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 ($\delta^{13}C$-CH_4, $\delta^{13}C$-C_2H_6, and δ^2H-CH_4), hydrocarbon ratios (methane to ethane and propane), and the ratio of the noble gas ^4He to CH_4 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.

carbon, hydrogen, and helium isotopes | groundwater contamination | geochemical fingerprinting | fracking | hydrology and ecology

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 (CH_4) in the United States rose to $\sim 2 \times 10^9$ m^3, 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 $\delta^{13}C$-CH_4 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., $\delta^{13}C$-CH_4, δ^2H-CH_4, $\delta^{13}C$-C_2H_6, $\delta^{13}C$-dissolved inorganic carbon ($\delta^{13}C$-DIC), and δ^2H-H_2O] and helium analysis ($^4He/CH_4$) 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 anticlines 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).

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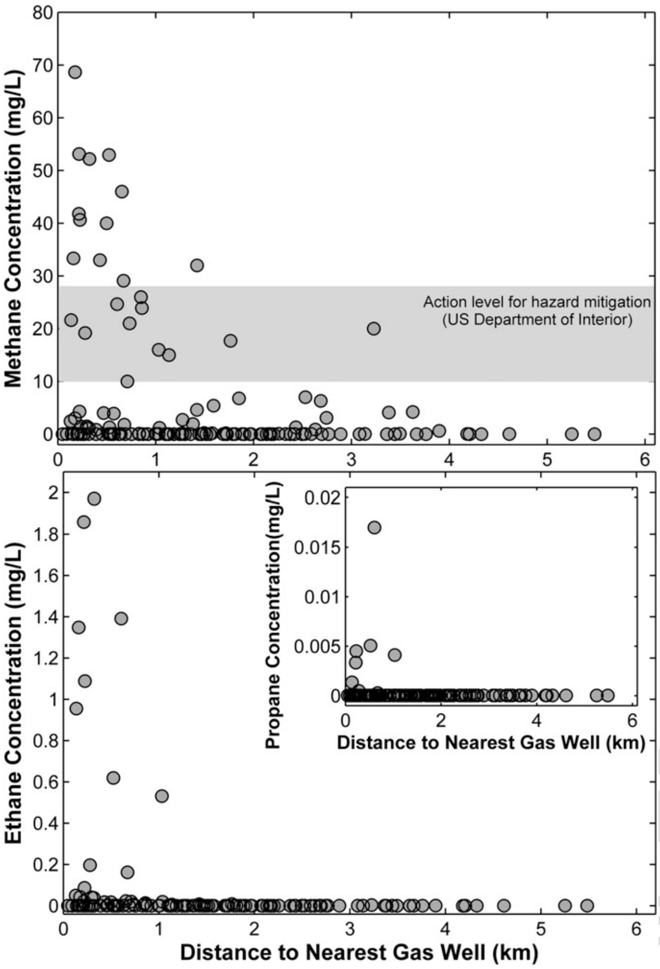

Fig. 1. Concentrations of (*Upper*) methane, (*Lower*) ethane, and (*Lower Inset*) propane (milligrams liter^{-1}) in drinking water wells vs. distance to natural gas wells (kilometers). The locations of natural gas wells were obtained from the Pennsylvania DEP and Pennsylvania Spatial Data Access databases (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.

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_2H_6) and propane (C_3H_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: 0.18 compared with 0.008 mg C_2H_6/L ($P = 0.001$, Kruskal–Wallis). Seven of eight C_2H_6 concentrations >0.5 mg/L were found <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 $[C3] = 0.0022$ 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).

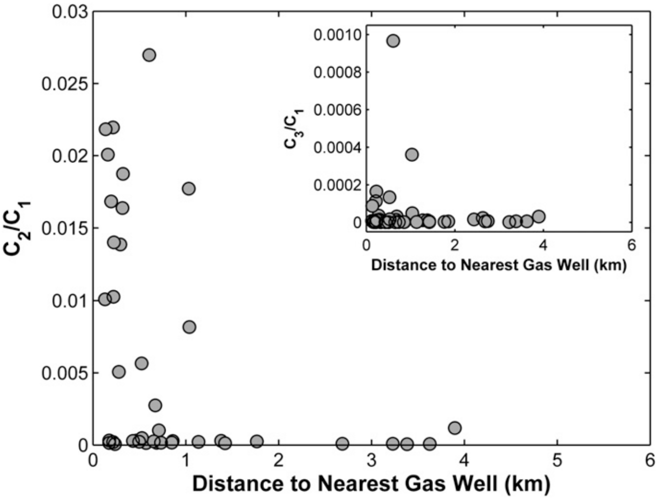

Fig. 2. The ratio of ethane to methane (C_2/C_1) and (*Inset*) propane to methane (C_3/C_1) concentrations in drinking water wells as a function of distance to natural gas wells (kilometers). The data are plotted for all cases where $[CH_4]$, $[C_2H_6]$, and $[C_3H_8]$ were above detection limits or $[CH_4]$ was >0.5 mg/L but $[C_2H_6]$ or $[C_3H_8]$ was below detection limits using the detection limits of 0.0005 and 0.0001 mg/L for $[C_2H_6]$ and $[C_3H_8]$, respectively.

Table 1. Statistical analyses for [CH_4] and [C_2H_6]

	Distance to gas wells	Distance to streams	Distance to ASF
[CH_4]			
Multiple regression	$P = 0.0007$	$P = 0.27$	$P = 0.11$
Pearson r	$P = 0.0003$	$P = 0.22$	$P = 0.04$
Spearman ρ	$P = 0.007$	$P = 0.01$	$P = 0.02$
[C_2H_6]			
Multiple regression	$P = 0.0034$	$P = 0.053$	$P = 0.45$
Pearson r	$P = 0.003$	$P = 0.36$	$P = 0.11$
Spearman ρ	$P = 0.004$	$P = 0.95$	$P = 0.21$

Isotopic signatures and gas ratios provide additional insight into the sources of gases in groundwater. Signatures of δ^{13}C-CH_4 > −40‰ (reference to Vienna Pee Dee Belemnite standard) generally suggest a thermogenic origin for methane, whereas δ^{13}C-CH_4 values < −60‰ suggest a biogenically derived methane source (27, 29, 30). Across our dataset, the most thermogenic δ^{13}C-CH_4 signatures (i.e., most enriched in ^{13}C) in drinking water were generally found in houses with elevated [CH_4] <1 km from natural gas wells (Fig. 3*A*). In fact, all drinking water wells with methane concentrations >10 mg/L, the US Department of Interior's threshold for considering remediation, have δ^{13}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 δ^{13}C-CH_4 signatures that seem to be microbial in origin, specifically those homes shown in Fig. 3*A*, lower left corner. The combination of our δ^{13}C-CH_4 (Fig. 3*A*) and δ^2H-CH_4 data (Fig. 3*B*) 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 δ^{13}C-CH_4 and δ^{13}C-C_2H_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 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_1:C_2^+ ratio and leading to isotopic compositions that become increasingly heavier or enriched (31). In most natural gases, the isotopic composition (δ^{13}C) of $C_3 > C_2 > C_1$ (i.e., δ^{13}C of ethane is heavier than methane). In thermally mature black shales, however, this maturity trend reverses, creating diagnostic isotopic reversals in which the δ^{13}C-CH_4 becomes heavier than δ^{13}C-C_2H_6 ($\Delta^{13}C = \delta^{13}C\text{-}CH_4 - \delta^{13}C\text{-}C_2H_6 > 1$) (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 δ^{13}C-CH_4 and $\Delta^{13}C > 0$ 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 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 δ^{13}C-CH_4 values in drinking water wells between −24.98‰ and -29.36‰ δ^{13}C-CH_4 and five samples with δ^{13}C-CH_4 values in the range of Marcellus gas defined in ref. 28. The heaviest methane isotopic signatures in the EPA samples

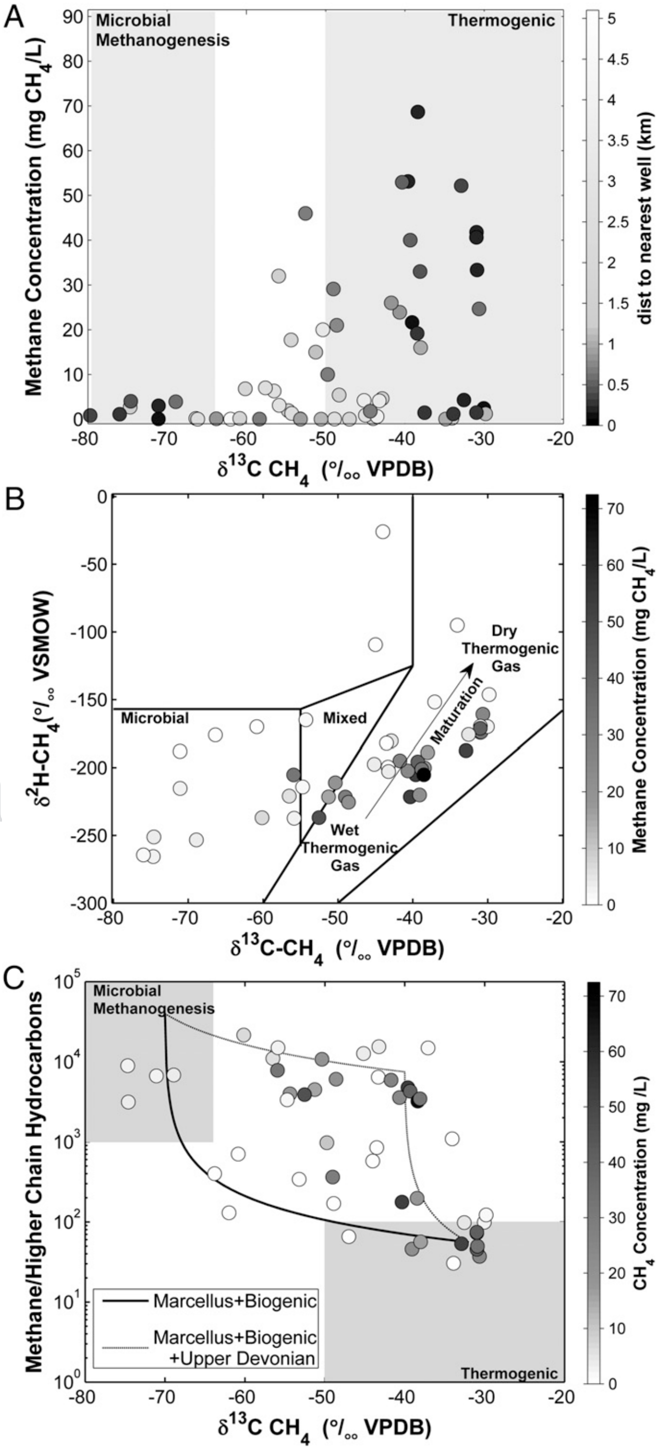

Fig. 3. (*A*) Methane concentration, (*B*) δ^2H-CH_4, and (*C*) methane to ethane + propane ratio plotted against δ^{13}C-CH_4. The grayscale shading refers to (*A*) distance to nearest gas wells and (*B* and *C*) methane concentration. The solid lines in *B* distinguishing natural gas sources are from ref. 27; the mixed line in *B* comes from the standard mixing equations in ref. 14. *C* shows two hypothetical trajectories: simple mixing between thermogenically and biogenically derived gas (lower curve) and either diffusive migration or a three-component mixture between Middle and Upper Devonian gases and shallow biogenic gases (upper curve).

