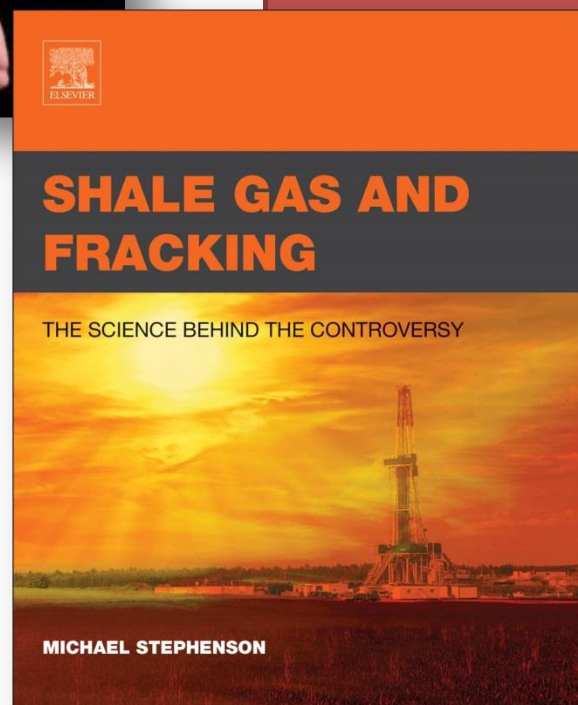
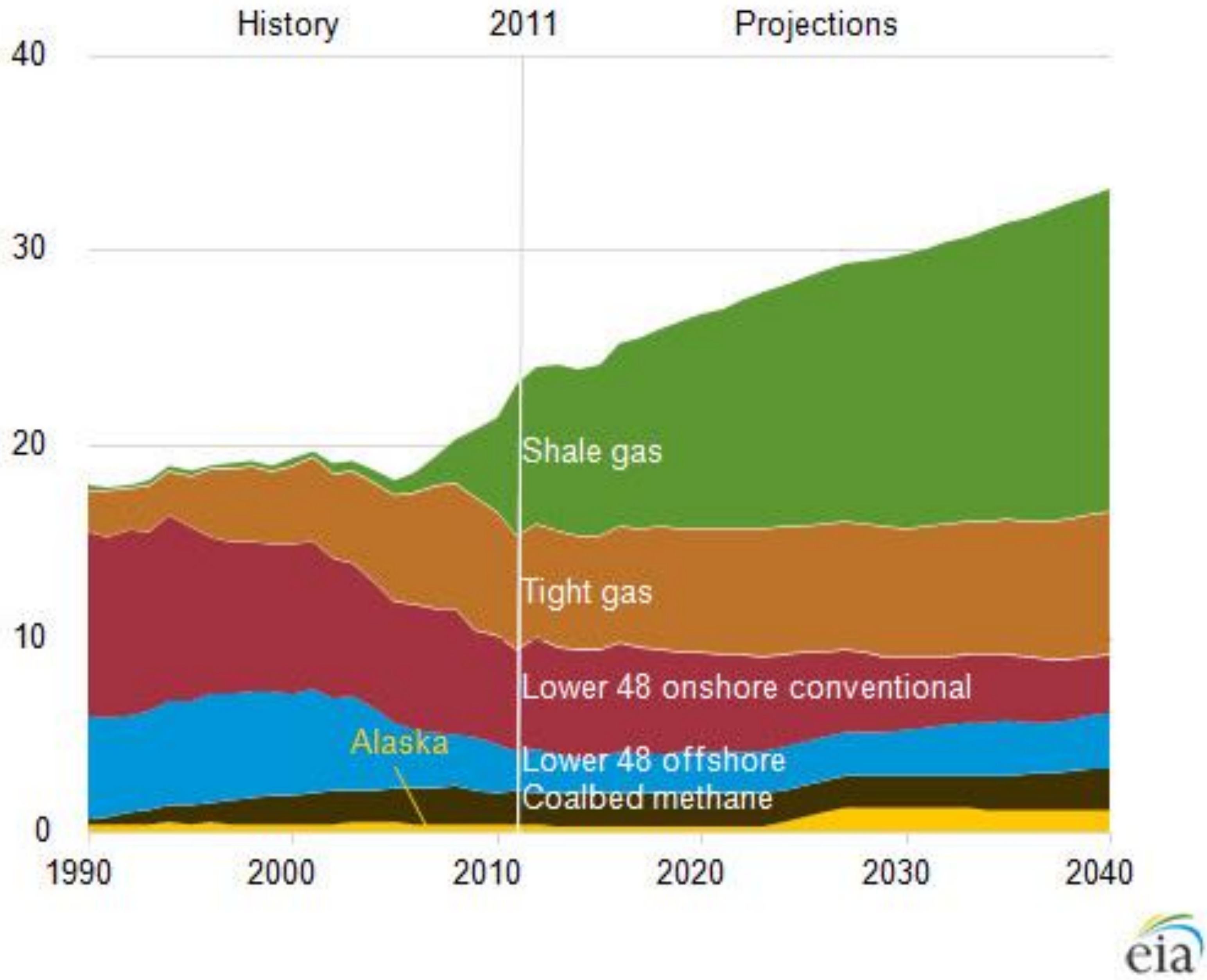
Shale gas and fracking: peril or saviour?

Mike Stephenson

British Geological Survey



Fact



EIA outlook

Fact?

Methane in domestic water supplies from fracking?

…or natural methane?


Fact?
Cracks in a bridge from earthquakes caused by fracking
…or cracks that were already there

Fact?

2006 to 2011, CO_2 from fossil fuels declined by 7.7% due to substitution of shale gas for coal in power stations

…but <u>more</u> greenhouse gas emissions due to ‘fugitive emissions’ of methane associated with fracking?

Contestable areas in shale gas

Does shale gas use too much water?

Do shale gas wells contaminate groundwater?

Does fracking cause dangerous earthquakes?

Does shale gas cause subsidence?

Does fracking produce dangerous radioactivity?

Is shale gas lower carbon than coal?

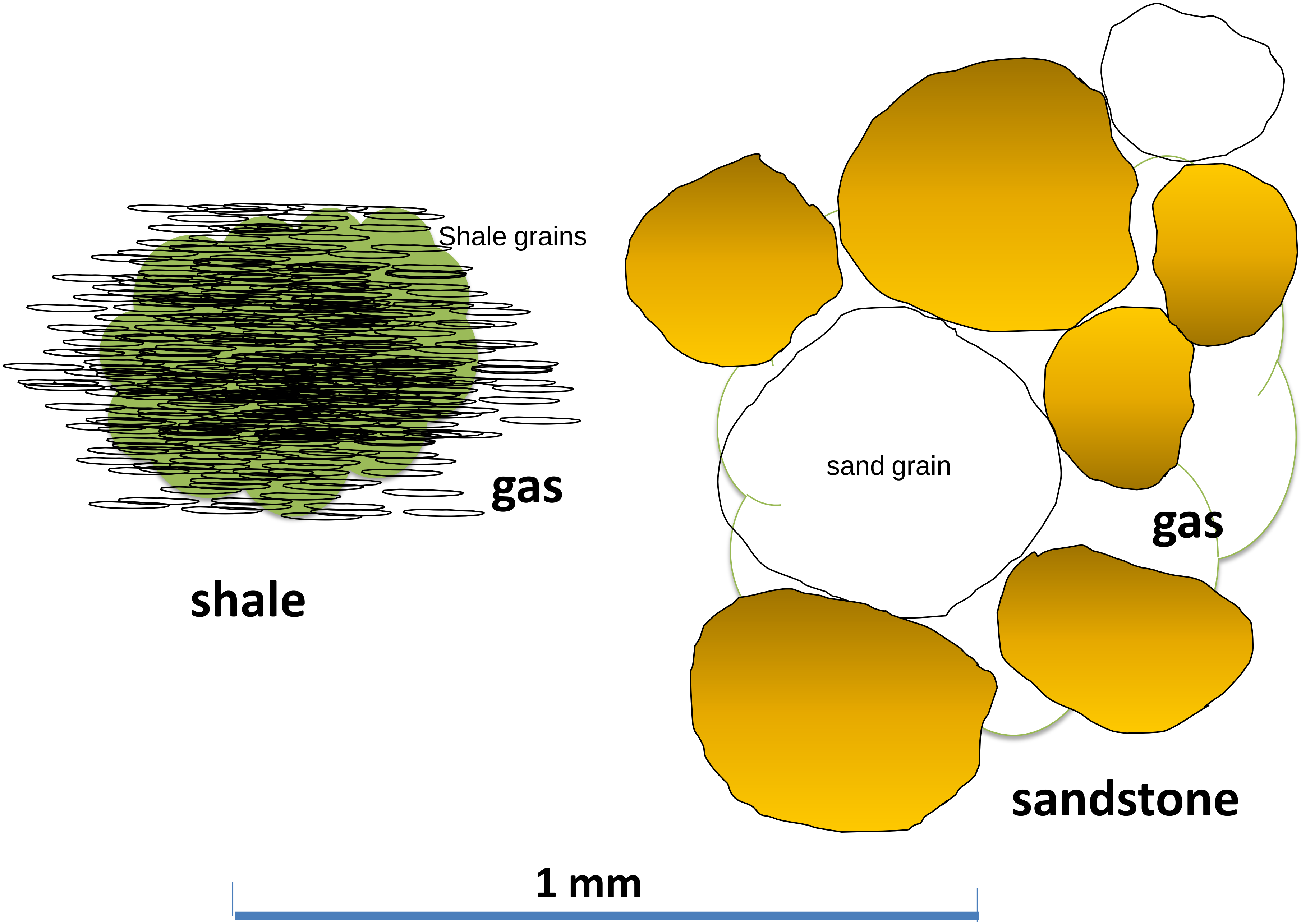
Shale gas

Peer reviewed science

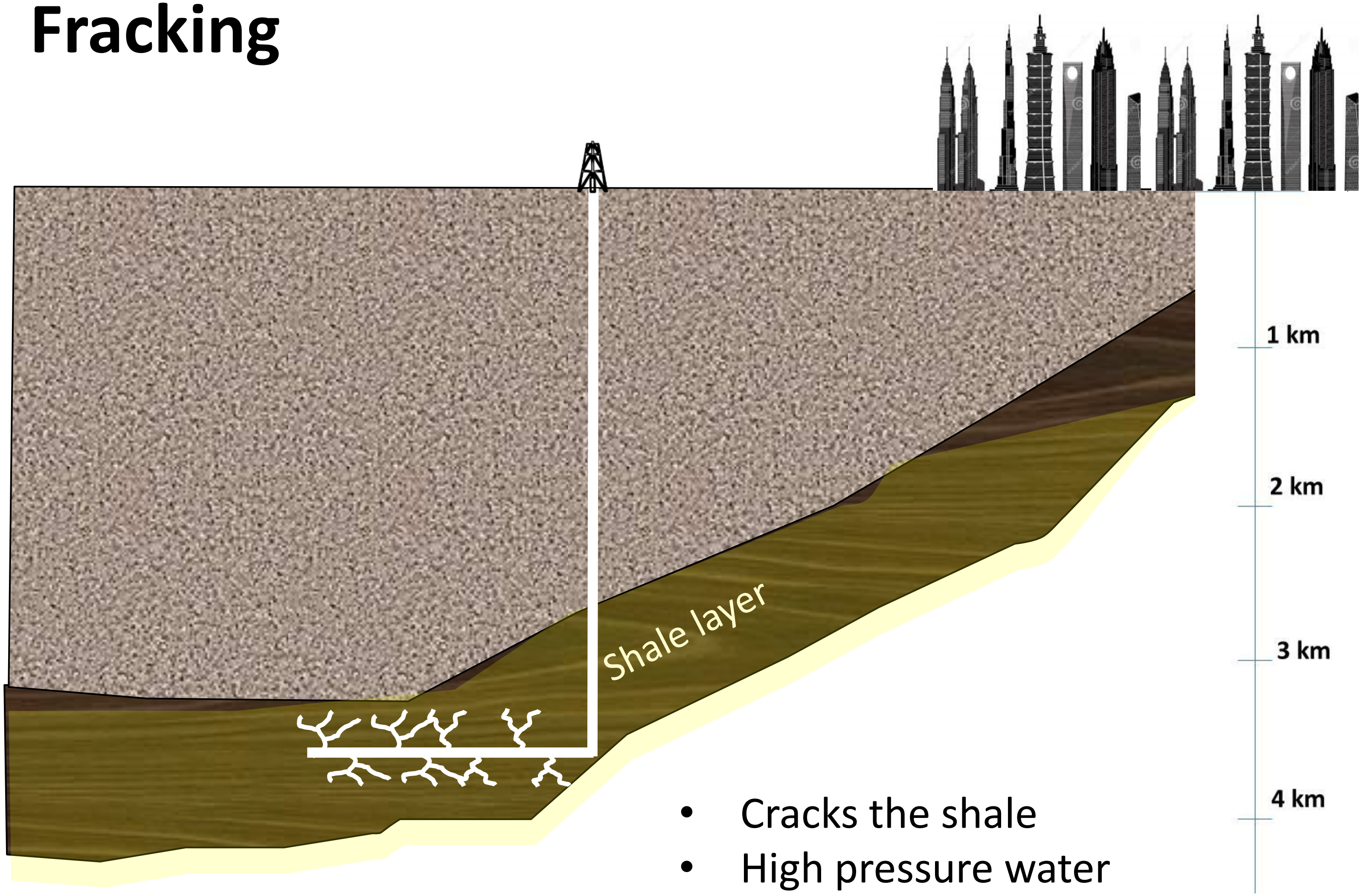
I'm going to show how science can be applied to some of these contestable issues.

