The Successful Development of Shale Energy Resources in the United States

Daniel J. Soeder

Research Geologist

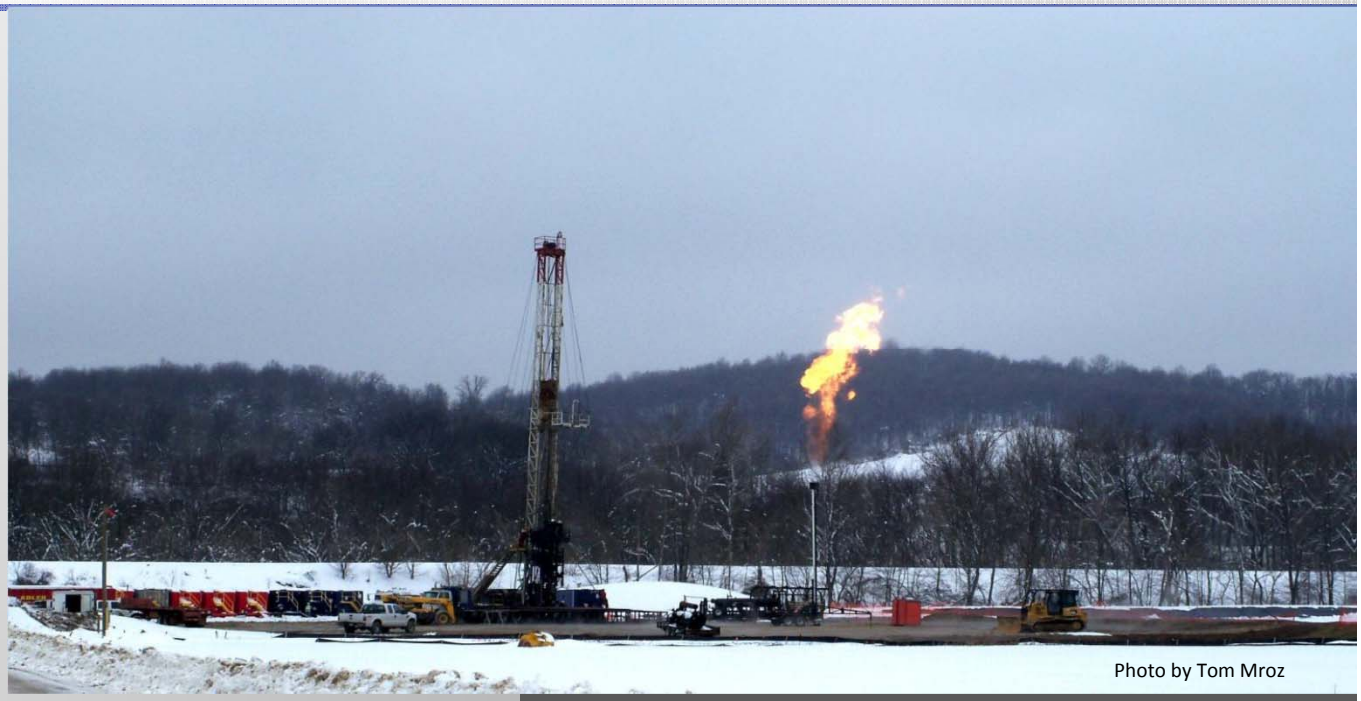


Photo by Tom Mroz

the **ENERGY** lab

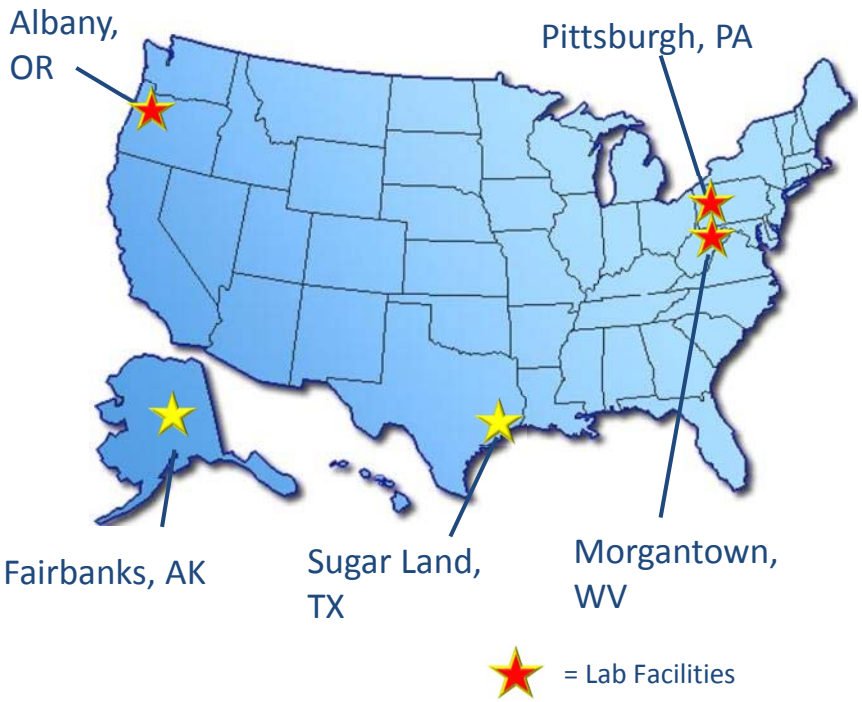
U.S. Department of Energy
National Energy Technology Laboratory
Office of Research and Development
Morgantown, WV

Presentation for NSF Workshop, Rapid City, SD, October 19-20, 2015

U.S. DEPARTMENT OF ENERGY

DOE National Energy Technology Laboratory

- National lab for fossil energy; 5 sites with ~1200 employees
- Fundamental science to technology demonstrations
- Onsite research (ORD), and extramural R&D (Strategic Centers)
- Office of Research & Development Focus Areas:
  - Materials Science and Engineering
  - Computational Science and Engineering
  - Energy Systems Dynamics
  - Geology and Environmental Systems
- Created in the late 90s from DOE Energy Technology Centers and other facilities

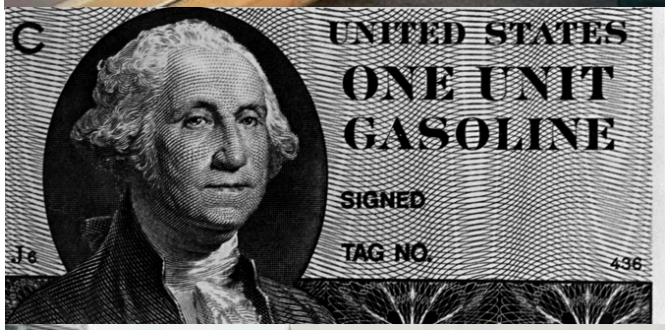


Dan Soeder

1. BS Cleveland State 1976; MS Bowling Green (OH)1978, both in geology
2. 1979-81 DOE Eastern Gas Shales Project contractor, Morgantown, WV
3. 1981-90 Research on tight sands, shale, coalbed methane: Gas Technology Institute, Chicago, IL