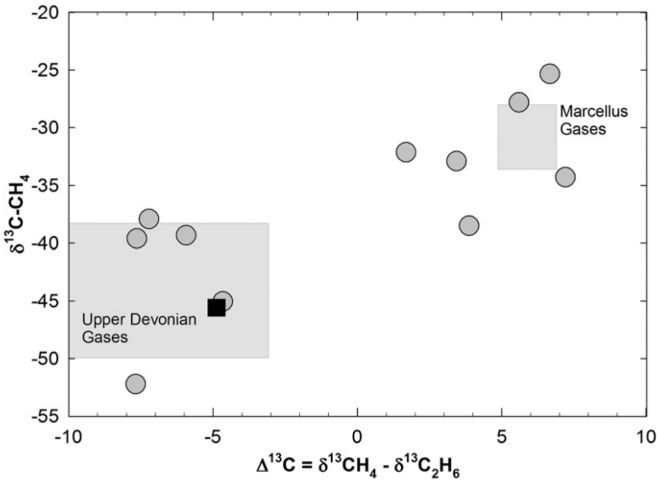

Fig. 4. Stable isotope signatures (‰ VPDB) of methane ($\delta^{13}C\text{-}CH_4$) vs. $\delta^{13}C$ for methane minus ethane ($\Delta^{13}C = \delta^{13}CH_4 - \delta^{13}C_2H_6$); 6 of 11 drinking water samples exhibited isotopic reversals and $\delta^{13}C\text{-}CH_4$ values consistent with Marcellus production gas (14, 28, 55). In contrast, five drinking water samples and the salt spring at Salt Springs State Park (filled square) had $\delta^{13}C\text{-}CH_4$ and $\Delta^{13}C < 0$ consistent with Upper Devonian production gases (14, 55). Eleven drinking water samples had sufficient ethane concentrations for isotopic determinations. Ten of the samples were <1 km distance from shale gas wells, and one sample is at 1.1 km distance (the point in the lower left corner of the plot).

(−24.98‰ $\delta^{13}C\text{-}CH_4$) exceeded the values observed for ethane (−31.2‰ $\delta^{13}C\text{-}C_2H_6$), an isotopic reversal ($\Delta^{13}C$ = 6.22‰) characteristic of Marcellus or other deeper gas compared with gases from Upper Devonian sequences (14, 28).

Helium is an inert noble gas with a radiogenic isotope, ^4He, that is a major component of thermogenic natural gas. Similar to hydrocarbon components, the abundance and isotopic composition of helium can help distinguish between potential sources and/or residence times of fluids in the crust, including natural gases (15, 16, 33). Across our dataset, the ratio of $^4He:CH_4$ in most drinking water wells showed a typical range between $\sim 2 \times 10^{-3}$ and 1×10^{-2}, independent of distance to natural gas wells (Fig. 5). In contrast, a subset of points with elevated $[CH_4]$ has a $^4He:CH_4$ ratio significantly below the range established for shallow drinking water in the region and consistent with a mixture between shallow groundwater and Marcellus production gases there ($\sim 2\text{–}5 \times 10^{-4}$) (Fig. 5) (15).

The relative proportions of methane to higher-chain hydrocarbons, such as ethane and propane, can also be used to help differentiate biogenically and thermogenically derived methane as well as different thermogenic sources of natural gas (34). As described above, low ratios of methane to higher-chain hydrocarbons (~<100) in water typically suggest a hydrocarbon gas derived from a thermogenic source, whereas ratios of methane to higher-chain hydrocarbons >>1,000 suggest a microbial origin for the gas (27). Across our hydrocarbon dataset, ~15 samples seem to fall within the range corresponding to thermogenic gas, whereas the composition of 5 or 6 samples seems to be microbial in origin (Fig. 3*C*). The other points fell on two intermediate trajectories. One trajectory is simple mixing between thermogenically and biogenically derived gas (lower curve in Fig. 3*C*). 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. 3*C*).

The relative distribution of ethane and propane provides additional insight into the source and mixture of gases. The ratio of propane to methane concentrations plotted against $[C_3H_8]$ (Fig. S5) shows that at least 6 of 10 water samples with detectable $[C_3H_8]$ had an order of magnitude greater $[C_3]/[C_1]$ ratio and $[C_3]$ 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 $[C_3]$ outside of our 11 samples (mean $[C_3]/[C_1] = 0.000029$ and $[C3] = 0.0022$ mg/L for the Salt Springs samples) (Fig. S5).

The abundance and relative proportions of aliphatic hydrocarbons (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 (C_3/C_2) in our dataset were generally higher than ratios for the Salt Springs State Park, and ratios of methane to ethane (C_1/C_2) were generally lower (Fig. S6), approaching ratios for Marcellus gases in some cases (Fig. S6). We also observed that the highest methane concentrations coincided with increased abundances 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 ($C_2 + C_3$) of at least 1–2% and C_3/C_2 of ~>0.03%, whereas Upper Devonian gases, specifically those gases observed in Upper Devonian aquifers before shale gas development (30), tend to be relatively depleted in wetter gases; samples from the Salt Springs State Park had intermediate wetness, which is discussed above (14, 30). As a result, increasing proportions of C_3/C_2 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 ^{13}C in DIC (e.g., $\delta^{13}C\text{-DIC} > +10‰$) and positive correlations between $\delta^{13}C\text{-DIC}$ and $\delta^{13}C\text{-}CH_4$ and between $\delta^2H\text{-}H_2O$ and $\delta^2H\text{-}CH_4$ have all been used as indicators of microbial methane sourced from relatively shallow depths (~<550 m) (38, 39). Most of our $\delta^{13}C\text{-DIC}$ values were 20–25‰ lighter (more negative) than typical for DIC influenced by microbially derived methane in shallow groundwater, and the $\delta^{13}C\text{-}CH_4$ values of the samples showed no evidence of a positive relationship with $\delta^{13}C\text{-DIC}$ (and even a slight negative relationship; $P = 0.003$) (Fig. S8, *Upper*). We also found no statistical relationship between the δ^2H values of methane and δ^2H 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

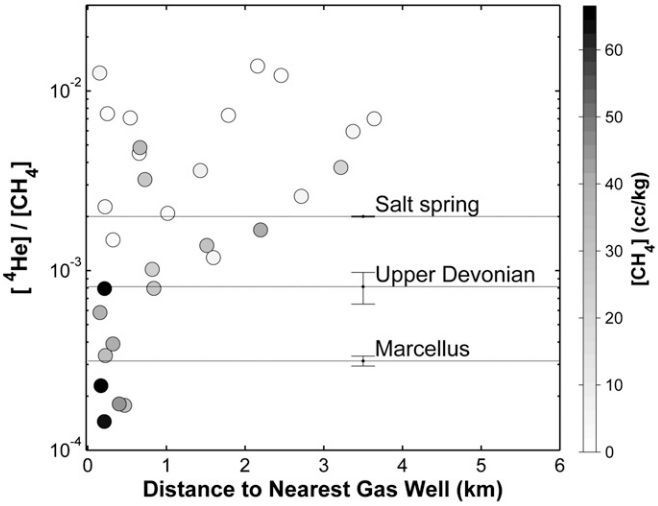

Fig. 5. The ratio of $^4He:CH_4$ concentrations in drinking water wells vs. distance to gas wells (kilometers). The values are compared with water samples (mean ± SE) from the salt spring at Salt Springs State Park (n = 3) and Marcellus (n = 4) and Upper Devonian (n = 5) production gases (15).

seem to be derived locally in the shallow aquifers, and the gas composition is not consistent with extensive microbial production from methanogenesis or sulfate reduction. Methanotrophy also does not seem to be occurring broadly across our dataset; it would decrease [CH_4] and C_1:C_2 ratios and increase $\delta^{13}CH_4$ values, reducing the differences that we observed for distance to gas wells. Overall, the combined results suggest that natural gas, derived at least in part from thermogenic sources consistent with Middle Devonian origin, is present in some of the shallow water wells <1 km away from natural gas wells.

The two simplest explanations for the higher dissolved gas concentrations that we observed in drinking water are (*i*) faulty or inadequate steel casings, which are designed to keep the gas and any water inside the well from leaking into the environment, and (*ii*) imperfections in the cement sealing of the annulus or gaps between casings and rock that keep fluids from moving up the outside of the well (4, 40–42). In 2010, the Pennsylvania Department of Environmental Protection (DEP) issued 90 violations for faulty casing and cementing on 64 Marcellus shale gas wells; 119 similar violations were issued in 2011.

Distinguishing between the two mechanisms is important because of the different contamination to be expected through time. Casing leaks can arise from poor thread connections, corrosion, thermal stress cracking, and other causes (43). If the protective casing breaks or leaks, then stray gases could be the first sign of contamination, with less mobile salts and metals from formation waters or chemicals from fracturing fluids potentially coming later. In contrast, faulty cement can allow methane and other gases from intermediate layers to flow into, up, and out of the annulus into shallow drinking water layers. In such a scenario, the geochemical and isotopic compositions of stray gas contamination would not necessarily match the target shale gas, and no fracturing chemicals or deep formation waters would be expected, because a direct connection to the deepest layers does not exist; also, such waters are unlikely to migrate upward. Comprehensive analyses of well integrity have shown that sustained casing pressure from annular gas flow is common. A comprehensive analysis of ∼15,500 oil and gas wells (43) showed that 12% of all wells drilled in the outer continental shelf area of the Gulf of Mexico had sustained casing pressure within 1 y of drilling, and 50–60% of the wells had it from 15 y onward. For our dataset, there is a weak trend to higher methane concentrations with increasing age of the gas wells ($P = 0.067$ for [CH_4] vs. time since initial drilling). This result could mean that the number of drinking water problems may grow with time or that drilling practices are improving with time; more research is needed before firm conclusions can be drawn.

In addition to well integrity associated with casings or cementing, two other potential mechanisms for contamination by hydraulic fracturing/horizontal drilling include enhancing deep-to-shallow hydraulic connections and intersecting abandoned oil and gas wells. Horizontal drilling and hydraulic fracturing can stimulate fractures or mineralized veins, increasing secondary hydraulic connectivity. The upward transport of gases is theoretically possible, including pressure-driven flow through open, dry fractures and pressure-driven buoyancy of gas bubbles in aquifers and water-filled fractures (44, 45). Reduced pressures after the fracturing activities could also lead to methane exsolving rapidly from solution (46). If methane were to reach an open fracture pathway, however, the gas should redissolve into capillary-bound water and/or formation water, especially at the lithostatic and hydrostatic pressures present at Marcellus depths. Legacy or abandoned oil and gas wells (and even abandoned water wells) are another potential path for rapid fluid transport. In 2000, the Pennsylvania DEP estimated that it had records for only 141,000 of 325,000 oil and gas wells drilled historically in the state, leaving the status and location of ∼184,000 abandoned wells unknown (47). However, historical drilling activity is minimal in our study area of northeastern Pennsylvania, making this mechanism unlikely there.

