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DISSOLVED-METHANE CONCENTRATIONS IN WELL WATER IN THE APPALACHIAN PLATEAU PHYSIOGRAPHIC PROVINCE OF MARYLAND

by

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INTRODUCTION

Methane in well water has been reported anecdotally over the years in the Appalachian Plateau of Maryland; however, no systematic study has been conducted regarding methane occurrence and distribution. The potential development of natural gas reserves in the Marcellus Shale in western Maryland has raised concerns about whether these activities could result in methane contamination of the water-supply aquifers in the region. Well water is not routinely tested for methane in Maryland, since it does not have an established Primary or Secondary Maximum Contaminant Level (MCL). Because of the concern over possible methane contamination of water wells resulting from Marcellus Shale gas-development activities, the Maryland Geological Survey (MGS) evaluated methane samples from 49 wells in 2012 and an additional 28 wells in 2013 in Garrett County and western Allegany County. The purpose of this study was to measure ambient methane concentrations in water wells in the region, and to begin to gain an understanding of the occurrence and distribution of methane in water wells. This report discusses the methane data collected in both years.

Situated in the westernmost part of Maryland, Garrett County and the western section of Allegany County are located within the Appalachian Plateau Physiographic Province, which is characterized by outcrops of sedimentary rocks of Carboniferous (Pennsylvanian and Mississippian) and Devonian periods. The gently folded strata form synclines and anticlines that are the source regions for coal and natural gas, respectively (Nutter and others, 1980). The five major coal basins in the region are the Lower Youghiogheny Basin, Upper Youghiogheny Basin, Castleman Basin, Upper Potomac Basin, and Georges Creek Basin (fig. 1).

Natural gas production and coal mining were once a large part of the economy in this region. The Accident Dome used to be an area of intensive natural gas extraction. Currently, the Accident Dome is used as a gas-storage facility (fig. 2). The other anticlinal structure, the Deer Park Anticline, contains several active natural gas-producing wells (Gregory Day, Maryland Department of the Environment, oral commun., 2012).

From an economic standpoint, coal mining is not as prominent today as it was in the past in Garrett County; however, both strip- and deep-mining operations still exist. There are several economically viable coal seams within the Pennsylvanian System that underlie the basins. Among them are the Upper Freeport coal, Waynesburg coal, Pittsburgh coal, Kittanning coal group, and Bakerstown coal (fig. 3). From a water-quality standpoint, coal seams are among significant sources of methane production (Eltschlager and others, 2001).

Methane is a colorless, odorless, flammable gas that can occur naturally in well water. Methane has a solubility of about 28 milligrams per liter (mg/L) (28,000 micrograms per liter [µg/L]) in water. Even though methane is not a regulated constituent in drinking water, it is recommended that methane levels above 10 mg/L (10,000 µg/L) need to be addressed to prevent asphyxiation and explosive conditions in confined spaces (Eltschlager and others, 2001). Prior to the present study, no quantitative measurements for methane have been done for well waters in Maryland on a regional basis, although methane has occasionally been detected in wells in western Maryland using a simple qualitative test (a flame test using well water placed in a jar) (Steve Sherrard, Garrett County Health Department, oral commun., 2012).

Methane has been identified in ground water in neighboring West Virginia and Pennsylvania. A study conducted in West Virginia from 1997 to 2005 by the U.S. Geological Survey (USGS) sampled 170 water wells for methane (Mathes and White, 2006) (fig. 4). They concluded that higher methane concentrations (greater than 10,000 µg/L) were found in wells completed in Pennsylvanian-age rock formations as well as those located in valleys and on hillsides. These findings suggest that topography and geology are contributing factors in the occurrence of methane. From sampling more than 1,700 wells in Susquehanna County, Pennsylvania, Molofsky and others (2011) also found that methane detection was linked to topography. A study conducted by Stoner and others (1987) in southwestern Pennsylvania showed that, particularly in Greene County, methane in ground water is ubiquitous with concentrations commonly exceeding 25,000 µg/L and as high as 74,000 µg/L.

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METHODS

Well Selection

Seventy-seven wells (mostly residential wells) were selected throughout the Appalachian Plateau Province and sampled for methane and other water-quality constituents. Forty-nine wells were sampled in June through September, 2012; 28 wells were sampled from April through July, 2013. Thirty-five wells were located in coal basins; 42 wells were located in non-coal regions. Topography was used as a selection criterion because of evidence that valley wells have higher methane than other wells (Molofsky and others, 2011). Thirty-two wells were located in valleys, and 45 wells were located in hilltop or hillside topographic settings. Thus, the sampled wells fell into four groups: coal/valley settings (15 wells), coal/hilltop+hillside settings (20 wells), non-coal/valley settings (17 wells), and non-coal/hilltop+hillside settings (25 wells) (tab. 1). Two other wells were sampled that were not included in the evaluation. A sample from well GA Ad 25 was determined (after sample collection) to have gone through a water-treatment system. The other well (GA Ga 19) had been overpurged and was producing a highly turbid sample that was not representative of normal well water. Data from these wells are reported with the other data but are not included in the Results and Discussion section of this report.

Coal basins were defined as those areas underlain by Pennsylvanian-age rocks, based on the 1953 geologic map of Garrett County (Amsden, 1953). Mississippian-age and older rock formations generally do not contain coal, and wells constructed in these formations were classified as non-coal wells. The geologic formation was assigned to each well site based on a Global Positioning System (GPS) location, a georeferenced geologic map by Amsden (1953), and examination of the well log description on the driller's well completion report, which was used to confirm the presence or absence of coal. The main formations are Conemaugh, Allegheny–Pottsville, Mauch Chunk, Greenbrier, Pocono, Hampshire, and Jennings (tab. 2). Of the 77 wells, 35 were completed in Pennsylvanian-age rock formations (mostly the Conemaugh Formation), 19 wells in Mississippian-age rock formations, and 23 wells in Devonian-age rock formations (fig. 5). The topographic setting of each well was determined using topographic maps and site inspections. The altitude of each well was determined from digital elevation model of the area. For each well, the well-permit number was used to acquire well-construction data. Well-construction information, site characteristics, and water-quality data are shown in tables 3 through 5. Other well-selection criteria were as follows:

- Well-permit applications and well-completion reports had to be available.
- Wells could not be equipped with jet pumps (which draw water by suction, which can cause degassing of methane from water).
- Wells were being used on a regular basis.
- Samples of untreated well-water could be obtained.
- Well water could be run for about 30 minutes (i.e. purging and sample collection).
- Well locations provided a reasonable spatial distribution throughout the study area.
- There were no obvious or potential sources of contamination (e.g., the well cap was installed securely; the well was located upgradient of the septic system; the well had not been recently chlorinated, etc.).

Site inspections were performed to determine suitability prior to sampling. Well locations for this study are shown in figure 6.

Sampling Procedures

Water samples were collected at the pressure-tank spigot or another tap source that dispenses untreated well water (fig. 7). A Y-valve would typically be attached to the spigot; a hose was attached to one branch of the Y-valve, and the well water was purged through this hose to a bucket, in which pH, specific conductance, and dissolved oxygen probes were submerged. Field measurements were recorded at 5-minute intervals until measurements stabilized as follows: pH, ± 0.1 pH unit; temperature, ± 0.2 degree Celsius; specific conductance, ± 5 percent (if value was less than 100 microsiemens per centimeter at 25 degrees Celsius [µS/cm]), or ± 3 percent (if value was greater than 100 µS/cm); dissolved oxygen, ± 0.3 mg/L. These measurements were made using a Orion Star A329 portable multiparameter meter[1]. Equipment calibrations were performed daily using appropriate standards and buffers.

Once the purge was completed, the water sample for methane analysis was collected from clear plastic tubing attached to the other branch of the Y-valve. Untreated well-water samples were collected in two 40-milliliter glass vials using the inverted bottle technique (fig. 8). Hydrochloric acid drops were then added to the vials to preserve the sample to pH less than 2; the vials were then re-capped, inverted several times, and stored on ice. The samples were brought back to MGS, and arrangements were made for pickup by the laboratory (ALS Laboratories, Middletown, Pennsylvania**).** The samples were analyzed for dissolved methane, propane, ethane, and ethene concentrations using the headspace method (RSK-175). Samples collected after September 1, 2012 were also analyzed for *n*-butane and isobutane (per change in the laboratory reporting procedure). The laboratory's reporting detection limits for samples analyzed prior to August 23, 2012 were 1 µg/L for methane and propane and 3 µg/L for ethane and ethene. Samples analyzed after August 23, 2012 had new reporting detection limits as a result of the laboratory's yearly instrumental checks. They were 1.5, 3.3, 2.4, 3.2, 4.3, and 4.6 µg/L for methane, ethane, ethene, propane, *n*-butane, and isobutane, respectively.

Alkalinity, chloride, and total hardness were measured by MGS personnel in the field on unfiltered water samples collected after purging had been completed. Alkalinity was measured by digital titration with sulfuric acid and reported as mg/L of $CaCO_3$ (Hach Company, 2008). Chloride concentration was analyzed colorimetrically by titration using a test kit with a minimum reporting limit of 10 mg/L (Hach Company, 2012a). Total hardness was also analyzed colorimetrically by titration (Hach Company, 2012b). These constituents were analyzed primarily because the tests could be quickly and inexpensively performed at the site. It was beyond the scope of this study to characterize overall water chemistry at each site.

In addition to the water-quality measurements, photographs were taken of the purging and sampling area and the wellhead. Latitude and longitude of each well were recorded using a handheld GPS unit (or in some cases using Google Earth). All related documentation, including well permits, completion reports, and field sheets, were compiled for each well.

Forty-nine wells were sampled from June through September 2012; another twenty-eight wells were sampled between April and July, 2013. Sixty-four wells were residential wells; the remaining 13 wells were public, institutional, or commercial water-supply wells.

Three wells (GA Ba 17, GA Cb 95, and GA Ea 65) were sampled monthly for methane and other dissolved gases between December, 2012 and August, 2013 (in addition to their initial sampling earlier in 2012). These samples were collected to determine variations in methane concentrations with time at individual wells. The wells were selected because they each had detectable levels of methane in the initial sample, and also represented a range of methane concentrations.

Two wells (GA Ba 17 and GA Ed 14) were tested for stable isotopes of carbon and hydrogen in the methane molecule (^{13}C and ^{2}H, reported as $\delta^{13}C_{CH4}$ and $\delta^{2}H_{CH4}$). Isotopic analysis can help determine whether the methane has a thermogenic (i.e., generated by heat at greater depths) or biogenic (generated by biological activity at shallower depths) origin.

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[1] The use of tradenames, product names, and laboratories in this report is for identification purposes only, and does not constitute endorsement by the Maryland Geological Survey or the agencies associated with this study.

Isotopic analysis was performed by Isotech Laboratories (Champaign, Illinois) using dual-inlet isotope ratio mass spectrometry. A third well (GA Dc 156) was also sampled for isotopic analysis, but did not contain the minimum 1 mg/L methane required for isotopic analysis (in contrast to an earlier sample collected from the well).

Eleven duplicate samples from seven wells were analyzed for methane and other gases. Methane concentrations in nine of the eleven duplicate pairs were within 15 percent of each other (tab. 6). Variability could originate from one or more sources, including natural methane fluctuations, instrumental error, or human error. The largest difference (2,130 and 3,920 µg/L, or 44 percent) was from a well that had small bubbles visible in the sample bottle, and the results may represent small differences in the time when each bottle was uncapped in order to acidify the sample. In the Results and Discussion section of this report, methane concentrations for wells with duplicate samples refer to the average of the duplicate samples.

RESULTS AND DISCUSSION

Dissolved-methane concentrations in the 77 untreated well-water samples collected from Garrett and Allegany Counties ranged from less than 1.5 to 8,550 µg/L (tab. 4; fig. 9), all of which were below the recommended action limit of 10,000 µg/L (Eltschlager and others, 2001). Methane concentrations in samples from 43 of the 77 wells (56 percent) were less than 1.5 µg/L, whereas 34 samples (44 percent) had dissolved-methane concentrations greater than 1.5 µg/L. Samples from four wells (5 percent) exceeded 1,000 µg/L (fig. 10).

Three wells (GA Aa 14, GA Ae 92, and GA Ed 14) had dissolved ethane concentrations of 3.6, 4.4, and 55.2 µg/L, respectively (tab. 4). No other wells had detectable ethane. None of the samples in this study contained any detectable ethene, propane, n-butane, or isobutane.

Methane in Relation to Topography and Coal/Non-Coal Areas

Methane concentrations with respect to topographic setting (valley versus hillside+hilltop) and geology (coal versus non-coal areas) are shown in figure 11 and table 7. Wells in coal basins had a greater proportion of methane detections[2] (20 of 35 wells, or 57 percent) than wells in non-coal areas (14 of 42 wells, or 33 percent). Most of the detections were from wells in the (Pennsylvanian) Conemaugh Formation, although methane was detected in all geologic formations sampled (tab. 8). Wells located in valleys had a higher proportion of methane detections (18 of 32 wells, or 56 percent) than wells located on hilltops and hillsides (16 of 45 wells, or 36 percent).

With respect to the four well-location categories targeted in this study (coal/valley, coal/hilltop+hillside, non-coal/valley, and non-coal/hilltop+hillside), valley wells in coal basins had the highest proportion of detections (11 of 15 wells, or 73 percent), followed by coal/hilltop+hillside (9 of 20 wells, or 45 percent), non-coal/valley wells (7 of 17 wells, or 41

[2] For the purpose of this report, a methane detection is defined as any sample having a dissolved-methane concentration of greater than or equal to 1.5 µg/L. This represents the higher of the two minimum reporting levels (1 and 1.5 µg/L) reported by ALS Laboratories during the course of the project.

percent), and non-coal/hilltop+hillside wells (7 of 25 wells, or 28 percent) (tab. 9). This is similar to the findings from the West Virginia study (Mathes and White, 2006).

Four wells (GA Ae 92, GA Ba 17, GA Dc 156, and GA Ed 14) had dissolved methane concentrations greater than 1,000 µg/L . Three of these wells (GA Ae 92, GA Ba 17, and GA Ed 14) are valley wells located in coal basins (fig. 11). Two or more coal seams were noted by the drillers on the well-completion reports for these wells, which are located in different coal basins (the Lower Youghiogheny, Upper Potomac, and Castleman Basins, respectively). During purging, water from these three wells showed a slightly cloudy appearance in the purge bucket from many small gas bubbles in the water. Well GA Ba 17 is located approximately 1,000 feet from a well where a buildup of methane gas had reportedly blown the cap off the top of the well (L. Brenneman, Brenneman Well Drilling, personal commun., 2012). The well was remediated by isolating and packing off a coal seam in the well, after which there were no additional problems with methane buildup. Well GA Dc 156 (located in a hilltop/hillside topographic setting) is completed in the Hampshire Formation in a non-coal basin; no coal seams were noted in the driller's log.

