Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing

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Directional drilling and hydraulic-fracturing technologies are dramatically increasing natural-gas extraction. In aquifers overlying the Marcellus and Utica shale formations of northeastern Pennsylvania and upstate New York, we document systematic evidence for methane contamination of drinking water associated with shale-gas extraction. In active gas-extraction areas (one or more gas wells within 1 km), average and maximum methane concentrations in drinking-water wells increased with proximity to the nearest gas well and were 19.2 and 64 mg CH₄ L⁻¹ (n = 26), a potential explosion hazard; in contrast, dissolved methane samples in neighboring nonextraction sites (no gas wells within 1 km) within similar geologic formations and hydrogeologic regimes averaged only 1.1 mg L⁻¹ (P < 0.05; n = 34). Average δ¹³C-CH₄ values of dissolved methane in shallow groundwater were significantly less negative for active than for nonactive sites (−37 ± 7‰ and −54 ± 11‰, respectively; P < 0.0001). These δ¹³C-CH₄ data, coupled with the ratios of methane-to-higher-chain hydrocarbons, and δ²H-CH₄ values, are consistent with deeper thermogenic methane sources such as the Marcellus and Utica shales at the active sites and matched gas geochemistry from gas wells nearby. In contrast, lower-concentration samples from shallow groundwater at nonactive sites had isotopic signatures reflecting a more biogenic or mixed biogenic/thermogenic methane source. We found no evidence for contamination of drinking-water samples with deep saline brines or fracturing fluids. We conclude that greater stewardship, data, and regulation are needed to ensure the sustainable future of shale-gas extraction and to improve public confidence in its use.

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Author manuscripts: S.G.O., A.V., and R.B.J. designed research; S.G.O. and N.R.W. performed research; A.V. contributed new reagents/analytic tools; S.G.O., A.V., N.R.W., and R.B.J. wrote the paper.

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northeast Pennsylvania (Catskill and Lockhaven formations) and upstate New York (Genesee formation) (see Figs. 1 and 2 and SI Text), including measurements of dissolved salts, water isotopes ($^{18}$O and $^2$H), and isotopes of dissolved constituents (carbon, boron, and radium). Of the 68 wells, 60 were also analyzed for dissolved-gas concentrations of methane and higher-chain hydrocarbons and for carbon and hydrogen isotope ratios of methane. Although dissolved methane in drinking water is not currently classified as a health hazard for ingestion, it is an asphyxiant in enclosed spaces and an explosion and fire hazard (8). This study seeks to evaluate the potential impact of gas drilling and hydraulic fracturing on shallow groundwater quality by comparing areas that are currently exploited for gas (defined as active—one or more gas wells within 1 km) to those that are not currently associated with gas drilling (nonactive; no gas wells within 1 km), many of which are slated for drilling in the near future.

Results and Discussion

Methane concentrations were detected generally in 51 of 60 drinking-water wells (85%) across the region, regardless of gas industry operations, but concentrations were substantially higher closer to natural-gas wells (Fig. 3). Methane concentrations were 17-times higher on average ($19.2 \pm 18.0 \text{mg CH}_4 \text{L}^{-1}$) in shallow wells from active drilling and extraction areas than in wells from nonactive areas ($1.1 \text{mg L}^{-1}$ on average; $P < 0.05$; Fig. 3 and Table 1). The average methane concentration in shallow groundwater in active drilling areas fell within the defined action level (14). Values of $\delta^{13}$C-CH$_4$ and $\delta^2$H-CH$_4$ values and the ratio of methane to higher-chain hydrocarbons (ethane, propane, and butane) can typically be used to differentiate shallower, biologically derived methane from deeper physically derived thermogenic methane (14). Values of $\delta^{13}$C-CH$_4$ less negative than approximately $-50\%$ are indicative of deeper thermogenic methane, whereas values more negative than $-64\%$ are strongly indicative of microbial methane (14). Likewise, $\delta^2$H-CH$_4$ values more negative than about $-175\%$ are strongly indicative of microbial methane (14). Further evidence for the difference between methane from water wells near active drilling sites and neighboring nonactive sites is the relationship of methane concentration to $\delta^{13}$C-CH$_4$ values (Fig. 4A) and the ratios of methane to higher-chain hydrocarbons (Table 1).