SOME SHALE AND FRACKING BASICS

Gas in sandstone and shale



Fracking



- Cracks the shale
- High pressure water or nitrogen, 350-700 bar
- Sand pumped in to hold cracks open

Fracking site in Alberta


Frack trucks


Flowback tanks
TRICAN
WELL SERVICE
DALER
PRESSURE SERVICES LTD
1-888-536-4272
elivery. Well Ahead.
CAMERON

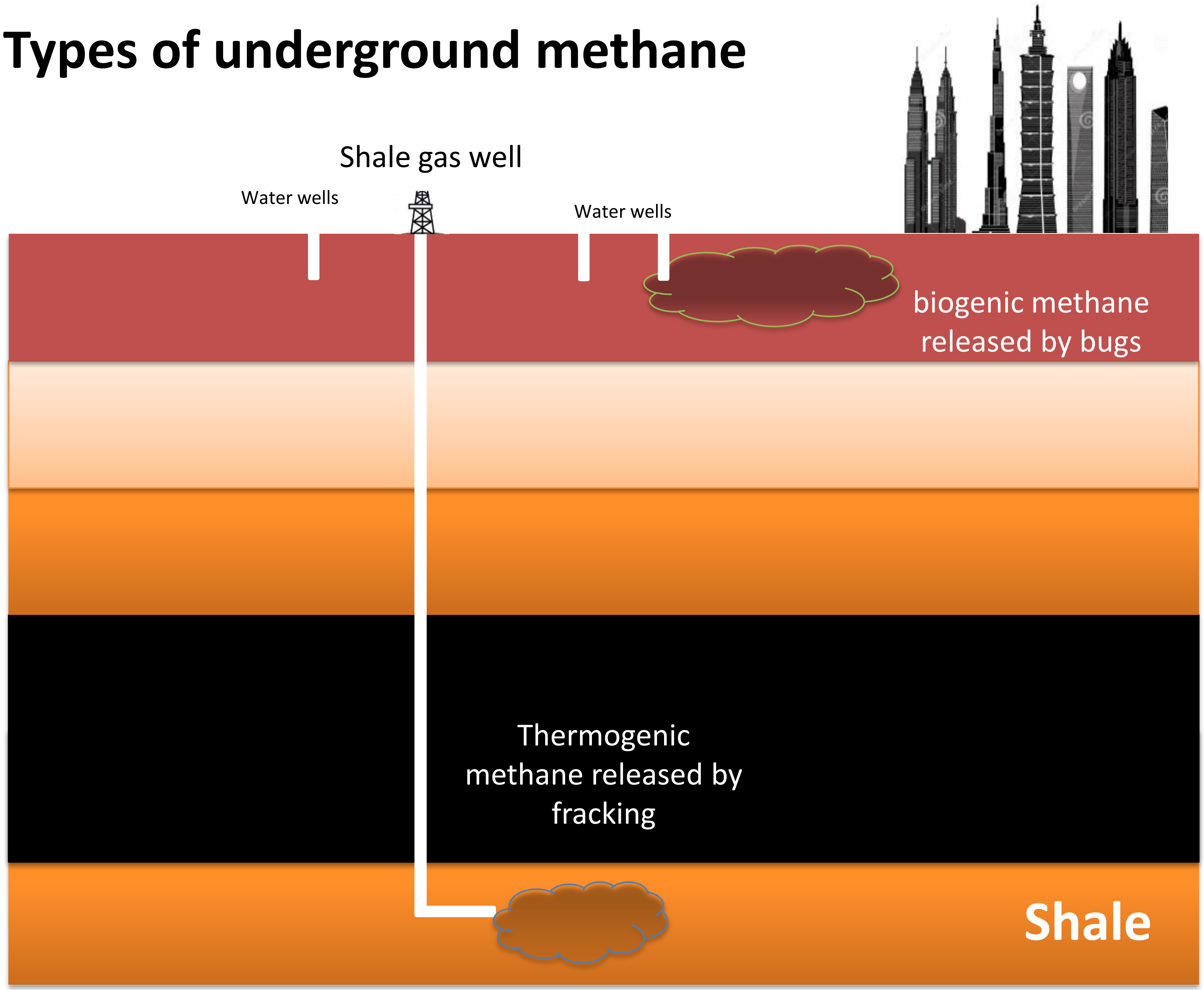
Truck carrying proppant

- **Do shale gas wells contaminate groundwater?**
- Does shale gas use too much water?
- Does fracking cause dangerous earthquakes?
- Does shale gas cause subsidence?
- Does fracking produce dangerous radioactivity?
- **Is shale gas lower carbon than coal?**

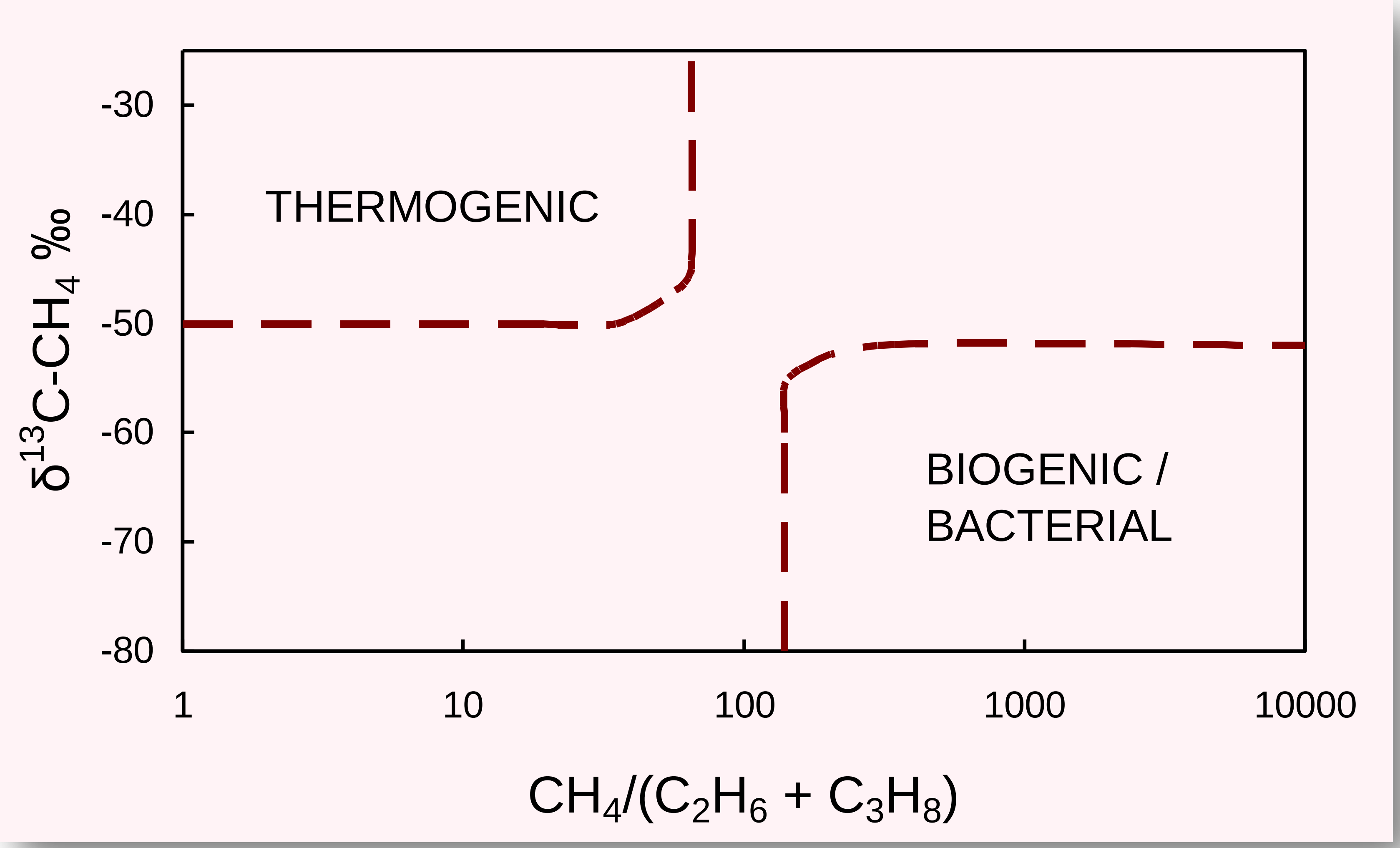
DO SHALE GAS WELLS CONTAMINATE GROUNDWATER?

