In cooperation with the Pennsylvania Department of Environmental Protection

Natural Gases in Ground Water near Tioga Junction, Tioga County, North-Central Pennsylvania—Occurrence and Use of Isotopes to Determine Origins, 2005

Scientific Investigations Report 2007-5085

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

Natural Gases in Ground Water near Tioga Junction, Tioga County, North-Central Pennsylvania—Occurrence and Use of Isotopes to Determine Origins, 2005

By Kevin J. Breen[1], Kinga Révész [1], Fred J. Baldassare[2], and Steven D. McAuley[1]

[1]U.S. Geological Survey, [2]Pennsylvania Department of Environmental Protection

Prepared in cooperation with Pennsylvania Department of Environmental Protection

Scientific Investigations Report Series 2007–5085

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

U.S. Department of the Interior
DIRK KEMPTHORNE, Secretary

U.S. Geological Survey
Mark D. Myers, Director

U.S. Geological Survey, Reston, Virginia: 2007

For product and ordering information:
World Wide Web: http://www.usgs.gov/pubprod
Telephone: 1-888-ASK-USGS

For more information on the USGS—the Federal source for science about the Earth,
its natural and living resources, natural hazards, and the environment:
World Wide Web: http://www.usgs.gov
Telephone: 1-888-ASK-USGS

Suggested citation:
Breen, K.J., Révész, Kinga, Baldassare, F.J., and McAuley, S.D., 2007, Natural gases in ground water near Tioga Junction, Tioga County, North-Central Pennsylvania—Occurrence and use of isotopes to determine origins, 2005: U.S. Geological Survey Scientific Investigations Report 2007-5085, 65 p.

Contents

Figures

Tables

Conversion Factors, Abbreviations, and Acronyms

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
gallon per minute (gal/min)	0.06309	liter per second (L/s)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)
	Pressure	
atmosphere, standard (atm)	101.3	kilopascal (kPa)
pound per square inch (lb/in^2)	6.895	kilopascal (kPa)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)

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

$$°F = (1.8 \times °C) + 32$$

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

$$°C = (°F - 32) / 1.8$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

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

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

per mil: Per mil units are equivalent to parts per thousand (‰ or 1/1000).

ANC	Acid Neutralizing Capacity
BOGM	Bureau of Oil and Gas Management
DIC	Dissolved Inorganic Carbon
GPS	Global Positioning System
IT	Incremental titration

NBS	National Bureau of Standards
PADEP	Pennsylvania Department of Environmental Protection
QA	Quality assurance
RDGL	Reston Dissolved Gas Laboratory
RSIL	Reston Stable Isotope Laboratory
SLAP	Standard Light Antarctic Precipitation
USGS	U.S. Geological Survey
VSMOW	Vienna Standard Mean Ocean Water
VPDB	Vienna PeeDee Belemnite

Chemical symbols and isotopes

$CaCO_3$	Calcium carbonate
CH_4	Methane
C_2H_6	Ethane
CO_2	Carbon dioxide
δ^2H or δD_{water}	Stable isotope composition of deuterium (^2H) and hydrogen (^1H) in water, in delta notation
$\delta^{18}O_{water}$	Stable isotope composition of oxygen-18 and oxygen-16 in water, in delta notation
$\delta^{13}C_{DIC}$	Stable isotope composition of carbon-13 and carbon-12 for dissolved inorganic carbon in water, in delta notation
$\delta^{13}C_{CH4}$	Stable isotope composition of carbon-13 and carbon-12 for methane gas, in delta notation
$\delta^{13}C_{C2H6}$	Stable isotope composition of carbon-13 and carbon-12 for ethane gas, in delta notation
δD_{CH4}	Stable isotope composition of deuterium and hydrogen for methane gas, in delta notation

Natural Gases in Ground Water near Tioga Junction, Tioga County, North-Central Pennsylvania—Occurrence and Use of Isotopes to Determine Origins, 2005

By Kevin J. Breen[1], Kinga Révész[1], Fred J. Baldassare[2], and Steven D. McAuley[1]

Abstract

In January 2001, State oil and gas inspectors noted bubbles of natural gas in well water during a complaint investigation near Tioga Junction, Tioga County, north-central Pa. By 2004, the gas occurrence in ground water and accumulation in homes was a safety concern; inspectors were taking action to plug abandoned gas wells and collect gas samples. The origins of the natural-gas problems in ground water were investigated by the U.S. Geological Survey, in cooperation with the Pennsylvania Department of Environmental Protection, in wells throughout an area of about 50 mi^2, using compositional and isotopic characteristics of methane and ethane in gas and water wells. This report presents the results for gas-well and water-well samples collected from October 2004 to September 2005.

Ground water for rural-domestic supply and other uses near Tioga Junction is from two aquifer systems in and adjacent to the Tioga River valley. An unconsolidated aquifer of outwash sand and gravel of Quaternary age underlies the main river valley and extends into the valleys of tributaries. Fine-grained lacustrine sediments separate shallow and deep water-bearing zones of the outwash. Outwash-aquifer wells are seldom deeper than 100 ft. The river-valley sediments and uplands adjacent to the valley are underlain by a fractured-bedrock aquifer in siliciclastic rocks of Paleozoic age. Most bedrock-aquifer wells produce water from the Lock Haven Formation at depths of 250 ft or less.

A review of previous geologic investigations was used to establish the structural framework and identify four plausible origins for natural gas. The Sabinsville Anticline, trending southwest to northeast, is the major structural feature in the Devonian bedrock. The anticline, a structural trap for a reservoir of deep native gas in the Oriskany Sandstone (Devonian) (origin 1) at depths of about 3,900 ft, was explored and tapped by numerous wells from 1930-60. The gas reservoir in the vicinity of Tioga Junction, depleted of native gas, was converted to the Tioga gas-storage field for injection and withdrawal of non-native gases (origin 2). Devonian shale gas (shallow native gas) also has been reported in the area (origin 3). Gas might also originate from microbial degradation of buried organic material in the outwash deposits (origin 4).

An inventory of combustible-gas concentrations in headspaces of water samples from 91 wells showed 49 wells had water containing combustible gases at volume fractions of 0.1 percent or more. Well depth was a factor in the observed occurrence of combustible gas for the 62 bedrock wells inventoried. As well-depth range increased from less than 50 ft to 51-150 ft to greater than 151 ft, the percentage of bedrock-aquifer wells with combustible gas increased. Wells with high concentrations of combustible gas occurred in clusters; the largest cluster was near the eastern boundary of the gas-storage field. A subsequent detailed gas-sampling effort focused on 39 water wells with the highest concentrations of combustible gas (12 representing the outwash aquifer and 27 from the bedrock aquifer) and 8 selected gas wells. Three wells producing native gas from the Oriskany Sandstone and five wells (two observation wells and three injection/withdrawal wells) with non-native gas from the gas-storage field were sampled twice. Chemical composition, stable carbon and hydrogen isotopes of methane ($\delta^{13}C_{CH4}$ and δD_{CH4}), and stable carbon isotopes of ethane ($\delta^{13}C_{C2H6}$) were analyzed. No samples could be collected to document the composition of microbial gas originating in the outwash deposits (outwash or "drift" gas) or of native natural gas originating solely in Devonian shale at depths shallower than the Oriskany Sandstone, although two of the storage-field observation wells sampled reportedly yielded some Devonian shale gas. Literature values for outwash or "drift" gas and Devonian shale gases were used to supplement the data collection.

Non-native gases from wells in the gas-storage field and native gases from wells producing from the Oriskany Sandstone were similar in chemical composition; methane (volume fraction ranging from 94.5 to 97.2 percent) and ethane (volume fraction ranging from 2.0 to 2.6 percent) were predominant. Isotopic composition data for storage-field gases (median $\delta^{13}C_{CH4}$ of about -44.1 per mil, δD_{CH4} of -168 per mil, and $\delta^{13}C_{C2H6}$ of -32.7 per mil) were different than gases from the Oriskany Sandstone (median $\delta^{13}C_{CH4}$ of -34.6 per mil, δD_{CH4} of -159 per mil, and $\delta^{13}C_{C2H6}$ of -40.4 per mil). Both Oriskany

---

[1] U.S. Geological Survey.

[2] Pennsylvania Department of Environmental Protection.

Sandstone and storage-field gases were thermogenic. Compositions of gases from storage-field observation wells were intermediate to, and likely related to mixing of, native gases from the Oriskany Sandstone and non-native gases from the storage-field injection/withdrawal wells.

In water-well samples, methane and ethane were the only hydrocarbons detected at reportable concentrations. Methane concentrations as high as 44.8 mg/L (milligrams per liter) were measured and methane concentrations were greater than 25 mg/L in 38 percent of the 39 samples. The $\delta^{13}C_{CH4}$ values were measurable in 35 well waters and had a bimodal distribution with modes at -65 per mil (14 wells) and -40 per mil (21 wells). Gas in water samples from the 14 wells in the -65 per mil mode had a small measure of microbial gas (outwash or "drift" gas) in the isotopic signature as determined by carbon-14 content of methane. The microbial gases were found chiefly in bedrock-aquifer well waters; 10 water wells representing upland and valley settings were along the northern flank of the Sabinsville Anticline. Waters with microbial gases contained traces of ethane (volume fraction of 0.01 percent or less) that were too small for determination of $\delta^{13}C_{C2H6}$. Gases from the 21 water-well samples in the -40 per mil mode for $\delta^{13}C_{CH4}$ were thermogenic. The δD_{CH4} and $\delta^{13}C_{C2H6}$ values for the 21 samples also showed thermogenic signatures. The thermogenic gases were found chiefly in a 17-well cluster on the axis of the Sabinsville Anticline at the eastern margin of the gas-storage field. This cluster corresponds with the cluster of wells with high concentrations of methane from the combustible-gases inventory. An observation well for the gas-storage field, TW805, was nearest to the cluster and three water wells in the cluster contained gases that nearly matched the stable carbon and hydrogen isotope composition in TW805. All the water wells had gas signatures indicating mixing of gases from different origins; however, the overall isotopic composition of methane and ethane showed that the gases in water wells at the eastern margin of the gas-storage field were principally thermogenic. The $\delta^{13}C_{CH4}$ and $\delta^{13}C_{C2H6}$ values of the majority of thermogenic gases from water wells either matched or were intermediate between the samples of storage-field gas from injection/withdrawal wells and the samples of storage-field gas from observation wells.

Proximity to the axis of the Sabinsville Anticline and the eastern margin of the gas-storage field correspond to the presence of thermogenic gas in water wells. Of the water-well gases with a thermogenic signature, about half are from outwash-aquifer wells and half from bedrock-aquifer wells. Of the bedrock-aquifer-well gases with a thermogenic signature, the majority are from wells drilled into bedrock beneath the Tioga River valley. Clay layers in the main Tioga River valley may play a role in keeping gas migration confined to the deep water-bearing zones of the outwash aquifer and the underlying bedrock aquifer.

Isotopic signatures have been used successfully in this study to help discern the origin of the gases in water wells near Tioga Junction. The thermogenic gas found in water wells does not match the composition of native gas from the Oriskany Sandstone. Mixing of Oriskany gases with storage-field gases has occurred, and there was also evidence for mixing of a microbial component of gas in some water wells. The possibility of three or more end-member compositions and many possible mixing scenarios for gases complicate the data interpretation. The lack of samples solely representing native shallow Devonian gas and the small number of storage-field gas samples places some limits on making firm conclusions about the origin of the methane in ground water. The weight of the evidence, however, points to storage-field gas as the likely origin of the natural gases found in water wells near Tioga Junction.

Introduction

In January 2001, State oil and gas inspectors noted bubbles of natural gas in well water during a complaint investigation near Tioga Junction, Tioga County, north-central Pa. A natural-gas storage field near Tioga Junction in the Oriskany Sandstone of Devonian age is a former native gas-production zone about 3,900 ft below land surface. Many abandoned native gas wells exist in the area. By 2004, natural gases, primarily methane, in ground water from household-supply wells were enough of an issue that inspectors were taking action to plug abandoned gas wells; however, plugging of wells did not solve the problem. Questions remained on the origin of the gases, and residents remained concerned.

Although it is common for ground water in the region to contain salt brine and hydrogen sulfide, natural gas in ground water was rarely noted by earlier investigators. Historic assessments of ground-water resources only mentioned natural gas in water-supply wells converted from gas wells (Lohman, 1939; Taylor and others, 1983; Williams and others, 1998).

In response to the concerns of the residents, the Bureau of Oil and Gas Management (BOGM) of the Pennsylvania Department of Environmental Protection (PADEP) sampled water from selected household-supply wells in 2001 to 2004. Analytical results for water samples indicated concentrations of dissolved methane as high as 92 mg/L, which greatly exceeds the solubility of methane of about 28 mg/L in water exposed to one atmosphere pressure of pure methane. Concentrations of this magnitude result in outgassing of methane and provide the possibility of accumulation of methane and subsequent explosion, with the potential for substantial property damage and loss of life. The potential for outgassing of dissolved methane in ground water may be estimated using well-construction factors and the water level in the well. A description of the maximum theoretical concentration of methane dissolved in ground water and a discussion of the risks and the importance of venting a plumbing system if methane gas is present in well water are presented in the appendix at the back of the report.

The extent of methane occurrence in shallow ground water in the area near Tioga Junction was not well known. The problem was most commonly reported in water wells in the valley of the Tioga River near Tioga Junction and on the ridge west of the valley (fig. 1). However, local residents noted that wells to the north near Lawrenceville, Pa. (fig. 1), also had high concentrations of natural gas.

The origin of the natural gas was unknown at the time of PADEP's investigation. The natural gas could be thermogenic, formed by the thermal breakdown of organic material in sediments resulting from high temperatures caused by deep burial. Possible origins of thermogenic gas include the following: native thermogenic natural gas in the Oriskany Sandstone; non-native thermogenic gas imported by pipeline and stored in one of three natural-gas storage fields near Tioga Junction (Tioga, West Tioga, and Meeker, at depths of 3,500 to 4,100 ft below land surface); or native gas from strata at depths greater or less than the Oriskany Sandstone. Alternatively, the natural gas could be formed in the shallow subsurface by microbial reduction of carbon dioxide or methyl-type microbial fermentation of organic debris. PADEP expressed concerns that the gas could be migrating from compromised gas wells (improperly plugged, leaking, or abandoned), leaking gas-storage fields, or new uncontrolled pathways opened by some event (possibly seismic) may have changed local permeability in the bedrock.

The U.S. Geological Survey (USGS), in cooperation with the PADEP, conducted a study to investigate the occurrence and origin of natural gas in ground water in the area of about 50 mi^2 near Tioga Junction, Tioga County, in the spring and summer of 2005. This report is a summary of findings from the study.

Purpose and Scope

This report describes an inventory of water wells completed in bedrock and in unconsolidated sediments to evaluate the extent of elevated concentrations of hydrocarbon gas in ground water and subsequent detailed isotopic analysis of samples from water and gas wells to investigate the origin of the gas in the ground water. For the inventory, combustible-gas concentrations and field water-quality characteristics, measured in 2005 in 91 wells in an area of about 50 mi^2 near Tioga Junction, Pa. For the subsequent detailed analysis, analytical results from sampling 39 water wells for field water-quality characteristics, natural-gas hydrocarbons, other gases (oxygen, carbon dioxide, nitrogen, argon, hydrogen, and helium), stable carbon and hydrogen isotopes of methane, stable carbon isotopes of ethane and dissolved inorganic carbon (DIC), and carbon-14 of methane (9 samples) are presented and discussed. The ground-water gas compositions are compared to 17 gas-well samples (nearby storage gas and native deep gas) and literature values for microbial gas to characterize the origin of natural gas in ground water in the study area. This study focused on the question of gas origin in well water and did not determine a specific source of the stray gases, mechanism of migration, or evaluate the ground waters for other contaminants.

Description of Study Area

The study area in northeastern Tioga County north of Mansfield (fig. 1) includes the Tioga River valley and adjacent uplands about 4 mi east and west of the valley (fig. 2). The area extends from just north of the Tioga and Hammond Reservoirs to the general area of Lawrenceville, Pa., a few miles north of Tioga Junction. Two gas wells south and east of Mansfield also were studied (fig. 1). The Meeker, West Tioga, and Tioga gas-storage fields lie at a depth of about 3,900 ft below a ridge on the western side of the Tioga River valley near Tioga Junction and extend about 8 mi westward.

Hydrogeologic Setting

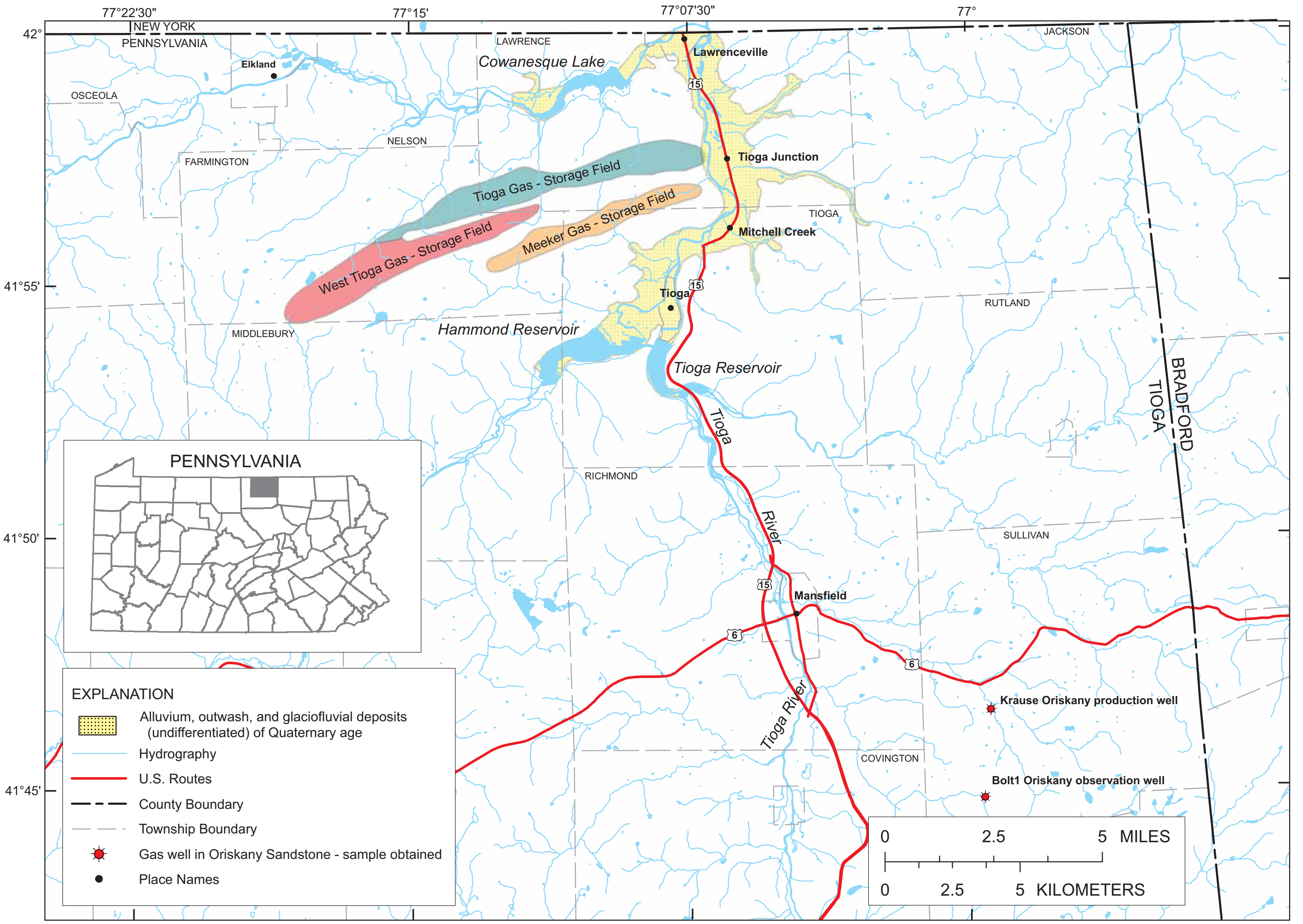
Ground water for rural-domestic supply and other uses near Tioga Junction is from two aquifer systems in and adjacent to the Tioga River valley. An unconsolidated aquifer of outwash sand and gravel of Quaternary age underlies the main river valley and extends into the valleys of tributaries. Fine-grained lacustrine sediments separate shallow and deep water-bearing zones of the outwash. Outwash-aquifer wells are seldom deeper than 100 ft. The river-valley sediments and uplands adjacent to the valley are underlain by a fractured-bedrock aquifer in siliciclastic rocks of Paleozoic age. Most bedrock-aquifer wells produce water from the Lock Haven Formation at depths of 250 ft or less.

Structural Geology

Eastern Tioga County straddles glaciated and non-glaciated areas of the Appalachian Plateaus Physiographic Province (Sevon, 2000). The geology of the study area is described in Fuller and Alden (1903), Cathcart and Myers (1934), Lytle (1963), Luce and Edmunds (1981), Williams and others (1998), and Harper (1999) and is excerpted here for the Silurian and younger-age rocks.

The Devonian and older rocks were structurally deformed from folding at the end of the Paleozoic Era into a series of synclines and anticlines with axes trending southwest-northeast. The Sabinsville Anticline (Fuller and Alden, 1903, p. 5) trends northeast from the southwest corner of Farmington Township to Tioga Junction and continues northeast (fig. 2). The anticline axis plunges to the southwest at 50 ft/mi or less. The dips on the north flank of the anticline are 150 to 350 ft/mi; the south flank has beds with dips ranging from 700 to 900 ft/mi.

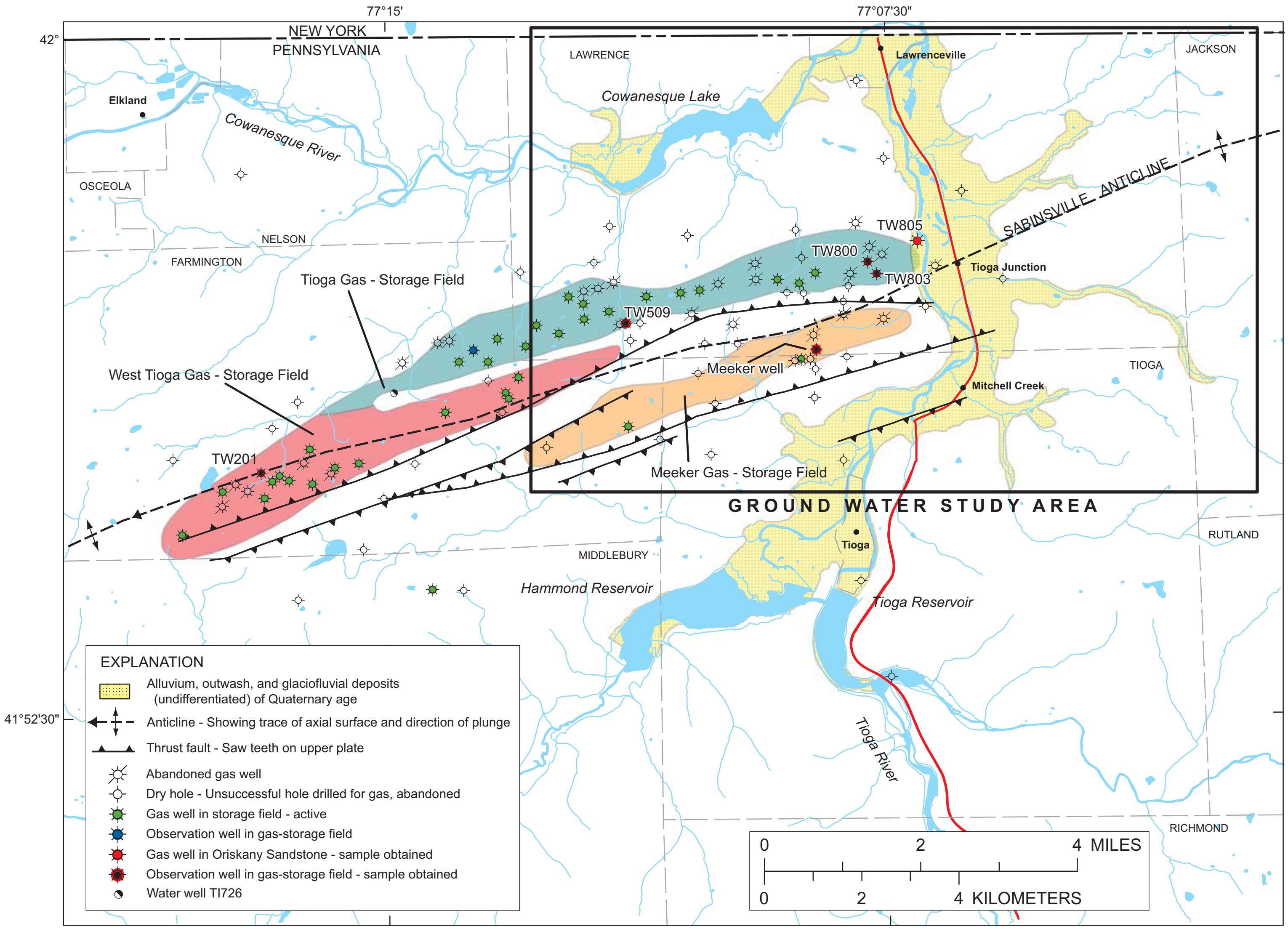
A fault block on the south flank of the anticline, bounded by two north-dipping faults with down-thrown beds to the south, is documented and mapped from gas-well drilling records (Cathcart and Myers, 1934, p. 16) at the top of the Lower Devonian Oriskany Sandstone (fig. 2). In the vicinity of Tioga Junction, the top of the Oriskany Sandstone is about 3,900 ft below land surface. The displacement of the faults is less in limestone beds above the Oriskany Sandstone than in the Oriskany Sandstone (Cathcart and Myers, 1934, p. 19). Addi-



Streams from U.S. Geological Survey, 2000
Township boundary and U.S. Routes from Commonwealth of Pennsylvania, 2006

Base from U.S. Department of Commerce digital data, 1993,
1:100,000 Albers Equal-Area Conic projection: Standard Parallels 29°30' N and 45°30' N,
Central Meridian 77°45' W, Latitude of Origin 23°00' N

Figure 1. Study area in northeastern Tioga County, gas-storage fields, selected gas wells in the Oriskany Sandstone, and extent of surficial unconsolidated sediments in the northern Tioga River valley, Pennsylvania. [Surficial-deposits boundaries are shown for only part of Lawrence and Tioga Townships and are from Commonwealth of Pennsylvania (1989) and Williams and others (1998). Gas-storage-field boundaries from Lytle (1963), Consolidated Gas Supply Corporation (1970), and NE Hub Partners, L.P., 1996, project application on file at Pennsylvania Department of Environmental Protection Bureau of Oil and Gas Management.]



Streams from U.S. Geological Survey, 2000
Township boundary and U.S. Routes from Commonwealth of Pennsylvania, 2006

Base from U.S. Department of Commerce digital data, 1993,
1:100,000 Albers Equal-Area Conic projection: Standard Parallels 29°30' N and 45°30' N,
Central Meridian 77°45' W, Latitude of Origin 23°00' N

Figure 2. Gas-storage-field area near Tioga Junction, major geologic structures, gas wells, gas-storage fields, and the boundary of the ground-water study area in northeastern Tioga County, Pennsylvania. [Surficial-deposits boundaries are shown only for parts of Lawrence and Tioga Townships and are from Commonwealth of Pennsylvania (1989) and Williams and others (1998). Well locations and types from Pennsylvania Topographic and Geologic Survey Digital Oil & Gas Well Location Maps (Jackson Summit, Tioga, and Elkland). Geologic data from NE Hub Partners, L.P., 1996, project application on file at Pennsylvania Department of Environmental Protection Bureau of Oil and Gas Management. Faults shown are mapped at depth in the Oriskany Sandstone. There is no evidence in the hydrogeologic literature for the Tioga Junction area that faults extend to near land surface and into the Lock Haven Formation.]

tional faults are shown in figure 2 as mapped at the top of the Oriskany Sandstone by Lytle and presented in Luce and Edmunds (1981, p. 63). The fault traces are approximated as dashed lines in all the earlier work. Recent seismic and drilling data have been used to refine the structural geology of the Oriskany Sandstone (Beardsley and others, 1999, p. 289; NE Hub Partners, L.P., 1996, project application on file at Pennsylvania Bureau of Oil and Gas Management). The recent mapping shows the fault traces as solid lines; these imply the faults are located with more certainty than in the earlier work. The faults in the Oriskany Sandstone do not extend into near-surface rocks (Beardsley and others, 1999, p. 289).

Upper Silurian (Salina Group) salt deposits occur (Norris, 1978) at depths greater than 4,500 ft and are proposed targets for solution mining and development of salt caverns for gas storage (Susquehanna River Basin Commission, 1996; NE Hub Partners, L.P., 1996, project application on file at Pennsylvania Bureau of Oil and Gas Management). The Upper Silurian Tonoloway Limestone is part of the Salina Group (Laughrey, 1999, p 105) at a depth of about 4,200 to 4,300 ft. Above the Tonoloway Limestone are Lower Devonian limestones and shales that include the basal Devonian Keyser Formation. Drillers call the Keyser Formation the "Helderberg" (Harper, 1999, p. 113).

Devonian age Oriskany Sandstone (hereafter termed "Oriskany") overlies the Keyser Formation. The Oriskany is equivalent to the Ridgeley Sandstone and drillers sometimes use the names interchangeably. The Oriskany is an almost pure quartzose sandstone (Harper, 1999, p. 114); however, it is described as calcareous. Above the Oriskany, the bedrock consists of shale, siltstone, and sandstone along with beds of limestone and calcareous rocks of Devonian age. Near the land surface, the rocks are part of the Upper Devonian Lock Haven Formation (Harper, 1999).

Unconsolidated sediments of glacial and postglacial origin cap the geologic section. Glacial ice entered the study area during the Pleistocene Epoch. The glaciers eroded the bedrock and deepened and widened the valleys. During glacial melting, the valleys were partly filled with sediments deposited by glacial ice, meltwater, and proglacial lakes. The uplands were mantled with till. In the postglacial period, the streams deposited alluvium and organic-rich deposits. Glacial and postglacial valley-fill sediments consist of stratified drift, outwash, alluvium, swamp deposits, lacustrine deposits, and till (Fuller and Alden, 1903).

The unconsolidated deposits are referred to in this report as outwash or alluvium. The outwash consists of poorly sorted to well-sorted sand, gravel, silt, and some clay deposited by glacial meltwater or glaciofluvial processes. Outwash, as indicated in this report, refers to the deposits of sand and gravel deposited as valley-trains in the Tioga River and tributary valleys in the study area (fig. 2). The alluvium is generally shallow sand and gravel or silt and fine sand found on floodplains and typically overlies the outwash deposits in the study area. The generalized extent of mapped unconsolidated deposits (Commonwealth of Pennsylvania, 1989; Williams and others, 1998) is shown in all the maps in this report. Till, consisting of clay, silt, some sand, and rock fragments deposited by the glacier, is on the hillsides and ridge tops of the study area but is unmapped in this report.

Aquifer Framework

The hydrogeologic characteristics in the study area were described by Williams and others (1998) and are excerpted here. The generalized framework of the outwash aquifer system with major ground-water recharge and discharge areas is shown in figure 3.

The outwash aquifers are stratified unconsolidated deposits of valley fill overlying lacustrine deposits or bedrock with till and bedrock as basal confining units. The lacustrine deposits, till, and bedrock typically have low primary permeability. Hydrogeologic sections (traces of sections shown on fig. 4) from Williams and others (1998) show sequences of glacial deposits that occur along the major stream valley in the study area (fig. 5).

The shallow deposits of alluvium and some outwash generally are thin and are unconfined aquifers. In the Tioga River valley, lacustrine deposits may form a local confining unit, and confined aquifers of outwash and related deposits may be present beneath.

Sources of natural recharge to the outwash aquifers consist of infiltration of precipitation on the valley floor, infiltration of unchanneled runoff from the uplands at the valley walls, ground-water inflow from the uplands, and infiltration from tributary streams (fig. 3). Mitchell Creek (fig. 5) has been shown by Williams and others (1998, p.16) to have losing reaches. Recharge to the confined outwash aquifers occurs mainly near the valley walls where surficial sand and gravel is in hydraulic connection with the outwash aquifer (fig. 3).

Most ground water flows from the outwash aquifers toward points of discharge, generally either the Tioga River, the lower reaches of principal tributaries to the Tioga River, or swampy areas. In the confined aquifers, ground-water flow discharges to the Tioga River and reaches near the mouths of the principal tributaries through either the confining-unit materials or through overlying unconfined aquifer materials where a confining unit is absent.

The outwash aquifer, unconfined or confined, in the glaciated valleys of Tioga and adjacent counties is characterized by a 20 gal/min median yield to wells (Williams and others, 1998, p. 26); however, yields can be larger for industrial and municipal supply wells. Domestic wells drilled into the outwash aquifers are completed as open-ended casing in a water-bearing zone.

The Lock Haven Formation is the principal bedrock aquifer and is recharged by precipitation. The bedrock is commonly mantled by till on hillsides and ridge tops.

Secondary permeability in the bedrock is dependent on fractures. Regional patterns of fractures or faults in the Lock Haven Formation have not been mapped; however, the southwest to northeast orientation of the channels of the Cowanesque River, Crooked Creek as it flows into Hammond Reservoir, other smaller tributary streams to the Tioga River, and the Tioga River near Mitchell Creek may be due to regional patterns of weakness or increased fracturing that allowed glacial and weathering processes to downcut preferentially in the bedrock, which led to river-channel incision and the present-day channel orientation. Reports by PADEP oil and gas inspectors of natural gas bubbling into streams at the channel bottoms (Robert Gleeson, Pennsylvania Department of Environmental Protection, oral commun., 2006) could support the concept that stream channels are zones of increased fracture density (Wyrick and Borchers, 1981) and preferential pathways for migration of natural gas from depth.

There is no evidence in the hydrogeologic literature for the Tioga Junction area that faults at depth in the Oriskany extend to near land surface and into the Lock Haven Formation to act as fractured or preferential pathways for ground-water flow. Nevertheless, the faults are mapped for reference in figure 4.

Locally, fractures in the bedrock may be in hydraulic connection with overlying outwash aquifers. Domestic and nondomestic water-supply wells intercept water from fractures in the bedrock and are completed as open boreholes with surface casing. The median yield from domestic wells in the Lock Haven Formation is 10 gal/min (Williams and others, 1998, p. 26).

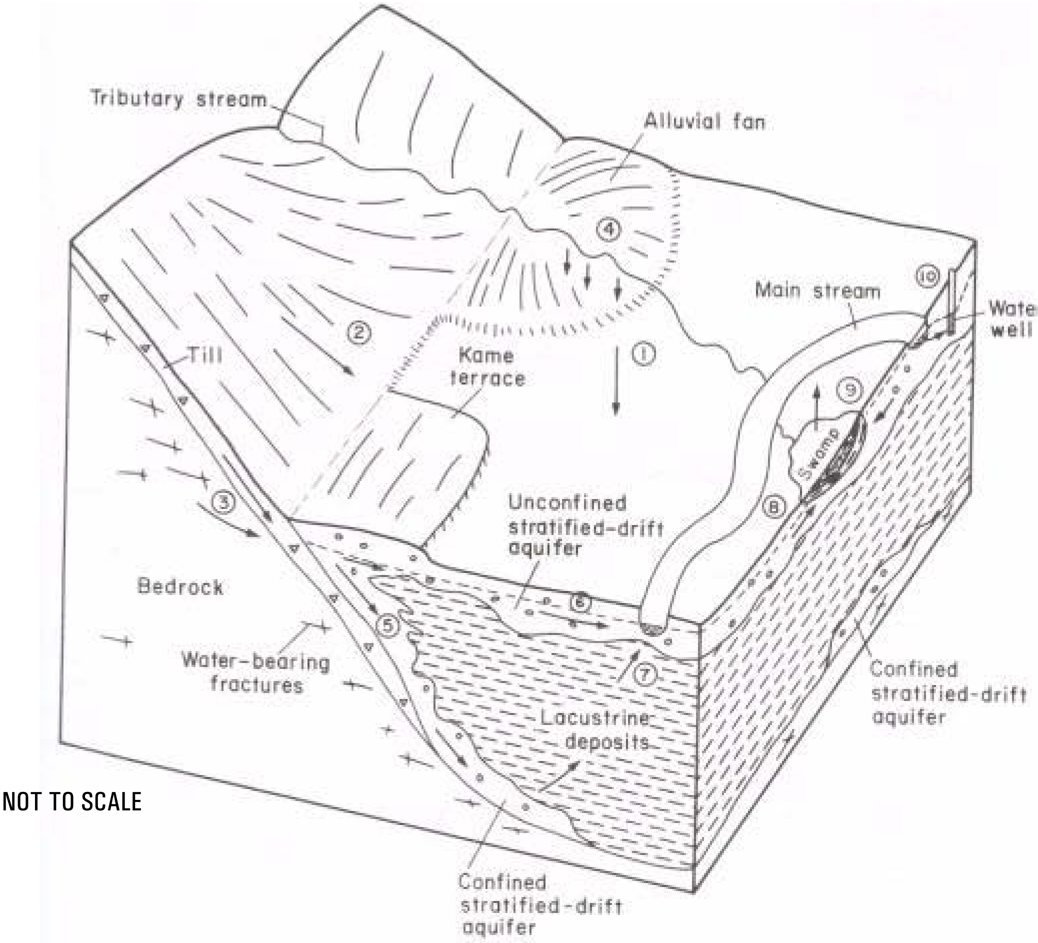
History of Gas Development and Gas Storage

The first gas well drilled into the dome in the Sabinsville Anticline in northern Tioga County near Tioga Junction produced gas from the Oriskany in 1930 (Cathcart and Myers, 1934). During the next several decades, the Oriskany gas was produced by many gas wells in the Sabinsville Anticline area. Drilling efforts also produced dozens of dry holes, and many drill holes were later abandoned (fig. 2). Natural gas was determined on the basis of pressure responses to reside in three independent "pools." The pools were labeled the Boom, the Meeker, and the Elbridge (Cathcart and Myers, 1934).

