO₃ type water than does the ground water in the Hebron Formation in the Colchester area. Ground water in the Brimfield Schist plots closer to the sulfate end member on the ternary diagram than ground water in other rock types, as would be expected in sulfidic rock. Several water samples reflect anthropogenic contamination, such as road salting and the application of nitrogen fertilizers. The water sample from CO 348, for example, appears to be affected by road salting (halite) as illustrated by a near 1:1 ratio of sodium (2.3 mmol/L or 53 mg/L) and chloride (2.4 mmol/L or 87 mg/L) (table 1). The water from sample WK 231 had high concentrations of nitrate (14 mg/L as nitrogen) and chloride (32 mg/L), indicating contamination by fertilizers, animal waste, and (or) road salt, and caused its placement closer to a (Ca, Mg)Cl-type water on the Piper diagram (fig. 6).

The total dissolved solids concentrations in ground water from silicate rocks typically were low (table 1); all specific conductance values were less than 400 μS/cm. Ground-water flow along fracture zones also restricts the interaction and weathering in many massive igneous rocks. High silica content in ground water generally indicates greater interaction with, and degradation of, silicate minerals, although most silicate minerals have low dissolution rates. The weathering of silicate minerals also is accompanied by an increase in cation concentrations and dissolved bicarbonate. Natural waters of low ionic strength, without a dominant carbonate source, are affected by the incongruent dissolution reactions and by atmospheric and biologically produced carbon dioxide in soils that also yield dissolved bicarbonate (Appelo and Postma, 1993).

Boxplots were prepared to compare water-quality variables among the different rock types (fig. 7). The water from wells in the Brimfield Schist had higher concentrations of silica than water from wells in other rock types (fig. 7A). Because the well depths were similar among the three major geologic units (fig. 7B), the higher concentration of silica may result from the greater weatherability of the Brimfield Schist, or a greater diffuse-flow component, compared to the other geologic units. The higher pH and bicarbonate concentrations in samples from the Woodstock area may result from higher concentrations of calcite or other carbonates or longer residence times in the rocks (figs. 7C and D). Calcite constituted as much as 15 percent of Hebron rocks in the Plainfield-Danielson area, but generally made up less than 10 percent in the Woodstock area (Dixon, 1968).

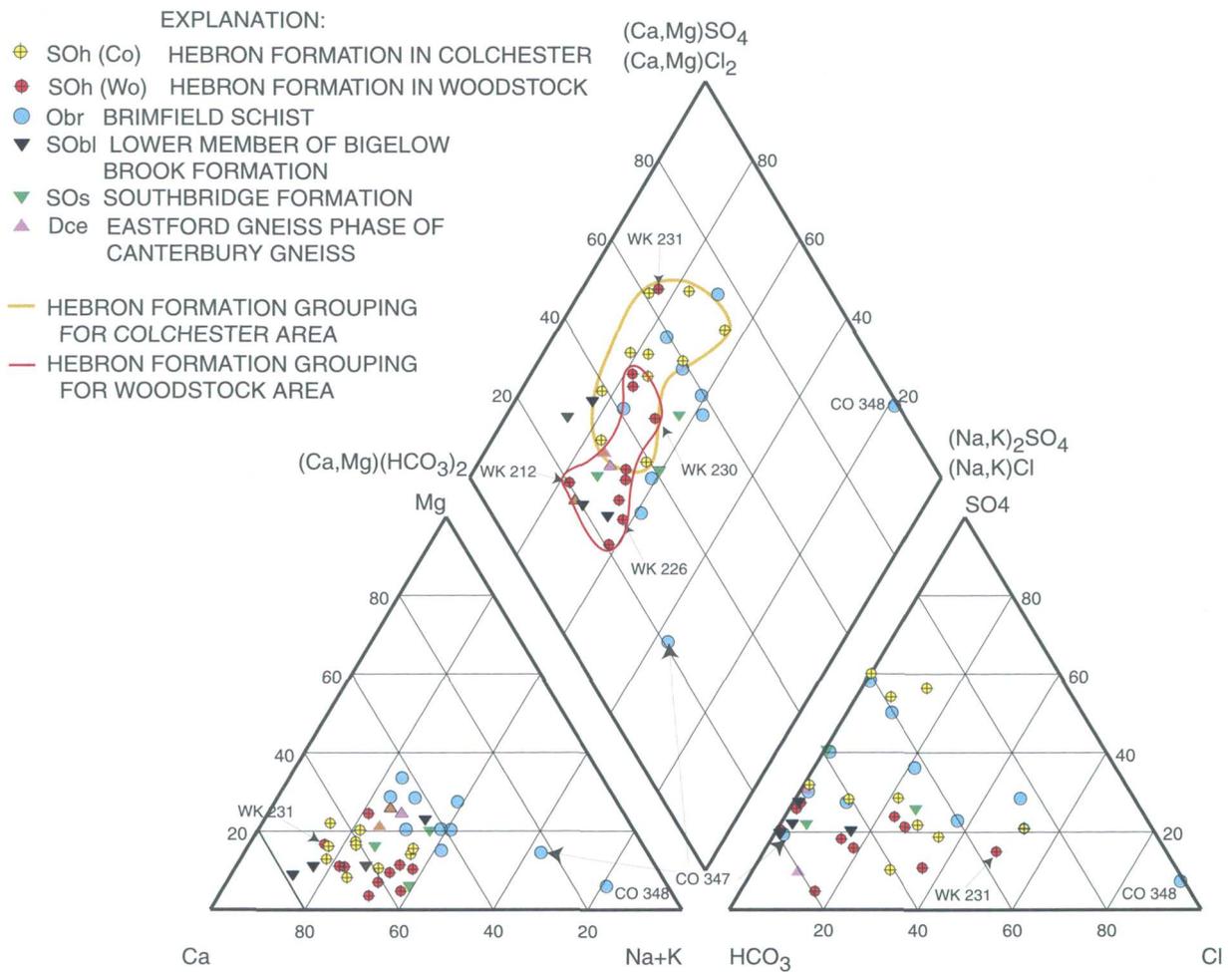


Figure 6. Geochemical differences among ground-water samples from bedrock wells, Colchester and Woodstock areas, Conn.

