

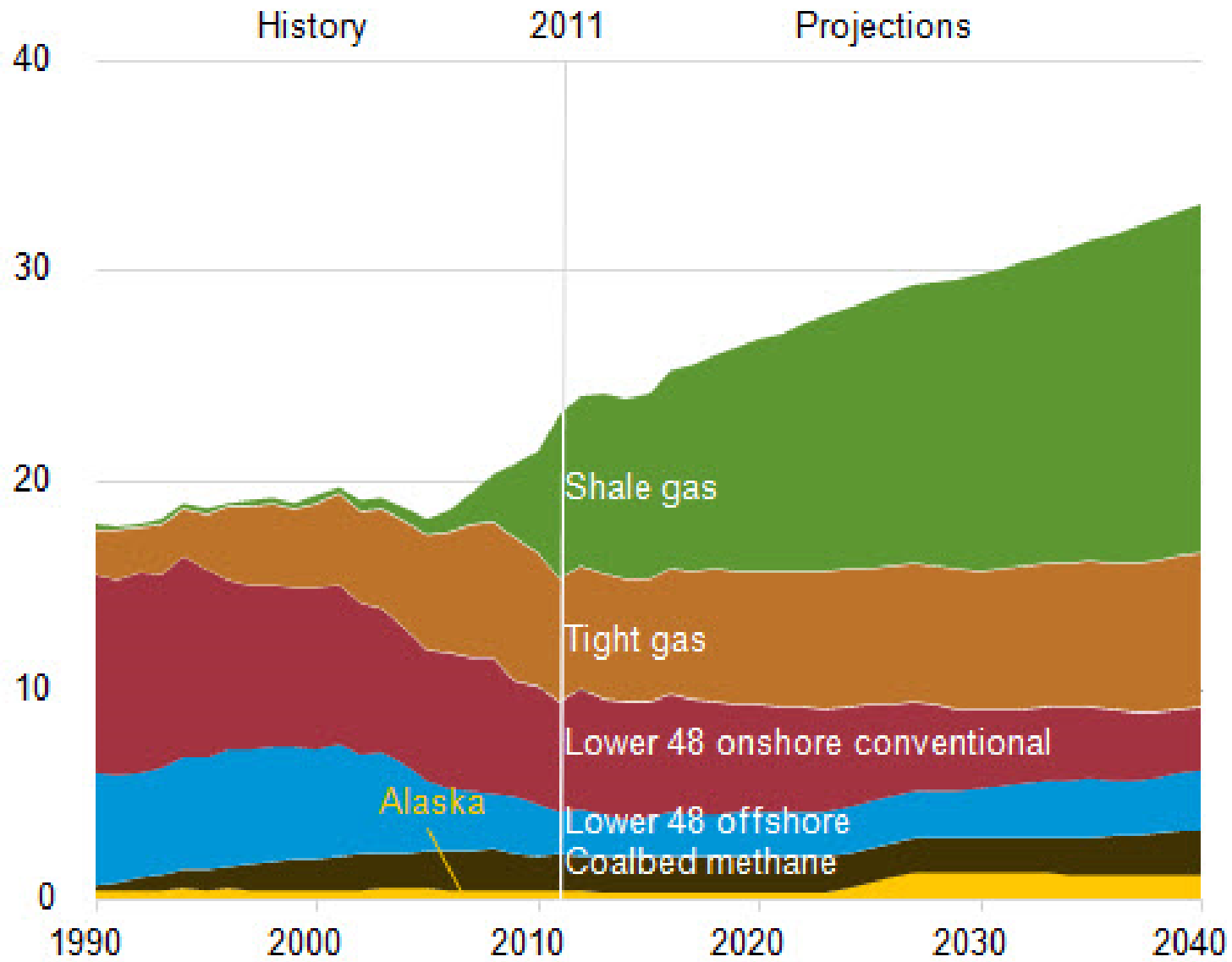


Shale gas : science and controversy

Mike Stephenson
British Geological Survey



Fact



Fact?

Methane in domestic
water supplies from
fracking?

...or natural methane?

GASLAND
THEMOVIE.COM

Do Not Drink
This Water



Fact?

Cracks in a bridge from earthquakes caused by fracking

...or cracks that were already there



Fact?

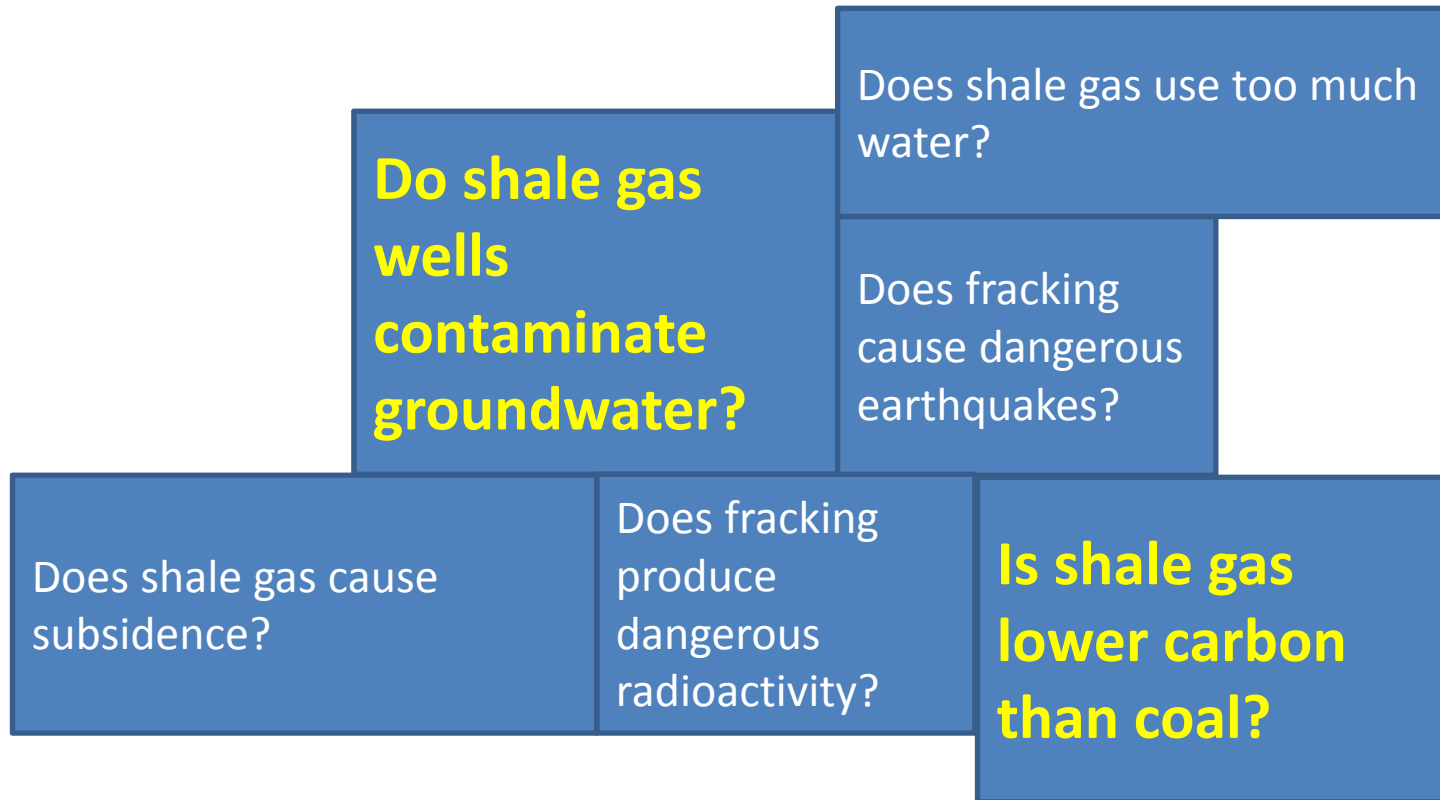


2006 to 2011, CO₂ from fossil fuels declined by 7.7% due to substitution of shale gas for coal in power stations

...but more greenhouse gas emissions due to 'fugitive emissions' of methane associated with fracking?



Contestable areas in shale gas



Shale gas

Peer reviewed science



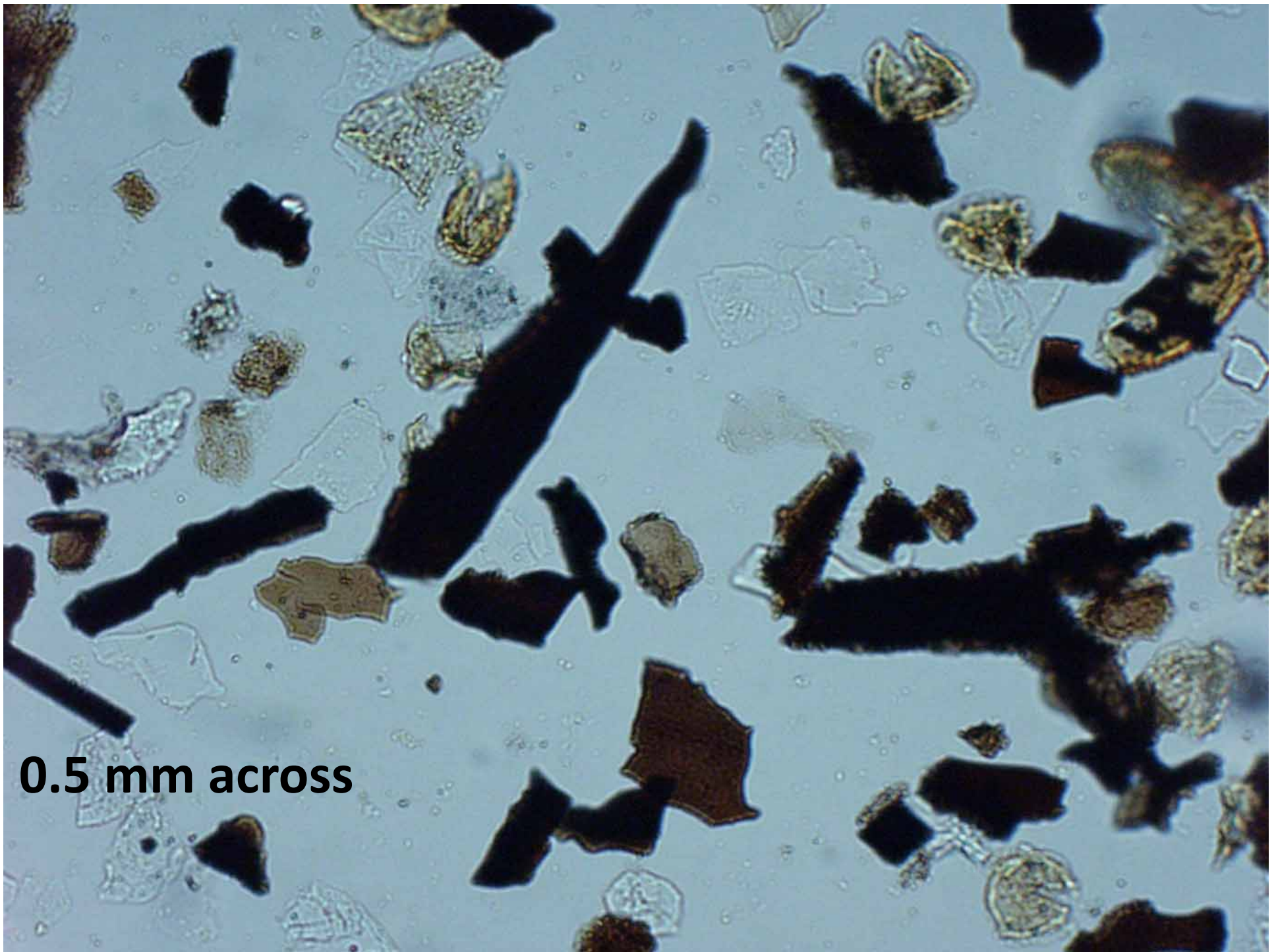
I'm going to show you how the 'science gauge' can be applied to some of these contestable issues.