Southeast of Tioga Junction in a separate anticline, the Oriskany is at a depth of about 5,800 ft at the Krause gas well (fig. 1, the Krause gas well has a total depth of 5,850 ft and the Oriskany is the producing zone of the gas). Other gas-producing strata such as the Trenton and Black River Limestones of Ordovician age are much deeper than the Oriskany—approximately at a depth of 12,000 ft in Tioga County (Christopher D. Laughrey, Pennsylvania Topographic and Geologic Survey, oral commun., 2006).

In the 1960s, the native Oriskany gas in the Sabinsville Anticline near Tioga Junction was depleted, and the pools or reservoirs were converted into gas-storage fields (Lytle, 1963). These reservoirs are now called the Tioga, Meeker, and West Tioga storage fields (fig. 1), respectively, and are collectively referred to as the Tioga gas-storage field.

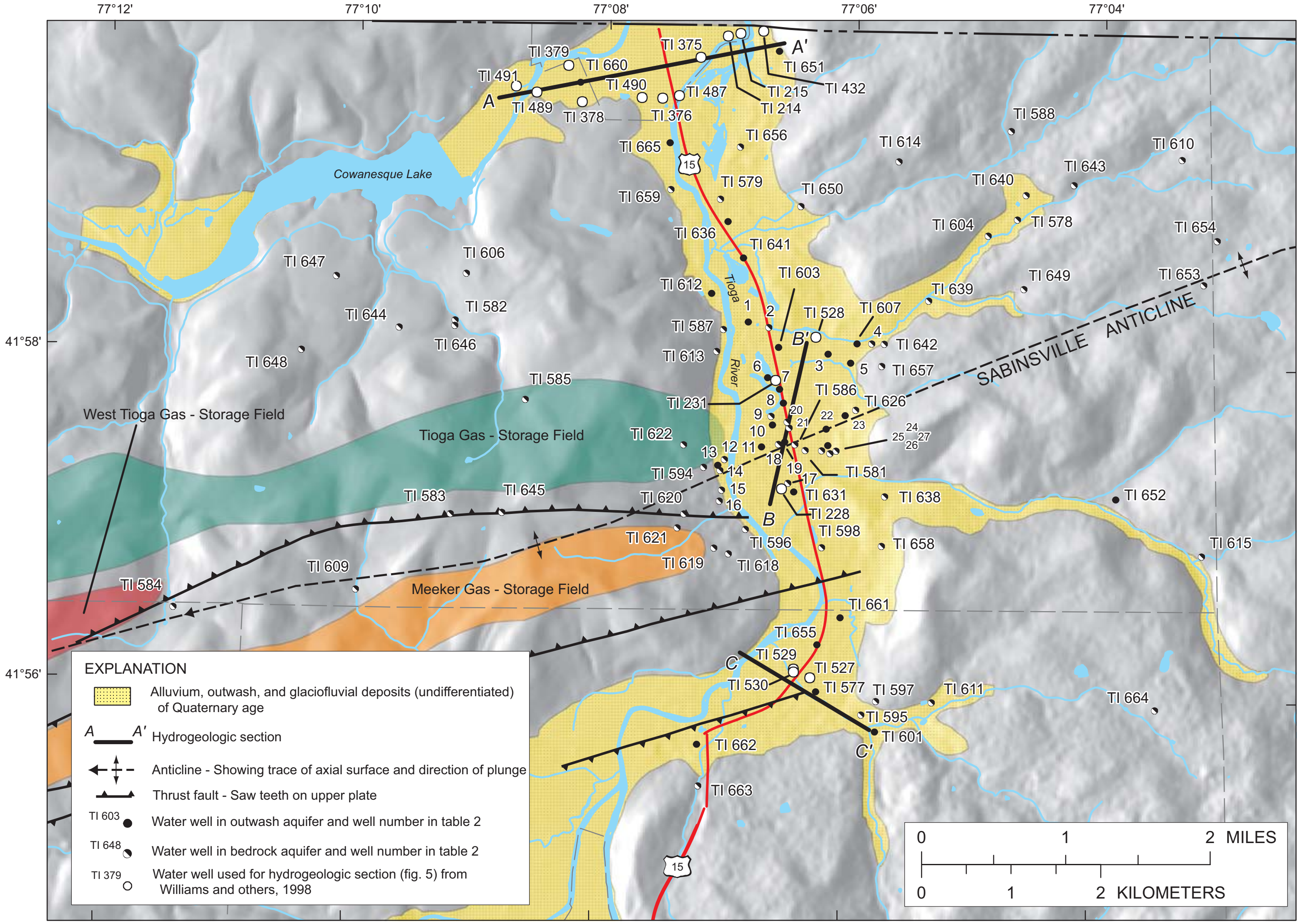
The gas-storage field receives gas primarily from the gas-producing areas of the Gulf of Mexico region of the United States but also from other areas of the Appalachian Plateaus Physiographic Province in the United States and Canada. Gas from a pipeline is injected into the field during spring, summer, and fall for future withdrawal. During winter, gas is usually withdrawn from the Tioga storage field and transmitted to a pipeline for distribution and use. The storage fields currently



EXPLANATION

1 Precipitation on valley
2 Unchanneled runoff from bedrock and till uplands
3 Ground-water inflow from bedrock and till uplands
4 Infiltration from tributary streams
5 Ground-water recharge to confined aquifer
6 Discharge to main stream
7 Upward leakage through confining unit
8 Ground-water discharge to swampy areas
9 Evapotranspiration
10 Induced infiltration by pumping

Figure 3. Schematic of generalized geometry and hydrology of the outwash-aquifer system (stratified-drift aquifers) in Tioga County, Pennsylvania (modified from Williams and others, 1998, fig. 8).



Surficial deposits from Commonwealth of Pennsylvania, 1989
Streams from U.S. Geological Survey, 2000
Township boundary and U.S. Routes from Commonwealth of Pennsylvania, 2006
Shaded relief prepared from U.S. Geological Survey National Elevation Dataset, 2004

Base from U.S. Department of Commerce digital data, 1993,
1:100,000 Albers Equal-Area Conic projection: Standard Parallels 29°30' N and 45°30' N,
Central Meridian 77°45' W, Latitude of Origin 23°00' N

Figure 4. Ground-water study area with locations of wells used for lines of hydrogeologic sections (fig. 5) and locations of 91 water wells inventoried to determine extent of combustible gases in ground water near Tioga Junction, Tioga County, Pennsylvania. Well identifiers are the USGS local well number with a Tioga County (TI) prefix except in the central Tioga River valley where an identifier from 1 to 27 is used. The identifiers are cross-referenced to the USGS local well number in table 2. [Faults shown are mapped at depth in the Oriskany Sandstone. There is no evidence in the hydrogeologic literature for the Tioga Junction area that faults extend to near land surface and into the Lock Haven Formation.]

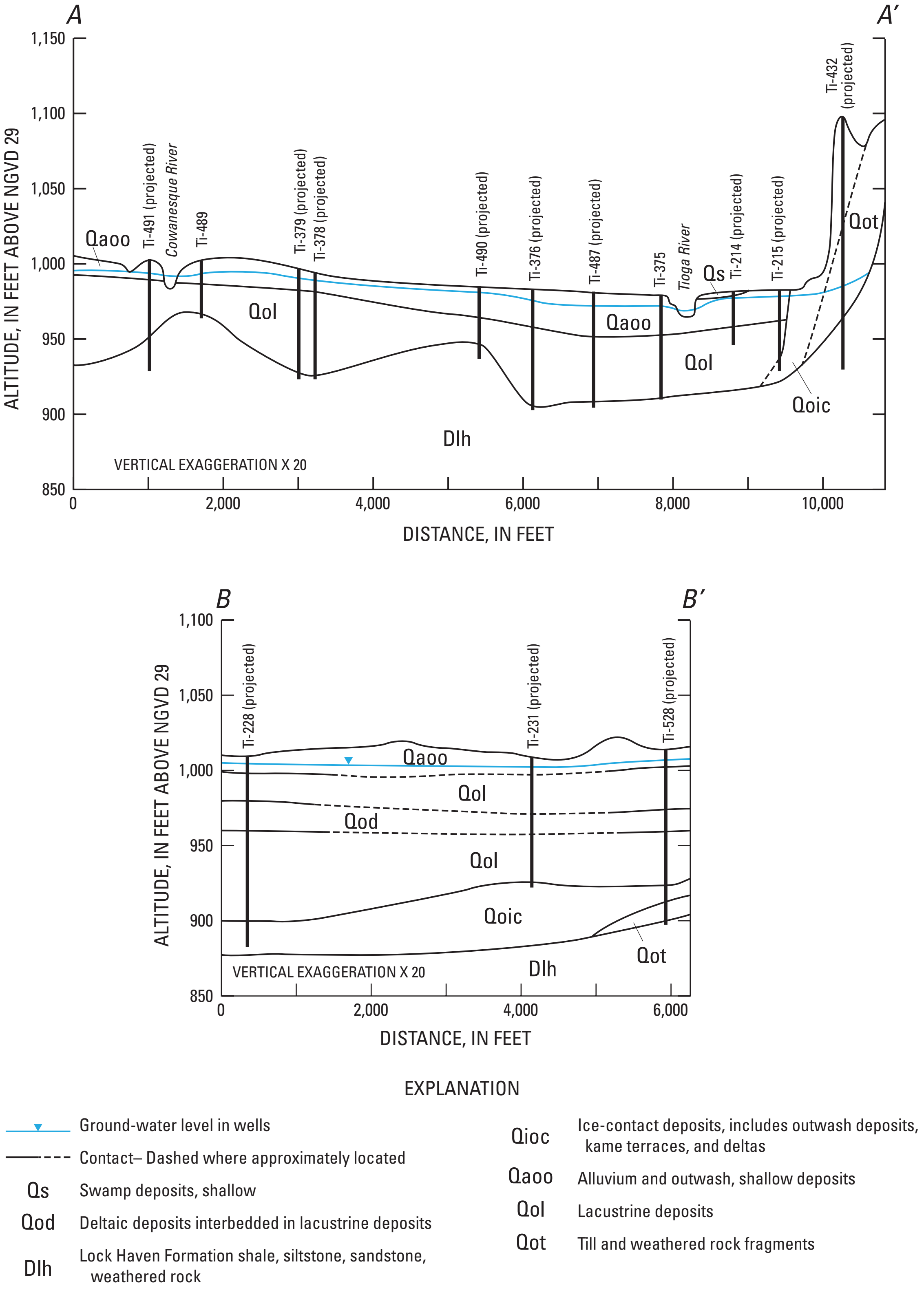


Figure 5. Three hydrogeologic sections typical of the Tioga River valley, Pennsylvania (modified from Williams and others, 1998). Section A–A′ is near Lawrenceville, section B–B′ is at Tioga Junction, and section C–C′ is at Mitchell Creek. Lines of sections are shown on figure 4.

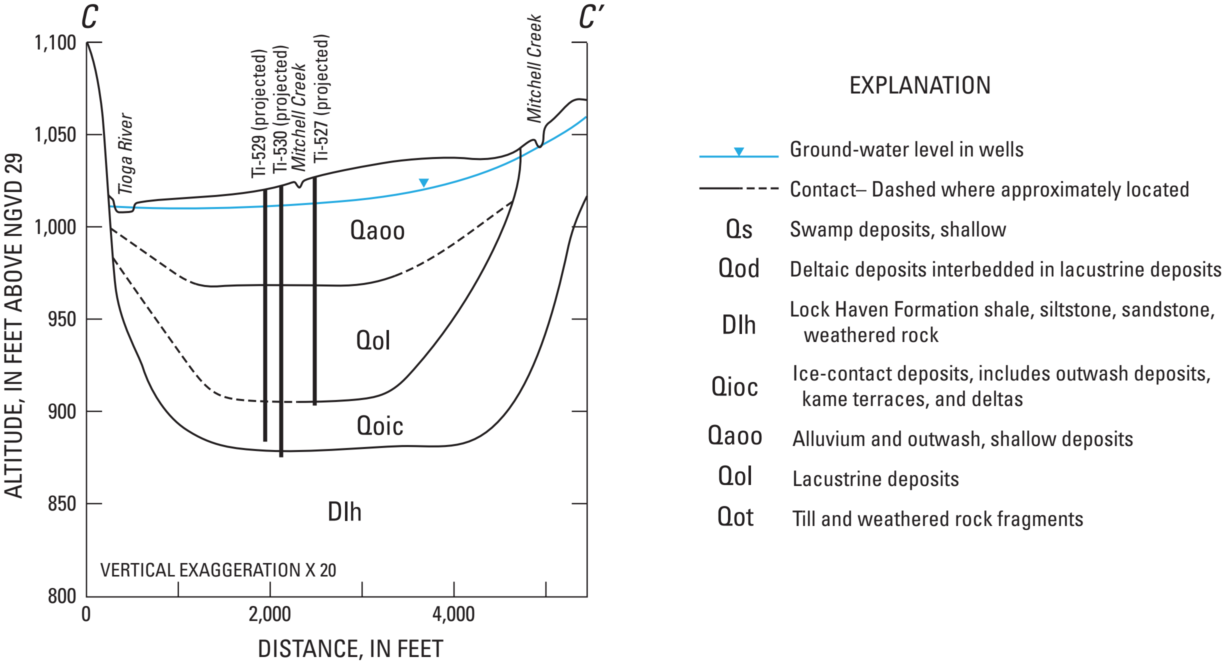


Figure 5. Three hydrogeologic sections typical of the Tioga River valley, Pennsylvania (modified from Williams and others, 1998)—Continued. Section A–A′ is near Lawrenceville, section B–B′ is at Tioga Junction, and section C–C′ is at Mitchell Creek. Lines of sections are shown on figure 4.

(2005) are managed by two gas companies. Dominion Gas Company manages the Tioga and West Tioga fields (Thomas Rice, Dominion Gas Company, written commun., 2005). Pennsylvania Power and Light manages the Meeker field (Douglas Welsh, Pennsylvania Department of Environmental Protection, written commun., 2005).

Methods

The methods used in the 1) field for data collection at gas wells and water wells, 2) interpretation of isotope data, and 3) laboratory for analysis of gas and water samples are described in the following sections along with the results of quality assurance. The methods used for determining well characteristics and collecting gas samples from gas wells are described first. Methods employed at water wells are then detailed. The chemical nomenclature for isotopes and a discussion of isotopic signatures in natural gas are provided as background for data interpretation. The procedures used for laboratory analyses of samples are summarized and the reader is directed to reference literature for details of the laboratory techniques. Finally, the types of quality-assurance samples collected and results of quality assurance are presented.

Gas-Well Data Collection

Permissions were obtained to visit the well locations and USGS personnel were accompanied to the well head by inspectors from PADEP. A handheld Global Positioning System (GPS) receiver was used to obtain latitude and longitude coordinates of the sampling point. Well characteristics were obtained from Pennsylvania Topographic and Geologic Survey Digital Oil & Gas Well Location Maps (2005, Jackson Summit, Tioga, and Elkland).

Eight gas wells were sampled for this study (table 1, figs. 1 and 2). Gas from the well head was collected in a gas-sampling bag for analysis by a commercial laboratory (Isotech Laboratories, Inc.) and in a glass container for analysis by the USGS Reston Stable Isotope Laboratory (RSIL).

To represent gas in the Tioga gas-storage field, three wells that function to inject or withdraw gas were sampled (TW800, Meeker, and TW201 wells). Well TW800 is open to the Tioga storage field, the Meeker well is open to the Meeker storage field, and well TW201 is open to the West Tioga storage field. Data for additional samples collected by PADEP from gas well TW201 and analyzed at Isotech Laboratories, Inc., also are used in this study (Christine Miner, Pennsylvania Department of Environmental Protection, written commun., 2005)

Two gas wells used for observation of pressures in the gas-storage field also were sampled (wells TW803 and TW509, fig. 2). Well TW803 reportedly had been plugged but continues to yield gas, and during drilling of the well, shallow gas was

Table 1. Records of gas wells sampled, Tioga Junction and vicinity, Tioga County, Pennsylvania, 2004-2005.

[Data from Pennsylvania Topographic and Geologic Survey digital oil and gas map files and geophysical log files; API, American Petroleum Institute; V, valley; S, hillside; H, hilltop; ft bls, feet below land surface; na, not applicable; obs., observation; WSG, with shallow gas; I/W, injection/withdrawal well]

Well number[1]	Latitude	Longitude	Topo-graphic setting	Rock unit	Gas-storage pool	Completion date	Depth of well (ft bls)	API identifier	Well description
Krause	41° 46' 31"	76° 59' 27"	V	Oriskany	na	10/16/1992	5,850	117-20159	Oriskany production (permit no. 37-117-20159)
Bolt1	41° 44' 46"	76° 59' 37"	V	Oriskany	na	9/11/1986	7,100	117-20148	Oriskany obs.--plugged well, yields gas (permit no. 37-117-20148)
TW805	41° 57' 45"	77° 07' 03"	V	Helderberg	Tioga	7/14/1932	3,342	117-20130	Oriskany—storage-field obs.
TW509	41° 56' 50"	77° 11' 26"	H	Helderberg	Tioga	2/16/1931	3,894	117-00122	Gas-storage field obs. WSG
TW803	41° 57' 22"	77° 07' 40"	S	Helderberg	Tioga	7/15/2003	3,646	117-00115	Gas-storage field obs. WSG (permit no. S-T10-27)
TW201	41° 55' 12"	77° 16' 55"	S	Ridgeley	Tioga (Palmer)	4/27/1932	4,122	117-00036	Gas-storage field I/W
Meeker	41° 56' 32"	77° 08' 37"	S	Ridgeley	Meeker	10/4/1988	4,264	117-20153	Gas-storage field I/W
TW800	41° 57' 30"	77° 07' 48"	S	Salina	Tioga	8/10/1949	3,991	117-00020	Gas-storage field I/W; deepened from 3,800 to 3,991 ft on 8/20/96

[1] Well identifier on figures 1 or 2.

encountered at about 100 ft below land surface (Douglas Welsh, Pennsylvania Department of Environmental Protection, written commun., 2005). TW509 also is reported to yield gas from shallow zones; hence, the notation "with shallow gas" is associated with TW509 and TW803 in table 1.

To represent the native natural gas from the Oriskany Sandstone, three gas wells were sampled. The Krause well (fig. 1) is an Oriskany production well. The Jennie M. Bolt #1 well (hereafter termed Bolt1, fig. 1) is an Oriskany production well serving as an observation well for the Oriskany gas because it had reportedly been plugged but yields gas (Douglas Welsh, Pennsylvania Department of Environmental Protection, written commun., 2005). Well TW805 is an Oriskany production well that was depleted and abandoned but is used as an observation well for the Oriskany gas. TW805 is approximately 500 ft northeast of the eastern boundary of the Tioga storage field (fig. 2). One sample from each of these wells was collected for this study, and data from additional samples from the Krause and Bolt1 wells, collected by the PADEP and analyzed at Isotech Laboratories, Inc. (Christine Miner, Pennsylvania Department of Environmental Protection, written commun., 2005), are used in this study.

Water-Well Data Collection

During the water-well reconnaissance (referred to as reconnaissance sampling or inventory), privately owned wells used for household supply and by local businesses (rural domestic use) were inventoried. One community-supply (mobile-home park) well also was included in the inventory. The well inventory was initiated based on reports of problem areas in the immediate area of Tioga Junction. The inventory then expanded outward in an attempt to delineate the extent of gas occurrence. Population density was not directly a factor in the inventory; however, the rural nature and low density of homes in the uplands and parts of the valleys certainly influenced where potential inventory data could be gathered.

Data on well depth, well-construction characteristics, and aquifer type (outwash or bedrock) yielding the water supply were determined from driller's records when available and by interviews with the well owner. It is not certain from well-construction data collected during this study whether the water-bearing zones tapped by domestic wells are unconfined or confined aquifers. Water levels were measured, with permission of the well owner, in wells with accessible casing and used to determine if artesian or confined conditions were present. Also with permission of the well owner, the household plumbing was inspected to locate a faucet for obtaining a sample of untreated (raw) well water.

A total of 91 water wells (62 completed in bedrock and 29 completed in outwash) were inventoried for this study [table 2 (at back of report), fig. 4]. Well identifiers in fig. 4 are the USGS local well number with a Tioga County (TI) prefix except in the central Tioga River valley where wells are close together and a cross-reference number from 1 to 27 is used. The cross reference to the USGS local well number is given in table 2. Symbols in figure 4 designate the well as completed in bedrock or outwash.

The inventory included testing for combustible gas fraction in gases associated with raw well water from the household faucet. The end of a hose carrying untreated well water from the raw-water faucet and a probe to measure water characteristics (temperature, pH, specific conductance, dissolved oxygen, and oxidation-reduction potential) were placed in the bottom of a bucket. Water was allowed to overflow the bucket, and at most sampled sites, characteristics of water were measured and were recorded until stable using standardized USGS protocols for data collection (U.S. Geological Survey, variously dated). The smell of sulfur and presence of bubbles "outgassing" in the sample discharge also were recorded. Due to poor yield of many wells, during the inventory the water was not purged for more than 10 minutes. Water characteristics recorded did not always represent a stable reading that was representative of water in the aquifer. In table 2, if two observations are listed for a well, the earlier date is the inventory result.

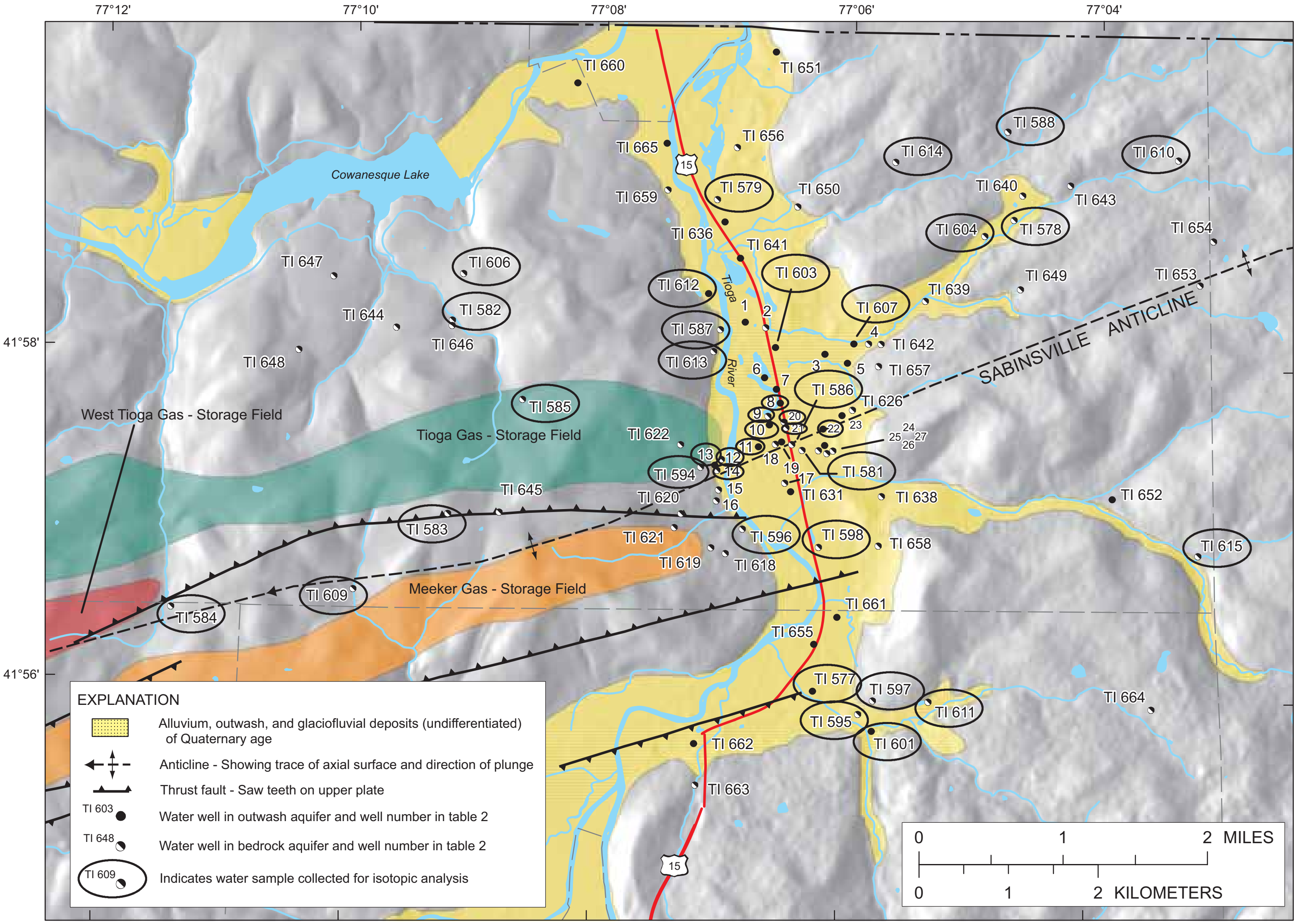
Combustible-gas fractions were determined on the headspace of water samples using a Mine Safety Appliances Gascope Model 60 combustible-gas indicator, calibrated to 2-percent methane gas, with a detection limit of 0.1 percent. The instrument was connected to a headspace chamber at a gas-collection port similar to that used by Chafin and others (1996, p. 9).

Of the 91 water wells inventoried, 49 wells (36 wells completed in bedrock and 13 in outwash) had combustible-gas concentrations equal to or greater than 0.1 percent. Of those 49 water wells, 39 wells (27 wells completed in bedrock and 12 in outwash) were selected for detailed sampling at a later date; 10 of the 49 wells could not be resampled because of access problems or low yield. Wells selected for sampling included 19 along the eastern extent of the gas-storage field near Tioga Junction and 20 in other locations to obtain a broad representation of samples throughout the study area (fig. 6). The remaining 42 of the 91 wells were not sampled because field measurements of combustible gas were less than 0.1 percent.

The detailed sampling included a repeat determination of the fraction of combustible gas in gases associated with raw well water and a repeat field measurement of water characteristics (table 2). The smell of sulfur and presence of "outgassing" were recorded in the same manner described for the inventory sampling. Samples were collected for determination of acid neutralizing capacity (ANC) by incremental titration at the USGS laboratory in New Cumberland and for laboratory analysis of selected hydrocarbons and isotopes.

Ground-water samples for gas analyses by Isotech Laboratories, Inc., were collected in 1-liter (L) plastic containers. A biocide was attached to the inside top of the lid of the container to prevent microbial activity that might consume or generate methane between the time of sample collection and the time of sample analysis.

In samples where no outgassing was observed, the 1-L sample containers were filled to the top at a low discharge rate



Surficial deposits from Commonwealth of Pennsylvania, 1989
Streams from U.S. Geological Survey, 2000
Township boundary and U.S. Routes from Commonwealth of Pennsylvania, 2006
Shaded relief prepared from U.S. Geological Survey National Elevation Dataset, 2004

Base from U.S. Department of Commerce digital data, 1993,
1:100,000 Albers Equal-Area Conic projection: Standard Parallels 29°30' N and 45°30' N,
Central Meridian 77°45' W, Latitude of Origin 23°00' N

Figure 6. Outwash-aquifer and bedrock-aquifer wells where water was collected for detailed analysis of dissolved gases near Tioga Junction, Tioga County, Pennsylvania, June-August 2005.

by inserting a plastic tube to the bottom of the container and filling slowly until full. The sample container was then immersed into the overflowing bucket to allow about 2 volumes of water to displace water already in the 1-L container. The container was immediately capped underwater. In samples where outgassing was observed, the filled container was submerged into the overflowing bucket and inverted, the tubing delivering well water to the submerged inverted container (Coleman and others, 1977; Keetch and Gaber, 1982). The bubbling gases were allowed to displace water in a headspace until about one-third of the water in the container was displaced. These sampling protocols were suggested by Isotech Laboratories, Inc., and modeled after protocols being developed by the Colorado Oil and Gas Conservation Commission (Steven Pelphrey, Isotech Laboratories, Inc., written commun., 2005).

Samples of ground water also were collected for USGS laboratories to analyze selected constituents in order to further research on isotopic fingerprints and for quality-assurance purposes. These analyses included stable carbon and hydrogen isotopes of methane, stable carbon isotopes of DIC, stable oxygen and hydrogen isotopes of water (water isotopes), and methane concentrations. At each of the 39 wells used for detailed sampling and at 3 additional “background” water wells where field measurements indicated no combustible gas was present, a DIC sample was collected in a 0.5-L glass bottle. The bottle was filled from the bottom through plastic tubing and 5 milliliters (mL) of strontium-chloride-ammonium solution was added according to standard USGS methodology (Tyler Coplen, U.S. Geological Survey, written commun., 2005). At 37 of the 39 detailed-sampling wells, samples for analysis of water isotopes and concentrations of dissolved methane were collected. The water-isotope samples were collected in 60-mL glass bottles (Wilde and others, 2004). The samples for dissolved gases were collected in 125-mL serum bottles and sealed with rubber stoppers without introducing any bubbles, according to methods developed by USGS Reston Dissolved Gas Laboratory (Busenberg and others, 1998). At 5 of the 39 detailed-sampling wells, samples for analysis of stable carbon and hydrogen isotopes of methane were collected using methods developed by Révész and others (1995).

Data Interpretation

This section first describes how the stable-isotope ratios are reported relative to a standard reference. Background is then provided on isotopic signatures of methane in natural gases of different origins.

Nomenclature for Isotope Ratios

Variations in stable-isotope amount ratios typically are small. Stable-isotope amount ratios commonly are determined as the relative difference in the ratio (R) of the less abundant isotope (usually the heavy isotope) to the more abundant isotope (usually the light isotope) of the sample with respect to a reference standard. This difference is designated $\delta(^{i}\mathrm{E})$, and it is defined according to the relation in equation 1 (Coplen and others, 2002):

$$\delta(^{i}\mathrm{E}) = \delta(^{i}\mathrm{E}/^{j}\mathrm{E}) = \left[\frac{n_{x}(^{i}\mathrm{E})/n_{x}(^{j}\mathrm{E}) - n_{ref}(^{i}\mathrm{E})/n_{ref}(^{j}\mathrm{E})}{n_{ref}(^{i}\mathrm{E})/n_{ref}(^{j}\mathrm{E})}\right] \qquad (1)$$

where $\delta(^{i}\mathrm{E})$ refers to the delta value of isotope numbers i and j, heavy and light, of element E of sample X relative to a reference standard (ref), $n_X(^{i}\mathrm{E})/n_X(^{j}\mathrm{E})$ and $n_{\mathrm{ref}}(^{i}\mathrm{E})/n_{\mathrm{ref}}(^{j}\mathrm{E})$ are the ratios of the isotope amounts in unknown X and a reference standard, and δ (delta) is the difference between the relative isotope-amount ratios of the unknown and the reference standard $[(R_X - R_{ref})/R_{ref}]$. A positive $\delta(^{i}\mathrm{E})$ value indicates the unknown is more enriched in the heavy isotope than the reference. A negative $\delta(^{i}\mathrm{E})$ value indicates the unknown is depleted in the heavy isotope relative to the reference. The $\delta(^{i}\mathrm{E})$ is commonly shortened to $\delta^{i}\mathrm{E}$. In this study, stable-isotope ratios are reported in parts per thousand (‰ or per mil) using the delta notation: $\delta^{13}\mathrm{C}$ for $^{13}\mathrm{C}/^{12}\mathrm{C}$; $\delta^{2}\mathrm{H}$ for $^{2}\mathrm{H}/^{1}\mathrm{H}$; and $\delta^{18}\mathrm{O}$ for $^{18}\mathrm{O}/^{16}\mathrm{O}$. Hereafter, $\delta^{2}\mathrm{H}$ is termed delta deuterium or $\delta\mathrm{D}$.

Stable carbon isotope ratios in this report are relative to Vienna PeeDee Belemnite (VPDB), which is defined by assigning a value of +1.95 per mil to National Bureau of Standards (NBS) 19 calcium carbonate. Hydrogen and oxygen isotope ratios in this report are relative to Vienna Standard Mean Ocean Water (VSMOW) (Gat and Gonfiantini, 1981) on scales such that the hydrogen and oxygen isotopic compositions of Standard Light Antarctic Precipitation (SLAP) are -428 and -55.5 per mil, respectively (Gonfiantini, 1978).

Isotopic Signatures of Methane in Natural Gas

Methane is the main constituent in natural gas and anthropogenic gases, such as landfill gas. Methane is known to be formed by two major processes, microbial or thermogenic. Microbial methane is the principal product of anaerobic and bacterial decomposition of buried organic material that can be present in glacial drift or glaciofluvial deposits and in near-surface sediments and rocks. Microbial methane found in relatively low temperature, near-surface environments due to acetate fermentation is called marsh gas, swamp gas, and landfill gas (Coleman and others, 1995). In glacial-drift deposits, the product gas formed by microbial reduction of carbon dioxide (CO_2) is referred to as drift gas. Thermogenic methane is formed by the thermal breakdown of organic material resulting from high temperatures created by deep burial of sediments (Schoell, 1980).

Various researchers have determined by examination of stable hydrogen and carbon isotopes of methane that there are common hydrogen and carbon isotopic compositions for thermogenic gas associated with coal and natural gas, drift gas, and other near-surface microbial gases (Craig, 1953; Coleman and others, 1977; Deines, 1980; Schoell, 1980; Rice and Claypool, 1981; Schoell, 1983; Whiticar, 1986; Wiese and Kvenvolden, 1993; Coleman, 1994; Baldassare and Laughrey, 1997; Kaplan and others, 1997; and Rowe and Muehlenbachs, 1999). For microbial methane found in near-surface environments due to acetate fermentation (marsh gas and landfill gas), $\delta^{13}C_{CH4}$ ranges from about -40 to -62 per mil and δD_{CH4} ranges from about -270 to -350 per mil. Microbial methane in outwash or "drift" gas generally has $\delta^{13}C_{CH4}$ values ranging from about -62 to -90 per mil and δD_{CH4} ranges from about -180 to -240 per mil. Thermogenic methane has a range of $\delta^{13}C_{CH4}$ from about -28 per mil to -50 or -60 per mil and δD_{CH4} values range from about -110 to -250 per mil. Values of $\delta^{13}C_{CH4}$ near -60 per mil associated with δD_{CH4} values in the -160 to -260 per mil range generally are attributed to mixing of thermogenic and microbial methane.

The ^{14}C content of methane also can be used to distinguish thermogenic gas from microbial gas. When plant material decomposes to methane, the methane contains nearly the same concentration of ^{14}C (the radioactive carbon isotope, formed in the atmosphere) as the organic material from which it was formed. The half-life of ^{14}C is 5,730 years, and ^{14}C content can be measured in organic materials that are less than about 50,000 years old (Coleman and others, 1995). The ^{14}C concentrations are expressed as percent modern carbon (pMC) and 100 pMC is the "natural" pre-atomic-bomb-testing ^{14}C concentration of atmospheric CO_2. The percent modern carbon can be greater than 100 percent for gases from materials formed during atomic-bomb-testing years. Outwash or "drift" gas, formed by buried peats covered by glaciers, has measurable ^{14}C, usually less than about 30 pMC. Methane from landfills has ^{14}C similar to that of currently living materials (120–150 pMC). Swamp and marsh gases have ^{14}C in the range of 30 to less than 120 pMC. Thermogenic gases are formed from organic materials that are millions of years old and do not contain measurable ^{14}C.

Laboratory Analyses

The constituents each laboratory analyzed and references for the laboratory methods are summarized in table 3. Analyses for gas-well and water-well samples are included. Where multiple laboratories were utilized for quality-assurance or research purposes, each laboratory is listed.

Quality Assurance

Quality-assurance samples were of three types. Two sample blanks were collected, a source blank and a field blank to check for laboratory bias of gas-composition analyses due to contamination. Four sequential replicate samples of ground water were collected to evaluate reproducibility of results (intra-laboratory replicates). Five samples with substantially different isotopic compositions were selected for splitting and submittal for $\delta^{13}C_{CH4}$ analysis to Isotech Laboratories, Inc., and the USGS RSIL (inter-laboratory splits). Quality-assurance data are summarized in table 4.