This study examined natural gas composition of drinking water using concentration and isotope data for methane, ethane, propane, and ^{4}He. 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 ^{4}He:CH_4 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 $\delta^{13}C$ and δ^2H 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 geochemistry of ^{4}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, publicly 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), and results were combined with 60 previous samples 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 ^{4}He (Fig. 5), samples from 30 drinking water wells were used to estimate concentration ratios of ^{4}He:CH_4. Wells were purged to remove stagnant water and then monitored for pH, electrical conductance, and temperature until stable values were recorded. Samples were collected upstream of any treatment systems and as close to the water well as possible, preserved in accordance with procedures detailed in *SI Text*, and returned immediately to Duke University for analyses. The chemical and isotope ($\delta^{13}C$-DIC, δ^2H-H_2O, and $\delta^{18}O$-H_2O) compositions of the collected waters were measured at Duke University's Environmental Stable Isotope Laboratory. Values of $\delta^{18}O$-H_2O and δ^2H-H_2O were measured using temperature conversion elemental analysis/continuous flow isotope ratio MS using a ThermoFinnigan temperature conversion elemental analysis and Delta+XL mass spectrometer and normalized to Vienna Standard Mean Ocean Water (analytical precision of ± 0.1‰ and ±1.5‰ for $\delta^{18}O$-H_2O and δ^2H-H_2O, respectively). Samples of ^{4}He were collected in refrigeration-grade copper tubes flushed with water before sealing with stainless steel clamps and analyzed using a VG 5400 MS at the University of Rochester (15, 51).

Dissolved gas samples were collected in the field using procedures detailed by Isotech Laboratories (52), stored on ice until delivery to their facilities, and analyzed for concentrations and isotopic compositions of methane, ethane, and propane. Procedures for gas analyses are summarized in ref. 4. Isotech Laboratories uses chromatographic separation followed by combustion and dual-inlet isotope ratio MS to measure dissolved gas concentrations, $\delta^{13}C$-CH_4, and $\delta^{13}C$-C_2H_6 (detection limits for C_1, C_2, and C_3 were 0.001, 0.0005, and 0.0001 mol %, respectively). Dissolved [CH_4] and $\delta^{13}C$-CH_4 were also determined by cavity ring-down spectroscopy in the Duke Environmental Stable Isotope Laboratory on eight samples using a Picarro G2112i.

Dissolved $[CH_4]$ was equilibrated using a head-space equilibration method (53) and diluted when necessary using zero air. A set of 33 groundwater samples with a range of $[CH_4]$ and $\delta^{13}C\text{-}CH_4$ was collected in duplicate and analyzed at both Duke University and Isotech Laboratories (Fig. S9). Hydrocarbon concentrations in groundwater were converted to milligrams of CH_4 L^{-1} from a correlation with mol % ($R^2 = 0.95$). As in refs. 4 and 11, the derived distances to gas wells represent planimetric lengths from sampling locations to nearest gas wells and do not account for the direction or extent of horizontal drilling underground. Distances to streams were determined as the shortest lengths from sampled locations to valley centerlines using the national stream network as the base map; distance to the Appalachian Structural Front was measured using GIS software. Statistical analyses were performed using MATLAB and R software.

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Supporting Information

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SI Text

Geological Setting. The study area (Fig. S1) was chosen because of its rapid expansion of drilling for natural gas from the Marcellus Shale (Pennsylvania); also, it has a limited history of prior oil and gas exploration. Additionally, the study area represents portions of both the upper Susquehanna and upper Delaware watersheds that provide drinking water to >15 million people. The geological setting and methods for the work have been described previously in the works by Osborn et al. (1) and Warner et al. (2). Briefly, the sedimentary geology represents periods of deposition, burial, lithification, uplift, and subsequent erosion that form relatively simple sets of horizontal strata dipping 1° to 3° to the south and east derived from depositional environments that ranged from proposed deep to midbasin black shales to terrestrial red beds (3–5). The monocline is bounded on the north by the Precambrian Canadian Shield and Adirondack uplift (north to northeast), the west by the Algonquin and Findlay arches, and the south and east by the Appalachian fold belt (the Valley and Ridge Province) (6, 7). In general, sedimentary deposition in the northern Appalachian Basin was relatively continuous throughout the Paleozoic era. However, several unconformities erase sequence records regionally, such as the Tri-States unconformity that removed Lower Devonian strata in western New York, but complete sequences are generally found in central New York and our study region of northeastern Pennsylvania (3).

The Appalachian Basin consists primarily of sedimentary sequences of Ordovician to Pennsylvanian age that are derived from the Taconic (~450 Ma), Acadian (~410–380 Ma), and Alleghanian (~330–250 Ma) orogenic events (8). Exposed at its northern extent near Lake Ontario is the Upper Ordovician–Lower Silurian contact (Cherokee unconformity). Younger deposits (Upper Silurian, Devonian, and Mississippian) occur in successive outcrop belts to the south to the Appalachian structural front (4, 9), whereas erosion has removed most post-Pennsylvanian deposition within western-central New York and most of our study area within northeastern Pennsylvania. Bedrock thickness within the basin ranges from ~920 m along the southern shore of Lake Ontario in northern New York to ~7,600 m along the Appalachian structural front to the south. A simplified stratigraphic reconstruction is presented in Fig. S2 for the study area, which constitutes a transition from the Valley and Ridge to the Plateau Province. Compared with the Valley and Ridge Province or the region near the Appalachian Structural Front, the plateau portion of the Marcellus Formation is significantly less deformed (10). Deformation began during the onset of the Alleghanian orogeny. In the plateau physiographic province, deformation is accommodated by a combination of layer parallel shortening, folding that led to low-amplitude anticline/syncline sequences, low angle thrust faulting structures, lineaments, joints, and natural fractures observable in northeastern Pennsylvania (4, 11, 12).

The Marcellus Formation is an organic-rich, hydrocarbon-producing, siliciclastic-rich black shale present beneath much of Pennsylvania, New York, West Virginia, and other northeastern states. It constitutes the stratigraphically lowest subgroup of the Middle Devonian Hamilton Group (5, 9) and was deposited in the foreland basin of the Acadian Orogeny (~385–375 Ma). The Marcellus Formation includes two distinct calcareous and iron-rich black shale members [i.e., the Union Springs (lower) and Mount Marion/Oatka Creek (upper)) interrupted by the Cherry Valley limestone].

Like the Marcellus, the upper part of the Devonian sequence is deposited in the foreland basin of the Acadian Orogeny and consists of material sourced from the Acadian orogeny as part of the Catskill Deltaic sequence. Above the Marcellus, the Hamilton Group consists of the Mahantango gray shale locally interbedded by limestones and the Tulley limestone. The Upper Devonian consists of thick synorogenic sequences of gray shales (i.e., the Brallier Formation) beneath the Lock Haven Formation sandstone and Catskill Formation clastic deltaic red sandstones. The Lock Haven and Catskill Formations constitute the two primary aquifer lithologies in northeastern Pennsylvania along with the overlying glacial and sedimentary alluvium, which is thicker in valleys than the uplands.

Additional geological information is in the work by Osborn et al. (1) and references therein and the work by Warner et al. (2) and references therein.

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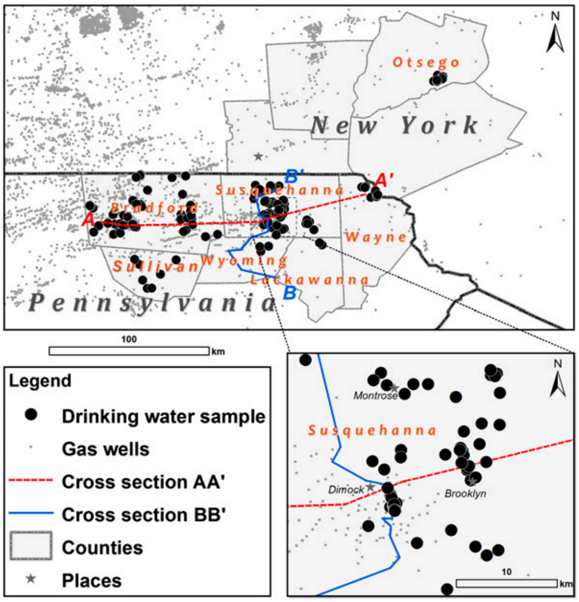

Fig. S1. Map of well water sampling locations in Pennsylvania and New York. The star in *Upper* represents the location of Binghamton, New York. (*Lower Right*) A close-up view of Susquehanna County, Pennsylvania. The stars in *Lower Right* represent the towns of Dimock, Brooklyn, and Montrose, Pennsylvania. The red and blue lines represent the approximate location of the cross-sections in Fig. S2.

