Shale Gas Production via Hydraulic Fracturing

AOSC 433/633 & CHEM 433

Ross Salawitch

Class Web Site: http://www.atmos.umd.edu/~rjs/class/spr2015

- Overview of shale gas production via horizontal drilling and hydraulic fracturing (aka fracking)
- Concerns about shale gas production:
  - Earthquakes
  - Contamination of ground water
  - Air quality (surface O_3 precursors and $PM_{2.5}$)
  - Climate (fugitive release of CH_4)

Lecture 21

30 April 2015

Hydraulic Fracturing

- Pumping of chemical brine to loosen deposits of natural gas from shale
- Extraction of CH_4 from shale gas became commercially viable in 2002/2003 when two mature technologies were combined: horizontal drilling and hydraulic fracturing
- High-pressure fluid is injected into bore of the well at a pressure that fractures the rock

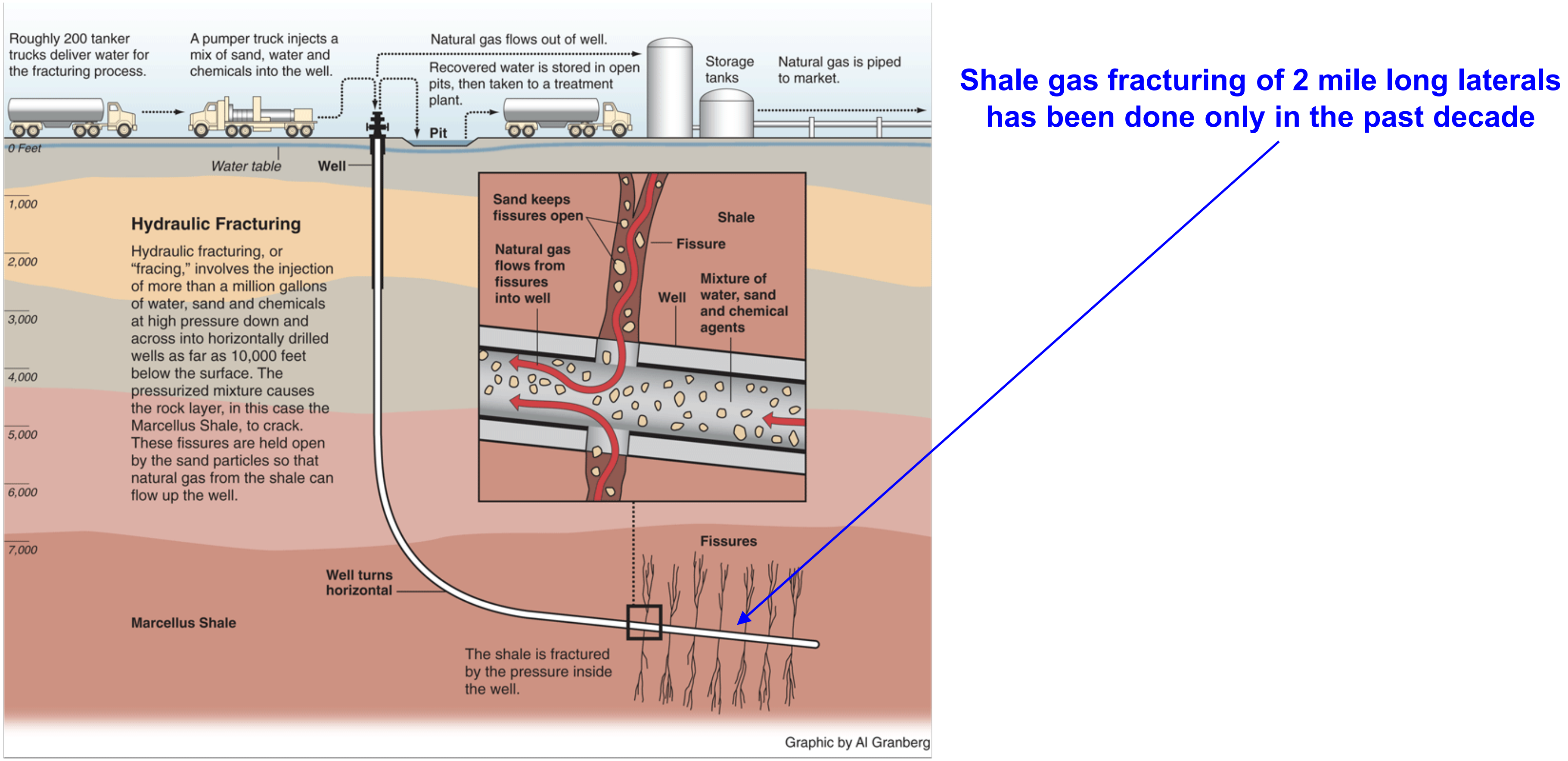
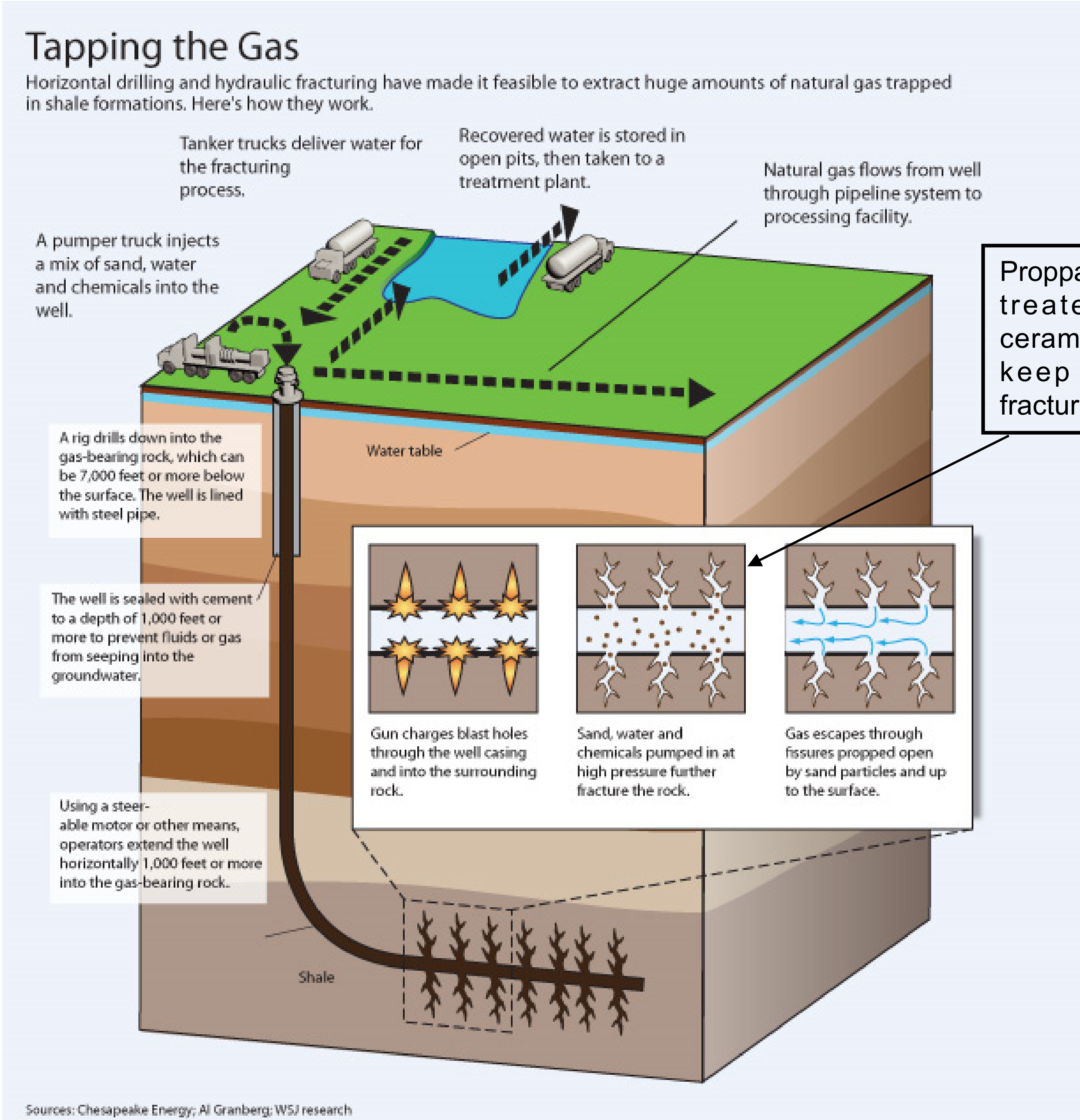


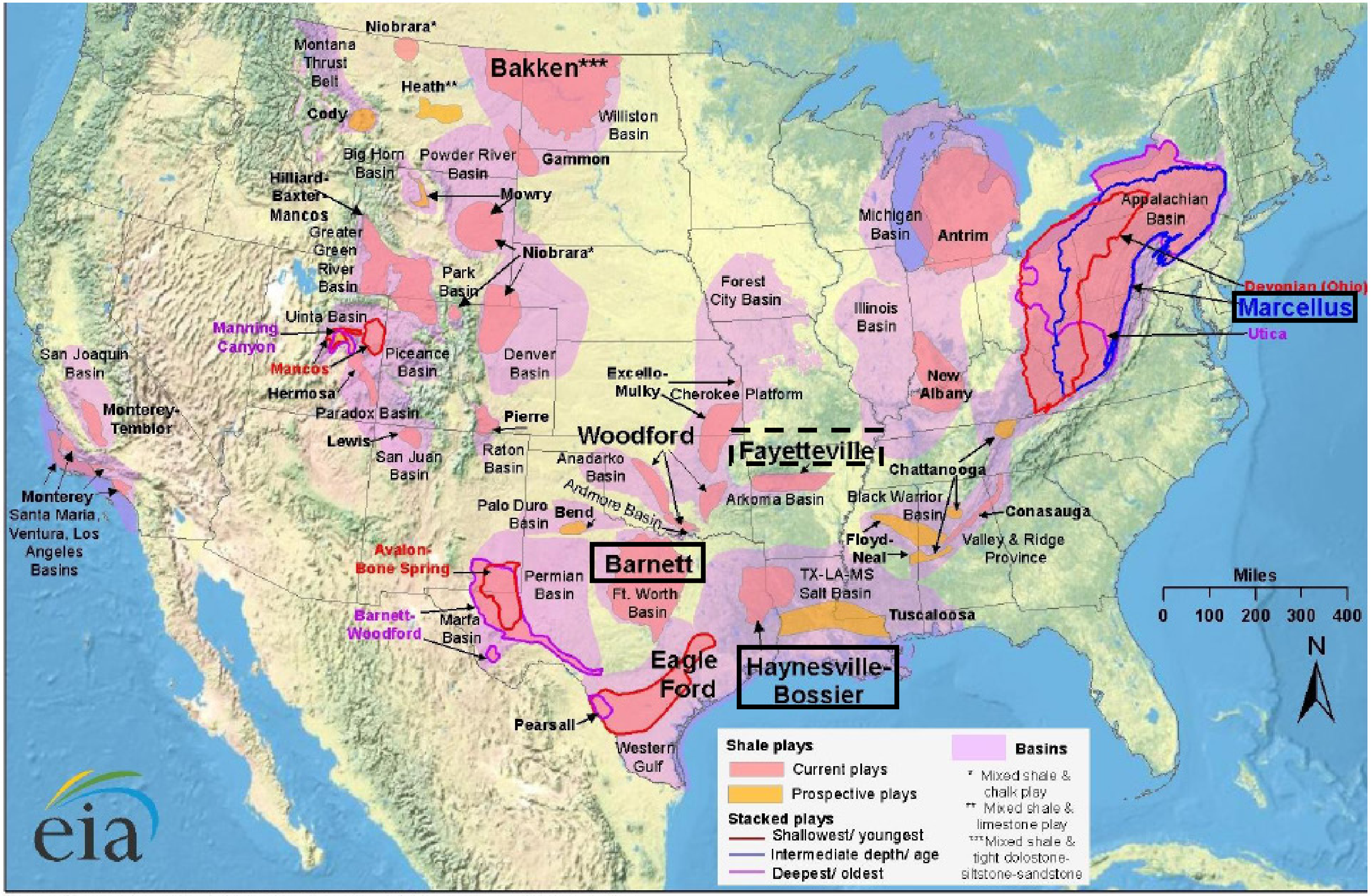
Image: http://www.propublica.org/images/articles/natural_gas/marcellus_hydraulic_graphic_090514.gif



Proppant: solid material, typically treated sand or man-made ceramic materials, designed to keep an induced hydraulic fracture open

Image: http://online.wsj.com/article/SB10001424052702303491304575187880596301668.html

Lower 48 Hydraulic Fracturing Geography



Source: Energy Information Administration based on data from various published studies.
Updated: May 9, 2011