Table 1. Concentrations of major elements, chemical species, and $\delta^{34}\text{S}$ in water samples from bedrock wells, Colchester, East Hampton, and Woodstock, Conn., 2000

[USGS, U.S. Geological Survey; ANC, acid neutralization capacity; CDPH, Connecticut Department of Public Health; $\mu\text{S}/\text{cm}$, microsiemens per centimeter at 25 degrees Celsius; <, less than; $^{\circ}\text{C}$, degrees Celsius; --, data not available; $\mu\text{g}/\text{L}$, micrograms per liter; mg/L , milligrams per liter; $\%$, per mil. Well locations shown in figure 2.

Bedrock types: Obr, Brimfield Schist; SOh(co), Hebron Formation in Colchester area; SOh(wo), Hebron Formation in Woodstock area; Dce, Eastford Gneiss phase of the Canterbury Gneiss; SOs, Southbridge Formation; SObl, lower member of the Bigelow Brook Formation]

Well identifier	Well depth (feet below land surface)	Date sampled	Bedrock type	Specific conduct., USGS field ($\mu\text{S}/\text{cm}$)	pH, USGS field	Water temp., USGS field ($^{\circ}\text{C}$)	O_2 , USGS field (mg/L)	ANC, USGS field (mg/L as CaCO_3)	HCO_3^- , USGS field (mg/L as HCO_3^-)	H_2S , USGS field (mg/L)	Ca^{2+} , CDPH lab (mg/L)	Mg^{2+} , CDPH lab (mg/L)	Na^+ , CDPH lab (mg/L)
CO 342	180	8/2/00	Obr	240	6.4	11.6	<0.1	52	63	<0.005	18	8.6	10
CO 343	260	8/3/00	Obr	140	6.6	12	.05	31	38	<0.005	6.1	3.0	6.2
CO 345	200	8/7/00	Obr	96	6.9	11.2	.08	26	32	<0.005	6.0	1.9	5.9
CO 347	400	8/8/00	Obr	82	7.4	12.9	<.1	2	2	.023	3.1	1.2	8.3
CO 348	80?	8/8/00	Obr	380	5.3	12.3	5.1	1	1	<0.005	7.6	2.1	53
CO 339	185	8/9/00	Obr	126	6.9	11.9	<.1	35	43	.005	8.9 ^a 8.5 ^b	2.7 ^a 2.7 ^b	7.5 ^a 7.1 ^b
CO 349	240	8/9/00	Obr	248	6.9	11.3	<.1	33	40	.005	14	5.7	8.4
CO 350	300	8/10/00	Obr	94	7.0	12	<.1	27	33	<0.005	6.7	1.4	6.1
CO 351	200?	8/29/00	Obr	208	6.8	11.6	<.1	33	40	<0.005	18	4.6	13
CO 352	200?	8/30/00	Obr	144	7.3	11.4	.05	30	37	<0.005	12	4.4	6.8
CO 340	175	7/31/00	SOh(co)	112	5.6	11.4	.70	11	13	<0.005	11	1.8	3.3
CO 341	150	8/2/00	SOh(co)	300	6.9	11.9	1.6	69	84	<0.005	35	2.6	13
CO 344	230	8/3/00	SOh(co)	248	6.6	11.2	4.8	37	45	<0.005	29	6.1	4.7
CO 346	250	8/7/00	SOh(co)	228	7.3	11.5	<.1	55	67	<0.005	29	3.3	6.5
East Hampton													
EHM 412	200	8/10/00	SOh(co)	--	6.6	14.9	1.6	22	27	<0.005	9.9	1.9	6.5
EHM 413	305	8/30/00	SOh(co)	116	6.9	11.3	<.1	31	38	<0.005	11.0	2.3	4.6
EHM 414	165	9/5/00	SOh(co)	202	6.0	11.6	.05	39	48	<0.005	23	4.0	8.4
EHM 415	130	9/5/00	SOh(co)	72	5.8	12.3	4.9	18	22	<0.005	6.5	1.1	4.3
EHM 411	280	9/12/00	SOh(co)	354	5.5	11.7	2.9	94	120	<0.005	46 ^a 47 ^b	6.6 ^a 7.0 ^b	11 ^a 12 ^b
EHM 416	345	11/29/00	SOh(co)	232	7.1	11.7	<.1	38	46	<0.005	25	2.7	14

Table 1. Concentrations of major elements, chemical species, and $\delta^{34}\text{S}$ in water samples from bedrock wells, Colchester, East Hampton, and Woodstock, Conn., 2000—Continued

[USGS, U.S. Geological Survey; ANC, acid neutralization capacity; CDPH, Connecticut Department of Public Health; $\mu\text{S}/\text{cm}$, microsiemens per centimeter at 25 degrees Celsius; <, less than; °C, degrees Celsius; --, data not available; $\mu\text{g}/\text{L}$, micrograms per liter; mg/L , milligrams per liter; %, per mil. Well locations shown in figure 2.