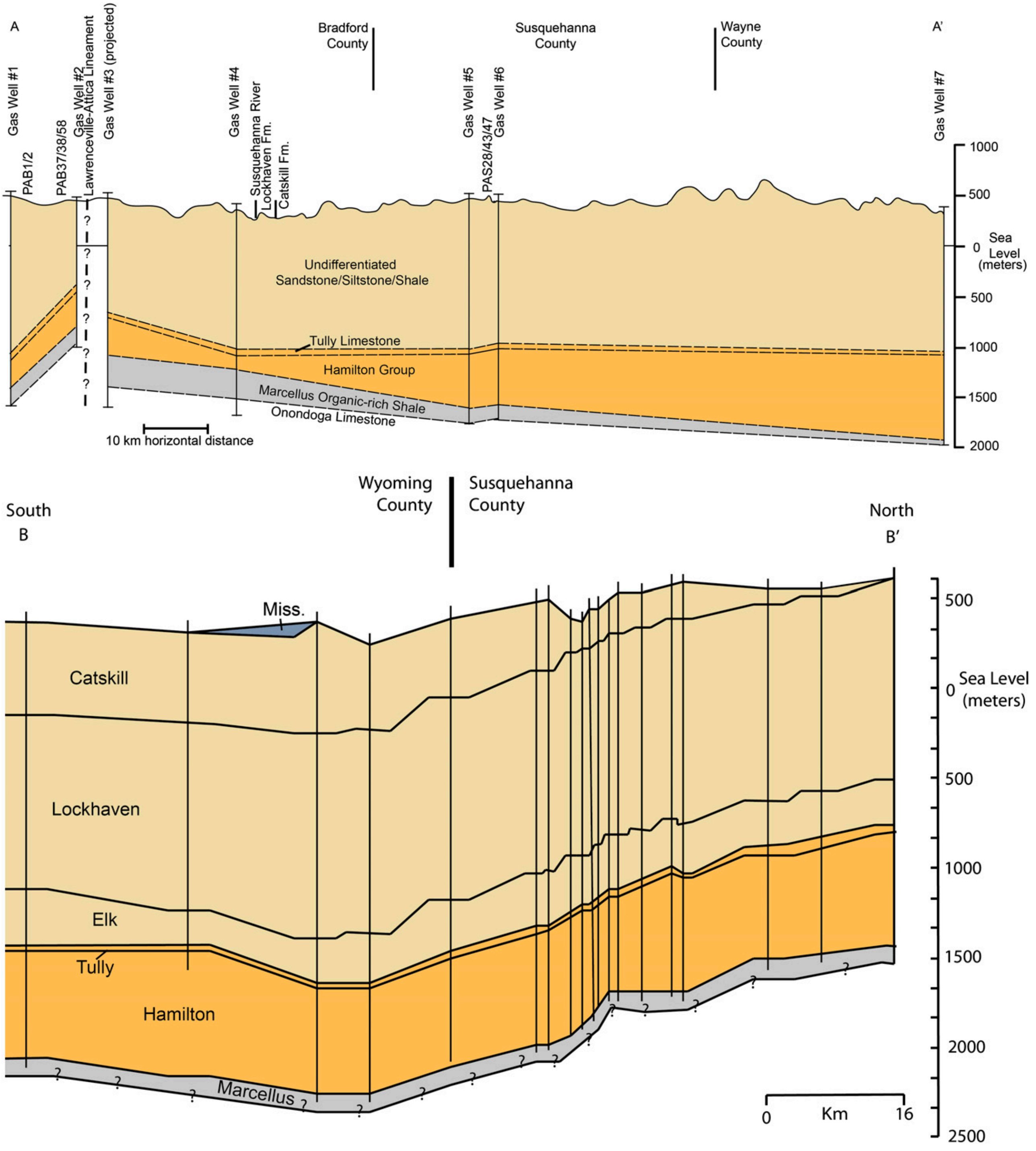

Fig. S2. Generalized stratigraphic section of the study region from the work by Osborn et al. (1), Molofsky et al. (2), and Warner et al. (3) and references therein. The cross sections shown here refer to the locations identified in Fig. S1.

1. Osborn SG, Vengosh A, Warner NR, Jackson RB (2011) Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. *Proc Natl Acad Sci USA* 108(20):8172–8176.
2. Molofsky LJ, Connor JA, Wylie AS, Wagner T, Farhat SK (2013) Evaluation of methane sources in groundwater in northeastern Pennsylvania. *Groundwater* 51(3):333–349.
3. Warner NR, et al. (2012) Geochemical evidence for possible natural migration of Marcellus Formation brine to shallow aquifers in Pennsylvania. *Proc Natl Acad Sci USA* 109(30): 11961–11966.

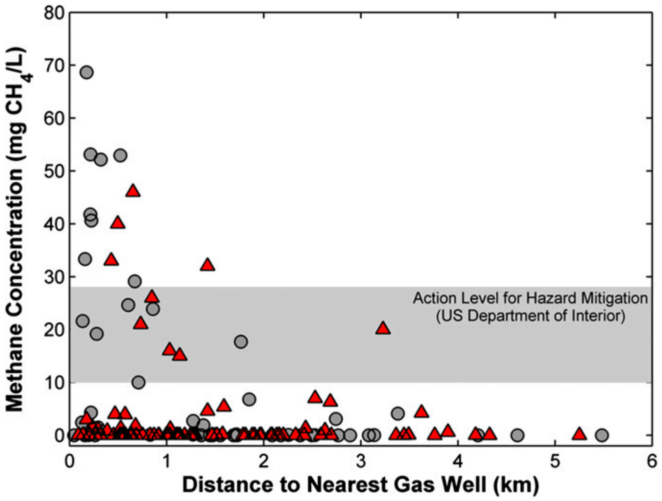

Fig. S3. Methane concentrations (milligrams per liter) vs. distance to nearest gas wells (kilometers) with data from the initial study (1) in filled circles and new observations in red triangles.

1. Osborn SG, Vengosh A, Warner NR, Jackson RB (2011) Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. *Proc Natl Acad Sci USA* 108(20):8172–8176.

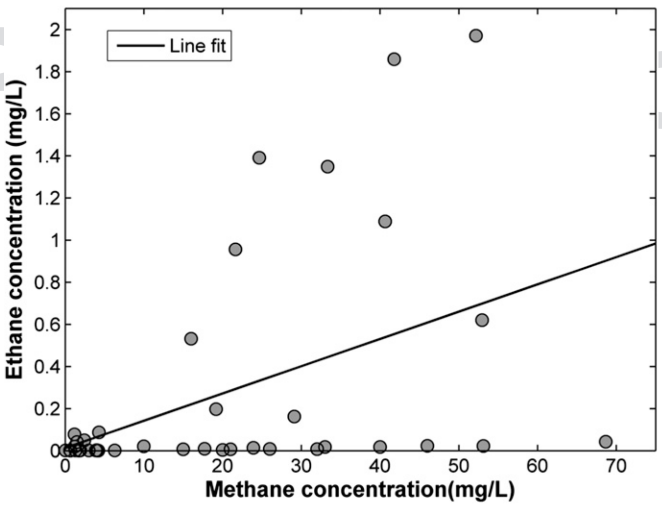

Fig. S4. Concentrations of ethane vs. methane across the groundwater dataset ($P = 0.0034$; $R^2 = 0.205$).

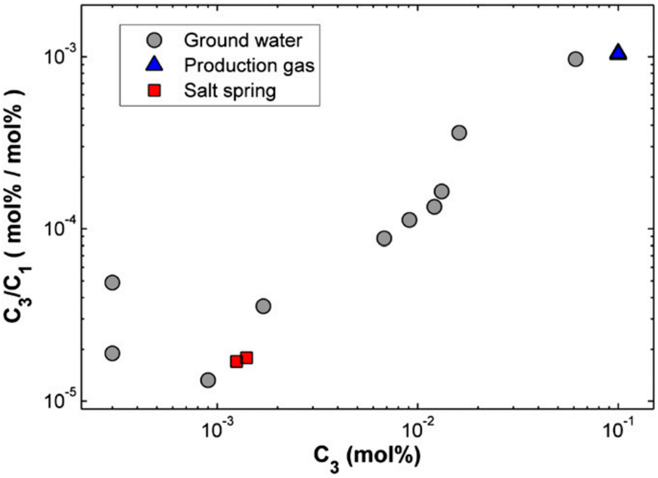

Fig. S5. The ratio of propane to methane concentrations vs. propane concentrations (mol%) for our data from drinking water wells (filled circles), the salt spring at Salt Springs State Park in Franklin Forks, Pennsylvania (red squares), and Marcellus production gas (blue triangle) (1).

1. Jenden PD, Drazan DJ, Kaplan IR (1993) Mixing of thermogenic natural gases in Northern Appalachian Basin. *Am Assoc Pet Geol Bull* 77(6):980–998.

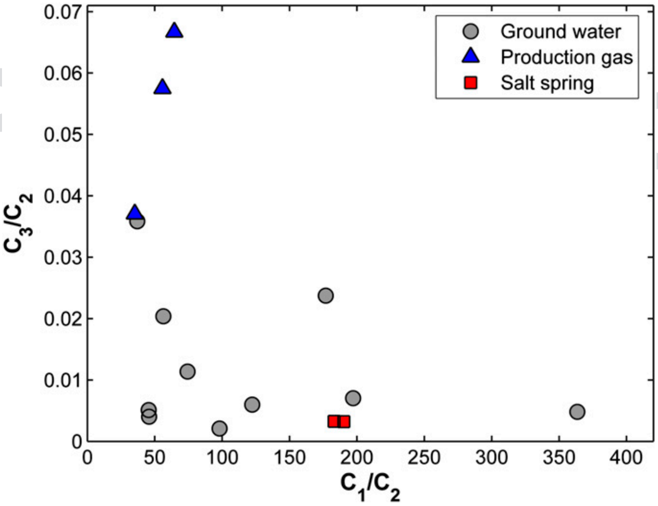

Fig. S6. The ratios of propane to ethane (C_3/C_2) and methane to ethane (C_1/C_2) concentrations for our data from drinking water wells (filled circles), the salt spring at Salt Springs State Park in Franklin Forks, Pennsylvania (red squares), and Marcellus production wells across the study area (blue triangles) (1, 2).

1. Jenden PD, Drazan DJ, Kaplan IR (1993) Mixing of thermogenic natural gases in Northern Appalachian Basin. *Am Assoc Pet Geol Bull* 77(6):980–998.
2. Laughrey CD, Baldassare FJ (1998) Geochemistry and origin of some natural gases in the Plateau province, central Appalachian basin, Pennsylvania and Ohio. *Am Assoc Pet Geol Bull* 82(2):317–335.

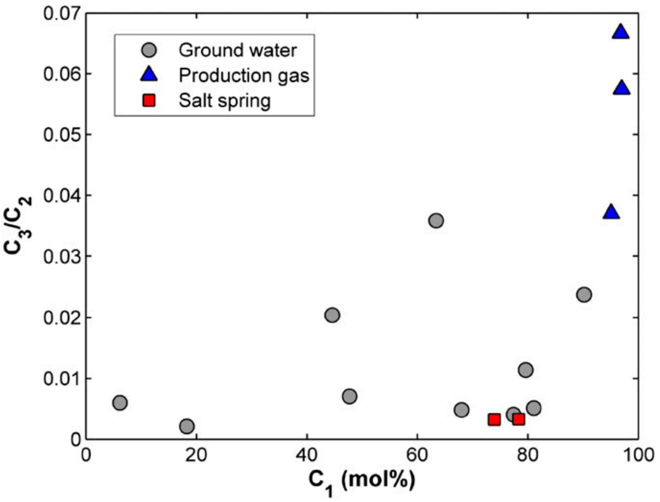

Fig. S7. The ratio of propane to ethane concentrations vs. methane concentrations (mol%) for our data from drinking water wells (filled circles), the salt spring at Salt Springs State Park in Franklin Forks, Pennsylvania (red squares), and production gases in the area (blue triangles) (1, 2).

1. Jenden PD, Drazan DJ, Kaplan IR (1993) Mixing of thermogenic natural gases in Northern Appalachian Basin. *Am Assoc Pet Geol Bull* 77(6):980–998.
2. Laughrey CD, Baldassare FJ (1998) Geochemistry and origin of some natural gases in the Plateau province, central Appalachian basin, Pennsylvania and Ohio. *Am Assoc Pet Geol Bull* 82(2):317–335.