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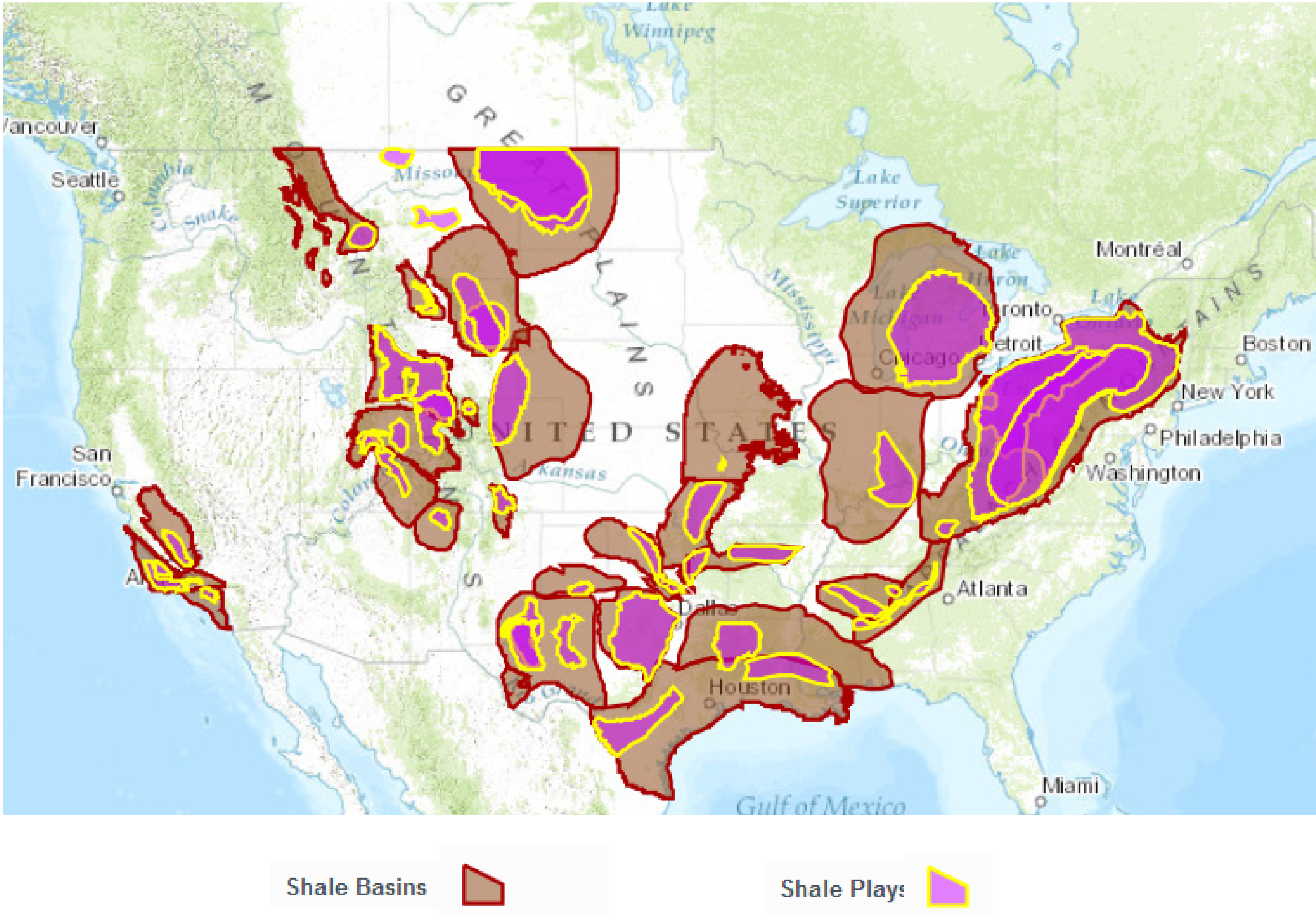
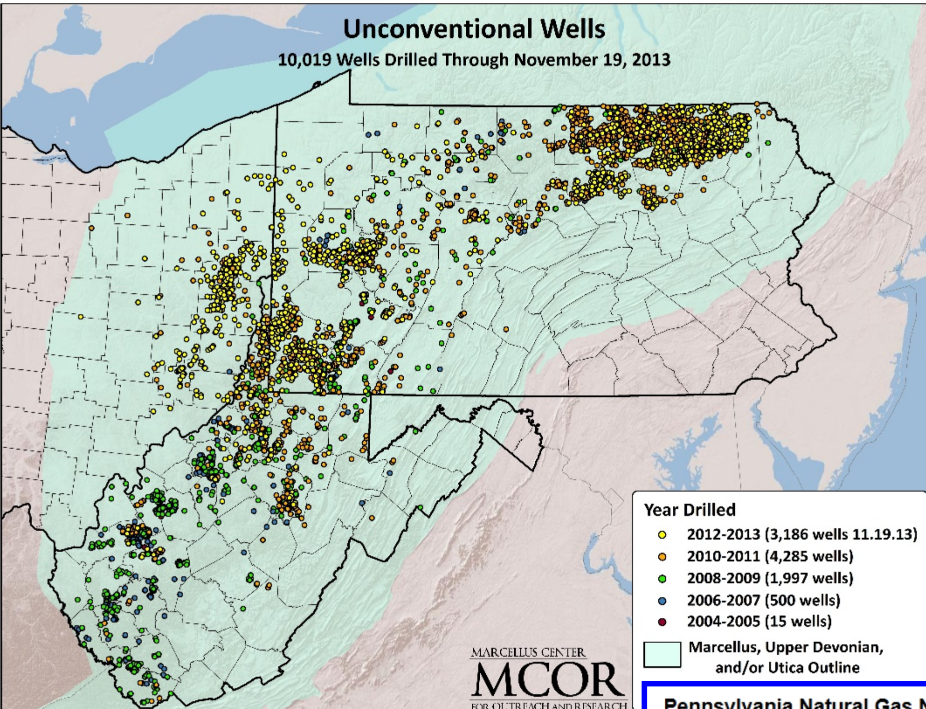
http://photos.state.gov/libraries/usoecd/19452/pdfs/DrNewell-EIA-Administrator-Shale-Gas-Presentation-June212011.pdf

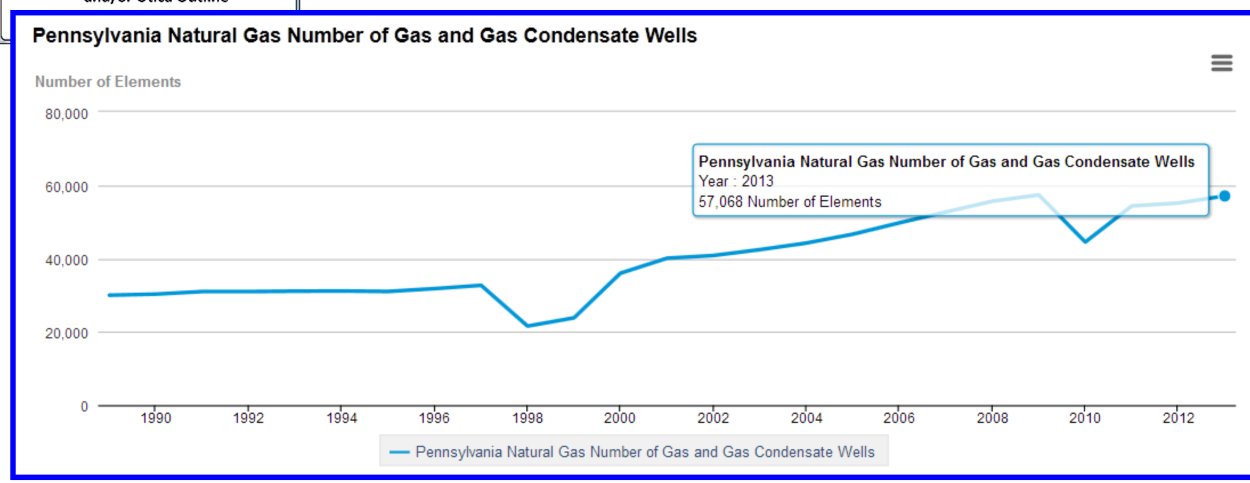
US Fracking Map: 29 April 2015 Update



http://maps.fractracker.org/latest/?webmap=b26c43968bf8435388cbd4b33f2c4b3d

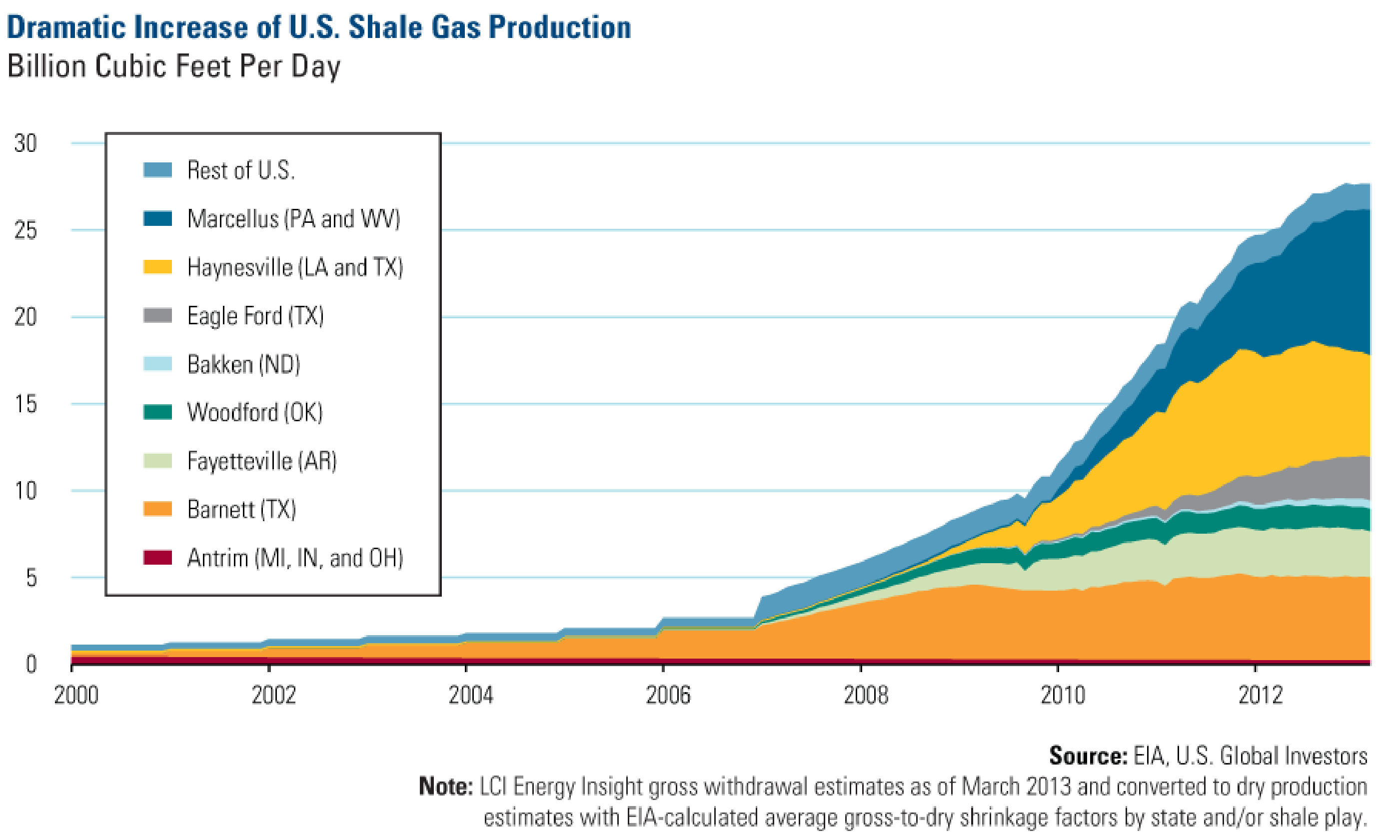
Pa Active Natural Gas Production





Map: http://www.marcellus.psu.edu/images/Spud%20Map%20All%2011.19.13.jpg
Chart: http://www.eia.gov/dnav/ng/hist/na1170_spa_8a.htm

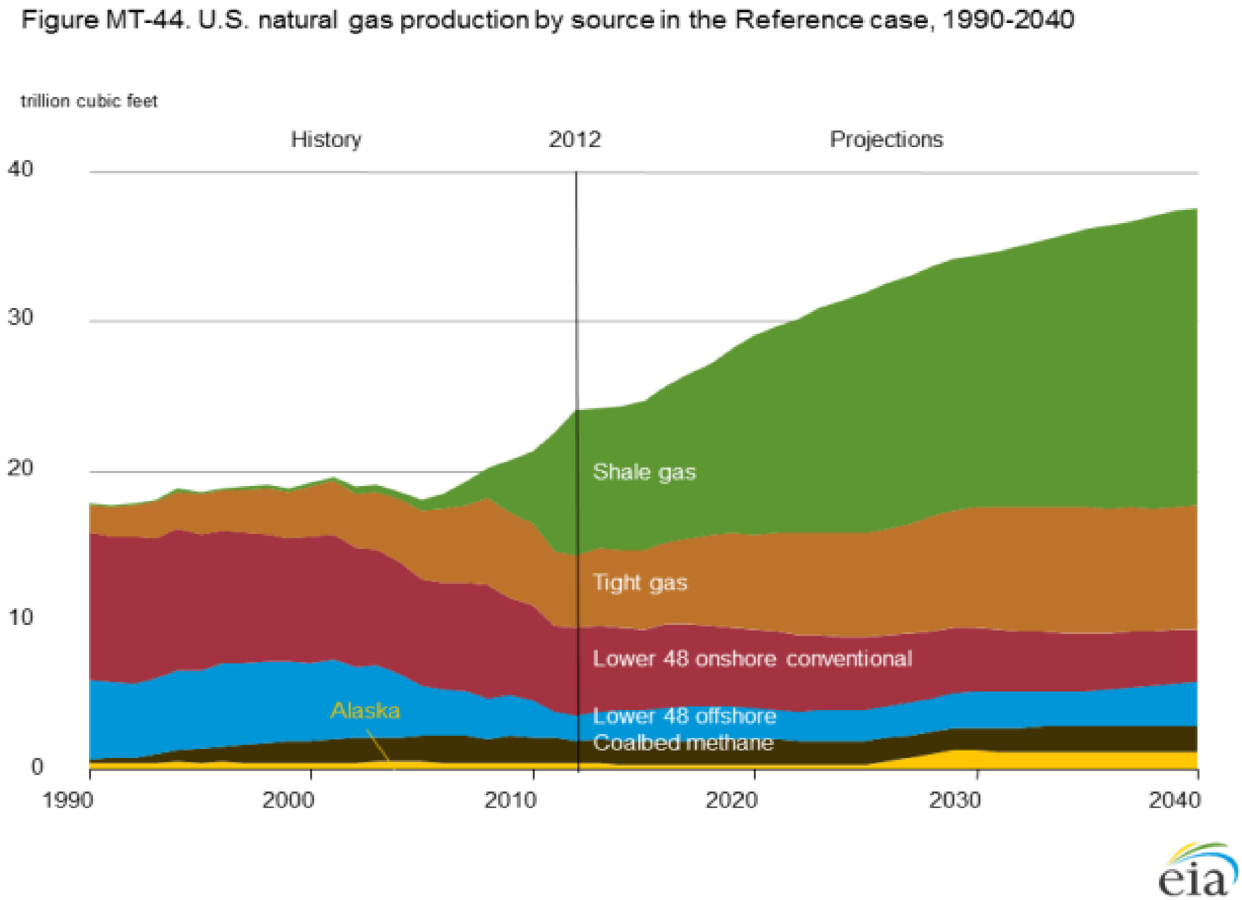
Shale Gas Production



Year	% of US Total CH_4 Production
2001	2
2006	6
2008	12
2011	29
2013	40

Figure: http://www.usfunds.com/media/images/investor-alert/_2013/2013-12-13/COMM-Dramatic-Increase-US-Shale-Gas-Production-12132013-LG.gif
Table: http://www.shalegas.energy.gov/resources/081811_90_day_report_final.pdf (2001 to 2011) & this figure / figure next page (2013)