The source blank consisted of volatile-organic-carbon (VOC) free blank water prepared by the USGS National Water Quality Laboratory. The field blank was VOC-free water collected in the 1-L sample container after passing through representative tubing used in the field to collect samples. The source blank had a small amount of methane; the field blank had no methane. Methane in the source blank is likely laboratory contamination, but the amount (volume fraction = 0.04 percent) is more than an order of magnitude smaller than amounts reported for any environmental sample except for the TI581 (0.107 percent) and TI583 (0.0066 percent) samples. Neither of these samples contained sufficient methane to determine isotopic compositions.

The replicate results for sample pairs compare closely. Gas-composition analyses by Isotech Laboratories, Inc., are based on standards accurate to within 2 percent (Steve Pelphrey, Isotech Laboratories, Inc., written commun., 2005). The difference in volume fractions for any pair is much less than 2 percent. For the intra-laboratory replicates sent to Isotech Laboratories, Inc., isotopic results for $\delta^{13}C_{CH4}$ and δD_{CH4} show that the differences are in the range of acceptable uncertainty (standard deviation equal to 0.3 per mil). Inter-laboratory split sample results show a range of differences in $\delta^{13}C_{CH4}$ within tolerances needed for differentiation of thermogenic and microbial gases.

Occurrence and Origins of Natural Gases in Ground Water

The inventory of combustible-gas concentrations in well water is summarized in this section and related to methane concentrations dissolved in ground water and water characteristics. Occurrence of combustible gas is examined spatially and by aquifer to determine if systematic patterns are present for ground water containing and lacking natural gas. Results of compositional and isotopic analyses of gas-well samples are used to define end-member compositions or "signatures" for Oriskany and storage-field gases. The end-member compositions are compared graphically to gas compositions observed in water-well samples to infer origins of the gases in water wells. Limitations of the available data also are summarized.

Occurrence of Natural-Gas Concentrations in Ground Water

Combustible gas was detected in 49 of the 91 well waters inventoried including 36 of 62 (58 percent) wells in the bedrock aquifer and 13 of 29 (45 percent) wells in the outwash aquifer. Combustible-gas concentrations ranged from the detection limit of 0.1 to about 30 percent. For bedrock wells visited twice (27

Table 3. Constituents analyzed and laboratory methods used to analyze gas- and water-well samples, Tioga Junction and vicinity, Tioga County, Pennsylvania.

[mg/L, milligrams per liter; per mil, parts per thousand; pMC, percent modern carbon; DIC, dissolved inorganic carbon; QA, quality assurance; Isotech, Isotech Laboratories, Inc.; USGS-RDGL, U.S. Geological Survey-Reston Dissolved Gas Laboratory; USGS-RSIL, U.S. Geological Survey-Reston Stable Isotope Laboratory]

Analysis type	Constituent group	Analyte	Units	Laboratory	Sample type	Method reference or URL
Compositional Analyses						
Gas, volume fraction	Hydrocarbon gases	methane (CH_4) ethane (C_2H_6) ethylene (C_2H_4) propane (C_3H_8) butane (C_4H_{10}) normal and iso- pentane (C_5H_{12}) normal and iso- hexane (C_6H_{14}) + (plus higher hydrocarbons)	percent	Isotech	gas well water well	Isotech Laboratories, Inc. (2005)
Gas, concentration dissolved in water	Hydrocarbon gases	methane (CH_4)	mg/L	USGS-RDGL	water well	Busenberg and others (1998)
Gas, volume fraction	Fixed gases	argon, carbon dioxide, carbon monoxide, helium, hydrogen, hydrogen sulfide, nitrogen, oxygen,	percent	Isotech	gas well water well	Isotech Laboratories, Inc. (2005)
Gas, concentration dissolved in water	Fixed gases	argon, carbon dioxide, nitrogen, oxygen,	mg/L	USGS-RDGL	water well	Busenberg and others (1998)
Stable-Isotope Analyses						
^{13}C : ^{12}C ratio	Carbon	methane (CH_4)	per mil	Isotech	gas well water well	Isotech Laboratories, Inc. (2005)
^{13}C : ^{12}C ratio	Carbon	ethane (C_2H_6)	per mil	Isotech	gas well water well	Isotech Laboratories, Inc. (2005)
^{2}H : ^{1}H ratio	Hydrogen	methane (CH_4)	per mil	Isotech	gas well water well	Isotech Laboratories, Inc. (2005)
^{13}C : ^{12}C ratio	Carbon	methane (CH_4)	per mil	USGS-RSIL	QA only water well	Continuous flow isotope ratio mass spectrometry with a gas chromatograph combustion interface. *http://isotopes.usgs.gov/Methods.htm*
^{13}C : ^{12}C ratio	Carbon	DIC	per mil	USGS-RSIL	water well	McCrea (1950) *http://isotopes.usgs.gov/Methods.htm*
^{2}H : ^{1}H ratio	Hydrogen	water	per mil	USGS-RSIL	water well	Coplen and others (1991) *http://isotopes.usgs.gov/Methods.htm*
^{18}O : ^{16}O ratio	Oxygen	water	per mil	USGS-RSIL	water well	Epstein and Mayeda (1953) *http://isotopes.usgs.gov/Methods.htm*
Radiogenic-Isotope Analyses						
Carbon-14, ^{14}C	Carbon	methane (CH_4)	pMC	Isotech	water well	*http://www.isotechlabs.com/analytical/radiogenic_gas.htm*

Table 4. Blank, replicate, and laboratory-split quality-assurance samples from water wells sampled in 2005, Tioga Junction and vicinity, Tioga County, Pennsylvania.

[All samples collected by U.S. Geological Survey (USGS). Analyses for stable isotopes, hydrocarbons, and headspace gases were performed at Isotech Laboratories, Inc., with split replicates to Reston Stable Isotope Laboratory (RSIL) for stable carbon isotopes of methane. Hydrogen stable isotope data reported relative to Vienna Standard Mean Ocean Water (VSMOW) and carbon stable isotope data reported relative to Vienna PeeDee Belemnite (VPDB). $\delta^{13}C_{CH4}$, carbon isotopes of methane; δD_{CH4}, hydrogen isotopes of methane; $\delta^{13}C_{C2H6}$, carbon isotopes of ethane; per mil, parts per thousand; vol%, volume percent; NA, not analyzed; ND not detected]

Sample identifier	Date	Time	$\delta^{13}C_{CH4}$, in per mil Isotech	$\delta^{13}C_{CH4}$, in per mil RSIL	δD_{CH4}, in per mil Isotech	$\delta^{13}C_{C2H6}$, in per mil Isotech	Concentration[1] in headspace, in volume percent						
							Methane	Ethane	Argon	Oxygen	Carbon dioxide	Nitrogen	Helium
						Blanks							
Source blank	8/16/2005	00:00	NA	NA	NA	NA	0.0497	ND	0.869	18.13	0.1	80.85	ND
Field blank	8/12/2005	00:00	NA	NA	NA	NA	ND	ND	.994	20.59	.1	78.32	ND
						Replicates[2] and Laboratory Splits							
TI599	7/20/2005	18:30	-40.15	NA	-168.6	NA	61.36	0.673	.670	2.98	3.16	31.14	0
TI599	7/20/2005	18:31	-40.22	NA	-168.8	NA	63.11	.691	.667	2.26	3.15	30.12	0
TI608	7/29/2005	12:00	-43.55	NA	-193.8	-33.23	83.69	.273	.292	.12	.07	15.55	.013
TI608	7/29/2005	12:01	-43.59	-43.91	-195.4	-33.47	83.31	.273	.305	.2	.08	15.82	.0127
TI610	8/10/2005	12:00	-64.29	NA	-266.4	NA	43.12	.0095	.831	2.31	.29	53.43	.005
TI610	8/10/2005	12:01	-64.29	-64.67	-266.5	NA	45.99	.01	.800	.98	.28	51.94	.0052
TI611	8/10/2005	16:00	-75.18	NA	-246.7	NA	51.62	.0058	.715	.4	.39	46.86	.0088
TI611	8/10/2005	16:01	-75.12	-74.94	-246.8	NA	52.28	.0056	.727	.41	.39	46.18	.0077
TI592	7/13/2005	20:00	-40.12	-41.25	NA	NA	NA	NA	NA	NA	NA	NA	NA
TI596	7/19/2005	14:45	-47.13	-47.64	NA	NA	NA	NA	NA	NA	NA	NA	NA

[1] Isotech Laboratories, Inc., results for gas composition are normalized to 100 percent and reported in mole percent. Mole percent is approximately equal to volume percent and is reported here as volume percent. Isotech Laboratories, Inc., analyzed for carbon monoxide, hydrogen sulfide, helium, hydrogen, argon, oxygen, nitrogen, carbon dioxide, methane, ethane, ethylene, propane, normal and iso-butane, normal and iso-pentane and hexane plus higher hydrocarbons. Only the detected constituents are reported in this table. There was 0.017 vol% carbon monoxide in sample TI599 at 18:30.

[2] Replicate sample pairs are denoted by times 1 minute apart.

wells), measured concentrations of combustible gas, when compared between inventory and detailed-sampling visits for the same well (table 2), had low variation (± 1 percentage point or less) at 11 wells (40 percent), moderate variation (± more than 1 percentage point to less than 5 percentage points) at 8 wells (30 percent), and high variation (± more than 5 percentage points) at 8 wells (30 percent). For outwash wells visited twice (12 wells), measured concentrations of combustible gas, when compared between inventory and detailed-sampling visits for the same well (table 2), had low variation (± 1 percentage point or less) at 7 wells (58 percent), moderate variation (± more than 1 percentage point to less than 5 percentage points) at 3 wells (25 percent), and high variation (± more than 5 percentage points) at 2 wells (17 percent). These results suggest some temporal variability in combustible-gas concentrations in samples collected weeks to months apart from selected wells. One well owner reported that the seasonality in operations of the storage field affects the presence of gas in well water. This well owner noted a change in water characteristics as the gas-storage field is filled in summer months (July through September) and emptied in the winter months. The data collected are not seasonal and represent the late spring and summer of 2005 only; hence, the data are not suitable for testing the observations of the well owner. The TI726 water well, a 140-ft-deep well in the bedrock aquifer, west of the study area (fig. 2) has been shown to respond to pressure changes in the underlying gas-storage field (Robert Gleeson, Pennsylvania Department of Environmental Protection, oral commun., 2006).

Samples from 39 of the 49 wells also have laboratory analyses for methane concentrations dissolved in ground waters. The detections of combustible gases and the associated methane measured in ground-water samples at concentrations greater than or equaling 2 mg/L indicated clusters of gas occurrences in the central and southern parts of the study area. Southwest to northeast trending bands of occurrence characterized the northern flank of the Sabinsville Anticline (fig. 7).

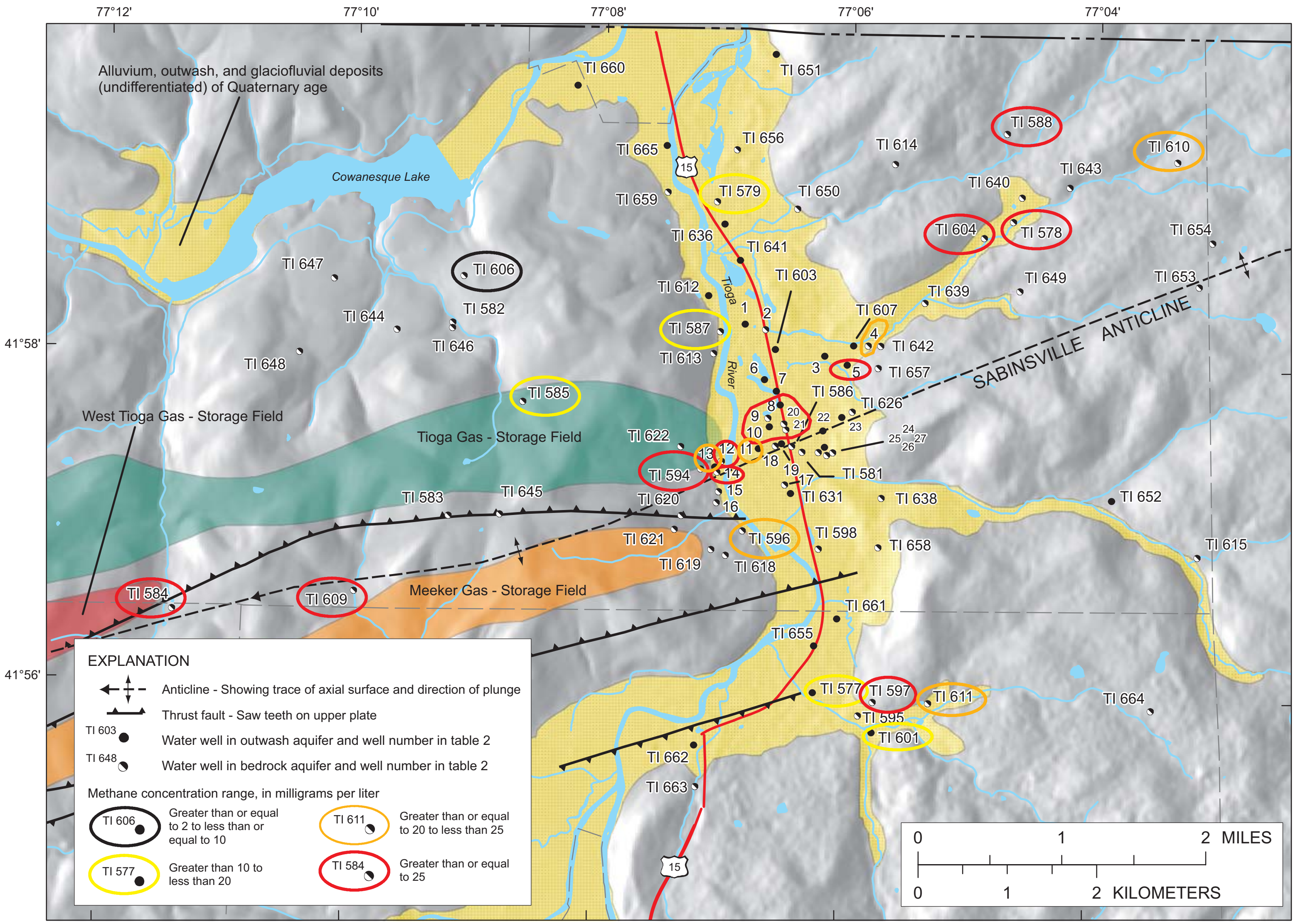
A plot of the fractions of combustible gas in gases associated with the well waters, as measured at the 39 wells in the field with the gas scope (table 2), and the methane concentrations dissolved in ground waters, as measured in the laboratory [table 5 (at back of report)], indicates a general positive correlation (possible linear or polynomial relation) of the data (fig. 8). If the outlier for well TI576 is eliminated, a linear relation of the form y= mx, where the slope m equals 3, explains 76 percent of the variability. This linear relation indicates the percentage of combustible gas in the headspace of a ground-water sample as measured in the field with a combustible-gas meter, when multiplied by a factor of three, gives an approximation of the concentration of methane dissolved in the ground water (in milligrams per liter).

Only methane and ethane were detected at reportable concentrations from the compositional analysis of hydrocarbon gases in the water samples (table 5). Waters from 15 of 39 wells (38 percent) had concentrations of dissolved methane greater than 25 mg/L (corresponding to methane volume fractions of 67 to 97 percent in headspace gases of ground water), with a maximum concentration of 44.8 mg/L (figs. 7 and 8). These included nine wells (seven bedrock and two outwash) clustered at the eastern end of the Tioga gas-storage field, two bedrock wells (TI584 and TI609) between the Meeker and the West Tioga gas-storage fields, one bedrock well (TI597) near Mitchell Creek, and three bedrock wells northeast of Tioga Junction (fig. 7). An additional 11 well waters (28 percent) had concentrations of methane between 10 and 25 mg/L (corresponding to methane volume fractions of 40 to 62 percent in headspace gases of ground water). Ethane, at volume fractions greater than 0.1 percent, was present in 15 of the 26 well waters that had concentrations of methane greater than 10 mg/L (fig. 8). Overall, ethane volume fractions in headspace gases of ground water ranged from 0.003 to 1.61 percent.

Relation of Combustible-Gas Occurrence to Chemical Characteristics of Ground Water

Data on chemical characteristics of water (table 2) combined from the inventory and detailed-sampling visits to water wells are summarized in table 6 to compare waters with and without combustible gas by aquifer. The median conductivities of 487 and 320 µS/cm, for bedrock-aquifer waters with and without gas, respectively, were larger than outwash-aquifer waters. Bedrock-aquifer waters with gas exhibited the largest range and the largest median conductivity of the four groups. The median pH of 6.8 for outwash-aquifer water without gas was the most acidic; the presence of gas seems to be associated with a buffering effect from geochemical or physical processes in the outwash-aquifer waters that yielded a more basic median pH than waters without gas (table 6). This relation holds for bedrock-aquifer waters, although the differences in median pH are less pronounced. The more basic pH values for waters with gas compared to waters without gas were also consistent with the ANC data (table 6); however, more ANC data are needed to make a valid comparison. ANC data also were compromised in selected samples due to the delay between field collection and laboratory titration. Samples with field pH greater than 8.3 lost carbonate alkalinity during the holding time; titrations should have been done at the field site.

Dissolved oxygen and Eh data provided evidence of a geochemical environment in the aquifers that was not oxygenated. The lack of oxygen suggests an environment in the aquifers where oxygen in recharge water is being consumed by geochemical processes such as iron oxidation. The lack of dissolved oxygen is conducive to anaerobic microbial reduction of sulfate to hydrogen sulfide and carbon dioxide to methane. Waters with combustible gas had lower median Eh and dissolved oxygen compared to waters without gas, regardless of aquifer (table 6). Wells sampled in this study probably have high concentrations of iron and manganese (as observed by staining on household fixtures or described by well owners). The Eh relation with pH indicates a ferrous iron and ferric iron



Surficial deposits from Commonwealth of Pennsylvania, 1989
Streams from U.S. Geological Survey, 2000
Township boundary and U.S. Routes from Commonwealth of Pennsylvania, 2006
Shaded relief prepared from U.S. Geological Survey National Elevation Dataset, 2004

Base from U.S. Department of Commerce digital data, 1993,
1:100,000 Albers Equal-Area Conic projection: Standard Parallels 29°30' N and 45°30' N,
Central Meridian 77°45' W, Latitude of Origin 23°00' N

Figure 7. Concentrations of dissolved methane equal to or greater than 2 milligrams per liter in ground water from wells completed in the outwash aquifer and bedrock aquifer near Tioga Junction, Tioga County, Pennsylvania, June-August 2005. [Faults shown are mapped at depth in the Oriskany Sandstone. There is no evidence in the hydrogeologic literature for the Tioga Junction area that faults extend to near land surface and into the Lock Haven Formation.]

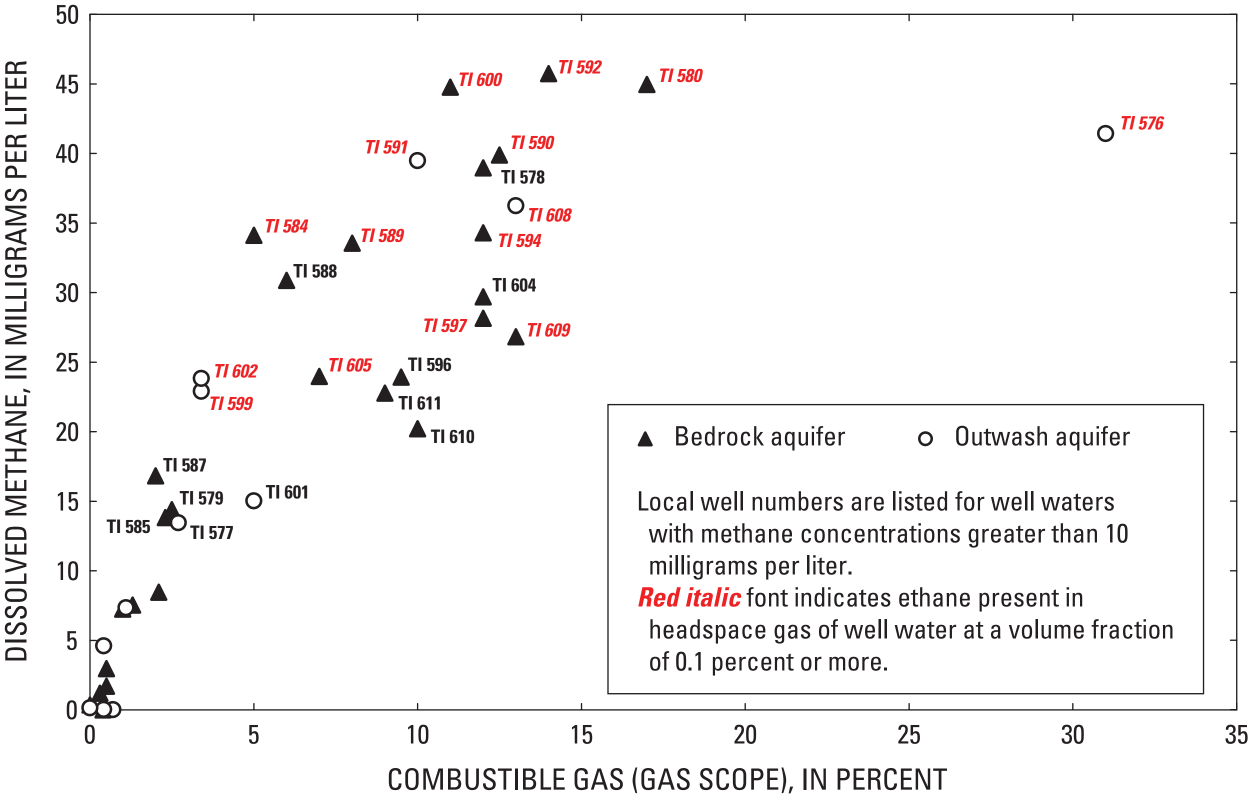


Figure 8. Relation between field measurements of percentage combustible gas and laboratory measurements of concentration of dissolved methane in water samples collected June-August 2005 from 39 wells near Tioga Junction, Tioga County, Pennsylvania.

Table 6. Summary statistics for characteristics of waters with and without combustible gas in bedrock and outwash aquifers, May-August 2005 at Tioga Junction, Tioga County, Pennsylvania.

[mg/L as $CaCO_3$, milligrams per liter as calcium carbonate; µS/cm, microsiemens per centimeter at 25°C; N, number of observations; Eh mV (SHE), oxidation-reduction potential in millivolts relative to the standard hydrogen electrode; <, less than]

Aquifer and gas grouping	Conductivity (µS/cm)			pH			Acid neutralizing capacity (ANC) (mg/L as $CaCO_3$)		
	N	Range	Median	N	Range	Median	N	Range	Median
Water from bedrock well with combustible gas	55	202 – 3,160	487	54	7.0 – 8.8	7.8	25	89 – 317	210
Water from bedrock well without combustible gas	18	175 – 702	320	18	6.5 – 8.5	7.5	1	– –	170
Water from outwash well with combustible gas	21	237 – 537	288	22	7.1 – 8.6	8.0	11	167 – 218	168
Water from outwash well without combustible gas	12	181 – 696	313	12	5.5 – 8.1	6.8	1	– –	32

Aquifer and gas grouping	Dissolved oxygen (mg/L)			Eh mV (SHE)			Temperature (°C)		
	N	Range	Median	N	Range	Median	N	Range	Median
Water from bedrock well with combustible gas	41	< 0.1 – 4.1	0.2	38	-77 – 333	68	48	9.9 – 14.6	11.5
Water from bedrock well without combustible gas	10	< 0.1 – 5.5	.3	8	-24 – 297	103	15	9.9 – 13.5	11.3
Water from outwash well with combustible gas	18	< 0.1 – 0.3	.1	21	-55 – 129	31	21	10.8 – 13.4	11.6
Water from outwash well without combustible gas	9	< 0.1 – 1.9	.3	7	0 – 404	228	12	10.6 – 12.3	11.2

oxidation-reduction reaction is likely controlling the pH and Eh characteristics in well water. During well-water sampling, the odor of hydrogen sulfide (“sulfur smell” in table 2) was common and is evidence of sulfate reduction by bacteria under conditions of low dissolved oxygen.

The field observation of “Yes” or “No” for outgassing is consistent with measured concentrations of dissolved methane greater than or less than 2 mg/L, respectively, in 36 of 39 well waters where concentrations of methane were determined (tables 2 and 5). Methane concentration in ambient air is about 0.00015 percent by volume (Hem, 1985, p. 10). As a result of this low concentration in air, ground water with even a detectable concentration of methane (~0.01 mg/L) is oversaturated with methane when exposed to the air at the land surface. Hence, outgassing was, in part, due to methane oversaturation; however, gases such as carbon dioxide and hydrogen sulfide in the ground-water samples may also be contributing to the observed outgassing. Carbon dioxide was measured in the headspace gases from ground-water samples (table 5) and given the measured pH, temperature, and ANC of ground water (table 2), ground waters were also commonly oversaturated with carbon dioxide. Hydrogen sulfide was not detected in the headspace gases from ground-water samples (table 5); however, the “sulfur smell” odor of rotten eggs noted during sampling (table 2) indicated hydrogen sulfide was also outgassing.

Data on stable-isotope characteristics of water (table 5) provide no additional information on the extent of gas occurrence. Stable-isotope composition of hydrogen in ground water (δD_{water}) and oxygen in ground water ($\delta^{18}O_{water}$) at Tioga Junction were determined for bedrock (26 samples) and outwash (10 samples) aquifers. The results were not different for wells with and without gas and did not correlate with gas concentrations. The two aquifers contained water of similar isotopic composition. When δD_{water} is plotted against $\delta^{18}O_{water}$ for Tioga Junction ground water and compared to typical river water in north-central Pennsylvania (fig. 9), the ground water (except the well TI582 outlier) was similar to the compositions of nearby river waters in Pennsylvania (Kendall and Coplen, 2001). Young Womans Creek is 65 mi southwest of Tioga Junction and most closely compares in latitude to the wells at Tioga Junction; the similarities in isotopic composition indicate the ground water is of relatively recent recharge age. The best-fit lines for north-central Pennsylvania river waters and for Tioga Junction ground waters (without the TI582 outlier) are $\delta D_{water} = 6.65(\delta^{18}O_{water}) + 0.91$ and $\delta D_{water} = 7.69(\delta^{18}O_{water}) + 9.99$, respectively.

There is no evidence that the waters from one or both aquifers represent Pleistocene-age water or water originating from a high-altitude or cold-environment source. Ground water of late Pleistocene age from temperate regions in North America and Europe would be isotopically depleted by about 2 per mil in ^{18}O and 15 per mil in ^{2}H compared to modern waters, and would plot to the lower left in figure 9 (Clark and Fritz, 1997). Precipitation that falls under high-altitude or cold-environment conditions is depleted in ^{18}O and ^{2}H (Fontes, 1980, p. 78-79).

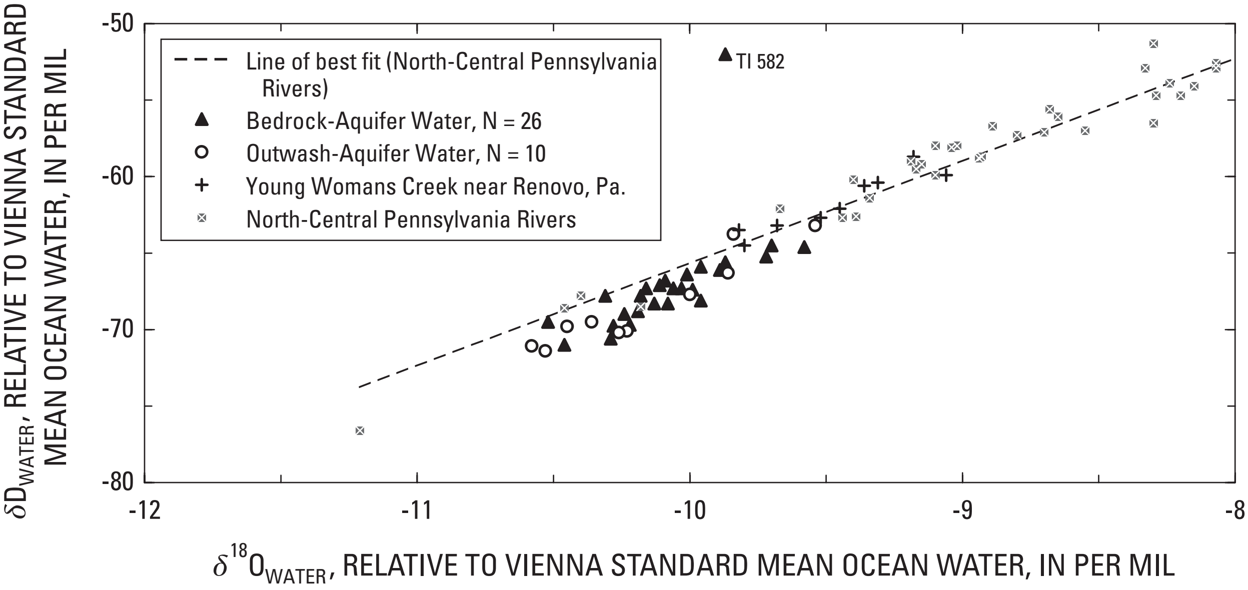


Figure 9. Stable-isotopic composition of hydrogen and oxygen in ground water collected June-August 2005 from wells in the bedrock and outwash aquifers at Tioga Junction, Tioga County, Pennsylvania, compared to the isotopic composition reported by Kendall and Coplen (2001) for the West Branch Susquehanna River, Susquehanna River, Juniata River, and Young Womans Creek (65 mi southwest of Tioga Junction).

Relation of Combustible-Gas Occurrence in Ground Water to Hydrogeologic Setting

There is an apparent southwest to northeast alignment pattern to the distribution of ground water containing high concentrations of combustible gas, methane, or ethane. The pattern is characterized by high concentrations of combustible gas in ground water from wells on or near the axis of the Sabinsville Anticline and parallel to the axis along the northern flank of the anticline (figs. 7 and 8). The wells represent both valley and upland settings. The pattern on or near the axis involves bedrock and outwash wells; the pattern along the northern flank of the anticline involves only bedrock wells. The cluster of high readings of combustible gas, manifest in ground water from bedrock and outwash wells near Mitchell Creek on the southern flank of the anticline, occurs at the eastern end of a fault structure mapped at depth in the Oriskany; however, the fault planes generally do not extend from the Oriskany to the surface (Beardsley and others, 1999).

Well depth was a factor influencing the observed occurrence of combustible gas for the 62 bedrock wells inventoried. Of seven shallow wells (all hillside or upland-draw settings with depths of 50 ft or less), three (43 percent) had waters with combustible-gas fractions greater than 0.1 percent and four did not. For 36 wells of intermediate depth (in a mix of settings, 51 to 150 ft), 21 (58 percent) had waters with combustible-gas fractions greater than 0.1 percent and 15 did not. For the 19 deepest bedrock wells inventoried (with depths of 151 ft or more), 12 (63 percent, about half valley and half hillside settings) had waters with combustible-gas fractions greater than 0.1 percent and 7 did not. As the well depth range increased, the percentage of wells with combustible gas increased.

For the setting in which a bedrock well was completed regardless of depth, the relation to the occurrence of combustible gas in well water was harder to discern. In hilltop settings, there were two well waters to compare. There was combustible gas in one and none detected in the other. In hillside and upland-draw settings, of 42 well waters to compare, there was combustible gas in 24 (57 percent) and none detected in the other 18 (43 percent). In valley settings, of 19 well waters to compare, there was combustible gas in 12 (63 percent) and none detected in the other 7 (37 percent).

Combining well depth and setting as factors, bedrock wells with depths of 151 ft or more in valley settings had the greatest likelihood of combustible gas in ground water. Of six wells in the category, five (83 percent) had waters with combustible-gas fractions greater than 0.1 percent.

For the 29 outwash wells inventoried, on the basis of known geology and the extent of aquifers in the Tioga River valley, there was a pattern of combustible-gas occurrence as a function of well depth. Of 11 shallow wells (with depths of 50 ft or less) inventoried in the Tioga River valley, only 2 had waters with combustible-gas fractions greater than 0.1 percent. These 11 wells likely produce from the shallow water-bearing zones of the outwash aquifer. Of 18 deep wells (with depths greater than 50 ft) inventoried in the Tioga River valley, 10 had waters with combustible-gas fractions greater than 0.1 percent. These higher concentrations may be a function of increased methane solubility due to increases in hydrostatic pressure associated with deeper wells. The presence of a confining unit in the main Tioga River valley, formed by lacustrine deposits, may also play a role in keeping gas confined to the lower outwash aquifer in the valley and the underlying bedrock aquifer. Artesian conditions, as indicated by flowing wells, were observed for the outwash aquifer in the center of the Tioga River valley.

Use of Isotopes to Determine Origins of Natural-Gas Concentrations in Ground Water

As noted earlier in the section on isotopic signatures, methane in natural gas can be generated by microbial CO_2-reduction and acetate-fermentation processes and by thermogenic processes. These processes lead to characteristic chemical and isotopic signatures of natural gas. Chemical and isotopic characteristics of known sources of methane and other natural gases are a useful means of describing end-member compositions and can be used as a fingerprint (Coleman and others, 1993; Kaplan and others, 1997). The isotopic end members fall into typical regions on an isotopic plot (fig. 10). When mixing of end-member compositions takes place, the composition of the mixture is between, or intermediate, to the end-member compositions. The composition of mixtures can vary widely and represent typical ranges of isotopic compositions, as shown in figure 10.

Plotting or graphical techniques commonly are used to differentiate types or origins of natural gas (either thermogenic or microbial) using distinguishable isotopic signatures of methane and by the composition of other hydrocarbons and gases present (Schoell, 1980, 1983; Laughrey and Baldassare, 1998; Coleman, 1994; Chafin, 1994, Coleman and others, 1995).

Four end-member compositions or gas origins were assumed to exist in the study area—native Oriskany gas, storage-field gas, Devonian shale gas (native shallow gas), and gas from microbial activity in the shallow subsurface. Gas-well samples could be obtained to characterize the native Oriskany gas and storage-field gas. End-member sources for Devonian shale gas and shallow subsurface gas were not identified for sampling. Hence, ^{14}C dating of carbon in methane gas from water wells was used to test for the presence of modern carbon, indicating carbon of microbial origin.

Isotopic Characteristics and Origins of Oriskany and Storage-Field Gases

To evaluate the origin of methane in ground water, this study first attempted to characterize the end-member compositions of natural gases in the vicinity of Tioga Junction. Compositional and isotopic analyses of samples from eight gas wells [table 7 (at back of report)] were used to define end-member characteristics of natural gas.

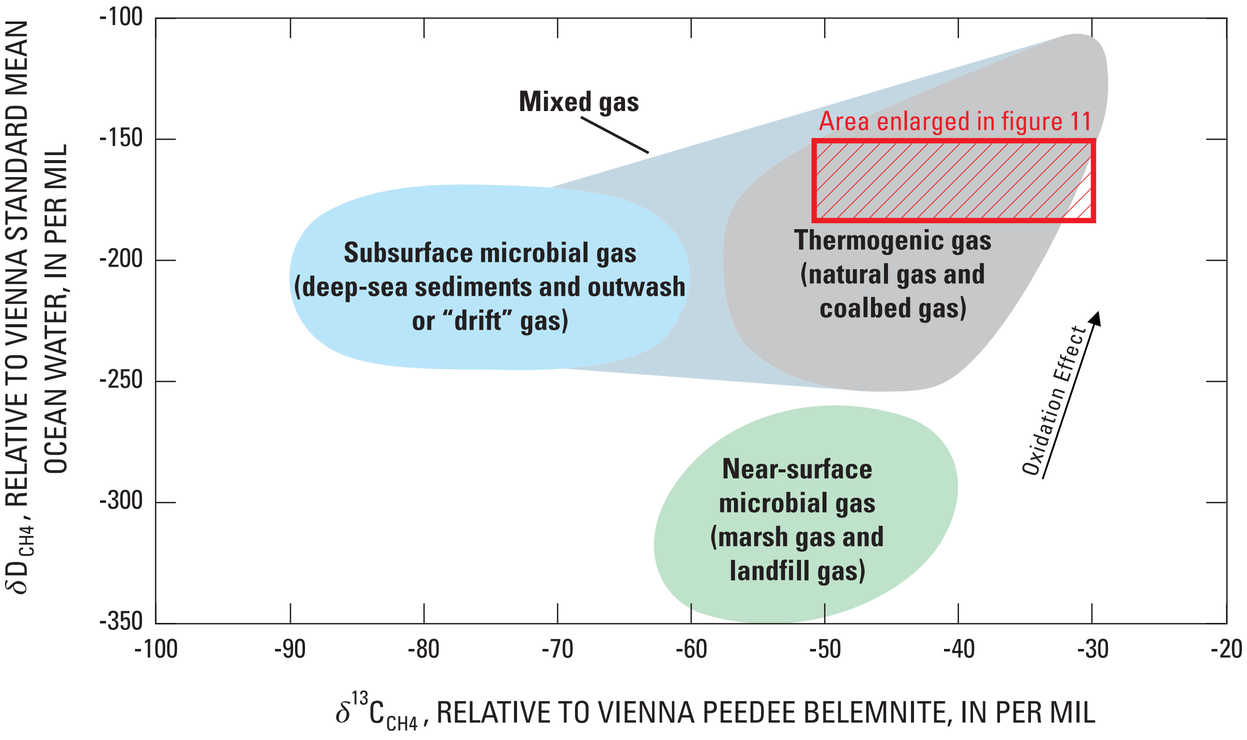


Figure 10. Stable-isotopic composition of carbon and hydrogen in methane, illustrating process end members observed in natural systems (modified from Coleman and others, 1993, based on the dataset of Schoell, 1980).