4. 1990-98 Research on hydrology of volcanic rocks, Yucca Mountain Project: U. S. Geological Survey, Las Vegas, NV
5. 1998-2009 Water resource and contaminant hydrology studies in DE-MD-DC, USGS, Baltimore, MD
6. 2009-present: Unconventional oil and gas development, CO_2 storage in geologic formations, environmental risks to groundwater and surface water: DOE – NETL, Morgantown, WV

Whence Shale Gas?

- **October 20, 1973 to Spring 1974: OPEC oil embargo against United States**
  - Price of gasoline quadrupled ($0.40-$1.60)
  - Gasoline was in short supply
- **U.S. Department of Energy formed by the Carter Administration on August 4, 1977**
- **DOE funded R&D projects to increase domestic energy supplies:**
  - Eastern Gas Shales
  - Western Tight Gas Sands
  - Coal Bed Methane
  - Geopressured Aquifers
- **Later projects (1990s)**
  - Methane hydrates
  - Ultra deep gas
- **DOE mission: offset imported oil by increasing domestic energy production in an environmentally-responsible manner.**



Soeder, D.J., 2012, Shale gas development in the United States, Chapter 1 in Advances in Natural Gas Technology, Edited by Hamid A. Al-Megren, ISBN 978-953-51-0507-7, InTech Open Access, Rijeka, Croatia, April 11, 2012; DOI: 10.5772/2324, 542 pages