Table 1. Mean values ± standard deviation of methane concentrations (as milligrams of CH$_4$ L$^{-1}$) and carbon isotope composition in methane in shallow groundwater $\delta^{13}$C-CH$_4$ sorted by aquifers and proximity to gas wells (active vs. nonactive)

<table>
<thead>
<tr>
<th>Water source, n</th>
<th>milligrams CH$_4$ L$^{-1}$</th>
<th>$\delta^{13}$C-CH$_4$, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonactive Catskill, 5</td>
<td>$1.9 \pm 6.3$</td>
<td>$-52.5 \pm 7.5$</td>
</tr>
<tr>
<td>Active Catskill, 13</td>
<td>$26.8 \pm 30.3$</td>
<td>$-33.5 \pm 3.5$</td>
</tr>
<tr>
<td>Nonactive Genesee, 8</td>
<td>$1.5 \pm 3.0$</td>
<td>$-57.5 \pm 9.5$</td>
</tr>
<tr>
<td>Active Genesee, 1</td>
<td>0.3</td>
<td>$-34.1$</td>
</tr>
<tr>
<td>Active Lockhaven, 7</td>
<td>$50.4 \pm 36.1$</td>
<td>$-40.7 \pm 6.7$</td>
</tr>
<tr>
<td>Total active wells, 21</td>
<td>19.2</td>
<td>$-37 \pm 7$</td>
</tr>
<tr>
<td>Total nonactive wells, 13</td>
<td>1.1</td>
<td>$-54 \pm 11$</td>
</tr>
</tbody>
</table>

The variable $n$ refers to the number of samples.

The average $\delta^{13}$C-CH$_4$ value in shallow groundwater in active drilling areas was $-37 \pm 7\%$, consistent with a deeper thermogenic methane source. In contrast, groundwater from nonactive areas in the same aquifers had much lower methane concentrations and significantly lower $\delta^{13}$C-CH$_4$ values (average of $-54 \pm 11\%$; $P < 0.0001$; Fig. 4A and Table 1). Both our $\delta^{13}$C-CH$_4$ data and $\delta^2$H-CH$_4$ data (see Fig. S2) are consistent with a deeper thermogenic methane source at the active sites and a more biogenic or mixed methane source for the lower-concentration samples from nonactive sites (based on the definition of Schoell, ref. 14).

Because ethane and propane are generally not coproduced during microbial methanogenesis, the presence of higher-chain hydrocarbons at relatively low methane-to-ethane ratios (less than approximately 100) is often used as another indicator of deeper thermogenic gas (14, 15). Ethane and other higher-chain hydrocarbons were detected in only 3 of 34 drinking-water wells from nonactive drilling sites. In contrast, ethane was detected in 21 of 26 drinking-water wells in active drilling sites. Additionally, propane and butane were detected ($>0.001$ mol %) in eight and two well samples, respectively, from active drilling areas but in no wells from nonactive areas.
Using a Bernard plot (15) for analysis (Fig. 4B), the enriched δ13C-CH4 (approximately > −50‰) values accompanied by low ratios of methane to higher-chain hydrocarbons (less than approximately 100) in drinking-water wells also suggest that dissolved gas is more thermogenic at active than at nonactive sites (Fig. 4B). For instance, 12 dissolved-gas samples at active drilling sites fell along a regional gas trajectory that increases with reservoir age and thermal maturity of organic matter, with samples from Susquehanna County, Pennsylvania specifically matching natural-gas geochemistry from local gas wells (Fig. 4B, orange oval). These 12 samples and local natural-gas samples are consistent with gas sourced from thermally mature organic matter of Middle Devonian and older depositional ages often found in Marcellus Shale from approximately 2,000 m below the surface in the northern Appalachian Basin (14–19) (Fig. 4B). In contrast, none of the methane samples from nonactive drilling areas fell upon this trajectory (Fig. 4B); eight dissolved-gas samples in Fig. 4B from active drilling areas and all of the values from nonactive areas may instead be interpreted as mixed biogenic/thermogenic gas (18) or, as Laughrey and Baldassare (17) proposed for their Pennsylvania gas data (Fig. 4B), the early migration of wet thermogenic gases with low-δ13C-CH4 values and high methane-to-higher-chain hydrocarbon ratios. One data point from a nonactive area in New York fell squarely in the parameters of a strictly biogenic source as defined by Schoell (14) (Fig. 4B, upper-left corner).