Samples were collected from the Oriskany Sandstone and from the Tioga gas-storage field (storage field) where natural gas from the Gulf Coast region of the United States (Gulf gas), areas of the Appalachian Plateaus Physiographic Province in the United States and Canada, and other distant sources is transported by pipeline to a gas reservoir (or structural trap) in the Oriskany Sandstone that previously produced Oriskany gas.

Compositional analyses indicated the non-native gases from wells in the gas-storage field and native gases from wells producing from the Oriskany Sandstone were similar in chemical composition. Methane (volume fraction ranging from 94.5 to 97.2 percent) and ethane (volume fraction ranging from 2.0 to 2.6 percent) were predominant.

Isotopic composition of carbon and hydrogen in methane (CH_4) and ethane (C_2H_6) was determined for the eight gas wells sampled. The differences in $\delta^{13}C_{CH4}$ and δD_{CH4} between gas produced from the Oriskany Sandstone and storage gas (Gulf gas, Appalachian basin gas, and gas from other distant sources) injected into the storage field are shown in figure 11. The methane in Oriskany gas is thermogenic and has a median $\delta^{13}C_{CH4}$ of about -34.6 per mil; gas injected into the gas-storage field also is thermogenic, but of a different origin, and has a median $\delta^{13}C_{CH4}$ of about -44.1 per mil. The storage gas also has methane depleted in deuterium (-168 per mil) compared to Oriskany gas (-159 per mil). The ethane in Oriskany gas has a median $\delta^{13}C_{C2H6}$ of about -40.4 per mil, whereas ethane in the gas injected into the gas-storage field has a median $\delta^{13}C_{C2H6}$ of about -30.4 per mil (table 7).

By combining $\delta^{13}C$ data for methane and ethane on the same plot (fig. 12), there is additional evidence for the different gas origins. The methane in Oriskany gas is more enriched in ^{13}C than methane in the storage-field gas. Ethane in the Oriskany gas also is more depleted in ^{13}C (fig. 12). Results for well TW805 that is near the eastern boundary of the storage field, along with results for the storage-field observation wells, plot between the two regions represented by Oriskany gas and storage-field gas, possibly indicating mixing of the two thermogenic gases.

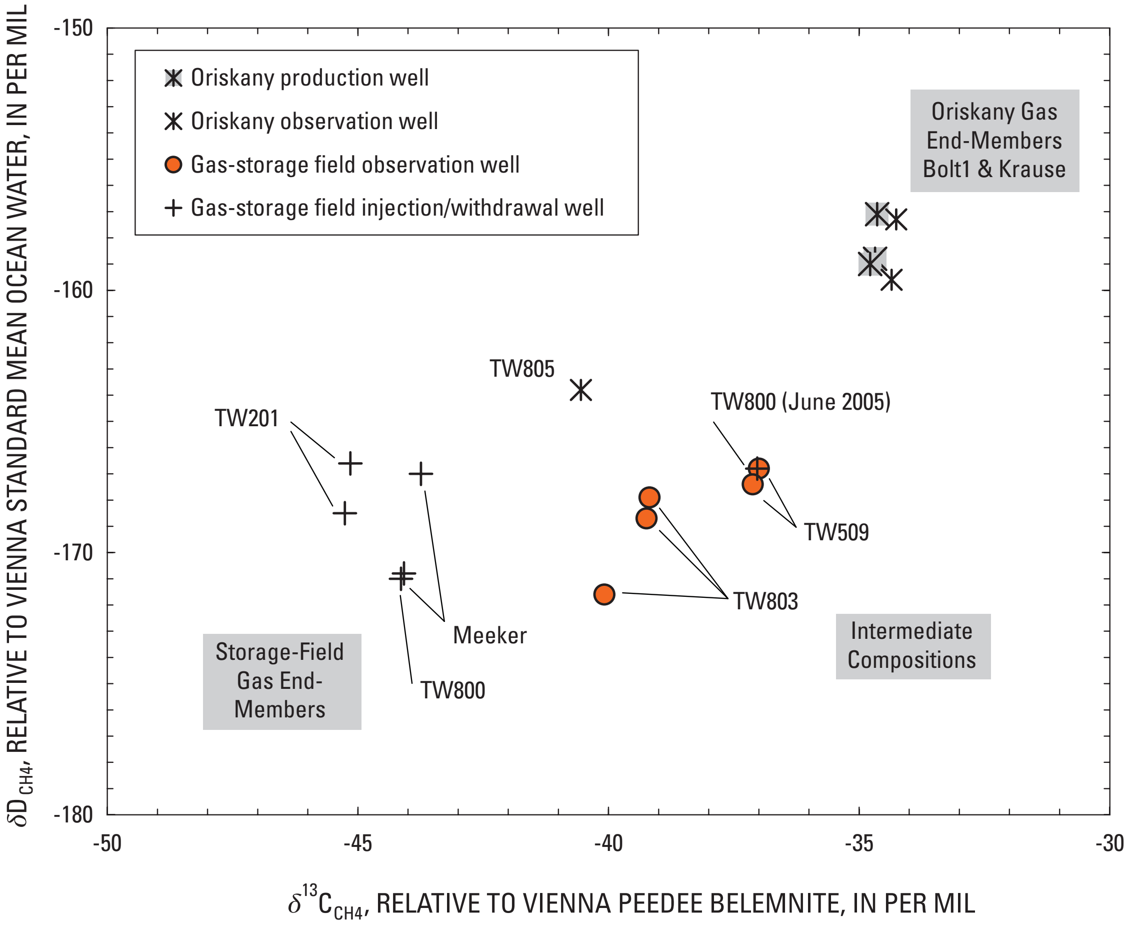


Figure 11. Stable carbon and hydrogen isotopes of methane in gas-well samples comprising end-member and intermediate compositions of thermogenic natural gas near Tioga Junction, Tioga County, Pennsylvania, October 2004-September 2005.

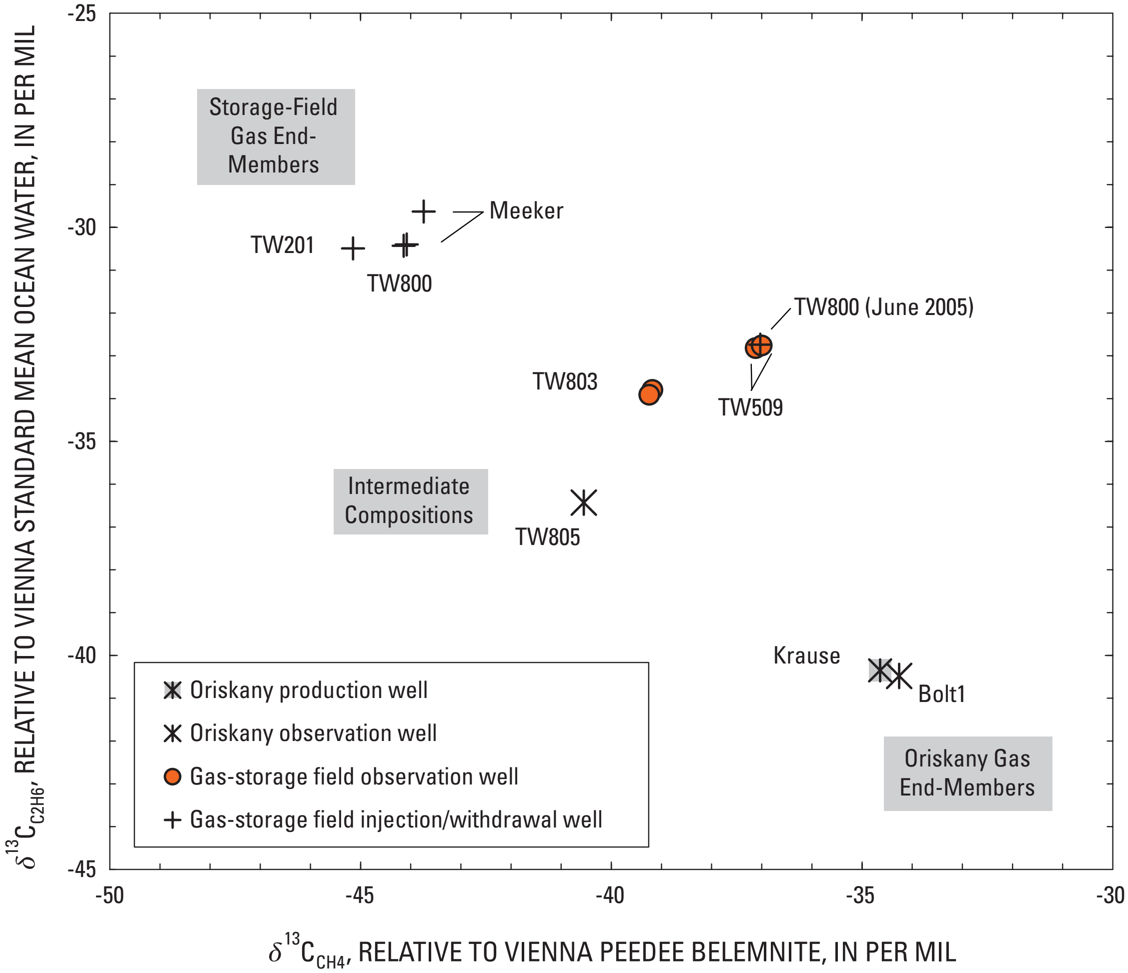


Figure 12. Stable carbon isotopes of methane and ethane for gas-well samples near Tioga Junction, Tioga County, Pennsylvania, October 2004-September 2005, with end-member and intermediate compositions indicated.

The data in figs. 11 and 12 demonstrate that the δD_{CH4}, $\delta^{13}C_{CH4}$, and $\delta^{13}C_{C2H6}$ values of Oriskany gas are different from that of the storage-field gas—confirming their different origins. A peculiar result from the $\delta^{13}C$ data for methane and ethane is the ethane is more depleted in ^{13}C than the methane in the same gas. However, such isotopic reversals have been observed previously (Burruss and Laughrey, 2006). Additional sampling and analysis are needed to verify this observation.

The Oriskany gas is more thermally mature than the storage-field gas and is more enriched in the ^{13}C and ^{2}H isotopes. These data correlate with limited published data for the Oriskany gas and a more comprehensive dataset for Appalachian basin production (Jenden and others, 1993; Claypool and others, 1978; Baldassare and Laughrey, unpublished data, 1999–2005). The $\delta^{13}C_{C2H6}$ data from Jenden and others (1993) are all less (more negative) than -32 per mil and most are less than -35 per mil.

The samples of storage-field gas from injection and withdrawal (I/W) wells reveal a larger range of $\delta^{13}C_{CH4}$ and δD_{CH4} values than do the samples of Oriskany gas. Isotopic variability of the storage-field I/W gases is attributable to mixing of gases of different origins. The wider range of isotopic compositions is characteristic of less thermally mature thermogenic gases. The two samples from I/W well TW800 are disparate in composition. One sample from TW800 collected in June 2005 is enriched in ^{13}C and is more similar in ^{13}C content to Oriskany gas than to the other samples of storage-field gas from I/W wells and is very similar to the gas sample from observation well TW509 (fig. 11). The reason for the wide variation in composition for samples collected only 2 months apart is not known. TW800 was reported to be in injection mode at the time of the June sampling (Thomas Rice, Dominion Gas Company, written commun., 2005), the same day another I/W well (Meeker well) in the Meeker storage field was sampled, together with the TW803 and TW509 storage-field observation wells, which are open to or receiving leakage from the Tioga storage field. The June 2005 result for TW800 appears related to mixing of gases of different origin.

Samples from observation wells in the storage field (TW509 and TW803) have isotopic compositions between the

Oriskany samples and samples of the storage-field gas from I/W wells (figs. 11 and 12). Drilling records for these wells note 'shows' or traces of natural gas from Devonian shale at depths above the Oriskany ("shallow gas" at about 1,000 ft depth). The TW509 and TW803 samples appear to be mixtures of storage gas, shallow gas that has an isotopic signature similar to that of Gulf gas in the storage field, and Oriskany gas (Laughrey and Baldassare, 1998, Dennis D. Coleman, Isotech Laboratories, Inc., oral commun., 2006, Baldassare and Laughrey, unpublished data, 1999–2005).

The gas samples from the storage-field observation wells are enriched in ^{13}C relative to the storage-field I/W gas but are not as enriched in ^{13}C as Oriskany gas. Well TW805, a depleted Oriskany well about 500 ft northeast of the eastern boundary now used for observation of the storage field, yields gas that is an example of mixing of Oriskany gas and storage-field gas (figs. 11 and 12). 'Shows' of shallow gas were never documented for TW805.

Isotopic mass-balance calculations were used to determine the fractions of the two end-member gases in the observation wells, for example in the TW805 sample ($\delta^{13}C_{CH4}$ = -40.55 per mil), based on the following equation:

$$\delta^{13}C_{CH4\ \text{storage field observation well gas}} = X \times \delta^{13}C_{CH4\ \text{storage field I/W gas}} + (1\text{-}X) \times \delta^{13}C_{CH4\ \text{Oriskany gas}} \quad (2)$$

where X is the fraction of storage-field I/W gas and 1-X is the fraction of Oriskany gas in the observation well TW805 sample. The same calculation could be performed by using the measured values of δD_{CH4} and $\delta^{13}C_{C2H6}$. All three calculations for this sample indicate a combination or mixing of Oriskany gas and storage-field I/W gas of about 50:50 assuming these are the only end members. This provides an initial line of evidence that some gas from the storage field is leaking or migrating toward well TW805.

Overall, the gas-well results are consistent with earlier work on storage gases. Coleman (1994) described typical isotopic compositions of storage gases in western Pennsylvania and New York (with Gulf gas as the principal storage gas) and typical compositions of natural gases from the northern Appalachian basin. The $\delta^{13}C$ results from this study indicate the storage-field gases have typical isotopic compositions ($\delta^{13}C_{CH4}$ values of about -50 to -42 per mil). Moreover, the samples of Oriskany gas are typical of Lower Devonian production from the northern Appalachian basin ($\delta^{13}C_{CH4}$ values of about -38 to -34 per mil).

Isotopic Characteristics and Origins of Methane and Ethane in Ground Water

Of the 39 water samples collected and submitted for compositional and isotopic analyses, 37 sequential replicates were sent to Isotech Laboratories, Inc., and all 39 were analyzed by the USGS. Of the 37 samples submitted to Isotech Laboratories, Inc., all 37 were analyzed for gas composition, 35 had a sufficient amount of methane to determine isotopic composition ($\delta^{13}C_{CH4}$ and δD_{CH4}), and 21 of the 35 samples had a sufficient amount of ethane to determine $\delta^{13}C_{C2H6}$. Of the 35 wells with isotopic data from Isotech Laboratories, Inc., 10 were drilled into the outwash aquifer and 25 were drilled into the bedrock aquifer (tables 2 and 5, fig. 6).

For the 37 water samples analyzed for composition of headspace gases, the dominant gases measured were methane (volume fraction ranging from 0.0066 to 94.4 percent), nitrogen (volume fraction ranging from 2.02 to 93.7 percent), carbon dioxide (volume fraction ranging from 0.067 to 3.30 percent), argon (volume fraction ranging from 0.09 to 1.9 percent), and ethane (volume fraction ranging from 0.003 to 1.61 percent).

For the water samples analyzed for isotopic composition of headspace gases, the range in $\delta^{13}C_{CH4}$ for 35 samples is from -35.54 per mil (well TI593, outwash aquifer) to -75.18 per mil (well TI611, bedrock aquifer). There is a bimodal distribution of $\delta^{13}C_{CH4}$ results (fig 13A) with modes at about -40 and -62 per mil. The -62 per mil mode is consistent with microbially generated gases (see fig. 10) and the -40 per mil mode is related to thermogenic gases. The range in δD_{CH4} for 21 samples is from -105.9 per mil (well TI586, bedrock aquifer) to -266.4 per mil (well TI610, bedrock aquifer). There also is a bimodal distribution of δD_{CH4} results (fig 13B) with modes at about -180 and -250 per mil. The -250 per mil mode is related to microbial gases and the -180 per mil mode is related to thermogenic gases primarily; some outliers indicate mixing of thermogenic and microbial gases. Outliers, with δD_{CH4} more positive (greater) than -130 per mil in figure 13B, may have been affected by bacterial oxidation which results in enrichment of the residual methane in ^{13}C and ^{2}H (Coleman and others, 1993, p. 309-310).

The bimodal distribution for $\delta^{13}C_{CH4}$ is comprised of two groups of samples. The -40 per mil mode for $\delta^{13}C_{CH4}$, hereafter referred to as the thermogenic mode, is comprised of 21 samples. The -62 per mil mode for $\delta^{13}C_{CH4}$, hereafter referred to as the microbial mode, is comprised of 14 samples (fig. 13A).

Activity of ^{14}C was used to further constrain the likelihood of a microbial natural gas composition in ground water. Methane in nine water-well samples was analyzed for ^{14}C content by Isotech Laboratories, Inc. Seven of the nine samples were from wells open to glacial outwash and other overburden sediments; two of the nine samples were from the bedrock aquifer. Methane in water from all nine water wells analyzed for ^{14}C was found to have measurable ^{14}C (fig. 14). By comparing the results to the data in Coleman and others (1993), microbial gas (probably glacial outwash or "drift" gas) is present in the study area.

The amount of ^{14}C is low—an indication that the microbial gas represents either a minor component relative to the thermogenic gas in the ground water or that the microbial methane portion in the sample was formed a long time ago and has decayed substantially, or both. Nevertheless, there is a satisfactory correlation between the ^{14}C and δD_{CH4} values for the same

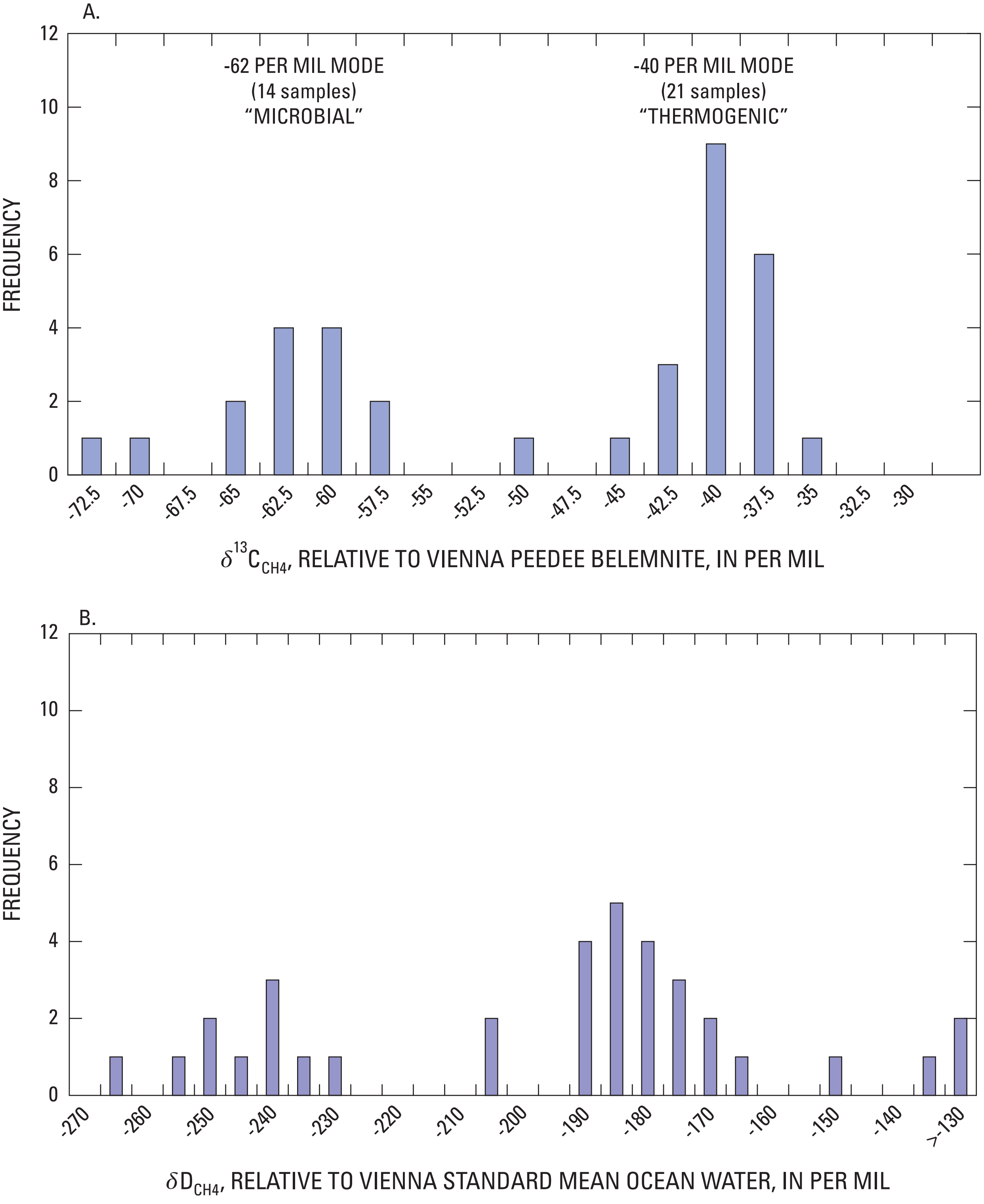


Figure 13. Histograms showing bimodal frequency distribution of A) stable carbon isotopic composition ($\delta^{13}C$) of methane, and B) stable hydrogen isotopic composition (δD) of methane for water-well samples near Tioga Junction, Tioga County, Pennsylvania, June-August 2005.

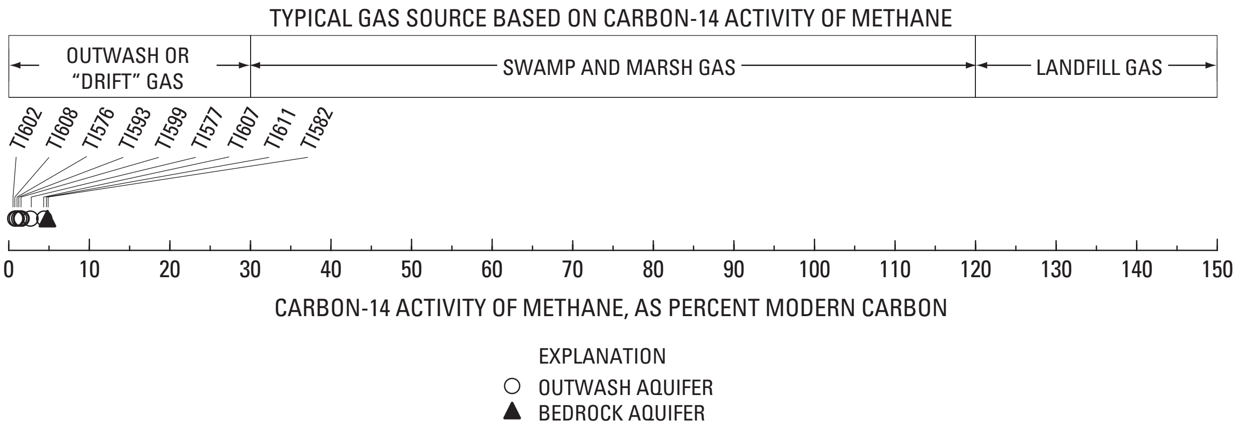


Figure 14. Carbon-14 content of methane in ground water from nine wells (seven in the outwash aquifer and two in the bedrock aquifer) near Tioga Junction, Tioga County, Pennsylvania, June-August 2005, compared to typical ranges of source gases from Coleman and others (1993).

gas (fig. 15), indicating simple mixing between the microbial and thermogenic gases. The -250 per mil mode or microbial mode (fig. 13B) for δD_{CH4}, if a result of mixing, suggests a very negative δD_{CH4} for a microbial end-member composition. Very negative δD_{CH4} values could be related to formation in Pleistocene-age waters with isotopic composition very depleted in ^2H although the present isotopic composition of ground water (see fig. 9) does not have this characteristic.

Samples with sufficient ethane (0.0075 to 1.61 volume percent) for $\delta^{13}C_{C2H6}$ determination yielded $\delta^{13}C_{C2H6}$ results ranging from -28.73 to -39.03 per mil (table 5); the median was -32.17 per mil. The frequency distribution does not have the bimodal character of the $\delta^{13}C_{CH4}$ results. Well waters with ethane chiefly contain thermogenic gas because ethane is typically not present in "drift" gas (Coleman, 1994). Hence, a thermogenic origin is likely for some component of the gases in the ethane-containing well waters. Of the 21 water-well samples that had sufficient ethane for isotopic analysis, 9 were outwash-aquifer wells and 12 were bedrock-aquifer wells (table 2).

The $\delta^{13}C$ of CO_2 also can be used for determining origins of stray gases (Laughrey and Baldassare, 2003); however, the CO_2 concentrations, occurring with the methane and ethane dissolved in well water near Tioga Junction (table 5), were too small for analysis.

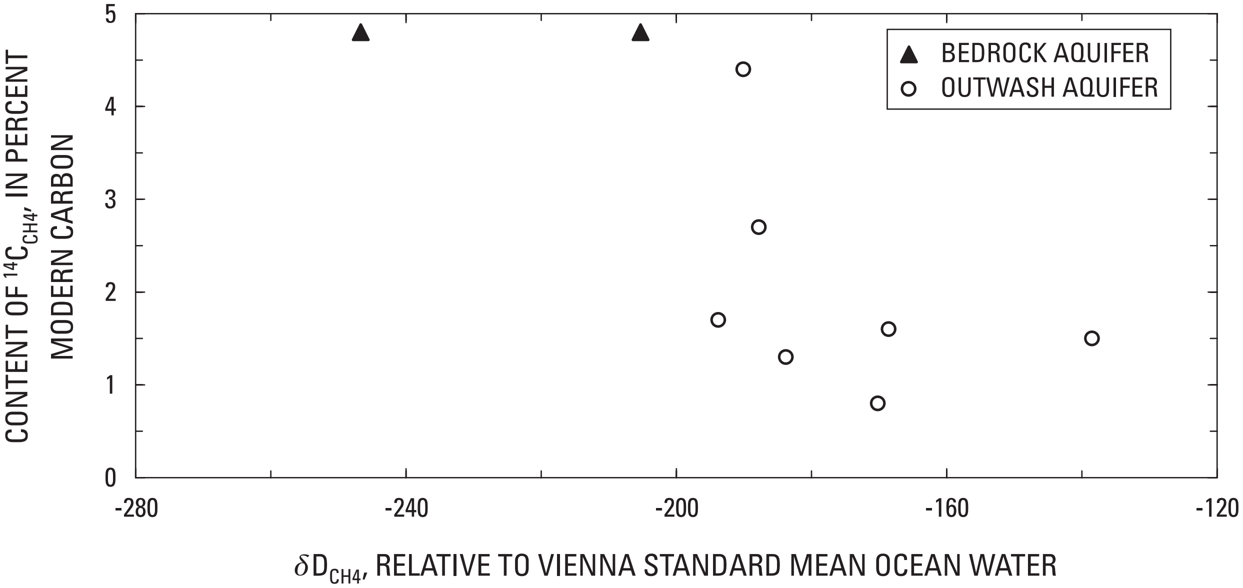


Figure 15. Relations between carbon-14 content and δD_{CH4} in ground waters from selected wells near Tioga Junction, Tioga County, Pennsylvania, June-August 2005.

Dissolved inorganic carbon was present in sufficient quantities for analysis of $\delta^{13}C$ ($\delta^{13}C_{DIC}$) in ground water and was analyzed in water from 12 outwash-aquifer wells and 28 bedrock-aquifer wells. The $\delta^{13}C_{DIC}$ values for water-well samples (table 5) ranged from -2.17 to -21.82 per mil. The isotopic analysis of the DIC indicates that there has not been oxidation of the methane or ethane. Oxidation of methane or other hydrocarbons would cause the $\delta^{13}C$ of DIC in ground water to become more negative, generally less than about -25 per mil. The $\delta^{13}C_{DIC}$ frequency distribution (fig. 16) is bimodal chiefly as a result of the $\delta^{13}C_{DIC}$ characteristics of water from the 28 bedrock-aquifer wells. The modes of the frequency distribution are not related to the origin of the associated methane in well water. The bedrock-aquifer samples in each mode are about equally divided between thermogenic and microbial origins for the methane. For water-well samples with thermogenic-mode gases, there is evidence of a positive linear correlation between $\delta^{13}C_{DIC}$ values and methane concentration in ground water (fig. 17A). For samples with a component of microbial gas, there is a strong positive linear correlation between $\delta^{13}C_{DIC}$ and concentrations of methane (bedrock-aquifer wells) as shown in figure 17C. The $\delta^{13}C_{DIC}$ relations with ANC are not as highly correlated as methane concentration, yet some weak positive linear correlations are evident (figs. 17B and 17D). Aravena and others (1995), describing a similar positive linear correlation for data from a methanogenic aquifer in Canada, concluded that the $\delta^{13}C_{DIC}$ results could not be from inorganic carbon reactions; rather, they were influenced by microbial production of methane. Despite the positive linear correlations with methane concentration and ANC, the $\delta^{13}C_{DIC}$ data provide no new insights on the source of carbon for the methane in ground water. Data for ^{14}C of DIC and for detailed chemical analyses of the ground water are needed to better understand these relations.

The characteristic type of natural gas found in water wells near Tioga Junction may be determined by comparing the isotopic signatures and composition of dissolved- and gas-phase hydrocarbons to samples from possible local sources of natural gas. The analysis approach was to first plot the gas-well and water-well results for $\delta^{13}C_{CH4}$ and δD_{CH4} and then superimpose the boundaries from figure 10.

The isotopic compositions for gas-well samples and water-well samples relative to isotopic compositions that typify thermogenic and microbial gases are shown in figure 18. The

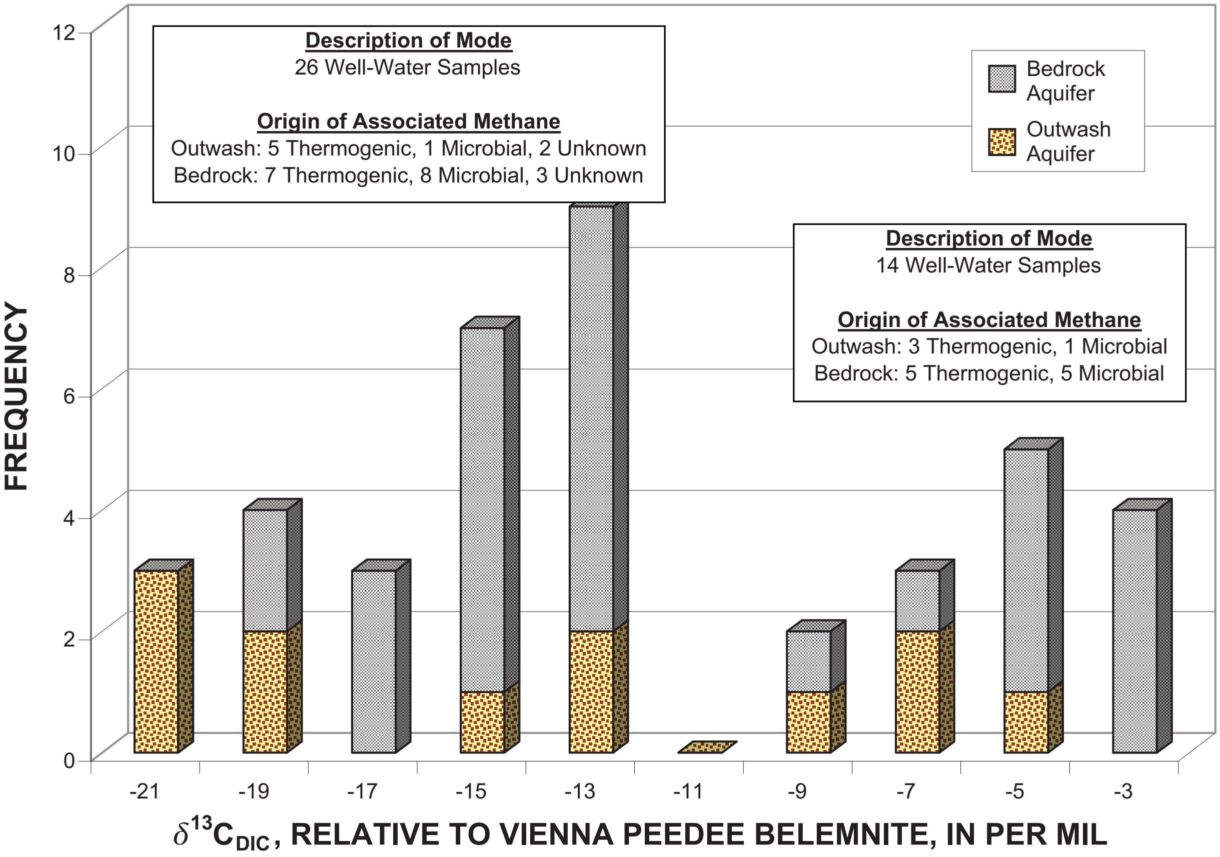


Figure 16. Frequency distribution of $\delta^{13}C_{DIC}$ in ground waters with a description of the origin of associated methane from bedrock- and outwash-aquifer wells near Tioga Junction, Tioga County, Pennsylvania, June-August 2005 (DIC is the abbreviation for dissolved inorganic carbon).

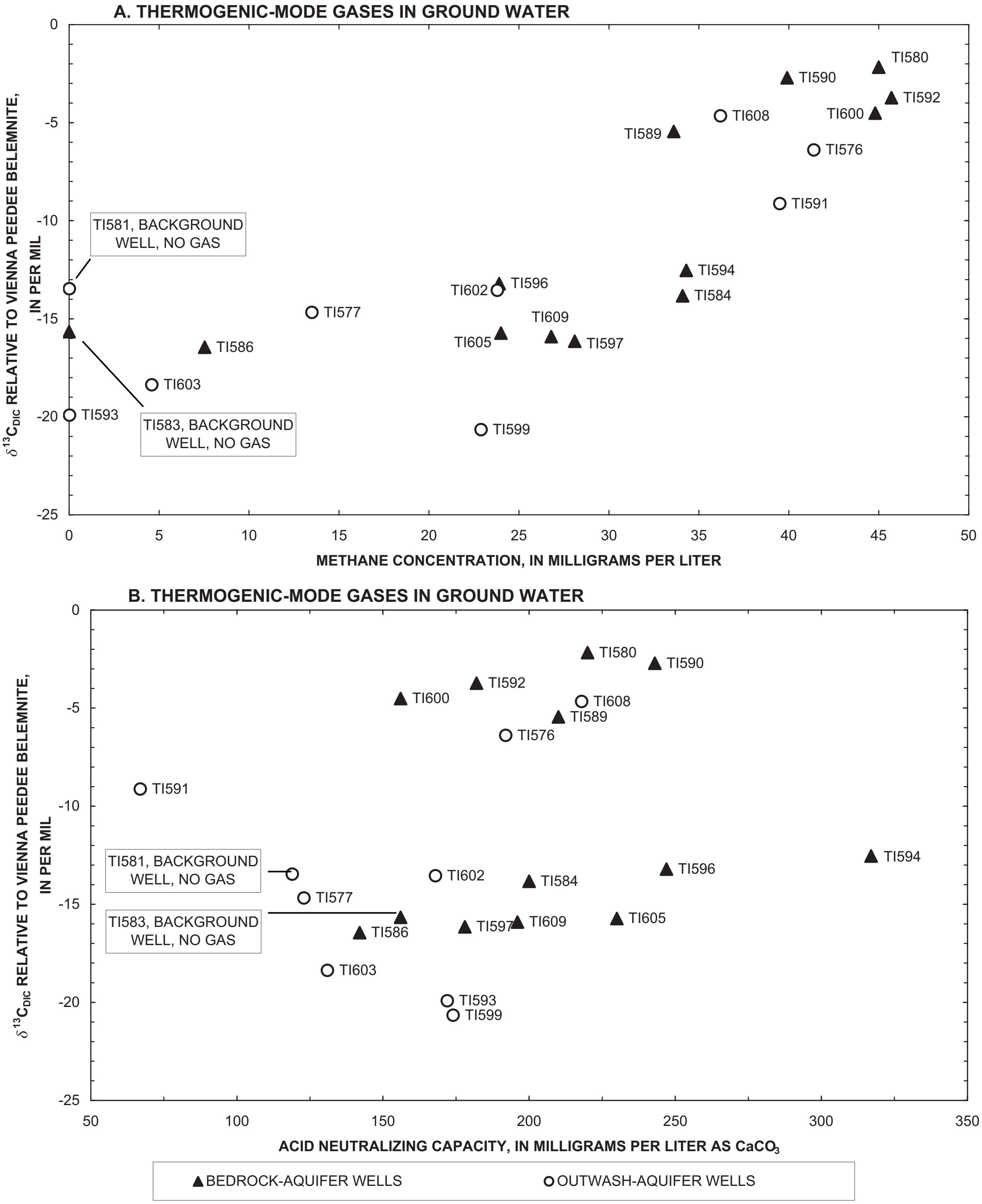


Figure 17. $\delta^{13}C_{DIC}$ as a function of methane concentration and acid neutralizing capacity (ANC) in ground waters with thermogenic (A, B) and microbial (C, D) methane from bedrock- and outwash-aquifer wells near Tioga Junction, Tioga County, Pennsylvania, June-August 2005 (DIC is the abbreviation for dissolved inorganic carbon).