Bedrock types: Obr, Brimfield Schist; SOh(co), Hebron Formation in Colchester area; SOh(wo), Hebron Formation in Woodstock area; Dce, Eastford Gneiss phase of the Canterbury Gneiss; SOs, Southbridge Formation; SObl, lower member of the Bigelow Brook Formation]

Well Identifier	Well depth (feet below land surface)	Date sampled	Bedrock type	Specific conduct., USGS field ($\mu\text{S}/\text{cm}$)	pH, USGS field	Water temp., USGS field (°C)	O_2 , USGS field (mg/L)	ANC, USGS field (as CaCO_3)		HCO_3^- , USGS field (as HCO_3^-)	H_2S , USGS field (mg/L)	Ca^{2+} , CDPH lab (mg/L)	Mg^{2+} , CDPH lab (mg/L)	Na^+ , CDPH lab (mg/L)
								(mg/L)	(mg/L)					
Woodstock														
WK 216	300	11/21/00	Soh(wo)	108	5.9	10.4	6.4	30	37	<0.005	11	1.1	6.3	
WK 219	295	11/28/00	Soh(wo)	198	8.1	10.8	<.1	69	84	.038	22	1.1	16	
WK 223	320	12/5/00	Soh(wo)	236	8.6	10.7	.40	68	83	<.005	32	3.2	11	
WK 212	112	12/5/00	Soh(wo)	160	7.7	10.3	6.5	55	67	<.005	20 ^a	2.0 ^a	6.3 ^a	5.8 ^b
WK 225	110	12/7/00	Soh(wo)	216	8.0	10.6	.80	70	85	.13	26	1.8	14	
WK 226	200	12/7/00	Soh(wo)	196	8.3	10.5	.75	68	83	<.005	20	2.4	14	
WK 227	145	12/11/00	Soh(wo)	106	8.0	10	<.1	30	37	.007	11	1.4	6.7	
WK 229	133	12/8/00	Soh(wo)	226	6.6	10.1	2.4	44	54	<.005	23	6.3	7.3	
WK 230	500	12/12/00	Soh(wo)	244	8.3	11.6	<.1	61	74	<.005	30	1.0	16	
WK 231	225	12/12/00	Soh(wo)	290	6.1	10	8.0	33	40	<.005	34	5.1	6.9	
WK 214	137	8/1/00	Dce	120	6.8	10.7	4.2	40	49	<.005	11	3.5	5.9	
WK 222	173	12/1/00	Dce	162	7.6	10.7	13	51	62	<.005	16	3.8	7.9	
WK 221	220	12/1/00	Dce	324	7.5	9.8	<.1	110	140	<.005	30	9.4	19	
WK 215	130	11/21/00	SOs	168	6.0	9.8	2.8	35	43	<.005	14	3.9	12	
WK 217	605	11/27/00	SOs	238	8.1	11.7	<.1	68	83	.008	26	1.7	20	
WK 213	180	12/11/00	SOs	144	6.8	10	.70	53	65	<.005	17 ^a	2.9 ^a	8.5 ^a	
											16 ^b	2.2 ^b	8.4 ^b	
WK 218	405	11/27/00	SObl	136	7.9	10	<.1	46	56	<.005	20	1.4	2.3	
WK 220	275	11/28/00	SObl	148	8.3	10.7	<.1	51	62	<.005	17	1.9	7.4	
WK 224	500	12/5/00	SObl	214	6.9	10.2	2.2	63	77	<.005	30	2.8	4.9	
WK 228	275	12/8/00	SObl	138	8.0	9.7	.55	43	52	<.005	12	3.9	10	

Table 1. Concentrations of major elements, chemical species, and $\delta^{34}\text{S}$ in water samples from bedrock wells in Colchester, East Hampton, and Woodstock, Conn.—Continued

[USGS, U.S. Geological Survey; ANC, acid neutralization capacity; CDPH, Connecticut Department of Public Health; $\mu\text{S}/\text{cm}$, microsiemens per centimeter at 25 degrees Celsius; <, less than; °C, degrees Celsius; --, data not available; $\mu\text{g}/\text{L}$, micrograms per liter; mg/L , milligrams per liter; %, per mil. Well locations shown in figure 2.

Bedrock types: Obr, Brimfield Schist; SOh(co), Hebron Formation in Colchester area; SOh(wo), Hebron Formation in Woodstock area; Dec, Eastford Gneiss phase of the Canterbury Gneiss; SOs, Southbridge Formation; SObl, lower member of the Bigelow Brook Formation]