Methane in Relation to Other Measured Constituents

pH, specific conductance, dissolved oxygen, alkalinity, chloride, and hardness values for all sites are summarized in table 10. Methane was closely associated with low (less than 1 mg/L) dissolved-oxygen levels (fig. 12). This is consistent with methanogenesis occurring in anaerobic (oxygen-depleted) environments and, thus, where there is methane detected, the dissolved-oxygen concentration would be expected to be low. Methane detections appear to be more prevalent in wells with low (less than 20 mg/L) chloride concentrations; there are few methane detections above 10 µg/L in samples associated with chloride concentrations above 10 mg/L (fig. 13). Approximately one-third of wells with pH less than 7.0 had methane detections, compared with approximately half of wells with pH 7.0 or more (fig. 14). This is likely related to methane being more common in carbonate-rich aquifers than in less reactive aquifers. There was little correlation between methane detections and alkalinity, hardness, or specific conductance (figs. 15 through 17).

Variations in Methane Concentrations in Individual Wells

Three wells (GA Ba 17, GA Cb 95, and GA Ea 65) were sampled for methane and other constituents at approximately monthly intervals between December, 2012 and August, 2013 (fig. 18; tab. 11). Monthly samples were collected because some studies of methane in ground water indicate that methane concentrations in the same well can vary by 30 to 50 percent due differences in atmospheric, hydrologic, and sampling conditions.

The average percent difference from the median monthly methane concentration in each well was between 20 and 30 percent, although individual variations in each well were frequently larger. Methane concentrations tended to vary more than specific conductance (an indicator of total dissolved solids). In well GA Ba 17, methane concentrations ranged from 3,020 to 8,550 µg/L, with an average difference of about 22 percent, whereas specific conductance values varied by less than 10 percent. There was a positive correlation between methane and specific conductance in this well (fig. 19). In well GA Cb 95, methane concentrations ranged from 32 to 109 µg/L, with samples differing from the median value by an average of 22 percent; for the same samples, specific conductance varied by less than about 5 percent. For well GA Ea 65, methane concentrations ranged from less than 1.5 to 795 µg/L; the average difference was about 30 percent, compared to the variation in specific conductance of less than 5 percent. There was a large decrease in methane concentration in the samples collected on January 24, 2013 from GA Cb 95 and GA Ea 65 (GA Ba 17 could not be sampled on that date due to inaccessibility of the sampling site), possibly as a result of a rapid influx of snowmelt or changes in atmospheric pressure. It seems unlikely that the changes observed in methane concentrations were due to differences in the sample collection process, since the differences in the duplicate samples from these sites is much less than the monthly changes.

Stable Isotope Analyses

Stable isotopes have been used by many researchers to help determine the origin of methane found in ground water. Because stable isotopes of an element have different masses, chemical reactions will cause the reactants and products to become preferentially enriched or depleted in a particular isotope. Stable isotopes of carbon and hydrogen in the methane molecule can be used to identify sources of methane (Révész and others, 2010; Molofsky and others, 2011). In particular, these isotopes can determine whether methane is derived from a biogenic source (such as from decomposition of organic material) or from thermogenic processes in the deep subsurface followed by transport into the shallow subsurface via joints, fractures, and other pathways. Stable isotopes of carbon and hydrogen are reported as $\delta^{13}C\text{-}CH_4$ and $\delta^{2}H\text{-}CH_4$, and are calculated as a ratio to a standard, as follows:

$$\delta^{13}C\text{-}CH_4\ (‰) = ([^{13}C_{sample}/^{13}C_{VPDB}] - 1) \times 1{,}000$$

and

$$\delta^{2}H\text{-}CH_4\ (‰) = ([^{2}H_{sample}/^{2}H_{VSMOW}] - 1) \times 1{,}000$$

where

VSMOW = Vienna Standard Mean Ocean Water
VPDB = Vienna Pee Dee Belemnite

Samples from two wells (GA Ba 17 and GA Ed 14) were analyzed for ^{13}C and ^{2}H in methane. (A sample was also collected from a third well [GA Dc 156] but there was insufficient methane [less than 1 mg/L] for the analysis, despite an earlier methane concentrations of 1.72 mg/L). Both of these wells penetrate coal seams. Isotopic data are shown in table 12 and figure 20. The two data points plot within the field for thermogenic gas (as shown by Molovsky and others, 2011). Isotopic data are also shown from Upper and Middle Devonian well-water samples from northeastern Pennsylvania, and also from Marcellus Shale gas in the same area. The trend in thermal maturation is toward the upper right of the graph. The data in Garrett County suggest that the methane is less thermally mature than samples from the Upper and Middle Devonian water samples from Pennsylvania. Wells GA Ba 17 and GA Ed 14 are completed in the (Pennsylvanian-age) Conemaugh and Allegheny-Pottsville Formations, respectively; these formations may not have achieved the thermal maturity of the Middle and Upper Devonian strata in Pennsylvania.

In addition to analyzing the samples for carbon and hydrogen isotopes, Isotech Laboratories also analyzed the samples for methane. A separate sample was also analyzed by ALS Laboratories (the laboratory that analyzed the standard methane samples). Methane analyses from Isotech were almost twice as high as the analyses from ALS Laboratories. The reason is not clear. The Isotech samples were collected in pre-treated plastic bags so that they were never exposed to the air, whereas the standard methane samples were briefly exposed to the air at the time the samples were acidified. These samples also had gas bubbles coming out of solution, while the other lower-methane samples did not. If the higher value is closer to the true methane concentration, the data collected in this study may be most useful as a comparative evaluation of methane concentrations in different settings. Even if the true methane concentrations were twice that reported by the ALS Laboratories, only two samples would have exceeded 10,000 µg/L.

Methane Concentrations in Relation to Gas Storage and Gas Production Areas

Three of the sampled wells (GA Bc 64, GA Bc 65, and GA Cc 75) are located in the vicinity of the Accident Dome gas storage field. Methane concentrations from these three wells were all less than 50 µg/L, and thus do not suggest that gas has migrated from the storage field to the wells. However, it would be prudent to collect additional samples in the vicinity of the field, as the possibility of leakage was not a specific objective of this study.

The southern portion of the Deer Park Anticline has several active natural gas wells that trend northeast-southwest (fig. 2). The surface geology common to these gas wells is the Jennings Formation. Well GA Ea 65 from this study is situated almost between two active gas wells (approximately 2 miles distant from each) and has the same surface geology. The dissolved methane concentration was 704 µg/L (tab. 3), which does not suggest methane migration from the gas wells. Three other sampled wells (GA Eb 79, GA Eb 80, and GA Eb 81) are in proximity to the active gas wells, but are located on the flanks of the anticline on different surface geology (i.e. the Hampshire and Pocono Formations); no methane was detected in these wells.

SUMMARY

Seventy-seven wells in the Appalachian Plateau Physiographic Province of Maryland were sampled for methane and other water-quality constituents in 2012 and 2013. Wells were selected in four geologic and topographic settings: coal/valley settings (15 wells), coal/hilltop+hillside settings (20 wells), non-coal/valley settings (17 wells), and non-coal/hilltop+hillside settings (25 wells). Data obtained from this study indicate:

- Dissolved-methane concentrations ranged from less than 1.5 to 8,550 µg/L. Forty-three of the 77 samples had less than 1.5 µg/L of dissolved methane. Thirty-four of the 77 wells had dissolved-methane concentrations greater than 1.5 µg/L. Samples from four wells exceeded 1,000 µg/L dissolved methane; all were below the recommended action level of 10,000 µg/L.

- Ethane was detected in three of the 77 wells. None of the samples in this study had detectable ethene, propane, n-butane, or isobutane.
- Methane detections (defined as methane concentrations of at least 1.5 µg/L) were observed in wells in both the coal basins and the non-coal areas, although a greater proportion of wells in the coal basins had methane detections (20 out of 35 wells, or about 57 percent) than in the non-coal areas (14 out of 42 wells, or about 33 percent).
- Methane was detected in all geological formations that were sampled.
- Methane was detected in a greater portion of wells in valley settings (18 out of 32 wells, or about 56 percent) than wells in hilltop+hillside settings (16 out of 45 wells; 36 percent).
- Valley wells in coal basins had the highest proportion of detections (11 of 15 wells, or 73 percent), followed by wells in coal/hilltop+hillside settings (9 of 20 wells; 45 percent), non-coal/valley settings (7 of 17 wells, about 41 percent), and non-coal/hilltop+hillside settings (7 of 25 wells, about 28 percent).
- Methane concentrations in monthly samples from three wells varied by 20 to 30 percent from the average median methane concentration in each well.
- Isotopic analyses of $^{13}C\text{-}CH_4$ and $^{2}H\text{-}CH_4$ analyses from two wells indicate a thermogenic origin for the methane.
- Differences were noted in reported methane concentrations in same-well samples by two laboratories, which may have resulted from differences in protocol collection between the two laboratories.

The data collected in this study indicate that methane is commonly present in low concentrations in well water throughout the Appalachian Plateau province of Maryland. Additional methane sampling near the Accident Dome gas field/storage facility would provide more data to as to whether any migration of methane to the shallow aquifers has occurred. We also recommend additional evaluation of inter-laboratory methane analysis.

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Table 1. Numbers of wells sampled in categories based on topography and geology.

	Valley	Hilltop+hillside	Total
Coal basin (syncline)	15	20	35
Non-coal basin (anticline)	17	25	42
Total	32	45	77

Table 2. Geologic formations and their water-bearing properties (Nutter and others, 1980, p. 3).

[gal/min, gallons per minute]

System	Formation	Thickness (feet)	Lithology	Water-bearing properties
Quaternary	Deposits of Holocene and Pleistocene age	0 – 70	Alluvium, peat deposits, slide rock, sand and gravel	Not important aquifers owing to small areal extent and thickness.
Pennsylvanian	Monogahela	240 - 270	Shale, siltstone, sandy shale, sandstone, coal seams	Not an important aquifer because of small areal extent, and the formation is partly drained by mine shafts and drifts.
	Conemaugh	850 – 950	Sandstone, shale, siltstone, red beds, clay, shaley limestone, coal seams	Important aquifer in the coal basins. Well yields range from 1 to 200 gal/min; mean yield 13.3 gal/min and median yield 7 gal/min.
	Allegheny	275 – 325	Sandstone, sandy shale, siltstone, clay beds, coal seams	Important aquifer in the coal basins. Formation is not mapped separately in Garrett County.
	Pottsville	180 – 250	Sandstone (conglomeratic in lower part), siltstone, shale, claystone, a few thin discontinuous coal seams	Moderately important aquifer along the flanks of coal basins. Relatively few wells derive water from this formation, but it has potential for yield moderately large quantities. Well-yield data combined with Allegheny. Well yields range from 0.5 to 150 gal/min; mean yield 13.1 gal/min and median yield 7 gal/min.
Mississippian	Mauch Chunk	500 – 700	Red and green sandy shale, platy sandstone beds	Moderately important aquifer along the flanks of Deer Park and Accident anticlines. Well yields range from 3 to 51 gal/min; mean yield 11.8 gal/min and median yield 10 gal/min.
	Greenbrier	200 – 300	Red and green shale, lenticular limestone, limy sandstone	Moderately important aquifer along flanks of anticlinal structures. Well yields range from 1 to 300 gal/min; mean yield 32.6 gal/min and median yield 14 gal/min. Numerous springs used for water supplies.
	Pocono	700 – 1,300	Coarse-grained sandstone (locally conglomeratic), shale, sandy shale	Important aquifer in Deer Park and Accident anticlines. Many wells and springs in Pocono including several fairly high-yielding wells. Yields range from 0.8 to 130 gal/min; mean yield 13.1 gal/min and median yield 7.5 gal/min.
Devonian	Hampshire	1,400 – 2,000	Brown and green sandy shale, shale, thin-bedded sandstone, red beds	Important aquifer in the Deer Park and Accident anticlines. Well yields range from 1 to 60 gal/min; mean yield 12 gal/min and median yield 8 gal/min.
	Jennings	4,000 – 5,000	Gray and green shale and sandy shale, sandy siltstone, thin-bedded sandstone	Important aquifer in Deer Park anticline area. Well yields range from 0.2 to 50 gal/min; mean yield 8.7 gal/min and median yield 7 gal/min.

Table 3. Well data for sites sampled during this study.

