Increased stray gas abundance in a subset of drinking water wells near Marcellus shale gas extraction

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Horizontal drilling and hydraulic fracturing are transforming energy production, but their potential environmental effects remain controversial. We analyzed 141 drinking water wells across the Appalachian Plateaus physiographic province of northeastern Pennsylvania, examining natural gas concentrations and isotopic signatures with proximity to shale gas wells. Methane was detected in 82% of drinking water samples, with average concentrations six times higher for homes <1 km from natural gas wells (P = 0.0006). Ethane was 23 times higher in homes <1 km from gas wells (P = 0.0013); propane was detected in 10 water wells, all within approximately 1 km distance (P = 0.01). Of three factors previously proposed to influence gas concentrations in shallow groundwater (distances to gas wells, valley bottoms, and the Appalachian Structural Front, a proxy for tectonic deformation), distance to gas wells was highly significant for methane concentrations (P = 0.007; multiple regression), whereas distances to valley bottoms and the Appalachian Structural Front were not significant (P = 0.27 and P = 0.11, respectively). Distance to gas wells was also the most significant factor for Pearson and Spearman correlation analyses (P < 0.01). For ethane concentrations, distance to gas wells was the only statistically significant factor (P < 0.005). Isotopic signatures (δ13C-CH4, δ13C-C2H6, and δ13C-H2O), hydrocarbon ratios (methane to ethane and propane), and the ratio of the noble gas 4He to CH4 in groundwater were characteristic of a thermally postmature Marcellus-like source in some cases. Overall, our data suggest that some homeowners living <1 km from gas wells have drinking water contaminated with stray gases.

Unconventional sources of gas and oil are transforming energy supplies in the United States (1, 2). Horizontal drilling and hydraulic fracturing are driving this transformation, with shale gas and other unconventional sources now yielding more than one-half of all US natural gas supply. In January of 2013, for instance, the daily production of methane (CH4) in the United States rose to ~2 x 1012 m3, up 30% from the beginning of 2005 (3).

Along with the benefits of rising shale gas extraction, public concerns about the environmental consequences of hydraulic fracturing and horizontal drilling are also growing (4, 5). These concerns include changes in air quality (6), human health effects for workers and people living near well pads (5), induced seismicity (7), and controversy over the greenhouse gas balance (8, 9). Perhaps the biggest health concern remains the potential for drinking water contamination from fracturing fluids, natural formation waters, and stray gases (4, 10–12).

Despite public concerns over possible water contamination, only a few studies have examined drinking water quality related to shale gas extraction (4, 11, 13). Working in the Marcellus region of Pennsylvania, we published peer-reviewed studies of the issue, finding no evidence for increased concentrations of salts, metals, or radioactivity in drinking water wells accompanying shale gas extraction (4, 11). We did find higher methane concentrations and less negative δ13C-CH4 signatures, consistent with a natural gas source, in water for homeowners living <1 km from shale gas wells (4). Here, we present a more extensive dataset for natural gas in shallow water wells in northeastern Pennsylvania, comparing the data with sources of thermogenic methane, biogenically derived methane, and methane found in natural seeps. We present comprehensive analyses for distance to gas wells and ethane and propane concentrations, two hydrocarbons that are not derived from biogenic activity and are associated only with thermogenic sources. Finally, we use extensive isotopic data [e.g., δ13C-CH4, δ34S-H2S, δ15N-H2O] and helium analysis (4He/3He) to distinguish among different sources for the gases observed (14–16).

Our study area (Figs. S1 and S2) is within the Appalachian Plateaus physiographic province (17, 18) and includes six counties in Pennsylvania (Bradford, Lackawanna, Sullivan, Susquehanna, Wayne, and Wyoming). We sampled 81 new drinking water wells from the three principle aquifers (Alluvium, Catskill, and Lock Haven) (Fig. S1) (11). We combined the data with results from 60 previously sampled wells in Pennsylvania (4) and included a few wells from the Genesee Formation in Otsego County of New York (4). The typical depth of drinking water wells in our study was 60–90 m (11). We also sampled a natural methane seep at Salt Springs State Park in Franklin Forks, Pennsylvania (N 41.91397, W 75.8663; Susquehanna County) to compare with drinking water from homes in our study, some located within a few kilometers of the spring.