Shale Gas Production



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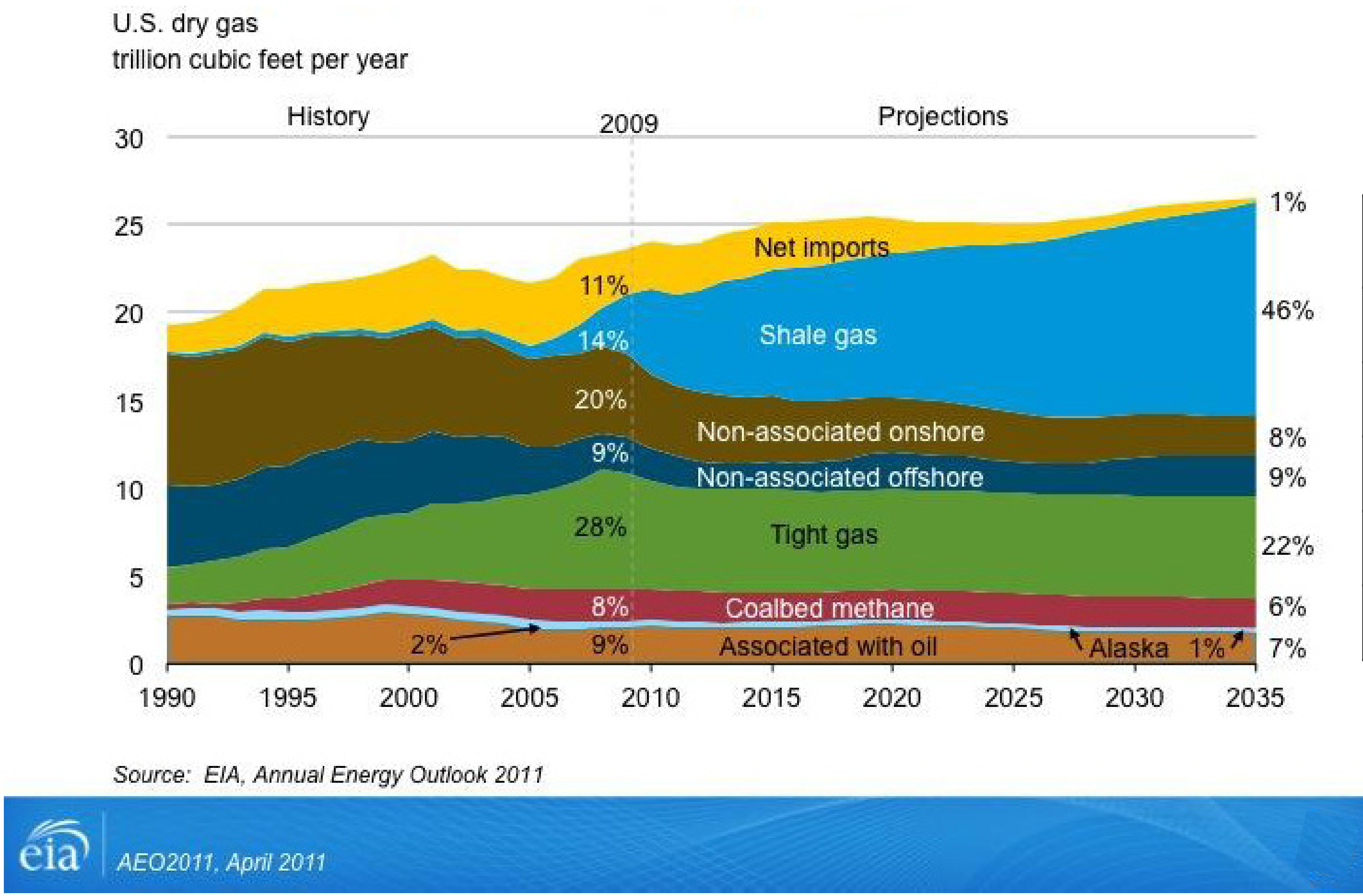
Shale Gas provides domestic source to meet U.S. consumer needs



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U.S. DOE 90 Day Shale Gas Subcommittee Interim Report (11 Aug 2011)
http://www.shalegas.energy.gov/resources/081811_90_day_report_final.pdf

Tight Gas and Shale Gas

Tight gas: CH_4 dispersed within low porosity silt or sand that create "tight fitting" environment; has been extracted for many years using hydraulic fracturing

Shale gas: CH_4 accumulated in small bubble like pockets within layers sedimentary rock such as shale, like tiny air pockets trapped in baked bread

Image:
http://www.wintershall.com/en/different-types-of-reserves-tight-gas-and-shale-gas.html

Shale Gas Production & Public Policy

- U.S. imports very little CH_4 (some imports from Canada)
- Price of CH_4 has fallen by a factor of 2 since 2008
- Concerns about shale gas production fall into four categories:
  - **Earthquakes**
  - **Contamination of ground water**
  - **Air quality (surface O_3 precursors and $PM_{2.5}$)**
  - **Climate (fugitive release of CH_4)**
- Former U.S. Dept of Energy Secretary David Chu (served 21 Jan 2009 to 22 April 2013) commissioned two reports from the Shale Gas Subcommittee of the Secretary of Energy Advisory Board (SEAB) to "identify measures that can be taken to reduce the environmental impact and to help assure the safety of shale gas production"
- First report (11 Aug 2011) identified 20 action items (see table, next slide)
- Second report (18 Nov 2011) outlined recommendations for implementation of action items
- EPA issued new standards for the oil and natural gas industry on 14 Jan 2015
- Notably absent is extended discussion of earthquake issue

http://www.epa.gov/airquality/oilandgas

Shale Gas Production & Public Policy

- First report (11 Aug 2011) identified 20 action items

1. Improve public information about shale gas operations
2. Improve communication among state and federal regulators
3. Improve air quality: 4. Industry to measure CH_4 & other air pollutants 5. Launch federal interagency effort to establish GHG footprint over shale gas extraction life cycle 6. Encourage companies & regulators to reduce emissions using proven technologies & best practices
7. Protect water quality: 8. Measure and report composition of water stock 9. Manifest all transfers of water among different locations 10. Adopt best practices for well casing, cementing, etc & conduct micro-seismic surveys to "assure that hydraulic growth is limited to gas producing formations" 11. Field studies of possible CH4 leakage from shale gas wells to water reservoirs 12. Obtain background water quality measurements (i.e., CH_4 levels in nearby waters prior to drilling)

Protect water quality (cont.): 13. Measure and report composition of water stock
14. Disclosure of fracking fluid composition
15. Reduce use of diesel fuel for surface power
16. Manage short-term & cumulative impacts on communities & wild life: sensitive areas can be deemed off-limit to drilling and support infrastructure through an appropriate science based process
17. Create shale gas industry organiz. to promote best practice, giving priority attention to: 18. Air: emission measurement & reporting at various points in production chain 19. Water: Pressure testing of cement casing & state-of-the-art technology to confirm formation isolation
20. Increase R & D support from Administration & Congress to promote technical advances such as the move from single well to multiple-well pad drilling

http://www.shalegas.energy.gov/resources/081811_90_day_report_final.pdf

Shale Gas Production & Public Policy

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Footnote 25:

Extremely small micro-earthquakes are triggered as an integral part of shale gas development. While essentially all of these earthquakes are so small as to pose no hazard to the public or facilities (they release energy roughly equivalent to a gallon of milk falling of a kitchen counter), earthquakes of larger (but still small) magnitude have been triggered during hydraulic fracturing operations and by the injection of flow-back water after hydraulic fracturing. It is important to develop a hazard assessment and remediation protocol for triggered earthquakes to allow operators and regulators to know what steps need to be taken to assess risk and modify, as required, planned field operations.

http://www.shalegas.energy.gov/resources/081811_90_day_report_final.pdf

Shale Gas Production & Public Policy

- First report (11 Aug 2011) identified 20 action items

The Subcommittee shares the prevailing view that the risk of fracturing fluid leakage into drinking water sources through fractures made in deep shale reservoirs is remote. Nevertheless the Subcommittee believes there is no economic or technical reason to prevent public disclosure of all chemicals in fracturing fluids, with an exception for genuinely proprietary information. While companies and regulators are moving in this direction, progress needs to be accelerated in light of public concern.

Protect water quality (cont.): 13. Measure and report composition of water stock
14. Disclosure of fracking fluid composition
15. Reduce use of diesel fuel for surface power
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http://www.shalegas.energy.gov/resources/081811_90_day_report_final.pdf

Concern #1: Earthquakes

2012 Seismological Society of America meeting

ARE SEISMICITY RATE CHANGES IN THE MIDCONTINENT NATURAL OR MANMADE?

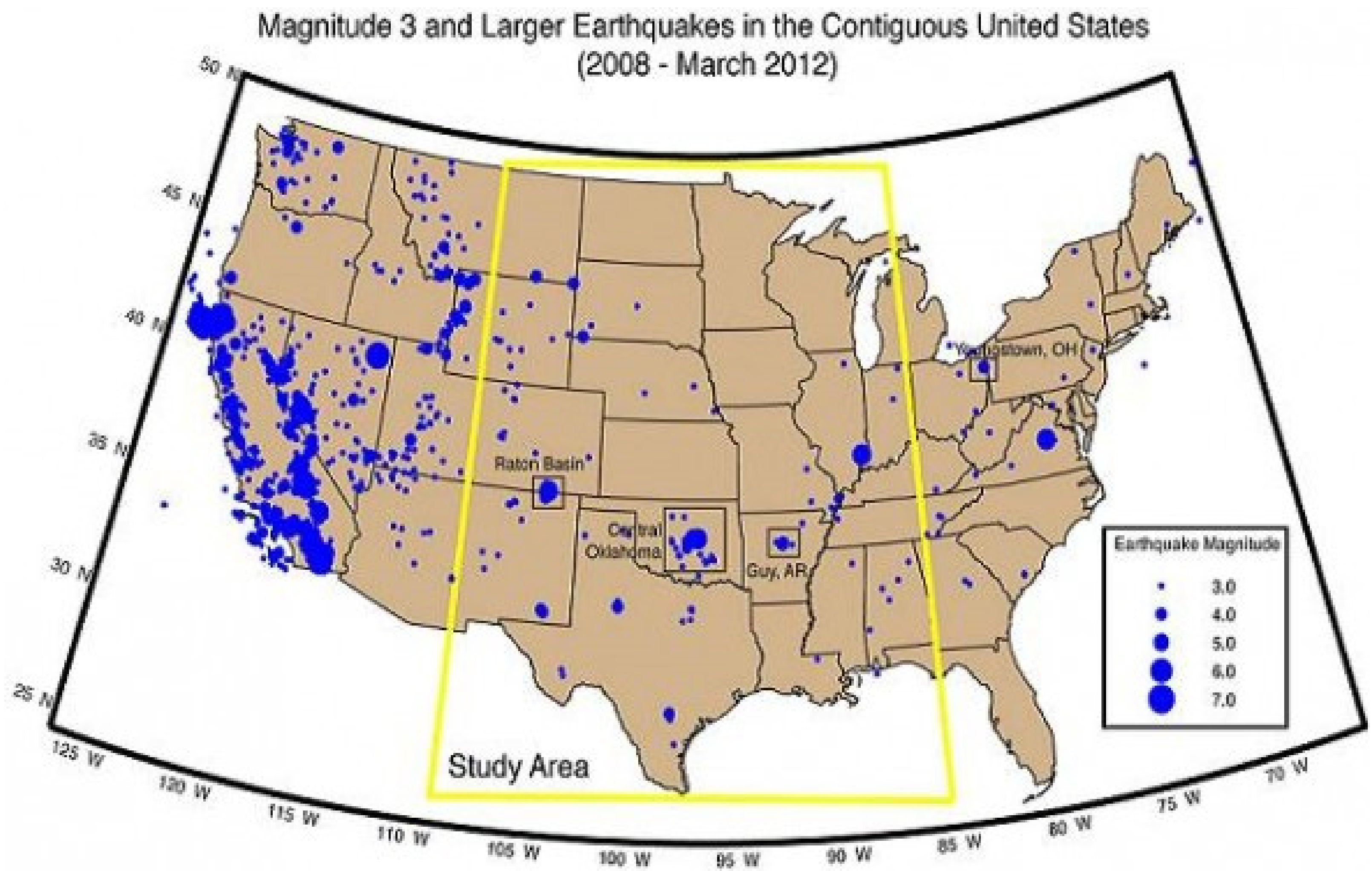
ELLSWORTH, W. L., US Geological Survey, Menlo Park, CA; HICKMAN, S. H., US Geological Survey, Menlo Park, CA; LLEONS, A. L., US Geological Survey, Menlo Park, CA; MCGARR, A., US Geological Survey, Menlo Park, CA; MICHAEL, A. J., US Geological Survey, Menlo Park, CA; RUBINSTEIN, J. L., US Geological Survey, Menlo Park, CA