Local well number	Well Permit number	Latitude (ddmmss)	Longitude (ddmmss)	Altitude (ft ASL)	Topographic setting	Coal vs. non-coal	Geologic formation at surface	Well depth (ft BLS)
AL Ac 54	AL-66-0059	394115	785338	1,523	Hilltop/hillside	Coal	Conemaugh	203
AL Ac 55	AL-94-0645	394241	785231	1,751	Hilltop/hillside	Coal	Conemaugh	400
AL Bb 25	AL-94-1377	393838	785723	2,093	Valley	Coal	Conemaugh	200
AL Bb 26	AL-94-0679	393942	785709	2,396	Hilltop/hillside	Coal	Conemaugh	225
AL Bc 70	AL-73-0726	393711	785332	2,178	Hilltop/hillside	Coal	Conemaugh	75
AL Cb 8	AL-01-2926	393342	785709	2,000	Hilltop/hillside	Coal	Conemaugh	86
AL Cb 28	AL-81-0233	393411	785556	2,024	Valley	Coal	Conemaugh	122
AL Da 23	AL-81-0400	392909	790135	1,558	Hilltop/hillside	Coal	Conemaugh	404
GA Aa 11	GA-73-1030	394126	792535	1,544	Valley	Coal	Conemaugh	60
GA Aa 12	GA-94-0550	394242	792631	2,085	Hilltop/hillside	Coal	Conemaugh	197
GA Aa 13	GA-88-1374	394207	792748	2,251	Hilltop/hillside	Coal	Conemaugh	220
GA Aa 14	GA-95-1620	394025	792753	2,262	Hilltop/hillside	Coal	Conemaugh	400
GA Ab 22	GA-81-0703	394243	792221	1,491	Valley	Coal	Conemaugh	103
GA Ac 35	GA-94-0709	394055	791530	2,920	Hilltop/hillside	Non-coal	Pocono	303
GA Ac 40	GA-95-0879	394223	791814	2,518	Hilltop/hillside	Non-Coal	Pocono	600
GA Ac 41	GA-94-0014	394318	791735	2,402	Hilltop/hillside	Non-coal	Greenbrier	122
GA Ac 42	GA-94-1529	394025	791916	2,339	Hilltop/hillside	Non-coal	Hampshire	360
GA Ad 24	GA-81-0177	394126	791013	2,200	Valley	Coal	Conemaugh	87
GA Ad 25[1]	GA-94-0137	394023	791133	2,202	Valley	Coal	Conemaugh	123
GA Ae 92	GA-88-0320	394148	790840	2,139	Valley	Coal	Conemaugh	200
GA Ae 93	GA-94-2679	394059	790725	2,677	Hilltop/hillside	Coal	Conemaugh	172
GA Ae 94	GA-73-2449	394001	790748	2,690	Hilltop/hillside	Coal	Conemaugh	185
GA Af 48	GA-73-2720	394318	790060	2,628	Hilltop/hillside	Non-coal	Hampshire	144
GA Af 49	GA-95-1099	394109	790040	2,597	Hilltop/hillside	Non-coal	Jennings	560
GA Af 50	GA-95-1768	394320	790405	2,479	Hilltop/hillside	Coal	Allegheny-Pottsville	260
GA Ag 42	GA-88-1031	394017	785924	2,426	Valley	Non-Coal	Hampshire	207
GA Ag 43	GA-94-0887	394248	785608	2,777	Hilltop/hillside	Non-coal	Pocono	223
GA Ag 44	GA-81-1150	394129	785734	2,759	Hilltop/hillside	Non-coal	Pocono	196
GA Ba 17	GA-95-1128	393902	792826	2,174	Valley	Coal	Conemaugh	300
GA Ba 18	GA-95-1744	393727	792654	2,249	Hilltop/hillside	Coal	Conemaugh	340
GA Bb 34	GA-88-0314	393915	792307	1,651	Valley	Non-Coal	Mauch Chunk	180
GA Bc 64	GA-88-0903	393841	791700	2,151	Valley	Non-Coal	Hampshire	198
GA Bc 65	GA-94-0354	393819	791902	2,516	Hilltop/hillside	Non-Coal	Hampshire	340
GA Bd 90	GA-88-0019	393722	791437	2,755	Hilltop/hillside	Coal	Conemaugh	160
GA Bd 91	GA-94-0666	393825	791116	2,201	Valley	Coal	Conemaugh	140
GA Be 13	GA-73-0358	393748	790803	2,560	Hilltop/hillside	Non-Coal	Mauch Chunk	123
GA Be 18	GA-88-0961	393651	790653	2,522	Hilltop/hillside	Non-Coal	Hampshire	350
GA Be 19	GA-94-0647	393744	790641	2,497	Hilltop/hillside	Non-Coal	Hampshire	207
GA Bf 25	GA-94-0412	393914	790006	2,493	Hilltop/hillside	Non-Coal	Hampshire	200
GA Bf 26	GA-95-0448	393952	790429	2,535	Valley	Non-Coal	Hampshire	182
GA Bf 27	GA-94-1283	393509	790406	2,542	Hilltop/hillside	Non-coal	Hampshire	183

[1] Sample had passed through treatment system; data not included in evaluation.

Table 3, continued.

Local well number	Well Permit number	Latitude (ddmmss)	Longitude (ddmmss)	Altitude (ft ASL)	Topographic Setting	Coal vs. Non-coal	Geologic Formation at surface	Well depth (ft BLS)
GA Ca 54	GA-94-1345	393108	792807	2,554	Valley	Non-coal	Mauch Chunk	100
GA Ca 55	GA-94-1347	393340	792820	2,648	Hilltop/hillside	Non-Coal	Mauch Chunk	280
GA Ca 56	GA-94-2286	393101	792728	2,689	Hilltop/hillside	Coal	Allegheny-Pottsville	400
GA Ca 57	GA-88-1211	393000	792520	2,426	Hilltop/hillside	Coal	Conemaugh	310
GA Ca 58	GA-95-0636	393147	792635	2,598	Hilltop/hillside	coal	Allegheny-Pottsville	200
GA Cb 94	GA-81-1419	393327	792253	2,421	Valley	Non-Coal	Greenbrier	220
GA Cb 95	GA-94-1667	393419	792346	2,207	Valley	Non-Coal	Pocono	143
GA Cb 96	GA-94-2428	393446	792420	2,614	Hilltop/hillside	Non-Coal	Greenbrier	1,200
GA Cb 97	GA-95-0336	393235	792030	2,550	Valley	Non-coal	Greenbrier	371
GA Cc 73	GA-88-0646	393014	791549	2,543	Valley	Non-Coal	Hampshire	258
GA Cc 74	GA-92-0258	393140	791923	2,750	Hilltop/hillside	Non-Coal	Mauch Chunk	165
GA Cc 75	GA-94-0734	393450	791931	2,784	Hilltop/hillside	Non-Coal	Pocono	700
GA Cc 76	GA-95-1612	393433	791636	2,688	Valley	Coal	Conemaugh	160
GA Cd 49	GA-69-0056	393245	791004	2,423	Hilltop/hillside	Non-Coal	Jennings	330
GA Cd 50	GA-94-1551	393041	791229	2,637	Hilltop/hillside	Non-coal	Jennings	505
GA Da 29	GA-73-1708	392711	792712	2,480	Valley	Coal	Conemaugh	357
GA Da 31	GA-94-0406	392511	792621	2,585	Valley	Coal	Conemaugh	160
GA Db 92	GA-92-0420	392729	792439	2,414	Valley	Coal	Conemaugh	548
GA Db 93	GA-94-2289	392853	792158	2,586	Hilltop/hillside	Non-coal	Greenbrier	182
GA Dc 154	GA-81-1093	392703	791826	2,504	Valley	Non-Coal	Jennings	160
GA Dc 155	GA-94-2145	392509	791720	2,553	Valley	Non-coal	Pocono	442
GA Dc 156	GA-94-2459	392835	791930	2,629	Hilltop/hillside	Non-coal	Hampshire	403
GA Dd 32	GA-66-0029	392735	791421	2,400	Valley	Non-coal	Hampshire	76
GA De 28	GA-95-0939	392637	790831	2,232	Hilltop/hillside	Coal	Conemaugh	505
GA Ea 64	GA-95-1011	392306	792833	2,387	Valley	Coal	Conemaugh	221
GA Ea 65	GA-88-0716	392044	792710	2,476	Valley	Non-Coal	Jennings	247
GA Ea 66	GA-94-1278	392058	792601	2,424	Valley	Non-coal	Jennings	163
GA Ea 67	GA-95-0227	392301	792516	2,672	Hilltop/hillside	Non-coal	Jennings	320
GA Eb 79	GA-94-1319	392126	792230	2,600	Valley	Non-Coal	Hampshire	303
GA Eb 80	GA-95-0987	392158	792136	2,474	Valley	Non-Coal	Hampshire	414
GA Eb 81	GA-95-1211	392156	792123	2,526	Valley	Non-Coal	Pocono	45
GA Ec 25	GA-94-1767	392358	791746	2,940	Hilltop/hillside	Non-Coal	Mauch Chunk	200
GA Ec 26	GA-95-0800	392250	791560	2,630	Hilltop/hillside	Coal	Conemaugh	702
GA Ec 27	GA-95-1686	392027	791959	2,589	Valley	Coal	Conemaugh	128
GA Ec 28	GA-95-0988	392012	791837	2,808	Hilltop/hillside	coal	Conemaugh	362
GA Ed 14	GA-94-0821	392333	791155	1,747	Valley	Coal	Allegheny-Pottsville	445
GA Fa 42	GA-88-1078	391844	792710	2,531	Hilltop/hillside	Non-coal	Jennings	70
GA Ga 19[2]	GA-94-2648	391302	792822	2,910	Hilltop/hillside	Coal	Conemaugh	242

[2] Sample was overpurged and is not considered representative of the well water; data not included in evaluation.

Table 4. Dissolved-methane and other gas concentrations from wells sampled during this study. [µg/L, micrograms per liter; <, less than; --, not analyzed]

Local well number	Date sampled	Ethane (µg/L)	Ethene (µg/L)	Methane (µg/L)	Propane (µg/L)	n-Butane (µg/L)	Isobutane (µg/L)
AL Ac 54	5/3/2013	<3.3	<2.4	12	<3.2	<4.3	<4.6
AL Ac 55	7/24/2013	<3.3	<2.4	10	<3.2	<4.3	<4.6
AL Bb 25	7/9/2013	<3.3	<2.4	4	<3.2	<4.3	<4.6
AL Bb 26	7/31/2013	<3.3	<2.4	3	<3.2	<4.3	<4.6
AL Bc 70	7/8/2013	<3.3	<2.4	<1.5	<3.2	<4.3	<4.6
AL Cb 8	6/19/2013	<3.3	<2.4	<1.5	<3.2	<4.3	<4.6
AL Cb 28	7/23/2013	<3.3	<2.4	70	<3.2	<4.3	<4.6
AL Da 23	7/8/2013	<3.3	<2.4	<1.5	<3.2	<4.3	<4.6
GA Aa 11	6/27/2012	<3	<3	220	<1	--	--
GA Aa 12	6/27/2012	<3	<3	<1	<1	--	--
GA Aa 13	4/24/2013	<3.3	<2.4	<1.5	<3.2	<4.3	<4.6
GA Aa 14	5/15/2013	3.6	<2.4	247	<3.2	<4.3	<4.6
GA Ab 22	9/21/2012	<3.3	<2.4	7	<3.2	<4.3	<4.6
GA Ac 35	5/15/2013	<3.3	<2.4	<1.5	<3.2	<4.3	<4.6
GA Ac 40	7/20/2012	<3	<3	2	<1	--	--
GA Ac 41	5/3/2013	<3.3	<2.4	<1.5	<3.2	<4.3	<4.6
GA Ac 42	4/24/2013	<3.3	<2.4	<1.5	<3.2	<4.3	<4.6
GA Ad 24	8/23/2012	<3.3	<2.4	6	<3.2	--	--
GA Ad 25[1]	8/24/2012	<3.3	<2.4	46	<3.2	--	--
GA Ae 92	8/14/2012	4.4	<3	2,730	<1	--	--
GA Ae 93	7/20/2012	<3	<3	2	<1	--	--
GA Ae 94	8/13/2012	<3	<3	<1	<1	--	--
GA Af 48	4/23/2013	<3.3	<2.4	<1.5	<3.2	<4.3	<4.6
GA Af 49	5/3/2013	<3.3	<2.4	2	<3.2	<4.3	<4.6
GA Af 50	4/23/2013	<3.3	<2.4	2	<3.2	<4.3	<4.6
GA Ag 42	7/18/2012	<3	<3	<1	<1	--	--
GA Ag 43	7/9/2013	<3.3	<2.4	2	<3.2	<4.3	<4.6
GA Ag 44	4/23/2013	<3.3	<2.4	7	<3.2	<4.3	<4.6
GA Ba 17	8/2/2012	<3	<3	8,550	<1	--	--
GA Ba 18	5/15/2013	<3.3	<2.4	6	<3.2	<4.3	<4.6
GA Bb 34	8/14/2012	<3	<3	16	<1	--	--
GA Bc 64	8/23/2012	<3.3	<2.4	43	<3.2	--	--
GA Bc 65	6/14/2012	<3	<3	<1	<1	--	--
GA Bd 90	9/21/2012	<3.3	<2.4	2	<3.2	<4.3	<4.6
GA Bd 91	9/20/2012	<3.3	<2.4	6	<3.2	<4.3	<4.6
GA Be 13	7/20/2012	<3	<3	<1	<1	--	--
GA Be 18	6/14/2012	<3	<3	<1	<1	--	--
GA Be 19	6/21/2012	<3	<3	<1	<1	--	--
GA Bf 25	6/21/2012	<3	<3	<1	<1	--	--
GA Bf 26	6/21/2012	<3	<3	<1	<1	--	--
GA Bf 27	5/16/2013	<3.3	<2.4	<1.5	<3.2	<4.3	<4.6

[1] Sample had passed through treatment system; data not included in evaluation.

Table 4, continued.

Local well number	Date sampled	Ethane (µg/L)	Ethene (µg/L)	Methane (µg/L)	Propane (µg/L)	n-Butane (µg/L)	Isobutane (µg/L)
GA Ca 54	9/19/2012	<3.3	<2.4	<1.5	<3.2	<4.3	<4.6
GA Ca 55	8/1/2012	<3	<3	<1	<1	--	--
GA Ca 56	7/19/2012	<3	<3	1	<1	--	--
GA Ca 57	8/28/2012	<3.3	<2.4	<1.5	<3.2	--	--
GA Ca 58	5/17/2013	<3.3	<2.4	2	<3.2	<4.3	<4.6
GA Cb 94	7/19/2012	<3	<3	7	<1	--	--
GA Cb 95	8/15/2012	<3	<3	61	<1	--	--
GA Cb 96	8/9/2012	<3	<3	15	<1	--	--
GA Cb 97	9/20/2012	<3.3	<2.4	<1.5	<3.2	<4.3	<4.6
GA Cc 73	8/15/2012	<3	<3	<1	<1	--	--
GA Cc 74	7/19/2012	<3	<3	<1	<1	--	--
GA Cc 75	8/2/2012	<3	<3	1	<1	--	--
GA Cc 76	6/27/2012	<3	<3	1	<1	--	--
GA Cd 49	6/20/2012	<3	<3	<1	<1	--	--
GA Cd 50	5/16/2013	<3.3	<2.4	4	<3.2	<4.3	<4.6
GA Da 29	8/28/2012	<3.3	<2.4	<1.5	<3.2	--	--
GA Da 31	8/13/2012	<3	<3	<1	<1	--	--
GA Db 92	6/15/2012	<3	<3	23	<1	--	--
GA Db 93	5/17/2013	<3.3	<2.4	<1.5	<3.2	<4.3	<4.6
GA Dc 154	6/20/2012	<3	<3	30	<1	--	--
GA Dc 155	9/20/2012	<3.3	<2.4	3	<3.2	<4.3	<4.6
GA Dc 156	5/2/2013	<3.3	<2.4	1,720	<3.2	<4.3	<4.6
GA Dd 32	9/19/2012	<3.3	<2.4	<1.5	<3.2	<4.3	<4.6
GA De 28	8/9/2012	<3	<3	<1	<1	--	--
GA Ea 64	8/29/2012	<3.3	<2.4	304	<3.2	--	--
GA Ea 65	8/1/2012	<3	<3	704	<1	--	--
GA Ea 66	5/2/2013	<3.3	<2.4	<1.5	<3.2	<4.3	<4.6
GA Ea 67	4/24/2013	<3.3	<2.4	<1.5	<3.2	<4.3	<4.6
GA Eb 79	7/18/2012	<3	<3	<1	<1	--	--
GA Eb 80	8/29/2012	<3.3	<2.4	<1.5	<3.2	--	--
GA Eb 81	8/29/2012	<3.3	<2.4	<1.5	<3.2	--	--
GA Ec 25	6/15/2012	<3	<3	<1	<1	--	--
GA Ec 26	6/15/2012	<3	<3	1	<1	--	--
GA Ec 27	9/21/2012	<3.3	<2.4	<1.5	<3.2	<4.3	<4.6
GA Ec 28	7/29/2013	<3.3	<2.4	<1.5	<3.2	<4.3	<4.6
GA Ed 14	8/29/2012	55.2	<2.4	7,810	<3.2	--	--
GA Fa 42	5/2/2013	<3.3	<2.4	<1.5	<3.2	<4.3	<4.6
GA Ga 19[2]	5/16/2013	<3.3	<2.4	<1.5	<3.2	<4.3	<4.6

[2] Sample was overpurged and is not considered representative of the well water; data not included in evaluation.