SOME BASICS

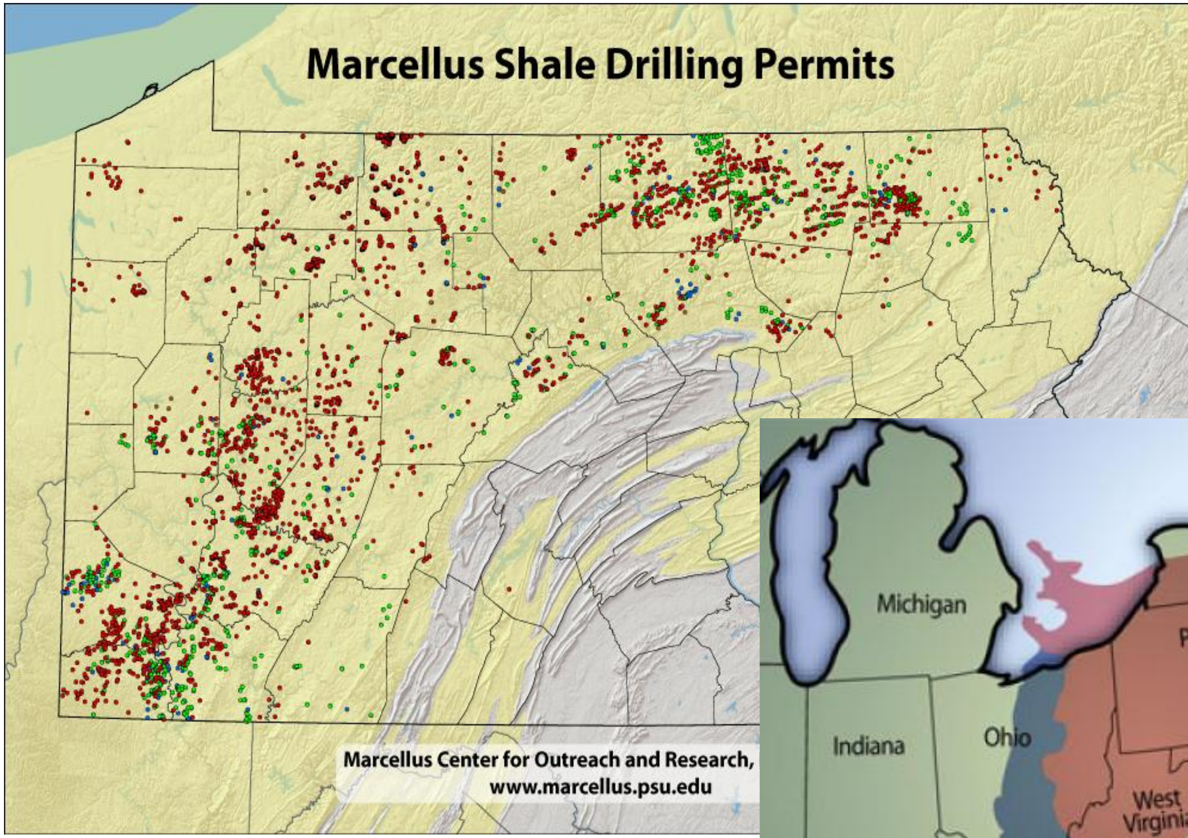
Types of underground methane

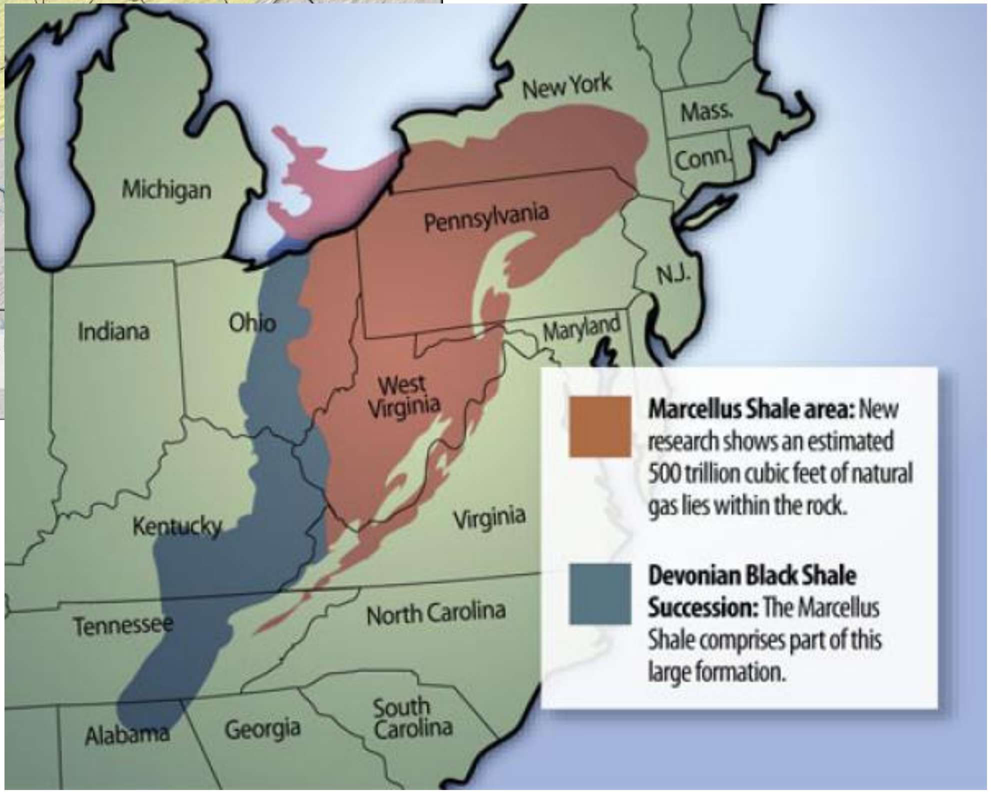


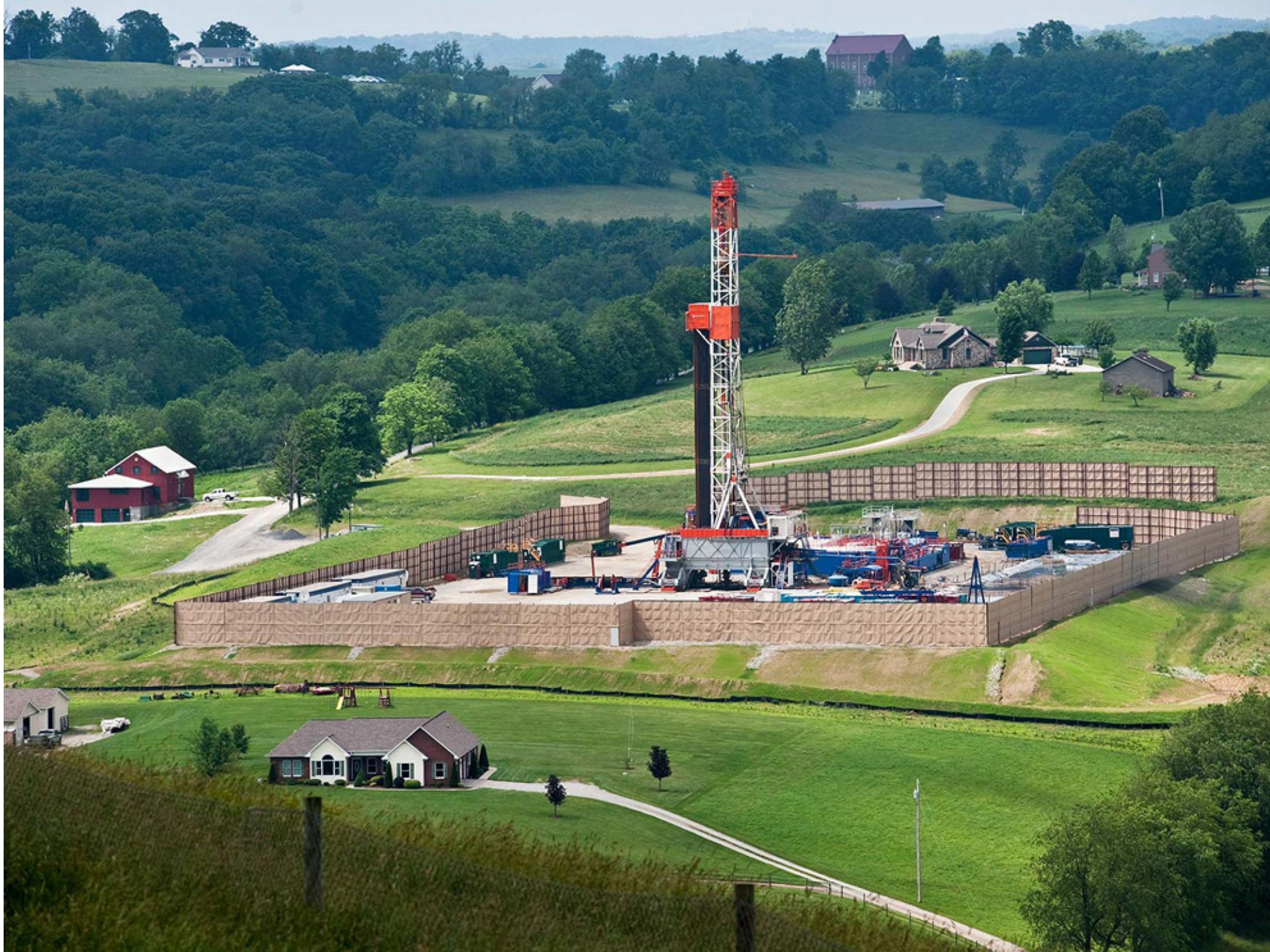
Distinguishing biogenic and thermogenic



Marcellus, Pennsylvania

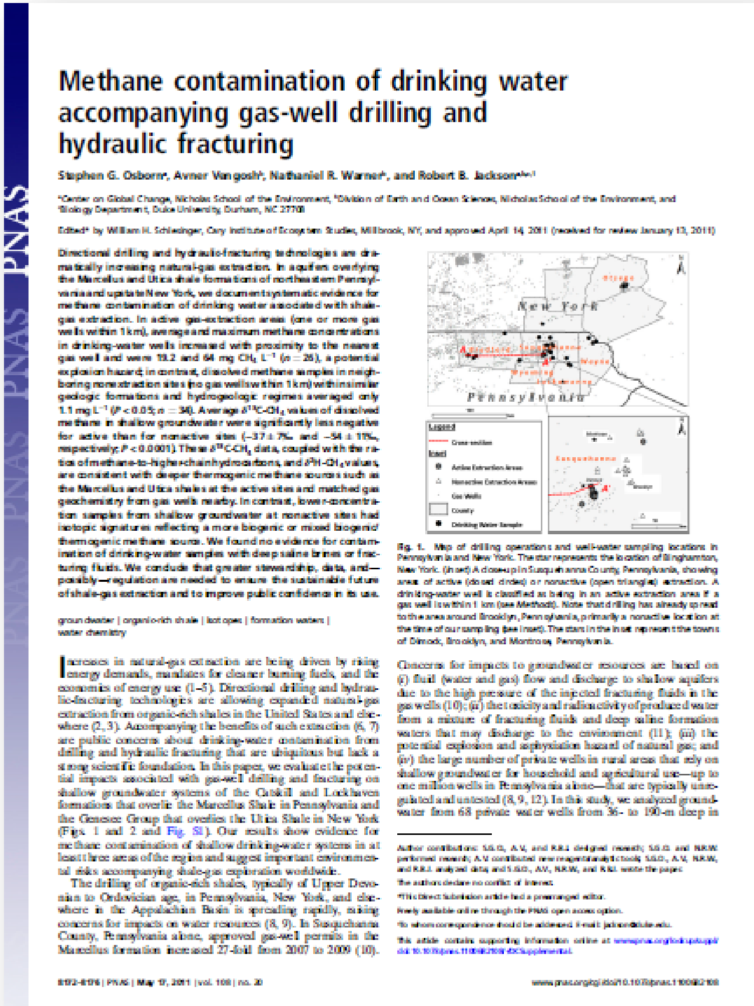






Contamination from fracking?

Osborn et al. 2011, Duke University



PNAS

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

Stephen G. Osborn[a], Avner Vengosh[b], Nathaniel R. Warner[b], and Robert B. Jackson[a,b,c,1]

[a]Center on Global Change, Nicholas School of the Environment; [b]Division of Earth and Ocean Sciences, Nicholas School of the Environment; and [c]Biology Department, Duke University, Durham, NC 27708

Edited* by William H. Schlesinger, Cary Institute of Ecosystem Studies, Millbrook, NY, and approved April 14, 2011 (received for review January 13, 2011)

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 CH_4 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 $\delta^{13}C$-CH_4 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 $\delta^{13}C$-CH_4 data, coupled with the ratios of methane-to-higher-chain hydrocarbons, and δ^2H-CH_4 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—possibly—regulation are needed to ensure the sustainable future of shale-gas extraction and to improve public confidence in its use.

groundwater | organic-rich shale | isotopes | formation waters | water chemistry

Fig. 1. Map of drilling operations and well-water sampling locations in Pennsylvania and New York. The star represents the location of Binghamton, New York. (Inset) A close-up in Susquehanna County, Pennsylvania, showing areas of active (closed circles) or nonactive (open triangles) extraction. A drinking-water well is classified as being in an active extraction area if a gas well is within 1 km (see Methods). Note that drilling has already spread to the area around Brooklyn, Pennsylvania, primarily a nonactive location at the time of our sampling (see inset). The stars in the inset represent the towns of Dimock, Brooklyn, and Montrose, Pennsylvania.

Increases in natural-gas extraction are being driven by rising energy demands, mandates for cleaner burning fuels, and the economics of energy use (1–5). Directional drilling and hydraulic-fracturing technologies are allowing expanded natural-gas extraction from organic-rich shales in the United States and elsewhere (2, 3). Accompanying the benefits of such extraction (6, 7) are public concerns about drinking-water contamination from drilling and hydraulic fracturing that are ubiquitous but lack a strong scientific foundation. In this paper, we evaluate the potential impacts associated with gas-well drilling and fracturing on shallow groundwater systems of the Catskill and Lockhaven formations that overlie the Marcellus Shale in Pennsylvania and the Genesee Group that overlies the Utica Shale in New York (Figs. 1 and 2 and Fig. S1). Our results show evidence for methane contamination of shallow drinking-water systems in at least three areas of the region and suggest important environmental risks accompanying shale-gas exploration worldwide.

The drilling of organic-rich shales, typically of Upper Devonian to Ordovician age, in Pennsylvania, New York, and elsewhere in the Appalachian Basin is spreading rapidly, raising concerns for impacts on water resources (8, 9). In Susquehanna County, Pennsylvania alone, approved gas-well permits in the Marcellus formation increased 27-fold from 2007 to 2009 (10).

Concerns for impacts to groundwater resources are based on (i) fluid (water and gas) flow and discharge to shallow aquifers due to the high pressure of the injected fracturing fluids in the gas wells (10); (ii) the toxicity and radioactivity of produced water from a mixture of fracturing fluids and deep saline formation waters that may discharge to the environment (11); (iii) the potential explosion and asphyxiation hazard of natural gas; and (iv) the large number of private wells in rural areas that rely on shallow groundwater for household and agricultural use—up to one million wells in Pennsylvania alone—that are typically unregulated and untested (8, 9, 12). In this study, we analyzed groundwater from 68 private water wells from 36- to 190-m deep in

Author contributions: 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. analyzed data; and S.G.O., A.V., N.R.W., and R.B.J. wrote the paper.

The authors declare no conflict of interest.

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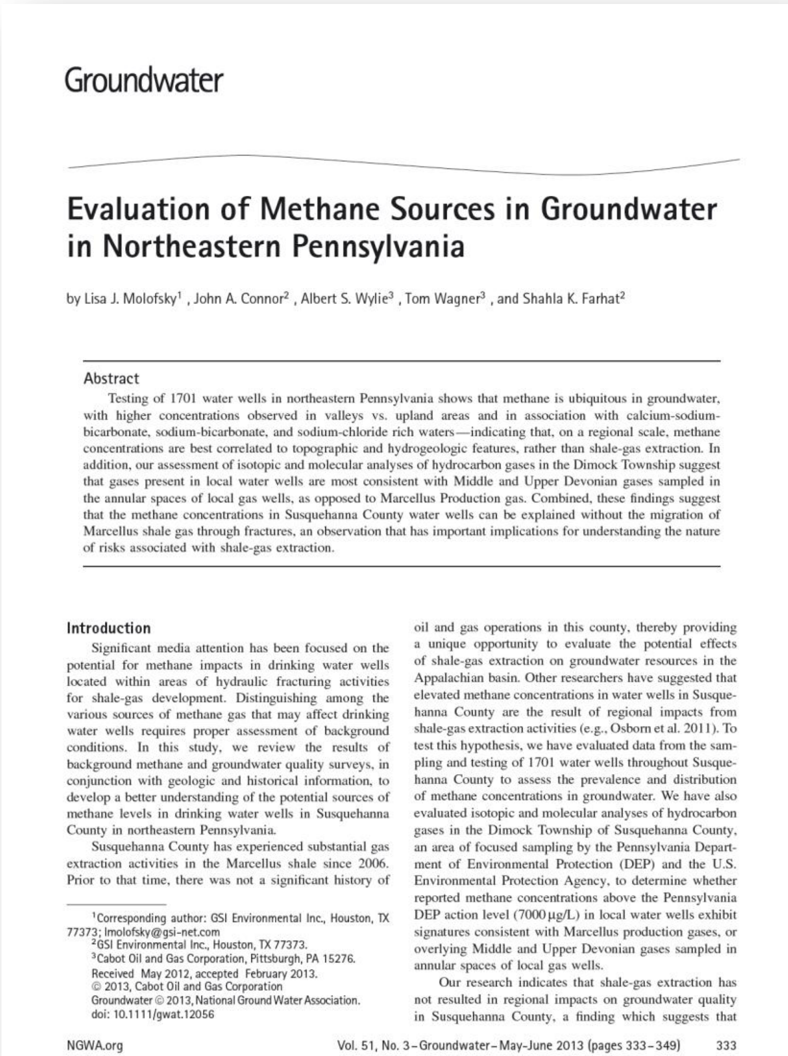
8172–8176 | PNAS | May 17, 2011 | vol. 108 | no. 20 www.pnas.org/cgi/doi/10.1073/pnas.1100682108

- Measured methane content and $\delta^{13}C$
- Higher methane concentrations in water wells close to shale gas wells
- $\delta^{13}C$ suggests thermogenic
- Authors then say ‘*likely to be shale gas from the fracking*’

Thermogenic methane unrelated to fracking?

Molofsky et al. 2013



Groundwater

Evaluation of Methane Sources in Groundwater in Northeastern Pennsylvania

by Lisa J. Molofsky[1], John A. Connor[2], Albert S. Wylie[3], Tom Wagner[3], and Shahla K. Farhat[2]

Abstract

Testing of 1701 water wells in northeastern Pennsylvania shows that methane is ubiquitous in groundwater, with higher concentrations observed in valleys vs. upland areas and in association with calcium-sodium-bicarbonate, sodium-bicarbonate, and sodium-chloride rich waters—indicating that, on a regional scale, methane concentrations are best correlated to topographic and hydrogeologic features, rather than shale-gas extraction. In addition, our assessment of isotopic and molecular analyses of hydrocarbon gases in the Dimock Township suggest that gases present in local water wells are most consistent with Middle and Upper Devonian gases sampled in the annular spaces of local gas wells, as opposed to Marcellus Production gas. Combined, these findings suggest that the methane concentrations in Susquehanna County water wells can be explained without the migration of Marcellus shale gas through fractures, an observation that has important implications for understanding the nature of risks associated with shale-gas extraction.

Introduction

Significant media attention has been focused on the potential for methane impacts in drinking water wells located within areas of hydraulic fracturing activities for shale-gas development. Distinguishing among the various sources of methane gas that may affect drinking water wells requires proper assessment of background conditions. In this study, we review the results of background methane and groundwater quality surveys, in conjunction with geologic and historical information, to develop a better understanding of the potential sources of methane levels in drinking water wells in Susquehanna County in northeastern Pennsylvania.

Susquehanna County has experienced substantial gas extraction activities in the Marcellus shale since 2006. Prior to that time, there was not a significant history of oil and gas operations in this county, thereby providing a unique opportunity to evaluate the potential effects of shale-gas extraction on groundwater resources in the Appalachian basin. Other researchers have suggested that elevated methane concentrations in water wells in Susquehanna County are the result of regional impacts from shale-gas extraction activities (e.g., Osborn et al. 2011). To test this hypothesis, we have evaluated data from the sampling and testing of 1701 water wells throughout Susquehanna County to assess the prevalence and distribution of methane concentrations in groundwater. We have also evaluated isotopic and molecular analyses of hydrocarbon gases in the Dimock Township of Susquehanna County, an area of focused sampling by the Pennsylvania Department of Environmental Protection (DEP) and the U.S. Environmental Protection Agency, to determine whether reported methane concentrations above the Pennsylvania DEP action level (7000 µg/L) in local water wells exhibit signatures consistent with Marcellus production gases, or overlying Middle and Upper Devonian gases sampled in annular spaces of local gas wells.

Our research indicates that shale-gas extraction has not resulted in regional impacts on groundwater quality in Susquehanna County, a finding which suggests that

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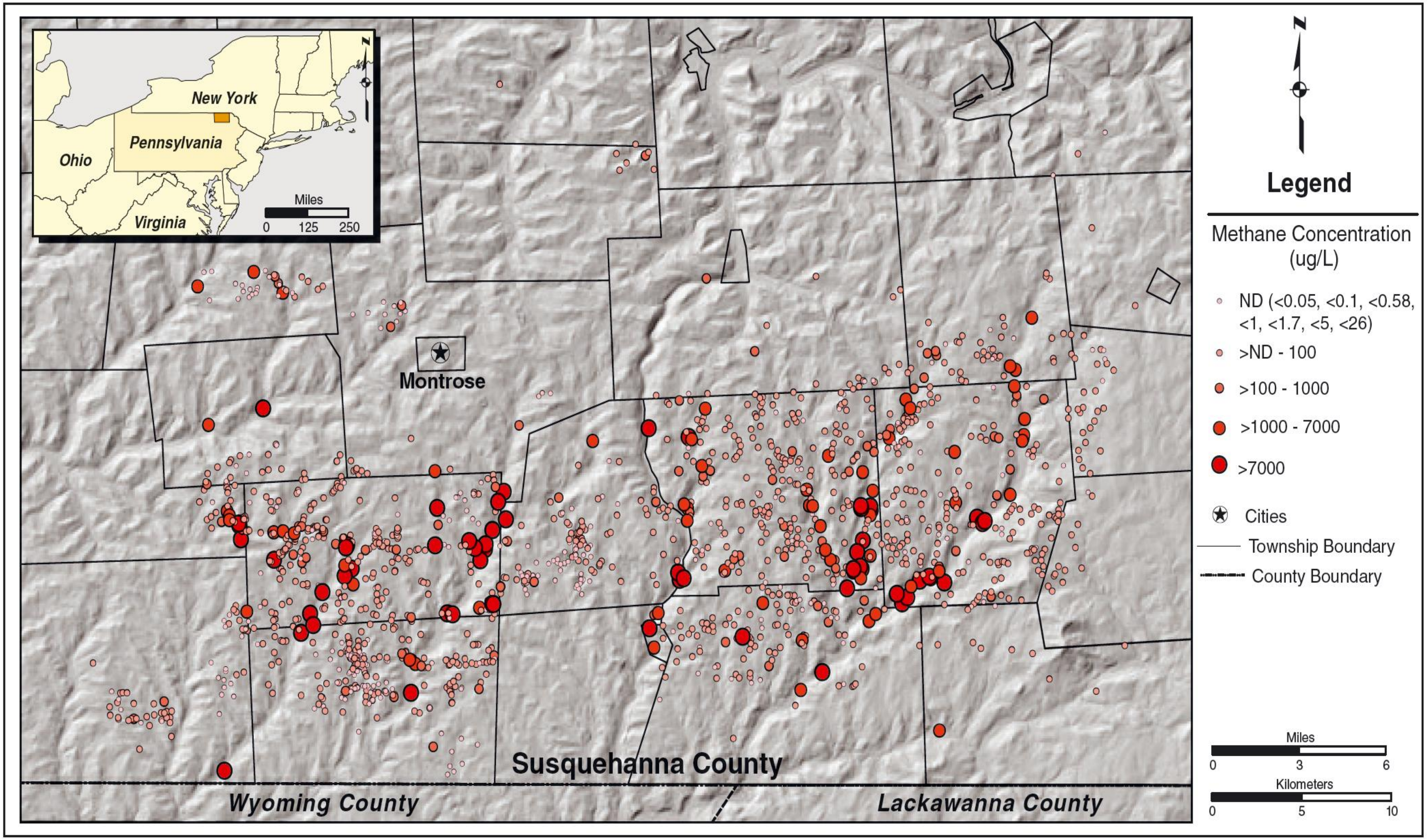
- Looked at some of the Osborn et al data
- Also at baseline water data: historical records show flammable and effervescing natural springs and water wells back to the late 1700s.