Descriptions of the underlying geology, including the Marcellus Formation found 1,500–2,500 m underground, are presented in refs. 4 and 11 and Fig. S2. Previous researchers have characterized the region’s geology and aquifers (19–23). Briefly, the two major bedrock aquifers are the Upper Devonian Catskill Formation, comprised primarily of a deltaic clastic wedge gray-green to gray-red sandstone, siltstone, and shale, and the underlying Lock Haven Formation, consisting of interbedded fine-grained sandstone, siltstone, and silty shale (19, 22, 24). The two formations can be as deep as ~1,000 m in the study area and have been exploited elsewhere for oil and gas historically. The sedimentary sequences are gently folded and dip shallowly (1–3°) to the east and south (Fig. S2), creating alternating exposures of synclines and anticylines at the surface (17, 23, 25). These formations are overlain by the Alluvium aquifer, comprised of unconsolidated glacial till, alluvium sediments, and postglacial deposits found primarily in valley bottoms (20, 22).
Results and Discussion

Dissolved methane was detected in the drinking water of 82% of the houses sampled (115 of 141). Methane concentrations in drinking water wells of homes <1 km from natural gas wells (59 of 141) were six times higher on average than concentrations for homes farther away ($P = 0.0006$, Kruskal–Wallis test) (Fig. 1 and Fig. S3). Of 12 houses where CH$_4$ concentrations were greater than 28 mg/L (the threshold for immediate remediation set by the US Department of the Interior), 11 houses were within 1-km distance of an active shale gas well (Fig. 1). The only exception was a home with a value of 32 mg CH$_4$/L at 1.4-km distance.

Similar to the results for methane, concentrations of ethane (C$_2$H$_6$) and propane (C$_3$H$_8$) were also higher in drinking water of homes near natural gas wells (Fig. 1). Ethane was detected in 40 of 133 homes (30%; 8 fewer homes were sampled for ethane and propane than for methane). Propane was detected in water wells in 10 of 133 homes, all approximately <1 km from a shale gas well ($P = 0.01$) (Fig. 1, Lower Inset). Ethane concentrations were 23 times higher on average for homes <1 km from a gas well (Fig. 1), with the eighth point only 1.1 km away (Fig. 1). Moreover, the higher ethane concentrations all occurred in groundwater with methane concentrations >15 mg/L ($P = 0.003$ for the regression of C$_2$ and C$_1$) (Fig. S4), although not all higher methane concentration waters had elevated ethane.

Ratios of ethane to methane (C$_2$/C$_1$) and propane to methane (C$_3$/C$_1$) were much higher for homes within ~1 km of natural gas wells (Fig. 2). Our high C$_3$/C$_1$ samples were also an order of magnitude greater than in salt-rich waters from a natural methane seep at the nearby Salt Springs State Park (mean [C$_3$]/[C$_1$] = 0.000029 and [C$_3$] = 0.0022 mg/L for the salt spring samples). Because microbes effectively do not produce ethane or propane in the subsurface (26, 27), our observed values within ~1 km of drilling seem to rule out a biogenic methane source, and they are consistent with both wetter (higher C$_2$ + C$_3$ content) gases found in the Marcellus Formation and our earlier observation of methane in drinking water wells in the region (4).