SOME SHALE AND FRACKING BASICS

Shale

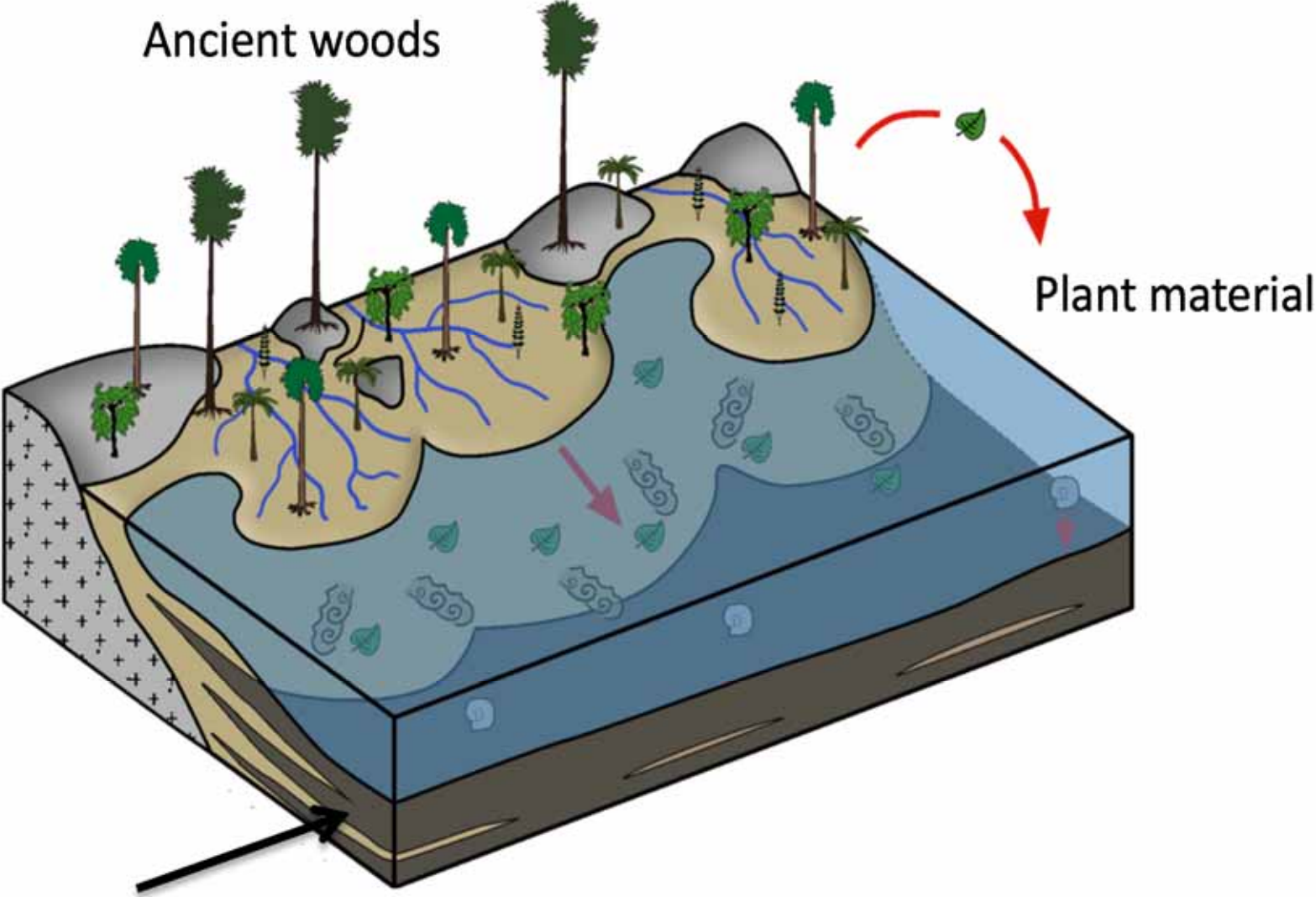


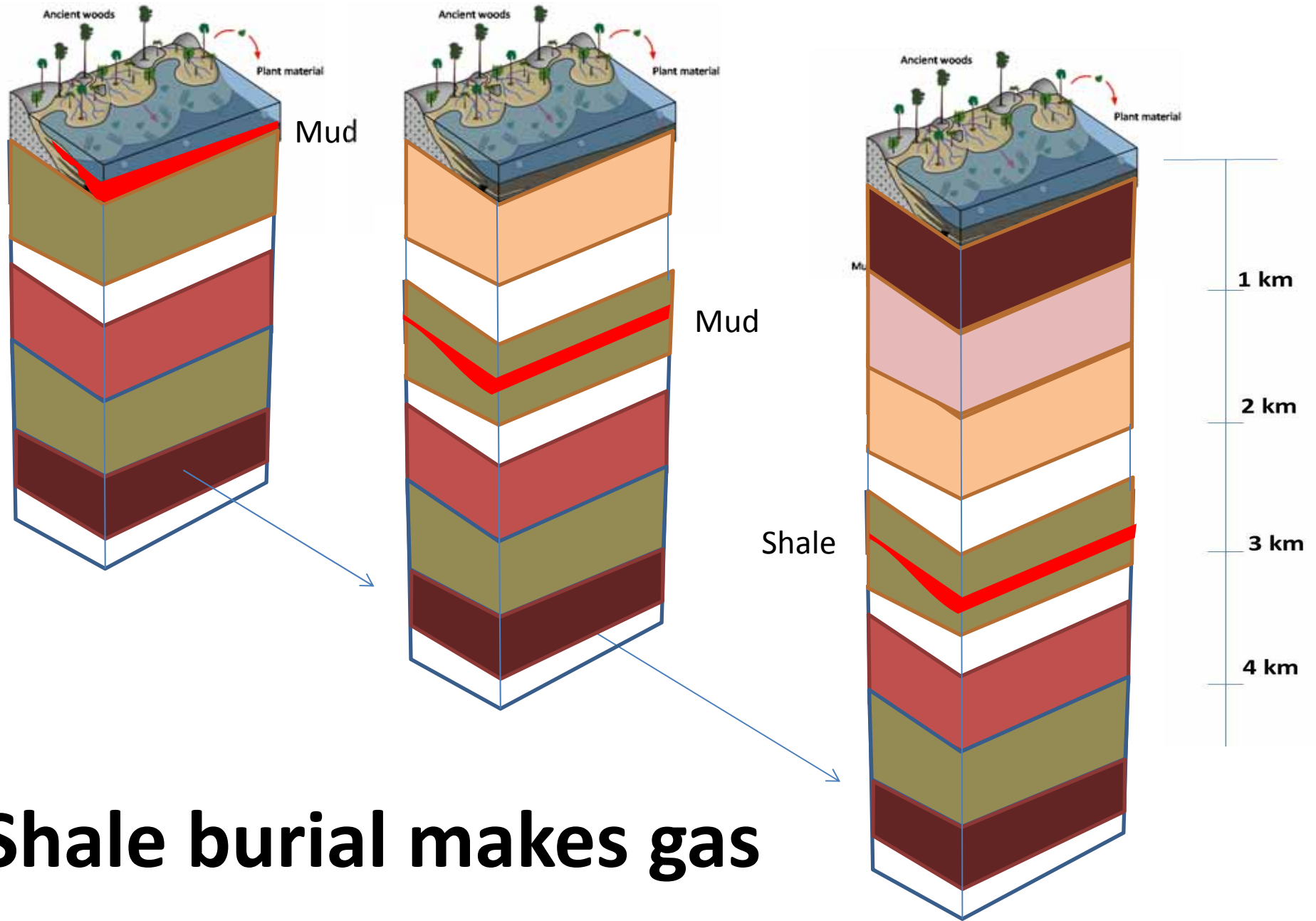
- Grey or black, soft
- Fine grained
- 70% of the world's surface rocks are sedimentary; 50% of those are shale
- Lots of organic matter (up to 10%)