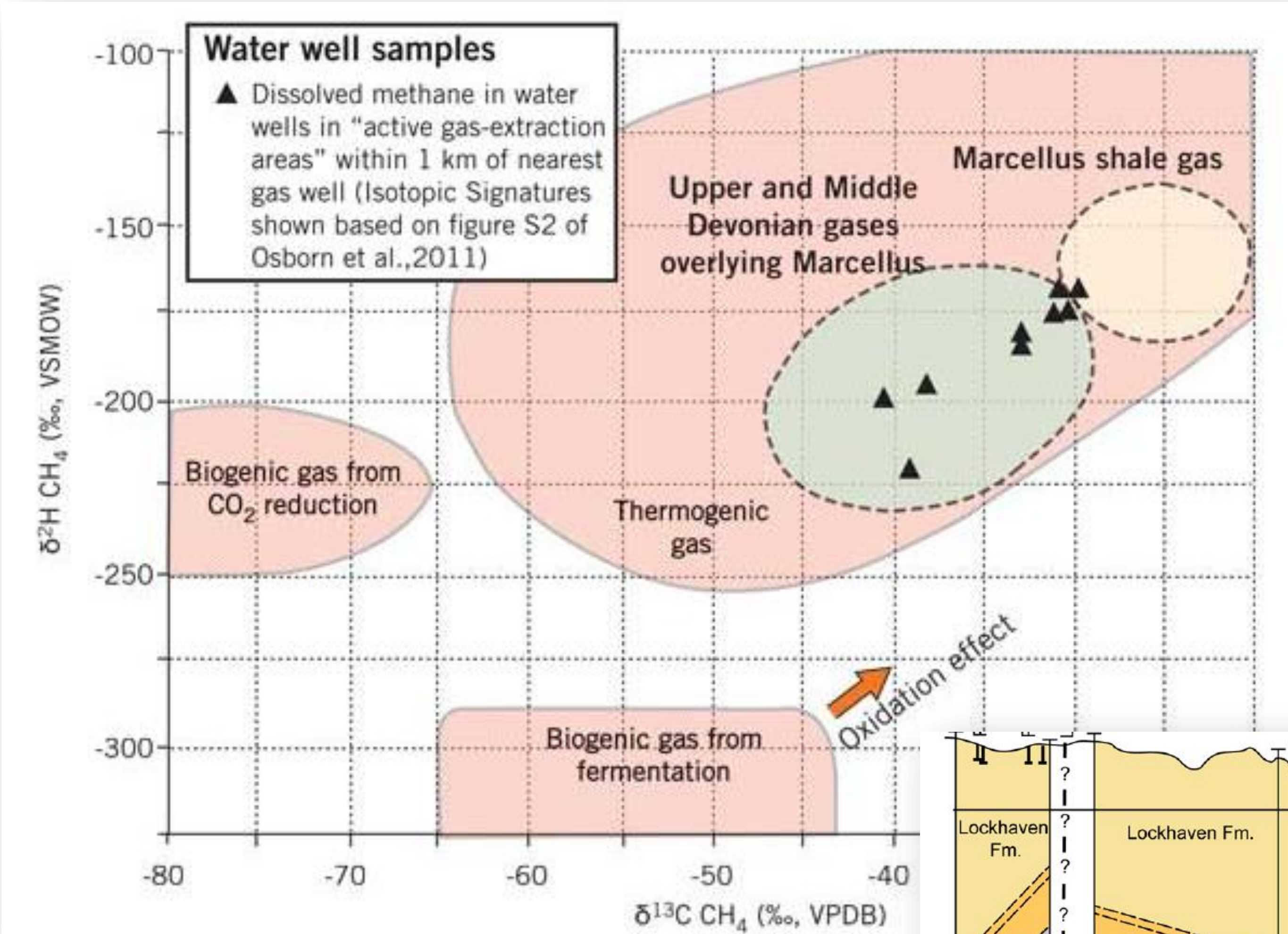
Dec 2011

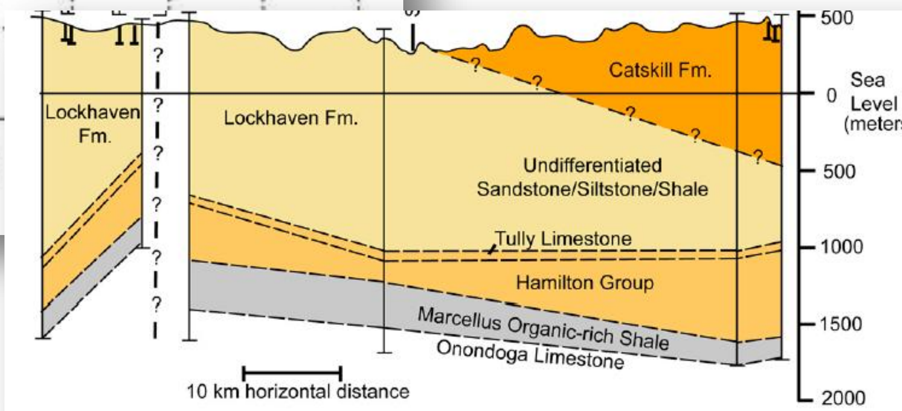
Thermogenic methane related to topography?



Molofsky et al. (2013).

Methane signature indicates layers above Marcellus





Molofsky et al. 2011

Another look at the water wells

Jackson et al. 2013

Duke University Group

Statistically significant evidence

141 water wells studied

methane concentrations six times higher for water wells within 1 km of shale gas wells

No correlation with topography (valleys)

PNAS PNAS PNAS PNAS PNAS

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

Robert B. Jackson[a,b,1], Avner Vengosh[a], Thomas H. Darrah[a], Nathaniel R. Warner[a], Adrian Down[a,b], Robert J. Poreda[c], Stephen G. Osborn[d], Kaiguang Zhao[a,b], and Jonathan D. Karr[a,b]

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Edited by Susan E. Trumbore, Max Planck Institute for Biogeochemistry, Jena, Germany, and approved June 3, 2013 (received for review December 17, 2012)

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 ($\delta^{13}C\text{-}CH_4$, $\delta^{13}C\text{-}C_2H_6$, and $\delta^{2}H\text{-}CH_4$), 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 $\delta^{13}C\text{-}CH_4$ 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., $\delta^{13}C\text{-}CH_4$, $\delta^{2}H\text{-}CH_4$, $\delta^{13}C\text{-}C_2H_6$, $\delta^{13}C$-dissolved inorganic carbon ($\delta^{13}C$-DIC), and $\delta^{2}H\text{-}H_2O$] 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).

Author contributions: R.B.J., A.V., T.H.D., N.R.W., and A.D. designed research; R.B.J., A.V., T.H.D., N.R.W., A.D., R.J.P., S.G.O., K.Z., and J.D.K. performed research; R.B.J., A.V., T.H.D., N.R.W., A.D., R.J.P., K.Z., and J.D.K. analyzed data; and R.B.J., A.V., T.H.D., N.R.W., and A.D. wrote the paper.

The authors declare no conflict of interest.

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ENVIRONMENTAL SCIENCES

More recent research

Llewellyn et al. 2015

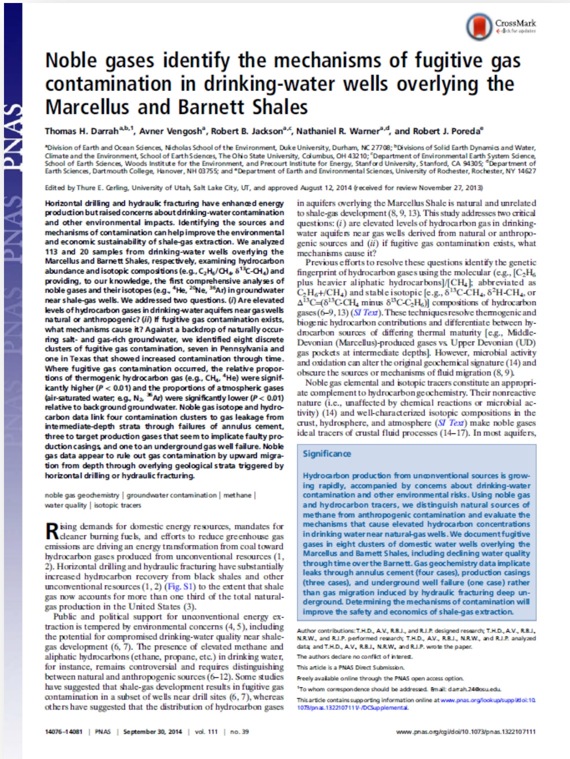
- groundwater supply contamination incident
- additives probably derived from drilling or hydraulic fracturing fluid were present in groundwater

Evaluating a groundwater supply contamination incident attributed to Marcellus Shale gas development

Garth T. Llewellyn, Frank Dorman, J. L. Westland, D. Yoxtheimer, Paul Grieve, Todd Sowers, E. Humston-Fulmer, and Susan L. Brantley

Darrah et al. 2014

- Noble gas and methane
- Suggests leakage at intermediate depth due to casing and cement problems

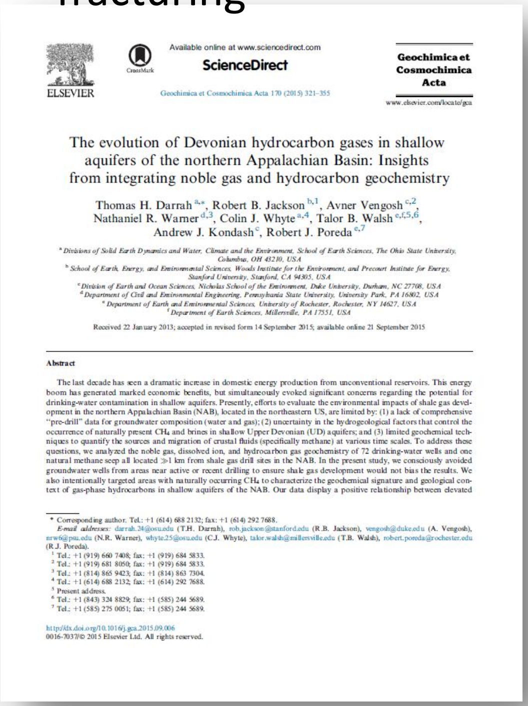


Noble gases identify the mechanisms of fugitive gas contamination in drinking-water wells overlying the Marcellus and Barnett Shales

Thomas H. Darrah, Avner Vengosh, Robert B. Jackson, Nathaniel R. Warner, and Robert J. Poreda

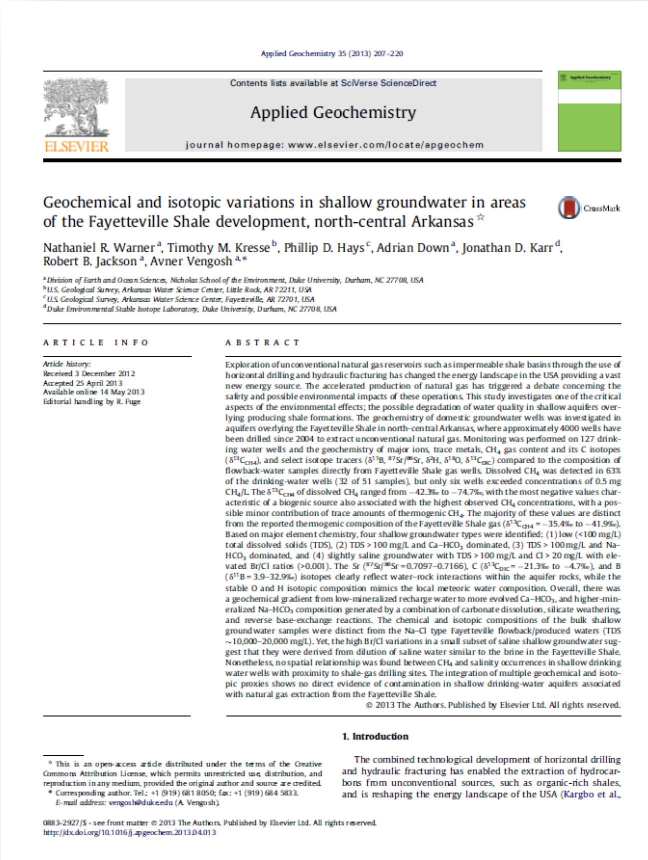
Darrah et al. 2015

- Noble gas, methane and other geochemistry
- Outside shale gas areas
- Diffusison of deep shale gas into shallow aquifers helped by neotectonic fracturing



The evolution of Devonian hydrocarbon gases in shallow aquifers of the northern Appalachian Basin: Insights from integrating noble gas and hydrocarbon geochemistry

Thomas H. Darrah, Robert B. Jackson, Avner Vengosh, Nathaniel R. Warner, Colin J. Whyte, Talor B. Walsh, Andrew J. Kondash, Robert J. Poreda


Applied Geochemistry 35 (2013) 207–220

Contents lists available at SciVerse ScienceDirect

Applied Geochemistry

journal homepage: www.elsevier.com/locate/apgeochem

Geochemical and isotopic variations in shallow groundwater in areas of the Fayetteville Shale development, north-central Arkansas ☆

Nathaniel R. Warner [a], Timothy M. Kresse [b], Phillip D. Hays [c], Adrian Down [a], Jonathan D. Karr [d], Robert B. Jackson [a], Avner Vengosh [a,*]

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[b] U.S. Geological Survey, Arkansas Water Science Center, Little Rock, AR 72211, USA
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ABSTRACT

Exploration of unconventional natural gas reservoirs such as impermeable shale basins through the use of horizontal drilling and hydraulic fracturing has changed the energy landscape in the USA providing a vast new energy source. The accelerated production of natural gas has triggered a debate concerning the safety and possible environmental impacts of these operations. This study investigates one of the critical aspects of the environmental effects; the possible degradation of water quality in shallow aquifers overlying producing shale formations. The geochemistry of domestic groundwater wells was investigated in aquifers overlying the Fayetteville Shale in north-central Arkansas, where approximately 4000 wells have been drilled since 2004 to extract unconventional natural gas. Monitoring was performed on 127 drinking water wells and the geochemistry of major ions, trace metals, CH_4 gas content and its C isotopes ($\delta^{13}C_{CH4}$), and select isotope tracers ($\delta^{11}B$, $^{87}Sr/^{86}Sr$, $\delta^{2}H$, $\delta^{18}O$, $\delta^{13}C_{DIC}$) compared to the composition of flowback-water samples directly from Fayetteville Shale gas wells. Dissolved CH_4 was detected in 63% of the drinking-water wells (32 of 51 samples), but only six wells exceeded concentrations of 0.5 mg CH_4/L. The $\delta^{13}C_{CH4}$ of dissolved CH_4 ranged from −42.3‰ to −74.7‰, with the most negative values characteristic of a biogenic source also associated with the highest observed CH_4 concentrations, with a possible minor contribution of trace amounts of thermogenic CH_4. The majority of these values are distinct from the reported thermogenic composition of the Fayetteville Shale gas ($\delta^{13}C_{CH4}$ = −35.4‰ to −41.9‰). Based on major element chemistry, four shallow groundwater types were identified: (1) low (<100 mg/L) total dissolved solids (TDS), (2) TDS > 100 mg/L and Ca–HCO_3 dominated, (3) TDS > 100 mg/L and Na–HCO_3 dominated, and (4) slightly saline groundwater with TDS > 100 mg/L and Cl > 20 mg/L with elevated Br/Cl ratios (>0.001). The Sr ($^{87}Sr/^{86}Sr$ = 0.7097–0.7166), C ($\delta^{13}C_{DIC}$ = −21.3‰ to −4.7‰), and B ($\delta^{11}B$ = 3.9–32.9‰) isotopes clearly reflect water–rock interactions within the aquifer rocks, while the stable O and H isotopic composition mimics the local meteoric water composition. Overall, there was a geochemical gradient from low-mineralized recharge water to more evolved Ca–HCO_3, and higher-mineralized Na–HCO_3 composition generated by a combination of carbonate dissolution, silicate weathering, and reverse base-exchange reactions. The chemical and isotopic compositions of the bulk shallow groundwater samples were distinct from the Na–Cl type Fayetteville flowback/produced waters (TDS ~10,000–20,000 mg/L). Yet, the high Br/Cl variations in a small subset of saline shallow groundwater suggest that they were derived from dilution of saline water similar to the brine in the Fayetteville Shale. Nonetheless, no spatial relationship was found between CH_4 and salinity occurrences in shallow drinking water wells with proximity to shale-gas drilling sites. The integration of multiple geochemical and isotopic proxies shows no direct evidence of contamination in shallow drinking-water aquifers associated with natural gas extraction from the Fayetteville Shale.