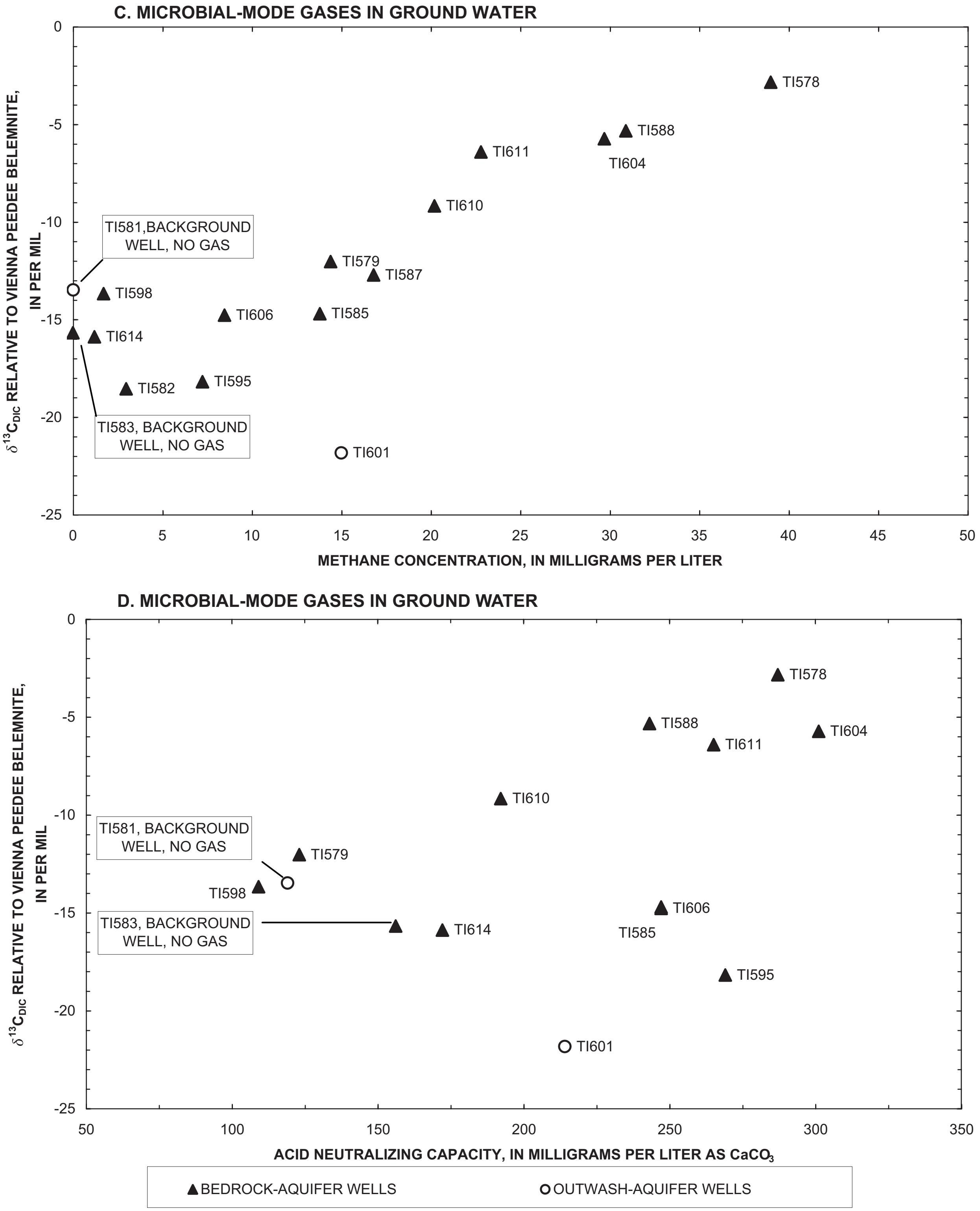


Figure 17. $\delta^{13}C_{DIC}$ as a function of methane concentration and acid neutralizing capacity (ANC) in ground waters with thermogenic (A, B) and microbial (C, D) methane from bedrock- and outwash-aquifer wells near Tioga Junction, Tioga County, Pennsylvania, June-August 2005 (DIC is the abbreviation for dissolved inorganic carbon).—Continued

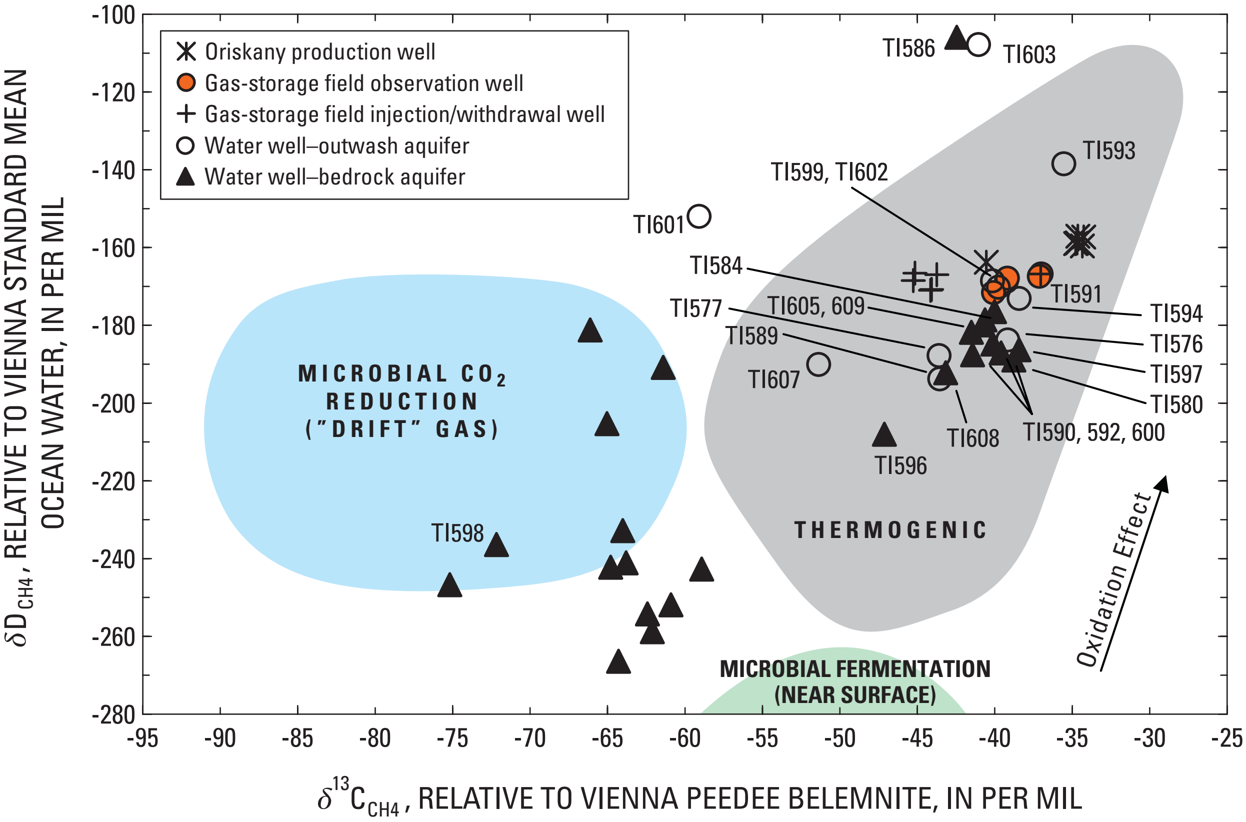


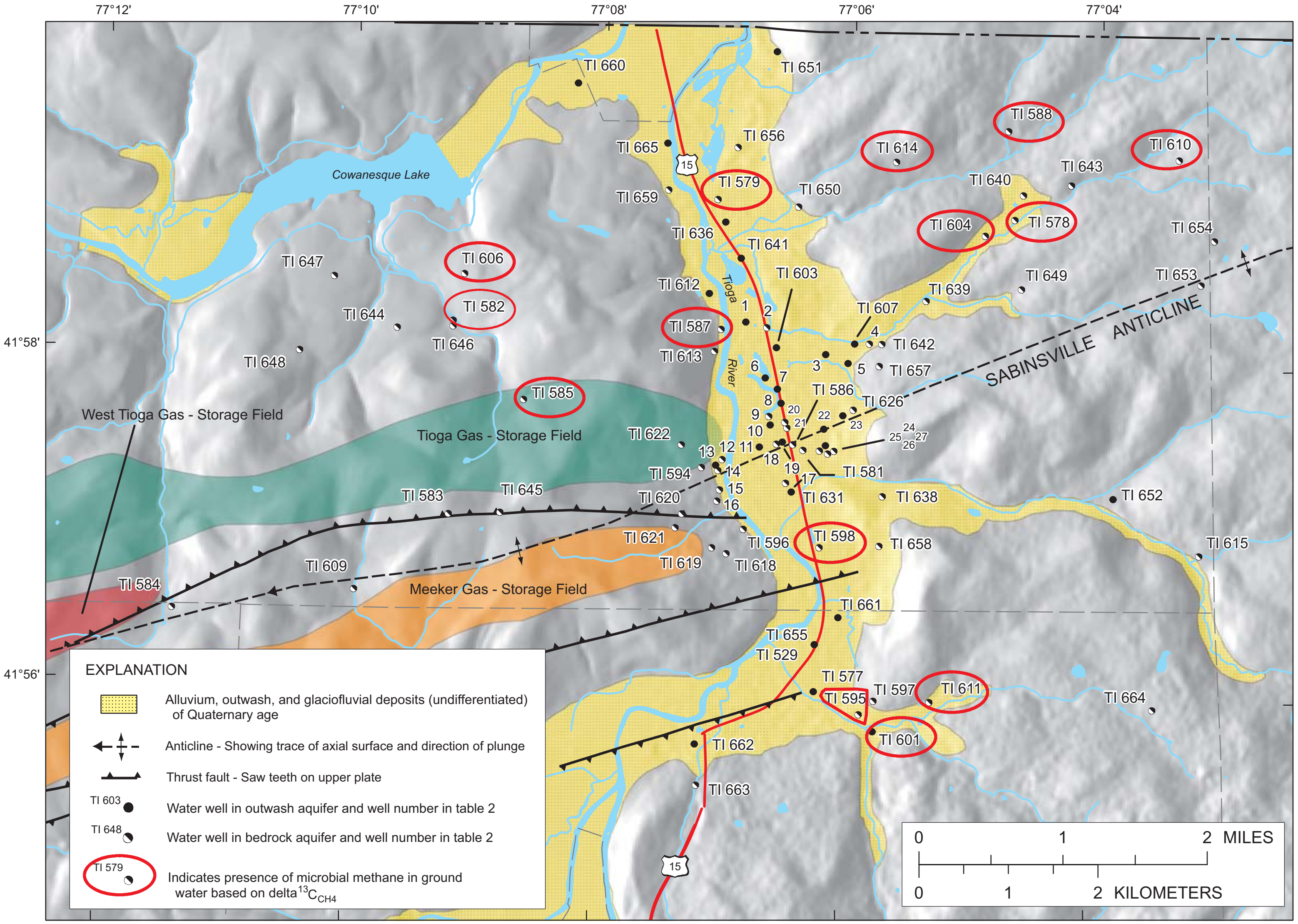
Figure 18. Stable carbon and hydrogen isotopes of methane for water and gas wells near Tioga Junction, Tioga County, Pennsylvania, October 2004-September 2005.

dashed and solid boundaries in the plot approximate the regions of typical ranges of isotopic compositions for thermogenic gas and two types of microbial gas (see fig. 10 or Coleman and others, 1993, p. 309). The plot area used to compare gas-well samples in figure 11 has been expanded; the gas-well results plot in a small area in the thermogenic gas region (fig. 18). Water-well samples are plotted in figure 18 by aquifer type. Isotopic signatures for methane in 19 ground-water samples from water wells fall into the thermogenic-gas region (fig. 18). The 19 samples were from 8 and 11 wells drilled into the outwash and bedrock aquifers, respectively. Bedrock-aquifer results showed scatter but, nevertheless, plotted in two general regions and illustrate the bimodal distributions noted earlier. In the outwash-aquifer samples, only data from wells TI601 and TI603 plotted outside the thermogenic-gas region. None of the ground-water samples in the thermogenic-gas region exhibited isotopic signatures that matched the Oriskany production gas composition determined from the Bolt1 and Krause gas wells. The isotopic composition of the gas in several water samples from the outwash aquifer closely resembled gas composition from samples of storage-field gas from observation wells.

Compositions that fell outside (have lower—more negative— $\delta^{13}C_{CH4}$ values than) the thermogenic-gas region in figure 18 were the 14 samples that make up the -62 per mil mode for $\delta^{13}C_{CH4}$ (see fig. 13A). The 14 samples were from 1 outwash-aquifer well (TI601) and 13 wells drilled into the bedrock aquifer. The isotopic composition of dissolved methane in the samples from these 14 wells was more depleted in the ^{13}C isotope than wells plotting in the thermogenic region and was characteristic of "drift" gas of microbial origin (fig. 10). Outwash or glacial "drift" gas has low $\delta^{13}C_{CH4}$ values because of the shallow depths and low-temperature regime associated with the paleo-environment of these methane precursors and because of depletion in the ^{13}C isotope by microorganisms (Rice and Claypool, 1981). These samples are indicative of a greater fraction of "drift" gas relative to thermogenic gas. For the 13 bedrock-aquifer wells, 5 have mapped glacial deposits overlying the rock and 8 do not. Williams and others (1998) suggest that organic material may be buried in a thin (unmapped) veneer above the rock. This organic material is a possible source for microbial gas in the upland areas.

The spatial distribution of the 14 water wells with the microbial-gas signature is shown in figure 19. Ten of the 14 wells were completed in the bedrock aquifer on the northern flank of the Sabinsville Anticline and represent both valley and upland settings. Outwash-aquifer well TI601 and the other three bedrock-aquifer wells with the microbial-gas signature are located in the Mitchell Creek area of the Tioga River valley.

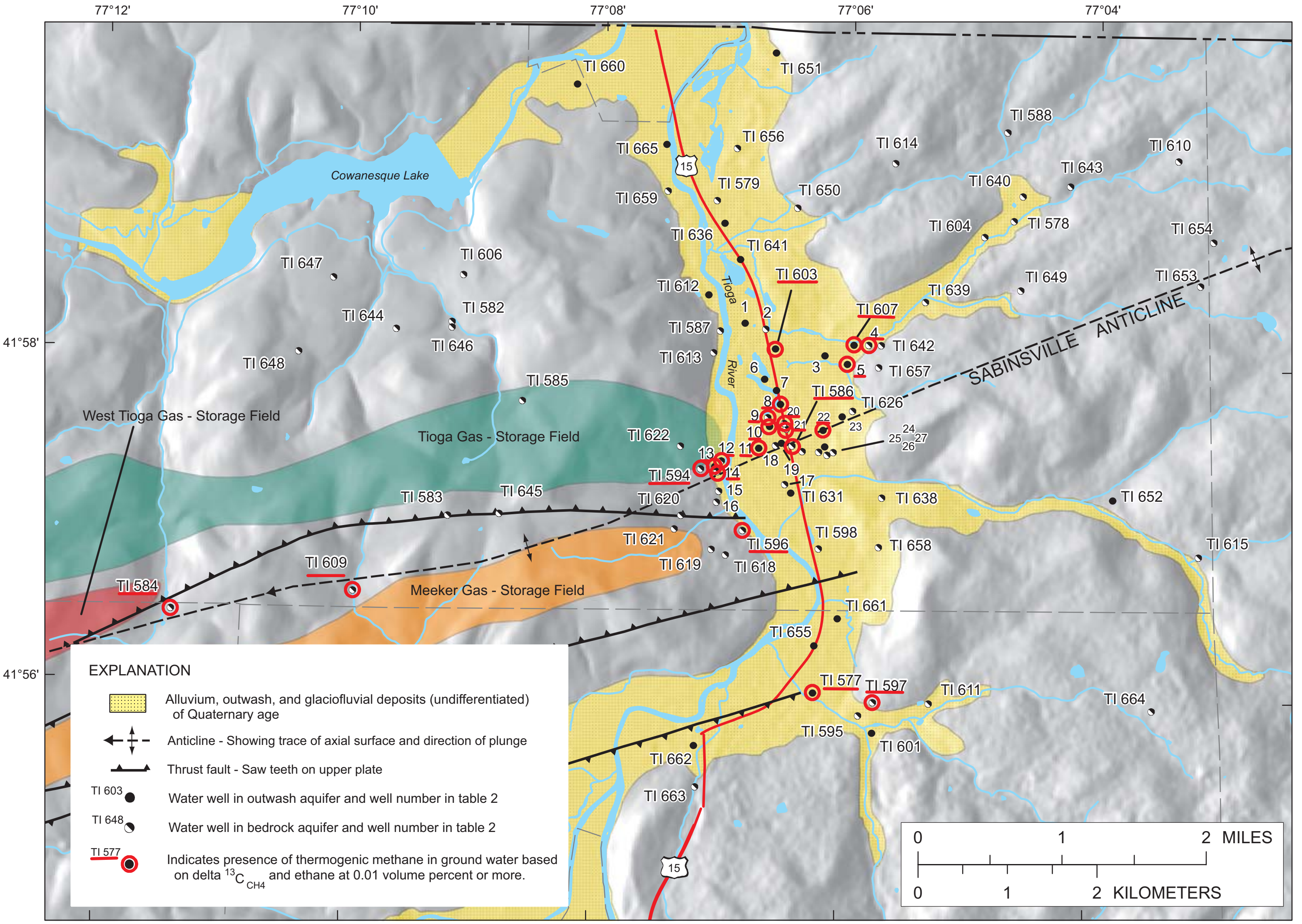
The spatial distribution of the well waters with a thermogenic-gas signature and where gas composition includes an ethane fraction of 0.01 percent or more is shown in figure 20.



Surficial deposits from Commonwealth of Pennsylvania, 1989
Streams from U.S. Geological Survey, 2000
Township boundary and U.S. Routes from Commonwealth of Pennsylvania, 2006
Shaded relief prepared from U.S. Geological Survey National Elevation Dataset, 2004

Base from U.S. Department of Commerce digital data, 1993,
1:100,000 Albers Equal-Area Conic projection: Standard Parallels 29°30' N and 45°30' N,
Central Meridian 77°45' W, Latitude of Origin 23°00' N

Figure 19. Locations of water wells with methane of microbial isotopic composition near Tioga Junction, Tioga County, Pennsylvania, June-August 2005. [Faults shown are mapped at depth in the Oriskany Sandstone. There is no evidence in the hydrogeologic literature for the Tioga Junction area that faults extend to near land surface and into the Lock Haven Formation.]



Surficial deposits from Commonwealth of Pennsylvania, 1989
Streams from U.S. Geological Survey, 2000
Township boundary and U.S. Routes from Commonwealth of Pennsylvania, 2006
Shaded relief prepared from U.S. Geological Survey National Elevation Dataset, 2004

Base from U.S. Department of Commerce digital data, 1993,
1:100,000 Albers Equal-Area Conic projection: Standard Parallels 29°30' N and 45°30' N,
Central Meridian 77°45' W, Latitude of Origin 23°00' N

Figure 20. Locations of water wells with methane of thermogenic isotopic composition and ethane at volume fraction of 0.01 percent or more near Tioga Junction, Tioga County, Pennsylvania, June-August 2005. [Faults shown are mapped at depth in the Oriskany Sandstone. There is no evidence in the hydrogeologic literature for the Tioga Junction area that faults extend to near land surface and into the Lock Haven Formation.]

The majority of wells cluster on the axis of the Sabinsville Anticline at the eastern margin of the Tioga and Meeker gas-storage fields. For the bedrock aquifer, 8 of the 11 samples plotting in the thermogenic-gas region were samples from wells drilled into the bedrock aquifer beneath the Tioga River valley. The remaining three samples were from wells drilled into the bedrock aquifer near upland streams on the ridge above the gas-storage field (TI584 and TI609) or on the upland adjacent to the valley near Mitchell Creek. Glacial overburden is not mapped by Fuller and Alden (1903) or Williams and others (1998) in either of these upland areas. The isotopic data indicate these three wells have chiefly thermogenic gas.

Ground-water samples containing ethane are indicative of thermogenic gas. Ethane composition and $\delta^{13}C_{C2H6}$ values of samples from gas and water wells were further analyzed graphically to infer the origin of methane and ethane in ground water. The concentration of ethane in well water was plotted against $\delta^{13}C_{CH4}$ in figure 21A to identify the distribution of ethane concentrations by aquifer and understand the relation of $\delta^{13}C_{CH4}$ and ethane occurrence in well water compared to the gas-well samples.

The volume fractions of ethane for gas-well and water-well samples range from 1.8 to 2.6 percent and from less than 0.1 to about 1.7 percent, respectively (fig. 21A). The bimodal nature of the $\delta^{13}C_{CH4}$ values is illustrated in figure 21A and suggests a progression of ethane concentrations from near zero to about 0.8 percent for samples in the thermogenic mode. Scatter along and towards the origin of the X axis results from concentrations of ethane that were either nondetectable or are one and two orders of magnitude lower than samples interpreted to be chiefly of thermogenic origin. An unusually high volume fraction of ethane is present in water from shallow well TI594 (bedrock aquifer) just west of Tioga Junction and just south of storage-field observation well TW805. The mixing relations are further illustrated in figure 21B by use of a Bernard graph (Bernard and others, 2001) where the methane to ethane concentration ratio, designated C1/C2, is plotted against $\delta^{13}C_{CH4}$. The unusual character of the gases in well TI594 again put it closest in composition to the thermogenic end members. Water from well TI611—the microbial end member with the most negative $\delta^{13}C_{CH4}$—plots in the upper left of figure 21B.

The relation between $\delta^{13}C_{CH4}$ and $\delta^{13}C_{C2H6}$ results shown previously for gas-well samples in figure 12 is expanded in figure 22 to include 21 water-well samples. Water-well results are plotted by aquifer. Variations in $\delta^{13}C_{CH4}$ results arise chiefly from addition of methane of microbial origin as indicated by the directional arrow on the figure. The anomalous $\delta^{13}C_{CH4}$ value in water from well TI601 suggests a gas mixture that includes gas of microbial origin and gas with an ethane component. Isotopic compositions for 15 of the 21 samples from ground-water wells are mostly intermediate between or identical to the samples of storage-field gas from the I/W wells and the samples of storage-field gas from observation wells. Wells TI593 and TI596 are the outliers in this group. Well TI596 appears to be on a possible mixing line between TI601 and the samples of native Oriskany gas. Five samples plot between the samples of Oriskany observation-well gas (which may have a mix of Oriskany and storage-field gas) and the samples of native Oriskany gas. These five wells (TI576, TI591, TI592, TI600, and TI602) could have a greater fraction of Oriskany gas mixed with storage-field gas or they could contain a "different source" of native gas.

The analyses a) relating field measurements of combustible-gas concentrations in well water and laboratory measurements of methane concentrations in well water, b) showing the occurrence and distribution of methane of microbial and thermogenic origin on maps, and c) plotting stable isotopic compositions for $\delta^{13}C_{CH4}$, δD_{CH4}, and $\delta^{13}C_{C2H6}$ are all consistent in terms of results by aquifer type. There were clustered occurrences and apparent southwest to northeast alignment pattern to the distribution of ground water containing high concentrations of combustible gas, methane, or ethane. The patterns were characterized by high concentrations of thermogenic gas in ground water from outwash and bedrock aquifer wells on or near the axis of the Sabinsville Anticline and high concentrations of microbial gas in ground water from bedrock wells parallel to the axis along the northern flank of the anticline. The thermogenic gases were found chiefly in a 17-well cluster on the axis of the Sabinsville Anticline at the eastern margin of the gas-storage field. From the graphical comparisons, the thermogenic gas in water wells near Tioga Junction is not native Oriskany composition. Storage-field gas is the likely origin and a possible source of the thermogenic gas in water wells near Tioga Junction.

Limitations of the Available Data

Detailed drilling records were not available for many of the inventoried water wells; hence, without expensive and invasive borehole tests, a detailed understanding of the gas occurrence in the aquifers could not be developed using the limited well data. Moreover, the distinction between bedrock and outwash is equivocal. Many of the bedrock wells are completed just below the depth of glacial overburden; a pathway for gas migration may include movement through the glacial overburden to the fractured-rock zone to the well.

Multiple samples from a single well are important for understanding variability in gas characteristics over time. This was accomplished to a limited degree with the gas-well samples and I/W well results that exhibited some variability in composition. Combustible-gas measurements, when compared between visits to the same water wells during May through August 2005, ranged from remarkably similar to widely disparate. One well water (TI615) had combustible gas detected in July and did not have combustible gas in August. Given the transient nature of field pressures and the variation in source of injection gases at the storage fields, such variability was expected. This variability might also be expected because 1) gas-migration pathways are from areas of high pressure to low pressure, such as water wells; 2) the migration of dissolved methane in ground water is influenced by the pumping of private water-supply wells;

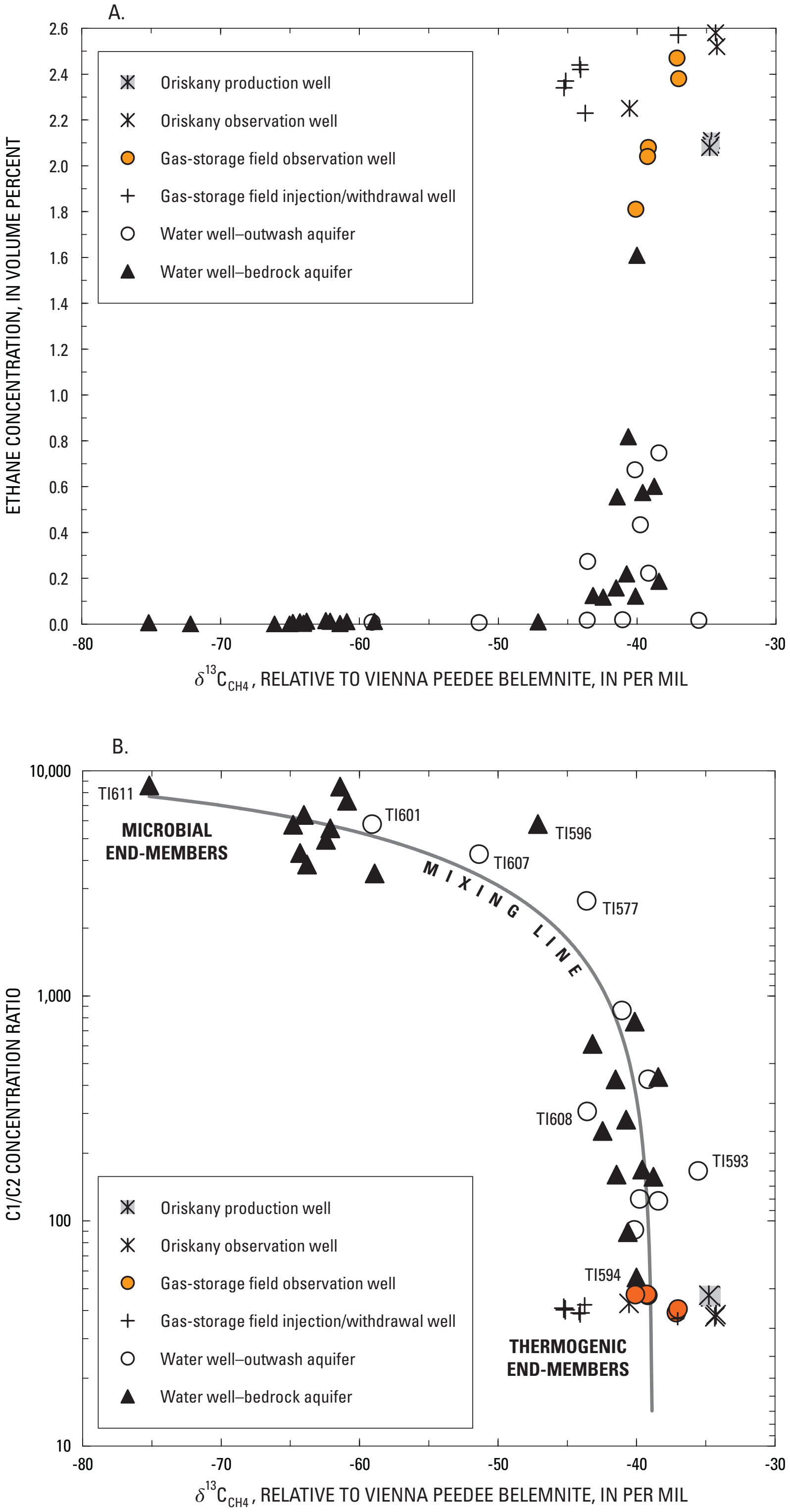


Figure 21. The $\delta^{13}C$ of methane for gas-well and water-well samples collected June-September 2005 near Tioga Junction, Tioga County, Pennsylvania in relation to A) ethane concentrations and B) the ratios of methane concentration to ethane concentration (Bernard diagram).

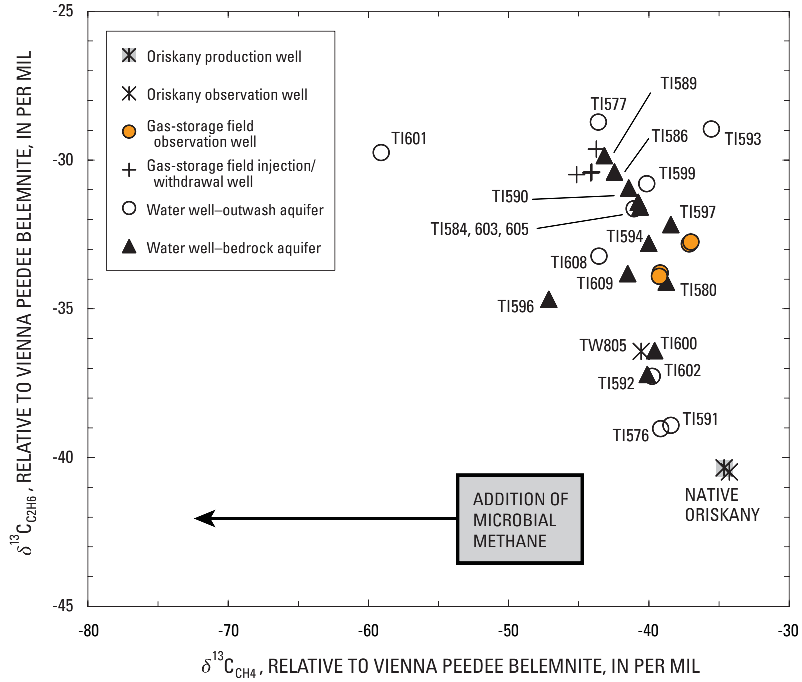


Figure 22. The $\delta^{13}C$ of methane and ethane for gas-well and water-well samples collected June-September 2005, Tioga Junction and vicinity, Tioga County, Pennsylvania.

3) reservoir or storage-field pressures driving gas flow are higher than hydraulic-head pressures driving water flow; and 4) gas diffuses more readily than water through porous media.

There were no repeat samples for isotopic measurements on water wells. Nevertheless, the narrow time window of isotopic sampling from June 28 to August 11, 2005, provides a representative snapshot of ground-water conditions.

Compositional and isotopic data are missing for two possible end-member gases. With storage-field and Oriskany gases characterized, the lack of data for a native shallow Devonian gas and "old" injection gas places limits on making firm conclusions about the origin and source of the methane in ground water. The storage-field I/W well samples are only a snapshot of the storage-field composition. Storage-field wells used for observation may have "old" injection gas or mixtures of multiple vintages, sometimes mixed with native gas. The possibility of three or more end-member compositions and many possible mixing scenarios for gases also complicate the data interpretation. The use of multiple lines of evidence is important in studies with these types of complications. Isotopic data provides powerful geochemical evidence as to the origin of the stray gas, however, it is important to consider and evaluate other lines of evidence to support the conclusion. The multiple-lines-of-evidence approach has been demonstrated herein.

Summary

As of 2005, methane gas was leaking into water wells near Tioga Junction, Tioga County, north-central Pa. State oil and gas inspectors found water from household-supply wells with concentrations of dissolved methane as high as 92 mg/L, which greatly exceeds the solubility of methane in water. Concentrations of this magnitude result in outgassing of methane and provide the possibility of accumulation of methane and subsequent explosion with the potential for substantial property damage and loss of life. The origin of the methane was investigated by the U.S. Geological Survey in cooperation with the Pennsylvania Department of Environmental Protection (PADEP) in an area of about 50 mi^2, using compositional and isotopic characteristics of methane and ethane in gas and water wells. This report presents the results from October 2004 to September 2005.

Ground water for rural-domestic supply and other uses near Tioga Junction is from two aquifer systems in and adjacent to the Tioga River valley. An unconsolidated aquifer of outwash sand and gravel of Quaternary age underlies the main river valley and extends into the valleys of tributaries. Fine-grained lacustrine sediments separate shallow and deep water-bearing zones within the outwash. Outwash-aquifer wells are seldom deeper than 100 ft. The river-valley sediments and uplands adjacent to the valley are underlain by a fractured-bedrock aquifer in siliciclastic rocks of Devonian age, primarily the Lock Haven

Formation. Most bedrock-aquifer wells produce water from the Lock Haven Formation at depths of 250 ft or less.

A review of previous geologic investigations was used to establish the structural geologic framework and identify four plausible origins of the natural gas. The Sabinsville Anticline, trending southwest to northeast, is the major structural feature in the Devonian bedrock. The anticline, a structural trap for a reservoir of deep native gas in the Oriskany Sandstone (origin 1) at depths of about 3,900 ft, was explored and tapped by numerous wells from 1930-60. The gas reservoir in the vicinity of Tioga Junction, depleted of native gas, was converted to the Tioga gas-storage field for injection and withdrawal of non-native gases (origin 2). Devonian shale gas (shallow native gas) also has been reported in the area (origin 3). Gas might also originate as outwash or glacial "drift" gas generated from buried and decomposed organic material in the outwash deposits (origin 4).

During May to August 2005, a combustible-gas inventory of 91 water wells (62 in the bedrock aquifer and 27 in the outwash aquifer) yielded 49 positive readings (greater than or equal to 0.1 percent) in the headspace of water samples (36 from wells completed in bedrock and 13 from wells completed in outwash). The percentage of combustible gas as measured in the headspace of ground-water samples collected in the vicinity of Tioga Junction, when multiplied by a factor of three, gave an approximation of the concentration of methane dissolved in ground water in milligrams per liter. High combustible-gas readings corresponded with methane concentrations in water greater than 10 mg/L; the occurrence was in clusters in the central and southern parts of the study area, and the largest cluster was near the eastern boundary of the gas-storage field. Southwest- to northeast-trending bands of occurrence characterized the northern flank of the Sabinsville Anticline.

A detailed gas-sampling effort from June 2005 to August 2005 focused on 39 water wells with the highest gas concentrations representing the bedrock aquifer (27 wells) and the outwash aquifer (12 wells). Detailed gas sampling also included 8 selected gas wells that were sampled twice—three wells producing native gas from the Oriskany Sandstone and five wells (two observation wells and three injection/withdrawal wells) with non-native gas from the gas-storage field. These data were combined with data collected earlier from the same wells by PADEP. Chemical composition of gas, stable carbon and hydrogen isotopes of methane ($\delta^{13}C_{CH4}$ and δD_{CH4}), and stable carbon isotopes of ethane ($\delta^{13}C_{C2H6}$) were analyzed. Isotopes are reliable indicators of the origin of different gases, whether thermogenic or microbial. No samples could be collected to document the composition of "drift" gas or of native natural gas originating solely in Devonian shale at depths more shallow than the Oriskany Sandstone, although two of the storage-field observation wells sampled reportedly yield some Devonian shale gas. Literature values for outwash or "drift" and Devonian shale gases were used to supplement the data collection.