Well Identifier	K ⁺ , CDPH lab (mg/L)	Cl ⁻ , CDPH lab (mg/L)	SO ₄ ²⁻ , CDPH lab (mg/L)	PO ₄ ²⁻ , CDPH lab (mg/L)	Silica, USGS lab (mg/L)	NO ₃ ⁻ as N, CDPH lab (mg/L)	Dissolved Fe, USGS lab (μg/L)	Dissolved Mn, CDPH lab (μg/L)	Dissolved As, USGS lab (μg/L)	Total As, CDPH lab (μg/L)	Dissolved As, CDPH lab (μg/L)	$\delta^{34}\text{S}$, USGS lab (‰)
Colchester												
CO 342	2.8	34	28	0.06	29	<0.1	4,700	130	<0.18	<3.0	<3.0	--
CO 343	3.1	5.2	37	.09	13	<1	17	140	2.7	<3.0	<3.0	--
CO 345	2.3	<1	11	.01	16	<1	180	80	<.18	<3.0	<3.0	--
CO 347	2.7	<1	6.5	.04	220	.1	2,500	40	<.18	<3.0	<3.0	--
CO 348	2.2	87	9.2	<.01	20	.3	17	80	1.2	<3.0	<3.0	--
CO 339	3.7 ^a 3.5 ^b	5.0 ^a 3.7 ^b	15 ^a 37 ^b	.01	29	<1	3,200	230	<.90	<3.0	<3.0	-3.1
CO 349	4.6	46	37	.11	28	.1	14,000	230	<.18	<3.0	<3.0	--
CO 350	2.0	9.6	22	.01	13	<1	28	60	<.18	<3.0	<3.0	--
CO 351	0.70	<1	45	.01	18	<1	<10	100	<.18	<3.0	<3.0	--
CO 352	--	<1	20	.02	23	.6	<10	<10	<.18	<3.0	<3.0	--
CO 340	2.4	3.6	20	<.01	16	<1	13	10	<.18	<3.0	<3.0	--
CO 341	3.3	29	29	.01	13	<1	170	20	<.18	<3.0	<3.0	--
CO 344	4.9	5	50	.01	16	.1	100	10	4.5	<3.0	<3.0	--
CO 346	3.9	17	30	<.01	14	<1	<10	30	.83	<3.0	<3.0	--
East Hampton												
EHM 412	2.8	30	16	.02	21	.1	21	10	<.18	<3.0	<3.0	--
EHM 413	--	<1	14	.04	27	<1	450	140	<.18	<3.0	<3.0	--
EHM 414	2.2	21	15	.01	29	<1	9,300	40	<.18	<3.0	<3.0	--
EHM 415	1.6	2.4	8.0	.01	27	<1	1,200	<10	<.18	<3.0	<3.0	--
EHM 411	2.0 ^a 2.1 ^b	32 ^a 37 ^b	15 ^a 10 ^b	.01	17	3.7	<10	<10	<.90	<3.0	<3.0	.8
EHM 416	1.3	<1	55	<.01	17	<1	87	110	<.18	<3.0	<3.0	--

Table 1. Concentrations of major elements, chemical species, and $\delta^{34}\text{S}$ in water samples from bedrock wells in Colchester, East Hampton, and Woodstock, Conn.—Continued

[USGS, U.S. Geological Survey; ANC, acid neutralization capacity; CDPH, Connecticut Department of Public Health; $\mu\text{S}/\text{cm}$, microsiemens per centimeter at 25 degrees Celsius; $<$, less than; $^{\circ}\text{C}$, degrees Celsius; --, data not available; $\mu\text{g}/\text{L}$, micrograms per liter; mg/L , milligrams per liter; $\%$, per mil. Well locations shown in figure 2.

Bedrock types: Obr, Brimfield Schist; SOh(co), Hebron Formation in Colchester area; SOh(wo), Hebron Formation in Woodstock area; Dce, Eastford Gneiss phase of the Canterbury Gneiss; SOs, Southbridge Formation; SObl, lower member of the Bigelow Brook Formation]

Well Identifier	K ⁺ , CDPH lab (mg/L)	Cl ⁻ , CDPH lab (mg/L)	SO ₄ ²⁻ , CDPH lab (mg/L)	PO ₄ ²⁻ , CDPH lab (mg/L)	Silica, USGS lab (mg/L)	NO ₃ ⁻ as N, CDPH lab (mg/L)	Dissolved Fe, USGS lab (μg/L)	Dissolved Mn, CDPH lab (μg/L)	Dissolved As, USGS lab (μg/L)	Total As, CDPH lab (μg/L)	Dissolved As, CDPH lab (μg/L)	$\delta^{34}\text{S}$, USGS lab (‰)
WK 216	1.8	4.7	7.7	.01	17	<1	87	<10	<.18	<3.0	<3.0	--
WK 219	1.3	<1	17	0.01	14	<0.1	<10	20	<0.18	<3.0	<3.0	--
WK 223	3.1	32	13	.01	11	<1	<10	20	<.18	<3.0	<3.0	--
WK 212	2.0 ^a 1.8 ^b	7.8 ^a 8.8 ^b	5.5 ^a 3.1 ^b	.02	16	.8	17	<10	14	39	17	-1.4
WK 225	2.9	14	16	<.01	28	<1	20 ^{b,c}	20	<.18 ^c	6.0	6.0	--
WK 226	4.6	1	23	.01	14	<1	20 ^{b,c}	60	<.18 ^c	4.0	4.0	--
WK 227	2.3	<1	11	.07	15	<1	<10	40	5.6	5.0	<3.0	--
WK 229	5.3	16	17	.01	27	3.7	1,900	20	<.18	<3.0	<3.0	--
WK 230	1.6	19	26	.01	13	.3	<10	10	24	23	23	--
WK 231	4.0	32	13	.01	21	14	46	10	.34	<3.0	<3.0	--
WK 214	1.1	3.5	4.5	.01	23	<1	<10	<10	<.18	<3.0	<3.0	--
WK 222	1.4	<1	22	.05	22	<1	<10	30	<.18	3.0	<3.0	--
WK 221	2.9	1	48	.01	18	<1	81	260	.86	<3.0	<3.0	--
WK 215	2.6	14	18	.01	16	1.3	<10	<10	<.18	<3.0	<3.0	--
WK 217	2.3	<1	45	<.01	17	<1	53	50	2.9	4.0	<3.0	--
WK 213	1.8 ^a 1.2 ^b	4.7 ^a 2.9 ^b	15 ^a 14 ^b	.01	19	.3	33	40	<.18	<3.0	<3.0	-4
WK 218	2.6	<1	17	<.01	15	<1	27	10	<.18	<3.0	<3.0	--
WK 220	2.2	<1	12	<.01	14	<1	20	30	<.18	<3.0	<3.0	--
WK 224	4.8	11	19	<.01	17	2.5	2,100	20	<.18	<3.0	<3.0	--
WK 228	1.6	<1	12	.03	16	<1	<10	140	<.18	<3.0	<3.0	--

^a Analyzed by U.S. Geological Survey National Water-Quality Laboratory.