1. Introduction

The combined technological development of horizontal drilling and hydraulic fracturing has enabled the extraction of hydrocarbons from unconventional sources, such as organic-rich shales, and is reshaping the energy landscape of the USA (Kargbo et al.,

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http://dx.doi.org/10.1016/j.apgeochem.2013.04.013

Outside Pennsylvania

Arkansas

127 drinking water wells

Fayetteville shale 4000 wells drilled since 2004

very low concentrations of methane

biogenic, not thermogenic

Shale gas wells do leak but only a small number…
And mostly in Pennsylvania….
Water contamination most likely from leaky wells - not fracking

Modelling studies…

2015

Reagan et al. 2015

Production will reduce chance of stray gas

- reduction of free gas
- lowering of reservoir pressure

2015

Nowamooz et al. 2015

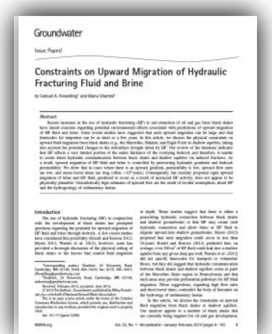
- Modelling hypothetical decommissioned shale gas well
- For the poorest cementation scenario, maximum stray gas within 1 year after well closure.

2015

Birdsell et al. 2015

- Much previous modelling studies neglected production
- overestimated the likelihood and quantity of stray HF

2014



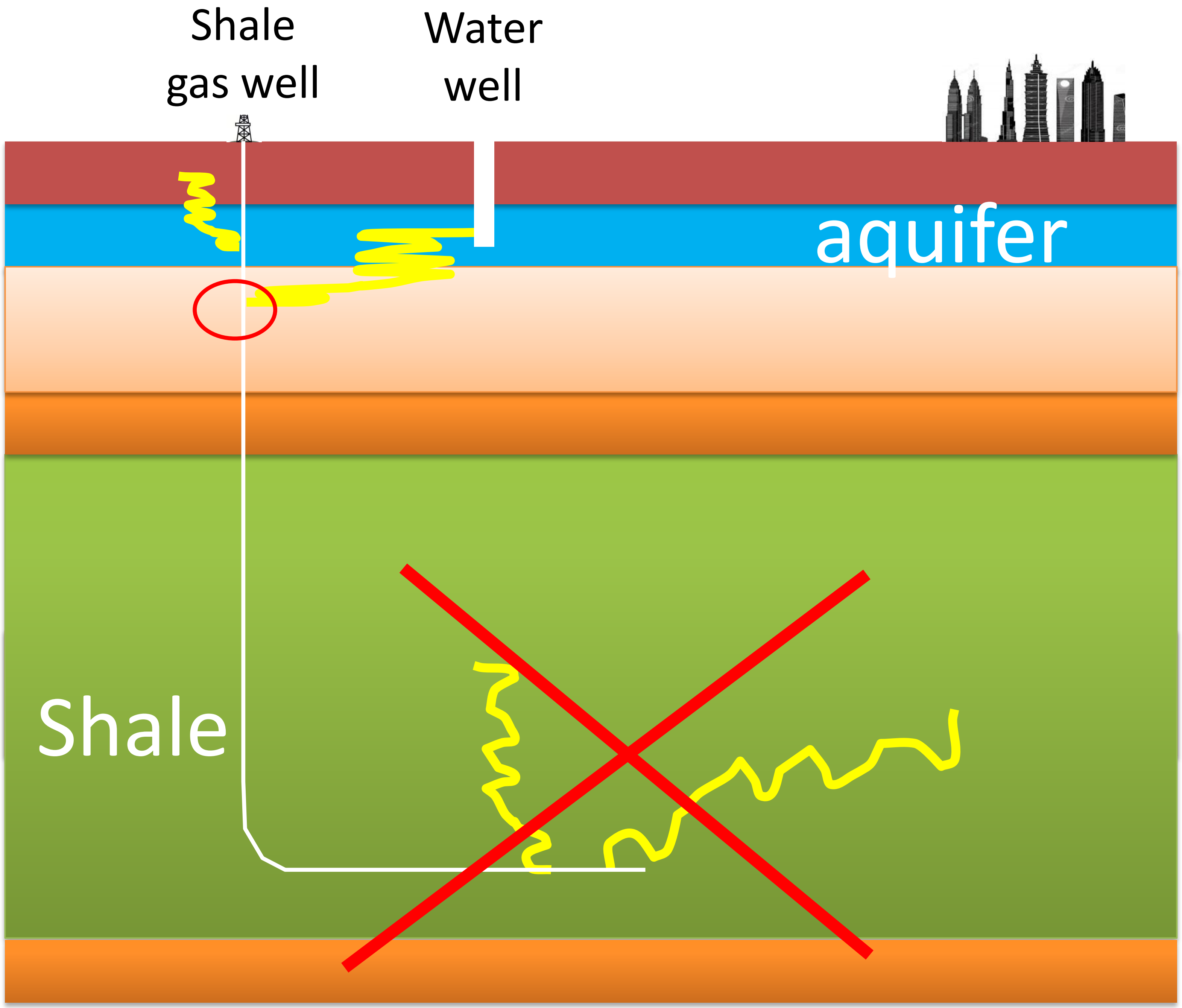
Flewwlling & Sharma 2014

- Where there is an upward gradient, permeability is low, upward flow rates are low, and mean travel times are long (often >1000000 years).

2014

Cai & Ofterdinger 2014

- Bowland Shale discrete fracture model
- Crack size affects likelihood of upward migration


Shale
gas well
Water
well
aquifer
Shale

Does shale gas use too much water?

Do shale gas wells contaminate groundwater?

Does fracking cause dangerous earthquakes?

Does shale gas cause subsidence?

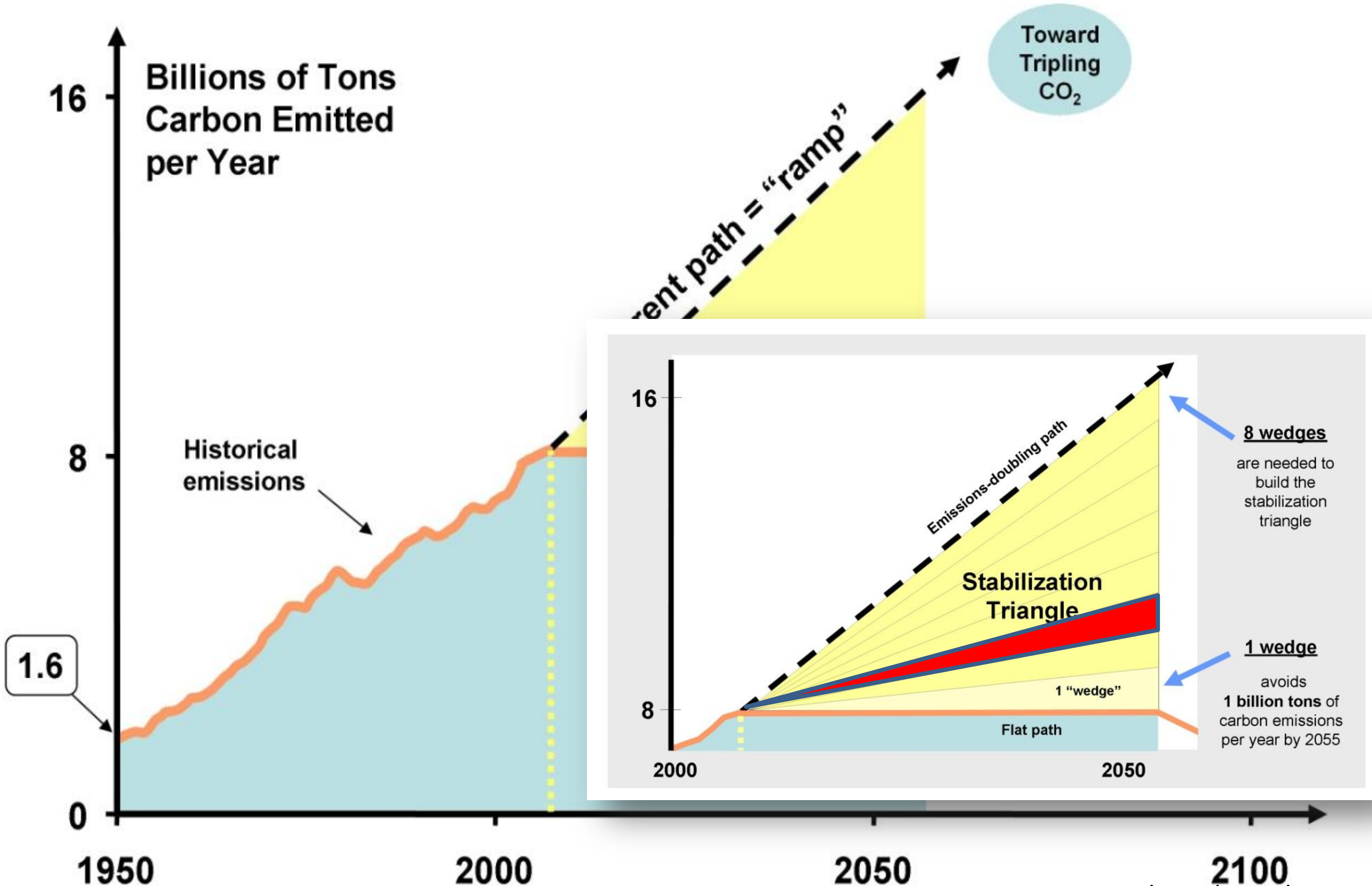
Does fracking produce dangerous radioactivity?

Is shale gas lower carbon than coal?

IS SHALE GAS ‘LOWER CARBON’ THAN COAL?

SOME BASICS

Context



Pacala and Socolow R 2004

If 1400 natural gas power stations were substituted for an equal number of coal-fired power stations then this would save one wedge of CO2 emissions

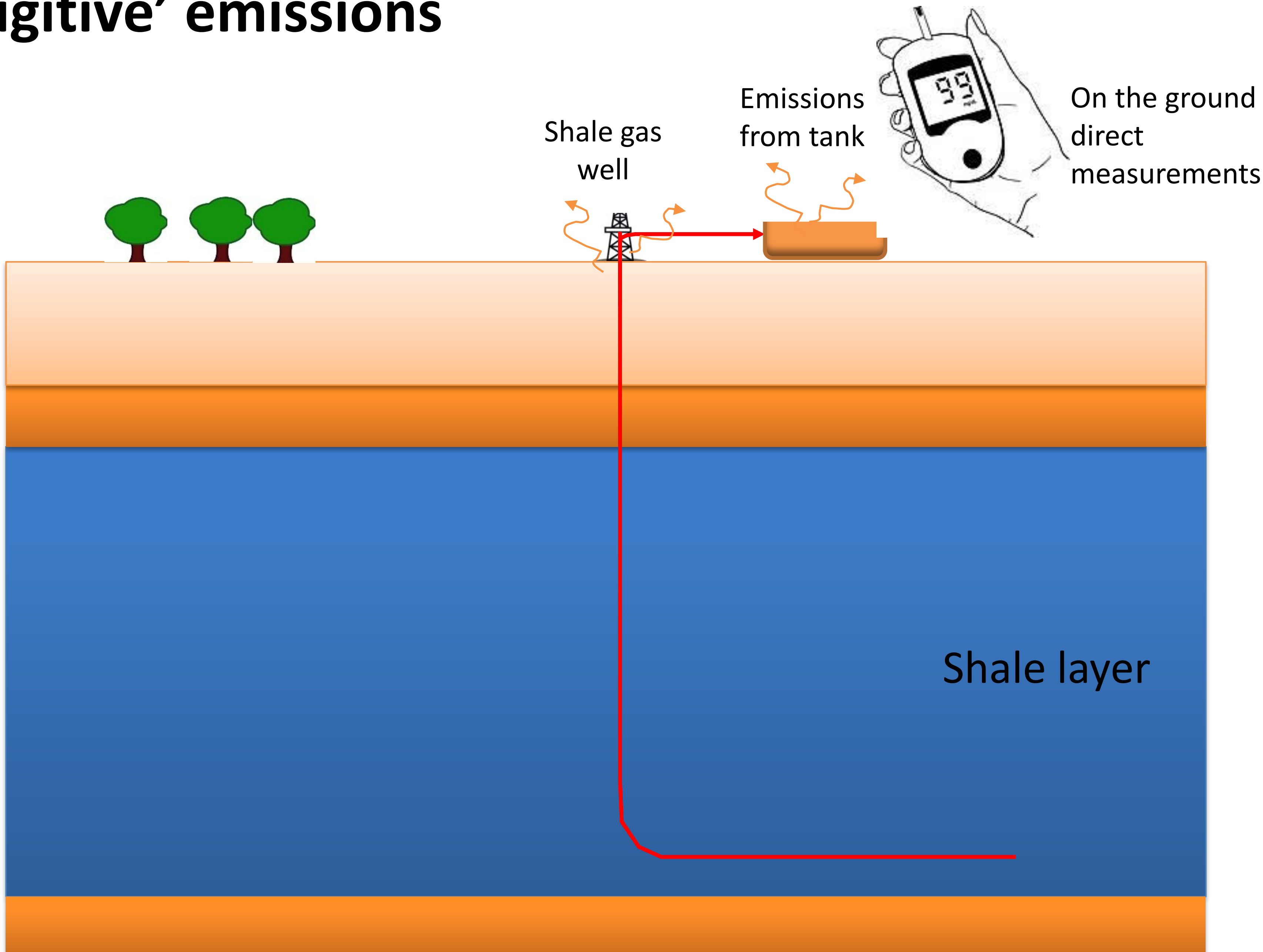
Fuel	Pounds of CO_2 emitted per million BTU of energy
Coal (anthracite)	228.6
Coal (bituminous)	205.7
Coal (lignite)	215.4
Coal (subbituminous)	214.3
Diesel fuel & heating oil	161.3
Gasoline	157.2
Propane	139
Natural gas	117

Source **US EIA**

Open flowback tanks

But what about methane?