Along with distance to gas wells (4), proximity to both valley bottom streams (i.e., discharge areas) (28) and the Appalachian Structural Front (ASF; an index for the trend in increasing thermal maturity and degree of tectonic deformation) has been suggested to influence dissolved gas concentrations. Of these factors, distance to gas wells was the dominant statistical factor in our analyses for both methane ($P = 0.0007$) (Table 1, multiple regression analysis) and ethane ($P < 0.005$) (Table 1). In contrast, neither distance to the ASF ($P = 0.11$) nor distance to valley bottom streams ($P = 0.27$) was significant for methane concentrations analysis using linear regression. For single correlation factors, distance to gas wells was again the dominant statistical term ($P = 0.0003$ and $P = 0.001$ for Pearson and Spearman coefficients, respectively). Distance to the ASF was slightly significant by Pearson and Spearman correlation analyses ($P = 0.04$ and $P = 0.02$, respectively), whereas distance to valley bottom streams was slightly significant only for the nonparametric Spearman analysis ($P = 0.22$ for Pearson and $P = 0.01$ for Spearman) (Table 1). For observed ethane concentrations, distance to gas wells was the only factor in our dataset that was statistically significant ($P < 0.005$, regardless of whether analyzed by multiple regression, Pearson correlation, or Spearman analyses) (Table 1).

Fig. 1. Concentrations of (Upper) methane, (Lower) ethane, and (Lower Inset) propane (milligrams liter$^{-1}$) in drinking water wells vs. distance to natural gas wells (kilometers). The locations of natural gas wells were obtained from the Pennsylvania DEP and Pennsylvania Spatial Data Access databases (54). The gray band in Upper is the range for considering hazard mitigation recommended by the US Department of the Interior (10–28 mg CH$_4$/L); the department recommends immediate remediation for any value >28 mg CH$_4$/L.

Fig. 2. The ratio of ethane to methane (C$_2$/C$_1$) and (Inset) propane to methane (C$_3$/C$_1$) concentrations in drinking water wells as a function of distance to natural gas wells (kilometers). The data are plotted for all cases where [CH$_4$], [C$_2$H$_6$], and [C$_3$H$_8$] were above detection limits or [CH$_4$] was >0.5 mg/L but [C$_2$H$_6$] or [C$_3$H$_8$] was below detection limits using the detection limits of 0.0005 and 0.0001 mg/L for [C$_2$H$_6$] and [C$_3$H$_8$], respectively.

from a gas well (Fig. 1), with the eighth point only 1.1 km away (Fig. 1). Moreover, the higher ethane concentrations all occurred in groundwater with methane concentrations >15 mg/L ($P = 0.003$ for the regression of C$_2$ and C$_1$) (Fig. S4), although not all higher methane concentration waters had elevated ethane.

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Table 1. Statistical analyses for \([\text{CH}_4]\) and \([\text{C}_2\text{H}_6]\)

<table>
<thead>
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<th>Distance to gas wells</th>
<th>Distance to streams</th>
<th>Distance to ASF</th>
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<td>([\text{CH}_4])</td>
<td>Multiple regression</td>
<td>(P = 0.0007)</td>
<td>(P = 0.11)</td>
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<td></td>
<td>Pearson (r)</td>
<td>(P = 0.0003)</td>
<td>(P = 0.04)</td>
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<td></td>
<td>Spearman (\rho)</td>
<td>(P = 0.007)</td>
<td>(P = 0.02)</td>
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<tr>
<td>([\text{C}_2\text{H}_6])</td>
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<td></td>
<td>Pearson (r)</td>
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<td>Spearman (\rho)</td>
<td>(P = 0.004)</td>
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Isotopic signatures and gas ratios provide additional insight into the sources of gases in groundwater. Signatures of \(\delta^{13}\text{C-CH}_4 > -40\%/oo\) (reference to Vienna Pee Dee Belemnite standard) generally suggest a thermogenic origin for methane, whereas \(\delta^{13}\text{C-CH}_4 < -60\%/oo\) suggest a biogenically derived methane source (27, 29, 30). Across our dataset, the most thermogenic \(\delta^{13}\text{C-CH}_4\) signatures (i.e., most enriched in \(^{13}\text{C}\)) in drinking water were generally found in houses with elevated \([\text{CH}_4]\) < 1 km from natural gas wells (Fig. 3A). In fact, all drinking water wells with methane concentrations >10 mg/L, the US Department of Interior’s threshold for considering remediation, have \(\delta^{13}\text{C-CH}_4\) signatures consistent with thermogenic natural gas. Our data also show a population of homes near natural gas wells with water that has \(\delta^{13}\text{C-CH}_4\) signatures that seem to be microbial in origin, specifically homes shown in Fig. 3A, lower left corner. The combination of our \(\delta^{13}\text{C-CH}_4\) (Fig. 3A) and \(\delta^{2}\text{H-CH}_4\) data (Fig. 3B) overall, however, suggests that a subset of homes near natural gas wells has methane with a higher thermal maturity than homes farther away.