Table 5. Field-measured water-quality data for wells sampled in this study.
[µg/L, micrograms per liter; <, less than; --, not analyzed]

Local well number	Date sampled	pH	Temper-ature (°C)	Specific conductance (µS/cm at 25 deg. C)	Dissolved oxygen (mg/L)	Alkalinity (mg/L as CaCO3)	Bicarb-onate (mg/L as HCO3-)	Chloride (mg/L)	Total hardness (mg/L)
AL Ac 54	5/3/2013	7.1	12.7	470	<1	128	156	<10	225
AL Ac 55	7/24/2013	6.8	13.4	1,960	<1	242	295	<10	1,385
AL Bb 25	7/9/2013	7.5	12.3	429	<1	213	260	<10	251
AL Bb 26	7/31/2013	7.0	11	898	<1	109	133	210	413
AL Bc 70	7/8/2013	6.6	10.8	116	<1	44	54	<10	88
AL Cb 8	6/19/2013	7.7	10.3	410	4.6	190	232	<10	200
AL Cb 28	7/23/2013	7.4	12	434	<1	175	213	<10	260
AL Da 23	7/8/2013	6.9	13.5	446	1.8	179	218	<10	246
GA Aa 11	6/27/2012	7.6	11.9	270	<1	133	162	<10	95
GA Aa 12	6/27/2012	7.5	12.7	403	<1	159	194	18	190
GA Aa 13	4/24/2013	6.6	11.6	110	<1	59	72	<10	49
GA Aa 14	5/15/2013	7.5	12.8	346	<1	173	211	<10	181
GA Ab 22	9/21/2012	7.6	12	396	<1	167	204	<10	169
GA Ac 35	5/15/2013	7.7	10.8	545	<1	106	129	85	220
GA Ac 40	7/20/2012	7.0	13.9	330	<1	69	84	50	125
GA Ac 41	5/3/2013	5.8	11.2	30	9.1	11	13	<10	12
GA Ac 42	4/24/2013	7.2	11.6	193	<1	95	116	<10	79
GA Ad 24	8/23/2012	7.5	11.5	636	<1	113	138	105	261
GA Ad 25[1]	8/24/2012	6.6	11.6	142	<1	61	74	<10	1
GA Ae 92	8/14/2012	7.2	16.8	743	<1	157	191	109	260
GA Ae 93	7/20/2012	6.5	10.4	132	<1	44	54	<10	50
GA Ae 94	8/13/2012	7.3	11.5	247	5.3	111	135	<10	117
GA Af 48	4/23/2013	6.0	10.3	72	6.8	9	11	<10	21
GA Af 49	5/3/2013	7.7	11.4	486	<1	85	104	90	198
GA Af 50	4/23/2013	6.4	10.5	79	<1	43	52	<10	19
GA Ag 42	7/18/2012	8.0	13.3	183	1.4	75	91	<10	75
GA Ag 43	7/9/2013	7.8	12.2	197	<1	90	110	<10	123
GA Ag 44	4/23/2013	5.4	11.2	371	<1	49	60	60.4	120
GA Ba 17	8/2/2012	8.8	12.7	297	<1	147	179	<10	8
GA Ba 18	5/15/2013	7.3	12.5	231	<1	106	129	<10	119
GA Bb 34	8/14/2012	8.6	12.6	291	<1	92	112	18	54
GA Bc 64	8/23/2012	6.9	12.7	202	1.5	58	71	12	45
GA Bc 65	6/14/2012	7.9	11.8	289	<1	116	141	<10	--
GA Bd 90	9/21/2012	7.5	11.2	276	3.2	125	152	<10	136
GA Bd 91	9/20/2012	7.6	11.3	298	<1	139	170	<10	39
GA Be 13	7/20/2012	8.3	13.4	179	5.5	72	88	<10	80
GA Be 18	6/14/2012	6.1	12.3	55	9.4	9	11	<10	--
GA Be 19	6/21/2012	7.1	12	263	<1	96	117	<10	100
GA Bf 25	6/21/2012	5.9	10.4	80	9.8	15	18	<10	30
GA Bf 26	6/21/2012	8.1	11.5	160	2.7	56	68	<10	60
GA Bf 27	5/16/2013	7.3	11	151	8.2	63	77	<10	63

[1] Sample had passed through treatment system; data not included in evaluation.

Table 5, continued.

Local well number	Date sampled	pH	Temper-ature (°C)	Specific conductance (µS/cm at 25 deg. C)	Dissolved oxygen (mg/L)	Alkalinity (mg/L as CaCO3)	Bicarb-onate (mg/L as HCO3-)	Chloride (mg/L)	Total Hard-ness (mg/L)
GA Ca 54	9/19/2012	6.6	10.4	83	5.4	36	44	<10	35
GA Ca 55	8/1/2012	7.0	11.5	150	7.6	54	66	<10	55
GA Ca 56	7/19/2012	6.3	12	58	<1	20	24	<10	10
GA Ca 57	8/28/2012	6.3	12.4	95	7	39	48	<10	39
GA Ca 58	5/17/2013	5.9	11	51	<1	13	16	<10	10
GA Cb 94	7/19/2012	8.4	12.1	202	<1	91	111	<10	45
GA Cb 95	8/15/2012	7.6	11.8	217	<1	87	106	<10	80
GA Cb 96	8/9/2012	7.8	13.9	375	3	149	182	<10	139
GA Cb 97	9/20/2012	6.9	11.4	106	4.1	44	54	<10	45
GA Cc 73	8/15/2012	7.6	10.7	152	1.4	52	63	<10	45
GA Cc 74	7/19/2012	5.5	12.4	69	4.7	8	10	<10	20
GA Cc 75	8/2/2012	8.2	12.2	220	2.1	95	116	<10	25
GA Cc 76	6/27/2012	7.1	11.3	257	<1	129	157	<10	130
GA Cd 49	6/20/2012	8.0	11.8	223	<1	98	120	<10	100
GA Cd 50	5/16/2013	8.2	11.5	231	<1	103	126	<10	105
GA Da 29	8/28/2012	7.8	12.1	218	<1	88	107	<10	102
GA Da 31	8/13/2012	7.8	14	264	<1	127	155	<10	130
GA Db 92	6/15/2012	7.0	11.9	209	<1	80	98	<10	30
GA Db 93	5/17/2013	8.2	10.7	165	9.1	83	101	<10	81
GA Dc 154	6/20/2012	8.4	11.1	196	<1	84	102	<10	80
GA Dc 155	9/20/2012	7.0	13.9	143	<1	56	68	<10	50
GA Dc 156	5/2/2013	7.6	11.2	153	<1	70	85	<10	60
GA Dd 32	9/19/2012	7.9	11	167	6	46	56	15	30
GA De 28	8/9/2012	7.0	13	262	5.3	108	132	<10	124
GA Ea 64	8/29/2012	7.5	11	274	<1	138	168	<10	122
GA Ea 65	8/1/2012	7.9	13.3	172	<1	84	102	<10	55
GA Ea 66	5/2/2013	7.0	11.7	418	1.3	116	141	62	44
GA Ea 67	4/24/2013	7.3	11.7	181	<1	80	98	<10	82
GA Eb 79	7/18/2012	8.2	11.9	130	1.7	49	60	<10	50
GA Eb 80	8/29/2012	8.4	10.8	196	<1	82	100	<10	35
GA Eb 81	8/29/2012	6.2	10	122	7.3	29	35	18	50
GA Ec 25	6/15/2012	5.9	13.6	63	4.5	15	18	<10	25
GA Ec 26	6/15/2012	7.2	13.3	362	1.7	110	134	<10	140
GA Ec 27	9/21/2012	7.4	12.3	671	3.8	154	188	<10	337
GA Ec 28	7/29/2013	7.5	12.4	251	5.0	120	146	<10	164
GA Ed 14	8/29/2012	8.9	13	343	<1	148	180	13	8
GA Fa 42	5/2/2013	6.6	11.8	138	<1	53	65	<10	46
GA Ga 19[1]	5/16/2013	7.3	11.4	205	5.4	88	107	<10	102

[2] Sample was overpurged and is not considered representative of the well water; data not included in evaluation.

Table 6. Duplicate sample analyses for methane and other gases.

[μg/L, micrograms per liter ; <, less than; --, not analyzed]

Local Well Number	Sample date	Ethane (μg/L)	Ethene (μg/L)	Methane (μg/L)	Propane (μg/L)	n-Butane (μg/L)	Isobutane (μg/L)
GA Ba 17	2/25/13	<3.3	<2.4	2,120	<3.2	<4.3	<4.6
		<3.3	<2.4	3,920	<3.2	<4.3	<4.6
	4/25/13	<3.3	<2.4	4,960	<3.2	<4.3	<4.6
		<3.3	<2.4	4,930	<3.2	<4.3	<4.6
	6/18/13	<3.3	<2.4	6,700	<3.2	<4.3	<4.6
		<3.3	<2.4	6,480	<3.2	<4.3	<4.6
GA Bc 64	8/23/2012	<3.3	<2.4	42.8	<3.2	--	--
		<3.3	<2.4	52.2	<3.2	--	--
GA Cb 95	2/25/13	<3.3	<2.4	105	<3.2	<4.3	<4.6
		<3.3	<2.4	91.6	<3.2	<4.3	<4.6
	3/29/13	<3.3	<2.4	103	<3.2	<4.3	<4.6
		<3.3	<2.4	96.2	<3.2	<4.3	<4.6
GA Dd 32	9/19/2012	<3.3	<2.4	<1.5	<3.2	<4.3	<4.6
		<3.3	<2.4	<1.5	<3.2	<4.3	<4.6
GA Ea 64	8/29/2012	<3.3	<2.4	304	<3.2	--	--
		<3.3	<2.4	286	<3.2	--	--
GA Ea 65	1/24/13	<3.3	<2.4	<1.5	<3.2	<4.3	<4.6
		<3.3	<2.4	<1.5	<3.2	<4.3	<4.6
	4/25/13	<3.3	<2.4	661	<3.2	<4.3	<4.6
		<3.3	<2.4	436	<3.2	<4.3	<4.6
GA Ed 14	8/29/2012	55.2	<2.4	7,810	<3.2	--	--
		54.4	<2.4	7,870	<3.2	--	--

Table 7. Summary of methane detections with respect to individual geologic and topographic settings.

[<, less than; ≥, greater than or equal to; µg/L, micrograms per liter]

Setting	Number and percentage of wells with methane <1.5 µg/L		Number and percentage of wells with methane ≥1.5 µg/L		Total number of wells in setting
	Number of wells	Percentage of wells	Number of wells	Percentage of wells	
Coal	15	43%	20	57%	35
Non-coal	28	67%	14	33%	42
Valley	14	44%	18	56%	32
Hilltop+hillside	29	64%	16	36%	45

Table 8. Dissolved-methane concentrations with respect to geologic formations in the Appalachian Plateau Province.

[<, less than; >, greater than]

System	Geologic formation	Number of wells with dissolved-methane concentrations (in micrograms per liter):			Total samples
		<1.5	1.5 – 1,000	>1,000	
Pennsylvanian	Conemaugh	14	15	2	**31**
	Allegheny and Pottsville	1	2	1	**4**
Mississippian	Mauch Chunk	5	1	0	**6**
	Greenbrier	3	2	0	**5**
	Pocono	3	5	0	**8**
Devonian	Hampshire	13	1	1	**15**
	Jennings	4	4	0	**8**
	Total samples	**43**	**30**	**4**	**77**

Table 9. Summary of methane detections by topographic setting within each geologic setting.

[<, less than; ≥, greater than or equal to; µg/L, micrograms per liter]

Geologic setting	Topographic setting	Number and percentage of wells with methane <1.5 µg/L: Number of wells	Number and percentage of wells with methane <1.5 µg/L: Percentage of wells	Number and percentage of wells with methane ≥1.5 µg/L: Number of wells	Number and percentage of wells with methane ≥1.5 µg/L: Percentage of wells	Total number of wells in setting
Coal	**Valley**	4	27%	11	73%	15
	Hilltop+hillside	11	30%	9	45%	20
Non-coal	**Valley**	10	59%	7	41%	17
	Hilltop+hillside	18	72%	7	28%	25

Table 10. Water-quality data summarized by geologic and topographic settings. Top number is median value; values in parentheses contain the range.

[µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; <, less than]

Category	Number of wells	Dissolved methane (µg/L)	pH	Specific conductance (µS/cm)	Dissolved oxygen (mg/L)	Alkalinity (mg/L as $CaCO_3$)	Chloride (mg/L)	Total hardness (mg/L as $CaCO_3$)
Coal/Valley	15	6.7 (<1.5 – 8,550)	7.5 (7 – 8.9)	298 (209 – 743)	<1 (<1 – 3.8)	139 (80 – 213)	<10 (<10 – 109)	130 (8 – 337)
Coal/Hilltop+Hillside	20	<1.5 (<1.5 – 247)	7.0 (5.9 – 7.7)	257 (51 – 1,960)	<1 (<1 – 7.0)	110 (13 – 242)	<10 (<10 – 210)	130 (10 – 1,385)
Non-Coal/Valley	17	<1.5 (<1.5 – 704)	7.9 (6.2 – 8.6)	172 (83 – 418)	1.4 (<1 – 7.3)	58 (29 – 116)	<10 (<10 – 18)	50 (30 – 80)
Non-Coal/Hilltop+Hillside	25	<1.5 (<1.5 – 14.7)	7.3 (5.4 – 8.3)	181 (30 – 545)	<1 (<1 – 9.8)	72 (8 – 149)	<10 (<10 – 90)	80[1] (12 – 220)

[1]Two wells were not tested for hardness.

Table 11. Monthly methane and other water-quality data from selected wells in Garrett County, Maryland.