‘Fugitive’ emissions



Climatic Change (2011) 106:679–690
DOI 10.1007/s10584-011-0061-5

LETTER

Methane and the greenhouse-gas footprint of natural gas from shale formations

A letter

Robert W. Howarth · Renee Santoro · Anthony Ingraffea

Received: 12 November 2010 / Accepted: 13 March 2011 / Published online: 12 April 2011

Abstract We evaluate the greenhouse gas footprint of natural gas obtained by high-volume hydraulic fracturing from shale formations, focusing on methane emissions. Natural gas is composed largely of methane, and 3.6% to 7.9% of the methane from shale-gas production escapes to the atmosphere in venting and leaks over the life-time of a well. These methane emissions are at least 30% more than and perhaps more than twice as great as those from conventional gas. The higher emissions from shale gas occur at the time wells are hydraulically fractured—as methane escapes from flow-back return fluids—and during drill out following the fracturing. Methane is a powerful greenhouse gas, with a global warming potential that is far greater than that of carbon dioxide, particularly over the time horizon of the first few decades following emission. Methane contributes substantially to the greenhouse gas footprint of shale gas on shorter time scales, dominating it on a 20-year time horizon. The footprint for shale gas is greater than that for conventional gas or oil when viewed on any time horizon, but particularly so over 20 years. Compared to coal, the footprint of shale gas is at least 20% greater and perhaps more than twice as great on the 20-year horizon and is comparable when compared over 100 years.

Keywords Methane · Greenhouse gases · Global warming · Natural gas · Shale gas · Unconventional gas · Fugitive emissions · Lifecycle analysis · LCA · Bridge fuel · Transitional fuel · Global warming potential · GWP

Electronic supplementary material The online version of this article (doi:10.1007/s10584-011-0061-5) contains supplementary material, which is available to authorized users.

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Springer

Howarth et al. 2011 (Cornell Uni)

direct measurements

3 to 8% of the total methane production escapes to the atmosphere through the lifetime of *every shale gas well*

This is enough leaking gas to really make a difference

Is shale gas is worse than coal?

Climatic Change
DOI 10.1007/s10584-011-0333-0

COMMENTARY

A commentary on "The greenhouse-gas footprint of natural gas in shale formations" by R.W. Howarth, R. Santoro, and Anthony Ingraffea

Lawrence M. Cathles III · Larry Brown · Milton Taam · Andrew Hunter

Received: 20 June 2011 / Accepted: 21 October 2011

Abstract Natural gas is widely considered to be an environmentally cleaner fuel than coal because it does not produce detrimental by-products such as sulfur, mercury, ash and particulates and because it provides twice the energy per unit of weight with half the carbon footprint during combustion. These points are not in dispute. However, in their recent publication in Climatic Change Letters, Howarth et al. (2011) report that their life-cycle evaluation of shale gas drilling suggests that shale gas has a larger GHG footprint than coal and that this larger footprint "undercuts the logic of its use as a bridging fuel over the coming decades". We argue here that their analysis is seriously flawed in that they significantly overestimate the fugitive emissions associated with unconventional gas extraction, undervalue the contribution of "green technologies" to reducing those emissions to a level approaching that of conventional gas, base their comparison between gas and coal on heat rather t
interval over w
does not captu
residence time
and comparison
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more reasonabl
is half and perh

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L. M. Cathles III ·
Department of Ear
e-mail: ldb7@corn

M. Taam
Electric Software,

A. Hunter
Department of Ch

Published online:

Cathles et al. 2012 (Cornell Uni) rebuttal

High leakage rates of Howarth unrepresentative?

(ten tests of wells drilled into the Haynesville shale)

Source (mainly scientific papers and reports)	Shale layer	Volume of Gas released during flowback (thousands of cubic metres per well)
Jiang	Marcellus	603
Howarth	Haynesville	6800
Howarth	Barnett	370
EPA	Various	260
O'Sullivan and Paltsev	Haynesville	1180
O'Sullivan and Paltsev	Barnett	273
O'Sullivan and Paltsev	Fayetteville	296
O'Sullivan and Paltsev	Marcellus	405
O'Sullivan and Paltsev	Woodford	487

from McKay and Stone (2013).

Measurements of methane emissions at natural gas production sites in the United States

David T. Allen[a,1], Vincent M. Torres[a], James Thomas[a], David W. Sullivan[a], Matthew Harrison[b], Al Hendler[b], Scott C. Herndon[c], Charles E. Kolb[c], Matthew P. Fraser[d], A. Daniel Hill[e], Brian K. Lamb[f], Jennifer Miskimins[g], Robert F. Sawyer[h], and John H. Seinfeld[i]

[a]Center for Energy and Environmental Resources, University of Texas, Austin, TX 78758; [b]URS Corporation, Austin, TX 78729; [c]Aerodyne Research, Inc., Billerica, MA 01821; [d]School of Sustainable Engineering and the Built Environment, Arizona State University, Tempe, AZ 85287; [e]Department of Petroleum Engineering, Texas A&M University, College Station, TX, 77843-3116; [f]Department of Civil and Environmental Engineering, Washington State University, Pullman, WA 99164; [g]Department of Petroleum Engineering, Colorado School of Mines, Golden, CO 80401; [h]Department of Mechanical Engineering, University of California, Berkeley, CA 94720-1740; and [i]Department of Chemical Engineering, California Institute of Technology, Pasadena, CA 91125

Edited by Susan L. Brantley, Pennsylvania State University, University Park, PA, and approved August 19, 2013 (received for review March 20, 2013)

Engineering estimates of methane emissions from natural gas production have led to varied projections of national emissions. This work reports direct measurements of methane emissions at 190 onshore natural gas sites in the United States (150 production sites, 27 well completion flowbacks, 9 well unloadings, and 4 workovers). For well completion flowbacks, which clear fractured wells of liquid to allow gas production, methane emissions ranged from 0.01 Mg to 17 Mg (mean = 1.7 Mg; 95% confidence bounds of 0.67–3.3 Mg), compared with an average of 81 Mg per event in the 2011 EPA national emission inventory from April 2013. Emission factors for pneumatic pumps and controllers as well as equipment leaks were both comparable to and higher than estimates in the national inventory. Overall, if emission factors from this work for completion flowbacks, equipment leaks, and pneumatic pumps and controllers are assumed to be representative of national populations and are used to estimate national emissions, total annual emissions from these source categories are calculated to be 957 Gg of methane (with sampling and measurement uncertainties estimated at ±200 Gg). The estimate for comparable source categories in the EPA national inventory is ~1,200 Gg. Additional measurements of unloadings and workovers are needed to produce national emission estimates for these source categories. The 957 Gg in emissions for completion flowbacks, pneumatics, and equipment leaks, coupled with EPA national inventory estimates for other categories, leads to an estimated 2,300 Gg of methane emissions from natural gas production (0.42% of gross gas production).

greenhouse gas emissions | hydraulic fracturing

Methane is the primary component of natural gas and is also a greenhouse gas (GHG). In the US national inventories of GHG emissions for 2011, released by the Environmental Protection Agency (EPA) in April 2013 (1), 2,545 Gg of CH_4 emissions have been attributed to natural gas production activities. These published estimates of CH_4 emissions from the US natural gas industry are primarily based on engineering estimates along with average emission factors developed in the early 1990s (2, 3). During the past two decades, however, natural gas production processes have changed significantly, so the emission factors from the 1990s may not reflect current practices. This work presents direct measurements of methane emissions from multiple sources at onshore natural gas production sites incorporating operational practices that have been adopted or become more prevalent since the 1990s.

Horizontal drilling and hydraulic fracturing are among the practices that have become more widely used over the past two decades. During hydraulic fracturing, materials that typically consist of water, sand and, additives, are injected at high pressure into low-permeability formations. The injection of the hydraulic fracturing fluids creates channels for flow in the formations (often shale formations), allowing methane and other hydrocarbon gases and liquids in the formation to migrate to the production well. The well and formation is partially cleared of liquids in a process referred to as a completion flowback, after which the well is placed into production. Production of natural gas from shale formations (shale gas) accounts for 30% of US natural gas production, and this percentage is projected to grow to more than 50% by 2040 (4).

Multiple analyses of the environmental implications of gas production using hydraulic fracturing have been performed, including assessments of water contamination (5–8), criteria air pollutant and air toxics releases (9–11), and greenhouse gas emissions (11–18). Greenhouse gas emission analyses have generally been based on either engineering estimates of emissions or measurements made 100 m to a kilometer downwind of the well site. This work reports direct on-site measurements of methane emissions from natural gas production in shale gas production regions.

Methane emissions were measured directly at 190 natural gas production sites in the Gulf Coast, Midcontinent, Rocky Mountain, and Appalachian production regions of the United States. The sites included 150 production sites with 489 wells, all of which were hydraulically fractured. In addition to the 150 production sites, 27 well completion flowbacks, 9 well unloadings, and 4 well workovers were sampled; the sites were operated by nine different companies. The types of sources that were targeted for measurement account for approximately two-thirds of

Significance

This work reports direct measurements of methane emissions at 190 onshore natural gas sites in the United States. The measurements indicate that well completion emissions are lower than previously estimated; the data also show emissions from pneumatic controllers and equipment leaks are higher than Environmental Protection Agency (EPA) national emission projections. Estimates of total emissions are similar to the most recent EPA national inventory of methane emissions from natural gas production. These measurements will help inform policymakers, researchers, and industry, providing information about some of the sources of methane emissions from the production of natural gas, and will better inform and advance national and international scientific and policy discussions with respect to natural gas development and use.

Author contributions: D.T.A. and M.H. designed research; D.T.A., V.M.T., J.T., D.W.S., M.H., A.H., and S.C.H. performed research; C.E.K., M.P.F., A.D.H., B.K.L., J.M., R.F.S., and J.H.S. analyzed data; and D.T.A. wrote the paper.

The authors declare no conflict of interest.

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1304880110/-/DCSupplemental.

Allen et al. 2014 (Uni Texas)

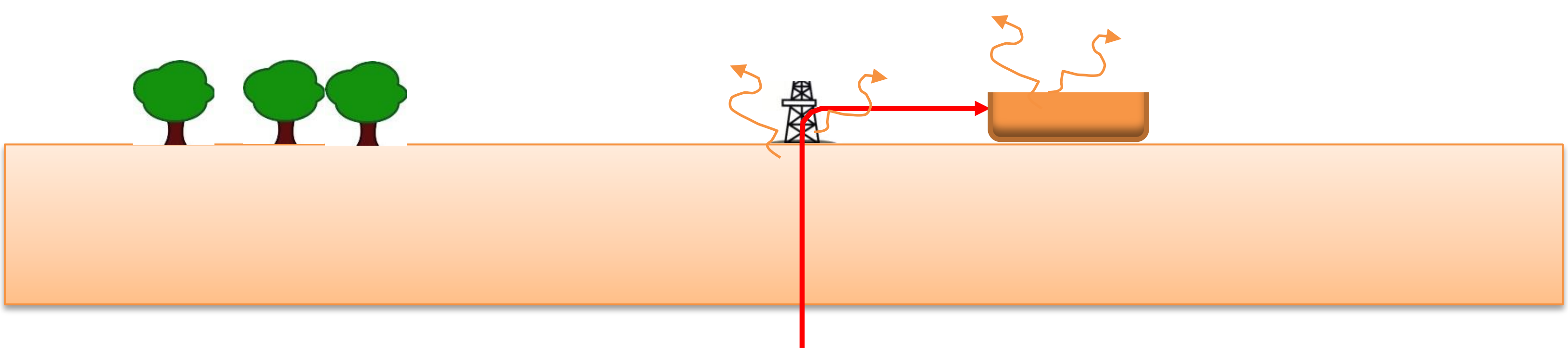
Direct measurement of 190 shale gas sites all over the US

leakage rate is about half of one percent of gas production,

much less than the 3 to 8% estimated by Howarth

Howarth et al
3 to 8%

Allen et al
<0.5%



Energy Science & Engineering

Open Access

RESEARCH ARTICLE

University of Texas study underestimates national methane emissions at natural gas production sites due to instrument sensor failure

Touché Howard

Indaco Air Quality Services, Inc., Durham, North Carolina

Keywords
Greenhouse gases, methane, natural gas

Correspondence
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Energy Science and Engineering 2015; 3(5):443–455

doi: 10.1002/ese3.81

Abstract

The University of Texas reported on a campaign to measure methane (CH_4) emissions from United States natural gas (NG) production sites as part of an improved national inventory. Unfortunately, their study appears to have systematically underestimated emissions. They used the Bacharach Hi-Flow® Sampler (BHFS) which in previous studies has been shown to exhibit sensor failures leading to underreporting of NG emissions. The data reported by the University of Texas study suggest their measurements exhibit this sensor failure, as shown by the paucity of high-emitting observations when the wellhead gas composition was less than 91% CH_4, where sensor failures are most likely; during follow-up testing, the BHFS used in that study indeed exhibited sensor failure consistent with under-reporting of these high emitters. Tracer ratio measurements made by the University of Texas at a subset of sites with low CH_4 content further indicate that the BHFS measurements at these sites were too low by factors of three to five. Over 98% of the CH_4 inventory calculated from their own data and 41% of their compiled national inventory may be affected by this measurement failure. Their data also indicate that this sensor failure could occur at NG compositions as high as 97% CH_4, possibly affecting other BHFS measurement programs throughout the entire NG supply chain, including at transmission sites where the BHFS is used to report greenhouse gas emissions to the United States Environmental Protection Agency Greenhouse Gas Reporting Program (USEPA GHGRP, U.S. 40 CFR Part 98, Subpart W). The presence of such an obvious problem in this high profile, landmark study highlights the need for increased quality assurance in all greenhouse gas measurement programs.