A remarkable increase in the rate of M 3 and greater earthquakes is currently in progress in the US midcontinent. The average number of M >= 3 earthquakes/year increased starting in 2001, culminating in a six-fold increase over 20th century levels in 2011. Is this increase natural or manmade? To address this question, we take a regional approach to explore changes in the rate of earthquake occurrence in the midcontinent (defined here as 85° to 108° West, 25° to 50° North) using the USGS Preliminary Determination of Epicenters and National Seismic Hazard Map catalogs. These catalogs appear to be complete for M >= 3 since 1970. From 1970 through 2000, the rate of M >= 3 events averaged 21 +- 7.6/year in the entire region. This rate increased to 29 +- 3.5 from 2001 through 2008. In 2009, 2010 and 2011, 50, 87 and 134 events occurred, respectively. The modest increase that began in 2001 is due to increased seismicity in the coal bed methane field of the Raton Basin along the Colorado-New Mexico border west of Trinidad, CO. The acceleration in activity that began in 2009 appears to involve a combination of source regions of oil and gas production, including the Guy, Arkansas region, and in central and southern Oklahoma. Horton, et al. (2012) provided strong evidence linking the Guy, AR activity to deep waste water injection wells. In Oklahoma, the rate of M >= 3 events abruptly increased in 2009 from 1.2/year in the previous half-century to over 25/year. This rate increase is exclusive of the November 2011 M 5.6 earthquake and its aftershocks. A naturally-occurring rate change of this magnitude is unprecedented outside of volcanic settings or in the absence of a main shock, of which there were neither in this region. While the seismicity rate changes described here are almost certainly manmade, it remains to be determined how they are related to either changes in extraction methodologies or the rate of oil and gas production.

Wednesday, April 18th / 3:45 PM Oral / Pacific Salon 4 & 5

Concern #1: Earthquakes

Ellsworth's study area:



http://www.esa.org/esablog/ecology-in-the-news/increase-in-magnitude-3-earthquakes-likely-caused-by-oil-and-gas-production-but-not-fracking

Concern #1: Earthquakes

Ellsworth's study suggests:

- Deep waste water injection wells are the culprit, especially if in the vicinity of a fault
- Increased fluid pressure in pores of the rock can reduce the slippage strain between rock layers
- Speed of pumping is important (slow better than fast)

USGS testimony:

- On 19 June 2012, Dr. William Leath of the U.S. Geological Survey testified before the U.S. Senate Committee on Energy and Natural Resources, stating:

> The injection and production practices employed in these technologies have, to varying degrees, the potential to introduce earthquake hazards
>
> Since the beginning of 2011 the central and eastern portions of the United States have experienced a number of moderately strong earthquakes in areas of historically low earthquake hazard. These include M4.7 in central Arkansas on Feb27, 2011; M5.3 near Trinidad, Colorado on Aug 23, 2011; M5.8 in central Virginia also on Aug 23, 2011; … M5.6 in central Oklahoma on Nov 6, 2011 … and M4.8 in east Texas on May 17, 2012. Of these *only the central Virginia earthquake is unequivocally a natural tectonic earthquake.*
>
> In all other cases, there is scientific evidence to at least raise the possibility that the earthquakes were induced by wastewater disposal or other oil- and gas-related activities.
>
> USGS scientists documented a seven-fold increase since 2008 in the seismicity of the central U.S., an increase largely associated with areas of wastewater disposal from oil, gas & coalbed methane production

First three bullets:
http://www.esa.org/esablog/ecology-in-the-news/increase-in-magnitude-3-earthquakes-likely-caused-by-oil-and-gas-production-but-not-fracking
USGS testimony:
http://www.usgs.gov/congressional/hearings/docs/leith_19june2012.DOCX

Concern #1: Earthquakes

28 Jan 2015 Washington Post

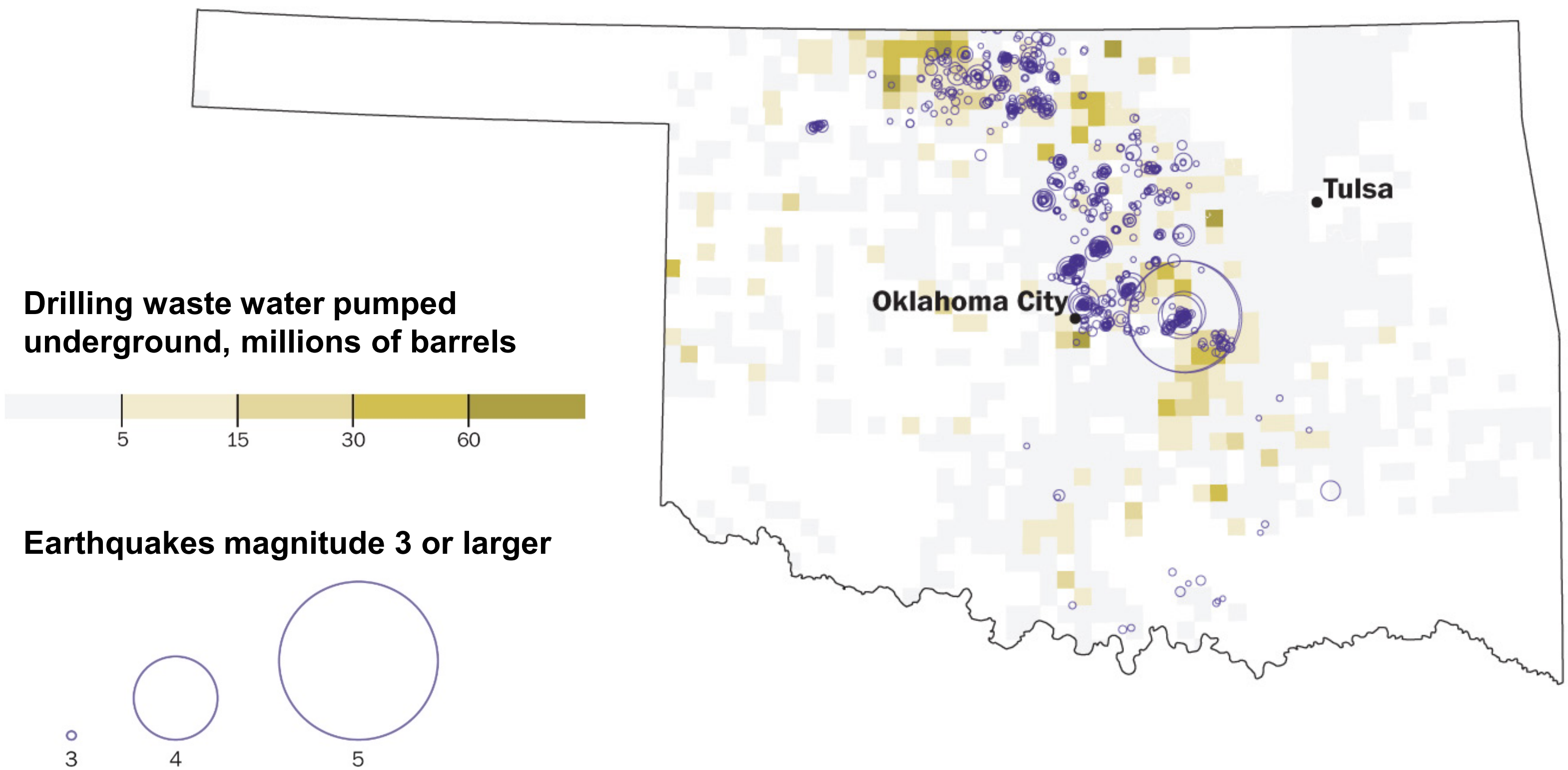
The Washington Post

Search

Economy

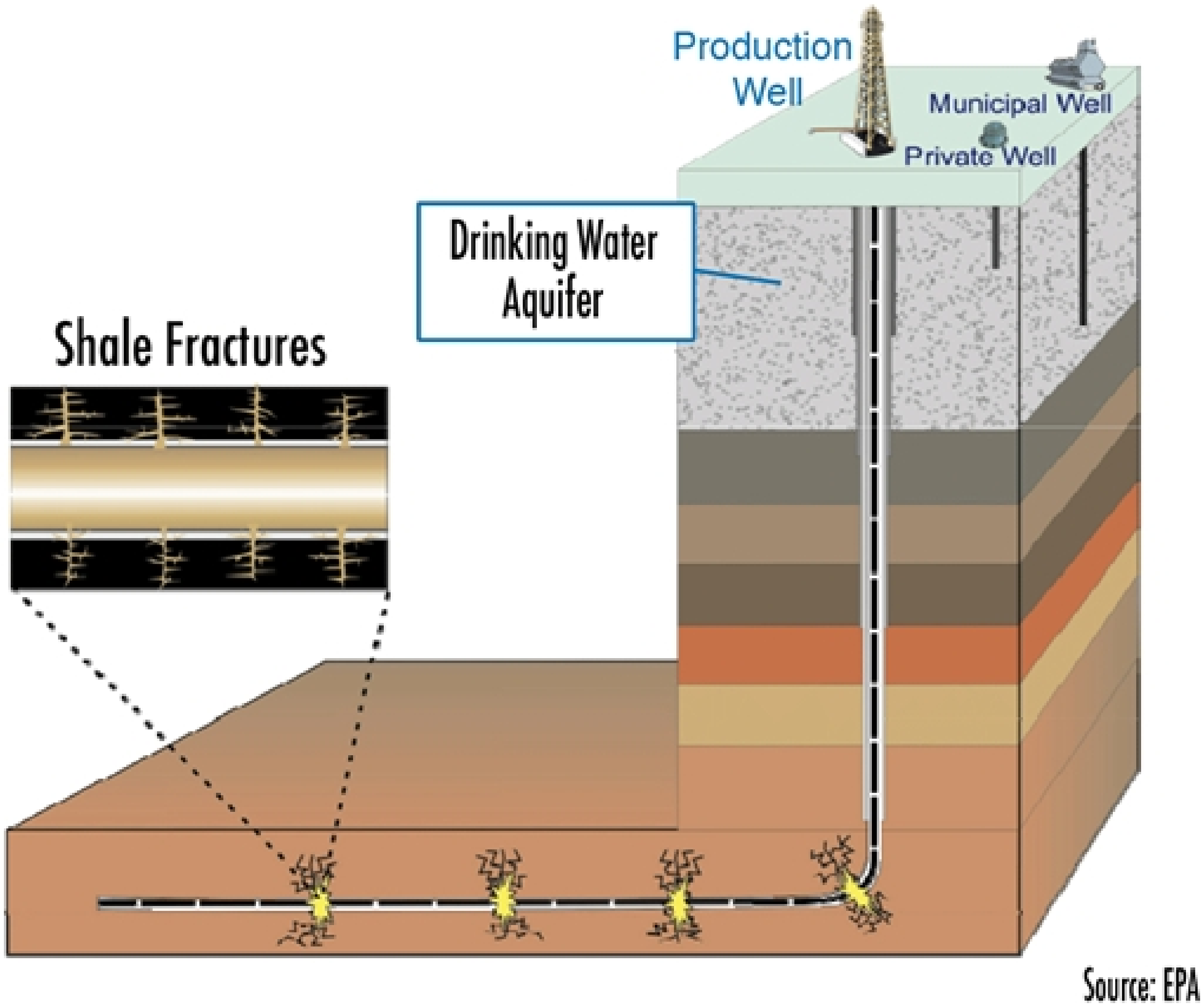
Oklahoma worries over swarm of earthquakes and connection to oil industry

2011 to 2013



http://www.washingtonpost.com/graphics/national/oklahoma-earthquakes/

Concern #2: Water Quality



http://savethewater.org/wp-content/uploads/2013/02/Stock-Save-the-water-New-Study-Predicts-Fracking-Fluids-Will-Seep-Into-Aquifers-Within-Years.jpg

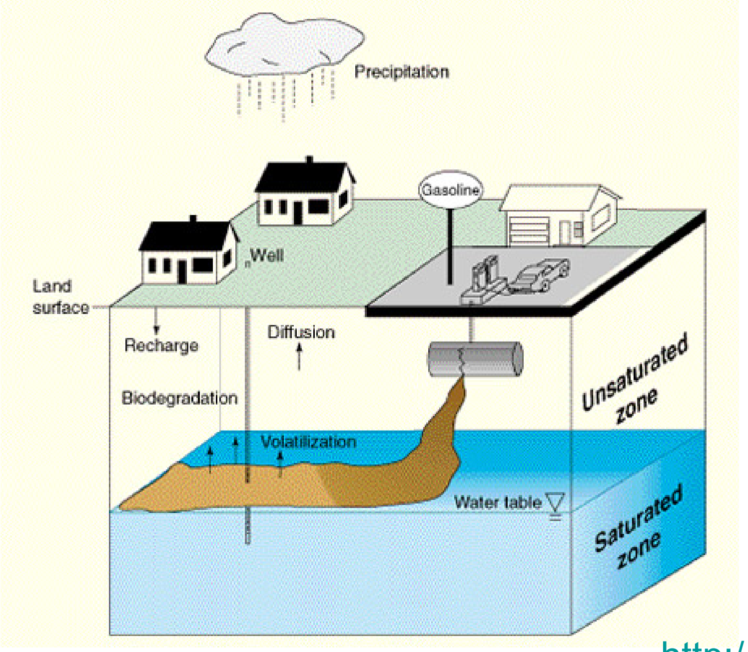
Concern #2: Water Quality

Spread of contaminants in ground water determined by

Dispersion – differential flow of water through small openings (pores) in soil

Diffusion – random molecular (Brownian) motion of molecules in water

Sorption – some chemicals may be *absorbed by soil* while others are *adsorbed* (adhere to surfaces)



Highly diffusive chemicals (e.g. MTBE) can spread very quickly even though ground water is relatively motionless.