[mg/L, milligrams per liter; µg/L, micrograms per liter; --, not analyzed]

Well number and Date sampled	pH	Temperature (°C)	Specific conductance (µS/cm at 25 deg.C)	Dissolved oxygen (mg/L)	Alkalinity (mg/L as $CaCO_3$)	Bicarbonate (mg/L as HCO_3^-)	Chloride (mg/L)	Total hardness (mg/L)	Ethane (µg/L)	Ethene (µg/L)	Methane (µg/L)	Propane (µg/L)	n-Butane (µg/L)	Isobutane (µg/L)
GA Ba 17														
8/2/2012	8.8	12.7	297	<1	147	179	<10	8	<3	<3	8,550	<1	--	--
12/20/2012	8.7	11.4	287	<1	154	188	<10	10	<3.3	<2.4	4,470	<3.2	<4.3	<4.6
2/25/2013[1]	7.6	10.6	217	<1	119	145	<10	18	<3.3	<2.4	3,020	<3.2	<4.3	<4.6
3/29/2013	8.4	11.3	260	<1	151	184	<10	10	<3.3	<2.4	5,530	<3.2	<4.3	<4.6
4/25/2013[1]	7.9	12.0	236	<1	134	163	<10	17	<3.3	<2.4	4,945	<3.2	<4.3	<4.6
5/21/2013	8.8	12.8	287	<1	147	179	<10	9	<3.3	<2.4	6,160	<3.2	<4.3	<4.6
6/18/2013[1]	8.8	12.5	301	<1	158	192	<10	8	<3.3	<2.4	6,590	<3.2	<4.3	<4.6
7/19/2013	8.8	13.1	289	<1	146	178	<10	9	<3.3	<2.4	7,190	<3.2	<4.3	<4.6
7/24/2013	8.7	12.9	291	<1	149	182	<10	--	<3.3	<2.4	6,800	<3.2	<4.3	<4.6
8/21/2013	9.0	12.9	300	<1	161	196	<10	--	<3.3	<2.4	8,140	<3.2	<4.3	<4.6
GA Cb 95														
8/15/2012	7.6	11.8	217	<1	87	106	<10	80	<3	<3	61.3	<1	--	--
12/20/2012	7.6	10.6	209	<1	92	112	<10	71	<3.3	<2.4	76.3	<3.2	<4.3	<4.6
1/24/2013	7.5	9.8	204	<1	102	124	<10	78	<3.3	<2.4	31.9	<3.2	<4.3	<4.6
2/25/2013[1]	7.6	10.4	207	<1	91	111	<10	73	<3.3	<2.4	98.3	<3.2	<4.3	<4.6
3/29/2013[1]	7.6	10.4	203	<1	84	102	<10	73	<3.3	<2.4	99.6	<3.2	<4.3	<4.6
4/25/2013	7.6	11.1	201	<1	94	115	<10	74	<3.3	<2.4	81.7	<3.2	<4.3	<4.6
5/21/2013	7.6	11.7	205	<1	86	105	<10	73	<3.3	<2.4	83.7	<3.2	<4.3	<4.6
6/18/2013	7.5	11.3	212	<1	86	105	<10	72	<3.3	<2.4	62.2	<3.2	<4.3	<4.6
7/19/2013	7.5	12.6	201	<1	87	106	<10	72	<3.3	<2.4	76.1	<3.2	<4.3	<4.6
8/21/2013	7.6	12.0	206	<1	87	106	<10	--	<3.3	<2.4	109	<3.2	<4.3	<4.6

[1] Ethane, ethene, methane, propane, n-butane, and isobutane values are averages of two replicate values

Table 11, continued.

Date sampled	pH	Temp-erature (°C)	Specific conduct-ance (µS/cm at 25 deg.C)	Dissolved oxygen (mg/L)	Alkalinity (mg/L as $CaCO_3$)	Bicarbonate (mg/L as $HCO3^-$)	Chloride (mg/L)	Total hardness (mg/L)	Ethane (µg/L)	Ethene (µg/L)	Methane (µg/L)	Propane (µg/L)	n-Butane (µg/L)	Isobutane (µg/L)
GA Ea 65														
8/1/2012	7.9	13.3	172	<1	84	102	<10	55	<3	<3	704	<1	--	--
12/20/2012	7.8	10.7	165	<1	94	115	11	53	<3.3	<2.4	487	<3.2	<4.3	<4.6
1/24/2013[1]	7.9	10.5	162	<1	95	116	<10	53	<3.3	<2.4	<1.5	<3.2	<4.3	<4.6
2/25/2013	7.9	10.4	163	<1	88	107	<10	52	<3.3	<2.4	677	<3.2	<4.3	<4.6
3/29/2013	7.9	10.5	161	<1	91	111	<10	52	<3.3	<2.4	103	<3.2	<4.3	<4.6
4/25/2013[1]	7.9	11.3	161	<1	96	117	<10	47	<3.3	<2.4	549	<3.2	<4.3	<4.6
5/21/2013	7.9	11.8	162	<1	84	102	<10	52	<3.3	<2.4	591	<3.2	<4.3	<4.6
6/18/2013	7.9	12.1	168	<1	89	109	<10	50	<3.3	<2.4	643	<3.2	<4.3	<4.6
7/19/2013	7.8	12.4	161	<1	81	99	<10	54	<3.3	<2.4	479	<3.2	<4.3	<4.6
8/22/2013	7.8	12.8	166	<1	87	106	<10	--	<3.3	<2.4	795	<3.2	<4.3	<4.6

[1] Ethane, ethene, methane, propane, n-butane, and isobutane values are averages of two replicate values

Table 12. $\delta^{13}C\text{-}CH_4$ and $\delta^{2}H\text{-}CH_4$ values and associated methane concentrations from wells GA Ba 17 and GA Ed 14.

[‰, per mil; µg/L, micrograms per liter]

Well number	Date	$\delta^{13}C\text{-}CH_4$ (‰)	$\delta^{2}H\text{-}CH_4$ (‰)	Methane (analyzed by Isotech Laboratories) (µg/L)	Methane (analyzed by ALS Laboratories) (µg/L)
GA Ba 17	7/24/2013	-52.54	-209.2	12,000	6,800
GA Ed 14	7/24/2013	-52.89	-214.5	14,000	8,010

$\delta^{13}C\text{-}CH_4$ (‰) = $([^{13}C_{sample}/^{13}C_{VPDB}] - 1) \times 1{,}000$

where VPDB = Vienna Pee Dee Belemnite

$\delta^{2}H\text{-}CH_4$ (‰) = $([^{2}H_{sample}/^{2}H_{VSMOW}] - 1) \times 1{,}000$

where VSMOW = Vienna Standard Mean Ocean Water

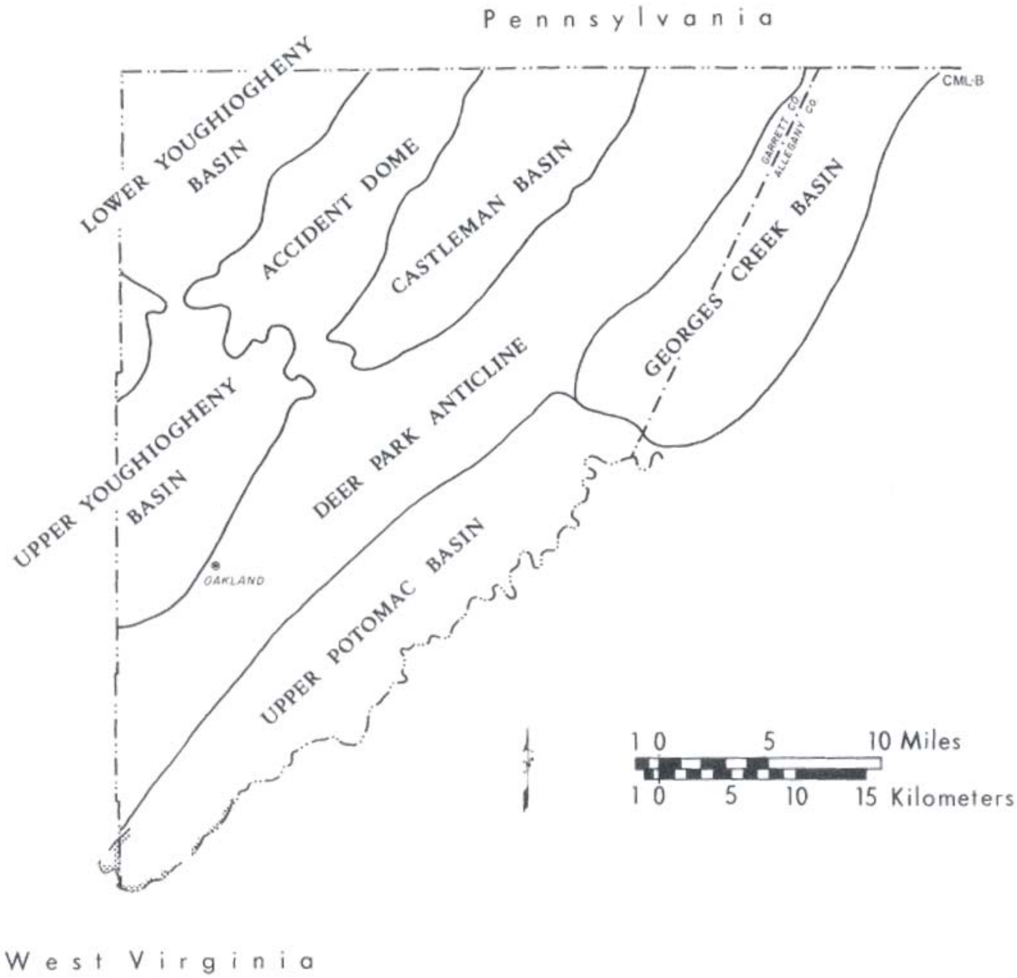

Figure 1. Geologic structure of Garrett County showing synclinal basins (Lower and Upper Youghiogheny Basin, Castleman Basin, Upper Potomac Basin and Georges Creek Basin), the Accident Dome and Deer Park Anticline (from Duigon and Smigaj, 1985).

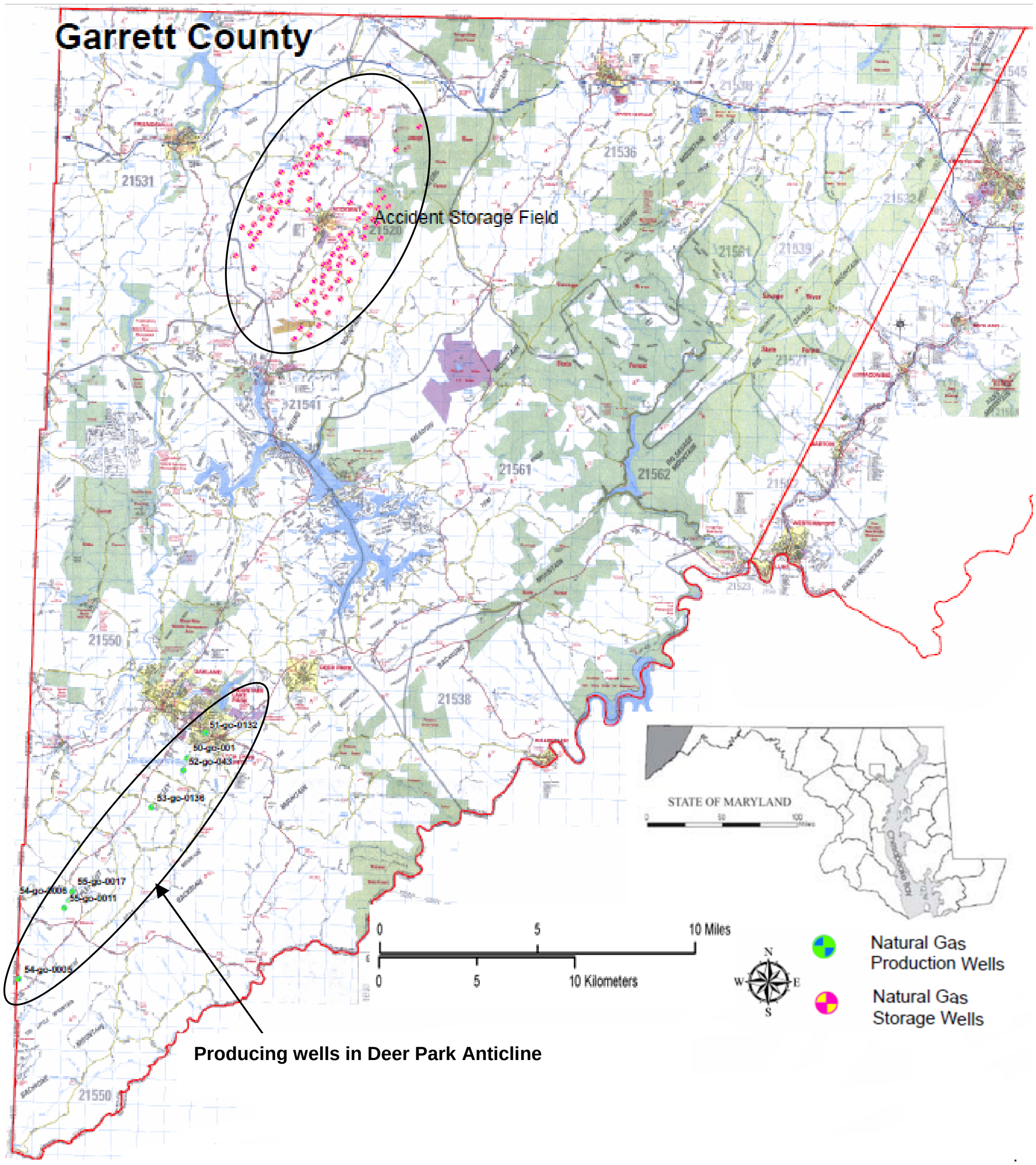

Figure 2. Location of natural gas production and storage wells in Garrett County, Maryland (modified from Maryland Department of the Environment Mining Program, 2007).