0.5 mm across

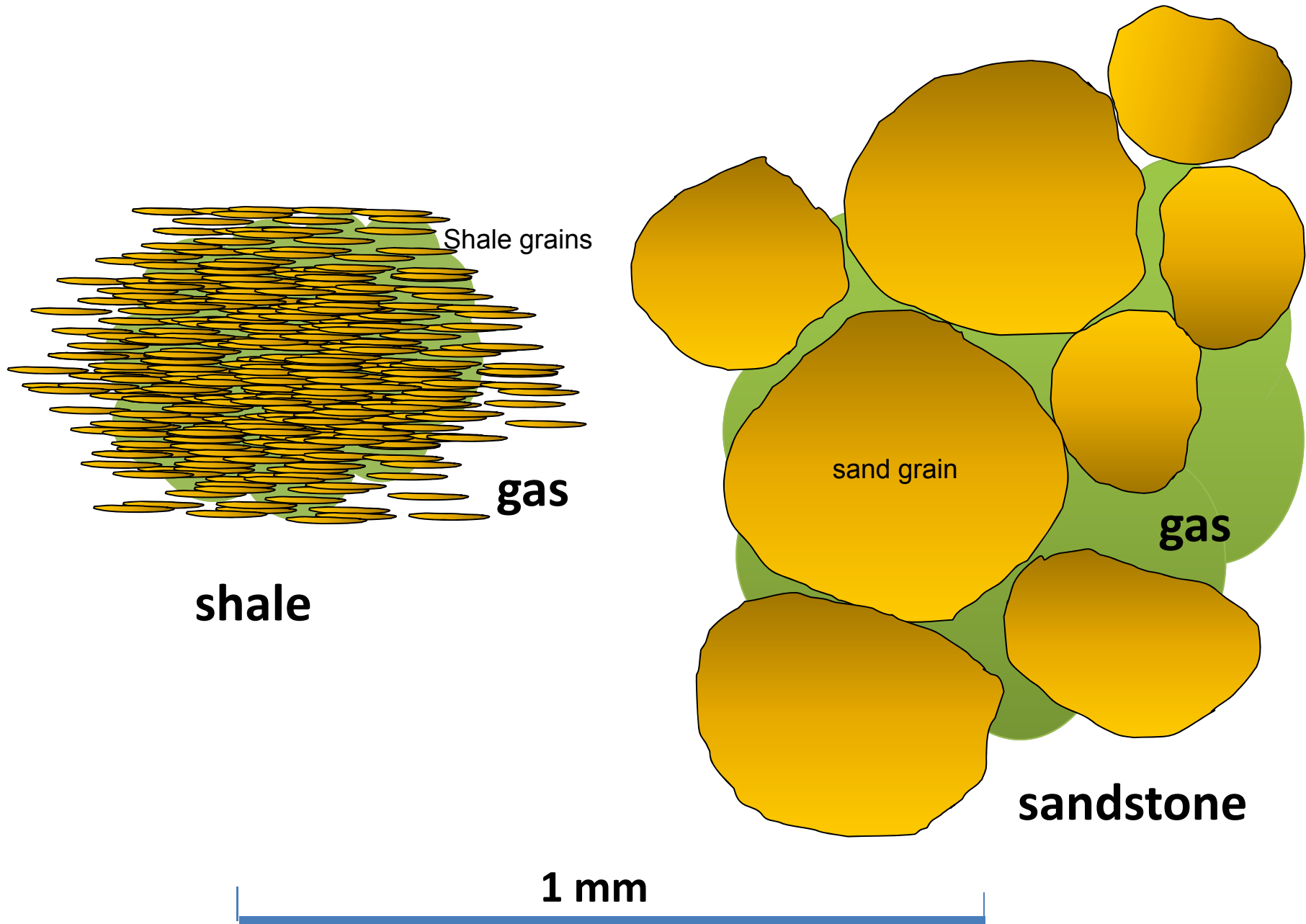
Where the organic matter comes from



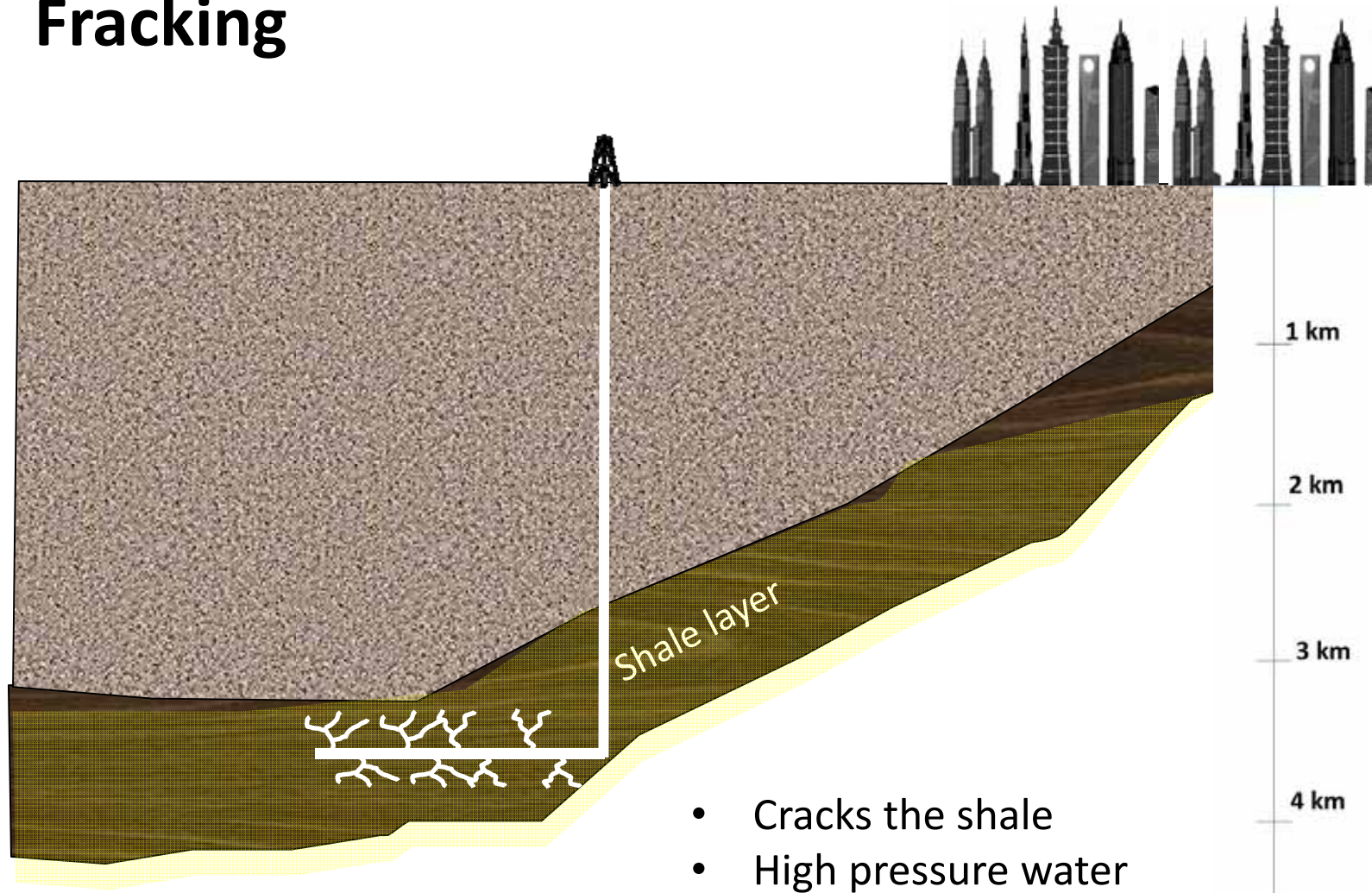


Shale burial makes gas

Gas in sandstone and shale



Fracking



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

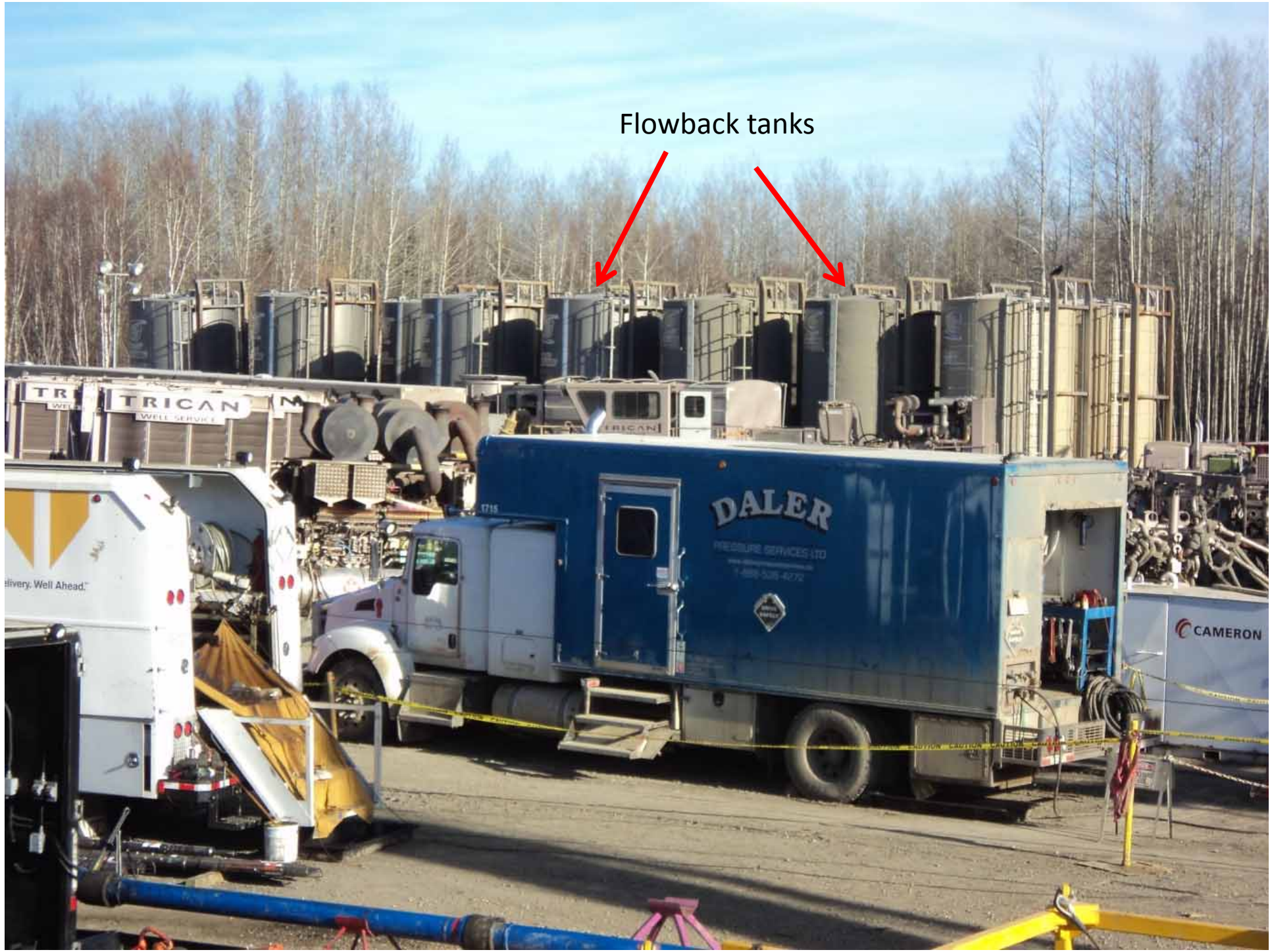
Fracking site in Alberta



Frack trucks

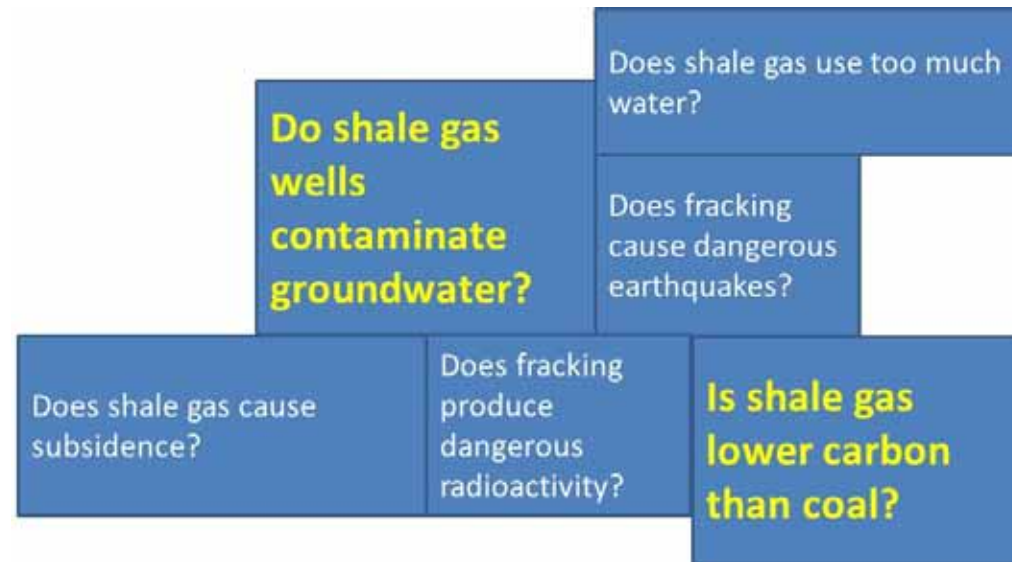


Flowback tanks



Truck carrying proppant

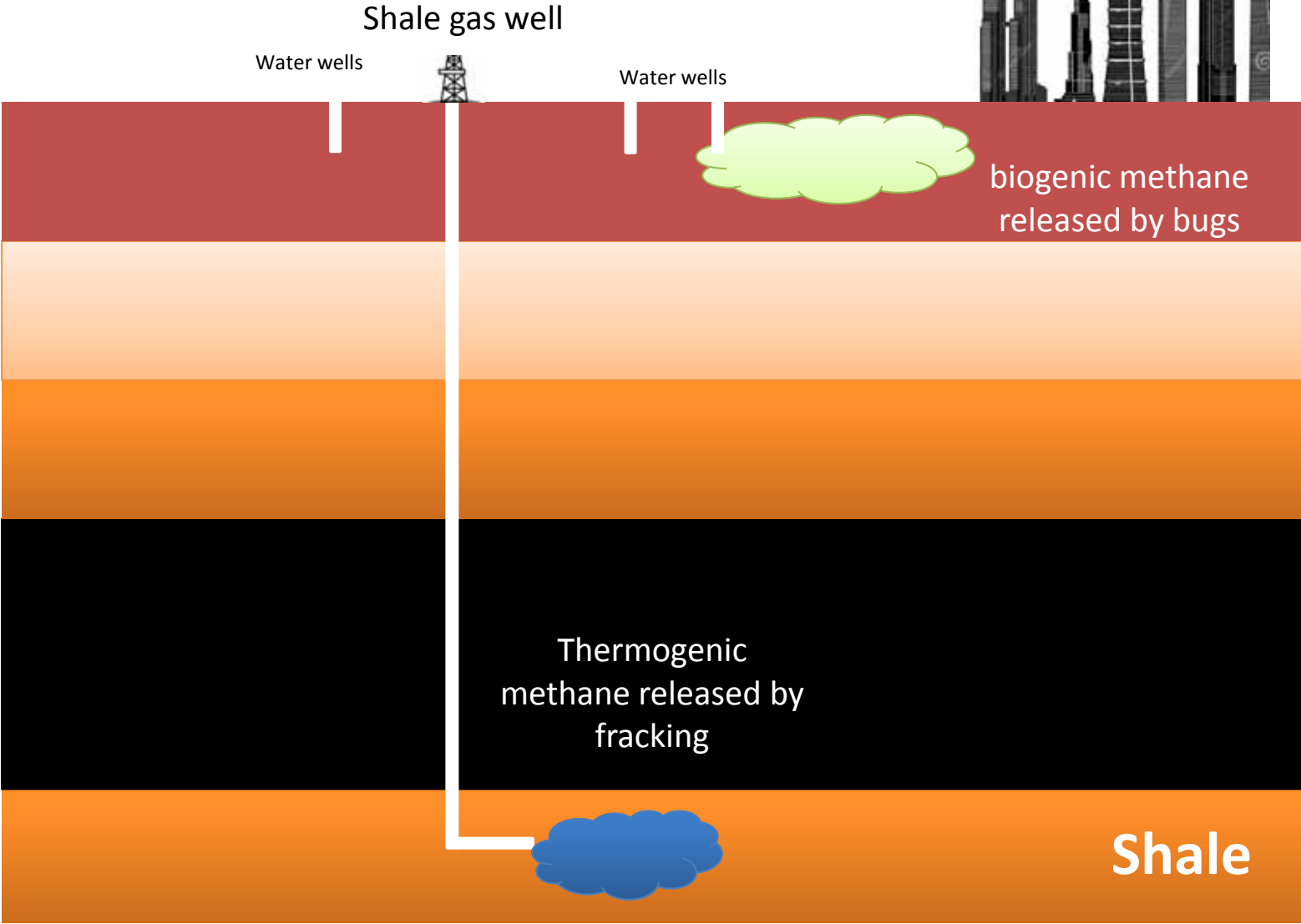




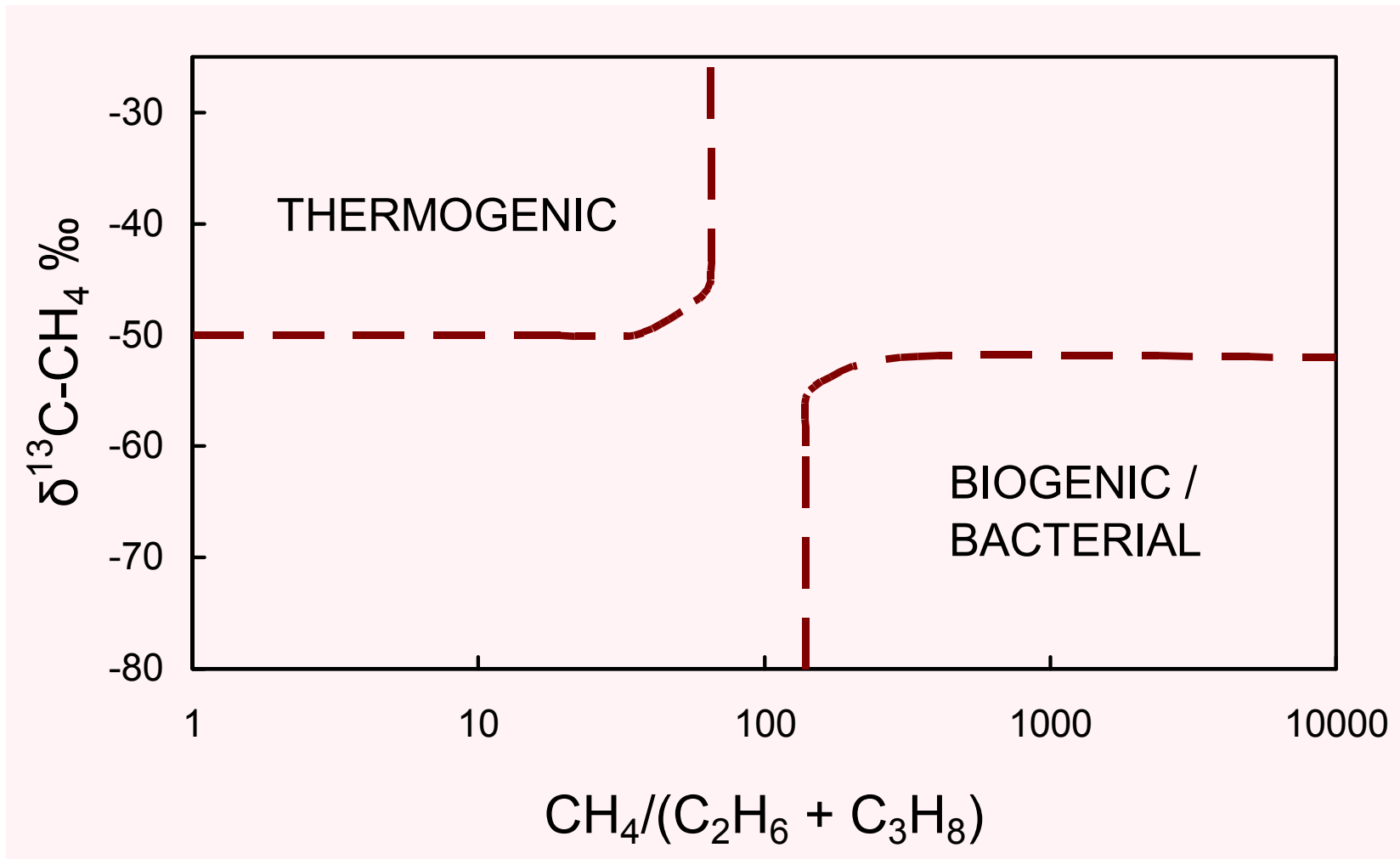
DO SHALE GAS WELLS CONTAMINATE GROUNDWATER?

SOME BASICS

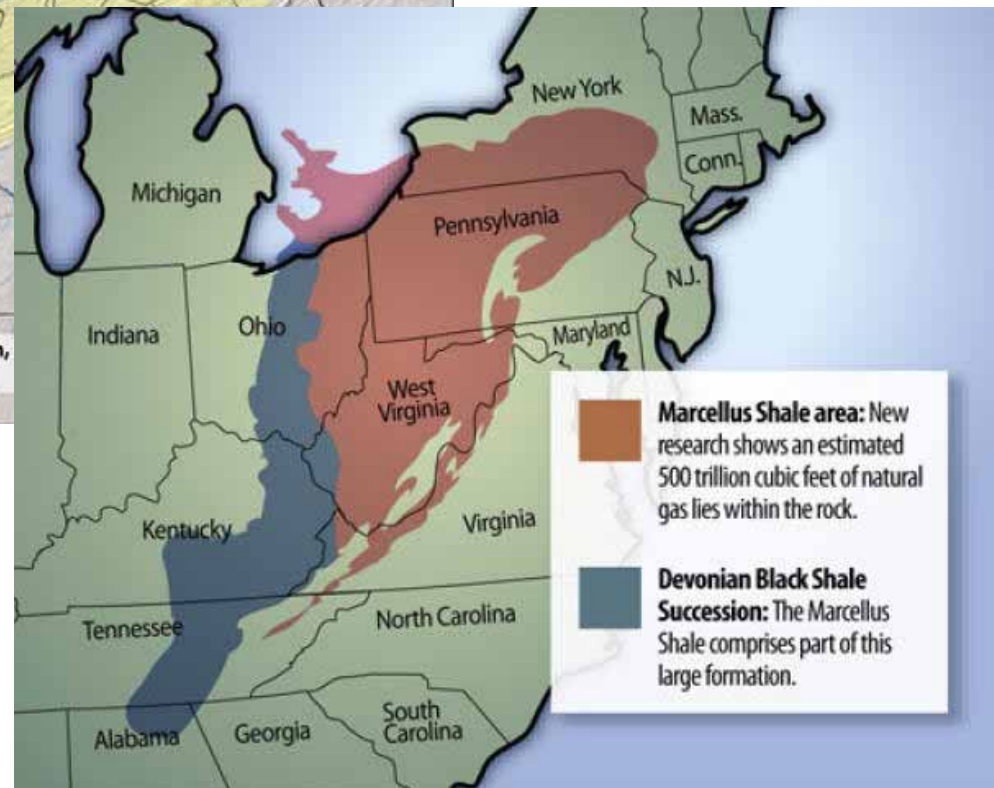
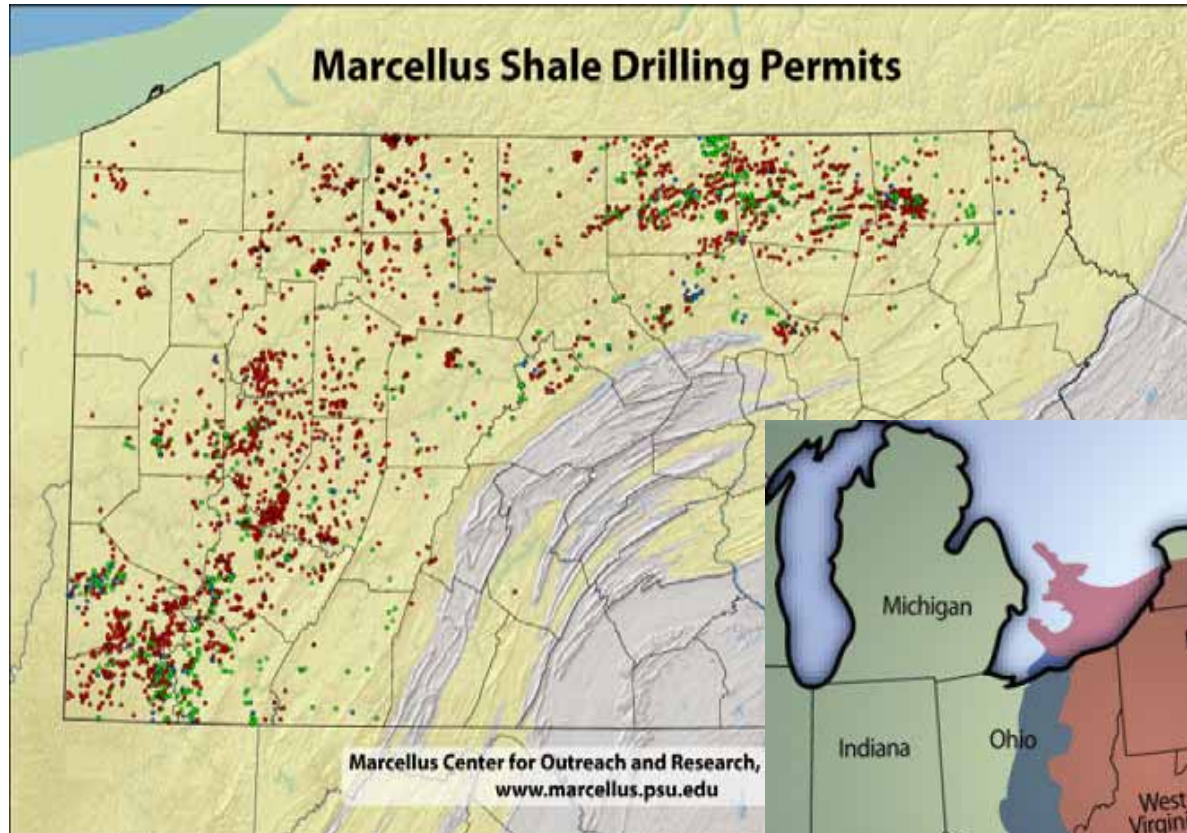
Types of underground methane



Distinguishing biogenic and thermogenic



Marcellus, Pennsylvania



Contamination from fracking?

Osborn et al. 2011, Duke University

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

Stephen G. Osborn¹, Avner Vengosh², Nathaniel R. Warner³, and Robert B. Jackson^{4,5,6}

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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 13.2 and 64 mg CH₄ L⁻¹ (n = 26), a potential explosion hazard; in contrast, dissolved methane samples in neighboring nonextraction sites (no gas well within 1 km) were 1.1 mg L⁻¹ (P < 0.05; n = 30). Average δ¹³C-CH₄ values of dissolved methane in shallow groundwater were significantly less negative for active than