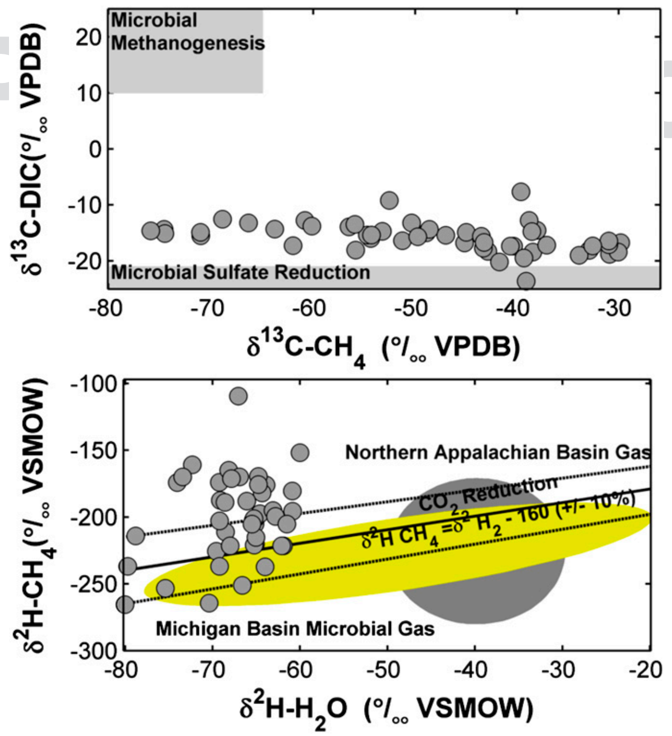

Fig. S8. (*Upper*) Plot of the carbon isotopes in $\delta^{13}C$ dissolved inorganic carbon ($\delta^{13}C$-DIC) in groundwater vs. carbon isotopes in coexisting methane ($\delta^{13}C$-CH_4), which illustrates that samples do not plot within methanogenesis or sulfate reduction zones. Ranges in $\delta^{13}C$-DIC for methanogenesis and sulfate reduction are taken from the work by Clark and Fritz (1). VPDB, Vienna Pee Dee belemnite. (*Lower*) Plot of $\delta^{2}H$-CH_4 of dissolved methane in groundwater vs. $\delta^{2}H$-H_2 of the groundwater. The fractionation line for microbial methanogenesis by CO_2 reduction depicted is from the work by Whiticar et al. (2). Microbial methane from the Michigan and Illinois Basins is depicted with the yellow oval (3, 4). Northern Appalachian Basin data are depicted in the gray oval (5). The lack of positive correlation between the two hydrogen sources indicates that microbial methane is negligible in the shallow groundwater. VSMOW, Vienna Standard Mean Ocean Water.

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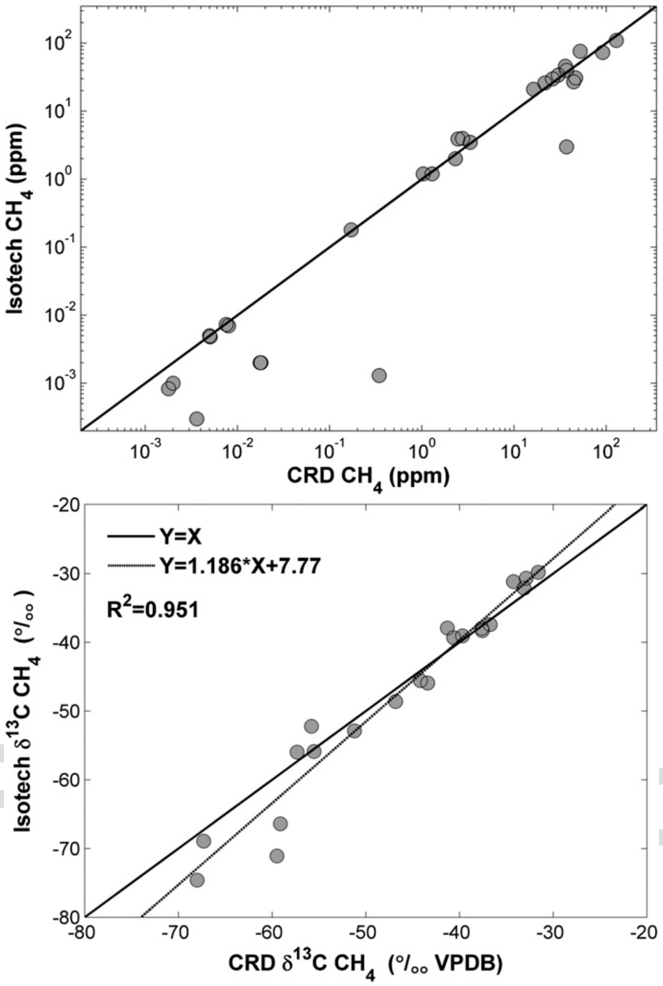

Fig. S9. Comparisons of Isotech Laboratories and cavity-ring down (CRD) spectrometry analyses for (*Upper*) [CH$_4$] and (*Lower*) δ^{13}C-CH$_4$ analyzed in duplicate at both Isotech Laboratories and the Duke Environmental Stable Isotope Laboratory. These results show statistically indistinguishable differences between the two data analysis methods.

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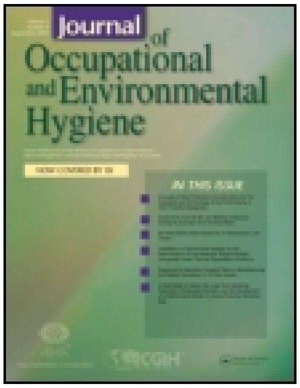

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Occupational Exposures to Respirable Crystalline Silica During Hydraulic Fracturing

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This report describes a previously uncharacterized occupational health hazard: work crew exposures to respirable crystalline silica during hydraulic fracturing. Hydraulic fracturing involves high pressure injection of large volumes of water and sand, and smaller quantities of well treatment chemicals, into a gas or oil well to fracture shale or other rock formations, allowing more efficient recovery of hydrocarbons from a petroleum-bearing reservoir. Crystalline silica ("frac sand") is commonly used as a proppant to hold open cracks and fissures created by hydraulic pressure. Each stage of the process requires hundreds of thousands of pounds of quartz-containing sand; millions of pounds may be needed for all zones of a well. Mechanical handling of frac sand creates respirable crystalline silica dust, a potential exposure hazard for workers. Researchers at the National Institute for Occupational Safety and Health collected 111 personal breathing zone samples at 11 sites in five states to evaluate worker exposures to respirable crystalline silica during hydraulic fracturing. At each of the 11 sites, full-shift samples exceeded occupational health criteria (e.g., the Occupational Safety and Health Administration calculated permissible exposure limit, the NIOSH recommended exposure limit, or the ACGIH threshold limit value), in some cases, by 10 or more times the occupational health criteria. Based on these evaluations, an occupational health hazard was determined to exist for workplace exposures to crystalline silica. Seven points of dust generation were identified, including sand handling machinery and dust generated from the work site itself. Recommendations to control exposures include product substitution (when feasible), engineering controls or modifications to sand handling machinery, administrative controls, and use of personal protective equipment. To our knowledge, this represents the first systematic study of work crew exposures to crystalline silica during hydraulic fracturing. Companies that conduct hydraulic fracturing using silica sand should evaluate their operations to determine the potential for worker exposure to respirable crystalline silica and implement controls as necessary to protect workers.

[Supplementary materials are available for this article. Go to the publisher's online edition of Journal of Occupational and Environmental Hygiene *for the following free supplemental resource: a file containing controls and recommendations to limit worker exposures to respirable crystalline silica at hydraulic fracturing work sites.]*

Keywords completions operations, crystalline silica, hydraulic fracturing, oil and gas extraction, sand

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INTRODUCTION

Occupational exposure to respirable crystalline silica is a well-established hazard in mining, sandblasting, foundry work, agriculture, and construction, but not for oil and gas extraction work, which includes hydraulic fracturing.(1–9) Hydraulic fracturing involves high pressure injection of large volumes of water ($\approx$95% of total volume) "proppant" ($\approx$ 4.5%, typically as silica sand) and lesser quantities ($\leq$1.0%) of treatment chemicals (commonly a combination of surfactants, acids, scale inhibitor, clay stabilizers, corrosion/precipitation inhibitors, pH adjusting agents, gels, gel breakers, and biocides) into hydrocarbon-bearing strata to enhance recovery of oil and gas, particularly from deep shale formations. Hydraulic fracturing creates and enhances cracks and fissures in the geology; proppant holds the fractures open, allowing more efficient and sustained flow back of gas or oil.

Also called "well stimulation," "pressure pumping," or "completions operations," hydraulic fracturing has been used since the 1940s and has increased substantially over the last 10 years with the advent of "unconventional" drilling techniques (e.g., directional and horizontal) to access oil and gas not previously feasible with vertical drilling techniques alone.

Although silica sand is the most commonly used proppant, aluminum pellets, sintered bauxite, man-made ceramics, and resin-coated sand can also be used depending on geological conditions.(10,11)

Onshore oil and gas extraction (well drilling, servicing, and hydraulic fracturing) falls within the jurisdiction of the Occupational Safety and Health Administration (OSHA). Workplace safety hazards (e.g., risks for fatal injuries) in the upstream oil and gas extraction industry are documented, but to our knowledge, there are few (if any) published studies of chemical exposure risks for land-based crews during hydraulic fracturing operations.(12,13) Occupational health knowledge gaps in completions operations (i.e., hydraulic fracturing) include (1) understanding which job titles have risks for chemical exposures; (2) quantifying the magnitude of exposure risks (if present) for both chemicals and minerals; and (3) understanding the relative contribution of all likely route(s) of exposure, including inhalation, dermal exposures, and ingestion.

Approximately 435,000 workers were employed in the U.S. oil and gas extraction industry in 2010, nearly half employed by well servicing companies, including companies that conduct hydraulic fracturing.(14) To evaluate possible occupational health hazards, NIOSH initiated the Field Effort to Assess Chemical Exposures in Oil and Gas Extraction Workers in 2010. The work began with observations of completions work sites; reviews of safety data sheets; and discussions with work crews, supervisors, and health and safety personnel at hydraulic fracturing sites.(15) To date, exposure assessments for respirable crystalline silica during hydraulic fracturing have been the predominant focus of the NIOSH field effort.

Crews and Machinery

At a typical site, 10–12 Driver/Operators position and set up equipment, configure and connect piping, pressure test, then operate the equipment (e.g., sand movers, blender, and chemical trucks) required for hydraulic fracturing. Other employees operate water tanks and water transport systems, and several control on-site traffic, including sand delivery trucks and other vehicles. An additional crew includes Wire Line (typically 3–5) who configure and assemble well casing perforation tools and operate cranes to move tools and equipment into and out of the well. Operators run the diesel-driven pump trucks necessary for hydraulic fracturing and operate sand movers and blender trucks to distribute and mix proppant (e.g., sand) and liquids. Chemical Truck Operators monitor and manage delivery of the necessary well treatment additives to the blender trucks for delivery to the well. Operationally, the entire process is monitored and controlled by personnel in on-site data vehicles with real-time monitoring of aboveground and in-well parameters, including temperatures, pressures, and flow rates of liquids and proppant.

On a typical 12-hr shift, workers may operate a specific piece of machinery (e.g., sand mover, blender truck) or may operate different machines over a shift. Roving Operators, Water Tank Operators, and Sand Coordinators/Ground Guides often work in different locations over a shift.

Sand Use, Transport, and Delivery in Modern, Unconventional Oil and Gas Extraction

A typical unconventional gas or oil well has 12–20 stages (also called zones) that are fractured; some wells can have 40 or more stages. As stages increase, more water and proppant are required. Moving proppant along transfer belts, pneumatically filling and operating sand movers, involves displacement of hundreds of thousands of pounds of sand per stage, which creates airborne dusts at the work site.

Proppant (e.g., sand) is delivered to the well site by sand trucks (e.g., dry-bulk tractor trailers). Depending on the number of stages to be completed, delivery may consist of a single sand transfer or require serial proppant deliveries throughout the day. Sand trucks are offloaded by the Driver/Operator who connects the delivery truck to a sand holding/sand transport vehicle, hereafter called "sand mover," that uses compressed air to pump sand through fill ports on sides of sand movers; offloading takes 30 to 45 min.