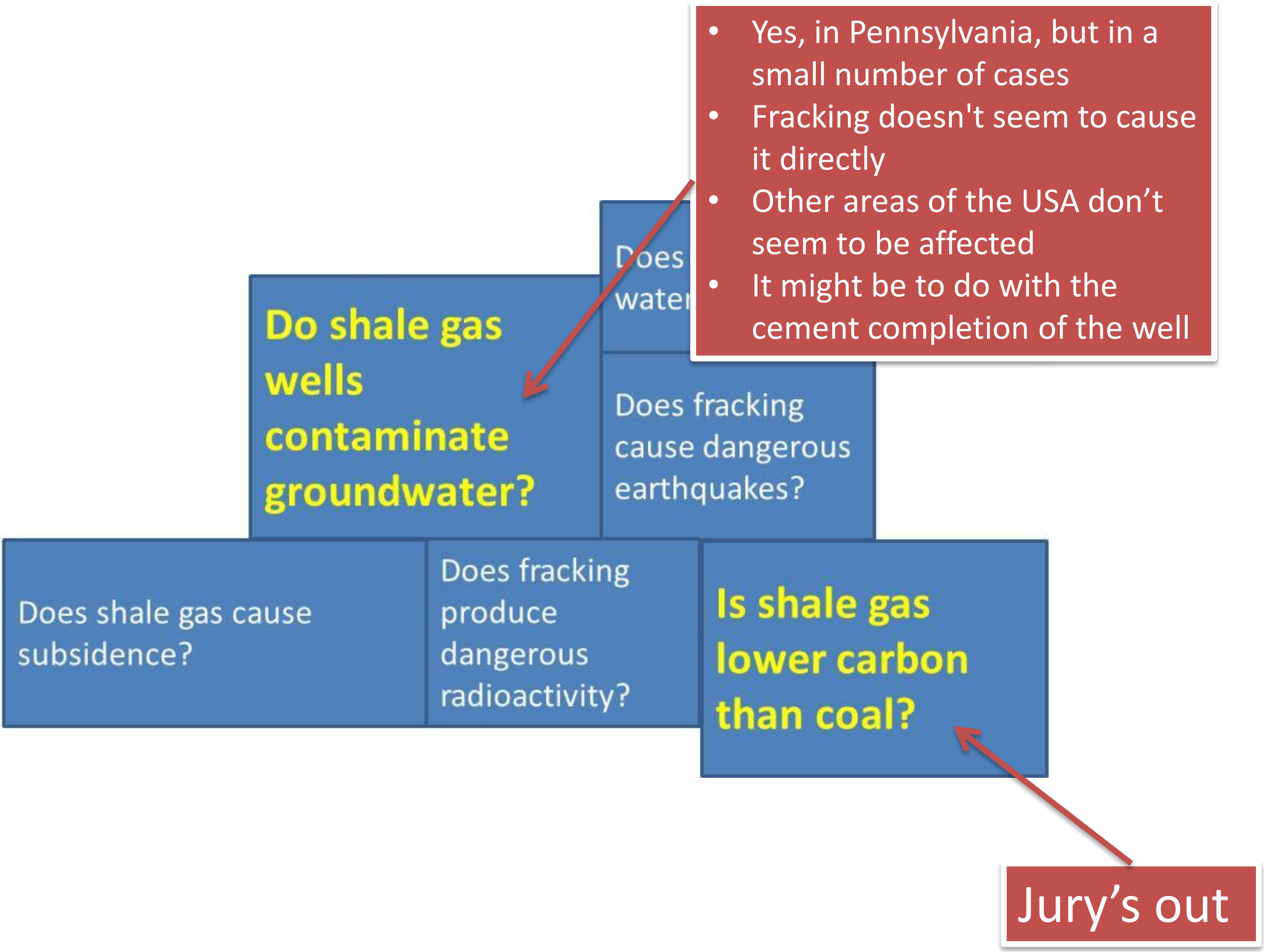
Introduction

The climatic benefits of switching from coal to natural gas (NG) depend on the magnitude of fugitive emissions of methane (CH_4) from NG production, processing, transmission, and distribution [12, 13, 27]. This is of particular concern as the United States increasingly exploits NG from shale formations: a sudden increase in CH_4 emissions due to increased NG production could trigger climate "tipping points" due to the high short-term global warming potential of CH_4 (86× carbon dioxide on a 20-year time scale) [19]. The United States Environmental Protection Agency (USEPA) estimates CH_4 emissions from the NG supply chain by scaling up individual ground-level measurements, mostly collected by reporting from industry [26]. However, some recent studies have questioned whether these "bottom-up" inventories are too low, since airborne measurements indicate that CH_4 emissions from NG production regions are higher than the inventories indicate [5, 14, 17, 20, 21].

In order to help determine the climate consequences of expanded NG production and use, and to address the apparent discrepancy in top-down and bottom-up measurements, the University of Texas (UT) at Austin and the

Touché Howard (2015)

- Allen et al. 2014 underestimated emissions
- They used the Bacharach Hi- Flow® Sampler which in previous studies has been shown to exhibit sensor failures
- The BHFS measurements at these sites were too low by factors of three to five


Yes, in Pennsylvania, but in a small number of cases
Fracking doesn't seem to cause it directly
Other areas of the USA don’t seem to be affected
It might be to do with the cement completion of the well
Does water
Do shale gas wells contaminate groundwater?
Does fracking cause dangerous earthquakes?
Does shale gas cause subsidence?
Does fracking produce dangerous radioactivity?
Is shale gas lower carbon than coal?
Jury’s out

Fracking

Minor earthquakes detected near fracking site in Lancashire

One tremor was magnitude 0.3, the level beyond which experts say fracking has to proceed with caution

Mattha Busby

@matthabusby

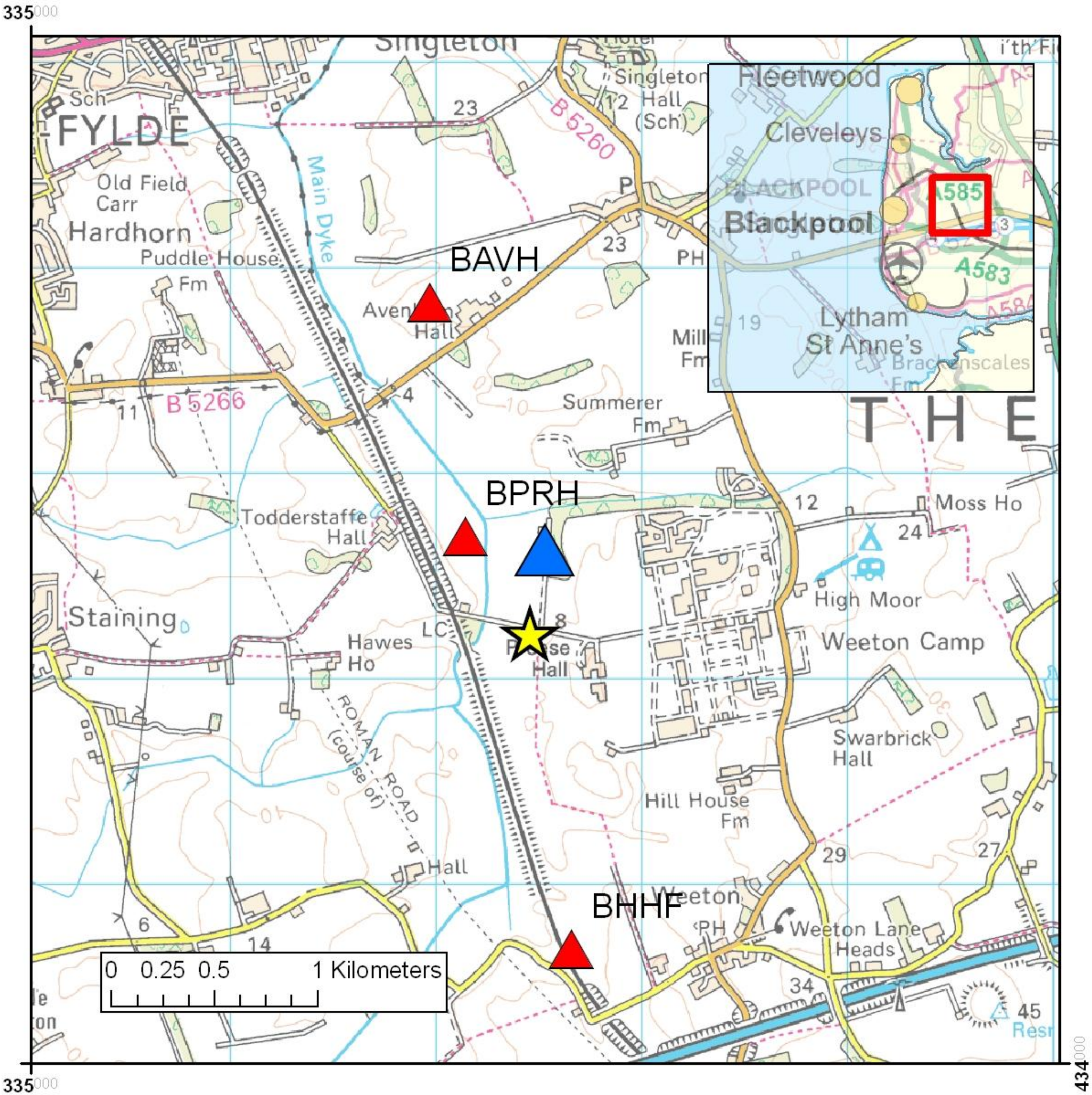
Sat 20 Oct 2018 13.01 BST

▲ Protesters' banner and placard at Cuadrilla's Preston New Road fracking site. Photograph: Christopher Thomond for the Guardian

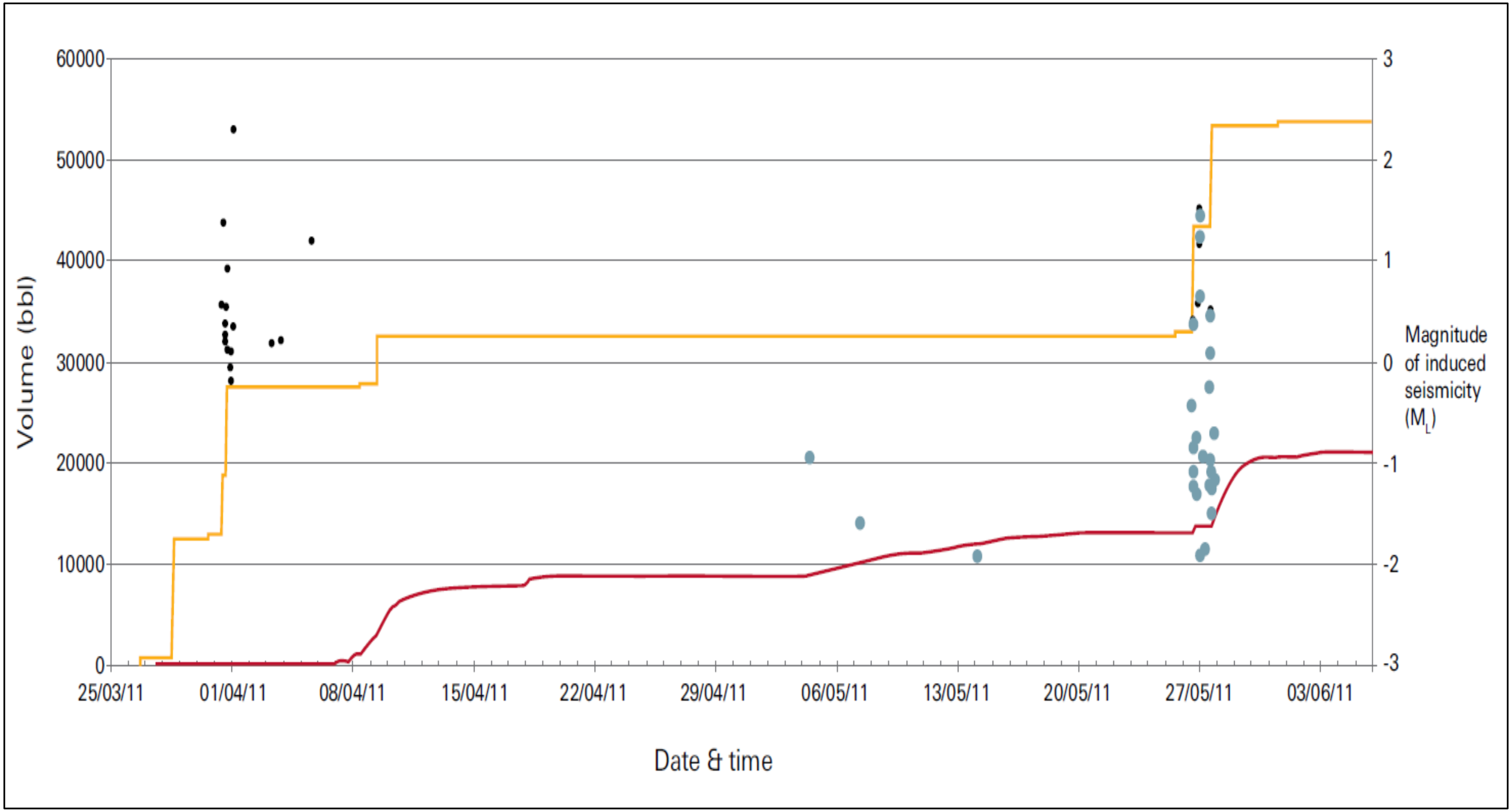
A series of small earthquakes have been detected in Lancashire close to the site where fracking operations began this week.

The British Geological Survey (BGS), which provides impartial advice on environmental processes, recorded four tremors in the vicinity of the energy firm Cuadrilla's site on Preston New Road near Blackpool on Friday.

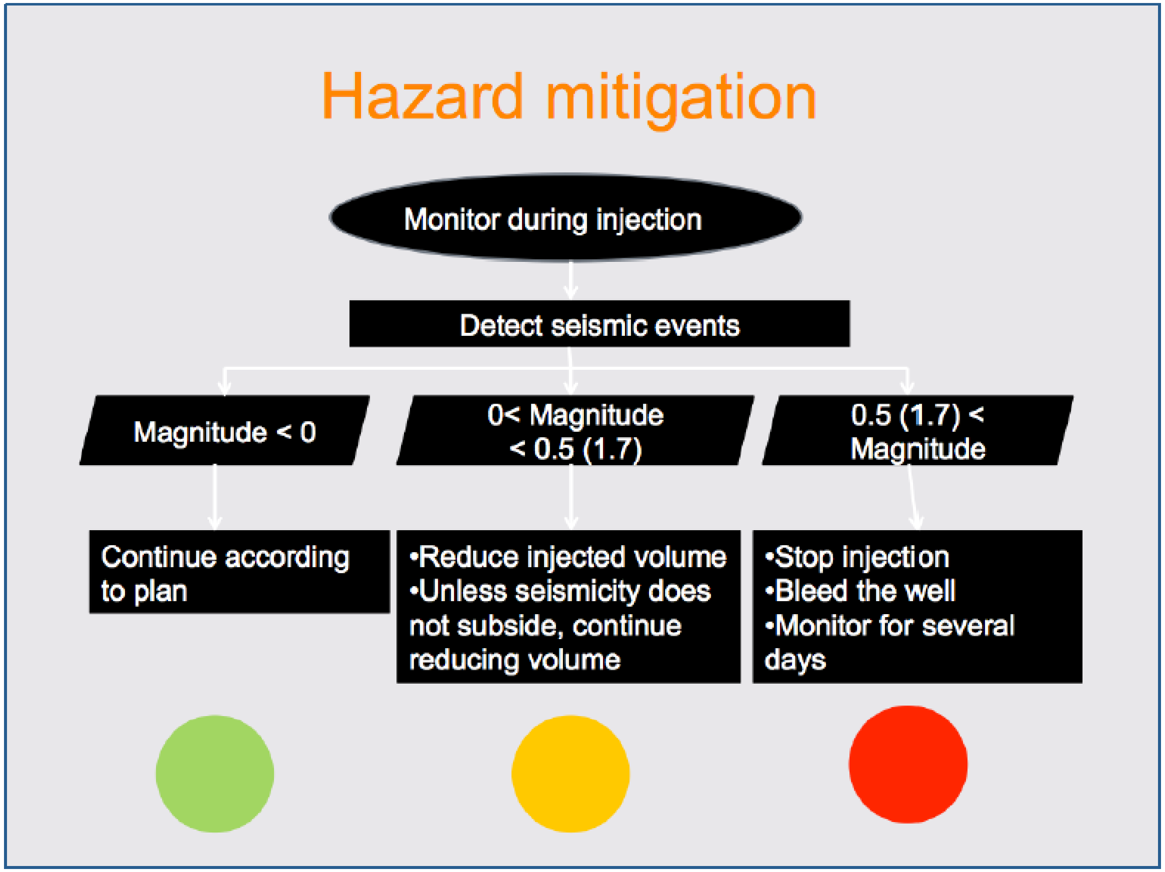
Fracking was stopped in 2011 after two earthquakes, one reaching 2.3 on the Richter scale, were triggered in close proximity to the site of shale gas test drilling. A subsequent report found that it was highly probable that the fracking operation caused the tremors.