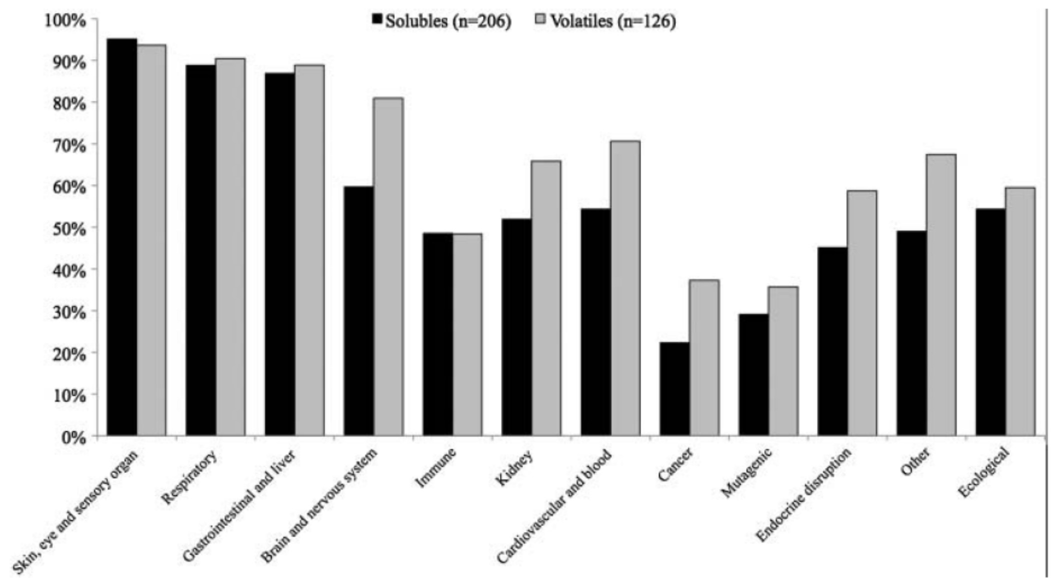
http://toxics.usgs.gov/topics/gwcontam_transport.html

Concern #2: Water Quality

Typical Chemical Additives Used in Frac Water

Compound	Purpose	Common application
Acids	Helps dissolve minerals and initiate fissure in rock (pre-fracture)	Swimming pool cleaner
Sodium Chloride	Allows a delayed breakdown of the gel polymer chains	Table salt
Polyacrylamide	Minimizes the friction between fluid and pipe	Water treatment, soil conditioner
Ethylene Glycol	Prevents scale deposits in the pipe	Automotive anti-freeze, deicing agent, household cleaners
Borate Salts	Maintains fluid viscosity as temperature increases	Laundry detergent, hand soap, cosmetics
Sodium/Potassium Carbonate	Maintains effectiveness of other components, such as crosslinkers	Washing soda, detergent, soap, water softener, glass, ceramics
Glutaraldehyde	Eliminates bacteria in the water	Disinfectant, sterilization of medical and dental equipment
Guar Gum	Thickens the water to suspend the sand	Thickener in cosmetics, baked goods, ice cream, toothpaste, sauces
Citric Acid	Prevents precipitation of metal oxides	Food additive; food and beverages; lemon juice
Isopropanol	Used to increase the viscosity of the fracture fluid	Glass cleaner, antiperspirant, hair coloring

Source: DOE, GWPC: Modern Gas Shale Development in the United States: A Primer (2009).



http://www.exxonmobilperspectives.com/2011/08/25/fracking-fluid-disclosure-why-its-important/

http://www.tandfonline.com/doi/pdf/10.1080/10807039.2011.605662

Many chemicals used in fracking have "everyday" uses …

We control how chemicals are used in homes, not the case for fracking

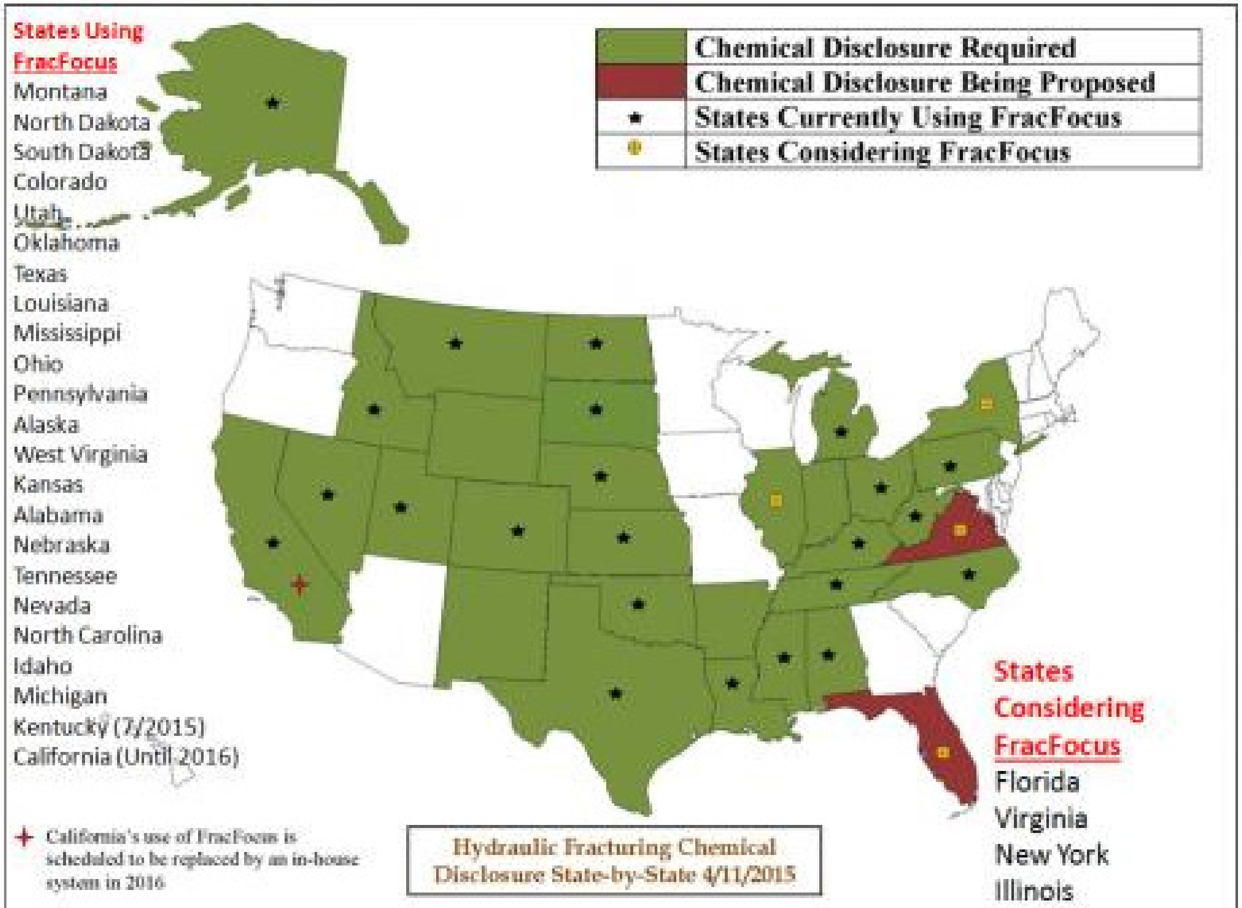
Fluid composition:

Concern #2: Water Quality

April 2011: www.fracfocus.org created as central disclosure registry for industry use

Currently, official disclosure venue for 23 states

Searchable database & Google map interface allow user to obtain info for individual wells



http://fracfocus.org/welcome

Fluid composition:

Concern #2: Water Quality

April 2011: www.fracfocus.org created as central disclosure registry for industry use

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Searchable database & Google map interface allow user to obtain info for individual wells

Trade Name	Supplier	Purpose	Ingredients	Chemical Abstract Service Number (CAS #)	Maximum Ingredient Concentration in Additive (% by mass)**	Maximum Ingredient Concentration in HF Fluid (% by mass)**	Comments
(WFR-3B)	Superior	Friction Reducer	Hydrotreated Light Distillate	64742-47-8	10.0 - 30.0%	0.17200%	
			Mineral Spirits	8052-41-3	< 10.0%		
			Propylene Glycol	57-55-6	< 25.0%		
			Ethoxylated Alcohols	68551-12-2	< 4.0%		
(KR-153SL)	Superior	Biocide	2,2-Dibromo-3-nitrilopropionamide	10222-01-2	20.0	0.02400%	
			Polyethylene Glycol	25322-68-3	50.0		
			Diethylene Glycol	111-46-6	1.5 - 3.5		
			Ethylene Glycol	107-21-1	1.0		
(Super Scale Control TSC)	Superior	Scale Inhibitor	Propylene Glycol	57-55-6	20.0 - 50.0	0.05400%	
			2 Phosphonobutane 1,2,4 Tricarboxylic Acid	37971-36-1	1.0 - 10.0		
			Anionic Copolymer	n/a	1.0 - 10.0		
			Anionic Polymer	n/a	1.0 - 10.0		
(FE OXCLEAR)	Superior	Oxygen Scavengar	Ammonium Bisulfite	10192-30-0	65.0 - 100%	0.09400%	
Sand (Proppant)	Superior	Propping Agent	Crystalline Silica	14808-60-7	99.90%	16.45000%	
Water	Provided by Customer	Base Fluid	Water		100.00%	83.21000%	

Concern #2: Water Quality

Fluid composition:

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Harvard Law School study highlights flaws in this system:

1) **Timing of Disclosures: Site does not notify States if company submits late**

2) **Substance of Disclosure: Site does not provide state specific forms, no minimum reporting standards**

3) **Nondisclosures: Companies not required to disclose chemicals if they are considered a "trade secret"**

~20% of all chemicals not reported.

http://www.eenews.net/assets/2013/04/23/document_ew_01.pdf

Concern #2: Water Quality

Research in progress:

- Isotopic analysis of sites in Pennsylvania indicate levels of CH_4 in wells near (< 1km) drilling sites 17 times higher than sites further away, Osborn et al. (*PNAS*, 2011)

- Independent analysis of these sites suggests elevated CH_4 due to topography rather than fracking, Molofsky et al. (*Oil Gas J*., 2011), no evidence of fracking fluid in wells, Schon (*PNAS*, 2011)

- Surface water quality degraded through release from treatment facilities (increases Cl^-) and through release from wells (increases total suspended solids), Olmstead et al. (*PNAS*, 2012)

Concern #2: Water Quality

Research in progress:

- **12 March 2015 publication states CH_4 is present in drinking water, but is unrelated to proximity to wells**

Environmental Science & Technology
Article
pubs.acs.org/est

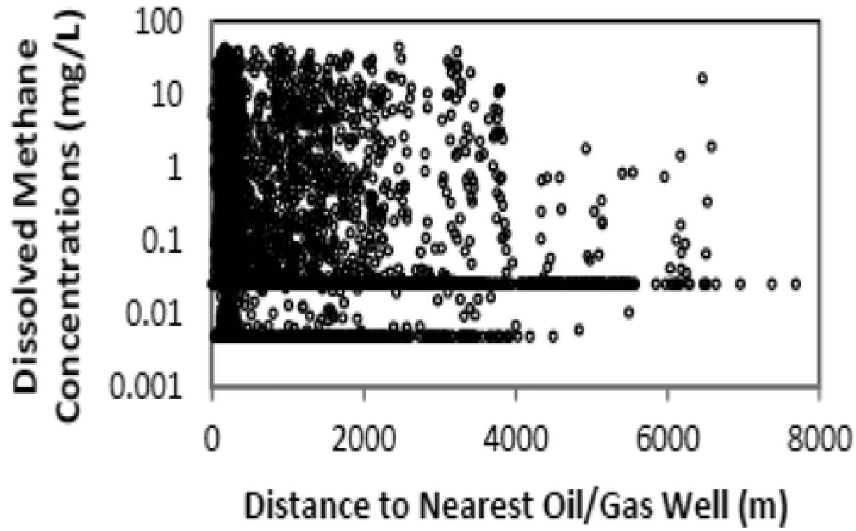
Methane Concentrations in Water Wells Unrelated to Proximity to Existing Oil and Gas Wells in Northeastern Pennsylvania

Donald I. Siegel,[*,†] Nicholas A. Azzolina,[‡] Bert J. Smith,[§] A. Elizabeth Perry,[‖] and Rikka L. Bothun[⊥]