Sand movers supply sand to blender trucks via a motor-driven belt assembly located beneath the mover. The assembly retracts and extends, elevates, and swings and is commonly referred to as the "dragon tail." Sand Mover Operator stations are located on top rear and side rear of the mover directly above and to the side of the dragon tail. Larger proppant loads are increasingly common, requiring multiple sand movers and a transfer or "T-belt" to convey sand between the sand mover and the blender truck. Sand Mover Operators control sand delivery by hydraulically controlling gates on the bottom of the sand mover and by manipulation of belt speed. Sand Mover Operators observe proppant being delivered into the blender hopper (or onto the T-belt) and communicate with Blender Operators and personnel in data monitoring vehicles. The intent is for the proppant to remain dry until it enters the wet section of the blender before pumping through a manifold, connection piping, and into the wellbore.

Despite differences in shape, size, color, and quality, all sand used for hydraulic fracturing consists of silicon, the second most abundant element in the earth's crust.(16) The most common crystalline form of silicon dioxide (SiO_2) is quartz.(16) Various types, sizes, colors, and treatments (e.g., Northern white; Texas yellow; 20/40, 40/70, and 100 mesh; plain vs. resin coated) of silica sand (typically 99% quartz) are used as the primary proppant for completions operations across the United States. Increased use and demand for silica sand proppant is expected to continue with ongoing completion operations in existing oil and gas basins and as operations increase across relatively newer, developing areas (e.g., Bakken formation in North Dakota and Niobrara in Northeast Colorado and parts of Kansas and Nebraska).(17) High-quality frac sand is typically defined as having consistent shape (sphericity), size, and compressive strength. The American Petroleum Institute (API) has developed specifications/standards (RP 56) for certain mesh sizes of frac sand.(18)

Silica-Related Disease

Inhalation of respirable crystalline silica can cause silicosis, lung cancer, autoimmune disorders, kidney disease, and an increased risk of tuberculosis.(19–24) Although U.S. mortality statistics typically undercount silicosis cases, death certificates document that between 2000 and 2005 an average of 162 annual deaths from all occupations described silicosis as the proximal cause or a prevailing condition.(25,26)

The NIOSH recommended exposure limit (REL) for respirable crystalline silica is 0.05 milligrams of respirable silica per cubic meter of air (mg/m^3) as a time-weighted average (TWA) for up to a 10-hr day to reduce the risk of developing silicosis, lung cancer and other adverse health effects.(27) The ACGIH® threshold limit value (TLV®) for respirable silica (as α quartz) is 0.025 mg/m^3 TWA for up to an 8-hr workday.(28) The OSHA permissible exposure limit (PEL) for respirable dust containing silica in general industry is inversely weighted by the proportion of silica in the sampled dust and determined by the formula:$10 mg/m^3 \div (\%silica + 2)$.(29) For comparisons to the OSHA criterion, a PEL is calculated for each sample. Assuming 100% silica, the calculated PEL would be $\approx$0.10 mg/m^3 as an 8-hr TWA. NIOSH recommends minimizing risks for silica exposures to workers exposed at or above the REL by substituting less hazardous materials, using engineering controls to limit exposures, and, if engineering controls cannot control exposures $<$ REL, using respiratory protection and making medical examinations available to exposed workers.(23)

METHODS

Exposure assessments for respirable crystalline silica were conducted for three consecutive days at 11 well sites in five states (Colorado, Texas, North Dakota, Arkansas, and Pennsylvania) from August 2010 through September 2011. Workers from 15 different job titles voluntarily participated. The purpose of the NIOSH field effort was explained to management and employees prior to sample collection; personal breathing zone (PBZ) samples were collected only on employees who agreed to participate. Workers participating on the first day were asked to participate on the two successive days of sampling, but sequential participation was not consistent at every site. After each day of sampling, NIOSH researchers discussed activities with employees and management to verify that samples were collected during typical hydraulic fracturing operations.

Full-shift (typically 12 hr) PBZ samples for respirable particulates and silica were simultaneously collected using AirChek XR 5000 (SKC Inc., Eighty Four, Pa.) personal sampling pumps connected to pre-weighed, 5-μm polyvinyl chloride filters in three-piece, 37-mm polystyrene sampling cassettes (Omega Specialty Division, SKC Inc.). The respirable fractions of dust were captured using BGI model GK2.69 cyclones (BGI Incorporated, Waltham, Mass.).(30) Sampling trains were calibrated in-line to the BGI recommended flow rate for respirable particulates at 4.2 L/min and post-calibrated with Dry Cal Defender 530 calibrators (Bios International, Butler Park, N.J.). Cyclones and cassettes were located in the worker's PBZ.

Kestrel model 4500 portable weather stations (Weather Republic, LLC, Downingtown, Pa.) were used to periodically measure temperature, relative humidity, and wind speed. Additional meteorological data were obtained from an on-line reporting service.

All samples were analyzed at an AIHA®-accredited laboratory, according to the *NIOSH Manual of Analytical Methods (NMAM)* method 0600, for gravimetric analysis of total particulates and NMAM method 7500, X-ray diffraction analysis for crystalline silica (as quartz, cristobalite, and tridymite).(31,32) For comparisons to the ACGIH TLV-TWA of 0.025 mg/m^3 and the NIOSH REL of 0.05 mg/m^3 as a TWA, calculations were made for the respirable fraction of silica alone. Numeric values reported by the laboratory for sample results between the limit of detection (LOD) and the limit of quantification (LOQ) were included in the statistical analysis of the data. If the respirable silica value was below the LOD, it was replaced by a value equal to the analytical LOD divided by the square root of 2, as described by Hornung and Reed.(33) Four samples for respirable quartz were below the LOD and included workers with job titles of Pump Truck Operator, QC Tech, and Wireline Operator.

To calculate TWA concentrations for the OSHA PEL for respirable dust containing $>1\%$ silica, percentage silica in the sample was determined by dividing the quartz results for each sample by amount of respirable dust and multiplying by 100. A PEL was calculated for each sample using the formula for general industry: $10 mg/m^3 \div (\%silica + 2)$.(29) PELs were not calculated for four samples where percentage quartz could not be determined because the respirable dust fraction was $<$ the LOD. Sample results are expressed for the full work shift (typically 12 hr); they were not adjusted for exposures exceeding the 8-hr OSHA or TLV criteria or the 8- to 10-hr REL.

Exposure severities were calculated by dividing the exposure TWA by the occupational exposure limit (PEL, REL) and expressed as a value greater or less than unity. Severities greater than unity exceed the respective exposure criterion. To compare and express the magnitude of work crew exposures in relation to a calculated PEL or REL, severity means, geometric means (GM), standard deviations, and minimum, maximum, and median values were calculated for the 15 job titles in units of mg/m^3.

A one-way analysis of variance was performed to evaluate for statistical differences in mean exposures among job titles with five or more samples (e.g., Blender Operators, Hydration Unit Operators, Sand Coordinators, Sand Mover Operators, T-belt Operators, and Water Tank Operators). Statistical differences between individual job title means were determined using the least significant difference (LSD) multiple comparison test (significance level, $p = 0.05$). The LSD can be seen as a t-test for differences between two means using a pooled error variance.(34) Analysis of variance and LSD statistical tests were also used for overall comparisons between the different work sites and for measured concentrations of respirable dust containing silica. All calculations were performed using SAS version 9.2 (SAS Institute Inc., Cary, N.C.).

RESULTS

The 11 locations included geographic, topographic, climatic, altitude, and environmental diversity. Site locations included the Eagle Ford shale play in the southwest Texas desert during the summer. Two sites were in the temperate, humid deciduous forests of the Marcellus and Fayetteville shale plays of Pennsylvania and Arkansas in the spring. Seven well sites were on the arid high plains of the Denver-Julesburg (DJ) basin in Colorado in late winter and summer; one site was on the northern plains of the Bakken formation in North Dakota during late summer. Elevations ranged from approximately 300 feet to slightly more than 5000 feet above sea level.

The exposure assessments occurred at single- and multi-well site locations during single and multiple-stage completions. Typically, two or three stages were completed in a shift. The DJ Basin 1 sites in Colorado involved refracturing one zone of two different wells each day over three consecutive days, for a total of six different well locations. With the exception of the Bakken site where approximately 60% of the proppant was Black Cat (a ceramic material), silica sand was the proppant used at the other locations and included 20/40, 40/70, and 100 mesh sieve sizes. At some sites, a proportion of the total proppant load included resin-coated sand, but proportions, usage time, and volumes were not available.

Weather

Meteorological conditions (average daily temperature and average daily low and high temperatures, sky conditions, precipitation, and wind speed) at the 11 sites are reported in Table I. Weather (wind, rain, or temperature) was never a limiting factor for site work. When it rained, rain was present for short periods, never interfering with sampling or completions operations. With exception of early to mid-morning periods, winds were typically measurable and varied, sometimes changing direction during the shift. Based on averages for the days the evaluations occurred, wind speed was in a range of 1.1–13 miles per hour (mph) at the sites. Average wind velocity and high wind was less (in a range of 1.1–5.4, and 10 mph, respectively) for the site on the Marcellus Shale in Pennsylvania.

Personal Breathing Zone Sampling Results

Quartz was the only silicate mineral detected; the median value was 53% and samples ranged from < LOD to 100% quartz. Figure 1 describes silica concentrations in four discrete quantiles of 90th, 75th, 50th, and 25th percentiles. At the 90th percentile, 100 samples were determined to have up to 88% or less quartz.

Distribution of airborne particulates were evaluated and determined to follow a lognormal distribution using the Shapiro-Wilk test for goodness-of-fit and normality plots.(35,36) Logarithms of measured concentrations of respirable silica were used to calculate GM and standard deviations (SD) and for all statistical tests.

Table II lists 15 job titles, number of samples for each job title, the GM and geometric standard deviation (GSD) for respirable quartz in mg/m^3, and minimum, maximum, and median values expressed as TWAs. Geometric means and 95% confidence intervals for respirable silica concentrations for job titles having five or more samples are presented in Figure 2. Job titles with the highest GM exposures included T-belt and Sand Mover Operators (0.327 and 0.259); workers with lower GMs included Hydration Unit and Blender Operators (0.072 and 0.091); workers with the lowest GM exposures included Sand Coordinators and Water Tank Operators (0.054 and 0.048).

After exclusion of an obvious outlier for a T-belt Operator, no statistical differences were determined for exposures to respirable dust containing silica between Sand Mover Operators and T-belt Operators. Statistically significant differences ($p \leq 0.05$) were found between T-belt Operators compared with Sand Coordinators and Water Tank Operators and also between Sand Mover Operators and Hydration Unit Operators, Blender Operators, Sand Coordinators, and Water Tank Operators. For respirable silica alone, no statistical differences were found between Sand Mover Operators and T-belt Operators but significant differences ($p \leq 0.05$) were found between Sand Mover Operators and Hydration Unit Operators, Blender Operators, Sand Coordinators, and Water Tank Operators.