Carbon isotopes of dissolved inorganic carbon (δ13C-DIC > +10‰) and the positive correlation of δ2H of water and δ2H of methane have been used as strong indicators of microbial methane, further constraining the source of methane in shallow groundwater (depth less than 550 m) (18, 20). Our δ13C-DIC values were fairly negative and show no association with the δ13C-CH4 values (Fig. S3), which is not what would be expected if methanogenesis were occurring locally in the shallow aquifers. Instead, the δ13C-DIC values from the shallow aquifers plot within a narrow range typical for shallow recharge waters, with the dissolution of CO2 produced by respiration as water passes downward through the soil critical zone. Importantly, these values do not indicate extensive microbial methanogenesis or sulfate reduction. The data do suggest gas-phase transport of methane upward to the shallow groundwater zones sampled for this study (<190 m) and dissolution into shallow recharge waters locally. Additionally, there was no positive correlation between the δ2H values of methane and δ2H of water (Fig. S4), indicating that microbial methane derived in this shallow zone is negligible. Overall, the combined gas and formation-water results indicate that thermogenic gas from thermally mature organic matter of Middle Devonian and older depositional ages is the most likely source of the high methane concentrations observed in the shallow water wells from active extraction sites.

A different potential source of shallow groundwater contamination associated with gas drilling and hydraulic fracturing is the introduction of hypersaline formation brines and/or fracturing fluids. The average depth range of drinking-water wells in northeastern Pennsylvania is from 60 to 90 m (12), making the average vertical separation between drinking-water wells and the Marcellus Shale in our study area between approximately 900 and 1,800 m (Fig. 2). The research area, however, is located in tectonically active areas with mapped faults, earthquakes, and lineament features (Fig. 2 and Fig. S1). The Marcellus formation also contains two major sets of joints (21) that could be conduits for directed pressurized fluid flow. Typical fracturing activities in the Marcellus involve the injection of approximately 13–19 million liters of water per well (22) at pressures of up to 69,000 kPa. The majority of this fracturing water typically stays underground and could in principle displace deep formation water upward into shallow aquifers. Such deep formation waters often have high concentrations of total dissolved solids >250,000 mg·L−1, trace...
toxic elements, (18), and naturally occurring radioactive materials, with activities as high as 16,000 picocuries per liter (1 pCi L\(^{-1}\) = 0.037 becquerels per liter) for \(^{226}\)Ra compared to a drinking-water standard of 5 pCi L\(^{-1}\) for combined \(^{226}\)Ra and \(^{228}\)Ra (23).

We evaluated the hydrochemistry of our 68 drinking-water wells and compared these data to historical data of 124 wells in the Catskill and Lockhaven aquifers (24, 25). We used three types of indicators for potential mixing with brines and/or saline fracturing fluids: (i) major inorganic chemicals; (ii) stable isotope signatures of water (\(\delta^{18}\)O, \(\delta^3\)H); and (iii) isotopes of dissolved constituents (\(\delta^{13}\)C-DIC, \(\delta^{15}\)B, and \(^{226}\)Ra). Based on our data (Table 2), we found no evidence for contamination of the shallow wells near active drilling sites from deep brines and/or fracturing fluids. All of the Na\(^+\), Cl\(^-\), Ca\(^{2+}\), and DIC concentrations in wells from active drilling areas were consistent with the baseline historical data, and none of the shallow wells from active drilling areas had either chloride concentrations >60 mg L\(^{-1}\) or Na-Ca-CI compositions that mirrored deeper formation waters (Table 2).

Furthermore, the mean isotopic values of \(\delta^{18}\)O, \(\delta^3\)H, \(\delta^{13}\)C-DIC, \(\delta^{15}\)B, and \(^{226}\)Ra in active and nonactive areas were indistinguishable. The \(^{226}\)Ra values were consistent with available historical data (25), and the composition of \(\delta^{18}\)O and \(\delta^3\)H in the well-water appeared to be of modern meteoric origin for Pennsylvania (26) (Table 2 and Fig. S5). In sum, the geochemical and isotopic features for water we measured in the shallow wells from both active and nonactive areas are consistent with historical data and inconsistent with contamination from mixing Marcellus Shale formation water or saline fracturing fluids (Table 2).