[†]Department of Earth Sciences, Syracuse University, 204 and 314 Heroy Geology Lab, Syracuse, New York 13244, United States
[‡]The CETER Group, Inc., 1027 Faversham Way, Green Bay, Wisconsin 54313, United States
[§]Enviro Clean Products and Services, 11717 North Morgan Road, P.O. Box 721090, Yukon, Oklahoma 73172-1090, United States
[‖]AECOM Technology Corporation, 250 Apollo Drive, Chelmsford, Massachusetts 01824, United States
[⊥]AECOM Technology Corporation, 1601 Prospect Parkway, Fort Collins, Colorado 80525, United States

Supporting Information

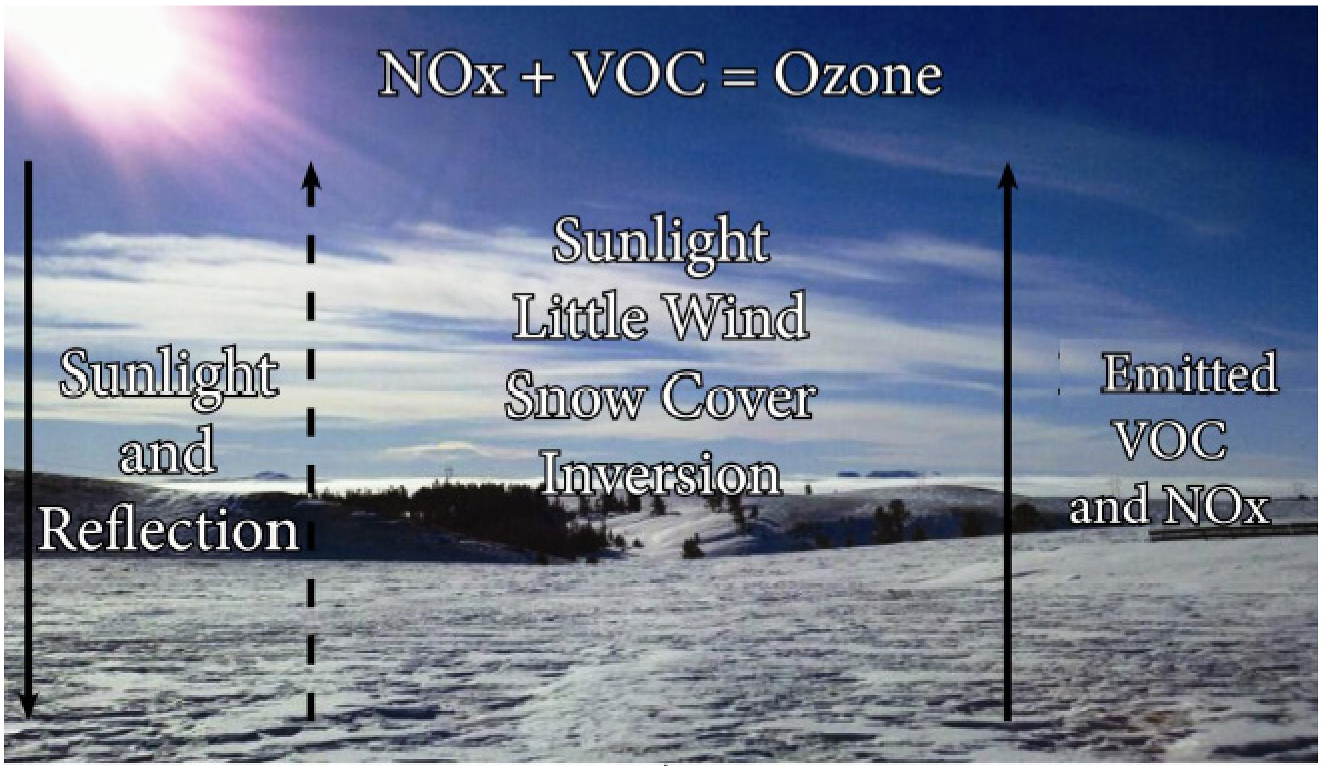
http://pubs.acs.org/doi/ipdf/10.1021/es505775c



Article received a commentary in Science:
http://news.sciencemag.org/environment/2015/03/methane-drinking-water-unrelated-fracking-study-suggests

Concern #3: Air Quality (Case Study: Wyoming)

Ozone: Wintertime Phenomenon



http://deq.state.wy.us/out/downloads/UGRBTaskForce02212012WDEQAQD.pdf

Concern #3: Air Quality (Case Study: Wyoming)

2011 Preliminary Data
(as of 3/20/2011)

10 Advisory Days
- February 28
- March 1, 2, 4, 5, 10, 13, 14, 15, 18

13 Elevated 8-Hour Ozone Days
- February 14, 15, 21
- March 1, 2, 3, 5, 6, 9, 10, 12, 14, 15

2011 Preliminary Raw Data (as of 3/20/2011)
Monitored Ozone Top Four 8-Hour Daily Maximum (ppb)

Wyoming Range	Pinedale	Daniel 2011 (2008)	Boulder 2011 (2008)	Juel Spring
84	90	85 (76)	124 (122)	95
81	84	80 (76)	121 (104)	86
80	81	77 (74)	116 (102)	85
73	77	76 (74)	104 (101)	77

NOTE: Three (3) year average of 4th high 8-Hour Daily Maximum is compared to NAAQS.

http://deq.state.wy.us/out/downloads/March22PublicMtg_2011Ozone_WDEQ.pdf

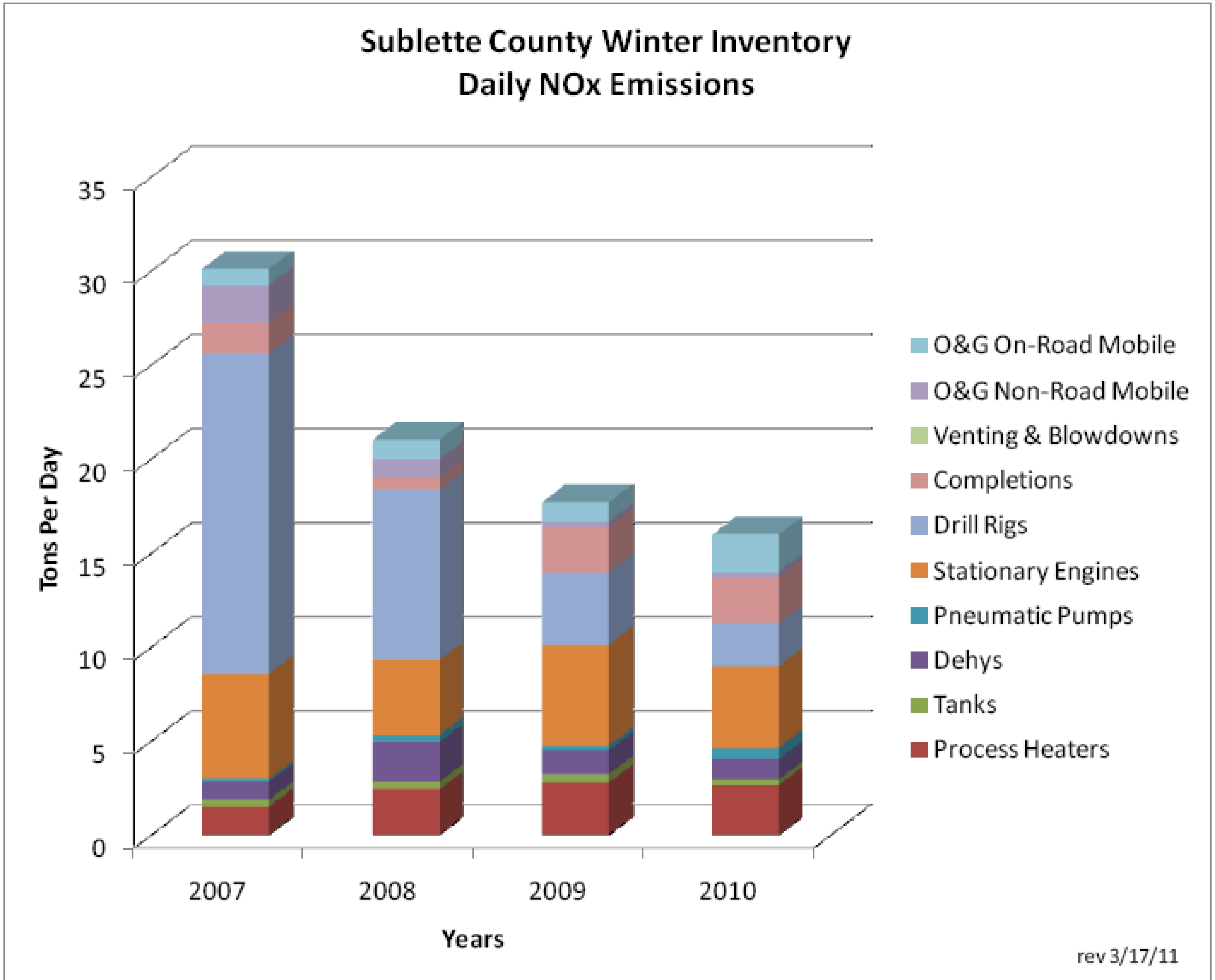
Concern #3: Air Quality (Case Study: Wyoming)

Sublette County Ozone & Weather History (2005 – 2011)

- Mid-January – March 2005
  - 8 Elevated 8-Hour O_3 Days > 75 ppb
- Mid-January – March 2006
  - 2 Elevated 8-Hour O_3 Days > 75 ppb
- Mid-January – March 2007
  - 0 Elevated 8-Hour O_3 Days > 75 ppb
  - Meteorological conditions not conducive to formation of elevated ozone levels.
- Mid-January – March 2008
  - 14 Elevated 8-Hour O_3 Days > 75 ppb
  - Higher magnitude than previous years
  - Met. conditions conducive to formation of elevated ozone levels.
- Mid-January – March 2009
  - 0 Elevated 8-Hour O_3 Days > 75 ppb
  - Limited met. conditions conducive to formation of elevated ozone levels.
- Mid-January – March 2010
  - 0 Elevated 8-Hour O_3 Days > 75 ppb
  - Met. conditions not conducive to formation of elevated ozone levels.
- Mid-January – March 2011
  - 13 Elevated 8-Hour O_3 Days > 75 ppb
  - Higher magnitude than previous years
  - Met. conditions conducive to formation of elevated ozone levels.

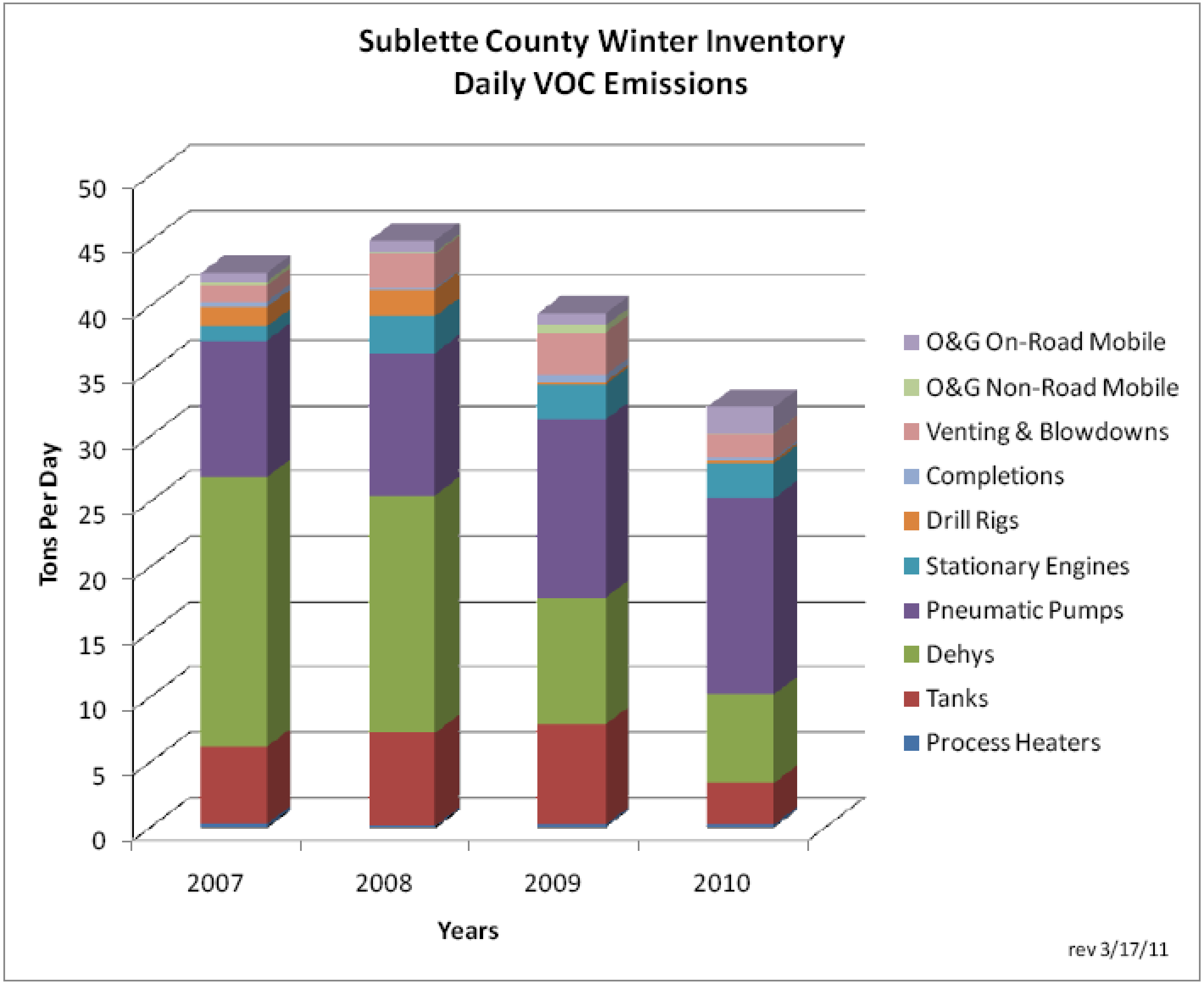
http://deq.state.wy.us/out/downloads/March22PublicMtg_2011Ozone_WDEQ.pdf