Table III lists the numbers and percentages of samples collected for each of the job titles that exceeded the ACGIH TLV, the NIOSH REL, or a calculated OSHA PEL. Figure 3 shows the comparisons for arithmetic means of respirable

TABLE I. Meteorological Data at Six Shale Play Locations, 2010–2011

Location	Season	°F Avg.	°F Low	°F High	Sky	Precip. (inches)	Wind Speed Avg. Range (mph)	Wind Speed High (mph)
Eagle Ford, Texas	Summer	87	75	101	Clear	0	8–11	14–15
DJ Basin #1, Colo.	Winter	49	38	71	Clear-partly cloudy	0	1.2–10	15–17
Fayetteville, Ark.	Spring	62	53	75	Cloudy	0.83 (0–1.5)	7–10	11–12
Marcellus, Pa.	Spring	74	63	92	Cloudy-partly cloudy	0.22	1.1–5.4	10
DJ Basin #2, Colo.	Summer	70	58	91	Clear-partly cloudy	0.05	10–13	15–16
Bakken, N.D.	Summer	68	56	89	Clear-partly cloudy	0.22–0.5	7–12	11–35

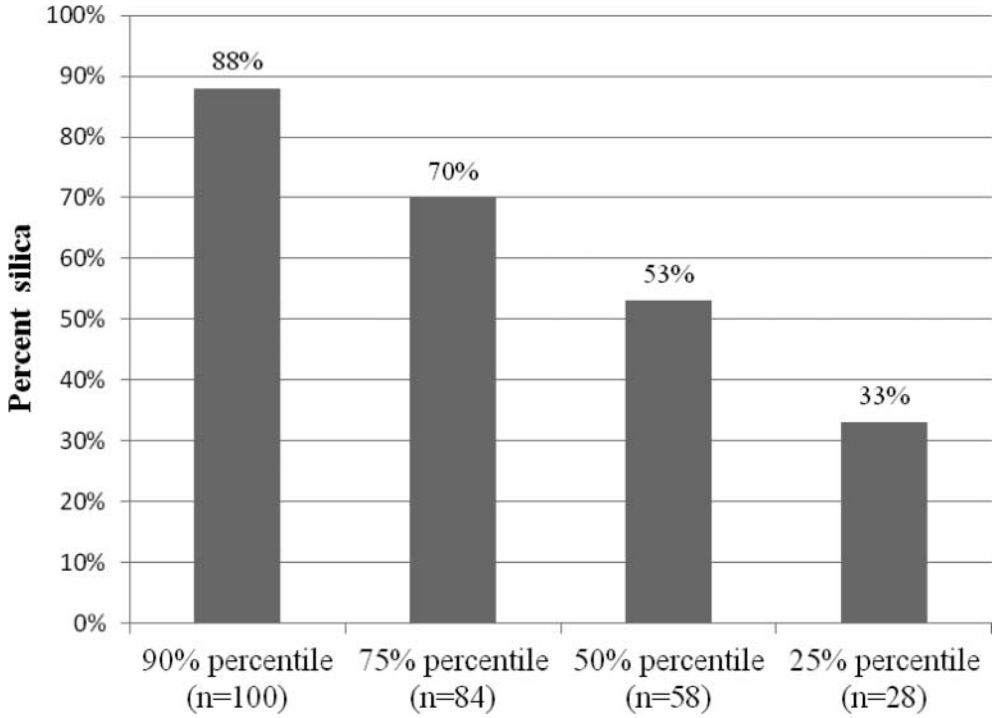

FIGURE 1. Quantiles, distribution of percent silica in PBZ samples (n = 111).

silica TWAs (mg/m^3) for job titles with five or more samples and a calculated OSHA PEL used for comparison purposes in this figure based the median value of 53% silica content in the 111 samples, and the NIOSH REL value.

To compare and express the magnitude of work crew exposures in relation to OSHA PELs for respirable dust containing silica and the NIOSH REL for respirable silica alone, means of job title severities were calculated and are listed in Tables IV and V for the NIOSH REL or the OSHA PEL, respectively. Arithmetic standard deviations (ASD), minimum, maximum, and median values are also listed as these can be used for direct comparisons to occupational exposure criteria (PEL, REL and

TABLE II. PBZ Statistics by Job Title, Respirable Quartz TWA (mg/m^3)

Job Title	No. of Samples	GM	GSD	Min TWA	Max TWA	Median TWA
Blender Operator	16	0.091	1.266	0.007	0.485	0.102
Chemical Truck Operator	3	0.121	1.828	0.040	0.319	0.139
Fueler	2	0.042	1.225	0.034	0.051	0.043
Hydration Unit Operator	5	0.072	2.209	0.009	0.746	0.044
Mechanic	3	0.052	1.511	0.023	0.088	0.069
Operator, Data Van	1	0.043	—	0.043	0.043	0.043
Pump Truck Operator	1	0.021	—	0.021	0.021	0.021
QC Tech	1	0.013	—	0.013	0.013	0.013
Roving Operator	4	0.019	1.628	0.006	0.059	0.020
Sand Coordinator	10	0.054	1.333	0.017	0.326	0.061
Sand Truck Driver	1	0.041	—	0.041	0.041	0.041
Sand Mover Operator	50	0.259	1.223	0.007	2.755	0.381
T-belt Operator	6	0.327	2.003	0.015	2.570	0.453
Water Tank Operator	7	0.048	1.339	0.019	0.136	0.056
Wireline Operator	1	0.007	—	0.007	0.007	0.007
Totals	111	0.122	1.152	0.006	2.755	0.109

Notes: Titles followed by superscripts are significantly different ($p \leq 0.05$). Values not calculated for statistics where N = 1.

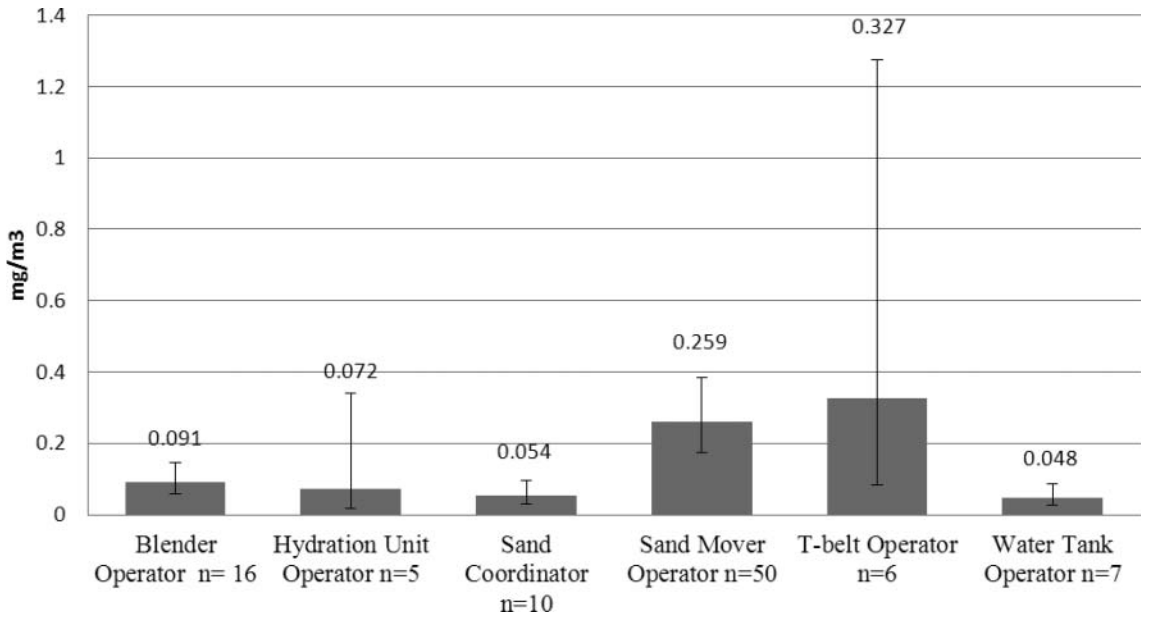

FIGURE 2. Respirable silica geometric means (mg/m^3) and 95% confidence intervals for job titles with 5 or more samples

TLV). Job titles with the highest mean severities included Transfer Belt and Sand Mover Operators (mean severities of 14.55 and 10.44, respectively, based on the NIOSH REL). Job titles with lowest exposures (mean severities less than one, and for samples where $n > 1$) included Roving Operator (0.52) and Fueler (0.85) who worked in a variety of locations at the sites or spent only short periods of time in site areas when sand was being transported on site. Job titles with exposures greater than 10 times the NIOSH REL included Sand Mover Operator ($n = 19$), Transfer Belt Operator ($n = 2$), and Hydration Unit Operator ($n = 1$).

Personal Breathing Zone Respirable Silica by Job Site

Statistically significant differences ($p \leq 0.05$) in overall concentrations of respirable silica were not found between the Eagle Ford, Fayetteville shale, DJ Basin 1 and 2 sites, and Marcellus shale formations; however, all these sites (except the Eagle Ford) did differ from the Bakken formation where ceramic was the primary proppant used at that site.

Table VI lists the sites, numbers of samples collected, and percentages that exceeded the TLV, REL, or the calculated PELs. Ninety three of 111 (83.8%) of the samples exceeded the TLV, 76 (68.5%) exceeded the REL, and 57

TABLE III. Samples Above ACGIH TLV, NIOSH REL, or OSHA PEL

Job Title	ACGIH TLV	NIOSH REL	OSHA PEL	No. of Samples
Blender Operator	15 (93.8%)	13 (81.3%)	8 (50%)	16
Chemical Truck Operator	3 (100%)	2 (66.7%)	2 (66.7%)	3
Fueler	2 (100%)	0	0	2
Hydration Unit Operator	4 (80%)	2 (40%)	2 (40%)	5
Mechanic	2 (66.7%)	2 (66.7%)	0	3
Operator, Data Van	1 (100%)	0	0	1
Pump Truck Operator	0	0	0	1
QC Tech	0	0	0	1
Roving Operator	2 (50%)	1 (25%)	0	4
Sand Coordinator	7 (70%)	5 (50%)	1 (10%)	10
Sand Truck Driver	1 (100%)	0	0	1
Sand Mover Operator	46 (92%)	42 (84%)	37 (74%)	50
T-belt Operator	5 (83.3%)	5 (83.3%)	5 (83.3%)	6
Water Tank Operator	5 (71.7%)	4 (57.1%)	2 (28.6%)	7
Wireline Operator	0	0	0	1
Totals	93 (83.8%)	76 (68.5%)	57 (51.4%)	111