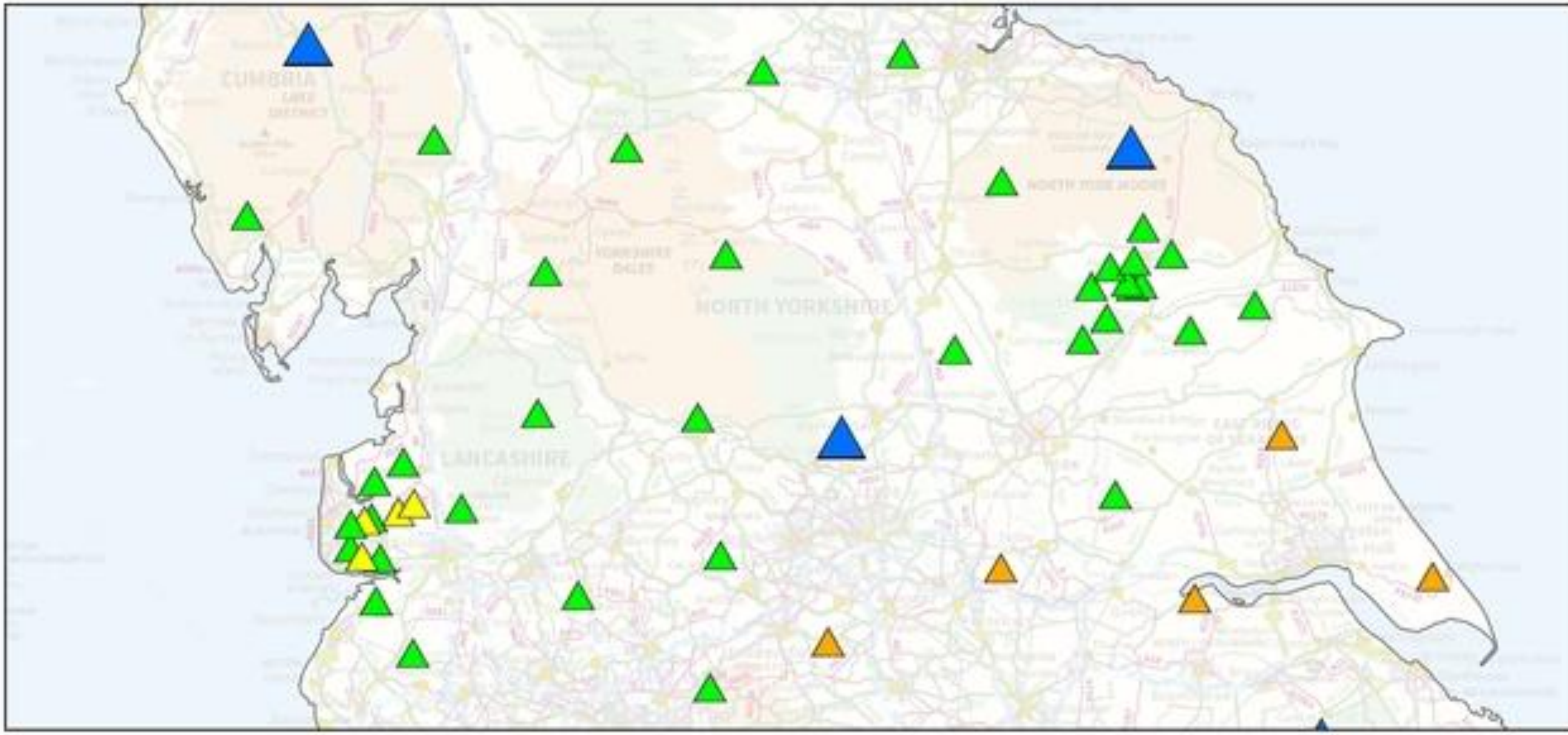
On 1 April and 27 May 2011, two earthquakes with magnitudes of 2.3 ML and 1.5 ML were detected in the Blackpool area



The volume of frack fluid (mainly water) injected in the fracking of the Preese Hall well and the volume of flowback coming back after the fracking. The yellow line showing water injected jumps in five places and these are the five separate fracks that were carried out on the Preese Hall well. The red line shows the volume of flowback water. From Royal Society and Royal Academy of Engineering (2012), modified from de Pater and Baisch (2011)



The *traffic light system* designed to manage earthquakes triggered by fracking. Essentially fracking can continue if earthquakes remain below zero on the ML scale. If earthquakes rise in energy to between zero and 0.5 ML then the amount of frack fluid injected must be reduced. If they go above 0.5 ML then injection must stop. From Green et al (2012)



Permanent (blue triangles) and temporary monitoring stations (green triangles) in the North of England

Seismicity at Preston New Road, October 2018

Earthquakes around the British Is ×

Not secure | www.earthquakes.bgs.ac.uk/earthquakes/recent_uk_events.html

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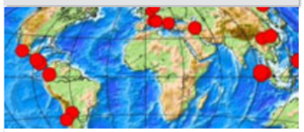
British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Earthquake Seismology

Home » Earthquakes » Earthquakes around the British Isles in the last 100 days

Earthquake Information



- *Recent British Earthquakes*
- Recent World Earthquakes
- Online Data Feeds
- Significant British Earthquakes
- Earthquake Database Search
- UK Macroseismic Database
- Have you felt an earthquake?

Earthquakes around the British Isles in the last 100 days

Last updated: Sat, 08 Dec 2018 19:40:01 (UTC)

This list is linked to a database that contains information about all the seismic events that we detect and locate. Locations and magnitudes may change as events are re-analysed and revised.

Depths are rounded to the nearest km and all events shallower than 1 km are listed as 1 km. Magnitudes are local magnitude (ML) and are calculated to one decimal place, as is standard practice in earthquake seismology.

Date	Time (UTC)	Lat	Lon	Depth (km)	Mag	Int	Region	Comment
2018/11/26	14:06:01.8	51.020	-4.644	31	1.3		OFF HARTLAND PT,DEVON	7KM OFFSHORE
2018/11/25	20:14:23.5	56.187	-5.156	3	1.0		INVERARAY,ARGYLL/BUTE	7KM SW INVERARAY
2018/11/25	19:29:19.5	56.522	-4.366	3	0.5		KILLIN,STIRLING	6KM NNW KILLIN

Earthquakes around the British Is ×

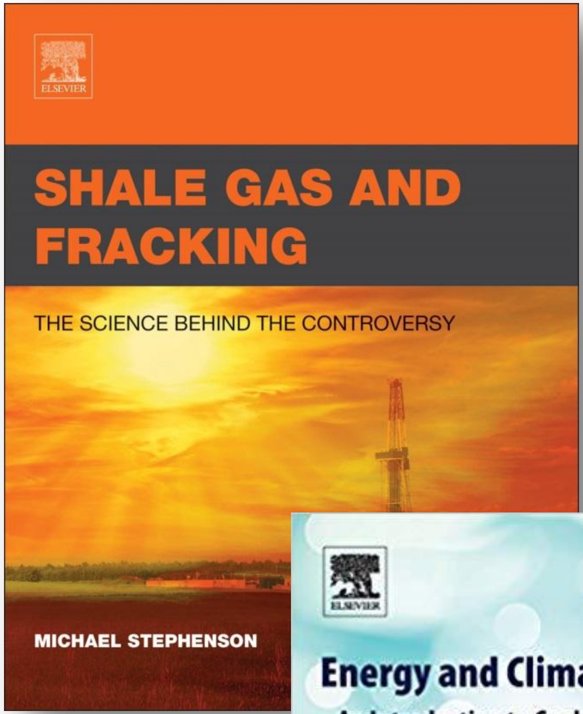
Not secure | www.earthquakes.bgs.ac.uk/earthquakes/recent_uk_events.html

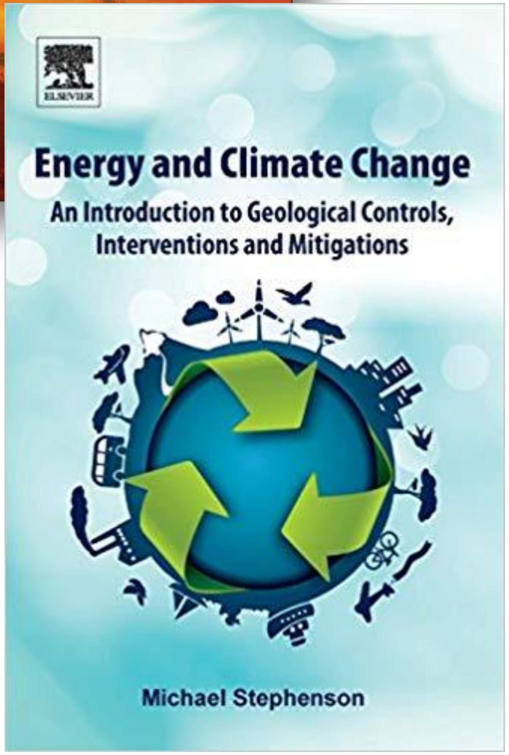
2018/10/29	18:01:12.2	53.788	-2.963	2	0.5		BLACKPOOL,LANCASHIRE	
2018/10/29	11:58:34.5	53.788	-2.964	2	0.0		BLACKPOOL,LANCASHIRE	
2018/10/29	11:43:29.3	53.786	-2.963	2	-0.4		BLACKPOOL,LANCASHIRE	
2018/10/29	11:44:41.8	53.788	-2.963	2	-0.2		BLACKPOOL,LANCASHIRE	
2018/10/29	11:30:38.9	53.789	-2.962	2	1.1	2	BLACKPOOL,LANCASHIRE	FELT BLACKPOOL
2018/10/27	13:12:34.7	53.787	-2.964	2	-0.4		BLACKPOOL,LANCASHIRE	
2018/10/27	11:44:31.1	53.788	-2.963	2	0.0		BLACKPOOL,LANCASHIRE	
2018/10/27	11:07:16.6	53.787	-2.964	2	-0.2		BLACKPOOL,LANCASHIRE	
2018/10/27	10:55:25.2	53.789	-2.963	2	0.8		BLACKPOOL,LANCASHIRE	
2018/10/27	10:47:37.4	53.787	-2.962	2	-0.3		BLACKPOOL,LANCASHIRE	
2018/10/26	20:39:22.7	53.786	-2.966	2	-0.1		BLACKPOOL,LANCASHIRE	
2018/10/26	11:36:58.4	53.787	-2.963	2	0.8		BLACKPOOL,LANCASHIRE	
2018/10/26	11:26:44.6	53.788	-2.964	2	0.2		BLACKPOOL,LANCASHIRE	
2018/10/26	02:13:01.6	53.787	-2.966	2	-0.2		BLACKPOOL,LANCASHIRE	
2018/10/25	17:04:13.3	53.786	-2.963	2	-0.6		BLACKPOOL,LANCASHIRE	
2018/10/25	17:00:33.8	53.787	-2.968	2	-0.1		BLACKPOOL,LANCASHIRE	
2018/10/25	14:59:27.1	53.788	-2.965	2	0.3		BLACKPOOL,LANCASHIRE	
2018/10/24	23:56:12.9	53.783	-2.968	3	0.0		BLACKPOOL,LANCASHIRE	
2018/10/24	20:18:05.6	52.942	-3.911	9	1.3	3	FFESTINIOG,GWYNEDD	FELT FFESTINIOG...
2018/10/24	14:38:30.3	53.785	-2.967	3	0.1		BLACKPOOL,LANCASHIRE	
2018/10/24	13:51:31.5	53.784	-2.970	2	-0.1		BLACKPOOL,LANCASHIRE	
2018/10/24	13:26:26.5	53.784	-2.970	3	0.4		BLACKPOOL,LANCASHIRE	
2018/10/24	13:02:29.3	53.785	-2.971	3	0.5		BLACKPOOL,LANCASHIRE	
2018/10/23	14:45:32.5	53.787	-2.977	3	0.4		BLACKPOOL,LANCASHIRE	
2018/10/23	09:44:57.0	51.971	-2.432	8	0.9		DYMOCK,GLOUCESTERSHIRE	
2018/10/21	14:45:52.7	57.196	-5.252	6	1.0		GLEN MORISTON,HIGHLAND	
2018/10/20	03:44:55.1	51.027	-2.897	2	1.2		CURRY RIVEL,SOMERSET	
2018/10/20	03:44:01.4	53.786	-2.978	3	0.0		BLACKPOOL,LANCASHIRE	
2018/10/19	23:43:44.9	51.178	-0.253	2	-0.4		NEWDIGATE,SURREY	

ENG UK 20:34 08/12/2018

Conclusions

- Science can be applied to the contestable issues in shale gas
- Leakage is a problem in Pennsylvania; not many other places
- Fugitive emissions yet to be quantified accurately
- Fracking has been intermittently been going ahead at Preston New Road





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REVIEW

Shale gas in North America and Europe

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Abstract

According to the U.S. Energy Information Administration, shale gas will provide half of the United States' domestic gas by 2035. The United States has already moved from being one of the world's largest importers of gas to being self-sufficient in less than a decade, bringing hundreds of thousands of jobs and attracting back companies that long ago left America in search of cheap manufacturing costs. But the increase in shale gas extraction has also had an environmental cost. There is clear scientific evidence of leaking shale gas wells and induced earthquakes, and in some areas a population increasingly turning against the industry. The technology of horizontal drilling and hydraulic fracturing that was developed in the United States is now being tried outside the United States, including in Europe, Argentina, and China. There are clear reasons why shale gas might be attractive to Europe. It may offer security of energy supply to some countries particularly dependent on Russian gas; it could stimulate growth and jobs; and it could supply a cleaner fuel than coal in power stations. However, prospective shale often underlies areas of high population density in Europe, and moreover, populations that are unfamiliar with onshore gas operations. The main challenge in Europe therefore is not mainly technological but for the industry to achieve a "social license" and for Government and regulations to be manifestly protecting the public and property.

Introduction

Shale is a fine grained, dark colored sedimentary rock that often contains natural gas (methane) as well as other gases. Its origins lie in mud deposited in sea and lake beds. Most of the mud is made up of stable minerals that are the result of advanced weathering of older rocks, but it also contains (often more than 10% by weight) organic matter that comes from plants growing on nearby land areas, as well as algae and plankton that live in the water column [1]. It is this organic material that, through heating and pressure supplied by deep burial under other later sediments, is converted to oil and gas through a complex series of chemical reactions. The temperature required is between 60°C and 120°C, with gas being formed at the high end of this range, and oil at the low end. Thus, shale can contain oil (known as "shale oil") in certain geological circumstances and gas in others. Shale whose thermal history lies outside the 60–120°C range may not contain any oil or gas [2].

The mineral material that makes up the bulk of shale is very fine and very tightly packed with the result that oil and gas created within the shale cannot readily move within the rock. Unless natural fractures are present, shale will tend to retain its hydrocarbons. This low permeability is the root of the idea of unconventional hydrocarbons, so-called because the oil and gas industry has to resort to new unconventional methods to extract oil and gas. The main advance in the last few decades has been hydraulic fracturing from long horizontal wells that target deep shale layers. Although hydraulic fracturing has been used for decades throughout the world [3], the extent to which the technique is being used now is unprecedented. About

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