Non-native gases from wells in the gas-storage field and native gases from wells producing from the Oriskany Sandstone were similar in chemical composition; methane (volume fraction ranging from 94.5 to 97.2 percent) and ethane (volume fraction ranging from 2.0 to 2.6 percent) were predominant. Isotopic-composition data for storage-field gases (median $\delta^{13}C_{CH4}$ of about -44.1 per mil, δD_{CH4} of -168 per mil, and $\delta^{13}C_{C2H6}$ of -32.7 per mil) were different than gases from the Oriskany Sandstone (median $\delta^{13}C_{CH4}$ of -34.6 per mil, δD_{CH4} of -159 per mil, and $\delta^{13}C_{C2H6}$ of -40.4 per mil). The Oriskany Sandstone and the storage-field gases were thermogenic, but of different origins. The $\delta^{13}C_{CH4}$, δD_{CH4}, and $\delta^{13}C_{C2H6}$ differences are because the Oriskany gas is more thermally mature than the storage-field gas and is more enriched in ^{13}C and ^{2}H. Compositions of gases from storage-field observation wells were intermediate to, and likely relate to mixing of, native gases from the Oriskany Sandstone and non-native gases from the storage-field injection/withdrawal wells. One depleted Oriskany gas well (TW805) that is approximately 500 ft northeast of the eastern boundary of the storage field and is used as an observation well for the storage field yielded about a 50:50 mixture of Oriskany gas and storage-field gas. This provided an initial line of evidence that there was some gas leaking and migrating from the eastern boundary of the storage field toward well TW805.

Chemical and stable-isotope characteristics of water-well samples with and without combustible gas were compared by aquifer. Bedrock-aquifer waters with gas exhibited the largest range and the largest median conductivity. The median pH of 6.8 for outwash-aquifer water without gas was the most acidic; the presence of gas seemed to be associated with a buffering effect. This relation also held for bedrock-aquifer waters with and without combustible gas, although the differences in median pH were less pronounced.

Dissolved oxygen and Eh data provided evidence of a geochemical environment in the aquifers that was not oxygenated. Waters with combustible gas had lower median Eh and dissolved oxygen compared to waters without gas, regardless of aquifer. The lack of dissolved oxygen is conducive to anaerobic microbial reduction of sulfate to hydrogen sulfide and carbon dioxide to methane. During well-water sampling, the odor of hydrogen sulfide or "sulfur smell" was common and provided evidence of sulfate reduction by bacteria under conditions of low dissolved oxygen.

Stable-isotope ratios for hydrogen and oxygen of ground water in bedrock (26 samples) and outwash (10 samples) aquifers were not different for wells with and without combustible gas and did not correlate with gas concentrations. When δD_{water} was plotted against $\delta^{18}O_{water}$ for Tioga Junction ground water and compared to typical river water in north-central Pennsylvania, the ground water composition was similar to that of nearby river waters. There is no strong evidence that the waters from one or both aquifers are isolated from recent recharge or represent Pleistocene-age water or water originating from a high-altitude or cold-environment source. The stable isotopes of water provided no additional information on gas occurrence or origin.

Methane and ethane were the only hydrocarbons detected at reportable concentrations in 37 and 32, respectively, of 37 water-well samples analyzed. The range of methane as a volume fraction in headspace gases ranged from 0.0066 to 94.4 percent; ethane ranged from 0.003 to 1.61 percent. Of the 35 wells with isotopic data for methane, 10 were completed in the outwash aquifer, and 25 were completed in the bedrock aquifer. The range in $\delta^{13}C_{CH4}$ for ground water was from -35.54 per mil (well TI593, outwash aquifer) to -75.18 per mil (well TI611, bedrock aquifer). The range of δD_{CH4} in ground water was from -105.9 per mil (well TI586, bedrock aquifer) to -266.4 per mil (well TI610, bedrock aquifer). There was a bimodal distribution of δD_{CH4} results with modes at about -180 and -250 per mil. The -250 per mil mode appears related to microbial gases, and the -180 per mil mode is related to thermogenic gases. The $\delta^{13}C_{CH4}$ values in well waters had a bimodal distribution with modes at -65 per mil (14 wells) and -40 per mil (21 wells). Gas in water samples from the 14 wells appears to have had a small measure of microbial gas (outwash or "drift" gas) in the isotopic signature as determined for well-water samples by ^{14}C content of methane. The amount of ^{14}C was low, an indication that the microbial gas represented a minor component relative to the other gases in the ground water. The microbial gases were found chiefly in bedrock-aquifer well waters; 10 wells representing upland and valley settings were located along the northern flank of the Sabinsville Anticline. Data for $\delta^{13}C$ of dissolved inorganic carbon give support to microbial processes contributing to the methane in these bedrock-aquifer wells; however, the data provided no new insights on the origin of the carbon in the methane.

Microbial gases typically do not contain ethane. The waters with microbial gases contained only traces of ethane (volume fraction of 0.01 percent or less). The trace ethane concentrations were too small for determination of $\delta^{13}C_{C2H6}$. For waters with ethane, the $\delta^{13}C_{C2H6}$ ranged from -28.73 to -39.03 per mil in a unimodal distribution; the median was -32.17 per mil. Waters from the 21 wells in the -40 per mil mode for $\delta^{13}C_{CH4}$ were thermogenic. The δD_{CH4} and $\delta^{13}C_{C2H6}$ values for the 21 samples also were thermogenic.

The thermogenic gases were found chiefly in a 17-well cluster on the axis of the Sabinsville Anticline at the eastern margin of the gas-storage field. This cluster corresponds with the cluster of wells with high concentrations of methane from the combustible-gases inventory. An observation well for the gas-storage field, TW805, is nearest to the cluster, and three water wells in the cluster had gases that nearly match the gas composition in TW805. This is evidence that the gas mixture in observation well TW805 was also migrating to ground-water wells.

All the water wells had gas signatures indicating mixing of gases from different origins; however, the overall isotopic composition of methane and ethane showed that the gas in water wells at the eastern margin of the gas-storage field is mostly thermogenic. The $\delta^{13}C_{CH4}$ and $\delta^{13}C_{C2H6}$ values of the majority of thermogenic gases from water wells either matched or were intermediate between the samples from storage-field gas injection/withdrawal wells and the samples from storage-field gas observation wells.

Proximity to the axis of the Sabinsville Anticline and the eastern margin of the gas-storage field corresponded to the presence of thermogenic gas in water wells. It is not known why certain wells had microbial gas and others did not. Detailed drilling records were not available for many of the inventoried water wells; hence, without expensive and invasive borehole tests, a detailed understanding of the gas occurrence in the aquifers could not be developed using the limited well data. Well depth was a factor in the observed occurrence of combustible gas for the 62 bedrock wells inventoried. As well-depth range increased from less than 50 ft to 51-150 ft to greater than 151 ft, the percentage of wells with combustible gas increased. On the basis of the known geology and the aquifer framework in the Tioga River valley, the presence of clay-rich layers formed by lacustrine deposits probably plays a role in keeping gas migration confined to the deep water-bearing zones of the outwash aquifer and the underlying bedrock aquifer. Of 11 shallow wells inventoried (with depths of 50 feet or less) in the Tioga River valley, 2 had ground waters with combustible-gas percentages greater than 0.1 percent. These 11 wells likely tap the shallow water-bearing zones of the outwash aquifer. Of 18 wells with depths greater than 50 ft inventoried in the Tioga River valley, 10 had waters with combustible-gas percentages greater than 0.1 percent.

Isotopic signatures have been used successfully in this study to help discern the origin of the gases in water wells near Tioga Junction. The thermogenic gas found in water wells does not match the composition of native gas from the Oriskany Sandstone. Mixing of Oriskany gases with storage-field gases is occurring, and there is also evidence for mixing of a microbial component of gas in some water wells. The possibility of three or more end-member compositions and many possible mixing scenarios for gases complicate the data interpretation. The limited numbers of storage-field gas samples place limits on making firm conclusions about the origin of the methane in ground water. The weight of the evidence, however, points to storage-field gas as the likely origin of the thermogenic gas found in water wells near Tioga Junction.

Acknowledgments

The authors wish to acknowledge the assistance and support given by the staff of the Pennsylvania Department of Environmental Protection Bureau of Oil and Gas Management office in Meadville, Pa. In particular, Robert Gleeson, Paul Kucsma, Craig Lobins, Christine Miner, Robert Sterba, and Douglas Welsh provided data and sources of hydrologic, geologic, and isotopic data; and information about the gas wells. The authors also thank Dominion Gas Company, Pennsylvania Power and Light, and Potter McKean Resources Company for permission to sample their gas wells. The study could not have been completed without the cooperation of the 91 local residents who granted permission to sample their water wells. The authors are most grateful for constructive reviews of earlier drafts of the manuscript by Dennis D. Coleman of Isotech Laboratories, Inc., and Tyler B. Coplen, Allan Kolker, Curtis L. Schreffler, Kim L. Otto, and Lisa A. Senior, all of the USGS. Scott A. Hoffman and Denis K. Sun of the USGS provided expert assistance with preparation of maps and figures.

References Cited

Aravena, R., Wassenaar, L.I., and Plummer, L.N., 1995, Estimating ^{14}C groundwater ages in a methanogenic aquifer: Water Resources Research, v. 31, no. 9, p. 2307-2317.

Baldassare, F.J., and Laughrey, C.D., 1997, Identifying the sources of stray methane by using geochemical and isotopic fingerprinting: Environmental Geosciences, v. 4, no. 2, p. 85-94.

Beardsley, R.W., Campbell, R.C., and Shaw, M.A., 1999, Appalachian plateaus, *in* Schultz, C.H., ed., The geology of Pennsylvania--Chapter 20: Pennsylvania Geological Survey Special Publication 1, p. 286-297.

Bernard, B.B., Brook, J.M., and Zumberge, J., 2001, Determining the origin of gases in near-surface sediments: AAPG Hedberg Conference, September 16-19, 2001, Vancouver, BC, Canada.

Burruss, R.C., and Laughrey, C.D., 2006, Stable isotopic constraints on abiogenic hydrocarbon gas: EOS Transactions. American Geophysical Union, v. 87, no. 36, Joint. Assembly Supplement, Abstract U24A-02.

Busenberg, E., Plummer, L.N., Bartholomay, R.C., and Wayland, J.E., 1998, Chlorofluorocarbons, sulfur hexafluoride, and dissolved permanent gases in ground water from selected sites in and near the Idaho National Engineering and Environmental Laboratory, Idaho, 1994-97: U.S. Geological Survey Open-File Report 98-274, 72 p.

Cathcart, S.H., and Myers, T.H., 1934, Gas in Tioga County, Pennsylvania: Pennsylvania Geological Survey, Bulletin 107, 42 p.

Chafin, D.T., 1994, Sources and migration pathways of natural gas in near-surface ground water beneath the Animas River valley, Colorado and New Mexico: U.S. Geological Survey Water-Resources Investigations Report 94-4006, 56 p.

Chafin, D.T., Swanson, D.M., and Grey, D.W., 1996, Methane-concentration and methane-isotope data for ground water and soil gas in the Animas River valley, Colorado and New Mexico, 1990-91: U.S. Geological Survey Water-Resources Investigations Report 93-4007, 49 p.

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

Claypool, G.E., Threlkeld, C.N., and Bostick, N.H., 1978, Natural gas occurrence related to regional thermal rank of organic matter (maturity) in Devonian rocks of the Appalachian basin: U.S. Department of Energy, Preprints, 2nd eastern Gas Shales Symposium, v. 1 (Metc/SP-78/6), p. 54-65.

Coleman, D.D., 1994, Advances in the use of geochemical fingerprinting for gas identification: American Gas Association, Operating Section Proceedings, p. 711-720.

Coleman, D.D., Liu, C.L., Hackley, K.C., and Benson, L.J., 1993, Identification of landfill methane using carbon and hydrogen isotope analysis: Proceedings of Sixteenth International Madison Waste Conference, University of Wisconsin, September 22-23, 1993, p. 303-314.

Coleman, D.D., Liu, C.L., Hackley, K.C., and Pelphrey, S.R., 1995, Isotopic identification of landfill methane: Environmental Geosciences, v. 2, no. 2, p. 95-103.

Coleman, D.D., Meents, W.F., Liu, C.L., and Keogh, R.A., 1977, Isotopic identification of leakage gas from underground storage reservoirs—A progress report: Illinois State Geological Survey, Illinois Petroleum No. 111, 10 p.

Commonwealth of Pennsylvania, 1989, Surficial materials of Pennsylvania: Map 64, W.D. Sevon, compiler, 1 pl., scale 1:2,000,000.

Consolidated Gas Supply Corporation, 1970, Tioga east storage pool—Oriskany sand in Lawrence and Farmington Townships, Tioga County, Pa.: Map dated May 1970 on file at Pa. Department of Environmental Protection Bureau of Oil and Gas Management, 1 sheet.

Coplen, T.B., Böhlke, J.K., DeBièvre, P., Ding, T., Holden, N.E., Hopple, J.A., Krouse, H.R., Lamberty, A., Peiser, H.S., Révész, K., Rieder, S.E., Rosman, K.J.R., Roth, E., Taylor, P.D.P., Vocke, Jr., R.D., and Xiao, Y.K., 2002, Isotope-abundance variations of selected elements: Pure Applied Chemistry, v. 74, no. 10, p. 1987-2017.

Coplen, T.B., Wildman, J.D., and Chen, J., 1991, Improvements in the gaseous hydrogen-water equilibration technique for hydrogen isotope ratio analysis: Analytical Chemistry, v. 63, p. 910–912.

Craig, H., 1953, The geochemistry of the stable carbon isotopes: Geochimica et Cosmochimica Acta, v. 3, p. 53-92.

Deines, P., 1980, The isotopic composition of reduced organic carbon, chap. 9 *of* Fritz, P., and Fontes, J., eds., Handbook of environmental isotope geochemistry, volume 1—the terrestrial environment, A: Elsevier, New York, p. 329-406.

Eltschlager, K.K., Hawkins, J.W., Ehler, W.C., and Baldassare, Fred, 2001, Technical measures for the investigation and mitigation of fugitive methane hazards in areas of coal mining: Office of Surface Mining Reclamation and Enforcement, 125 p.

Epstein, S., and Mayeda, T., 1953, Variation of O-18 content of water from natural sources: Geochimica et Cosmochimica Acta, v. 4, p. 213-224.

Fontes, J., 1980, Environmental isotopes in groundwater hydrology, chap. 3 of Fritz, P., and Fontes, J., eds., Handbook of environmental isotope geochemistry, volume 1—The terrestrial environment, A: Elsevier, New York, p. 75-140.

Fuller, M.L., and Alden, W.C., 1903, Description of the Elkland and Tioga quadrangles, Pennsylvania: U.S. Geological Survey Geologic Folio No. 93, 9 p. with 8 map sheets.

Gat, J.R., and Gonfiantini, R., eds., 1981, Stable isotope hydrology, deuterium and oxygen-18 in the water cycle: Vienna, International Atomic Energy Agency, 339 p.

Gonfiantini, R., 1978, Standards for stable isotope measurements in natural compounds: Nature, v. 271, p. 534-536.

Harper, J.A., 1999, Devonian, *in* Schultz, C.H., ed., The Geology of Pennsylvania--Chapter 7: Pennsylvania Geological Survey Special Publication 1, p. 108-127.

Hem, J.D., 1985, Study and interpretation of the chemical characteristics of natural water: U.S. Geological Survey Water-Supply Paper 2254, 263 p.

Isotech Laboratories, Inc., 2005, Instrumentation: accessed November 23, 2005, at *http://isotechlabs.com/*

Jenden, P.D., Drazan, D.J., and Kaplan, I.R., 1993, Mixing of thermogenic natural gases in Northern Appalachian Basin: American Association of Petroleum Geologists Bulletin, v. 77, no. 6, p. 980-998.

Kaplan, I.R., Galperin, Y., Lu, S., and Lee, R., 1997, Forensic environmental geochemistry—Differentiation of fuel-types, their sources and release times: Organic Geochemistry, v. 27, no. 5/6, p. 289-317.

Keech, D.K., and Gaber, M.S., 1982, Methane in water wells: Water Well Journal, February, p. 33-36.

Kendall, C., and Coplen, T.B., 2001, Distribution of oxygen-18 and deuterium in river waters across the United States: Hydrological Processes, v. 15, p. 1363-1393.

Laughrey, C.D., 1999, Silurian and transition to Devonian, *in* Schultz, C.H., ed., The geology of Pennsylvania--Chapter 6: Pennsylvania Geological Survey Special Publication 1, p. 91-107.

Laughrey, C.D., and Baldassare, F.J., 1998, Geochemistry and origin of some natural gases in the Plateau Province, Central Appalachian Basin, Pennsylvania and Ohio: American Association of Petroleum Geologists Bulletin, v. 82, no. 2, p. 317-335.

Laughrey, C.D., and Baldassare, F.J., 2003, Some applications of isotope geochemistry for determining sources of stray carbon dioxide gas: Environmental Geosciences, v. 10, no. 3, p. 107-122.

Lohman, S.W., 1939, Ground water in north-central Pennsylvania: Pennsylvania Geological Survey, 4th ser., Water Resource Report 6, 219 p.

Luce, P.B., and Edmunds, W.E., 1981, Economic geology of Tioga and Bradford Counties: Guidebook for the 46th Annual Field Conference of Pennsylvania Geologists, p. 57-74.

Lytle, W.S., 1963, Underground gas storage in Pennsylvania: Pennsylvania Geological Survey, 4th ser., Mineral Resource Report M46.

McCrea, J.M., 1950, On the isotopic chemistry of carbonates and a paleotemperature scale: Journal of Chemical Physics, v. 18, p. 849-857.

Norris, S.E., 1978, Hydrologic environment of the Silurian salt deposits in parts of Michigan, Ohio and New York: U.S. Geological Survey Open-File Report 78-684, 31 p.

Révész, K., Coplen, T.B., Baedecker, M.J., Glynn, P.D., and Hult, M., 1995, Methane production and consumption monitored by stable H and C isotope ratios at a crude oil site, Bemidji, Minnesota: Applied Geochemistry, v. 10, no. 5, p. 505-516.

Rice, D.D., and Claypool, G.E., 1981, Generation, accumulation, and resource potential of biogenic gas: American Association of Petroleum Geologists Bulletin, v. 65, p. 5-25.

Rowe, D., and Muehlenbachs, K., 1999, Isotopic fingerprinting of shallow gases in the Western Canadian sedimentary basin—Tools for remediation of leaking heavy oil wells: Organic Geochemistry, v. 30, p. 861-871.

Sevon, W.D., 2000, Physiographic provinces of Pennsylvania: Pennsylvania Geologic Survey, 4th Series, Map 13, 4th ed., scale 1:2,000,000.

Schoell, M., 1980, The hydrogen and carbon isotopic composition of methane from natural gases of various origins: Geochimica et Cosmochimica Acta, v. 44, p. 649-661.

Schoell, M., 1983, Genetic characteristics of natural gases: American Association of Petroleum Geologists Bulletin, v. 67, no. 12, p. 2225-2238.

Susquehanna River Basin Commission, 1996, Application 19960303 NE Hub Partners, L.P. Tioga Natural Gas Storage Project: approval docket for water withdrawal dated March 14, 1996, 4 p.

Taylor, L.E., Werkheiser, W.H., and Kriz, M.L., 1983, Groundwater resources of the West Branch Susquehanna River Basin, Pennsylvania: Pennsylvania Geological Survey, 4th ser., Water Resource Report 56, 143 p.

U.S. Geological Survey, 2000, The National Hydrography Dataset [online]: accessed January 3, 2006, at *http://nhd.usgs.gov/chapter1/index.html.*

U.S. Geological Survey, 2001, Digital line graphs: U.S. Geological Survey data available on the web, accessed January 2006, at *http://edc.usgs.gov/deodata*.

U.S. Geological Survey, 2004, National elevation dataset: U.S. Geological Survey data available on the web, accessed January 2006, at *http://ned.usgs.gov/*.

U.S. Geological Survey, variously dated, National field manual for the collection of water quality data: U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chaps. A1-A9, available online at *http://pubs.water.usgs.gov/twri9A*.

Whiticar, M., 1986, Biogenic methane formation in marine and freshwater environments – CO2 reduction versus acetate fermentation – isotope evidence: Organic Geochemistry, 10, p. 759-768.

Wiese, K., and Kvenvolden, K.A., 1993, Introduction to microbial and thermal methane, in Howell, D.G., Wiese, K., Fanelli, M., Zink, L., and Cole, F., eds., The future of energy gases: U.S. Geological Survey Professional Paper 1570, p. 13-20.

Wilde, F.D., Radtke, D.B., Gibs, Jacob, and Iwatsubo, R.T., eds., April 2004, Processing of water samples (version 2.1): U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chap. A5.6.3, accessed April 22, 2005, at *http://water.usgs.gov/owq/FieldManual/chapter5/html/5.6.3.html*.

Williams, J.H., Taylor, L.E., and Low, D.J., 1998, Hydrogeology and groundwater quality of the glaciated valleys of Bradford, Tioga, and Potter Counties, Pennsylvania: Pennsylvania Geological Survey, 4th ser., Water Resource Report 68, 89 p.

Wyrick, G.G., and Borchers, J.W., 1981, Hydrologic effects of stress-relief fracturing in an Appalachian valley: U.S. Geological Survey Water-Supply Paper 2177, 51 p.

Table 2. Water wells inventoried, well records, and associated water-quality field characteristics data, Tioga Junction and vicinity, Tioga County, Pennsylvania.

[Inventory by U.S. Geological Survey (USGS). USGS local well number consists of a county prefix (TI=Tioga) and a well number. In the central Tioga River valley, inventoried wells were too close together for the local well number to be used on maps. Instead, a cross-reference number from 1 to 27 was used on maps and the cross-reference number is listed in parentheses following the local well number. Aquifer type: outwash, well completed in unconsolidated valley-fill deposits; outwashT, test well drilled through valley-fill deposits to bedrock; bedrock, well completed in Lock Haven Formation. Topographic setting: H, hilltop; S, hillside; V, valley; W, upland draw. Letter code associated with well depth is source of depth data: D, driller; O, owner; S, USGS. Other abbreviations—ft bls, feet below land surface; IT, incremental titration; mg/L, milligrams per liter, °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25°C; mV, millivolts; N, no; Y, yes; <, less than; > greater than; NA, not applicable; NC, not collected. A few samples have data missing for some field characteristics because of meter malfunctions.]

USGS local well number (and cross reference on fig. 4)	Inventory date[1]	Aquifer type	Topographic setting	Well depth (ft bls)	Water level (ft bls)	Sulfur smell	Outgassing	Combustible gas (percent)	Temperature (°C)
TI214	5/17/1974	outwash	V	30	12	NC	NC	NC	NC
TI215	6/11/1974	outwash	V	33	12	NC	NC	NC	NC
TI228	7/20/1981	outwash	V	137	120	NC	NC	NC	NC
TI231	7/20/1981	outwash	V	75	NC	NC	NC	NC	NC
TI375	5/1/1974	outwash	V	72	9	NC	NC	NC	NC
TI376	5/3/1974	outwash	V	87	6	NC	NC	NC	NC
TI378	5/6/1974	outwashT	V	71	NC	NC	NC	NC	NC
TI379	5/8/1974	outwashT	V	70	NC	NC	NC	NC	NC
TI432	7/20/1983	bedrock	S	120	62	NC	NC	NC	10.5
TI487	5/8/1974	outwash	V	30	11	NC	NC	NC	NC
TI489	5/13/1974	outwashT	V	47	NC	NC	NC	NC	NC
TI490	5/20/1974	outwash	V	30	8	NC	NC	NC	NC
TI491	8/14/1974	bedrock	V	75	NC	NC	NC	NC	NC
TI527	7/12/1984	outwash	V	122	12	NC	NC	NC	NC
TI528	7/12/1984	outwash	V	130	21	NC	NC	NC	NC
TI529	7/12/1984	outwash	V	140	11	NC	NC	NC	NC
TI530	7/12/1984	bedrock	V	146	NC	NC	NC	NC	NC
TI576 (8)	5/18/2005	outwash	V	29 O	-.5	Y	Y	11.0	11.2
	7/19/2005				-.3	N	Y	31.0	11.9
TI577	6/23/2005	outwash	V	124 D	NC	Y	Y	2.6	11.2
	7/21/2005				26.8	NC	NC	2.7	11.6
TI578	6/9/2005	bedrock	V	145 O	NC	Y	Y	19.0	11.9
	7/19/2005				21.7	Y	Y	12.0	11.2
TI579	6/24/2005	bedrock	V	187 O	NC	Y	NC	15.0	13.6
	6/29/2005				NC	NC	Y	2.5	12.6
TI580 (21)	5/13/2005	bedrock	V	220 D	NC	Y	Y	20.0	12.0
	6/30/2005				7.9	NC	Y	17.0	12.0
TI581	5/18/2005	outwash	V	110 O	NC	N	N	1.6	11.9
	6/28/2005				NC	NC	N	.7	13.4

---

[1] Wells inventoried prior to 2005 are from Williams and others (1998) and were used for making the hydrogeologic sections in figure 5. Wells inventoried in 2005 are those sampled for this study; the wells are primarily used for rural domestic or business water supply. If two dates are listed for a well, the earlier of the two is the date the well was first inventoried and the later is the date the detailed sampling was conducted.

Table 2. Water wells inventoried, well records, and associated water-quality field characteristics data, Tioga Junction and vicinity, Tioga County, Pennsylvania—Continued

Inventory by U.S. Geological Survey (USGS). USGS local well number consists of a county prefix (TI= Tioga) and a well number. In the central Tioga River valley, inventoried wells were too close together for the local well number to be used on maps. Instead, a cross-reference number from 1 to 27 was used on maps and the cross-reference number is listed in parentheses following the local well number. Aquifer type: outwash, well completed in unconsolidated valley-fill deposits; outwashT, test well drilled through valley-fill deposits to bedrock; bedrock, well completed in Lock Haven Formation. Topographic setting: H, hilltop; S, hillside; V, valley; W, upland draw. Letter code associated with well depth is source of depth data: D, driller; O, owner; S, USGS. Other abbreviations--ft bls, feet below land surface; IT, incremental titration; mg/L, milligrams per liter, °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25°C; mV, millivolts; N, no; Y, yes; <, less than; > greater than; NA, not applicable; NC, not collected. A few samples have data missing for some field characteristics because of meter malfunctions.]

Specific con-ductance (µS/cm)	pH (units)	Acid neutralizing capacity, IT, in milligrams per liter as $CaCO_3$	Dissolved oxygen (mg/L)	Oxidation-reduction potential, relative to reference electrode		Latitude	Longitude	USGS local well number (and cross reference on fig. 4)
				Ag-AgCl_2 electrode (mV)	Hydrogen electrode (mV)			
NC	NC	NC	NC	NC	NC	41° 59’ 56"	77° 07’ 04"	TI214
NC	NC	NC	NC	NC	NC	41° 59’ 57"	77° 06’ 58"	TI215
NC	NC	NC	NC	NC	NC	41° 57’ 13"	77° 06’ 33"	TI228
NC	NC	NC	NC	NC	NC	41° 57’ 52"	77° 06’ 37"	TI231
NC	NC	NC	NC	NC	NC	41° 59’ 48"	77° 07’ 17"	TI375
NC	NC	NC	NC	NC	NC	41° 59’ 33"	77° 07’ 35"	TI376
NC	NC	NC	NC	NC	NC	41° 59’ 31"	77° 08’ 14"	TI378
NC	NC	NC	NC	NC	NC	41° 59’ 44"	77° 08’ 21"	TI379
280	NC	NC	NC	NC	NC	41° 59’ 58"	77° 06’ 47"	TI432
NC	NC	NC	NC	NC	NC	41° 59’ 34"	77° 07’ 27"	TI487
NC	NC	NC	NC	NC	NC	41° 59’ 34"	77° 08’ 36"	TI489
NC	NC	NC	NC	NC	NC	41° 59’ 33"	77° 07’ 17"	TI490
NC	NC	NC	NC	NC	NC	41° 59’ 36"	77° 08’ 46"	TI491
NC	NC	NC	NC	NC	NC	41° 56’ 05"	77° 06’ 17"	TI527
NC	NC	NC	NC	NC	NC	41° 58’ 08"	77° 06’ 18"	TI528
NC	NC	NC	NC	NC	NC	41° 56’ 08"	77° 06’ 25"	TI529
NC	NC	NC	NC	NC	NC	41° 56’ 07"	77° 06’ 25"	TI530
248	8.0	NC	<0.2	-167	45	41° 57’ 44"	77° 06’ 33"	TI576 (8)
244	8.2	192	<.1	-203	9			
239	8.3	NC	.1	-184	28	41° 55’ 60"	77° 06’ 14"	TI577
237	8.2	123	.12	-197	15			
902	7.7	NC	NC	-118	94	41° 58’ 52"	77° 04’ 42"	TI578
853	7.9	287	.13	-164	48			
3,160	7.9	NC	1.4	NC	NC	41° 58’ 57"	77° 07’ 06"	TI579
858	7.9	123	NC	-163	48			
360	8.7	NC	.1	-246	-34	41° 57’ 35"	77° 06’ 30"	TI580 (21)
404	8.8	220	.1	-289	-77			
274	7.8	NC	<.2	-147	64	41° 57’ 27"	77° 06’ 22"	TI581
272	8.1	119	<.1	-174	36			

Table 2. Water wells inventoried, well records, and associated water-quality field characteristics data, Tioga Junction and vicinity, Tioga County, Pennsylvania.—Continued

[Inventory by U.S. Geological Survey (USGS). USGS local well number consists of a county prefix (TI=Tioga) and a well number. In the central Tioga River valley, inventoried wells were too close together for the local well number to be used on maps. Instead, a cross-reference number from 1 to 27 was used on maps and the cross-reference number is listed in parentheses following the local well number. Aquifer type: outwash, well completed in unconsolidated valley-fill deposits; outwashT, test well drilled through valley-fill deposits to bedrock; bedrock, well completed in Lock Haven Formation. Topographic setting: H, hilltop; S, hillside; V, valley; W, upland draw. Letter code associated with well depth is source of depth data: D, driller; O, owner; S, USGS. Other abbreviations—ft bls, feet below land surface; IT, incremental titration; mg/L, milligrams per liter, °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25°C; mV, millivolts; N, no; Y, yes; <, less than; > greater than; NA, not applicable; NC, not collected. A few samples have data missing for some field characteristics because of meter malfunctions.]

USGS local well number (and cross reference on fig. 4)	Inventory date[1]	Aquifer type	Topo-graphic setting	Well depth (ft bls)	Water level (ft bls)	Sulfur smell	Out-gassing	Com-bustible gas (percent)	Temper-ature (°C)
TI582	6/9/2005	bedrock	W	48 D	2	Y	Y	0.5	14.3
	6/29/2005				NC	NC	Y	.5	12.4
TI583	6/9/2005	bedrock	S	128 O	NC	N	Y	.4	NC
	6/29/2005				61.65	NC	NC	.1	11.6
TI584	6/9/2005	bedrock	V	90 O	.5	Y	Y	8.0	10.7
	6/29/2005				NC	NC	Y	5.0	11.2
TI585	6/9/2005	bedrock	S	80 D	FLOWING	Y	NC	3.7	11.5
	6/29/2005				NC	NC	NC	2.3	NC
TI586	5/13/2005	bedrock	V	135 O	NC	Y	Y	1.0	14.6
	6/30/2005				NC	Y	NC	1.3	14.1
TI587	5/11/2005	bedrock	S	200 O	NC	NC	Y	2.0	NC
	6/30/2005				NC	NC	NC	2.2	12.2
TI588	6/24/2005	bedrock	S	100 O	NC	Y	Y	11.0	10.9
	6/30/2005				NC	NC	NC	6.0	10.9
TI589 (12)	5/13/2005	bedrock	V	83 O	NC	Y	NC	9.0	11.0
	6/30/2005				NC	NC	NC	8.0	11.3
TI590 (14)	5/13/2005	bedrock	S	100 O	NC	NC	Y	18.0	12.0
	7/13/2005				21.05	Y	Y	12.5	13.3
TI591 (10)	5/19/2005	outwash	V	85 O	NC	Y	Y	15.0	11.2
	7/13/2005				4	NC	Y	10.0	11.7
TI592 (9)	5/18/2005	bedrock	V	180 O	NC	N	N	10.0	NC
	7/13/2005				NC	NC	NC	14.0	11.7
TI593 (22)	5/19/2005	outwash	V	20 O	NC	N	Y	.7	12.2
	7/14/2005				NC	Y	Y	.4	12.2
TI594	5/11/2005	bedrock	S	120 D	NC	N	Y	8.0	11.3
	7/14/2005				39.9	NC	Y	12.0	11.9
TI595	6/22/2005	bedrock	S	200 O	NC	NC	NC	.5	NC
	7/14/2005				79	Y	Y	1.0	12.0
TI596	5/12/2005	bedrock	V	825 O	30	Y	NC	2.0	11.0
	7/19/2005				NC	Y	Y	9.5	13.8
TI597	6/22/2005	bedrock	S	145 S	NC	Y	Y	12.0	14.3
	7/20/2005				46	NC	NC	12.0	11.1

---

[1] Wells inventoried prior to 2005 are from Williams and others (1998) and were used for making the hydrogeologic sections in figure 5. Wells inventoried in 2005 are those sampled for this study; the wells are primarily used for rural domestic or business water supply. If two dates are listed for a well, the earlier of the two is the date the well was first inventoried and the later is the date the detailed sampling was conducted.

[2] Potentials for TI588 affected by chlorinator used for water treatment.

Table 2. Water wells inventoried, well records, and associated water-quality field characteristics data, Tioga Junction and vicinity, Tioga County, Pennsylvania—Continued

Inventory by U.S. Geological Survey (USGS). USGS local well number consists of a county prefix (TI= Tioga) and a well number. In the central Tioga River valley, inventoried wells were too close together for the local well number to be used on maps. Instead, a cross-reference number from 1 to 27 was used on maps and the cross-reference number is listed in parentheses following the local well number. Aquifer type: outwash, well completed in unconsolidated valley-fill deposits; outwashT, test well drilled through valley-fill deposits to bedrock; bedrock, well completed in Lock Haven Formation. Topographic setting: H, hilltop; S, hillside; V, valley; W, upland draw. Letter code associated with well depth is source of depth data: D, driller; O, owner; S, USGS. Other abbreviations--ft bls, feet below land surface; IT, incremental titration; mg/L, milligrams per liter, °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25°C; mV, millivolts; N, no; Y, yes; <, less than; > greater than; NA, not applicable; NC, not collected. A few samples have data missing for some field characteristics because of meter malfunctions.]

Specific conductance (µS/cm)	pH (units)	Acid neutralizing capacity, IT, in milligrams per liter as $CaCO_3$	Dissolved oxygen (mg/L)	Oxidation-reduction potential, relative to reference electrode		Latitude	Longitude	USGS local well number (and cross reference on fig. 4)
				Ag-$AgCl_2$ electrode (mV)	Hydrogen electrode (mV)			
439	7.7	NC	0.3	-144	65	41° 58’ 11"	77° 09’ 13"	TI582
426	7.8	NC	<.1	-170	41			
NC	NC	NC	NC	NC	NC	41° 57’ 01"	77° 09’ 13"	TI583
345	7.7	156	NC	-24	188			
380	7.8	NC	<.2	-121	91	41° 56’ 25"	77° 11’ 26"	TI584
384	7.9	200	NC	-154	59			
640	7.7	NC	.2	-90	122	41° 57’ 43"	77° 08’ 38"	TI585
701	7.8	247	.4	-88	NC			
279	8.2	NC	<.2	-160	49	41° 57’ 29"	77° 06’ 27"	TI586
276	8.2	142	<.2	-198	11			
838	8.5	NC	NC	NC	NC	41° 58’ 10"	77° 07’ 03"	TI587
943	8.6	NC	.2	-259	-48			
590	7.6	NC	<.2	^{2}594	^{2}806	41° 59’ 24"	77° 04’ 46"	TI588
569	7.7	243	.17	^{2}549	^{2}762			
479	7.8	NC	.2	-147	66	41° 57’ 23"	77° 07’ 01"	TI589 (12)
492	7.8	210	.2	-116	96			
738	7.5	NC	<.7	NC	NC	41° 57’ 19"	77° 07’ 03"	TI590 (14)
624	7.5	243	.1	-96	115			
288	8.1	NC	NC	-203	9	41° 57’ 36"	77° 06’ 38"	TI591 (10)
286	8.2	67	.04	-236	-24			
NC	NC	NC	NC	NC	NC	41° 57’ 39"	77° 06’ 39"	TI592 (9)
328	8.5	182	.1	-231	-19			
367	7.7	NC	NC	-82	129	41° 57’ 35"	77° 06’ 12"	TI593 (22)
367	7.9	172	NC	-117	95			
487	7.7	NC	<.2	12	224	41° 57’ 20"	77° 07’ 11"	TI594
602	7.7	317	<.1	-56	155			
NC	NC	NC	NC	NC	NC	41° 55’ 52"	77° 05’ 52"	TI595
500	7.6	269	<.1	-110	101			
489	8.2	NC	NC	18	230	41° 56’ 58"	77° 06’ 50"	TI596
529	8.3	247	.24	-213	-4			
344	8.0	NC	<.1	-89	120	41° 55’ 57"	77° 05’ 45"	TI597
330	7.8	178	.1	-193	19			

Table 2. Water wells inventoried, well records, and associated water-quality field characteristics data, Tioga Junction and vicinity, Tioga County, Pennsylvania.—Continued

[Inventory by U.S. Geological Survey (USGS). USGS local well number consists of a county prefix (TI=Tioga) and a well number. In the central Tioga River valley, inventoried wells were too close together for the local well number to be used on maps. Instead, a cross-reference number from 1 to 27 was used on maps and the cross-reference number is listed in parentheses following the local well number. Aquifer type: outwash, well completed in unconsolidated valley-fill deposits; outwashT, test well drilled through valley-fill deposits to bedrock; bedrock, well completed in Lock Haven Formation. Topographic setting: H, hilltop; S, hillside; V, valley; W, upland draw. Letter code associated with well depth is source of depth data: D, driller; O, owner; S, USGS. Other abbreviations—ft bls, feet below land surface; IT, incremental titration; mg/L, milligrams per liter, °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25°C; mV, millivolts; N, no; Y, yes; <, less than; > greater than; NA, not applicable; NC, not collected. A few samples have data missing for some field characteristics because of meter malfunctions.]