^b Analyzed by Connecticut Department of Public Health Laboratory.

^c Dissolved value was suspect; therefore, the dissolved arsenic value obtained by the CDPH Laboratory was used.

Arsenic Concentrations

Arsenic concentrations in private wells varied considerably between the two study areas (fig. 2). Dissolved arsenic concentrations were below the detection limit (<0.18 or <0.9 $\mu\text{g/L}$) in 16 of the 20 wells (20-percent detection frequency) in the Colchester area. Arsenic concentrations in samples from wells in the Hebron Formation and the Brimfield Schist in the Colchester area (fig. 7E) were not substantially different, but concentrations of dissolved oxygen were lower and concentrations of dissolved iron and manganese were higher in the Brimfield Schist (figs. 7F, 7G, and 7H). In the Woodstock area, where arsenic concentrations in bedrock wells historically have been high, eight wells had dissolved arsenic concentrations greater than the detection limits (40-percent detection frequency; table 1). Six of these wells were in the Hebron Formation in the southeastern part of Woodstock, near the village of South Woodstock. Samples from two of these wells had dissolved arsenic concentrations that exceeded the USEPA arsenic standard (10 $\mu\text{g/L}$)—24 $\mu\text{g/L}$ (WK 230) and 14 $\mu\text{g/L}$ (WK 212); the total arsenic concentration measured by CDPH for the WK 212 sample was 39 $\mu\text{g/L}$ (table 1). Sample WK 212 was taken from a well that became turbid during pumping and did not clear up before sampling; furthermore, the substantial fraction (25 $\mu\text{g/L}$) of filterable (greater than 0.45- μM) arsenic indicates that arsenic could be sorbed to particulates and (or) colloids. Samples WK 217 and WK 222 also were taken from wells that became turbid during pumping, and both samples had concentrations of total arsenic (4 and 3 $\mu\text{g/L}$, respectively) that were higher than those of dissolved arsenic (2.9 and <0.18 $\mu\text{g/L}$, respectively).

Detectable arsenic concentrations in ground water generally did not coincide with either oxic or reducing conditions. Redox conditions ranged from oxic to iron reducing to sulfate reducing (methane was not measured) and the Brimfield, a sulfidic schist, generally had wells with more reducing conditions than those in the other rock types. Redox conditions can be assessed qualitatively by occurrences and concentrations of redox-active constituents in ground water. Ground-water samples from bedrock wells, however, can be derived from multiple fractures within the boreholes; therefore, some samples may consist of a mixture of waters from different fractures that are different chemically and not in redox equilibrium.

Constituents indicative of reducing conditions include sulfide species and dissolved iron and manganese. Those constituents indicative of oxic or suboxic conditions include dissolved oxygen and nitrate. Redox species of arsenic and iron were not measured separately in this study. Arsenic concentrations were highest in ground water with low concentrations of dissolved iron and manganese (fig. 8A), and the well with a sample containing the highest total arsenic concentration and the second highest dissolved arsenic concentration (WK 212) was oxic (table 1; fig. 8B). Wells in the Hebron Formation in Woodstock (WK 225, WK 227, WK 217) with detected sample concentrations of dissolved sulfide (0.13, 0.007, and 0.008 mg/L), however, also had detected concentrations of dissolved arsenic (6 $\mu\text{g/L}$, 5.6 $\mu\text{g/L}$, and 2.9 $\mu\text{g/L}$) and could indicate that arsenic was desorbed or reduced from ferric hydroxides or manganous oxides under reducing conditions.

Water from six of the eight wells with the highest arsenic concentrations were from the Woodstock area and had pH levels greater than 7.7 (fig. 8C). These pH levels indicate that arsenic occurrences could be related to ion exchange, such as the desorption of arsenate at high pH, although concentrations of sulfate and phosphate did not correlate with arsenic (fig. 8D). Bedrock wells in other parts of New England have shown a predominance of arsenate (arsenic(V)) in both oxic and reduced ground water (J. D. Ayotte, U.S. Geological Survey, oral commun., 2001). Well depth and silica content (fig. 8E) and sulfate (fig. 8D) generally did not correlate with detectable concentrations of arsenic and thus precludes any relation between arsenic concentrations in wells and either shallow or deep sources of arsenic or the extent of rock weathering. Ground-water flow through fractures is different than flow through granular media, however, and silica probably is a better indicator of water-rock interaction than depth in fractured bedrock aquifers. Previous studies of the Hebron Formation do not indicate the local presence of arsenic-bearing minerals, but whole-rock chemistry data are sparse. Petrographic or whole-rock analyses of Hebron rocks showed no evidence of sulfide minerals or arsenic in the Danielson and Plainfield quadrangles (Dixon, 1968) to the southeast, or the Putnam (Dixon, 1982) or Eastford (Pease, 1972) quadrangles, which make up the Woodstock area study site. Rocks in the