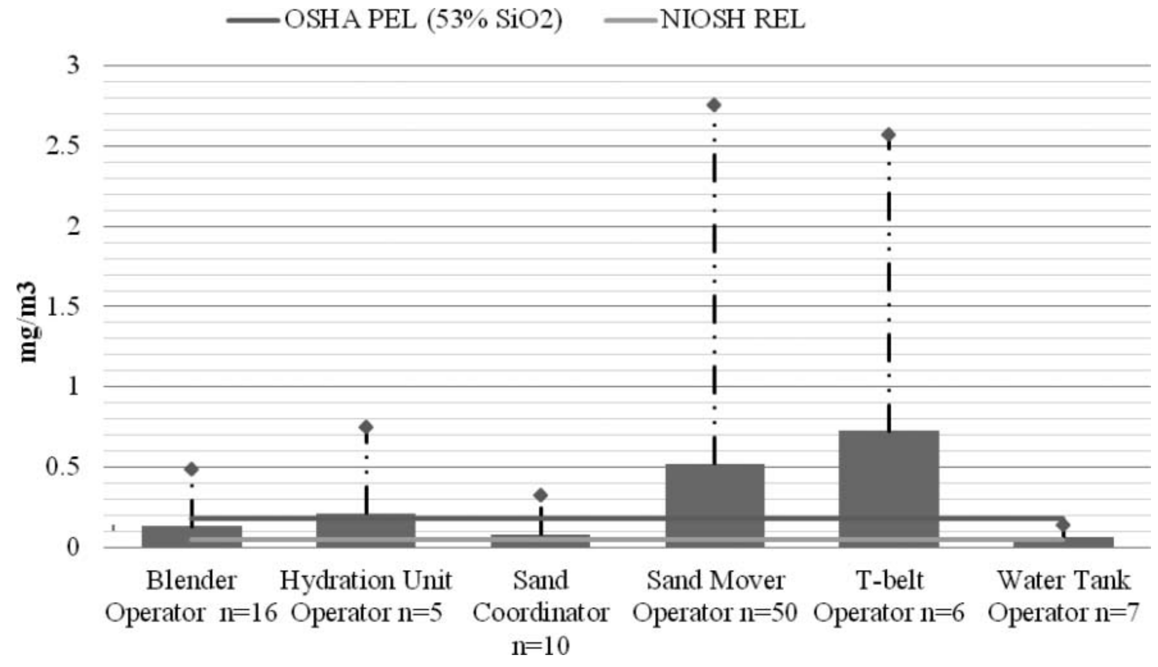

FIGURE 3. Comparisons of arithmetic means of TWAs (mg/m^3) for job titles with five or more samples in relation to a calculated OSHA PEL (based on 53% silica) and NIOSH REL for respirable silica. Maximum values for each job title shown by diamonds at the end of dashed lines.

(51.4%) exceeded a calculated PEL for respirable dust containing silica.

Magnitude of Full-Shift Exposures to Respirable Crystalline Silica

Silica exposures for some job titles exceeded the assigned protection factor of 10 for the half-mask, air-purifying respirators most commonly used at the locations. PBZ exposures exceeding a REL or PEL by a factor of 10 or more included Sand Mover Operators, n = 19 for the REL, n = 8 for the OSHA PEL, and T-belt Operators, and n = 2 and 1 for the REL and PEL, respectively. In some cases, exposures exceeded OELs by a factor greater than 20, including Sand Mover Operator (n = 7) and T-belt Operators (n = 1) for the

TABLE IV. PBZ NIOSH REL Mean Severities

Job Title	No. of Samples	AM	ASD	Min	Max	Median
Blender Operator	16	2.58	0.59	0.14	9.70	2.03
Chemical Truck Operator	3	3.32	1.63	0.80	6.38	2.78
Fueler	2	0.85	0.17	0.68	1.02	0.85
Hydration Unit Operator	5	4.28	2.79	0.18	14.92	0.88
Mechanic	3	1.20	0.39	0.46	1.76	1.38
Operator, Data Van	1	0.86	—	0.86	0.86	0.86
Pump Truck Operator	1	0.42	—	0.42	0.42	0.42
QC Tech	1	0.26	—	0.26	0.26	0.26
Roving Operator	4	0.52	0.24	0.12	1.18	0.39
Sand Coordinator	10	1.60	0.57	0.34	6.52	1.22
Sand Truck Driver	1	0.82	—	0.82	0.82	0.82
Sand Mover Operator	50	10.44	1.59	0.14	55.10	7.62
T-belt Operator	6	14.55	7.57	0.30	51.40	9.06
Water Tank Operator	7	1.23	0.34	0.38	2.72	1.12
Wireline Operator	1	0.14	—	0.14	0.14	0.14
Totals	111	6.45	0.93	0.12	55.10	2.18

Note: Values not calculated for samples where n = 1.

TABLE V. PBZ OSHA PEL Mean Severities

Job Title	No. of Samples	AM	ASD	Min	Max	Median
Blender Operator	16	1.34	0.30	0.09	4.93	1.08
Chemical Truck Operator	3	1.70	0.82	0.45	3.23	1.41
Fueler	1	0.57	—	0.57	0.57	0.57
Hydration Unit Operator	5	2.19	1.42	0.09	7.58	0.4
Mechanic	3	0.61	0.20	0.23	0.90	0.70
Operator, Data Van	1	0.49	—	0.49	0.49	0.49
Pump Truck Operator	0					
QC Tech	1	0.14	—	0.14	0.14	0.14
Roving Operator	4	0.25	0.09	0.08	0.50	0.21
Sand Coordinator	10	0.81	0.27	0.18	3.10	0.65
Sand Truck Driver	1	0.41	—	0.41	0.41	0.41
Sand Mover Operator	50	5.66	0.86	0.13	28.71	4.26
T-belt Operator	6	7.62	4.05	0.18	27.39	4.65
Water Tank Operator	7	0.63	0.17	0.21	1.36	0.54
Wireline Operator	1	0.07	—	0.07	0.07	0.07

Note: Values not calculated for samples where n = 1.

NIOSH REL, and n = 3 and n = 1 for the same job titles for the OSHA calculated PEL. If the sampling results were adjusted for an extended work shift, that is, the difference between an 8-hr shift and a 12-hr work shift, the exposure severities would be 50% greater than those listed and described.

DISCUSSION

Sources of Silica-Containing Dust Identified at the Work Sites

Dust is visibly present during hydraulic fracturing especially when sand movers are refilled and actively operating, which is referred to as "hot loading." Workers closest to sand moving operations included T-belt and Sand Mover Operators (Figure 2), followed by Blender and Hydration Unit Operators. Direction and wind speed, as well as the configuration of the sand handling and other equipment on site, appear to influence the concentration, direction, and migration of airborne sand dusts. Predictably, when workers were near or downwind from point sources of dust generation they had greater risks for exposures than if farther away or upwind. At some sites, how equipment was configured and positioned created enclosed or restricted environments that may have limited natural dilution of airborne particulates and contributed to increased exposures to airborne dusts.

Workers less commonly observed in the immediate area of sand moving machinery included Sand Coordinators (Ground Guides), Water Tank Operators, and Chemical Truck Operators. However, in some cases, these job titles had exposures > TLV, REL, or the PEL, indicating that PBZ exposures exceeding these concentrations can occur even when workers were not in proximity to the primary source(s) of dust generation. This could be due to silica-containing environmental dust carried onto the site or dusts generated from on-site vehicular traffic.

Blender, Chemical Truck, and Hydration Unit Operators worked in both closed and open cabs on their machinery, and these job titles had exposures that exceeded OELs even when Operators reported or were observed to spend most of the day in a cab. Blender trucks typically had enclosed cabs, but none had high-efficiency particulate filtration or positive pressurization. Respirable silica concentrations for workers in

TABLE VI. Samples Above ACGIH TLV, NIOSH REL, or OSHA PEL

Site	ACGIH TLV	NIOSH REL	OSHA PEL	Total No. Samples
Fayetteville, Ark.	24 (92.3%)	19 (73.1%)	14 (53.9%)	26
DJ Basin 1, Colo.	16 (84.2%)	14 (73.7%)	12 (63.2%)	19
Eagle Ford, Texas	5 (62.5%)	5 (62.5%)	4 (50.0%)	8
DJ Basin 2, Colo.	19 (90.5%)	14 (66.7%)	9 (42.9%)	21
Marcellus, Pa.	25 (92.6%)	23 (85.2%)	18 (66.7%)	27
Bakken, N.D.	4 (40%)	1 (10%)	0	10
Totals	93 (83.8%)	76 (68.5%)	57 (51.4%)	111

vehicles having doors with tight-fitting seals and conditioned environments (e.g., data vans) did not exceed the TLV, REL, or PELs, with the exception of one Operator who spent time near sand moving equipment for a portion of the day.

Seven points of dust generation were consistent at each of the 11 work sites:

(1) Dust ejected from "thief hatches" on the tops of sand movers during filling. This source contributes to exposures to Sand Mover and Blender Operators and, depending on winds, may expose workers farther away, such as Water Tank Operators.

(2) Dusts released from the sand mover belt. This point source was observed to contribute to exposures to Sand Mover Operators, especially if the wind is strong and the Operator station is on the downwind side of the machine.

(3) Dust created at the blender hopper from the momentum of falling proppant below the dragon tail can contribute to exposure to Sand Mover and Blender Operators; the area below the dragon tail can be confined due to interacting machinery (Blender, Sand Movers, the T-belt), and depending on climatic conditions, there could also be a lack of natural ventilation.

(4) Dust released from T-belts when proppant is deposited onto the belt and conveyed to the blender. Sand impacting the belt as well as rotational and vibrational movement of the belt contributes to dust generation.

(5) Dust generated as proppant leaves the end of the dragon tail. This can be a secondary contributing source for both Blender Operators (i.e., cab-based operator and the hopper-based operator or other downwind work crews).

(6) Dust ejected from fill ports of sand movers during refilling operations. An absence of caps on the fill ports contributes to silica exposures of Sand Mover Operators, Blender Operators, and Sand Truck Drivers.

(7) Dust generated by site traffic, including frictional forces from truck tires, vehicle momentum, and release of air pressure from pneumatic brakes, contributes to exposures to Sand Coordinators and Sand Truck Drivers. Dust blown onto the work site from off-site sources was also observed on several occasions and may be a small and variable contributor to work crew exposures.

CONCLUSION

Full-shift, PBZ exposures to respirable crystalline silica is an occupational exposure hazard for workers at hydraulic fracturing sites. Quartz was the only silicate mineral identified; median percentage quartz in the 111 PBZ samples was 53%. Workplace concentrations of airborne respirable silica exceeded OELs by factors of 10, 20, or more, with Sand Mover and Transfer Belt Operators having the highest relative exposures. Although workers typically wore elastomeric half-mask, air-purifying (or filtering-facepiece style) respirators, due to the magnitude of the silica concentrations measured, half-masks may not be sufficiently protective because, in some cases, respirable crystalline silica concentrations exceeded the maximum use concentration (10 times the OEL) for that type of respirator.

Although effective engineering controls for crystalline silica are well established in other industries, controls to limit silica-containing dust generation during hydraulic fracturing are only now emerging due to the relatively recent understanding of the hazard and magnitude of exposure risks. Sand movers configured with some proposed controls (e.g., a mini-baghouse retrofit assembly, skirting and shrouding at the base of the machine and on the dragon tail, and use of caps on fill ports) are described in Figures 1 and 2 in the online supplemental material discussing controls and recommendations. At one site (Bakken formation in North Dakota) substitution of a ceramic proppant for a portion of silica sand resulted in lower overall measured silica exposures, but assessing the technical and economic feasibility of using ceramic proppant was beyond the scope of this study.

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DISCLAIMER

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