for nonactive sites (-37 ± 7‰ and -54 ± 15‰, respectively; P < 0.0001). These δ¹³C-CH₄ data, coupled with the ratio of methane-to-higher-chain hydrocarbons, and δ²H-CH₄ values, are consistent with deeper thermogenic methane sources such as the Marcellus and Utica shales at the active sites and matched gas geochemistry from gas wells nearby. In contrast, lower-concentration samples from shallow groundwater at nonactive sites had isotopic signatures reflecting a more biogenic or mixed biogenic/thermogenic methane source. We found no evidence for contamination of drinking-water samples with deep saline brines or fracturing fluids. We conclude that greater stewardship, data, and—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

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 operation 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, making 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).

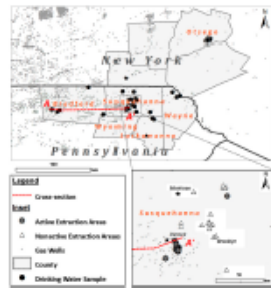


Fig. 1. Map of drilling operations and well-water sampling locations in Pennsylvania and New York. The star represents the location of Binghamton, New York. (Inset) A close-up in Susquehanna County, Pennsylvania, showing areas of active (solid circle) or nonactive (open triangle) extraction. A drinking-water 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 to reach 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.