Analyses of \(\delta^{13}\text{C-CH}_4\) and \(\delta^{13}\text{C-C}_2\text{H}_6\) can help constrain potential sources of thermally mature natural gases (14, 15, 30). Because organic matter cracks to form oil and then natural gas, the gases initially are enriched in higher aliphatic hydrocarbons \(C_2 \text{ and } C_3\) (e.g., \(C_3 > C_2 > C_1\); i.e., a relatively wet gas). With increasing thermal maturity, the heavier hydrocarbons are progressively broken down, increasing the \(C_3: C_2: C_1\) ratio and leading to isotopic compositions that become increasingly heavier or enriched (31). In most natural gases, the isotopic composition \((\delta^{13}\text{C})\) of \(C_2 > C_3 > C_1\) (i.e., \(\delta^{13}\text{C}\) of ethane is heavier than methane). In thermally mature black shales, however, this maturity trend reverses, creating diagnostic isotopic reversals in which the \(\delta^{13}\text{C-CH}_4\) becomes heavier than \(\delta^{13}\text{C-C}_2\text{H}_6\) \((\Delta^{13}\text{C} = \delta^{13}\text{C-CH}_4 - \delta^{13}\text{C-C}_2\text{H}_6 > 1)\) (14, 15, 28, 30, 32).

For 11 drinking water samples in our dataset with sufficient ethane to analyze isotopic signatures, 11 samples were located <1.1 km from drilling, and 6 samples exhibited clear isotopic reversals similar to Marcellus production gases (Fig. 4). Conversely, five drinking water samples and spring water from Salt Springs State Park showed the more common trend consistent with Upper Devonian production gases (Fig. 4). In the study area, these isotopic values suggest multiple sources for hydrocarbon gases. The Upper Devonian gases are likely introduced into the shallow crust either by natural processes over geologic time or through leakage around the casing in the annular space of the production well. In contrast, natural gas with heavy \(\delta^{13}\text{C-CH}_4\) and \(\Delta^{13}\text{C} > 0\) likely stems from Marcellus production gases or a mixture of Marcellus gases and other annulus gases that migrated to the surface during drilling, well completion, or production.

Similar to our data, independent \(\text{CH}_4\) measurements taken by the US Environmental Protection Agency (EPA) in Dimock, Pennsylvania (Residential Data Reports found at http://www.epaosc.org/site/doc_list.aspx?site_id=7555) in January of 2012 also show three \(\delta^{13}\text{C-CH}_4\) values in drinking water wells between -24.98‰ and -29.36‰ \(\delta^{13}\text{C-CH}_4\) and five samples with \(\delta^{13}\text{C-CH}_4\) values in the range of Marcellus gas defined in ref. 28. The heaviest methane isotopic signatures in the EPA samples

![Fig. 3](image-url)
Content more representative

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for the Salt Springs

Upper and 1

www.pnas.org/cgi/doi/10.1073/pnas.1221635110

values consistent with Mar-

cellus gases in some cases (Fig. S6). We also observed that

the highest methane concentrations coincided with increased abun-
dances of ethane and propane and a higher proportion of propane
relative to ethane (Fig. S7). The observed gas composition in

groundwater samples also had a substantially higher proportion of

propane relative to ethane than water from the Salt Springs State

Park, which is known to have historic methane-rich discharges (11,

37) (Fig. S7). Based on limited available production data, the

Marcellus production gases have a wetness (C2 + C3) of at least

1–2% and C3/C2 of >>0.03%, whereas Upper Devonian gases,
specifically those gases observed in Upper Devonian aquifers be-

fore shale gas development (30), tend to be relatively depleted in

gasser waters; samples from the Salt Springs State Park had in-

termediate wetness, which is discussed above (14, 30). As a result,

increasing proportions of C3/C2 tend to be more representative of
gases from Marcellus-producing wells (Fig. S6) than Upper

Devonian Formations or Salt Springs State Park.