There are at least three possible mechanisms for fluid migration into the shallow drinking-water aquifers that could help explain the increased methane concentrations we observed near gas wells (Fig. 3). The first is physical displacement of gas-rich fluids through dry or water-saturated fractures and density-driven transport of gases (Rn, CH\(_4\), CO\(_2\)) from depth to the surface (e.g., refs. 27 and 28). Such leaks could occur at hundreds of meters underground, with methane passing laterally and vertically through fracture systems. The third mechanism is that the process of hydraulic fracturing generates new fractures or enlarges existing ones above the target shale formation, increasing the connectivity of the fracture system. The reduced pressure following the fracturing activities could release methane in solution, leading to methane exsolving rapidly from solution (29), allowing methane gas to potentially migrate upward through the fracture system.

Methane migration through the 1- to 2-km-thick geological formations that overlie the Marcellus and Utica shales is less likely as a mechanism for methane contamination than leaky well casings, but might be possible due to both the extensive fracture systems reported for these formations and the many older, uncased wells drilled and abandoned over the last century and a half in Pennsylvania and New York. The hydraulic conductivity in the overlying Catskill and Lockhaven aquifers is controlled by a secondary fracture system (30), with several major faults and linear features for water we measured in the shallow wells from both active and nonactive areas (26) (Table 2 and Fig. S5). Consequently, the high methane concentrations with distinct positive \(\delta^{13}\)C-CH\(_4\) and \(\delta^3\)H-CH\(_4\) values in the shallow groundwater from active areas could in principle reflect the transport of a deep methane source associated with gas drilling and hydraulic-fracturing activities. In contrast, the low-level methane migration to the surface ground-water aquifers, as observed in the nonactive areas, is likely a natural phenomenon (e.g., ref. 31). Previous studies have shown that naturally occurring methane in shallow aquifers is typically associated with a relatively strong biogenic signature indicated by depleted \(\delta^{13}\)C-CH\(_4\) and \(\delta^3\)H-CH\(_4\) compositions (32) coupled with high ratios of methane to higher-chain hydrocarbons (33), as we observed in Fig. 4B. Several models have been developed to explain the relatively common phenomenon of rapid vertical transport of gases (Rn, CH\(_4\), and CO\(_2\)) from depth to the surface (e.g., ref. 31), including pressure-driven continuous gas-phase flow through dry or water-saturated fractures and density-driven buoyancy of gas microbubbles in aquifers and water-filled fractures (34).

Based on our groundwater results and the litigious nature of shale-gas extraction, we believe that long-term, coordinated sampling and monitoring of industry and private homeowners is needed. Compared to other forms of fossil-fuel extraction, hydraulic fracturing is relatively poorly regulated at the federal level. Fracturing wastes are not regulated as a hazardous waste under the Resource Conservation and Recovery Act, fracturing wells are not covered under the Safe Drinking Water Act, and only recently has the Environmental Protection Agency asked fracturing

Table 2. Comparisons of selected major ions and isotopic results in drinking-water wells from this study to data available on the same formations (Catskill and Lockhaven) in previous studies (24, 25) and to underlying brines throughout the Appalachian Basin (18).