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 100-m deep in

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

The authors declare no conflict of interest.

*This Direct Submission article had a prearranged editor.

Freely available online through the PNAS open access option.

© 2011 Osborn et al. 0973-8191/11/081004-06\$15.00/0

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1104004108/-/DCSupplemental.

- Measured methane content and δ¹³C
- Higher methane concentrations in water wells close to shale gas wells
- δ¹³C 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. Molofsky¹, John A. Connor², Albert S. Wyllie³, Tom Wagner³, and Shahla K. Farhat²

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

- 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.

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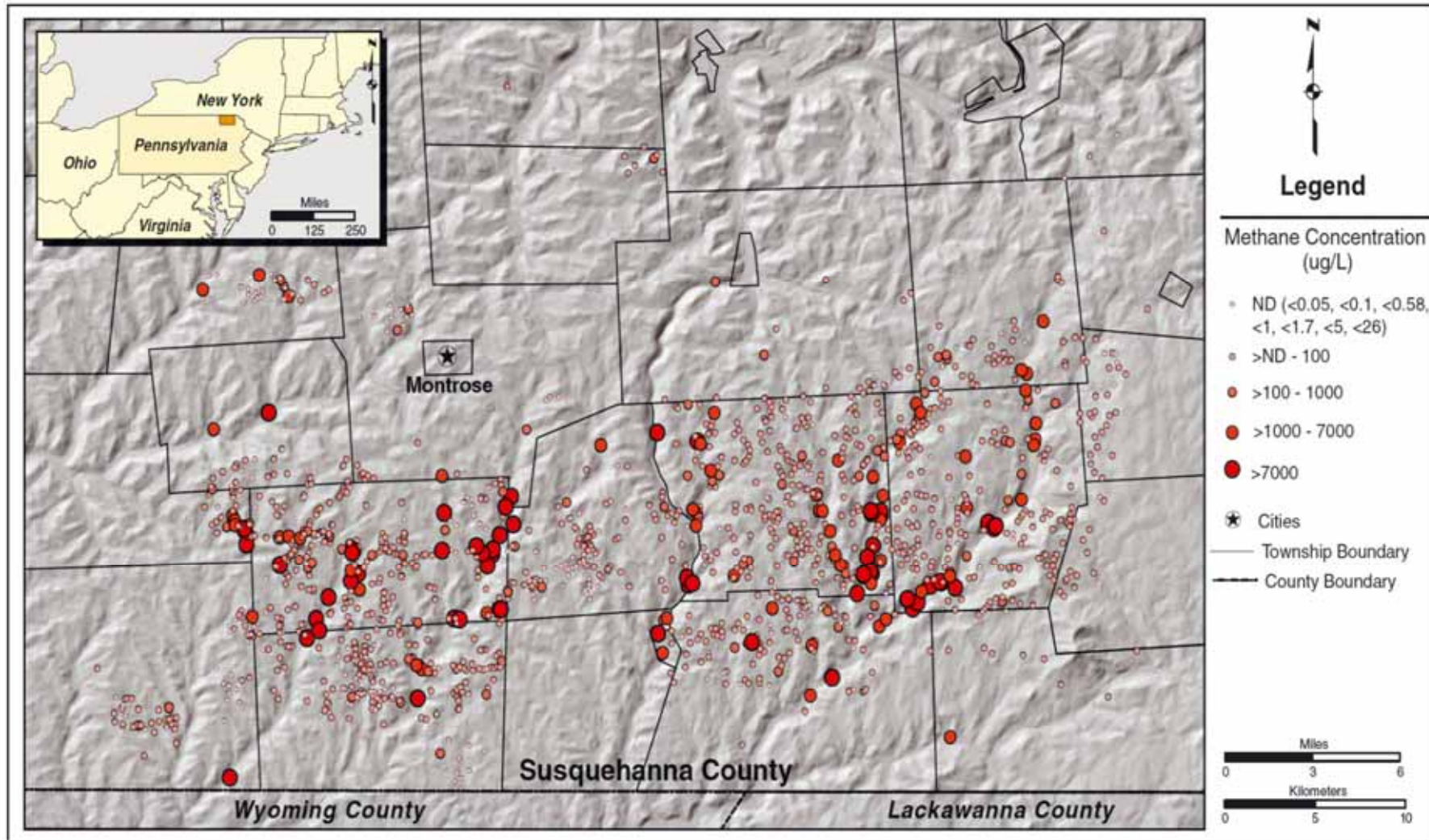
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Groundwater © 2013, National Ground Water Association.

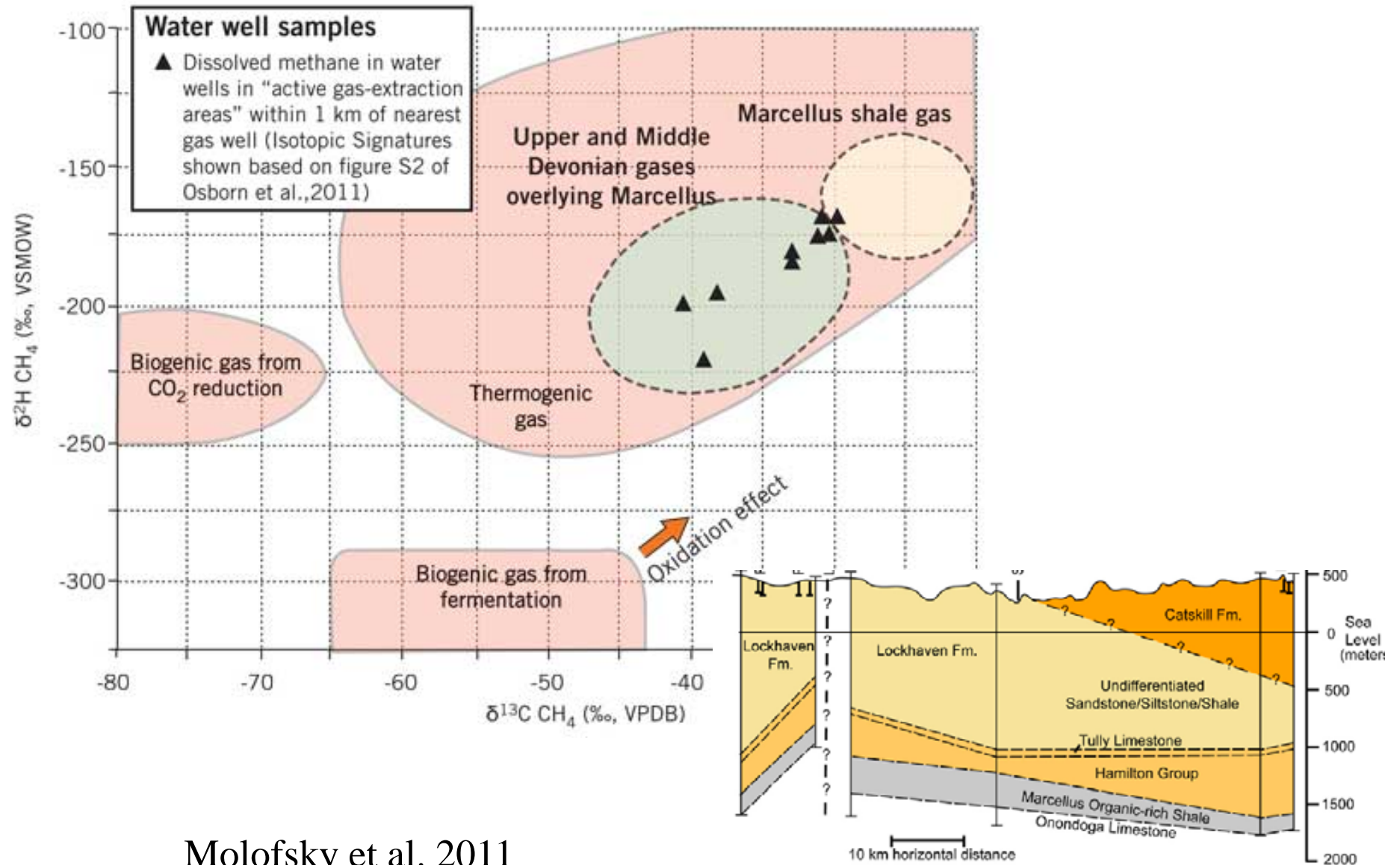
doi: 10.1111/jgwat.12056

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)

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

Robert E. Jackson^{1,2,3}, Arner Vengosh⁴, Thomas H. Darrah⁵, Nathaniel R. Warner⁶, Adrian Down^{1,2}, Robert J. Poreda⁷, Stephen G. Osborn⁸, Kaiqiang Zhao^{1,2}, and Jonathan D. Karst^{1,2}

¹Division of Earth and Ocean Sciences, Nicholas School of the Environment and ²Center on Global Change, Duke University, Durham, NC 27708; ³Department of Earth and Environmental Sciences, University of Rochester, Rochester, NY 14627; and ⁴Geological Sciences Department, California State Polytechnic University, Pomona, CA 91768

Edited by Susan E. Truesdell, Max Planck Institute for Biogeochemistry, Jena, Germany, and approved June 5, 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 ($P = 0.0004$). 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 Propane and Isopentane correlation analyses ($P < 0.01$). For ethane concentrations, distance to gas wells was the only statistically significant factor ($P < 0.005$). Isotopic signatures ($\delta^{13}\text{C-CH}_4$, $\delta^{13}\text{C-C}_2\text{H}_6$, and $\delta^{15}\text{N-CH}_4$), hydrocarbon ratios (methane to ethane and propane), and the ratio of the noble gas ^3He 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 gas.

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 2011, for instance, the daily production of methane (CH_4) in the United States rose to $\sim 2 \times 10^9 \text{ m}^3$, 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 (7), 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 concern 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 $\delta^{13}\text{C-CH}_4$ 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., $\delta^{13}\text{C-CH}_4$, $\delta^{13}\text{C-C}_2\text{H}_6$, $\delta^{13}\text{C-dissolved inorganic carbon}$ ($\delta^{13}\text{C-DIC}$), and $\delta^{15}\text{N-CH}_4$] and helium analysis ($^3\text{He/CH}_4$) 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 141 new drinking water wells from three principal aquifers (Allegheny, 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 41.91207, W 75.866); Susquehanna County) to compare with drinking water from homes in our study, some located within a few kilometers of the seep.

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 $\sim 1,000$ 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 Allegheny aquifer, comprised of unconformated glacial till, alluvium, sediments, and postglacial deposits found primarily in valley bottoms (20, 22).

Author contributions: R.E.J., A.V., T.H.D., N.R.W., and A.D. designed research; R.E.J., A.V., T.H.D., N.R.W., A.D., S.G.O., K.Z., and J.D.K. performed research; R.E.J., A.V., T.H.D., N.R.W., A.D., R.J.P., S.G., and J.D.K. analyzed data; and R.E.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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It is in the public domain in the United States of America.

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1219311110/-DC2.

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^{1,2}, Frank Zeman^{3,4}, G. L. Whitford⁵, D. Yousefian⁶, Paul Orland⁷, Todd Sorenson⁸, R. Shannon-Parker⁹, and Susan L. Brantley¹⁰

Abstract
High-volume hydraulic fracturing (HFV) has revolutionized the oil and gas industry worldwide but has been accompanied by highly environmental incidents of reported water contamination for various groundwater contaminants by three natural gas and surface of brine and other gas drilling-related fluids is known to occur. However, contamination of shallow potable aquifers by HFV at depth has never been fully documented. We investigated a case where Marcellus Shale gas wells in Pennsylvania caused headwater loss of natural gas and hydraulic fracturing fluids to be used for several households. With comprehensive 2D gas flow modeling we traced the flow of light non-halogenated (LNH) gas, an unsaturated complex mixture of organic compounds not identified in the aquifer. Similar signatures were also observed in headwater from Marcellus Shale gas wells. A compound identified as 1,1-dichloro-2,2-difluoroethane (DCE) was also positively identified in one of the flowing drinking water wells at integration gas flow concentrations. The most likely explanation of the incident is that dry natural gas and drilling or HFV components were drawn ~3 m along shallow to intermediate-depth fractures to the surface and at a potable water source. Part of the problem may have been exacerbated from a pit loss reported at the water gas well and the very nearby gas well with more hydraulically fractured before the contamination incident, or leakage of drilling gas and vent fluids that have occurred (2009-2010) origin have disrupted the contaminant source. Salt evaporation would contribute significantly to better management practices at the shale gas industry to avoid incidents.