New Sources of Natural Gas

- **Resources were known and in some cases substantial, but production was typically small.**
  - Dunkirk Shale in NY (1821)
  - Huron Shale in KY (early 1900s)
  - Coal seam gas
  - Tight sands
- **Engineering challenges**
  - Black shale + natural fractures = natural gas (not always)
  - Two-phase flow is difficult in low permeability rocks
  - Formation contact is limited with vertical wells and single hydraulic fractures
- **Economic challenges**
  - Not enough production to justify the cost of wells

SPE 7628

Potential New Sources of Natural Gas

Leo A. Schrider, SPE, U.S. DOE
Robert L. Wise, U.S. DOE

Introduction

Natural gas continues to be one of the major sources of energy produced and used in the U.S. Declining gas reserves and curtailment of supplies have reemphasized the major influence this energy source has on the U.S. economy. The U.S. DOE is investigating several options for increasing the supply, including a program for unconventional gas recovery (UGR). Four UGR projects currently are being assessed: western tight gas sands, geopressured reservoirs, Devonian shales, and methane from coalbeds.

Both the Devonian shale and methane-from-coalbeds projects are paramount in this assessment, since they underlie a large section of the U.S.

The eastern (Devonian) shales contain a vast, essentially unexplored volume of natural gas. This area could represent new gas recovery from approximately 250,000 sq miles throughout the U.S. Studies by the government and industry have been focused on shale characterization to determine the magnitude of potential gas reserves and technology development needed to improve current state-of-the-art stimulation techniques. The initial R&D results have shown promise and point out the technology needed for successful development.

The goal of the methane-from-coalbeds project is to provide natural gas from coal seams. While coal itself is recognized as a major energy source, it also contains vast quantities of methane gas. This methane source is not new, since coal mine operators have been aware of its presence and release into the atmosphere during mining opertions. Technology studies are being conducted to learn the production potential of this methane and to show how this gas may be put to widespread use.

Devonian Shales

The Devonian shales of the Appalachian, Michigan, and Illinois basins have produced natural gas since the 1800's. These shales in the eastern U.S. (Fig. 1) contain a high volume of gas. Independent estimates of the recoverable gas range from 3 Tcf to several hundred times that amount. To date, the gas produced from these shales has been limited to an estimated 2.5 Tcf[1,2] because of the unpredictable behavior and economics shown by existing Devonian shale wells. Similarly, these uncertainties have restricted private-sector R&D funding and development of technology needed for Devonian shale gas production.

Background

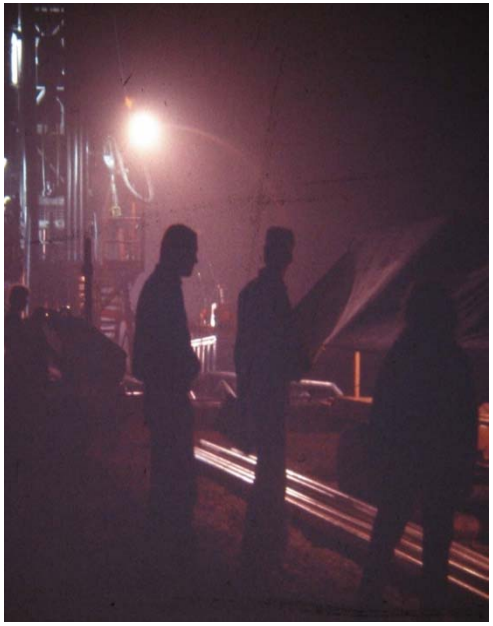
The DOE program for development of Devonian shale natural gas production is the Eastern Gas Shales Project (EGSP), which provides for a DOE-industry partnership to conduct projects that will

0149-2136/80/0004-7628$00.25

The U.S. DOE's gas resource program aims at resolving existing technological barriers to effective recovery of natural gas from Devonian shale and methane from coalbeds. Upon completion of these projects, DOE expects the technology developed jointly with industry to result in wide-scale recovery and use of these new sources of natural gas.