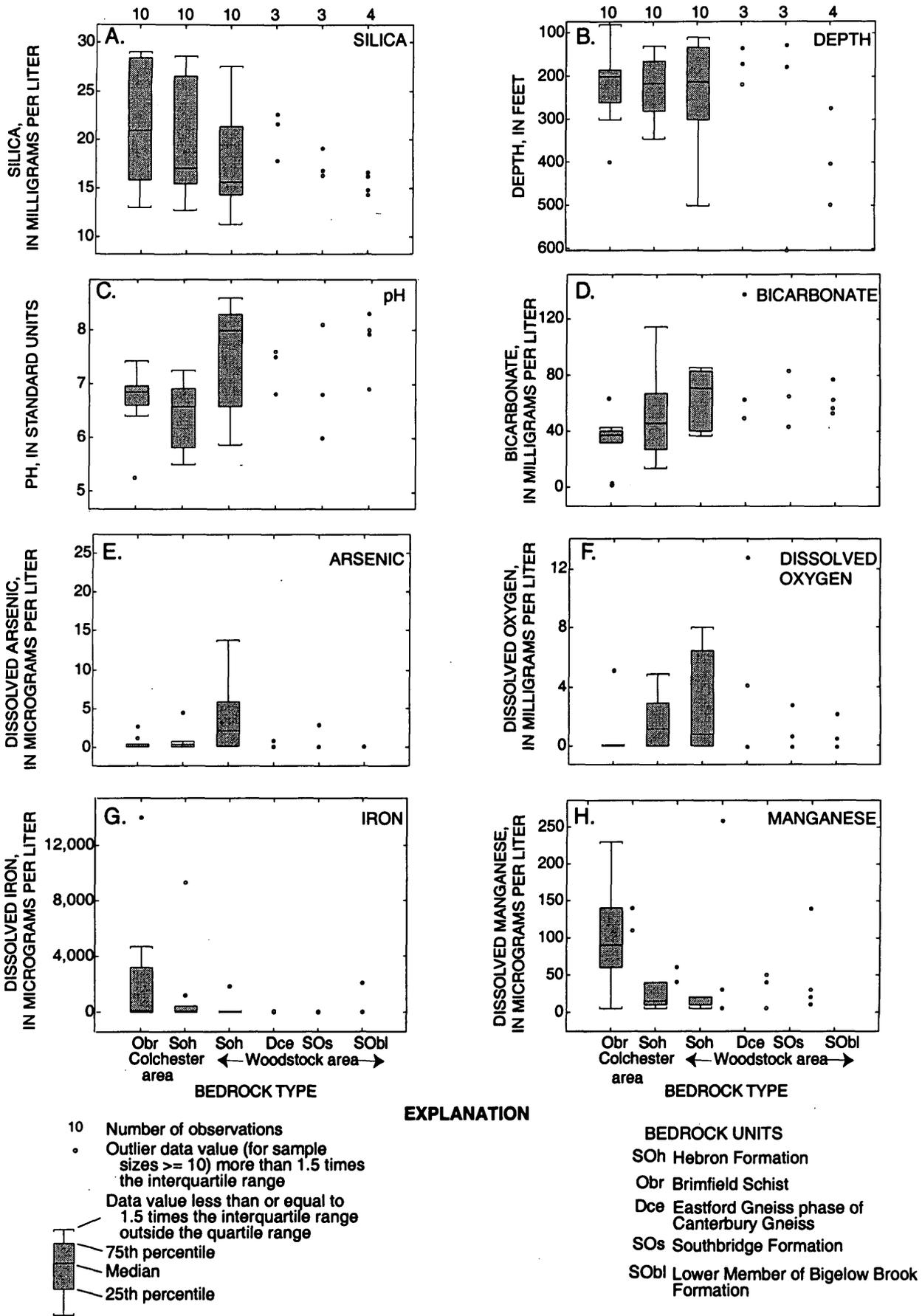


Figure 7. Geochemical differences among ground-water samples from bedrock wells, Colchester and Woodstock areas, Conn.

Hampton quadrangle to the south, however, contained muscovite-schist lenses within the Hebron that are described as a strongly rusty weathering, pyrite-graphite-quartz-muscovite schist; pyrite nodules were found on a joint surface in the schist (Dixon, 1968). Small pegmatite intrusions and vein-filled fractures are common throughout the Hebron Formation and also may be a source of arsenic-bearing minerals.

The clustering of arsenic concentrations in wells in southeastern Woodstock, despite the similarity in land use throughout the area, indicates that geochemical variations in the Hebron Formation could result in the locally high pH and detectable arsenic concentrations. Furthermore, the major ions and nutrients in water samples from wells with the highest arsenic concentrations (WK 212 and WK 230) did not show obvious signs of anthropogenic contamination, such as locally high nitrate or chloride concentrations (table 1 and fig. 6) that might indicate an anthropogenic contribution or induced pathway of arsenic. Further study will be necessary to determine whether the higher frequency of arsenic occurrences are from arsenic in the Hebron Formation, from overlying glacial deposits, or from anthropogenic contamination, such as the application of pesticides that contain arsenic and lime that raises the pH.

The $\delta^{34}\text{S}$ of sulfate in selected wells was used in an attempt to determine the mineral sources and processes associated with sulfur and to better understand arsenic occurrences. Isotopically light ($<0\text{‰}$) values typically indicate the oxidation of sulfide minerals, which commonly have high concentrations of arsenic. The $\delta^{34}\text{S}$ of sulfate in areas of recharge

should be indicative of atmospheric sulfate and, therefore, “heavy”—the $\delta^{34}\text{S}$ of atmospheric precipitation ranges from about 20 ‰ in regions containing only sea-spray sulfate to about 0 ‰ in highly industrialized regions (Coplen, 1993). Ground water moving down-gradient from the point of recharge will become “lighter” with depth or interaction with fracture surfaces if FeS_2 minerals (pyrite or marcasite) are present as a result of the oxidative dissolution. Although $\delta^{34}\text{S}$ compositions of sulfide minerals were not analyzed for this study, $\delta^{34}\text{S}$ values typically are less than 0 ‰ in open systems² (McKibben and Eldridge, 1989; Brown and others, 2000). Gypsum, which has a $\delta^{34}\text{S}$ of about +10 ‰, is another potential source of sulfate. The relatively low $\delta^{34}\text{S}$ values in ground-water sulfate supports the scarcity of gypsum in the local rocks and precludes a significant source in local fertilizers. Water from the two wells in rock types that are sulfidic (Brimfield Schist) or potentially sulfidic (Southbridge Formation) had lower $\delta^{34}\text{S}$ (-3.1 and -4.0 ‰, respectively) than waters from the Hebron Formation at either area, although the lighter samples did not have higher concentrations of arsenic that might result from the oxidation of arsenic-bearing sulfide minerals (fig. 9). Further sampling and analyses of water samples and solid-phase chemistry at the study sites would be required to more completely understand the chemical processes involved in sulfur chemistry and concentrations of arsenic in sulfide minerals.