Concern #3: Air Quality (Case Study: Wyoming)



http://www.shalegas.energy.gov/resources/071311_corra.pdf

Concern #3: Air Quality (Case Study: Wyoming)



http://www.shalegas.energy.gov/resources/071311_corra.pdf

Concern #3: Air Quality (Case Study: Wyoming)

Tropospheric Ozone Production versus NO_x and VOCs

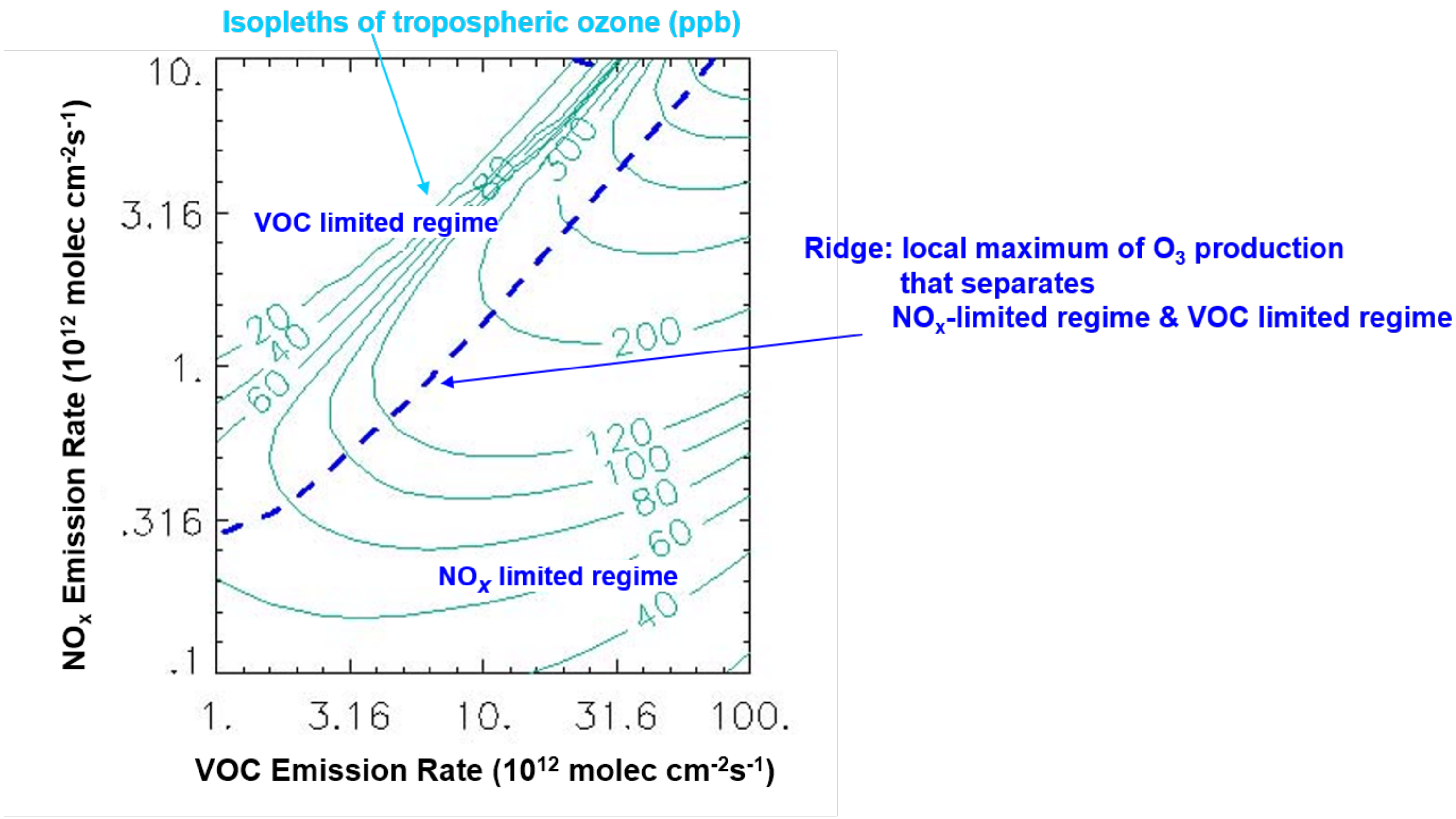
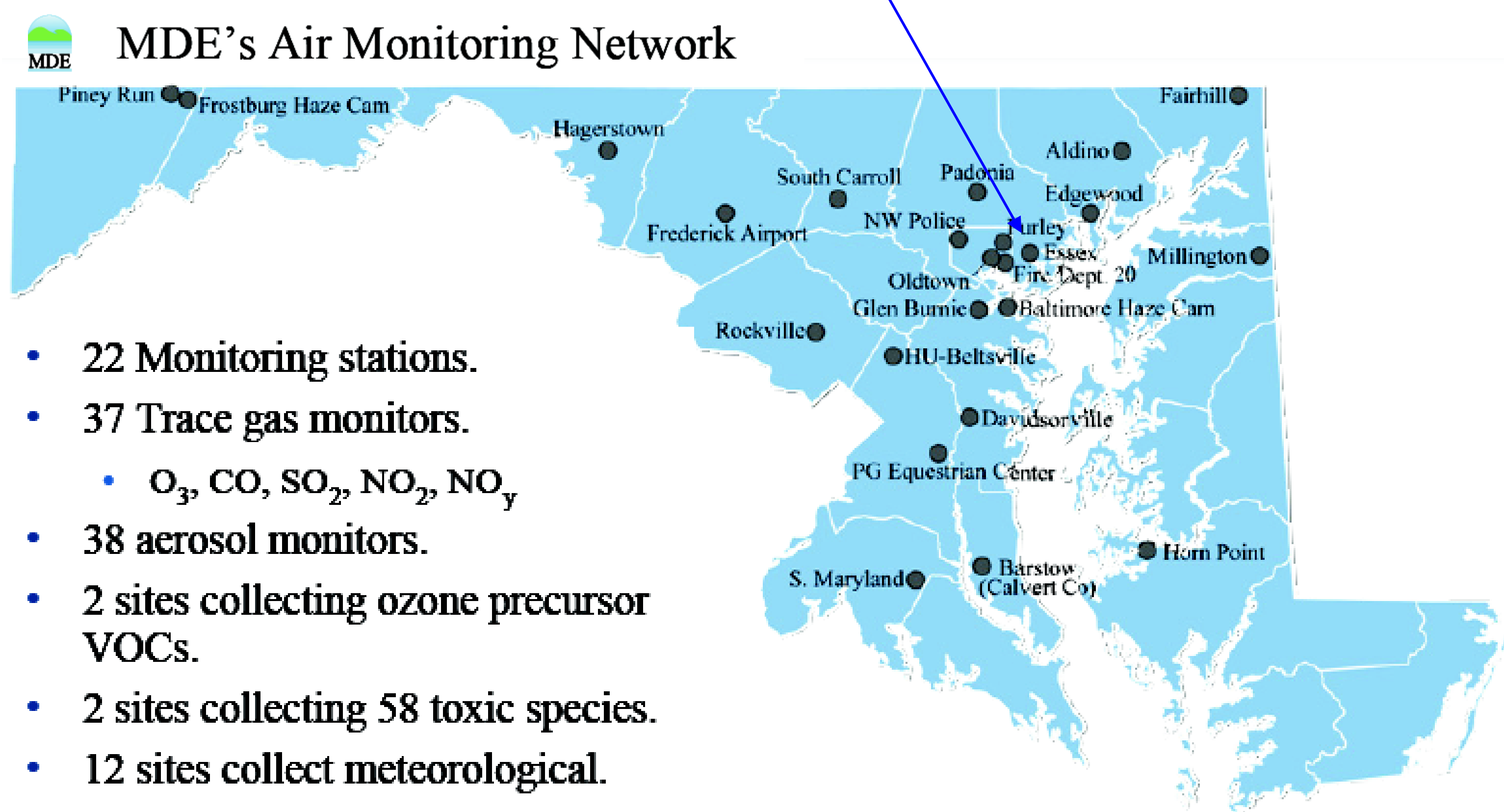


Figure: http://www-personal.umich.edu/~sillman/ozone.htm

Concern #3: Air Quality (Case Study: Maryland)

- Air mass trajectories (meteorological modeling) show air parcels affected by fracking can reach the Baltimore/DC region
- Fracking releases a stew of VOCs, including ethane (C_2H_6)
- Ethane and other VOCs measured at **Essex** MDE site



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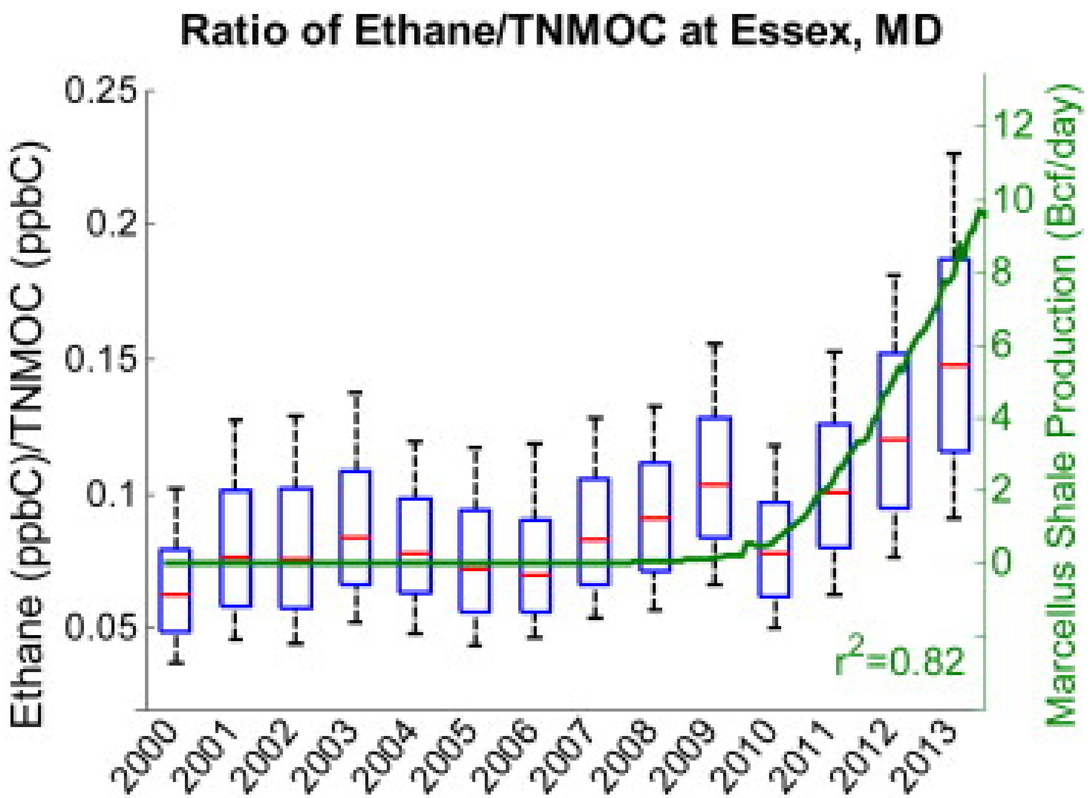

Vinciguerra *et al*., Atmospheric Environment, 2015

Concern #4: Climate

As shown in Lecture 18, under normal operating conditions w/ no leaks, less CO_2 is released to the atmosphere per kWh if gas (CH_4) is used to generate electricity than if coal is used to generate the equivalent amount of electricity:

Fossil Fuel	GHG Output (pounds CO_2 per kWh)
Oil Sands	**5.6**
Coal	**2.1**
Oil	**1.9**
Gas	**1.3**

Since CH_4 has a larger GWP than CO_2, if CH_4 escapes via leakage rather than being oxidized via combustion, the **net GWP** of the sum of rising atmospheric CH_4 due to leakage plus rising CO_2 following combustion of natural gas can exceed the GWP of CO_2 from the combustion of fossil fuel.

http://www.eia.gov/cneaf/electricity/page/co2_report/co2emiss.pdf
http://www.iop.org/EJ/abstract/1748-9326/4/1/014005