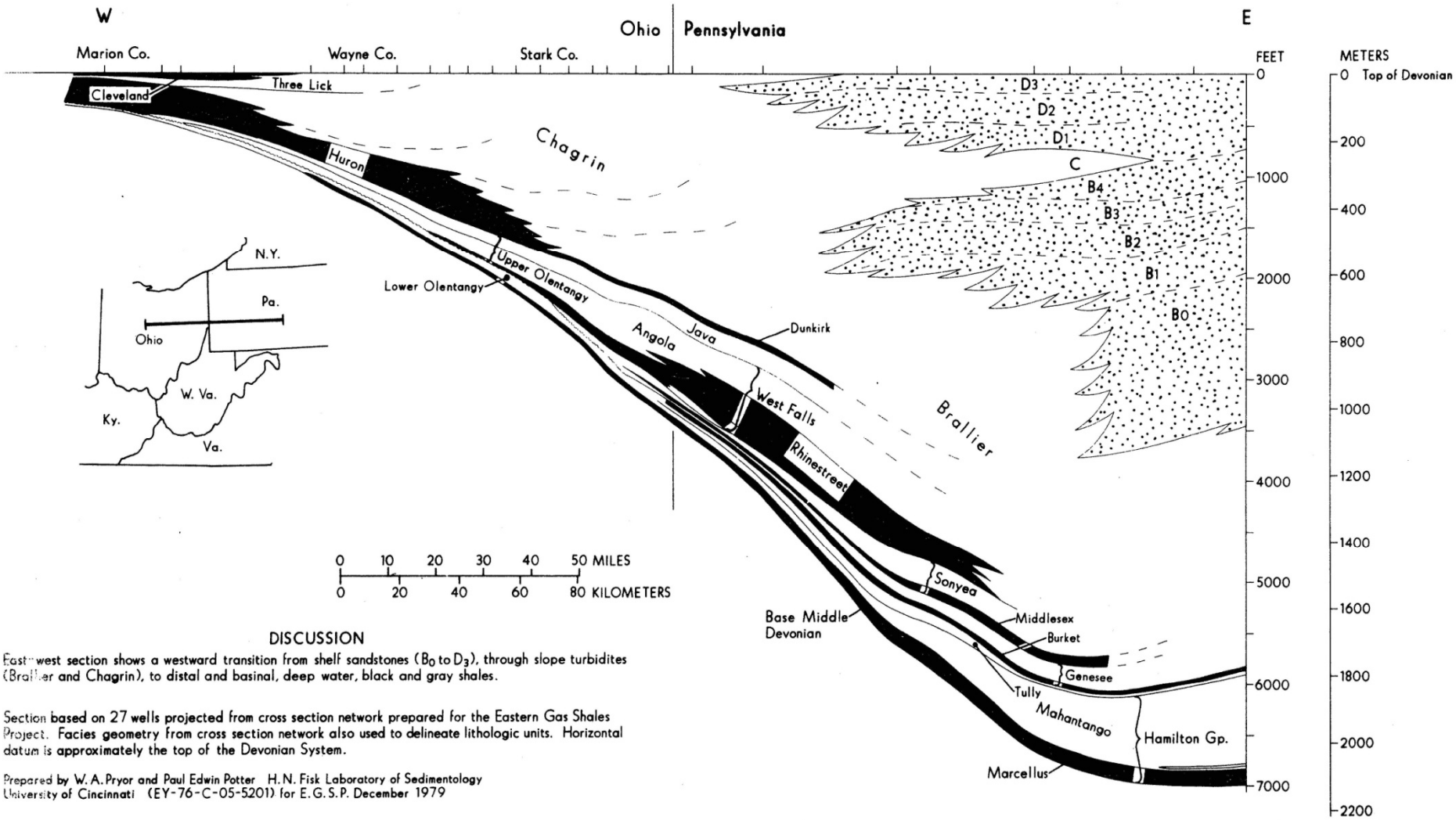
Schrider, L. A. and Wise, R.L., 1980, Potential new sources of natural gas: Journal of Petroleum Technology, April 1980, p. 703-716.