Significance
Recent drilling and high-volume hydraulic fracturing (HFV) are used to enhance or extract natural gas, condensate, and oil from shale reservoirs in the United States and across the world continent (Liu et al. 2014). In the Marcellus Shale, natural gas wells are drilled to depths of 2000–3000 m, leading to ~2000–3000 m of shale gas production (PAG) that is a variable volume source. This production is attributed to hydraulic fracturing using large volumes of water and sand with relatively small volumes of acids, brines, and other components (Liu et al. 2014). The rate of shale gas development in the northeastern United States has led to several cases of water resource impacts, including surface discharge of condensate or mud as surface gas seepage (Liu et al. 2014). Although little reports of incidents are common, published reports are few (Liu et al. 2014). The most widely cited case is the contamination incident in the natural gas well in a high depth of shale gas wells. This incident is a "multiple lines of evidence" approach (Liu et al. 2014) to generally recognize and integrate geological, hydrological, and geochemical data to trace the flow of natural gas through contamination between gas well and natural gas and groundwater (NG) components of gas well contamination, (1) chemical analysis of hydrological characteristics, and (2) hydrological characteristics.

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^{1,2}, Arun Vengosh^{3,4}, Robert B. Jackson^{5,6}, Nathaniel R. Warner^{7,8}, and Robert J. Foor⁹

Abstract
Noble gas and methane signatures in drinking water wells overlying the Marcellus and Barnett Shales, respectively, suggest hydrocarbon leakage and/or cement degradation. We analyzed 115 and 30 samples from drinking water wells overlying the Marcellus and Barnett Shales, respectively, comparing hydrocarbon and noble gas signatures (e.g., ¹³⁶Xe/¹³⁸Xe, ¹³⁴Xe/¹³⁶Xe, and ¹³⁰Ar/¹³²Ar) and comparing to our knowledge of the natural gas and hydrocarbon levels of hydrocarbon gases in drinking water aquifers near gas wells (natural or anthropogenic) and of fugitive gas contamination events, what mechanisms cause (1) if fugitive gas contamination events, what mechanisms cause (2) if fugitive gas contamination events, and (3) if fugitive gas contamination events, what mechanisms cause (3) if fugitive gas contamination events.

Significance
Noble gas and methane signatures in drinking water wells overlying the Marcellus and Barnett Shales, respectively, suggest hydrocarbon leakage and/or cement degradation. We analyzed 115 and 30 samples from drinking water wells overlying the Marcellus and Barnett Shales, respectively, comparing hydrocarbon and noble gas signatures (e.g., ¹³⁶Xe/¹³⁸Xe, ¹³⁴Xe/¹³⁶Xe, and ¹³⁰Ar/¹³²Ar) and comparing to our knowledge of the natural gas and hydrocarbon levels of hydrocarbon gases in drinking water aquifers near gas wells (natural or anthropogenic) and of fugitive gas contamination events, what mechanisms cause (1) if fugitive gas contamination events, what mechanisms cause (2) if fugitive gas contamination events, and (3) if fugitive gas contamination events, what mechanisms cause (3) if fugitive gas contamination events.

Darrah et al. 2015

- Noble gas, methane and other geochemistry
- Outside shale gas areas
- Diffusion 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^{1,2}, Robert B. Jackson^{3,4}, Arun Vengosh^{5,6}, Nathaniel R. Warner^{7,8}, Colin J. Whyte^{9,10}, Talor B. Wicks^{11,12}, Andrew J. Kondash¹³, Robert J. Foor¹⁴

Abstract
The last decade has seen a dramatic increase in domestic energy production from unconventional resources. This energy boom has generated marked economic benefits, but concurrently created significant concerns regarding the potential for drinking-water contamination in shallow aquifers. Previous efforts to evaluate the environmental impacts of shale gas development in the northern Appalachian Basin (NAB), focused on the northeastern US, are limited by (1) a lack of comprehensive “geo-DB” data for groundwater composition (water and gas), (2) uncertainty in the hydrogeological factors that control the occurrence of naturally occurring gas, and (3) limited geochemical tools available to quantify the water and nitrogen of natural fluids (especially methane or noble gas) in water wells. To address these questions, we study the noble gas, dissolved gas, and hydrocarbon geochemistry of 72 drinking-water wells and one natural methane well of focused on the three shale gas fields in the NAB. In the present study, we consistently analyze groundwater wells from areas near active or recent shale gas development (and also the nearby natural gas well) to assess the impact of shale gas development on shallow aquifers. We also investigate regional-scale shale gas history (including the geological signature and geophysical control of gas-bearing basins) in the study region of the NAB. Our data suggest a prominent relationship between abundant



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

2015



Nowamooz et al. 2015

2015



Birdsell et al. 2015

2014



Flewelling & Sharma 2014

2014



Cai & Ofterdinger 2014

Production will reduce chance of stray gas

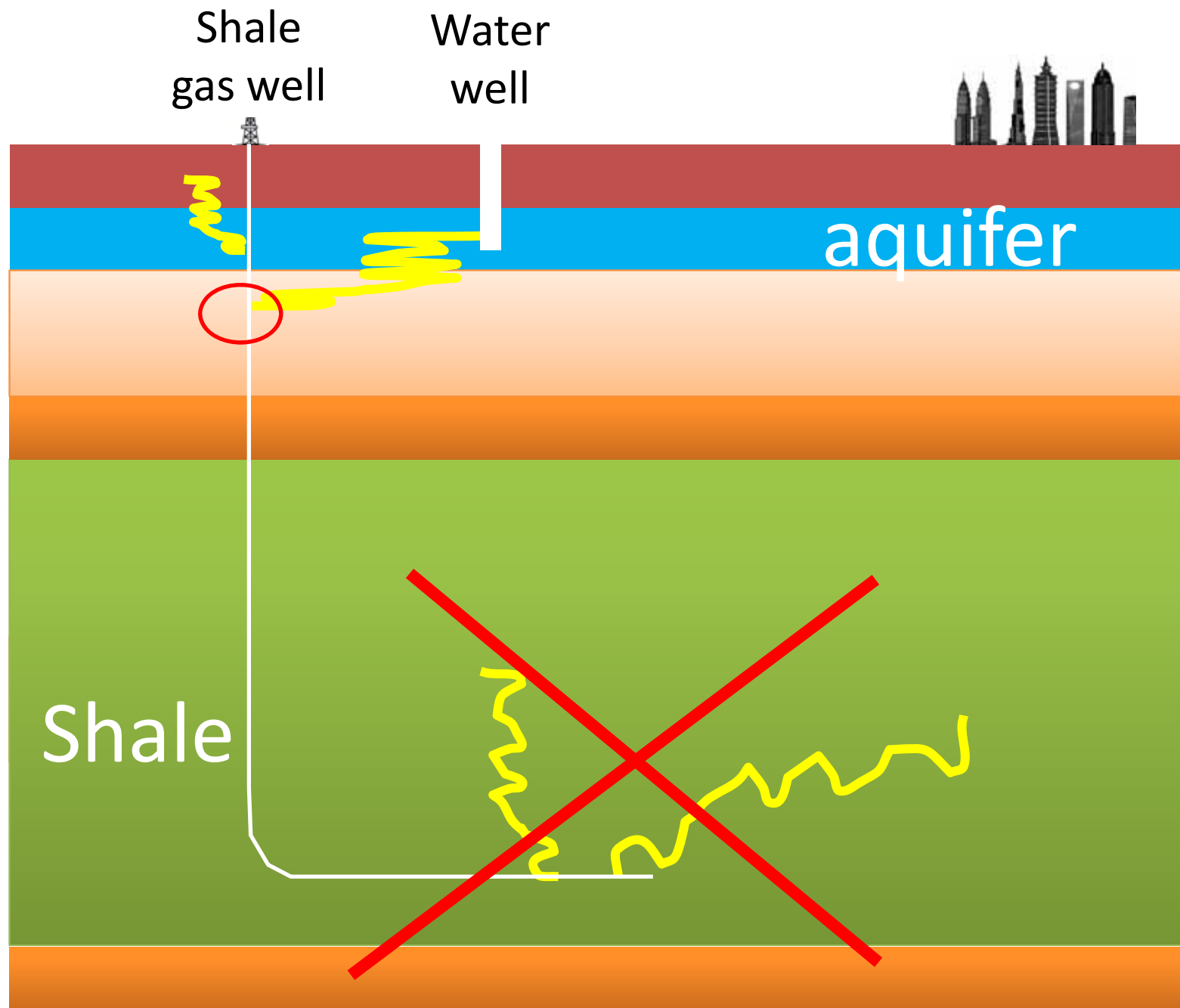
- reduction of free gas
- lowering of reservoir pressure

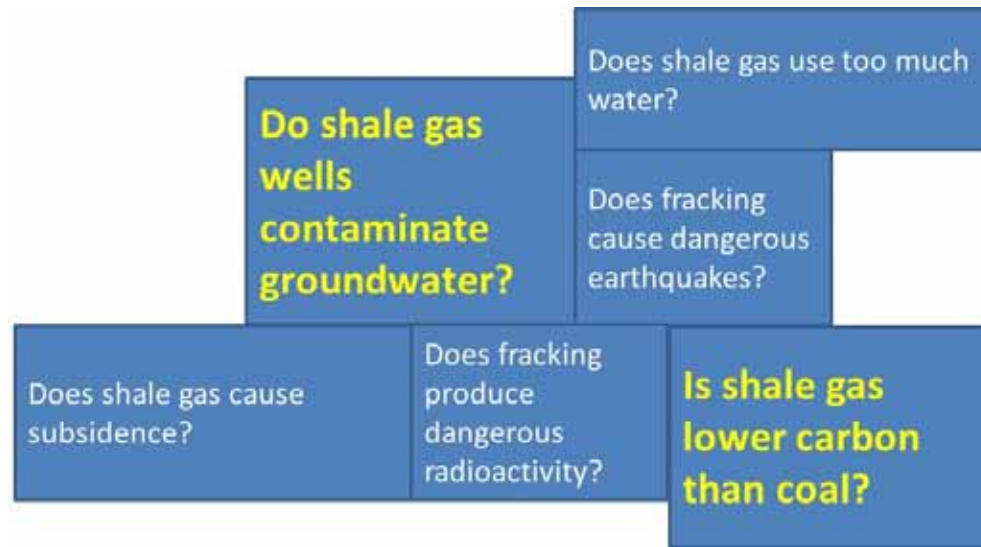
- Modelling hypothetical decommissioned shale gas well
- For the poorest cementation scenario, maximum stray gas within 1 year after well closure.