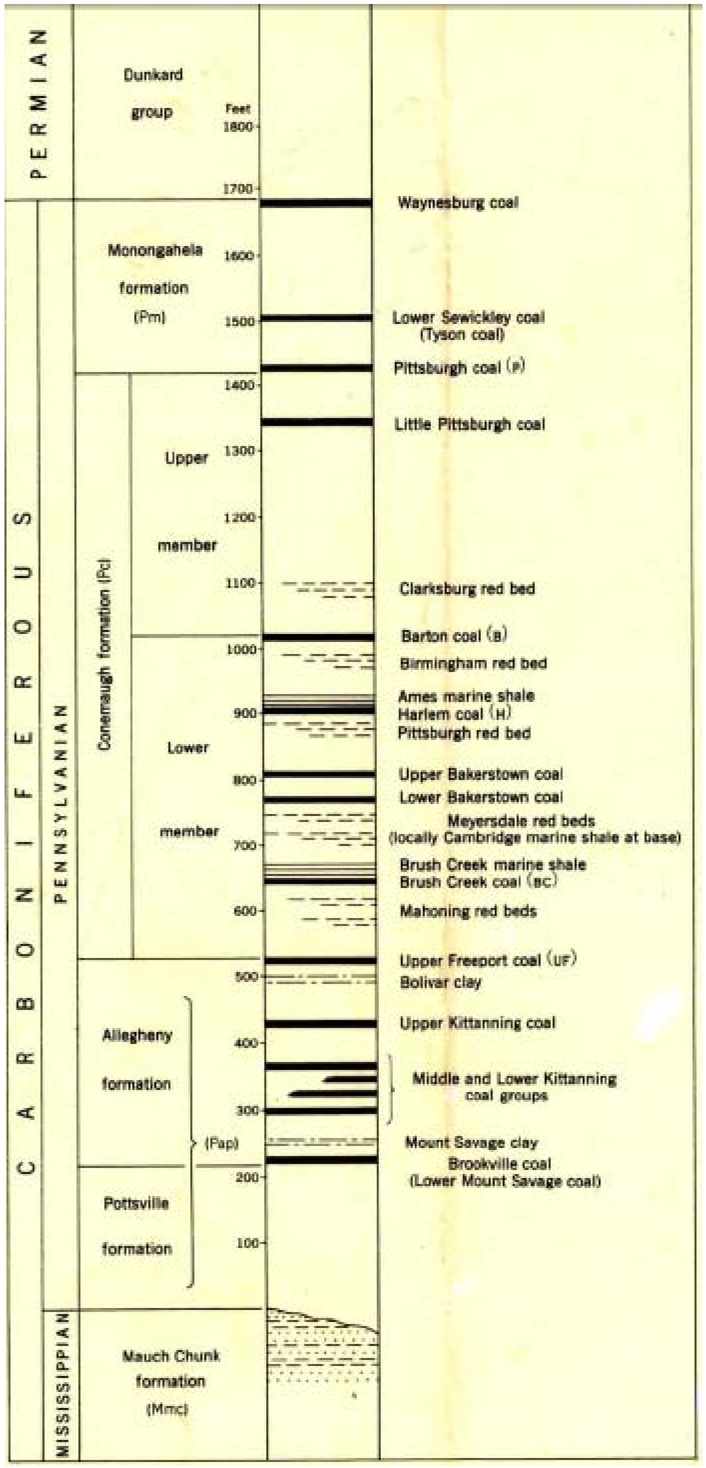

Figure 3. Subdivisions of the Pennsylvanian strata in Maryland (from Amsden, 1953).

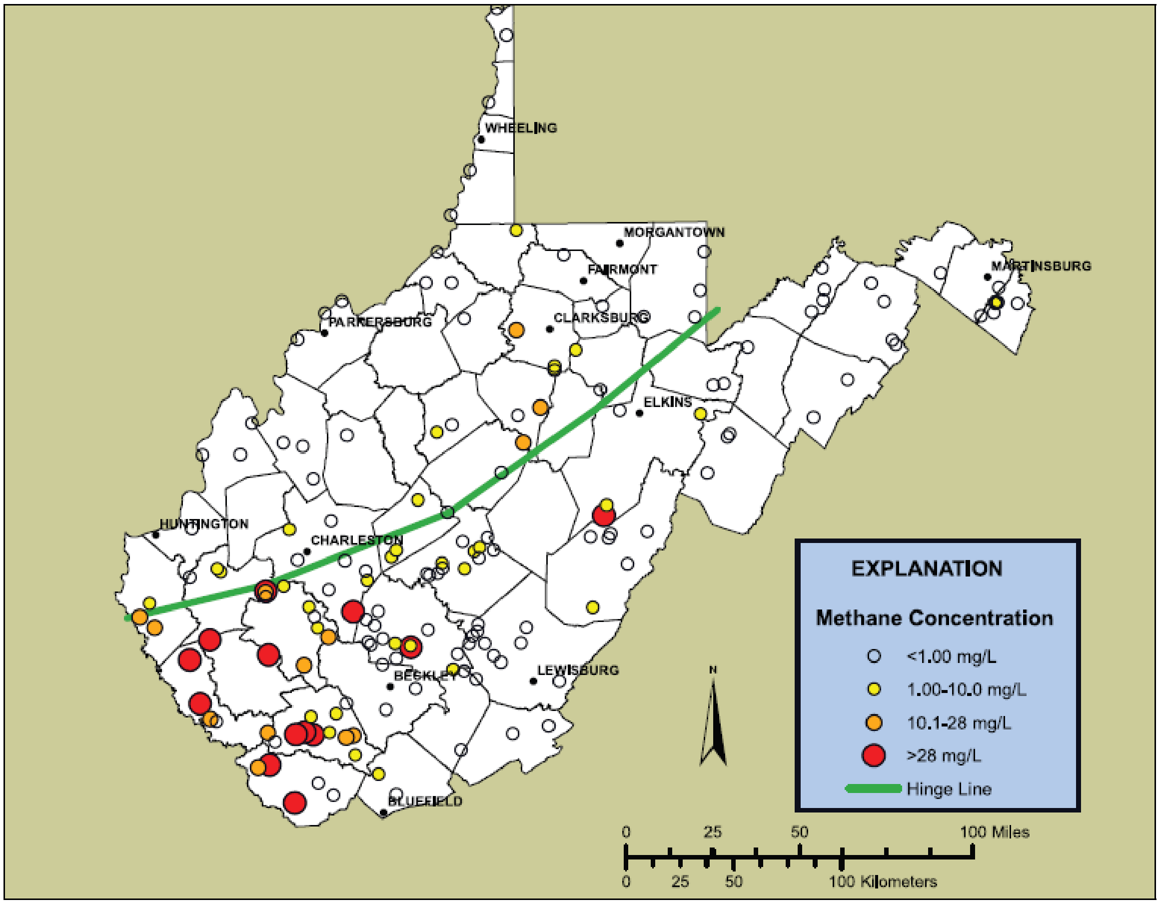

Figure 4. Methane concentrations in water wells of West Virginia. South of the hinge line is the low-sulfur coal; north of the hinge line is high-sulfur coal (Mathes and White, 2006).

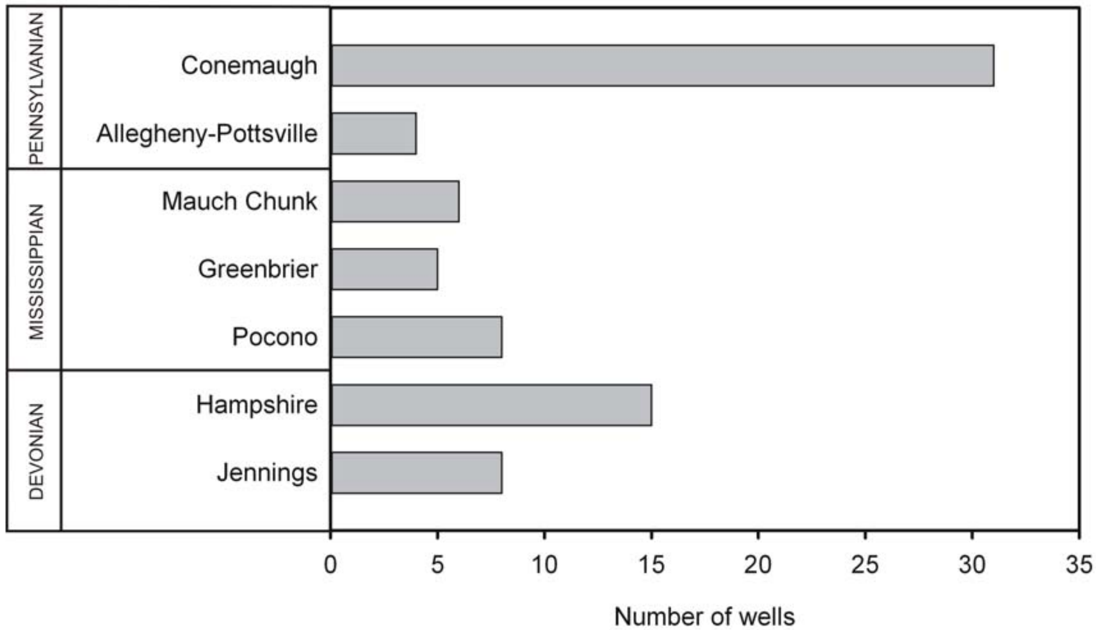

Figure 5. Number of wells associated with each geologic formation in the Appalachian Plateau Province.

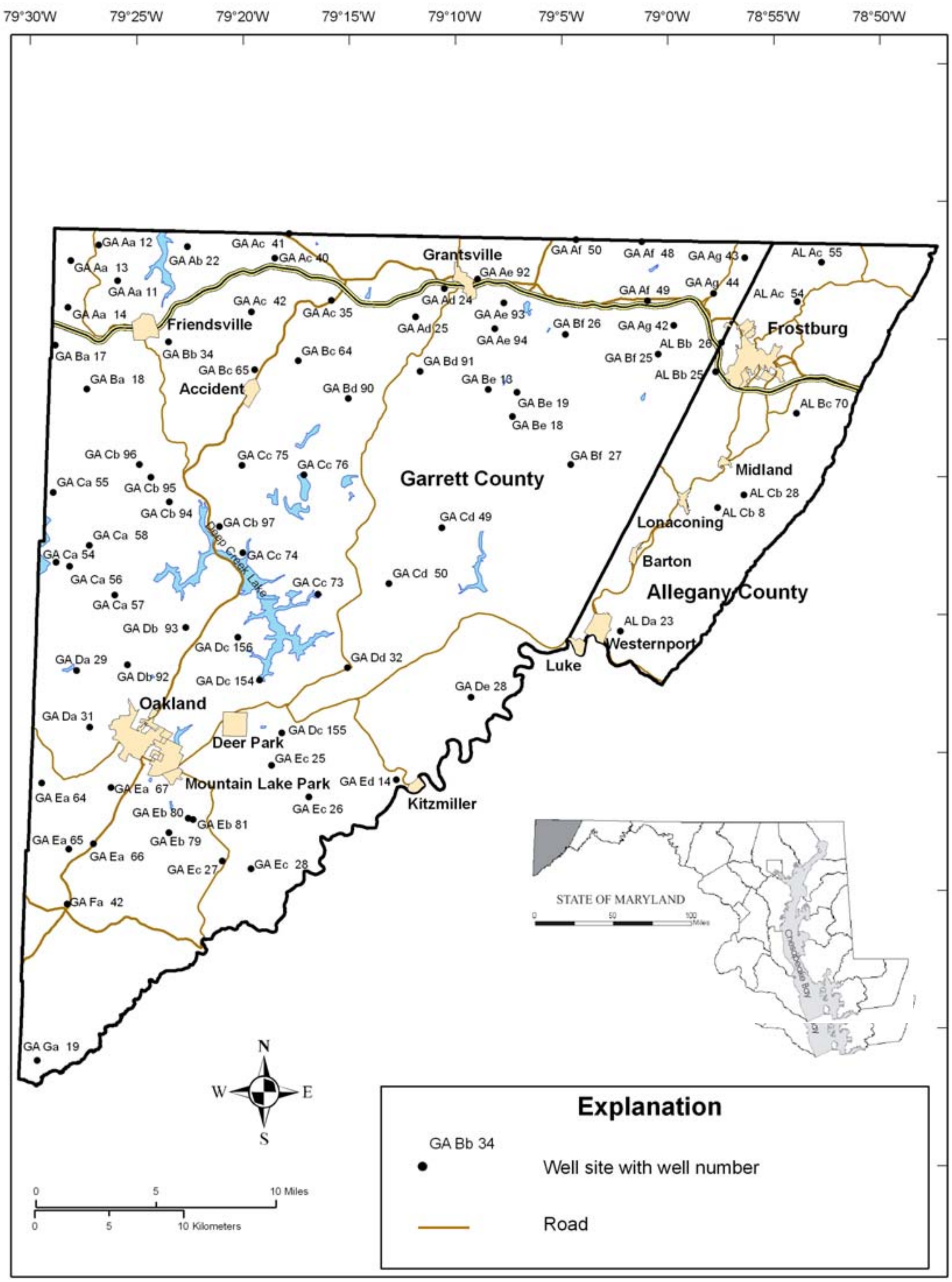

Figure 6. Well locations and well permit numbers for wells sampled in this study.

A B

Figure 7. Photographs showing different sampling ports for dissolved-methane collection. Water treatment systems, if present, were bypassed during purging and sampling.

A B C

Figure 8. Inverted bottle technique for dissolved-methane collection of well-water samples. Step A: Clear tubing is connected to untreated water source (e.g., pressure tank spigot), and the water is turned on to fill up the sampling bucket. Step B: Cap is removed from glass vial. Step C: Glass vial is inverted and placed over the clear tubing. Water fills the vial and is allowed to flush three vial volumes before the vial is capped underwater (modified from Hirsche and Mayer, 2009).