Concern #4: Climate

Modeling of Shale Gas Production

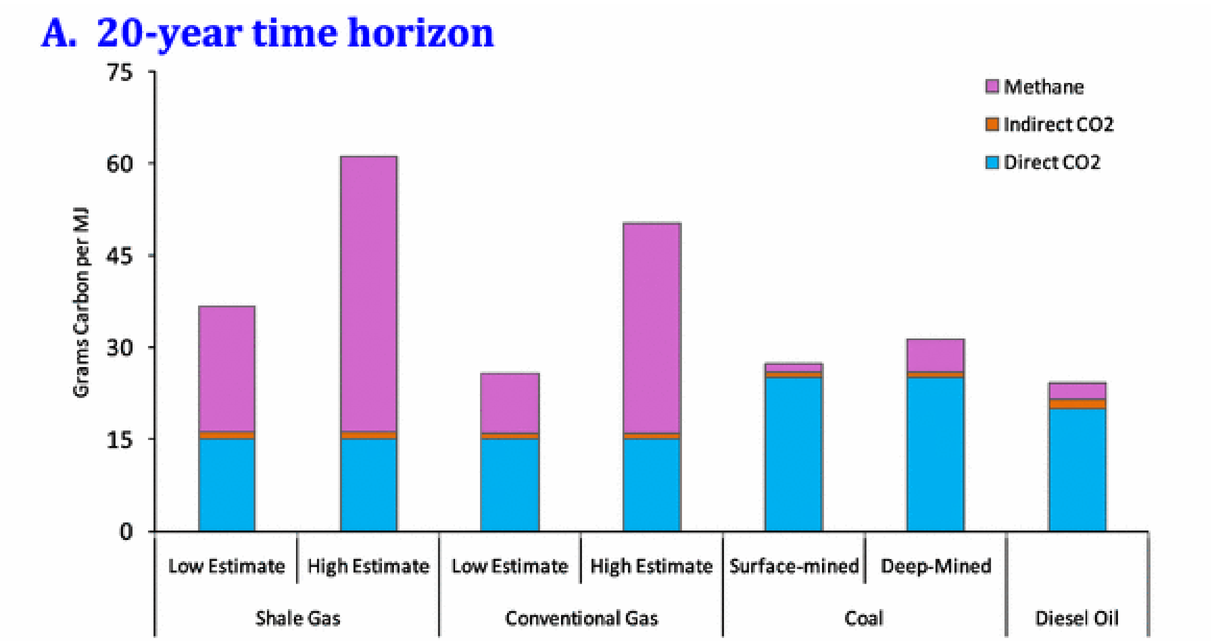

Table 2 Fugitive methane emissions associated with development of natural gas from conventional wells and from shale formations (expressed as the percentage of methane produced over the lifecycle of a well)

	Conventional gas	Shale gas
Emissions during well completion	0.01%	1.9%
Routine venting and equipment leaks at well site	0.3 to 1.9%	0.3 to 1.9%
Emissions during liquid unloading	0 to 0.26%	0 to 0.26%
Emissions during gas processing	0 to 0.19%	0 to 0.19%
Emissions during transport, storage, and distribution	1.4 to 3.6%	1.4 to 3.6%
Total emissions	1.7 to 6.0%	3.6 to 7.9%

Howarth et al., *Climatic Change*, 2011

Concern #4: Climate

Criticism of Modeling of Shale Gas Production

Cathles et al. believe Howarth et al.'s argument fails on four critical points:

1) The 7.9% upper limit for CH_4 leakage from well drilling exceeds a reasonable upper limit by about a factor of 3

2) Importance of rapidly improving technology to reduce fugitive CH_4 emissions is dismissed

3) Study places undue emphasis on 20 yr time horizon:

   As Pierrehumbert (2011) explains, "Over the long term, CO_2 accumulates in the atmosphere like mercury in the body of a fish, whereas CH_4 does not. For this reason, it is the CO_2 emissions, and the CO_2 emissions alone, that determine the climate that humanity will need to live with."

4) CH_4 end use for heating is compared to coal end use for electricity generation:

   "Electric industry has large stock of old, inefficient coal-fired electric generating plants that could be considered for replacement by natural gas … The much lower construction costs associated with gas power plants means modern gas technology will likely replace this old coal technology as it is retired. If total (well drilling to delivery) leakage is limited to less than 2% (which may be the current situation …) switching from coal to natural gas would dramatically reduce the greenhouse impact of electricity generation."

Cathles III et al., *Climatic Change*, 2012

Concern #4: Climate

Criticism of Modeling of Shale Gas Production

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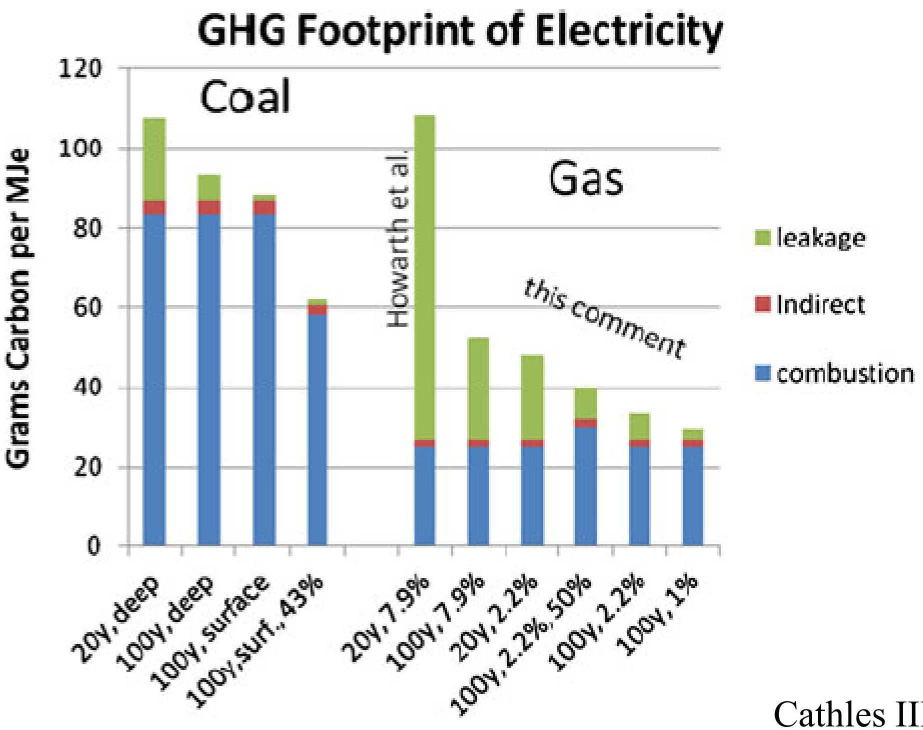


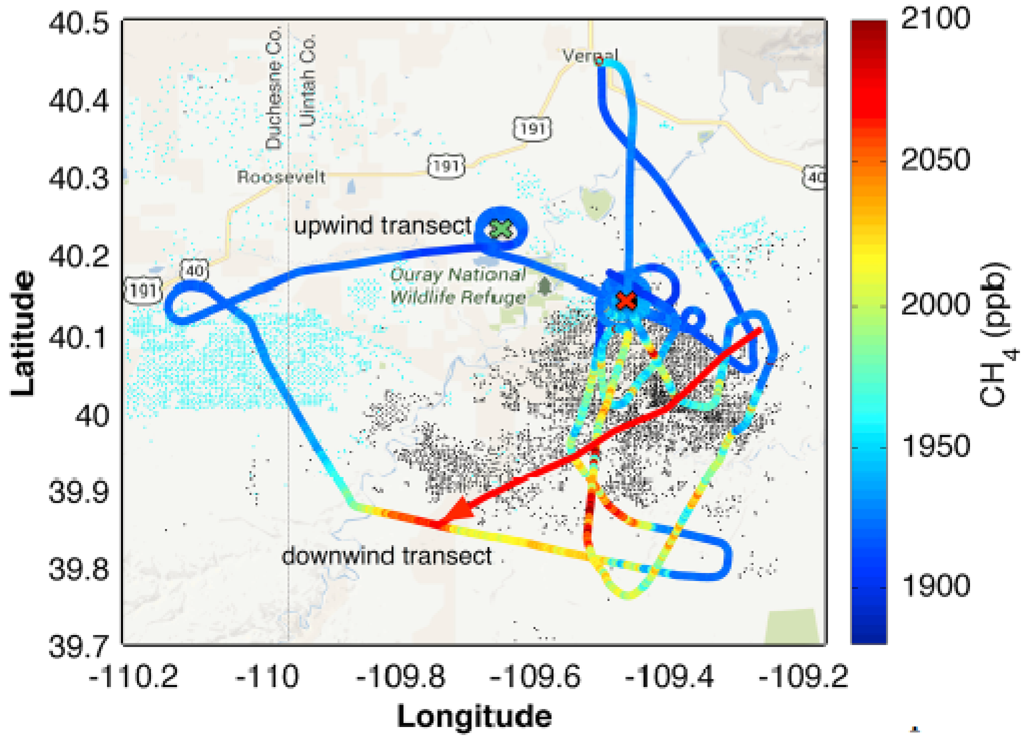
Cathles III et al., *Climatic Change*, 2012

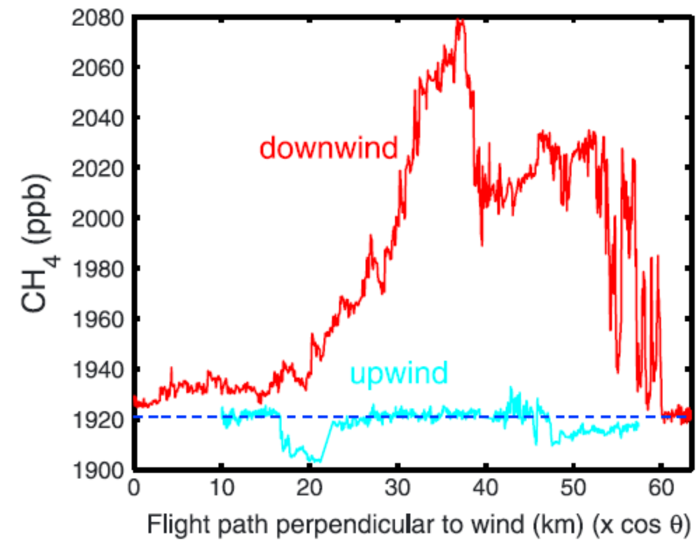
Concern #4: Climate

Observed fugitive CH_4 emissions

Karion et al. report report leakage of 9% (6.2 to 11.7% range) of CH_4 from a field study in the Uinta Basin Utah nearly double the cumulative loss rates estimated from industry data

KARION ET AL.: CH_4 EMISSIONS OVER A NATURAL GAS FIELI





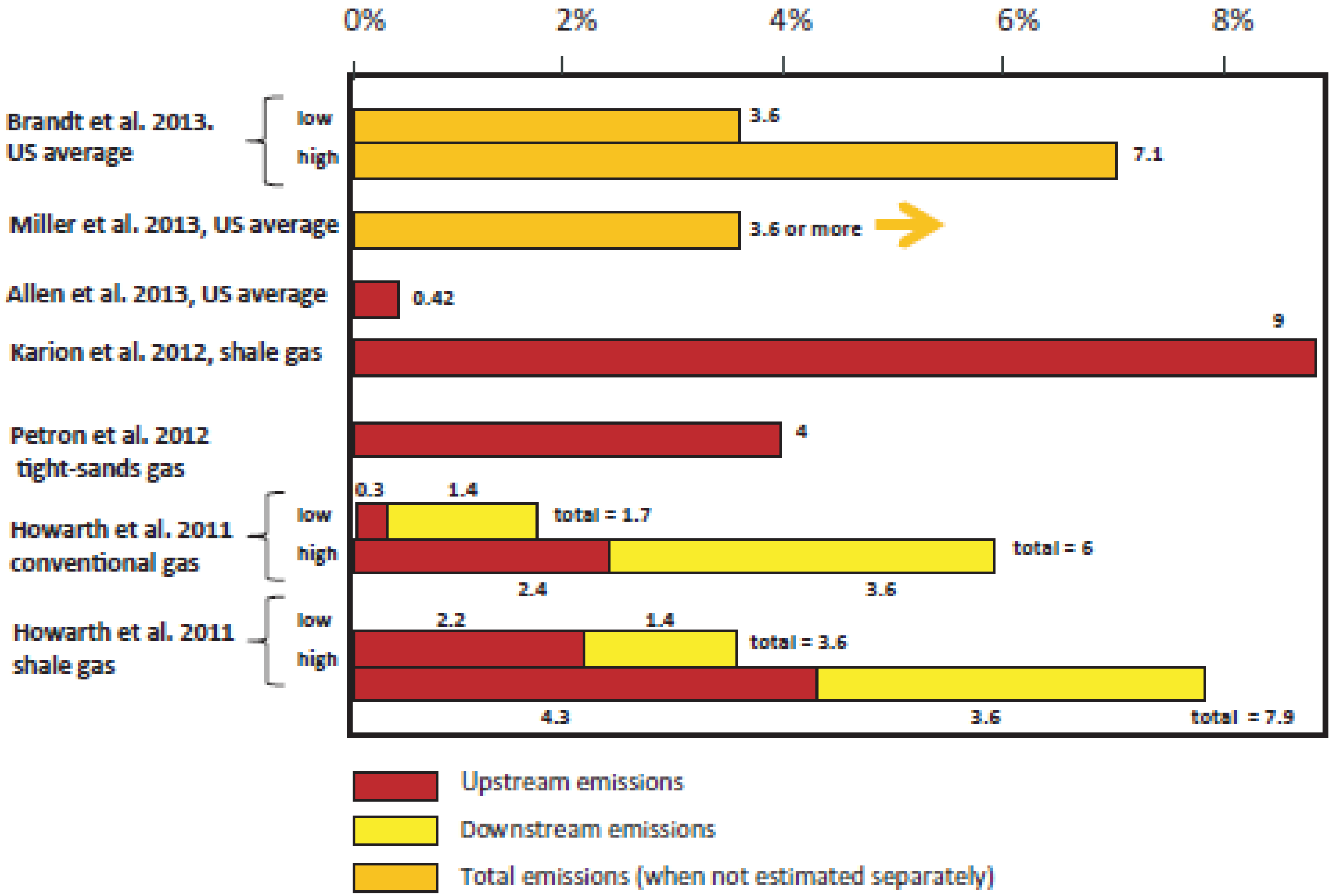
Karion et al, GRL, 2013

CH_4 flux is derived to be

$$\text{flux}_{CH_4} = V\int_{-b}^{b} X_{CH_4}\left(\int_{z_{\text{ground}}}^{z_{\text{PBL}}} n_{\text{air}}\,dz\right)\cos\theta\,dx \qquad (1)$$

Concern #4: Climate

Observed fugitive CH_4 emissions



Howarth et al, ESE, 2014