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

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

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

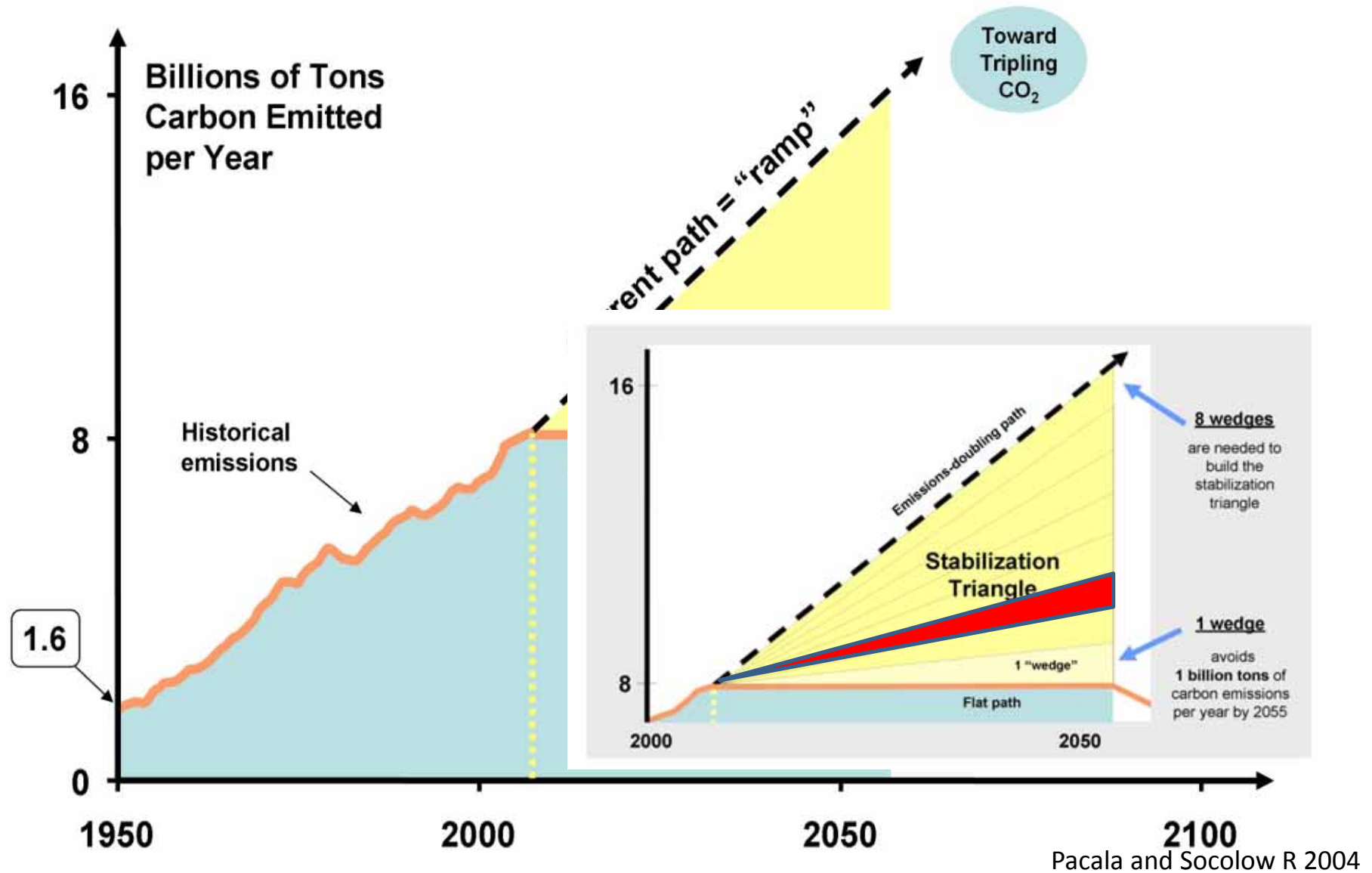




IS SHALE GAS 'LOWER CARBON' THAN COAL?

SOME BASICS

Context



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 CO₂ 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**

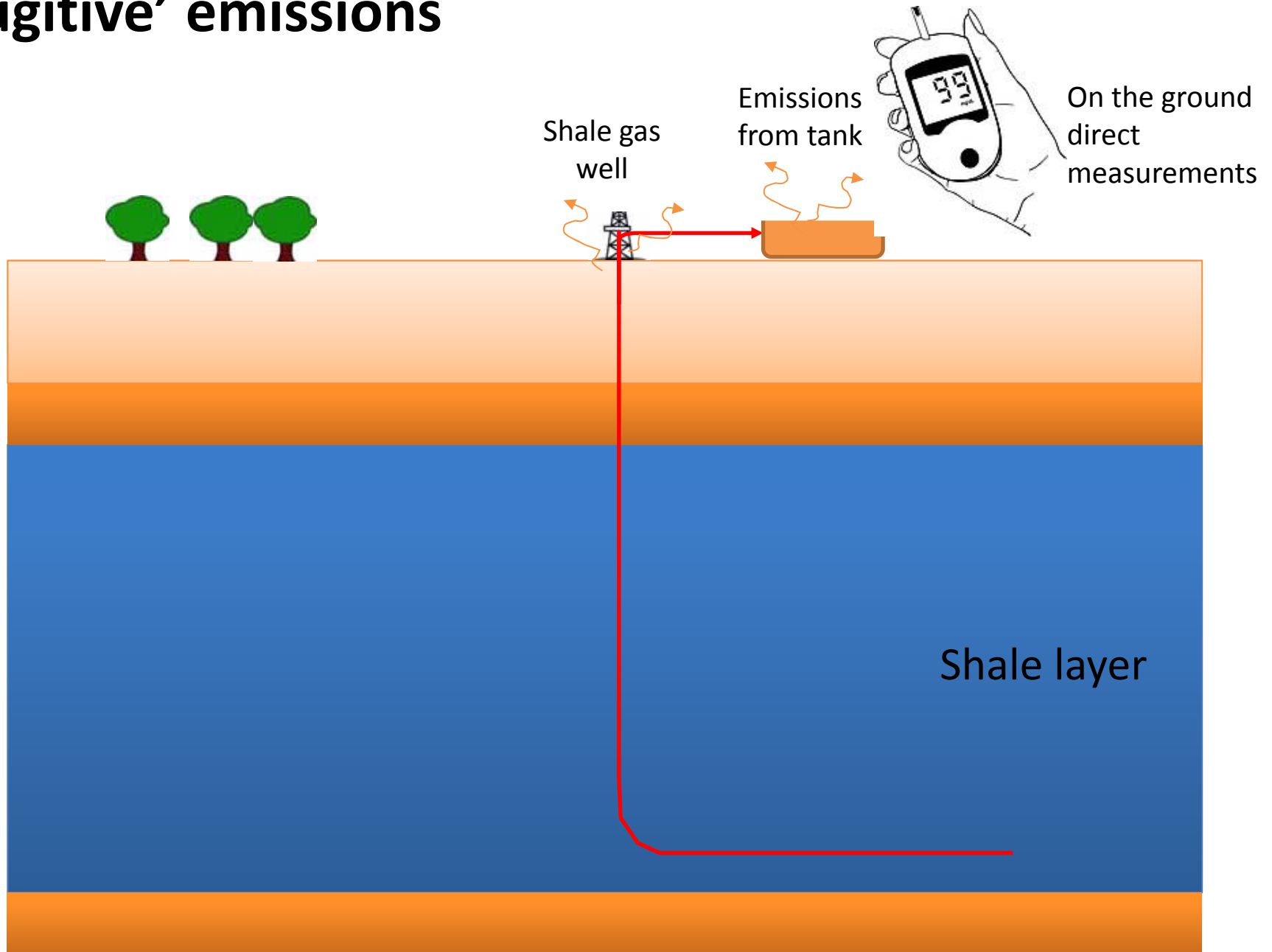


Open flowback tanks



But what about methane?

'Fugitive' emissions



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

A letter

Robert W. Howarth · Renee Santoro ·
Anthony Ingraffea

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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 lifetime 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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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?

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 Tsam · Andrew Hunter

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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 than on energy content, do not adjust for the different residence time and composition of gas and coal, and do not account for the fact that the methane content of gas is half and per cent

Electronic supplementary material
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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^{1,2}, Vincent M. Torres¹, James Thomas¹, David W. Sullivan¹, Matthew Kayeiser¹, Al Hendler¹, Scott C. Howarth¹, Charles E. Kolb¹, Matthew P. Fraser¹, A. David Hill¹, Brian K. Lamb¹, Jennifer Mikolajewicz¹, Robert F. Sparger¹, and John H. Satterfield¹

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Engineering estimates of methane emissions from natural gas production have not kept pace with the rapid expansion of natural gas production. This work reports direct measurements of methane emissions at 190 natural gas production sites in the United States (134 production sites, 17 well completion flowbacks, 4 well shuttings, and 4 workovers). For well completion flowbacks, which clear fractured wells of fluid to allow gas production, methane emissions ranged from 0.07 kg to 1.7 kg (mean = 1.7 kg, 95% confidence interval of 0.63–3.3 kg), compared with an average of 0.1 kg per event in the 2011 EPA national emissions inventory from April 2010. 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 are incorporated into estimates of methane emissions from natural gas production, total annual methane emissions from these source categories are calculated to be 937 Gg of methane (with sampling and measurement uncertainties estimated at ±300 Gg). The estimate for comparable source categories in the EPA national inventory is ~1,200 Gg. Additional measurements of workovers and shuttings are needed to produce national methane estimates for these source categories. The 937 Gg in emissions for completion flowbacks, pneumatic, 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).

Keywords: methane emissions; hydrocarbon venting

Methane is the primary component of natural gas and is also a greenhouse gas (GHG). In the US national greenhouse gas (GHG) inventory for 2012, released by the Environmental Protection Agency (EPA) in April 2013 (1), 2,345 Gg of CH₄ emissions have been attributed to natural gas production activities. These published estimates of CH₄ emissions from the US natural gas industry are primarily based on engineering estimates using well average emission factors developed in the early 1990s (2, 3). During the past two decades, however, natural gas production processes have changed significantly, as the natural gas basins from the 1990s are not their current production. This work presents direct measurements of methane emissions from multiple sources at natural gas production sites in operating operations that have been subject to 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 pressures into low permeability formations. The injection of the fracturing fluids creates channels for flow in the formation either along stable fractures, allowing methane and other hydrocarbon gases and liquids in the formation to migrate to the

www.pnas.org/cgi/doi/10.1073/pnas.1508001112

PNAS Daily Edition • July 14, 2015

Allen et al. 2014 (Uni Texas)

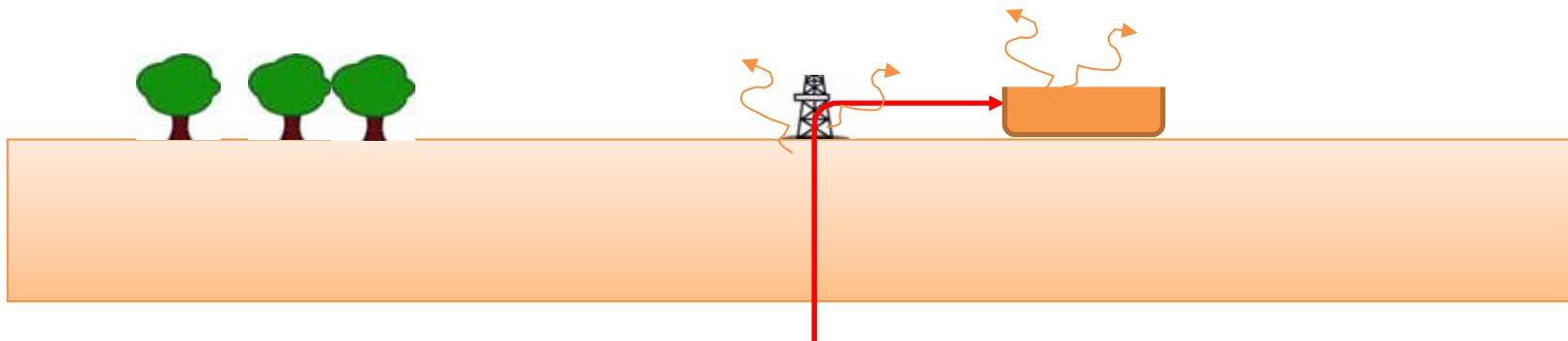
Direct measurement of 190 shale gas sites all over the US

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%



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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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