An enrichment of 13C in DIC (e.g., δ13C-DIC > +10‰) and positive correlations between δ13C-DIC and δ13C-C3H8 and be-
tween δ13C-C2H6 and δ13C-C3H8 have all been used as indicators of microbially derived methane sourced from relatively shallow depths (~<550 m) (38, 39). Most of our δ13C-DIC values were 20–25‰ lighter than typical for DIC influenced by microbial-ly derived methane in shallow groundwater, and the δ13C-C3H8 values of the samples showed no evidence of a positive relationship with δ13C-DIC (and even a slight negative relationship; P = 0.003) (Fig. S8, Upper). We also found no statistical relationship between the δ13C values of methane and δ13C of water (Fig. S8, Lower).

Based on these data and similar to the observations in the work by Osborn et al. (4), most of the methane in our samples does not

content than spring water from the natural methane seep at the

Salt Springs State Park. The salt spring is the only location for

which we found detectable [C3] outside of our 11 samples (mean

[C3]/[C1] = 0.000029 and [C3] = 0.0022 mg/L for the Salt Springs

samples) (Fig. S5).

The abundance and relative proportions of aliphatic hydro-
carbons (i.e., propane and ethane) and methane in groundwater
are also useful for comparing with production gases (14, 36) and
samples from the Salt Springs State Park. Ratios of propane to

ethane (C2/C3) in our dataset were generally higher than ratios for

the Salt Springs State Park, and ratios of methane to ethane (C1/

C2) were generally lower (Fig. S6), approaching ratios for Mar-
cellus gases in some cases (Fig. S6). The other points fell on two intermediate trajectories. One trajectory is simple mixing between thermogenically and biogenically derived gas (lower curve in Fig. 3C). The other trajectory reflects either diffusive migration or a more complex, three-component mixture between Middle and Upper Devonian gases and shallow biogenic sources (30, 35) (upper trajectory in Fig. 3C).

The relative distribution of ethane and propane provides addi-
tional insight into the source and mixture of gases. The ratio of

propane to methane concentrations plotted against [C2H6] (Fig. S5) shows that at least 6 of 10 water samples with detectable

[C2H6] had an order of magnitude greater [C3]/[C1] ratio and [C3]
This study examined natural gas composition of drinking water using concentration and isotope data for methane, ethane, propane, and 3He. Based on the spatial distribution of the hydrocarbons (Figs. 1 and 2), isotopic signatures for the gases (Figs. 3 and 4), wetness of the gases (Fig. 2 and Figs. S5, S6, and S7), and observed differences in 3He:CH4 ratios (Fig. 5), we propose that a subset of homeowners has drinking water contaminated by drilling operations, likely through poor well construction. Future research and greater data disclosure could improve understanding of these issues in several ways. More research is needed across the Marcellus and other shale gas plays where the geological characteristics differ. For instance, a new study by Duke University and the US Geological Survey showed no evidence of drinking water contamination in a part of the Fayetteville Shale with a less fractured or tectonically deformed geology than the Marcellus and good confining layers above and below the drinking water layers (48). More extensive predrilling data would also be helpful. Additional isotopic tools and geochemical tracers are needed to determine the source and mechanisms of stray gas migration that we observed. For instance, a public database disclosing yearly gas compositions (molecular and isotopic δ13C and δ18O for methane and ethane) from each producing gas well would help identify and eliminate sources of stray gas (49). In cases where carbon and hydrogen isotopes may not distinguish deep Marcellus-derived methane from shallower, younger Devonian methane, the geochemical δ3He of He and other noble gases provides a promising approach (15, 50). Another research need is a set of detailed case studies of water-quality measurements taken before, during, and after drilling and hydraulic fracturing. Such studies are underway, including partnerships of EPA- and Department of Energy-based scientists and industry in Pennsylvania, Texas, and North Dakota. In addition to predrilling data, disclosure of data from mud-log gases and wells to regulatory agencies and ideally, publically would build knowledge and public confidence. Ultimately, we need to understand why, in some cases, shale gas extraction contaminates groundwater and how to keep it from happening elsewhere.