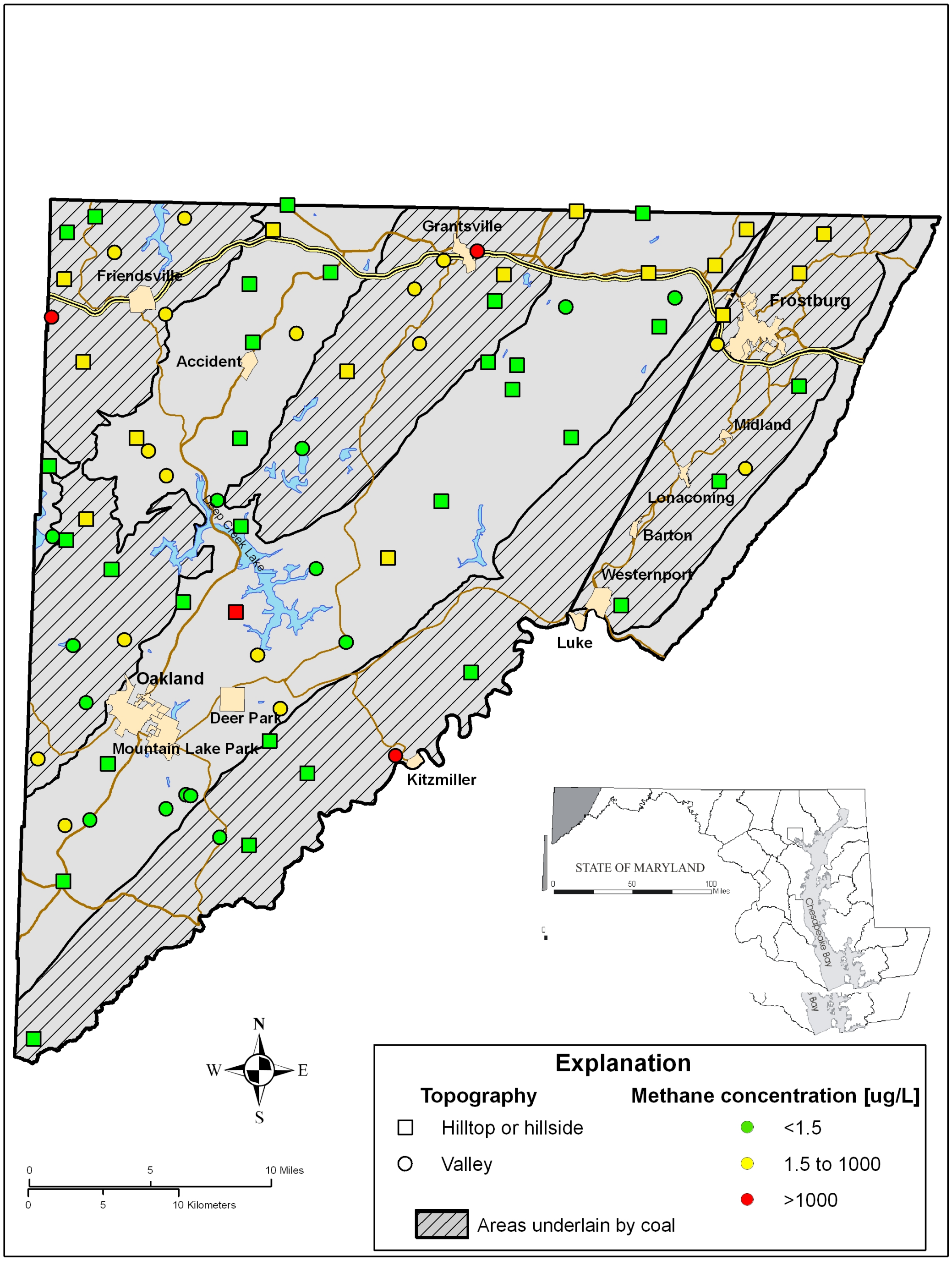

Figure 9. Map showing dissolved-methane concentrations with respect to geologic and topographic setting. The red labels display the dissolved methane concentration values.

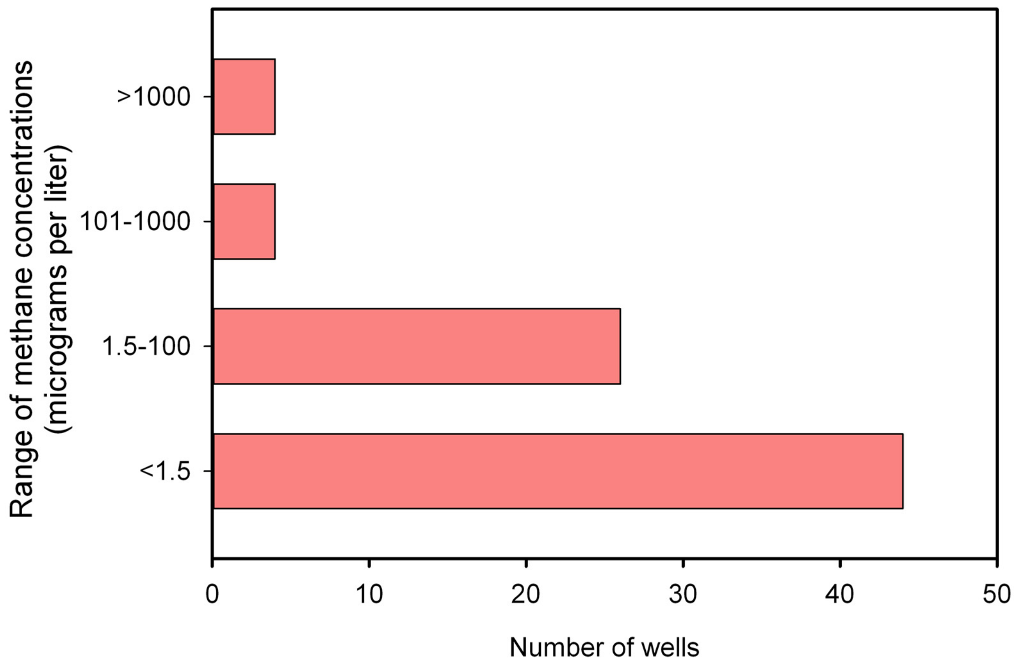

Figure 10. Number of wells associated with each range of dissolved-methane concentrations for well-water sampled in this study.

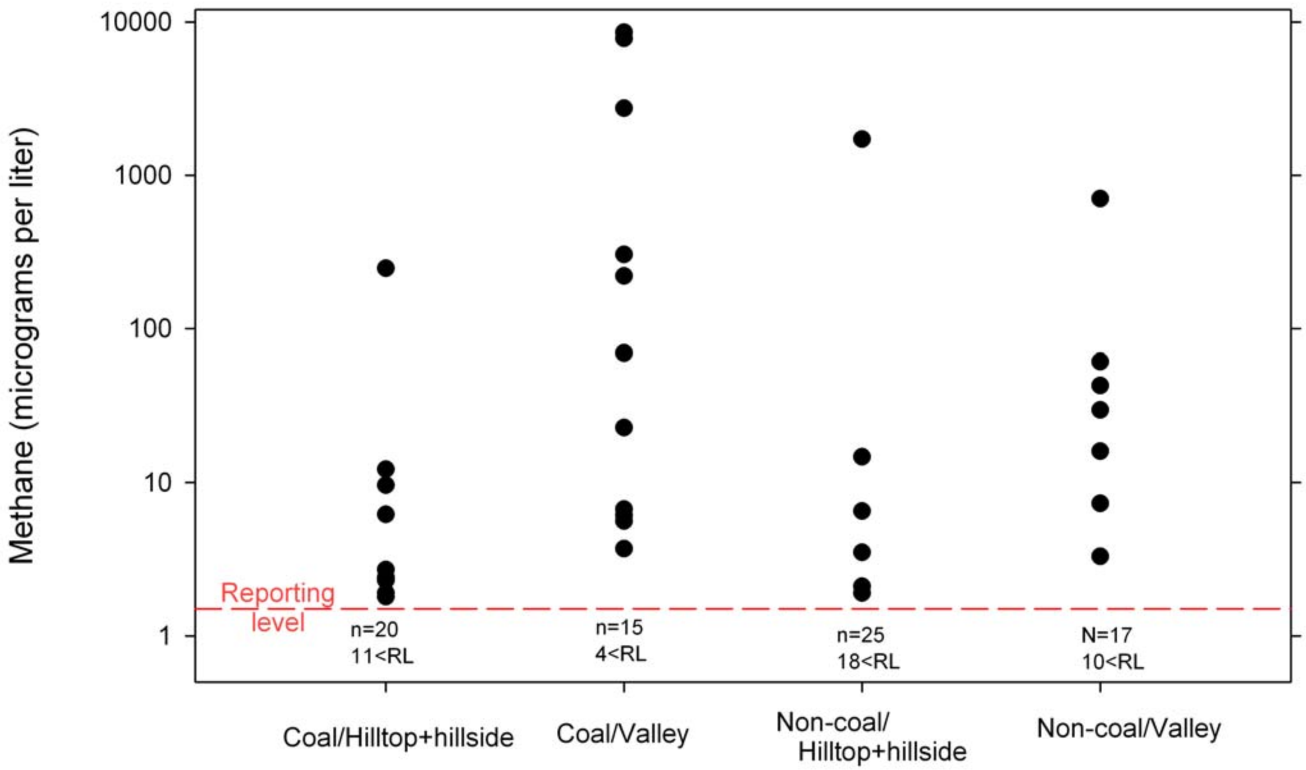

Figure 11. Relation of dissolved-methane concentrations to topographic (valley versus hilltop/hillside) and geologic (coal basin vs. non-coal basin) settings. The number of non-detects per category is shown below the graph, but is not plotted.

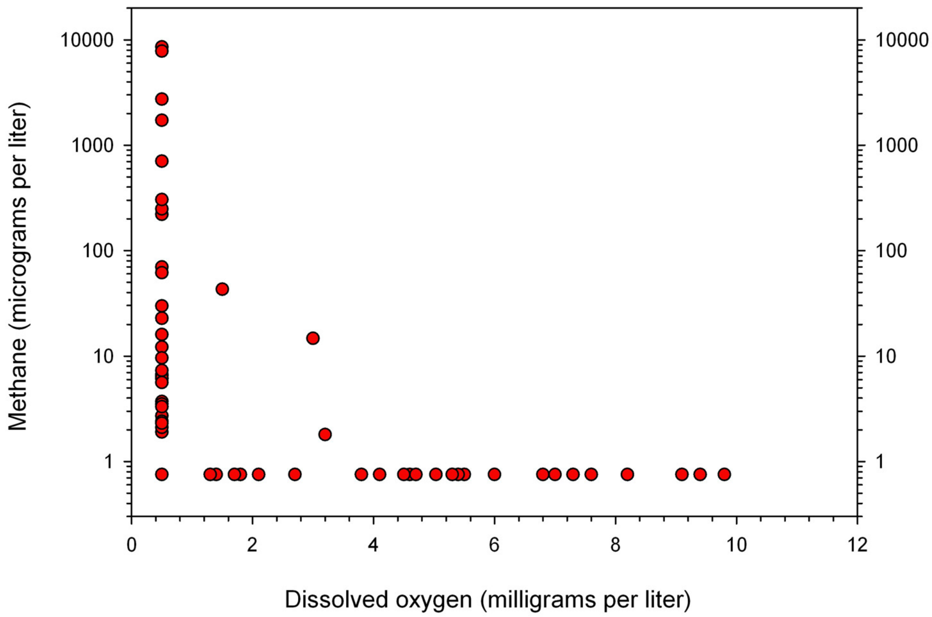

Figure 12. Relation of methane and dissolved oxygen in well-water samples in the Appalachian Plateau Province.

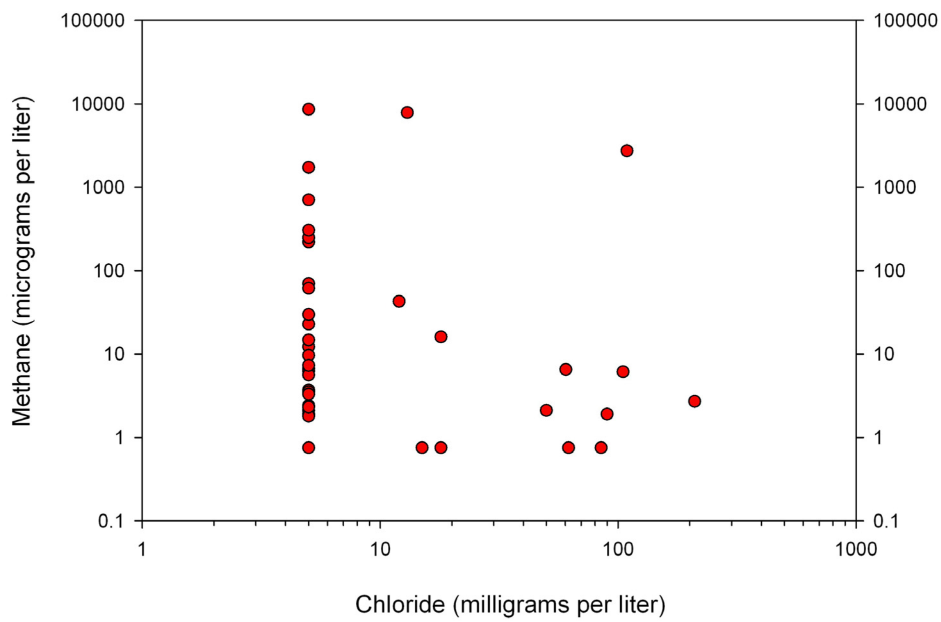

Figure 13. Relation of methane and chloride in well-water samples in the Appalachian Plateau Province.

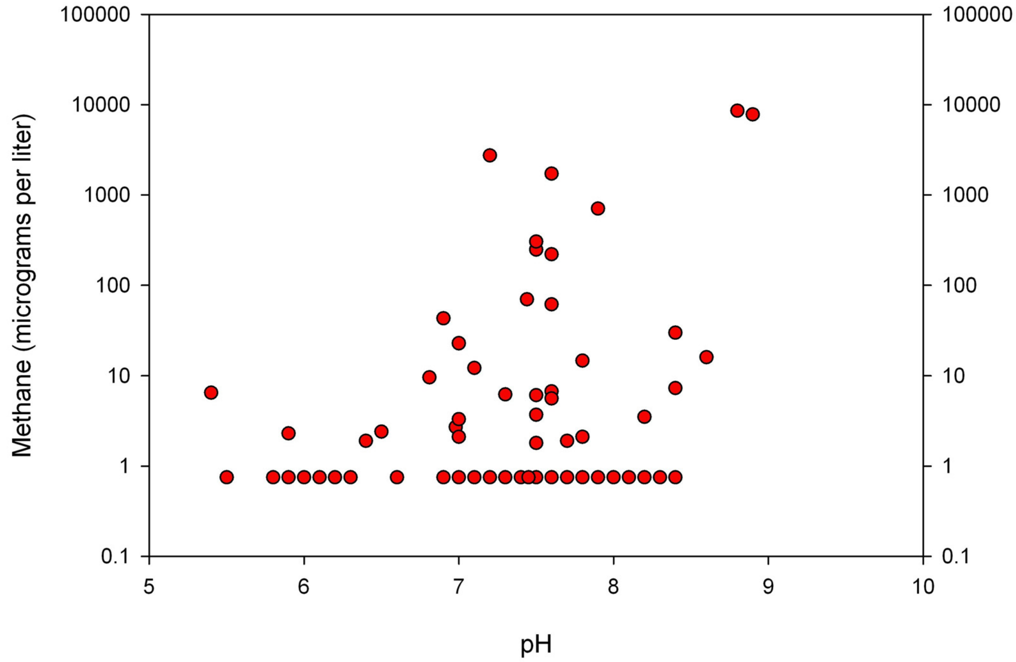

Figure 14. Relation of methane and pH in well-water samples in the Appalachian Plateau Province.