<table>
<thead>
<tr>
<th>Formation</th>
<th>Active Lockhaven</th>
<th>Active Catskill</th>
<th>Nonactive Catskill</th>
<th>Genesee group</th>
<th>Previous studies (background)</th>
<th>Appalachian brines</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N = 8</td>
<td>N = 25</td>
<td>N = 22</td>
<td>N = 12</td>
<td>Lockhaven formation (25)</td>
<td>Catskill formation (24)</td>
</tr>
<tr>
<td></td>
<td>N = 45</td>
<td>N = 79</td>
<td>N = 21</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alkalinity as HCO(_3)(^-), mg L(^{-1})</td>
<td>285 ± 36</td>
<td>157 ± 56</td>
<td>127 ± 53</td>
<td>158 ± 56</td>
<td>209 ± 77</td>
<td>133 ± 6</td>
</tr>
<tr>
<td>mM</td>
<td>(4.7 ± 0.6)</td>
<td>(2.6 ± 0.9)</td>
<td>(2.1 ± 0.9)</td>
<td>(2.6 ± 0.9)</td>
<td>[2.4 ± 1.3]</td>
<td>[2.2 ± 1.0]</td>
</tr>
<tr>
<td>Sodium, mg L(^{-1})</td>
<td>87 ± 22</td>
<td>23 ± 30</td>
<td>17 ± 25</td>
<td>29 ± 23</td>
<td>100 ± 312</td>
<td>21 ± 37</td>
</tr>
<tr>
<td>Chloride, mg L(^{-1})</td>
<td>25 ± 17</td>
<td>11 ± 12</td>
<td>17 ± 40</td>
<td>9 ± 19</td>
<td>132 ± 550</td>
<td>13 ± 42</td>
</tr>
<tr>
<td>Calcium, mg L(^{-1})</td>
<td>22 ± 12</td>
<td>31 ± 13</td>
<td>27 ± 9</td>
<td>26 ± 5</td>
<td>49 ± 39</td>
<td>29 ± 11</td>
</tr>
<tr>
<td>Boron, µg L(^{-1})</td>
<td>412 ± 156</td>
<td>93 ± 167</td>
<td>42 ± 93</td>
<td>200 ± 130</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>(\delta^{11})B, ‰</td>
<td>27 ± 4</td>
<td>22 ± 6</td>
<td>23 ± 6</td>
<td>26 ± 6</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>(^{226})Ra, pCi L(^{-1})</td>
<td>0.24 ± 0.2</td>
<td>0.16 ± 0.15</td>
<td>0.17 ± 0.14</td>
<td>0.2 ± 0.15</td>
<td>0.56 ± 0.74</td>
<td>0.56 ± 0.74</td>
</tr>
<tr>
<td>(\delta^3)H, ‰</td>
<td>-66 ± 5</td>
<td>-63 ± 3</td>
<td>-76 ± 5</td>
<td>-41 ± 5</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>(\delta^{18})O, ‰</td>
<td>-10 ± 1</td>
<td>-10 ± 0.5</td>
<td>-11 ± 1</td>
<td>-12 ± 1</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

Some data for the active Genesee Group and nonactive Lockhaven Formation are not included because of insufficient sample sizes (NA). Values represent means ± 1 standard deviation. NA, not available.

N values for \(\delta^{11}\)B analysis are 8, 10, 3, 6, and 5 for active Lockhaven, active Catskill, nonactive Genesee, nonactive Catskill, and brine, respectively. N values for \(^{226}\)Ra are 6, 7, 3, 10, and 5, and 13 for active Lockhaven, active Catskill, nonactive Genesee, nonactive Catskill, background Lockhaven, and brine, respectively. \(\delta^{18}\)O normalized to National Institute of Standards and Technology Standard Reference Material 951. \(\delta^3\)H and \(\delta^{18}\)O normalized to Vienna Standard Mean Ocean Water (VSMOW).
firms to voluntarily report a list of the constituents in the fracturing fluids based on the Emergency Planning and Community Right-to-Know Act. More research is also needed on the mechanism of methane contamination, the potential health consequences of methane, and establishment of baseline methane data in other locations. We believe that systematic and independent data on groundwater quality, including dissolved-gas concentrations and isotopic compositions, should be collected before drilling operations begin in a region, as is already done in some states. Ideally, these data should be made available for public analysis, recognizing the privacy concerns that accompany this issue. Such baseline data would improve environmental safety, scientific knowledge, and public confidence. Similarly, long-term monitoring of groundwater and surface methane emissions during and after extraction would clarify the extent of problems and help identify the mechanisms behind them. Greater stewardship, knowledge, and—possibly—regulation are needed to ensure the sustainable future of shale-gas extraction.

35. Pennsylvania Spatial Data Access (PASDA) Online mapping, data access wizard, oil and gas locations. (Pennsylvania Dept of Environmental Protection, Harrisburg, PA); http://www.pasda.psu.edu/us/SearachResults.aspx?search&Type=mapservice&condition=OR&entry=PASDA.