DOE Eastern Gas Shales Project 1976-1992



All photos - DOE

Middle to Upper Devonian Appalachian Basin



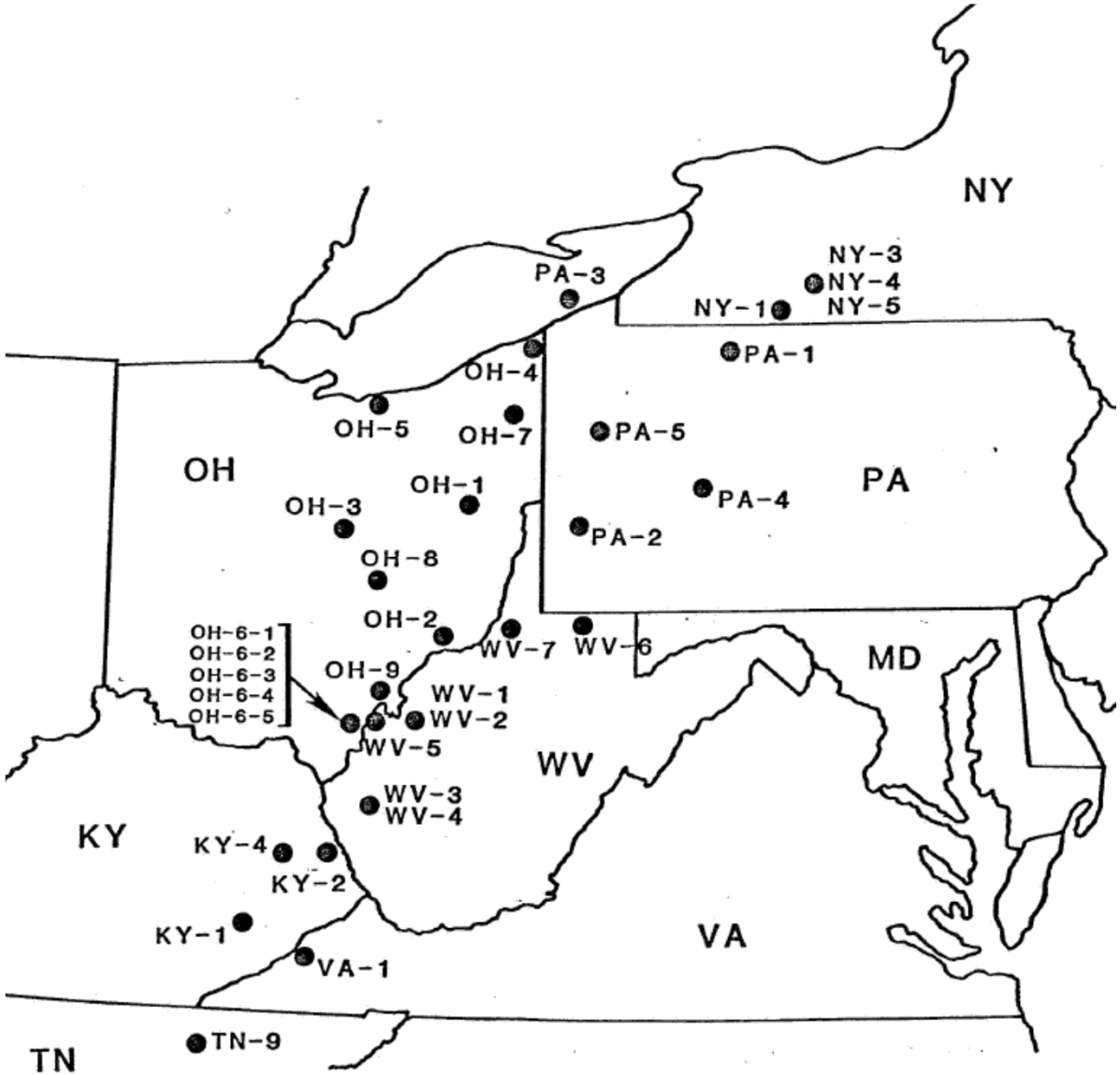
Potter, P.E., Maynard, B., and Pryor, W.A., 1980, Final report of special geological, geochemical, and petrological studies of the Devonian shales of the Appalachian Basin: University of Cincinnati, prepared for U.S. Department of Energy under contract EY-76-C-05-5201, January, 94 p.

EGSP Cored Well Locations

44 cores total

- 34 wells in the Appalachian Basin
  - Most Upper Devonian
  - Only 9 wells to Marcellus Shale
    - WV-6, WV-7
    - OH-4, OH-7, OH-8,
    - PA-1, PA-2, PA-4, PA-5
- 3 wells in Michigan Basin (Antrim Shale)
- 7 wells in the Illinois Basin (New Albany Shale)

- "Stimulation alone is insufficient to achieve commercial shale gas production." - Horton, 1981



Horton, A. I., 1981, A comparative analysis of stimulations in the eastern gas shales, report DOE/METC 145: U.S. Department of Energy, Morgantown Energy Technology Center, 120 p.