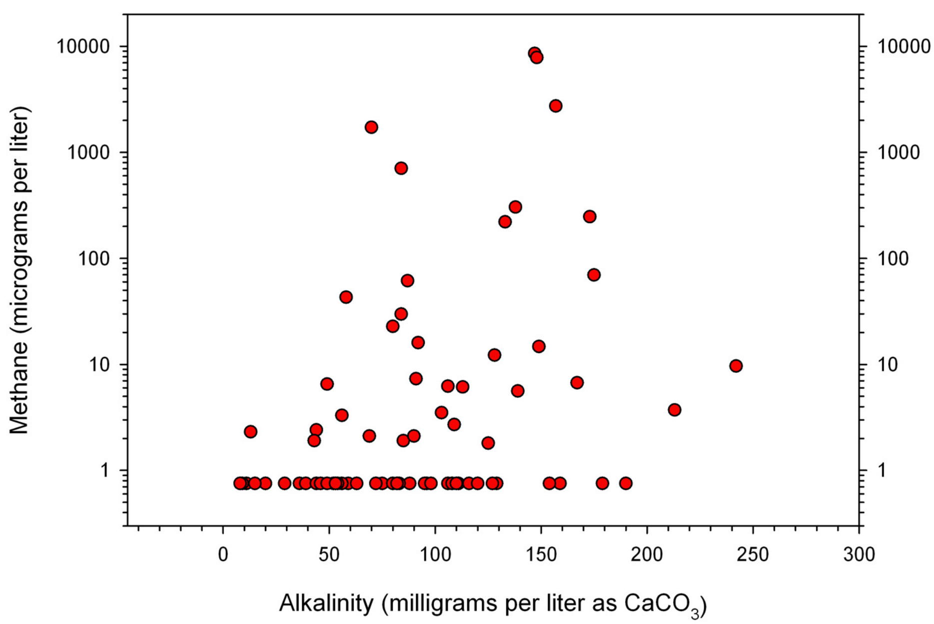

Figure 15. Relation of methane and alkalinity in well-water samples in the Appalachian Plateau Province.

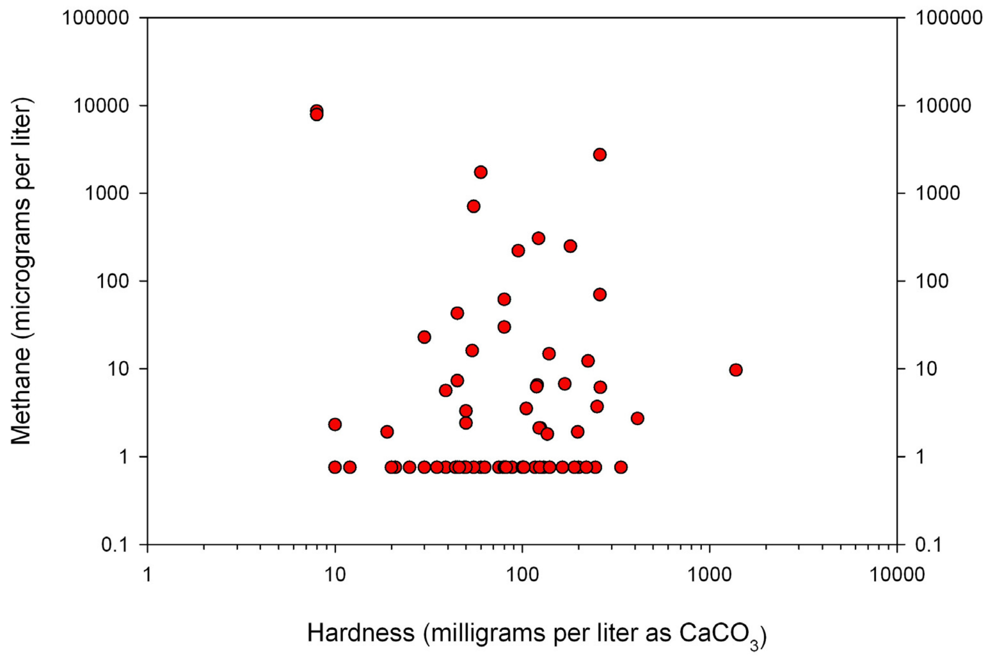

Figure 16. Relation of methane and total hardness in well-water samples in the Appalachian Plateau Province.

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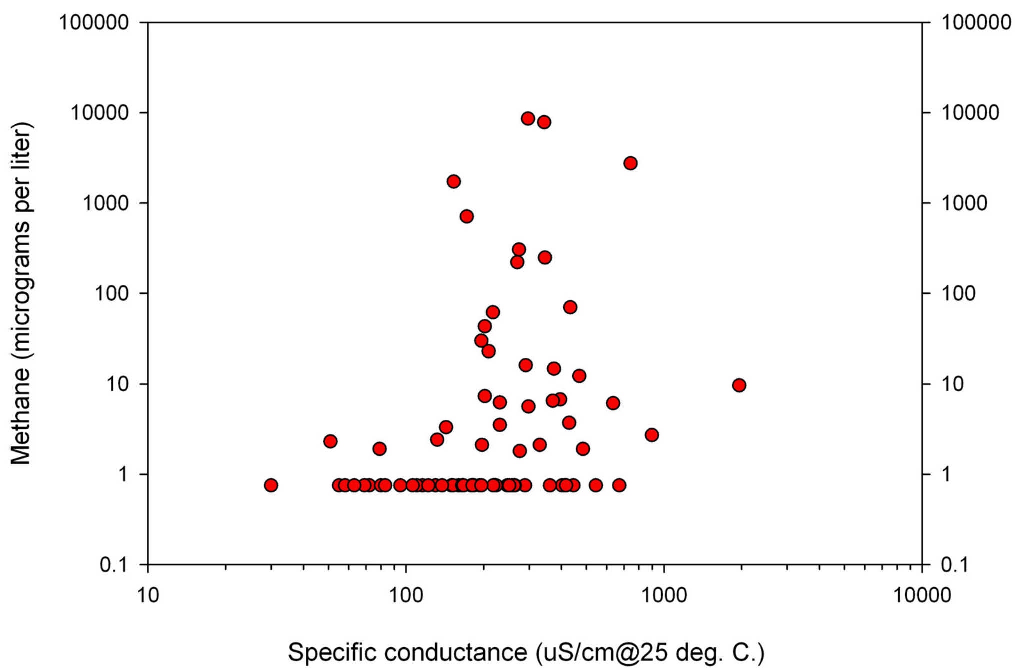

Figure 17. Relation of methane and specific conductance in well-water samples in the Appalachian Plateau Province.

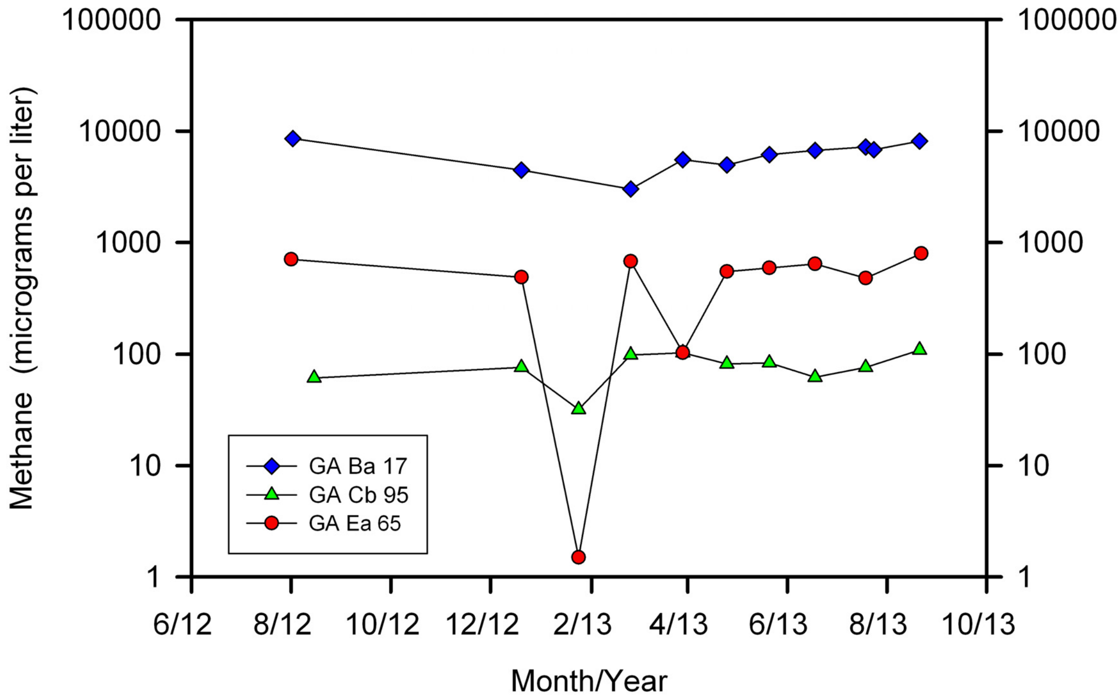

Figure 18. Methane concentrations from samples collected from August, 2012 through August, 2013 from wells GA Ba 17, GA Cb 95, and GA Ea 65.

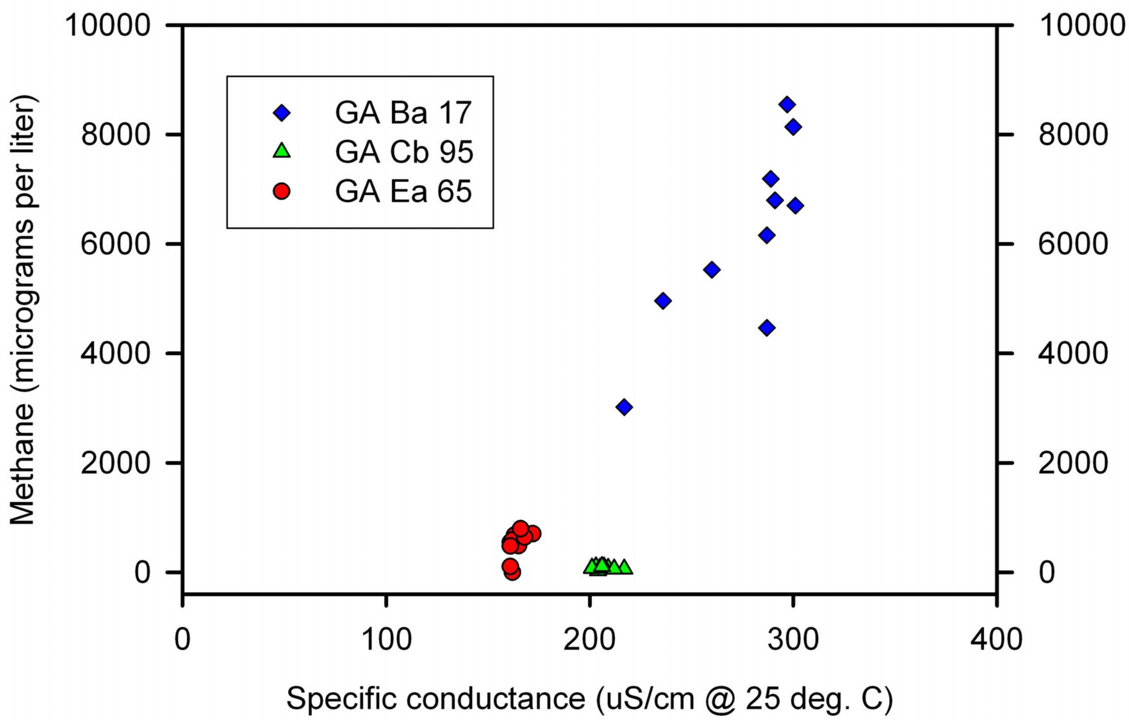

Figure 19. Relation of methane and specific conductance in samples collected from August, 2012 through August, 2013 from wells GA Ba 17, GA Cb 95, and GA Ea 65.

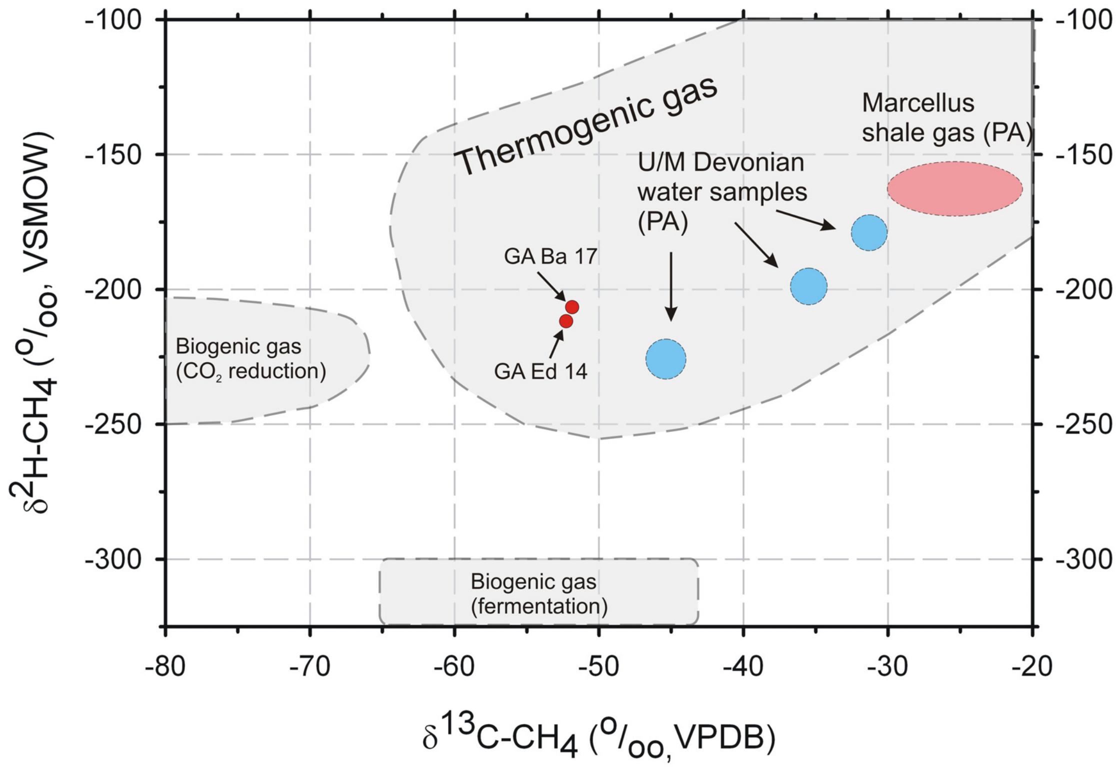

Figure 20. $\delta^{13}C$-CH_4 and $\delta^{2}H$-CH_4 values and associated methane concentrations from wells GA Ed 14 and GA Ba 17.