USGS local well number (and cross reference on fig. 4)	Inventory date[1]	Aquifer type	Topo-graphic setting	Well depth (ft bls)	Water level (ft bls)	Sulfur smell	Out-gassing	Com-bustible gas (percent)	Temper-ature (°C)
TI598	6/22/2005	bedrock	V	115 O	NC	N	N	1.0	NC
	7/20/2005				0.3	Y	NC	.5	11.7
TI599 (13)	5/18/2005	outwash	V	60 O	15	Y	NC	4.1	11.4
	7/20/2005				NC	Y	NC	3.4	11.6
TI600 (20)	5/11/2005	bedrock	V	168 D	NC	Y	NC	11.0	NC
	7/21/2005				NC	Y	Y	22.0	11.7
TI601	6/24/2005	outwash	V	78 D	NC	Y	NC	11.0	NC
	7/27/2005				36.5	Y	Y	5.0	11.6
TI602 (11)	6/20/2005	outwash	V	92 S	8.2	Y	Y	8.0	11.6
	7/27/2005				7.4	Y	Y	4.0	11.9
TI603	5/26/2005	outwash	V	89 S	NC	Y	NC	.5	10.9
	7/28/2005				4	Y	Y	1.0	10.8
TI604	5/25/2005	bedrock	S	180 O	NC	N	Y	10.0	9.9
	7/28/2005				43.3	NC	Y	12.0	10.5
TI605 (4)	7/28/2005	bedrock	V	120 D	28.5	Y	Y	7.0	10.6
TI606	6/9/2005	bedrock	S	250 O	NC	Y	N	1.8	NC
	7/28/2005				NC	Y	N	2.1	11.1
TI607	5/26/2005	outwash	V	65 O	NC	NC	NC	1.7	12.4
	7/29/2005				NC	Y	NC	1.1	11.8
TI608 (5)	5/26/2005	outwash	V	88 S	9.5	Y	Y	11.0	10.8
	7/29/2005				12	NC	Y	13.0	10.9
TI609	6/8/2005	bedrock	W	115 O	NC	NC	NC	4.8	NC
	6/29/2005				NC	NC	NC	13.0	11.6
TI610	6/21/2005	bedrock	S	145 O	NC	Y	NC	3.8	NC
	8/10/2005				NC	Y	Y	10.0	10.6
TI611	6/23/2005	bedrock	S	180 O	NC	N	Y	3.7	NC
	8/10/2005				NC	NC	Y	9.0	11.1
TI612	6/30/2005	outwash	V	23 D	NC	NC	N	0	10.8
	8/10/2005				12	NC	N	0	11.2
TI613	5/11/2005	bedrock	S	180 O	NC	Y	N	0	11.3
	8/11/2005				NC	NC	N	0	11.4
TI614	6/21/2005	bedrock	S	160 D	NC	Y	N	.5	NC
	8/11/2005				NC	Y	N	.3	11.4

---

[1] Wells inventoried prior to 2005 are from Williams and others (1998) and were used for making the hydrogeologic sections in figure 5. Wells inventoried in 2005 are those sampled for this study; the wells are primarily used for rural domestic or business water supply. If two dates are listed for a well, the earlier of the two is the date the well was first inventoried and the later is the date the detailed sampling was conducted.

Table 2. Water wells inventoried, well records, and associated water-quality field characteristics data, Tioga Junction and vicinity, Tioga County, Pennsylvania—Continued

Inventory by U.S. Geological Survey (USGS). USGS local well number consists of a county prefix (TI= Tioga) and a well number. In the central Tioga River valley, inventoried wells were too close together for the local well number to be used on maps. Instead, a cross-reference number from 1 to 27 was used on maps and the cross-reference number is listed in parentheses following the local well number. Aquifer type: outwash, well completed in unconsolidated valley-fill deposits; outwashT, test well drilled through valley-fill deposits to bedrock; bedrock, well completed in Lock Haven Formation. Topographic setting: H, hilltop; S, hillside; V, valley; W, upland draw. Letter code associated with well depth is source of depth data: D, driller; O, owner; S, USGS. Other abbreviations--ft bls, feet below land surface; IT, incremental titration; mg/L, milligrams per liter, °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25°C; mV, millivolts; N, no; Y, yes; <, less than; > greater than; NA, not applicable; NC, not collected. A few samples have data missing for some field characteristics because of meter malfunctions.]

Specific conductance (µS/cm)	pH (units)	Acid neutralizing capacity, IT, in milligrams per liter as $CaCO_3$	Dissolved oxygen (mg/L)	Oxidation-reduction potential, relative to reference electrode		Latitude	Longitude	USGS local well number (and cross reference on fig. 4)
				Ag-$AgCl_2$ electrode (mV)	Hydrogen electrode (mV)			
NC	NC	NC	NC	NC	NC	41° 56' 52"	77° 06' 13"	TI598
276	8.6	109	<0.2	-222	-10			
421	7.1	NC	.14	-85	127	41° 57' 21"	77° 07' 04"	TI599 (13)
404	7.2	174	.12	-122	90			
297	8.1	NC	NC	NC	NC	41° 57' 37"	77° 06' 31"	TI600 (20)
283	8.2	156	.13	-223	-11			
NC	7.4	NC	NC	-64	NC	41° 55' 46"	77° 05' 45"	TI601
NC	7.6	214	.1	-136	76			
303	8.4	NC	<.2	-267	-55	41° 57' 28"	77° 06' 43"	TI602 (11)
310	8.5	168	<.1	-238	-26			
274	8.0	NC	.12	-175	37	41° 58' 04"	77° 06' 36"	TI603
265	8.2	131	.07	-194	19			
929	8.0	NC	.1	-145	69	41° 58' 46"	77° 04' 56"	TI604
806	7.7	301	.11	-190	23			
670	7.4	230	.17	-112	101	41° 58' 06"	77° 05' 51"	TI605 (4)
589	7.8	NC	NC	NC	NC	41° 58' 28"	77° 09' 08"	TI606
568	7.6	247	.1	-199	14			
537	7.7	NC	.2	-168	44	41° 58' 06"	77° 05' 58"	TI607
502	7.6	168	.25	-180	31			
392	8.6	NC	.04	-227	-15	41° 57' 59"	77° 06' 01"	TI608 (5)
461	NC	218	.08	-239	-26			
420	7.1	NC	NC	-109	NC	41° 56' 33"	77° 09' 58"	TI609
408	7.5	196	NC	-147	65			
424	7.9	NC	NC	NC	NC	41° 59' 15"	77° 03' 23"	TI610
390	7.7	192	<.2	NC	NC			
NC	NC	NC	NC	NC	NC	41° 55' 57"	77° 05' 18"	TI611
730	7.9	265	.1	NC	NC			
519	5.6	NC	NC	192	404	41° 58' 23"	77° 07' 09"	TI612
425	5.5	32	<.8	NC	NC			
371	7.9	NC	NC	-93	119	41° 58' 02"	77° 07' 06"	TI613
358	7.9	170	.15	NC	NC			
513	7.2	NC	<NC	NC	NC	41° 59' 12"	77° 05' 40"	TI614
521	7.2	172	.6	NC	NC			

Table 2. Water wells inventoried, well records, and associated water-quality field characteristics data, Tioga Junction and vicinity, Tioga County, Pennsylvania.—Continued

[Inventory by U.S. Geological Survey (USGS). USGS local well number consists of a county prefix (TI=Tioga) and a well number. In the central Tioga River valley, inventoried wells were too close together for the local well number to be used on maps. Instead, a cross-reference number from 1 to 27 was used on maps and the cross-reference number is listed in parentheses following the local well number. Aquifer type: outwash, well completed in unconsolidated valley-fill deposits; outwashT, test well drilled through valley-fill deposits to bedrock; bedrock, well completed in Lock Haven Formation. Topographic setting: H, hilltop; S, hillside; V, valley; W, upland draw. Letter code associated with well depth is source of depth data: D, driller; O, owner; S, USGS. Other abbreviations—ft bls, feet below land surface; IT, incremental titration; mg/L, milligrams per liter, °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25°C; mV, millivolts; N, no; Y, yes; <, less than; > greater than; NA, not applicable; NC, not collected. A few samples have data missing for some field characteristics because of meter malfunctions.]

USGS local well number (and cross reference on fig. 4)	Inventory date[1]	Aquifer type	Topo-graphic setting	Well depth (ft bls)	Water level (ft bls)	Sulfur smell	Out-gassing	Com-bustible gas (percent)	Temper-ature (°C)
TI615	7/29/2005	bedrock	W	34.5 O	11.2	NC	N	1.4	10.9
	8/11/2005				NC	N	N	0	10.8
TI616 (18)	5/6/2005	bedrock	V	150 O	NC	N	NC	.3	NC
TI617 (7)	5/11/2005	outwash	V	80 O	NC	NC	NC	3.9	NC
TI618	5/12/2005	bedrock	S	104 D	76.3	N	NC	.1	11.1
TI619	5/12/2005	bedrock	S	80 O	NC	Y	NC	0.15	10.8
TI620	5/12/2005	bedrock	S	108 O	NC	NC	NC	.7	10.9
TI621	5/12/2005	bedrock	W	300 O	92	NC	NC	0	9.9
TI622	5/12/2005	bedrock	S	250 O	NC	Y	NC	0	11.4
TI623 (15)	5/18/2005	bedrock	S	109 O	NC	Y	N	.1	11.6
TI624 (24)	5/19/2005	outwash	V	90 O	NC	NC	N	0	NC
TI625 (23)	5/19/2005	outwash	V	67 O	NC	N	N	0	NC
TI626	5/19/2005	bedrock	S	260 O	NC	N	N	0	NC
TI627 (19)	5/20/2005	outwash	V	100 O	NC	Y	N	0	11.3
TI628 (27)	5/20/2005	bedrock	S	75 O	NC	N	N	0	12.5
TI629 (16)	5/20/2005	bedrock	S	91 O	NC	N	N	0	11.8
TI630 (25)	5/20/2005	bedrock	V	129 O	3	Y	N	0	11.1
TI631	5/20/2005	outwash	V	100 O	NC	N	N	0	12.3
TI632 (26)	5/23/2005	bedrock	S	100 O	NC	N	NC	0	11.1
TI633 (1)	5/23/2005	outwash	V	25 O	NC	Y	NC	0	10.7
TI634 (6)	5/23/2005	outwash	V	44 O	NC	Y	NC	0	NC
TI635 (2)	5/24/2005	bedrock	V	96 O	NC	Y	NC	0	NC
TI636	5/24/2005	outwash	V	50 O	NC	N	N	0	11.0
TI637 (3)	5/25/2005	outwash	V	139 O	NC	Y	N	0	10.6
TI638	5/25/2005	bedrock	V	129 D	NC	N	N	0	10.3
TI639	5/25/2005	bedrock	W	50 O	NC	Y	NC	0	10.9
TI640	5/25/2005	bedrock	S	30 O	NC	N	N	0	10.5
TI641	5/26/2005	outwash	V	50 O	NC	N	N	0	11.4
TI642	5/26/2005	bedrock	S	125 O	NC	Y	NC	.5	10.1
TI643	6/7/2005	bedrock	S	125 O	NC	Y	NC	0	NC
TI644	6/8/2005	bedrock	S	175 O	NC	Y	NC	0	NC
TI645	6/8/2005	bedrock	H	156 O	NC	N	Y	.2	11.4
TI646	6/9/2005	bedrock	W	45 O	NC	Y	Y	.1	NC

---

[1] Wells inventoried prior to 2005 are from Williams and others (1998) and were used for making the hydrogeologic sections in figure 5. Wells inventoried in 2005 are those sampled for this study; the wells are primarily used for rural domestic or business water supply. If two dates are listed for a well, the earlier of the two is the date the well was first inventoried and the later is the date the detailed sampling was conducted.

Table 2. Water wells inventoried, well records, and associated water-quality field characteristics data, Tioga Junction and vicinity, Tioga County, Pennsylvania—Continued

Inventory by U.S. Geological Survey (USGS). USGS local well number consists of a county prefix (TI= Tioga) and a well number. In the central Tioga River valley, inventoried wells were too close together for the local well number to be used on maps. Instead, a cross-reference number from 1 to 27 was used on maps and the cross-reference number is listed in parentheses following the local well number. Aquifer type: outwash, well completed in unconsolidated valley-fill deposits; outwashT, test well drilled through valley-fill deposits to bedrock; bedrock, well completed in Lock Haven Formation. Topographic setting: H, hilltop; S, hillside; V, valley; W, upland draw. Letter code associated with well depth is source of depth data: D, driller; O, owner; S, USGS. Other abbreviations--ft bls, feet below land surface; IT, incremental titration; mg/L, milligrams per liter, °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25°C; mV, millivolts; N, no; Y, yes; <, less than; > greater than; NA, not applicable; NC, not collected. A few samples have data missing for some field characteristics because of meter malfunctions.]

Specific conductance (µS/cm)	pH (units)	Acid neutralizing capacity, IT, in milligrams per liter as $CaCO_3$	Dissolved oxygen (mg/L)	Oxidation-reduction potential, relative to reference electrode		Latitude	Longitude	USGS local well number (and cross reference on fig. 4)
				Ag-AgCl_2 electrode (mV)	Hydrogen electrode (mV)			
202	NC	NC	<0.3	-69	143	41° 56’ 52"	77° 03’ 09"	TI615
208	7.2	89	<.3	NC	NC			
NC	NC	NA	NC	NC	NC	41° 57’ 29"	77° 06’ 35"	TI616 (18)
282	7.8	NA	NC	NC	NC	41° 57’ 49"	77° 06’ 35"	TI617 (7)
394	7.5	NA	4.1	121	333	41° 56’ 49"	77° 06’ 58"	TI618
359	7.6	NA	.2	-58	154	41° 56’ 51"	77° 07’ 05"	TI619
398	7.9	NA	.2	-139	74	41° 57’ 03"	77° 07’ 20"	TI620
266	6.5	NA	NC	NC	NC	41° 56’ 51"	77° 07’ 38"	TI621
702	7.6	NA	NC	-107	105	41° 57’ 37"	77° 07’ 20"	TI622
548	7.4	NA	<.2	-88	124	41° 57’ 12"	77° 07’ 02"	TI623 (15)
NC	NC	NA	NC	-141	NC	41° 57’ 29"	77° 06’ 11"	TI624 (24)
NC	NC	NA	NC	NC	NC	41° 57’ 40"	77° 06’ 03"	TI625 (23)
NC	NC	NA	NC	NC	NC	41° 57’ 42"	77° 05’ 58"	TI626
286	8.0	NA	<.3	-158	54	41° 57’ 30"	77° 06’ 32"	TI627 (19)
262	7.8	NA	NC	NC	NC	41° 57’ 27"	77° 06’ 07"	TI628 (27)
667	7.3	NA	<.3	-112	100	41° 57’ 08"	77° 07’ 03"	TI629 (16)
294	7.9	NA	<.3	-141	71	41° 57’ 27"	77° 06’ 14"	TI630 (25)
236	6.8	NA	NC	NC	NC	41° 57’ 12"	77° 06’ 27"	TI631
303	8.5	NA	<.2	-237	-24	41° 57’ 26"	77° 06’ 10"	TI632 (26)
181	6.6	NA	<.2	15	228	41° 58’ 13"	77° 06’ 51"	TI633 (1)
NC	NC	NA	NC	NC	NC	41° 57’ 53"	77° 06’ 41"	TI634 (6)
NC	NC	NA	NC	NC	NC	41° 58’ 11"	77° 06’ 41"	TI635 (2)
271	6.7	NA	NC	NC	NC	41° 58’ 49"	77° 07’ 02"	TI636
224	8.1	NA	.1	-213	0	41° 58’ 02"	77° 06’ 12"	TI637 (3)
175	7.1	NA	5.5	84	297	41° 57’ 11"	77° 05’ 43"	TI638
391	7.8	NA	<.1	-156	56	41° 58’ 22"	77° 05’ 24"	TI639
336	7.2	NA	.2	-22	191	41° 59’ 01"	77° 04’ 38"	TI640
463	5.9	NA	<.6	155	367	41° 58’ 36"	77° 06’ 54"	TI641
469	7.4	NA	<.2	-89	124	41° 58’ 06"	77° 05’ 45"	TI642
NC	NC	NA	NC	NC	NC	41° 59’ 05"	77° 04’ 15"	TI643
564	7.1	NA	NC	NC	NC	41° 58’ 08"	77° 09’ 40"	TI644
332	7.0	NA	NC	NC	NC	41° 57’ 02"	77° 08’ 48"	TI645
NC	NC	NA	NC	NC	NC	41° 58’ 09"	77° 09’ 13"	TI646

Table 2. Water wells inventoried, well records, and associated water-quality field characteristics data, Tioga Junction and vicinity, Tioga County, Pennsylvania.—Continued

[Inventory by U.S. Geological Survey (USGS). USGS local well number consists of a county prefix (TI=Tioga) and a well number. In the central Tioga River valley, inventoried wells were too close together for the local well number to be used on maps. Instead, a cross-reference number from 1 to 27 was used on maps and the cross-reference number is listed in parentheses following the local well number. Aquifer type: outwash, well completed in unconsolidated valley-fill deposits; outwashT, test well drilled through valley-fill deposits to bedrock; bedrock, well completed in Lock Haven Formation. Topographic setting: H, hilltop; S, hillside; V, valley; W, upland draw. Letter code associated with well depth is source of depth data: D, driller; O, owner; S, USGS. Other abbreviations—ft bls, feet below land surface; IT, incremental titration; mg/L, milligrams per liter, °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25°C; mV, millivolts; N, no; Y, yes; <, less than; > greater than; NA, not applicable; NC, not collected. A few samples have data missing for some field characteristics because of meter malfunctions.]

USGS local well number (and cross reference on fig. 4)	Inventory date[1]	Aquifer type	Topographic setting	Well depth (ft bls)	Water level (ft bls)	Sulfur smell	Outgassing	Combustible gas (percent)	Temperature (°C)
TI647	6/10/2005	bedrock	S	145 O	NC	Y	NC	0.5	11.9
TI648	6/10/2005	bedrock	S	90 O	NC	N	N	0	12.0
TI649	6/10/2005	bedrock	S	92 O	NC	Y	N	0	NC
TI650	6/10/2005	bedrock	V	100 O	NC	NC	NC	0	NC
TI651	6/10/2005	outwash	S	92 O	NC	N	N	0	NC
TI652	6/20/2005	outwash	V	55 D	NC	N	N	0	NC
TI653	6/21/2005	bedrock	S	38 O	NC	Y	NC	0	NC
TI654	6/21/2005	bedrock	H	108 O	NC	N	N	0	NC
TI655	6/21/2005	outwash	V	128 O	NC	N	N	0	11.1
TI656	6/22/2005	bedrock	V	250 O	NC	N	N	0	10.6
TI657	6/22/2005	bedrock	S	112 O	NC	Y	N	0	11.3
TI658	6/22/2005	bedrock	S	70 O	NC	N	N	0	NC
TI659	6/22/2005	bedrock	S	40 O	NC	N	N	0	NC
TI660	6/23/2005	outwash	V	20 O	NC	N	N	0	11.0
TI661	6/23/2005	outwash	V	28 O	NC	N	N	.3	NC
TI662	8/9/2005	outwash	V	32 O	NC	N	N	0	11.2
TI663	8/9/2005	bedrock	V	70 O	NC	Y	N	0	13.5
TI664	8/10/2005	bedrock	S	160 O	3	N	N	0	11.7
TI665	8/11/2005	outwash	V	32 O	NC	N	N	0	11.4
TI666 (17)	8/12/2005	bedrock	V	125 O	NC	N	N	0	12.3

[1] Wells inventoried prior to 2005 are from Williams and others (1998) and were used for making the hydrogeologic sections in figure 5. Wells inventoried in 2005 are those sampled for this study; the wells are primarily used for rural domestic or business water supply. If two dates are listed for a well, the earlier of the two is the date the well was first inventoried and the later is the date the detailed sampling was conducted.

Table 2. Water wells inventoried, well records, and associated water-quality field characteristics data, Tioga Junction and vicinity, Tioga County, Pennsylvania—Continued

Inventory by U.S. Geological Survey (USGS). USGS local well number consists of a county prefix (TI= Tioga) and a well number. In the central Tioga River valley, inventoried wells were too close together for the local well number to be used on maps. Instead, a cross-reference number from 1 to 27 was used on maps and the cross-reference number is listed in parentheses following the local well number. Aquifer type: outwash, well completed in unconsolidated valley-fill deposits; outwashT, test well drilled through valley-fill deposits to bedrock; bedrock, well completed in Lock Haven Formation. Topographic setting: H, hilltop; S, hillside; V, valley; W, upland draw. Letter code associated with well depth is source of depth data: D, driller; O, owner; S, USGS. Other abbreviations--ft bls, feet below land surface; IT, incremental titration; mg/L, milligrams per liter, °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25°C; mV, millivolts; N, no; Y, yes; <, less than; > greater than; NA, not applicable; NC, not collected. A few samples have data missing for some field characteristics because of meter malfunctions.]

Specific conductance (µS/cm)	pH (units)	Acid neutralizing capacity, IT, in milligrams per liter as $CaCO_3$	Dissolved oxygen (mg/L)	Oxidation-reduction potential, relative to reference electrode		Latitude	Longitude	USGS local well number (and cross reference on fig. 4)
				Ag-AgCl$_2$ electrode (mV)	Hydrogen electrode (mV)			
714	7.2	NA	NC	NC	NC	41° 58’ 26"	77° 10’ 11"	TI647
193	6.5	NA	NC	NC	NC	41° 57’ 59"	77° 10’ 27"	TI648
NC	NC	NA	NC	NC	NC	41° 58’ 27"	77° 04’ 38"	TI649
NC	NC	NA	NC	NC	NC	41° 58’ 55"	77° 06’ 27"	TI650
NC	NC	NA	NC	NC	NC	41° 59’ 51"	77° 06’ 39"	TI651
NC	NC	NA	NC	NC	NC	41° 57’ 12"	77° 03’ 51"	TI652
NC	NC	NA	NC	NC	NC	41° 58’ 30"	77° 03’ 11"	TI653
NC	NC	NA	NC	NC	NC	41° 58’ 46"	77° 03’ 05"	TI654
415	7.5	NA	<1.9	-33	179	41° 56’ 17"	77° 06’ 14"	TI655
354	6.9	NA	NC	NC	NC	41° 59’ 16"	77° 06’ 57"	TI656
465	7.3	NA	2	3	215	41° 57’ 58"	77° 05’ 46"	TI657
NC	NC	NA	NC	NC	NC	41° 56’ 53"	77° 05’ 44"	TI658
NC	NC	NA	NC	NC	NC	41° 59’ 00"	77° 07’ 30"	TI659
696	7.1	NA	<.1	68	281	41° 59’ 38"	77° 08’ 15"	TI660
NC	NC	NA	NC	NC	NC	41° 56’ 27"	77° 06’ 03"	TI661
273	6.9	NA	<.1	NC	NC	41° 55’ 40"	77° 07’ 11"	TI662
276	7.6	NA	NC	NC	NC	41° 55’ 33"	77° 07’ 10"	TI663
273	7.1	NA	<1	NC	NC	41° 55’ 56"	77° 03’ 30"	TI664
340	6.2	NA	<.3	NC	NC	41° 59’ 17"	77° 07’ 31"	TI665
223	8.0	NA	.15	NC	NC	41° 57’ 15"	77° 06’ 30"	TI666 (17)

Table 5. Laboratory water-quality results for water wells sampled in 2005, Tioga Junction and vicinity, Tioga County, Pennsylvania.

[Results are presented in this table for detailed analyses of waters from 40 wells. All samples collected by U.S. Geological Survey (USGS). No samples were collected or analyzed for 51 additional inventoried wells numbered TI616 to TI666. Analyses for isotopes, hydrocarbons, and headspace gases were performed at Isotech Laboratories, Inc. Dissolved gas concentrations were analyzed at USGS Reston Dissolved Gas Laboratory (RDGL) and stable isotopes of hydrogen and oxygen in water and dissolved inorganic carbon in water were analyzed at USGS Reston Stable Isotope Lab (RSIL); $\delta^{13}C_{CH4}$, carbon isotopes of methane; δD_{CH4}, hydrogen isotopes of methane; $\delta^{13}C_{C2H6}$, carbon isotopes of ethane; $^{14}C_{CH4}$, carbon-14 isotope of methane; $\delta^{13}C_{DIC}$,carbon isotopes of dissolved inorganic carbon analyzed at RSIL; δD_{water}, hydrogen isotopes of water analyzed at RSIL; $\delta^{18}O_{water}$, oxygen isotopes of water analyzed at RSIL; hydrogen and oxygen stable isotope data reported relative to Vienna Standard Mean Ocean Water (VSMOW); carbonate stable isotope data reported relative to Vienna PeeDee Belemnite (VPDB); per mil, parts per thousand; pMC, percent modern carbon; mg/L milligrams per liter; ND, not detected; NA, not analyzed; —, missing data]

USGS local well number (and cross reference on fig. 4)[1]	Date sampled	Aquifer type	Isotopic composition, in per mil						$^{14}C_{CH4}$ (pMC)
			$\delta^{13}C_{CH4}$	δD_{CH4}	$\delta^{13}C_{C2H6}$	$\delta^{13}C_{DIC}$	δD_{water}	$\delta^{18}O_{water}$	
TI576 (8)	7/19/2005	outwash	-39.16	-183.8	-39.03	-6.39	-71.1	-10.58	1.3
TI577	7/21/2005	outwash	-43.59	-187.8	-28.73	-14.68	-66.3	-9.86	2.7
TI578	7/19/2005	bedrock	-60.91	-251.9	ND	-2.83	-67.8	-10.18	NA
TI579	6/29/2005	bedrock	-58.92	-242.7	ND	-12.02	-67.4	-9.99	NA
TI580 (21)	6/30/2005	bedrock	-38.77	-188.9	-34.1	-2.17	-70.6	-10.29	NA
TI581	6/28/2005	outwash	ND	ND	ND	-13.47	-71.4	-10.53	NA
TI582	6/29/2005	bedrock	-65.04	-205.3	ND	-18.54	-52	-9.87	4.8
TI583	6/29/2005	bedrock	ND	ND	ND	-15.66	-69.5	-10.52	NA
TI584	6/29/2005	bedrock	-40.63	-178.6	-31.58	-13.83	-67.3	-10.16	NA
TI585	6/29/2005	bedrock	-64.8	-242.2	ND	-14.69	-68.3	-10.13	NA
TI586	6/30/2005	bedrock	-42.45	-105.9	-30.4	-16.45	-71	-10.46	NA
TI587	6/30/2005	bedrock	-63.8	-241.1	ND	-12.7	-69.7	-10.22	NA
TI588	6/30/2005	bedrock	-62.11	-258.8	ND	-5.32	-66.4	-10.01	NA
TI589 (12)	6/30/2005	bedrock	-43.17	-192.2	-29.85	-5.45	-64.6	-9.58	NA
TI590 (14)	7/13/2005	bedrock	-41.44	-187.6	-30.94	-2.71	-65.2	-9.72	NA
TI591 (10)	7/13/2005	outwash	-38.42	-173.1	-38.92	-9.13	-70.2	-10.26	NA
TI592 (9)	7/13/2005	bedrock	-40.12	-184.8	-37.21	-3.73	-67.8	-10.31	NA
TI593 (22)	7/14/2005	outwash	-35.54	-138.5	-28.96	-19.92	-69.8	-10.45	1.5
TI594	7/14/2005	bedrock	-40.01	-176.5	-32.8	-12.54	-64.5	-9.7	NA
TI595	7/14/2005	bedrock	-61.4	-190.8	ND	-18.17	-68.1	-9.96	NA

---

[1] Well identifier on figure 4. USGS local well number consists of a county prefix (TI=Tioga) and a well number. In the central Tioga River valley, inventoried wells were too close together for the local well number to be used on maps. Instead, a cross-reference number from 1 to 27 was used on maps and the cross-reference number is listed in parentheses following the local well number.

Table 5. Laboratory water-quality results for water wells sampled in 2005, Tioga Junction and vicinity, Tioga County, Pennsylvania.—Continued

[Results are presented in this table for detailed analyses of waters from 40 wells. All samples collected by U.S. Geological Survey (USGS). No samples were collected or analyzed for 51 additional inventoried wells numbered TI616 to TI666. Analyses for isotopes, hydrocarbons, and headspace gases were performed at Isotech Laboratories, Inc. Dissolved gas concentrations were analyzed at USGS Reston Dissolved Gas Laboratory (RDGL) and stable isotopes of hydrogen and oxygen in water and dissolved inorganic carbon in water were analyzed at USGS Reston Stable Isotope Lab (RSIL); $\delta^{13}C_{CH4}$, carbon isotopes of methane; δD_{CH4}, hydrogen isotopes of methane; $\delta^{13}C_{C2H6}$, carbon isotopes of ethane; $^{14}C_{CH4}$, carbon-14 isotope of methane; $\delta^{13}C_{DIC}$,carbon isotopes of dissolved inorganic carbon analyzed at RSIL; δD_{water}, hydrogen isotopes of water analyzed at RSIL; $\delta^{18}O_{water}$, oxygen isotopes of water analyzed at RSIL; hydrogen and oxygen stable isotope data reported relative to Vienna Standard Mean Ocean Water (VSMOW); carbonate stable isotope data reported relative to Vienna PeeDee Belemnite (VPDB); per mil, parts per thousand; pMC, percent modern carbon; mg/L milligrams per liter; ND, not detected; NA, not analyzed; —, missing data]

USGS local well number (and cross reference on fig. 4)[1]	Date sampled	Aquifer type	Isotopic composition, in per mil						$^{14}C_{CH4}$ (pMC)
			$\delta^{13}C_{CH4}$	δD_{CH4}	$\delta^{13}C_{C2H6}$	$\delta^{13}C_{DIC}$	δD_{water}	$\delta^{18}O_{water}$	
TI596	7/19/2005	bedrock	-47.13	-208	-34.68	-13.21	-65.9	-9.96	NA
TI597	7/20/2005	bedrock	-38.43	-186.3	-32.17	-16.15	-66.8	-10.09	NA
TI598	7/20/2005	bedrock	-72.17	-236.4	ND	-13.66	-66.1	-9.89	NA
TI599 (13)	7/20/2005	outwash	-40.15	-168.6	-30.8	-20.66	-63.2	-9.54	1.6
TI600 (20)	7/21/2005	bedrock	-39.59	-187.1	-36.41	-4.51	-69.8	-10.28	NA
TI601	7/27/2005	outwash	-59.08	-152	-29.75	-21.82	-67.7	-10	NA
TI602 (11)	7/27/2005	outwash	-39.76	-170.2	-37.27	-13.55	-70.1	-10.23	.8
TI603	7/28/2005	outwash	-41.04	-107.8	-31.64	-18.37	-69.5	-10.36	NA
TI604	7/28/2005	bedrock	-62.42	-254.2	ND	-5.72	-69	-10.24	NA
TI605 (4)	7/28/2005	bedrock	-40.76	-179.9	-31.42	-15.73	-67.3	-10.06	NA
TI606	7/28/2005	bedrock	-64.02	-232.8	ND	-14.76	-65.6	-9.87	NA
TI607	7/29/2005	outwash	-51.37	-190.1	ND	-7.35	-63.8	-9.84	4.4
TI608 (5)	7/29/2005	outwash	-43.55	-193.8	-33.23	-4.66	-63.8	-10.01	1.7
TI609	6/29/2005	bedrock	-41.51	-181.8	-33.82	-15.91	-67.3	-10.03	NA
TI610	8/10/2005	bedrock	-64.29	-266.4	ND	-9.16	-68.8	-10.19	NA
TI611	8/10/2005	bedrock	-75.18	-246.7	ND	-6.4	-67.1	-10.11	4.8
TI612	8/10/2005	outwash	NA	NA	NA	-21.32	NA	NA	NA
TI613	8/11/2005	bedrock	NA	NA	NA	-13.24	NA	NA	NA
TI614	8/11/2005	bedrock	-66.12	-180.7	ND	-15.87	-68.3	-10.08	NA
TI615	8/11/2005	bedrock	NA	NA	NA	-16.69	NA	NA	NA

[1] Well identifier on figure 4. USGS local well number consists of a county prefix (TI=Tioga) and a well number. In the central Tioga River valley, inventoried wells were too close together for the local well number to be used on maps. Instead, a cross-reference number from 1 to 27 was used on maps and the cross-reference number is listed in parentheses following the local well number.

Table 5. Laboratory water-quality results for water wells sampled in 2005, Tioga Junction and vicinity, Tioga County, Pennsylvania.—Continued

[Results are presented in this table for detailed analyses of waters from 40 wells. All samples collected by U.S. Geological Survey (USGS). No samples were collected or analyzed for 51 additional inventoried wells numbered TI616 to TI666. Analyses for isotopes, hydrocarbons, and headspace gases were performed at Isotech Laboratories, Inc. Dissolved gas concentrations were analyzed at USGS Reston Dissolved Gas Laboratory (RDGL) and stable isotopes of hydrogen and oxygen in water and dissolved inorganic carbon in water were analyzed at USGS Reston Stable Isotope Lab (RSIL); $\delta^{13}C_{CH4}$, carbon isotopes of methane; δD_{CH4}, hydrogen isotopes of methane; $\delta^{13}C_{C2H6}$, carbon isotopes of ethane; $^{14}C_{CH4}$, carbon-14 isotope of methane; $\delta^{13}C_{DIC}$,carbon isotopes of dissolved inorganic carbon analyzed at RSIL; δD_{water}, hydrogen isotopes of water analyzed at RSIL; $\delta^{18}O_{water}$, oxygen isotopes of water analyzed at RSIL; hydrogen and oxygen stable isotope data reported relative to Vienna Standard Mean Ocean Water (VSMOW); carbonate stable isotope data reported relative to Vienna PeeDee Belemnite (VPDB); per mil, parts per thousand; pMC, percent modern carbon; mg/L milligrams per liter; ND, not detected; NA, not analyzed; —, missing data]

USGS local well number (and cross reference on fig. 4)[1]	Date sampled	Aquifer type	Concentration dissolved in water, in mg/L, as measured at USGS Reston Dissolved Gas Laboratory					Concentration in headspace, in volume percent, as measured at Isotech Laboratories, Inc.[2]			
			Argon	Oxygen	Carbon dioxide	Nitrogen	Methane	Argon	Oxygen[3]	Carbon dioxide	Nitrogen
TI576 (8)	7/19/2005	outwash	0.128	0	0	1.89	41.4	0.142	0.149	0.17	4.93
TI577	7/21/2005	outwash	.632	0	0	15.9	13.5	1.09	1.42	.27	52.38
TI578	7/19/2005	bedrock	.381	0	0	8.05	39	.363	.144	.37	18.11
TI579	6/29/2005	bedrock	.716	—	3.43	20.6	14.4	1.02	1.93	.55	54.54
TI580 (21)	6/30/2005	bedrock	.216	—	.71	8.58	45	.086	1.04	.087	3.77
TI581	6/28/2005	outwash	.732	.14	17.4	21.5	.02	1.77	3.7	.67	93.71
TI582	6/29/2005	bedrock	.827	—	6.71	24.1	2.97	1.31	6.31	1.07	82.45
TI583	6/29/2005	bedrock	.857	1.32	8.21	24.9	0	1.79	5.1	1.48	91.62
TI584	6/29/2005	bedrock	.49	0	5.77	13	34.1	.485	2.25	.65	22.89
TI585	6/29/2005	bedrock	.793	0	13.8	22.2	13.8	1.13	1.43	1.99	55.14
TI586	6/30/2005	bedrock	.735	—	1.76	19.8	7.54	1.28	1.04	.33	67.57
TI587	6/30/2005	bedrock	.748	0	.9	20.4	16.8	1.01	1.35	.13	47.64
TI588	6/30/2005	bedrock	.585	—	11.2	15.2	30.9	.534	.912	1.2	25.15
TI589 (12)	6/30/2005	bedrock	.43	—	6.92	12	33.6	.412	.862	.79	21.26
TI590 (14)	7/13/2005	bedrock	.18	0	15.9	4.06	39.9	.181	.154	.97	8.9
TI591 (10)	7/13/2005	outwash	.121	0	1.96	2.02	39.5	.159	.991	.36	6.09
TI592 (9)	7/13/2005	bedrock	.161	0	1.2	2.53	45.7	.152	.324	.088	5.66
TI593 (22)	7/14/2005	outwash	1.144	12.5	6.98	25.2	.03	1.33	22.58	.35	73.05
TI594	7/14/2005	bedrock	.037	0	13	.64	34.3	.09	1.42	1.61	5.05
TI595	7/14/2005	bedrock	.691	0	11.8	18.2	7.24	1.35	2.11	2.03	68.96

---

[1] Well identifier on figure 4. USGS local well number consists of a county prefix (TI=Tioga) and a well number. In the central Tioga River valley, inventoried wells were too close together for the local well number to be used on maps. Instead, a cross-reference number from 1 to 27 was used on maps and the cross-reference number is listed in parentheses following the local well number.