Methods

A total of 81 samples from drinking water wells were collected in six counties in Pennsylvania (Bradford, Lackawanna, Sullivan, Susquehanna, Wayne, and Wyoming) (46), with 69 previously described in the work by Osborn et al. (4). The samples were obtained from homeowner associations and contacts with the goal of sampling Alluvium, Catskill, and Lock Haven groundwater wells across the region. For analyses of 3He (Fig. 5), samples from 30 drinking water wells were used to estimate concentration ratios of 3He:CH4. Wells were purged to remove stagnant water and then measured for pH, electrical conductivity, and dissolved oxygen. Hydrogen isotopes were measured on eight samples using a Picarro G2112i. This study examined natural gas composition of drinking water using concentration and isotope data for methane, ethane, propane, and 3He. Based on the spatial distribution of the hydrocarbons (Figs. 1 and 2), isotopic signatures for the gases (Figs. 3 and 4), wetness of the gases (Fig. 2 and Figs. S5, S6, and S7), and observed differences in 3He:CH4 ratios (Fig. 5), we propose that a subset of homeowners has drinking water contaminated by drilling operations, likely through poor well construction. Future research and greater data disclosure could improve understanding of these issues in several ways. More research is needed across the Marcellus and other shale gas plays where the geological characteristics differ. For instance, a new study by Duke University and the US Geological Survey showed no evidence of drinking water contamination in a part of the Fayetteville Shale with a less fractured or tectonically deformed geology than the Marcellus and good confining layers above and below the drinking water layers (48). More extensive predrilling data would also be helpful. Additional isotopic tools and geochemical tracers are needed to determine the source and mechanisms of stray gas migration that we observed. For instance, a public database disclosing yearly gas compositions (molecular and isotopic δ13C and δ18O for methane and ethane) from each producing gas well would help identify and eliminate sources of stray gas (49). In cases where carbon and hydrogen isotopes may not distinguish deep Marcellus-derived methane from shallower, younger Devonian methane, the geochemical δ3He of He and other noble gases provides a promising approach (15, 50). Another research need is a set of detailed case studies of water-quality measurements taken before, during, and after drilling and hydraulic fracturing. Such studies are underway, including partnerships of EPA- and Department of Energy-based scientists and industry in Pennsylvania, Texas, and North Dakota. In addition to predrilling data, disclosure of data from mud-log gases and wells to regulatory agencies and ideally, publically would build knowledge and public confidence. Ultimately, we need to understand why, in some cases, shale gas extraction contaminates groundwater and how to keep it from happening elsewhere.

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Dissolved \( \text{CH}_4 \) was equilibrated using a headspace-equilibration method (S3) and diluted when necessary using zero air. A set of 33 groundwater samples with a range of \( \text{CH}_4 \) and \( \delta^{13} \text{C}-\text{CH}_4 \) was collected in duplicate and analyzed. The authors performed a statistical analysis of the data, which was measured using GIS software. Statistical analyses were performed using MATLAB and R software.

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10. DiGiulio DC, Wilkin RT, Miller C, Oberley G (2011) Marcellus Formation flow to nearest gas wells and do not account for the direction or extent of horizontal drilling underground. Distance to streams were determined as the shortest lengths from sampled locations to valley centerlines using the national stream network as the base map, distance from Appalachian Structural Front was measured using GIS software. Statistical analyses were performed using MATLAB and R software.