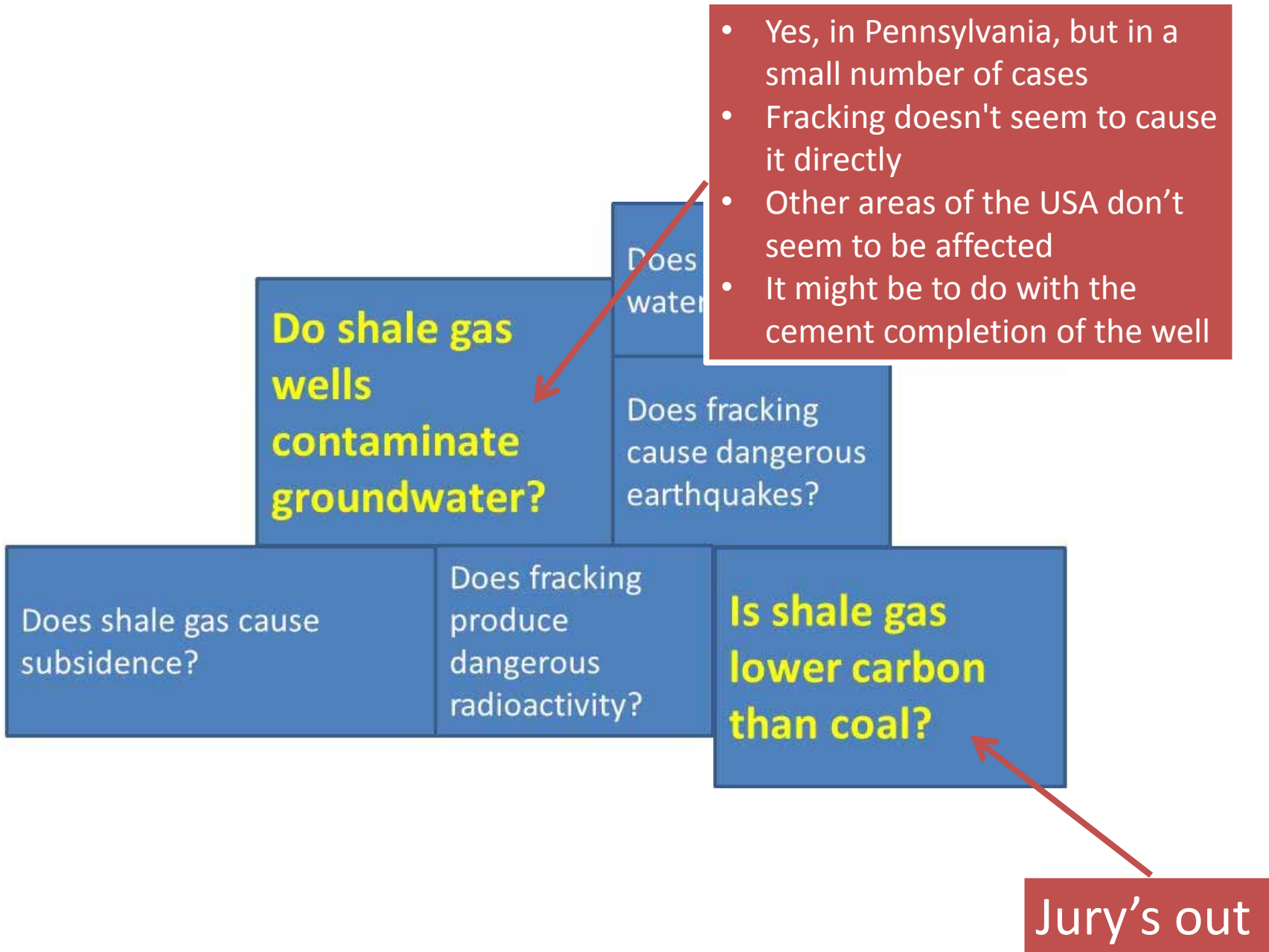
The climatic benefits of switching from coal to natural gas (NG) depend on the magnitude of fugitive emissions of methane (CH_4) from NG production, processing, transmission, and distribution [12, 13, 27]. This is of particular concern as the United States increasingly exploits NG from shale formations: 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 (86x 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



Post truth



MARCH FOR SCIENCE

'Science communicated in popular media leaves the public confused'

In the 'post-truth' world, scientists risk further marginalization in a society that '*...is increasingly weighing evidence and making decisions without them*'.

WORLD VIEW A personal take on events



Give the public the tools to trust scientists

Anita Makri argues that the form of science communicated in popular media leaves the public vulnerable to false certainty.

What is truth? How do we find it and does it still carry weight in public debate? Given recent political events, these are important and urgent questions. But of the two industries I work in that are concerned with truth — science and journalism — only the latter has seriously engaged and looked for answers. Scientists need to catch up, or they risk further marginalization in a society that is increasingly weighing evidence and making decisions without them.

Whereas journalists are debating facts and falsehood, their own role and possible ways to react, scientists seem to see themselves as victims of, rather than active players in, the new political scene. Most debate centres on how the new political order threatens scientific knowledge and research funding, or downgrades climate-change policy.

All are important, but what's overlooked by many is how science is losing its relevance as a source of truth. To reclaim this relevance, scientists, communicators, institutions and funders must work to change the way that socially relevant science is presented to the public. This is not about better media training for researchers. It demands a rethink about the kind of science that we want to communicate to broader society. This message may sound familiar but the new focus on post-truth shows there is now a tangible danger that must be addressed.

Much of the science that the public knows about and admires imparts a sense of wonder and fun about the world, or answers big existential questions. It's in the popularization of physics through the television programmes of physicist Brian Cox and in articles about new fossils and quirky animal behaviour on the websites of newspapers. It is reliable and familiar science: rooted in hypothesis testing, experiments and discovery.

Although this science has its place, it leaves the public (not to mention policymakers) with a different, outdated view to that of scientists of what constitutes science. People expect science to offer authoritative conclusions that correspond to the deterministic model. When there's incomplete information, imperfect knowledge or changing advice — all part and parcel of science — its authority seems to be undermined. We see this in the public debate over food and health: first, fat was bad and now it's sugar. A popular conclusion of that shifting scientific ground is that experts don't know what they're talking about.

But the questions that people face in their lives typically rely on incremental science, a kind that accumulates evidence about complex systems with numerous variables and fuzzy social parameters. It feeds into policy and decisions about how to handle environmental pollution, vaccine safety, emerging infections, drug risks, food choices or the impacts of climate change.

This kind of socially relevant science and discussion of uncertainty does feature in the media, but it is more typical of articles that discuss

the politics and the controversies around it, perhaps under the label of environment or health. This is not about manipulating or persuading the public to accept decisions, but rather providing them with the tools with which to make sense of the evidence, put the uncertainties in perspective and judge for themselves what contribution scientific information makes to truth. Without that capacity, emotions and beliefs that pander to false certainties become more credible.

It's more difficult to talk about science that's inconclusive, ambivalent, incremental and even political — it requires a shift in thinking and it does carry risks. If not communicated carefully, the idea that scientists sometimes don't know can open the door to those who want to contest evidence.

Still, if the public is better equipped to navigate this science, it would restore trust and improve understanding of different verdicts, and perhaps help people to see through some of the fake news that circulates on scientific matters. Lifting the lid on these realities about socially relevant science is mostly about changing the content and framing of what's being communicated. And it could be encouraged by targeting various points of contact between science and the public. Public-engagement programmes of research, educational or cultural institutions are an obvious option. Closer links between educators, communicators and scientists can also strengthen how socially relevant science is represented in articles and curricula. Wider trends aren't incentivizing this sort of science story. So the push will need to come from science first. For example, science academies could offer more grants to support more sophisticated journalism.

Scientists can influence what's being presented by articulating how this kind of science works when they talk to journalists, or when they advise on policy and communication projects. It's difficult to do, because it challenges the position of science as a singular guide to decision making, and because it involves owning up to not having all of the answers all the time while still maintaining a sense of authority. But done carefully, transparency will help more than harm. It will aid the restoration of trust, and clarify the role of science as a guide.

Current debates about truth are far from trivial. More scientists and communicators of science need to get involved, update practices and reposition themselves in a way that gets with the times and shows that science matters — while it still does. ■

Anita Makri is a freelance writer, editor and producer, on the advisory board of the Global Health Film Initiative and a member with the New York Academy of Sciences.
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SCIENTISTS MUST WORK TO CHANGE THE WAY THAT SOCIALLY RELEVANT SCIENCE IS PRESENTED TO THE PUBLIC.

'Sense of wonder science'

'...imparts a sense of wonder and fun about the world, or answers big existential questions. It's in the popularization of physics through the television programmes of physicist Brian Cox and in articles about new fossils and quirky animal behaviour on the websites of newspapers. It is sellable and familiar science...'



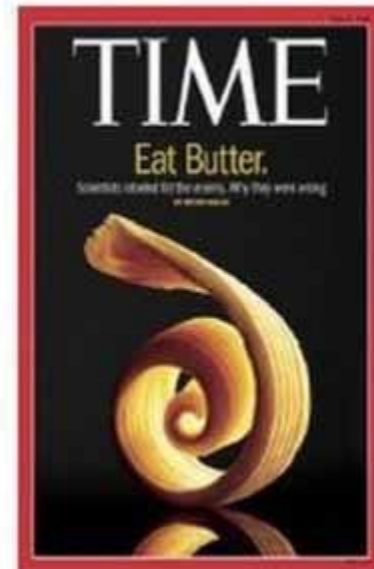
'...sellable and familiar...'

'...first, fat was bad and now it's sugar...'

Does
'sense of wonder science'
makes it **harder** for applied
scientists who work in the
area of socially-relevant
'incremental' science

*'It's more difficult to talk
about science that's
inconclusive, ambivalent,
incremental and even
political*

*If not communicated
carefully, the idea that
scientists sometimes 'don't
know' can open the door to
those who want to contest
evidence.'*



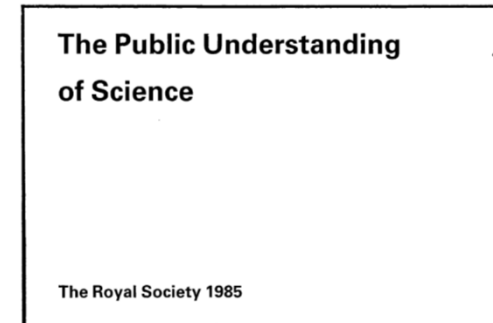
The 'deficit model' of science communication

Royal Society 1985 – 'The Public Understanding of Science'

the public doesn't believe or care much about science because they aren't being told about it efficiently enough

Social scientists who study communication, believe that scientists worry far too much about the words they use and the diagrams they show, and too little about finding out about how their public or 'publics' think or feel.

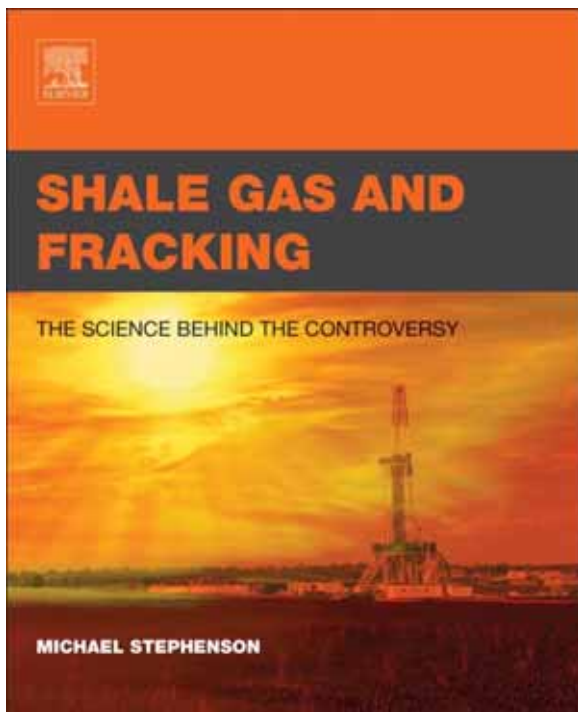
Social scientist Ruth Dixon says that academics need '*...to question, with some humility, their own 'deficit model' of the public understanding of politics*', and try to empathise a bit with our chosen public.



Conclusions

- Science can be applied to the contestable issues in shale gas
- Science is important to society and not just big telescopes and synchrotrons!
- But when we talk about it to the public we should use our (emotional) intelligence!





Free summary paper

Energy Science & Engineering

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REVIEW

Shale gas in North America and Europe

Michael H. Stephenson

British Geological Survey, Nottingham NG12 0GG, United Kingdom

Keywords

Europe, environment, hydraulic fracturing, shale gas

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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 to 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 linking 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 diverse fuel that could be used in power stations. However, prospective shale often underlies areas of high population density in Europe, and numerous populations that are unfamiliar with industrial 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 regulators to be steadfastly protecting the public and property.

Introduction

Shale is a fine grained, dark colored sedimentary rock that often contains dissolved gas (methane) as well as other gases. Its origin lies 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 glauconite 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 40°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 40–120°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. The 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