²Refers to parts of the aquifer that are not isolated from atmospheric sources of sulfate.

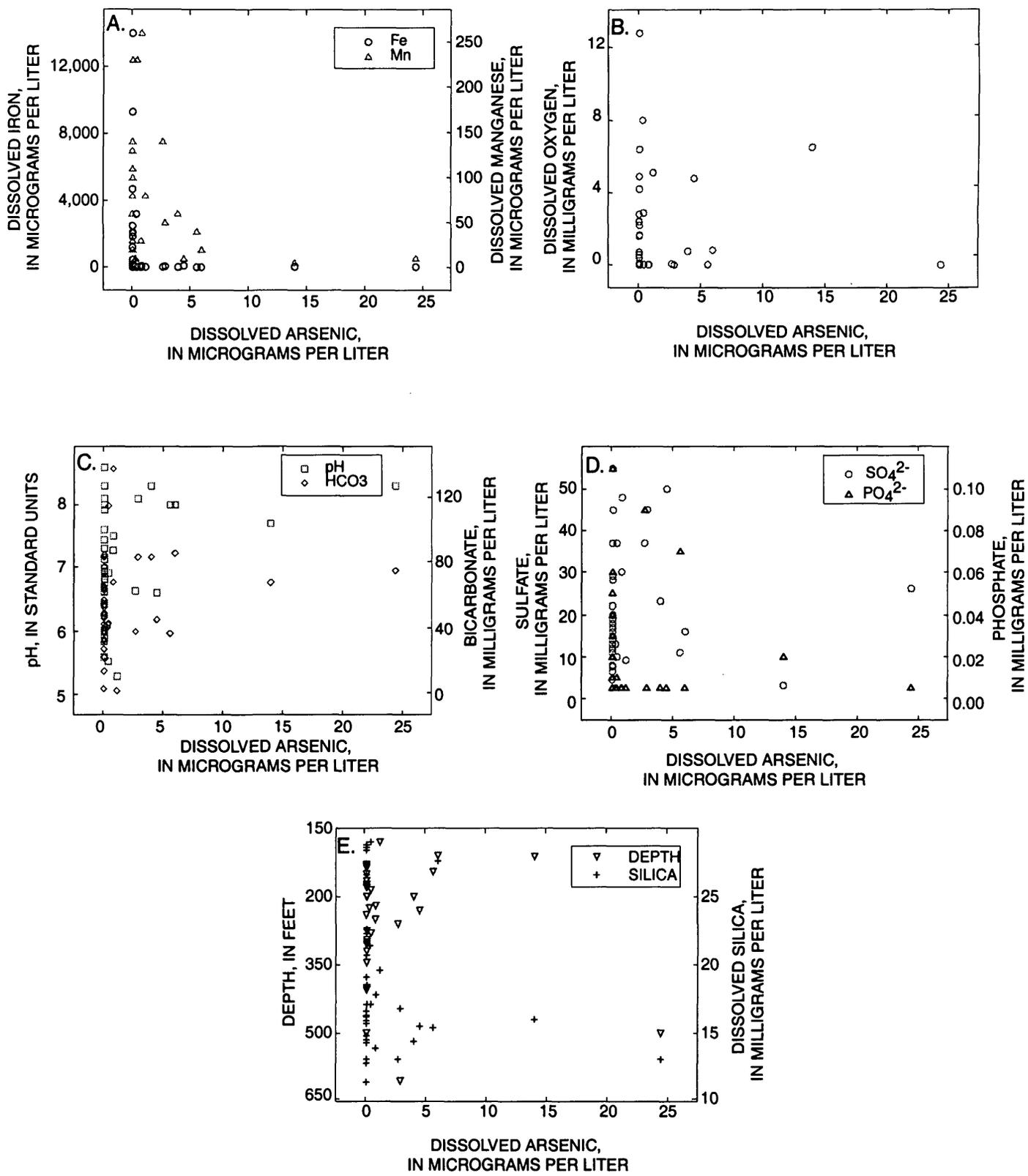


Figure 8. Geochemical differences among ground-water samples from bedrock wells, Colchester and Woodstock areas, Conn.

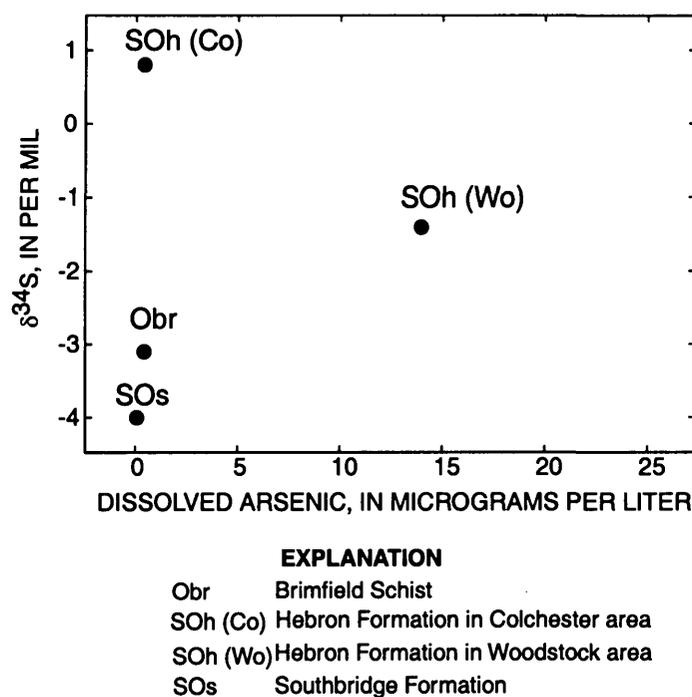


Figure 9. $\delta^{34}\text{S}$ of sulfate in ground water from bedrock wells in the Colchester and Woodstock areas, Conn.