[2] Isotech Laboratories, Inc. results for gas composition are normalized to 100 percent and reported in mole percent. Mole percent is approximately equal to volume percent and is reported here as volume percent. Isotech Laboratories, Inc. analyzed for carbon monoxide, hydrogen sulfide, helium, hydrogen, argon, oxygen, nitrogen, carbon dioxide, methane, ethane, ethylene, propane, normal and iso-butane, normal and iso-pentane and hexane plus higher hydrocarbons. Selected undetected constituents are omitted in this table.

[3] Biocide added to sample may have increased the amount of oxygen in the sample analyzed by Isotech Laboratories, Inc.

Table 5. Laboratory water-quality results for water wells sampled in 2005, Tioga Junction and vicinity, Tioga County, Pennsylvania.—Continued

[Results are presented in this table for detailed analyses of waters from 40 wells. All samples collected by U.S. Geological Survey (USGS). No samples were collected or analyzed for 51 additional inventoried wells numbered TI616 to TI666. Analyses for isotopes, hydrocarbons, and headspace gases were performed at Isotech Laboratories, Inc. Dissolved gas concentrations were analyzed at USGS Reston Dissolved Gas Laboratory (RDGL) and stable isotopes of hydrogen and oxygen in water and dissolved inorganic carbon in water were analyzed at USGS Reston Stable Isotope Lab (RSIL); $\delta^{13}C_{CH4}$, carbon isotopes of methane; δD_{CH4}, hydrogen isotopes of methane; $\delta^{13}C_{C2H6}$, carbon isotopes of ethane; $^{14}C_{CH4}$, carbon-14 isotope of methane; $\delta^{13}C_{DIC}$,carbon isotopes of dissolved inorganic carbon analyzed at RSIL; δD_{water}, hydrogen isotopes of water analyzed at RSIL; $\delta^{18}O_{water}$, oxygen isotopes of water analyzed at RSIL; hydrogen and oxygen stable isotope data reported relative to Vienna Standard Mean Ocean Water (VSMOW); carbonate stable isotope data reported relative to Vienna PeeDee Belemnite (VPDB); per mil, parts per thousand; pMC, percent modern carbon; mg/L milligrams per liter; ND, not detected; NA, not analyzed; —, missing data]

USGS local well number (and cross reference on fig. 4)[1]	Date sampled	Aquifer type	Concentration dissolved in water, in mg/L, as measured at USGS Reston Dissolved Gas Laboratory					Concentration in headspace, in volume percent, as measured at Isotech Laboratories, Inc.[2]			
			Argon	Oxygen	Carbon dioxide	Nitrogen	Methane	Argon	Oxygen[3]	Carbon dioxide	Nitrogen
TI596	7/19/2005	bedrock	.557	0	0	13.1	23.9	.735	.126	.15	41.01
TI597	7/20/2005	bedrock	.287	0	2.95	5.28	28.1	.39	.374	.83	16.7
TI598	7/20/2005	bedrock	.755	0	0	21.2	1.71	1.9	2.74	.15	87.55
TI599 (13)	7/20/2005	outwash	.377	0	10	9.9	22.9	.67	2.98	3.16	31.14
TI600 (20)	7/21/2005	bedrock	.061	0	0	.93	44.8	.058	.11	.13	2.02
TI601	7/27/2005	outwash	.571	0	0	13.6	15	.961	3.32	2.19	47.2
TI602 (11)	7/27/2005	outwash	.589	0	0	14.9	23.8	.682	1.01	.078	43.61
TI603	7/28/2005	outwash	.732	.2	0	21.5	4.6	1.44	3.45	.42	78.3
TI604	7/28/2005	bedrock	.447	0	0	8.63	29.7	.492	.473	.41	24.54
TI605 (4)	7/28/2005	bedrock	.392	0	0	13.5	24	.738	2.51	1.54	33.24
TI606	7/28/2005	bedrock	0.824	0.21	0	23.5	8.47	1.28	1.96	1.11	70.16
TI607	7/29/2005	outwash	.597	0	0	17.6	7.34	1.15	2.4	.89	70.03
TI608 (5)	7/29/2005	outwash	.287	0	0	5.4	36.2	.292	.115	.067	15.55
TI609	6/29/2005	bedrock	.523	0	19.1	13.4	26.8	.588	.474	2.75	28.86
TI610	8/10/2005	bedrock	.687	0	0	17.7	20.2	.831	2.31	.29	53.43
TI611	8/10/2005	bedrock	.668	0	0	16.9	22.8	.715	.397	.39	46.86
TI612	8/10/2005	outwash	.748	.1	0	23.7	.15	NA	NA	NA	NA
TI613	8/11/2005	bedrock	.732	0	0	20.7	.35	NA	NA	NA	NA
TI614	8/11/2005	bedrock	.758	.78	0	21.7	1.2	1.57	5.57	3.3	84.7
TI615	8/11/2005	bedrock	NA	NA	NA	NA	NA	NA	NA	NA	NA

---

[1] Well identifier on figure 4. USGS local well number consists of a county prefix (TI=Tioga) and a well number. In the central Tioga River valley, inventoried wells were too close together for the local well number to be used on maps. Instead, a cross-reference number from 1 to 27 was used on maps and the cross-reference number is listed in parentheses following the local well number.

[2] Isotech Laboratories, Inc. results for gas composition are normalized to 100 percent and reported in mole percent. Mole percent is approximately equal to volume percent and is reported here as volume percent. Isotech Laboratories, Inc. analyzed for carbon monoxide, hydrogen sulfide, helium, hydrogen, argon, oxygen, nitrogen, carbon dioxide, methane, ethane, ethylene, propane, normal and iso-butane, normal and iso-pentane and hexane plus higher hydrocarbons. Selected undetected constituents are omitted in this table.

[3] Biocide added to sample may have increased the amount of oxygen in the sample analyzed by Isotech Laboratories, Inc.

Table 5. Laboratory water-quality results for water wells sampled in 2005, Tioga Junction and vicinity, Tioga County, Pennsylvania.—Continued

[Results are presented in this table for detailed analyses of waters from 40 wells. All samples collected by U.S. Geological Survey (USGS). No samples were collected or analyzed for 51 additional inventoried wells numbered TI616 to TI666. Analyses for isotopes, hydrocarbons, and headspace gases were performed at Isotech Laboratories, Inc. Dissolved gas concentrations were analyzed at USGS Reston Dissolved Gas Laboratory (RDGL) and stable isotopes of hydrogen and oxygen in water and dissolved inorganic carbon in water were analyzed at USGS Reston Stable Isotope Lab (RSIL); $\delta^{13}C_{CH4}$, carbon isotopes of methane; δD_{CH4}, hydrogen isotopes of methane; $\delta^{13}C_{C2H6}$, carbon isotopes of ethane; $^{14}C_{CH4}$, carbon-14 isotope of methane; $\delta^{13}C_{DIC}$,carbon isotopes of dissolved inorganic carbon analyzed at RSIL; δD_{water}, hydrogen isotopes of water analyzed at RSIL; $\delta^{18}O_{water}$, oxygen isotopes of water analyzed at RSIL; hydrogen and oxygen stable isotope data reported relative to Vienna Standard Mean Ocean Water (VSMOW); carbonate stable isotope data reported relative to Vienna PeeDee Belemnite (VPDB); per mil, parts per thousand; pMC, percent modern carbon; mg/L milligrams per liter; ND, not detected; NA, not analyzed; —, missing data]

USGS local well number (and cross reference on fig. 4)[1]	Date sampled	Aquifer type	Concentration in headspace, in volume percent as measured at Isotech Laboratories, Inc.[2]									
			Helium	Hydrogen	Methane	Ethane	Propane	Iso-butane	Normal butane	Iso-pentane	Normal pentane	Hexanes plus
TI576 (8)	7/19/2005	outwash	0.004	ND	94.38	0.222	ND	ND	ND	ND	ND	ND
TI577	7/21/2005	outwash	ND	ND	44.82	.017	ND	ND	ND	ND	ND	ND
TI578	7/19/2005	bedrock	.01	ND	80.99	.011	ND	ND	ND	ND	ND	ND
TI579	6/29/2005	bedrock	ND	ND	41.95	.012	ND	ND	ND	ND	ND	ND
TI580 (21)	6/30/2005	bedrock	ND	ND	94.42	.601	ND	ND	ND	ND	ND	ND
TI581	6/28/2005	outwash	ND	ND	.107	0	ND	ND	ND	ND	ND	ND
TI582	6/29/2005	bedrock	ND	ND	8.86	0	ND	ND	ND	ND	ND	ND
TI583	6/29/2005	bedrock	ND	ND	.0066	0	ND	ND	ND	ND	ND	ND
TI584	6/29/2005	bedrock	ND	ND	72.91	.818	ND	ND	ND	ND	ND	ND
TI585	6/29/2005	bedrock	ND	ND	40.3	.007	ND	ND	ND	ND	ND	ND
TI586	6/30/2005	bedrock	ND	ND	29.66	.118	ND	ND	ND	ND	ND	ND
TI587	6/30/2005	bedrock	ND	ND	49.86	.013	ND	ND	ND	ND	ND	ND
TI588	6/30/2005	bedrock	ND	ND	72.19	.013	ND	ND	ND	ND	ND	ND
TI589 (12)	6/30/2005	bedrock	ND	ND	76.55	.125	ND	ND	ND	ND	ND	ND
TI590 (14)	7/13/2005	bedrock	.005	ND	89.23	.555	ND	ND	ND	ND	ND	ND
TI591 (10)	7/13/2005	outwash	ND	ND	91.65	.747	ND	ND	ND	ND	ND	ND
TI592 (9)	7/13/2005	bedrock	.005	ND	93.65	.122	ND	ND	ND	ND	ND	ND
TI593 (22)	7/14/2005	outwash	ND	ND	2.67	.016	ND	ND	ND	ND	ND	ND
TI594	7/14/2005	bedrock	ND	ND	90.22	1.61	ND	ND	ND	ND	ND	ND
TI595	7/14/2005	bedrock	ND	ND	25.52	.003	ND	ND	ND	ND	ND	ND

[1] Well identifier on figure 4. USGS local well number consists of a county prefix (TI=Tioga) and a well number. In the central Tioga River valley, inventoried wells were too close together for the local well number to be used on maps. Instead, a cross-reference number from 1 to 27 was used on maps and the cross-reference number is listed in parentheses following the local well number.

[2] Isotech Laboratories, Inc. results for gas composition are normalized to 100 percent and reported in mole percent. Mole percent is approximately equal to volume percent and is reported here as volume percent. Isotech Laboratories, Inc. analyzed for carbon monoxide, hydrogen sulfide, helium, hydrogen, argon, oxygen, nitrogen, carbon dioxide, methane, ethane, ethylene, propane, normal and iso-butane, normal and iso-pentane and hexane plus higher hydrocarbons. Selected undetected constituents are omitted in this table.

Table 5. Laboratory water-quality results for water wells sampled in 2005, Tioga Junction and vicinity, Tioga County, Pennsylvania.—Continued

[Results are presented in this table for detailed analyses of waters from 40 wells. All samples collected by U.S. Geological Survey (USGS). No samples were collected or analyzed for 51 additional inventoried wells numbered TI616 to TI666. Analyses for isotopes, hydrocarbons, and headspace gases were performed at Isotech Laboratories, Inc. Dissolved gas concentrations were analyzed at USGS Reston Dissolved Gas Laboratory (RDGL) and stable isotopes of hydrogen and oxygen in water and dissolved inorganic carbon in water were analyzed at USGS Reston Stable Isotope Lab (RSIL); $\delta^{13}C_{CH4}$, carbon isotopes of methane; δD_{CH4}, hydrogen isotopes of methane; $\delta^{13}C_{C2H6}$, carbon isotopes of ethane; $^{14}C_{CH4}$, carbon-14 isotope of methane; $\delta^{13}C_{DIC}$,carbon isotopes of dissolved inorganic carbon analyzed at RSIL; δD_{water}, hydrogen isotopes of water analyzed at RSIL; $\delta^{18}O_{water}$, oxygen isotopes of water analyzed at RSIL; hydrogen and oxygen stable isotope data reported relative to Vienna Standard Mean Ocean Water (VSMOW); carbonate stable isotope data reported relative to Vienna PeeDee Belemnite (VPDB); per mil, parts per thousand; pMC, percent modern carbon; mg/L milligrams per liter; ND, not detected; NA, not analyzed; —, missing data]

USGS local well number (and cross reference on fig. 4)[1]	Date sampled	Aquifer type	Concentration in headspace, in volume percent as measured at Isotech Laboratories, Inc.[2]									
			Helium	Hydrogen	Methane	Ethane	Propane	Iso-butane	Normal butane	Iso-pentane	Normal pentane	Hexanes plus
TI596	7/19/2005	bedrock	.024	ND	57.94	.01	ND	ND	ND	ND	ND	ND
TI597	7/20/2005	bedrock	ND	ND	81.52	.187	ND	ND	ND	ND	ND	ND
TI598	7/20/2005	bedrock	ND	ND	7.62	0	ND	ND	ND	ND	ND	ND
TI599 (13)	7/20/2005	outwash	ND	ND	61.36	.673	ND	ND	ND	ND	ND	ND
TI600 (20)	7/21/2005	bedrock	.006	ND	97.1	.574	ND	ND	ND	ND	ND	ND
TI601	7/27/2005	outwash	ND	ND	46.32	.008	ND	ND	ND	ND	ND	ND
TI602 (11)	7/27/2005	outwash	.013	ND	54.15	.433	ND	ND	ND	ND	ND	ND
TI603	7/28/2005	outwash	ND	ND	16.34	.019	ND	ND	ND	ND	ND	ND
TI604	7/28/2005	bedrock	.007	ND	74.06	.015	ND	ND	ND	ND	ND	ND
TI605 (4)	7/28/2005	bedrock	ND	ND	61.75	.219	ND	ND	ND	ND	ND	ND
TI606	7/28/2005	bedrock	ND	ND	25.49	0.004	ND	ND	ND	ND	ND	ND
TI607	7/29/2005	outwash	ND	ND	25.52	.006	ND	ND	ND	ND	ND	ND
TI608 (5)	7/29/2005	outwash	0.013	ND	83.69	.273	ND	ND	ND	ND	ND	ND
TI609	6/29/2005	bedrock	ND	ND	67.17	.158	ND	ND	ND	ND	ND	ND
TI610	8/10/2005	bedrock	.005	ND	43.12	.01	ND	ND	ND	ND	ND	ND
TI611	8/10/2005	bedrock	.009	ND	51.62	.006	ND	ND	ND	ND	ND	ND
TI612	8/10/2005	outwash	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
TI613	8/11/2005	bedrock	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
TI614	8/11/2005	bedrock	ND	ND	4.86	0	ND	ND	ND	ND	ND	ND
TI615	8/11/2005	bedrock	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

[1] Well identifier on figure 4. USGS local well number consists of a county prefix (TI=Tioga) and a well number. In the central Tioga River valley, inventoried wells were too close together for the local well number to be used on maps. Instead, a cross-reference number from 1 to 27 was used on maps and the cross-reference number is listed in parentheses following the local well number.

[2] Isotech Laboratories, Inc. results for gas composition are normalized to 100 percent and reported in mole percent. Mole percent is approximately equal to volume percent and is reported here as volume percent. Isotech Laboratories, Inc. analyzed for carbon monoxide, hydrogen sulfide, helium, hydrogen, argon, oxygen, nitrogen, carbon dioxide, methane, ethane, ethylene, propane, normal and iso-butane, normal and iso-pentane and hexane plus higher hydrocarbons. Selected undetected constituents are omitted in this table.

Table 7. Laboratory data for gas samples from gas wells, Tioga Junction and vicinity, Tioga County, Pennsylvania.

[Samples collected by U.S. Geological Survey (USGS) and Pennsylvania Department of Environmental Protection (PADEP). Analyses for isotopes and hydrocarbon and other gases were performed at Isotech Laboratories, Inc. Hydrogen stable isotope data reported relative to Vienna Standard Mean Ocean Water (VSMOW) and carbon stable isotope data reported relative to Vienna PeeDee Belemnite (VPDB). $\delta^{13}C_{CH4}$, carbon isotopes of methane; δD_{CH4}, hydrogen isotopes of methane; $\delta^{13}C_{C2H6}$, carbon isotopes of ethane; $^{14}C_{CH4}$, carbon-14 isotope of methane; $\delta^{13}C_{DIC}$, carbon isotopes of dissolved inorganic carbon; diss, dissolved; per mil, parts per thousand; pMC, percent modern carbon; NA, not analyzed; ND, not detected; obs., observation; —, missing data; WSG, with shallow gas; I/W, injection/withdrawal well]

Well number[1]	Date sampled	Time	Sampling agency	Isotopic composition, in per mil					Well description
				$\delta^{13}C_{CH4}$	δD_{CH4}	$\delta^{13}C_{C2H6}$	$\delta^{13}C_{DIC}$	$^{14}C_{CH4}$	
Krause	06/07/05	13:00	USGS	-34.64	-157.1	-40.35	NA	NA	Oriskany production
Krause	10/25/04	—	PADEP	-34.68	-158.8	ND	NA	NA	Oriskany production
Krause	—	—	PADEP	-34.78	-159.0	ND	NA	NA	Oriskany production
Bolt1	09/07/05	14:00	PADEP	-34.26	-157.3	-40.48	NA	NA	Oriskany obs.--plugged well, yields gas
Bolt1	10/25/04	—	PADEP	-34.35	-159.6	ND	NA	NA	Oriskany obs.--plugged well, yields gas
TW805	09/07/05	8:00	USGS	-40.55	-163.8	-36.43	NA	NA	Oriskany--storage-field obs.
TW509	09/08/05	10:17	USGS	-37.12	-167.4	-32.82	NA	NA	Gas-storage field obs. WSG
TW509	06/08/05	10:45	USGS	-37.00	-166.8	-32.76	NA	NA	Gas-storage field obs. WSG
TW803	09/08/05	9:45	USGS	-39.18	-167.9	-33.80	NA	NA	Gas-storage field obs. WSG
TW803	06/08/05	9:55	USGS	-39.24	-168.7	-33.91	NA	NA	Gas-storage field obs. WSG
TW803	10/06/04	—	PADEP	-40.08	-171.6	ND	NA	NA	Gas-storage field obs. WSG; vent sample
TW201	09/08/05	12:00	USGS	-45.15	-166.6	-30.49	NA	NA	Gas-storage field I/W
TW201	10/25/04	—	PADEP	-45.26	-168.5	ND	NA	NA	Gas-storage field I/W
Meeker	08/09/05	8:00	USGS	-44.08	-170.8	-30.40	NA	NA	Gas-storage field I/W
Meeker	06/08/05	8:40	USGS	-43.74	-167.0	-29.63	NA	NA	Gas-storage field I/W
TW800	08/09/05	9:00	USGS	-44.14	-171.0	-30.43	NA	NA	Gas-storage field I/W
TW800	06/08/05	9:15	USGS	-37.03	-166.8	-32.74	NA	NA	Gas-storage field I/W

Table 7. Laboratory data for gas samples from gas wells, Tioga Junction and vicinity, Tioga County, Pennsylvania.—Continued

[Samples collected by U.S. Geological Survey (USGS) and Pennsylvania Department of Environmental Protection (PADEP). Analyses for isotopes and hydrocarbon and other gases were performed at Isotech Laboratories, Inc. Hydrogen stable isotope data reported relative to Vienna Standard Mean Ocean Water (VSMOW) and carbon stable isotope data reported relative to Vienna PeeDee Belemnite (VPDB). $\delta^{13}C_{CH4}$, carbon isotopes of methane; δD_{CH4}, hydrogen isotopes of methane; $\delta^{13}C_{C2H6}$, carbon isotopes of ethane; $^{14}C_{CH4}$, carbon-14 isotope of methane; $\delta^{13}C_{DIC}$, carbon isotopes of dissolved inorganic carbon; diss, dissolved; per mil, parts per thousand; pMC, percent modern carbon; NA, not analyzed; ND, not detected; obs., observation; —, missing data; WSG, with shallow gas; I/W, injection/withdrawal well]

Well number[1]	Date sampled	Time	Sampling agency	Concentration, in milligrams per liter as measured at USGS Reston Dissolved Gas Laboratory					Well description
				Argon	Oxygen	Carbon dioxide	Nitrogen	Methane	
Krause	06/07/05	13:00	USGS	NA	NA	NA	NA	NA	Oriskany production
Krause	10/25/04	—	PADEP	NA	NA	NA	NA	NA	Oriskany production
Krause	—	—	PADEP	NA	NA	NA	NA	NA	Oriskany production
Bolt1	09/07/05	14:00	PADEP	NA	NA	NA	NA	NA	Oriskany obs.--plugged well, yields gas
Bolt1	10/25/04	—	PADEP	NA	NA	NA	NA	NA	Oriskany obs.--plugged well, yields gas
TW805	09/07/05	8:00	USGS	NA	NA	NA	NA	NA	Oriskany--storage-field obs.
TW509	09/08/05	10:17	USGS	NA	NA	NA	NA	NA	Gas-storage field obs. WSG
TW509	06/08/05	10:45	USGS	NA	NA	NA	NA	NA	Gas-storage field obs. WSG
TW803	09/08/05	9:45	USGS	NA	NA	NA	NA	NA	Gas-storage field obs. WSG
TW803	06/08/05	9:55	USGS	NA	NA	NA	NA	NA	Gas-storage field obs. WSG
TW803	10/06/04	—	PADEP	NA	NA	NA	NA	NA	Gas-storage field obs. WSG; vent sample
TW201	09/08/05	12:00	USGS	NA	NA	NA	NA	NA	Gas-storage field I/W
TW201	10/25/04	—	PADEP	NA	NA	NA	NA	NA	Gas-storage field I/W
Meeker	08/09/05	8:00	USGS	NA	NA	NA	NA	NA	Gas-storage field I/W
Meeker	06/08/05	8:40	USGS	NA	NA	NA	NA	NA	Gas-storage field I/W
TW800	08/09/05	9:00	USGS	NA	NA	NA	NA	NA	Gas-storage field I/W
TW800	06/08/05	9:15	USGS	NA	NA	NA	NA	NA	Gas-storage field I/W

Table 7. Laboratory data for gas samples from gas wells, Tioga Junction and vicinity, Tioga County, Pennsylvania.—Continued

[Samples collected by U.S. Geological Survey (USGS) and Pennsylvania Department of Environmental Protection (PADEP). Analyses for isotopes and hydrocarbon and other gases were performed at Isotech Laboratories, Inc. Hydrogen stable isotope data reported relative to Vienna Standard Mean Ocean Water (VSMOW) and carbon stable isotope data reported relative to Vienna PeeDee Belemnite (VPDB). $\delta^{13}C_{CH4}$, carbon isotopes of methane; δD_{CH4}, hydrogen isotopes of methane; $\delta^{13}C_{C2H6}$, carbon isotopes of ethane; $^{14}C_{CH4}$, carbon-14 isotope of methane; $\delta^{13}C_{DIC}$, carbon isotopes of dissolved inorganic carbon; diss, dissolved; per mil, parts per thousand; pMC, percent modern carbon; NA, not analyzed; ND, not detected; obs., observation; —, missing data; WSG, with shallow gas; I/W, injection/withdrawal well]

Well number[1]	Date sampled	Time	Sampling agency	Concentration[2], in volume percent, as measured at Isotech Laboratories, Inc.					Well description
				Argon	Oxygen	Carbon dioxide	Nitrogen	Helium	
Krause	06/07/05	13:00	USGS	0	0.0606	0.054	0.57	0.0139	Oriskany production
Krause	10/25/04	—	PADEP	0	.0476	.056	.44	.0147	Oriskany production
Krause	—	—	PADEP	0	.0398	.053	.47	.0147	Oriskany production
Bolt1	09/07/05	14:00	PADEP	0	.0603	0	.51	.0109	Oriskany obs.--plugged well, yields gas
Bolt1	10/25/04	—	PADEP	0	.032	0	.37	.0114	Oriskany obs.--plugged well, yields gas
TW805	09/07/05	8:00	USGS	0	.0402	0	.59	.0124	Oriskany--storage-field obs.
TW509	09/08/05	10:17	USGS	.0064	.0921	0	.64	.0161	Gas-storage field obs. WSG
TW509	06/08/05	10:45	USGS	.0115	.192	0	.65	.0164	Gas-storage field obs. WSG
TW803	09/08/05	9:45	USGS	.0	.0391	0	.52	.0187	Gas-storage field obs. WSG
TW803	06/08/05	9:55	USGS	.011	.204	0	1.13	.0184	Gas-storage field obs. WSG
TW803	10/06/04	—	PADEP	.109	2.44	0	10.05	.0164	Gas-storage field obs. WSG; vent sample
TW201	09/08/05	12:00	USGS	.0092	.103	.46	.97	.0075	Gas-storage field I/W
TW201	10/25/04	—	PADEP	.0049	.0303	.47	.63	.0074	Gas-storage field I/W
Meeker	08/09/05	8:00	USGS	.0117	.125	1	1.27	.0151	Gas-storage field I/W
Meeker	06/08/05	8:40	USGS	.0165	.245	1.04	1.31	.0129	Gas-storage field I/W
TW800	08/09/05	9:00	USGS	.0127	.143	.98	1.31	.0166	Gas-storage field I/W
TW800	06/08/05	9:15	USGS	.0139	.192	.91	1.12	.0132	Gas-storage field I/W

Table 7. Laboratory data for gas samples from gas wells, Tioga Junction and vicinity, Tioga County, Pennsylvania.—Continued

[Samples collected by U.S. Geological Survey (USGS) and Pennsylvania Department of Environmental Protection (PADEP). Analyses for isotopes and hydrocarbon and other gases were performed at Isotech Laboratories, Inc. Hydrogen stable isotope data reported relative to Vienna Standard Mean Ocean Water (VSMOW) and carbon stable isotope data reported relative to Vienna PeeDee Belemnite (VPDB). $\delta^{13}C_{CH4}$, carbon isotopes of methane; δD_{CH4}, hydrogen isotopes of methane; $\delta^{13}C_{C2H6}$, carbon isotopes of ethane; $^{14}C_{CH4}$, carbon-14 isotope of methane; $\delta^{13}C_{DIC}$, carbon isotopes of dissolved inorganic carbon; diss, dissolved; per mil, parts per thousand; pMC, percent modern carbon; NA, not analyzed; ND, not detected; obs., observation; —, missing data; WSG, with shallow gas; I/W, injection/withdrawal well]

Well number[1]	Date sampled	Time	Sampling agency	Concentration[2], in volume percent, as measured at Isotech Laboratories, Inc.				Well description
				Hydrogen	Methane	Ethane	Propane	
Krause	06/07/05	13:00	USGS	0.0228	97.06	2.11	0.0917	Oriskany production
Krause	10/25/04	—	PADEP	.0248	97.21	2.09	.0933	Oriskany production
Krause	—	—	PADEP	.0251	97.21	2.08	.0949	Oriskany production
Bolt1	09/07/05	14:00	PADEP	0	96.76	2.52	.124	Oriskany obs.--plugged well, yields gas
Bolt1	10/25/04	—	PADEP	.0073	96.85	2.58	.131	Oriskany obs.--plugged well, yields gas
TW805	09/07/05	8:00	USGS	0	96.88	2.25	.192	Oriskany--storage-field obs.
TW509	09/08/05	10:17	USGS	.1070	96.51	2.47	.135	Gas-storage field obs. WSG
TW509	06/08/05	10:45	USGS	.1080	96.50	2.38	.124	Gas-storage field obs. WSG
TW803	09/08/05	9:45	USGS	.1930	96.96	2.08	.147	Gas-storage field obs. WSG
TW803	06/08/05	9:55	USGS	.1890	96.22	2.04	.144	Gas-storage field obs. WSG
TW803	10/06/04	—	PADEP	.1800	85.20	1.81	.143	Gas-storage field obs. WSG; vent sample
TW201	09/08/05	12:00	USGS	.0101	95.52	2.37	.382	Gas-storage field I/W
TW201	10/25/04	—	PADEP	.0111	95.95	2.34	.379	Gas-storage field I/W
Meeker	08/09/05	8:00	USGS	.0217	94.53	2.42	.388	Gas-storage field I/W
Meeker	06/08/05	8:40	USGS	.0201	94.59	2.23	.345	Gas-storage field I/W
TW800	08/09/05	9:00	USGS	.0237	94.48	2.44	.387	Gas-storage field I/W
TW800	06/08/05	9:15	USGS	.0196	94.64	2.57	.334	Gas-storage field I/W

Table 7. Laboratory data for gas samples from gas wells, Tioga Junction and vicinity, Tioga County, Pennsylvania.—Continued

[Samples collected by U.S. Geological Survey (USGS) and Pennsylvania Department of Environmental Protection (PADEP). Analyses for isotopes and hydrocarbon and other gases were performed at Isotech Laboratories, Inc. Hydrogen stable isotope data reported relative to Vienna Standard Mean Ocean Water (VSMOW) and carbon stable isotope data reported relative to Vienna PeeDee Belemnite (VPDB). $\delta^{13}C_{CH4}$, carbon isotopes of methane; δD_{CH4}, hydrogen isotopes of methane; $\delta^{13}C_{C2H6}$, carbon isotopes of ethane; $^{14}C_{CH4}$, carbon-14 isotope of methane; $\delta^{13}C_{DIC}$, carbon isotopes of dissolved inorganic carbon; diss, dissolved; per mil, parts per thousand; pMC, percent modern carbon; NA, not analyzed; ND, not detected; obs., observation; —, missing data; WSG, with shallow gas; I/W, injection/withdrawal well]

Well number[1]	Date sampled	Time	Sampling agency	Concentration[2], in volume percent, as measured at Isotech Laboratories, Inc.					Well description
				Iso-butane	Normal butane	Iso-pentane	Normal pentane	Hexanes plus	
Krause	06/07/05	13:00	USGS	0.0057	0.0099	0.0024	ND	ND	Oriskany production
Krause	10/25/04	—	PADEP	.0056	.0104	.0021	0	.0015	Oriskany production
Krause	—	—	PADEP	.0053	.0097	.0019	0	0	Oriskany production
Bolt1	09/07/05	14:00	PADEP	.0026	.0093	0	0	0	Oriskany obs.--plugged well, yields gas
Bolt1	10/25/04	—	PADEP	.0031	.0099	0	0	.0016	Oriskany obs.--plugged well, yields gas
TW805	09/07/05	8:00	USGS	.0187	.0179	.0020	0	0	Oriskany--storage-field obs.
TW509	09/08/05	10:17	USGS	.0105	.0111	.0012	0	0	Gas-storage field obs. WSG
TW509	06/08/05	10:45	USGS	.0092	.0091	ND	ND	.0033	Gas-storage field obs. WSG
TW803	09/08/05	9:45	USGS	.0173	.0169	.0044	.0018	.0027	Gas-storage field obs. WSG
TW803	06/08/05	9:55	USGS	.0169	.0162	.0040	.0014	.0031	Gas-storage field obs. WSG
TW803	10/06/04	—	PADEP	.0181	.0184	.0057	.0024	.0036	Gas-storage field obs. WSG; vent sample
TW201	09/08/05	12:00	USGS	.0633	.0618	.0218	.0133	.0107	Gas-storage field I/W
TW201	10/25/04	—	PADEP	.0643	.0638	.0221	.0133	.0140	Gas-storage field I/W
Meeker	08/09/05	8:00	USGS	.0687	.0729	.0298	.0182	.0243	Gas-storage field I/W
Meeker	06/08/05	8:40	USGS	.0581	.0636	.0262	.0163	.0226	Gas-storage field I/W
TW800	08/09/05	9:00	USGS	.0677	.0714	.0291	.0183	.0232	Gas-storage field I/W
TW800	06/08/05	9:15	USGS	.0594	.0619	.0260	.0163	.0212	Gas-storage field I/W

[1] Well identifier on figures 1 or 2.

[2] Isotech Laboratories, Inc., results for gas composition are normalized to 100 percent and reported in mole percent. Mole percent is approximately equal to volume percent and is reported here as volume percent. Isotech Laboratories, Inc., analyzed for carbon monoxide, hydrogen sulfide, helium, hydrogen, argon, oxygne, nitrogen, carbon dioxide, methane, ethane, ethylene, propane, normal and iso-butane, normal and iso-pentane and hexane plus higher hydrocarbons. Ony the detected constituents are reported in this table.

Appendix: The Problems with Methane in Water Wells

The problems of methane dissolved in ground water and why it is important to mitigate the risks

Methane is a colorless, odorless, tasteless gas that is lighter than air; it has been found as a dissolved gas in ground-water samples. Methane can ignite at concentrations between 5 to 15 percent by volume in air, and higher concentrations of methane can quickly dilute to flammable levels (Keech and Gaber, 1982; Eltschlager and others, 2001). The accumulation of methane in an enclosed area may cause oxygen-deficient conditions that can lead to asphyxiation and may cause an explosive environment in which an ignition source such as an electrical outlet, pilot light, match, or a well pump could trigger a violent explosion. Air or gas locking of a submersible pump is also a common problem in gas-producing wells that can result in loss of water pressure or even an explosion in the well. Because methane is lighter than air, it leaves the casing through a vented well cap; thus, proper venting at the well head is essential and other mitigation measures may be needed [see Keech and Gaber (1982)].

How to use well-construction information to estimate how much methane the well water can hold

Because of changes at the source and seasonal variability, the concentration of dissolved methane in well water may fluctuate over time. For these reasons, it is advisable to evaluate dissolved methane concentrations in water from a well as a potential worse-case scenario (maximum concentration). The amount of methane that can be dissolved in ground water is chiefly a function of hydrostatic pressure. The greater the hydrostatic pressure, the greater the theoretical concentration of dissolved methane in the ground water at depth. The relation is linear. Estimating the concentration of dissolved methane in the ground water at depth is possible if well depth and the static ground-water level in the well are known. Driller records typically have this information.

The estimate takes four steps:

1. subtract depth to water from well depth to determine the height of the well water column (H_w);
2. multiply H_w in feet by 0.43 lb/in^2-ft (the weight of a one-inch square column of water one foot high); the result is water pressure in pounds per square inch (psi);
3. divide the weight of the water by 14.7 psi per atmosphere (atm), which provides the weight of the water in atm;
4. multiply the weight of water in atm by 28 mg/L per atm (average solubility of methane in water under one atm pressure of pure methane gas).

For example, consider a water well that is 200 ft deep with a static water level of 100 ft. H_w=200 ft–100 ft=100 ft. The resulting water-column pressure is 100 ft x 0.43 psi/ft = 43 psi or 43 psi / 14.7 psi/atm = 2.93 atm. Hence, the maximum dissolved methane at 100 ft (base of water column in well) is 28 mg/L/atm x 2.93 atm = 82 mg/L.

Dangerous outgassing of methane from well water can involve everyday activities—the 10-minute shower

If 200 liters of water (about 50 gal) containing 82 mg/L dissolved methane is drawn from the bottom of the well into the submersible pump, through the household plumbing, and discharged with outgassing of 82 mg/L methane during a 10-minute shower, the methane gas in a closed 5 × 5 × 7 ft^3 (5,000 L) shower room at 25°C is 82 × 200 = 16,400 mg methane. Using the standard gas-law formula, about 25 L of pure methane outgasses from the water during a 10-minute shower. In the shower room, the resulting composition of the room air would be below the 5-15 percent flammable limits at 0.5 percent. This example is simplified yet illustrates that it takes only 10 minutes for methane to build to near a 1 percent level. It is important to recognize and be aware of the dangers of methane in well water. For more information, see Eltschlager and others (2001, p. 38-39).