SUMMARY AND CONCLUSIONS

Moderate to high concentrations ($>10 \mu\text{g/L}$) of arsenic, a known human carcinogen, have been detected in bedrock wells in Connecticut. The U.S. Geological Survey (USGS), in cooperation with the Connecticut Department of Public Health (CDPH), collected water samples from private bedrock wells in eastern Connecticut to evaluate the relative importance of bedrock type and redox chemistry on the occurrence and mobility of arsenic in ground water from bedrock aquifers. Samples were collected from wells along transects in two areas where (1) bedrock contains sulfide minerals, which can have high arsenic concentrations, or (2) arsenic concentrations have been detected in water from bedrock wells. Water samples also were collected from wells in adjacent bedrock types that were not expected to have a high arsenic content. Each transect area included 20 wells. Total and dissolved arsenic, redox-sensitive constituents (dissolved oxygen, iron, manganese, and sulfide), and the major inorganic chemistry of water from specific bedrock types were analyzed to help determine the sources and pathways of arsenic in bedrock wells.

Dissolved arsenic concentrations were below the detection limits used by the NWQL ($<0.18 \mu\text{g/L}$ and $<0.9 \mu\text{g/L}$) in 16 of the 20 wells (20-percent detection frequency) in Colchester and East Hampton in east-central Connecticut (Colchester area). Arsenic concentrations showed little or no difference in samples from wells in the Hebron Formation, which has a high occurrence of arsenic in public-supply wells in northeastern Connecticut, and the Brimfield Schist, which is sulfidic and therefore more likely to contain a high arsenic content. Concentrations of dissolved iron, manganese, and sulfate were higher in samples from wells in the Brimfield Schist than those from wells in the Hebron Formation.

In northeastern Connecticut (Woodstock area), where arsenic concentrations in some public-supply wells in bedrock historically have been $>10 \mu\text{g/L}$, water samples from eight wells had dissolved arsenic concentrations greater than the detection limit ($0.18 \mu\text{g/L}$ or $3 \mu\text{g/L}$; 40-percent detection frequency). Six of these wells are in the Hebron Formation near South Woodstock. Water samples from two of these wells had dissolved arsenic concentrations that exceeded the new (2001) U.S. Environmental Protection Agency arsenic

standard of 10 $\mu\text{g/L}$ —24 $\mu\text{g/L}$ and 14 $\mu\text{g/L}$, and total arsenic concentrations as high as 39 $\mu\text{g/L}$. The latter sample had a substantial fraction (25 $\mu\text{g/L}$) of filterable (greater than 0.45 μM) arsenic. Two other samples that were taken from wells that became turbid during pumping also had concentrations of total arsenic (4 and 3 $\mu\text{g/L}$, respectively) that were higher than those of dissolved arsenic (2.9 and 0.1 $\mu\text{g/L}$, respectively). The differences between total (unfiltered) and dissolved arsenic concentrations in these turbid ground-water samples indicates that arsenic could be sorbed to particulates and (or) colloids under certain conditions.

Arsenic concentrations detected in ground water were not limited to reducing conditions. Redox conditions ranged from oxic to iron-reducing to sulfate-reducing (methane was not measured). The Brimfield Schist, which is sulfidic, generally had reducing conditions in more of its wells than the other rock types. Arsenic concentrations were highest in ground water with low concentrations of dissolved iron and manganese, and the well with the higher total arsenic and second highest dissolved arsenic concentration was oxic. Wells in the Hebron Formation in Woodstock that had detected concentrations of dissolved sulfide, however, also had detected concentrations of dissolved arsenic and could indicate that arsenic was desorbed or reduced from ferric hydroxides or manganous oxides under reducing conditions. Water from six of the eight wells with the highest arsenic concentrations were in Woodstock and had pH levels greater than 7.7; these levels indicate that arsenic occurrences could be related to ion exchange, such as the desorption of arsenate at high pH.

The Hebron Formation ranges from an interbedded quartz-biotite-plagioclase schist and calc-silicate gneiss in the Colchester area to a well-layered feldspathic biotite-quartz schist in the South Woodstock area; previous studies of the Hebron Formation do not indicate an abundance of arsenic-bearing minerals, but whole-rock chemistry data are sparse. Small pegmatite intrusions and vein-filled fractures are common in the Hebron Formation and contain sulfide minerals that could have a high arsenic content. The clustering of detected arsenic concentrations in southeastern Woodstock, despite the similarity in land use throughout the area, indicates that variations in the Hebron Formation could result in the locally high pH levels and arsenic concentrations. The major ions and nutrients in water samples from wells with high (>10 $\mu\text{g/L}$) arsenic did not show obvious signs of

anthropogenic contamination, such as locally high nitrate or chloride concentrations that could indicate an anthropogenic contribution or induced pathway of arsenic. Further study would be necessary to determine whether the high frequency of arsenic occurrences are from arsenic in the Hebron Formation, from overlying glacial deposits, or from anthropogenic contamination.

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