Gas Shale Geology

- Fine-grained, clastic mudrock, composed of clay, quartz, carbonate, organic matter, and other minerals.

- Shale is organic-rich (black), or organic lean (gray), and (by definition) fissile.

- Shale porosity (ϕ) ~ 10%
- Shale permeability (k): μd to nd

- Small grains = small pores = small flowpaths
- ϕ can be intergranular, intragranular, and intra-organic.

- Gas occurs in fractures, in pores and adsorbed or dissolved onto organic materials and clays.

Photo by Dan Soeder

Soeder, D. J., 1988, Porosity and permeability of eastern Devonian gas shale: SPE Formation Evaluation, v. 3, no. 2, p. 116-124, DOI 10.2118/15213-PA.

Petroleum Geology Review

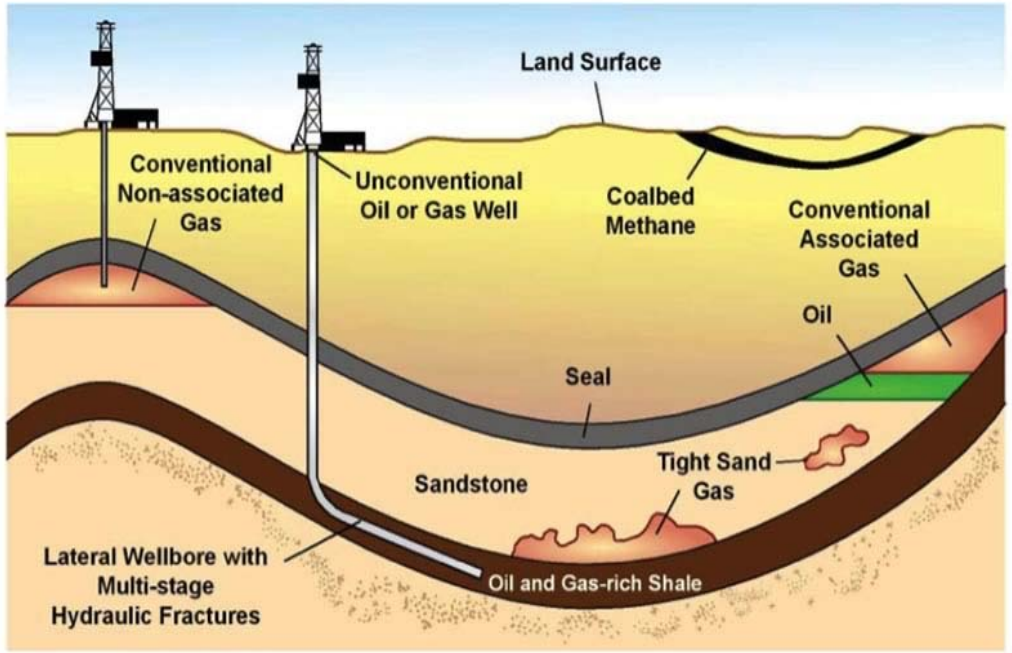
Conventional: concentrated deposit of recoverable oil and/or gas.

NEED:

1. Source rock: 1-2% organics
   a. Type I kerogen (lacustrine)
   b. Type II kerogen (marine)
   c. Type III kerogen (terrestrial)
2. Thermal maturity
3. Reservoir rock
4. Trap and Seal
5. Migration pathway

If any one of these is missing, no production.

The Geology of Conventional and Unconventional Oil and Gas



Source: EIA

Unconventional: production directly from a thermally-mature, high-organic content source rock. No reservoir rock, trap or seal needed.

- "My source rock is now my reservoir rock!" – Anonymous Geologist
- USGS calls this a "continuous resource" producible anywhere
- Drilling location is based on infrastructure, not geologic structure.

Charpentier, R.R., and Cook, T.A., 2011, USGS Methodology for Assessing Continuous Petroleum Resources: U.S. Geological Survey Open File Report 2011–1167, 75 p.

Defining the Engineering Challenge

< Conventional sandstone gas reservoir versus black shale >

Typical values:

Porosity (% void space)

< 20% 10%>

Water saturation (as % of occupied pore space)

< 40% 20%>

Gas volume/rock volume

<12% *8%>

* Excludes adsorbed component of gas

Permeability (dry gas)

< 10^{-3} darcy (md)

10^{-9} darcy (nd) >

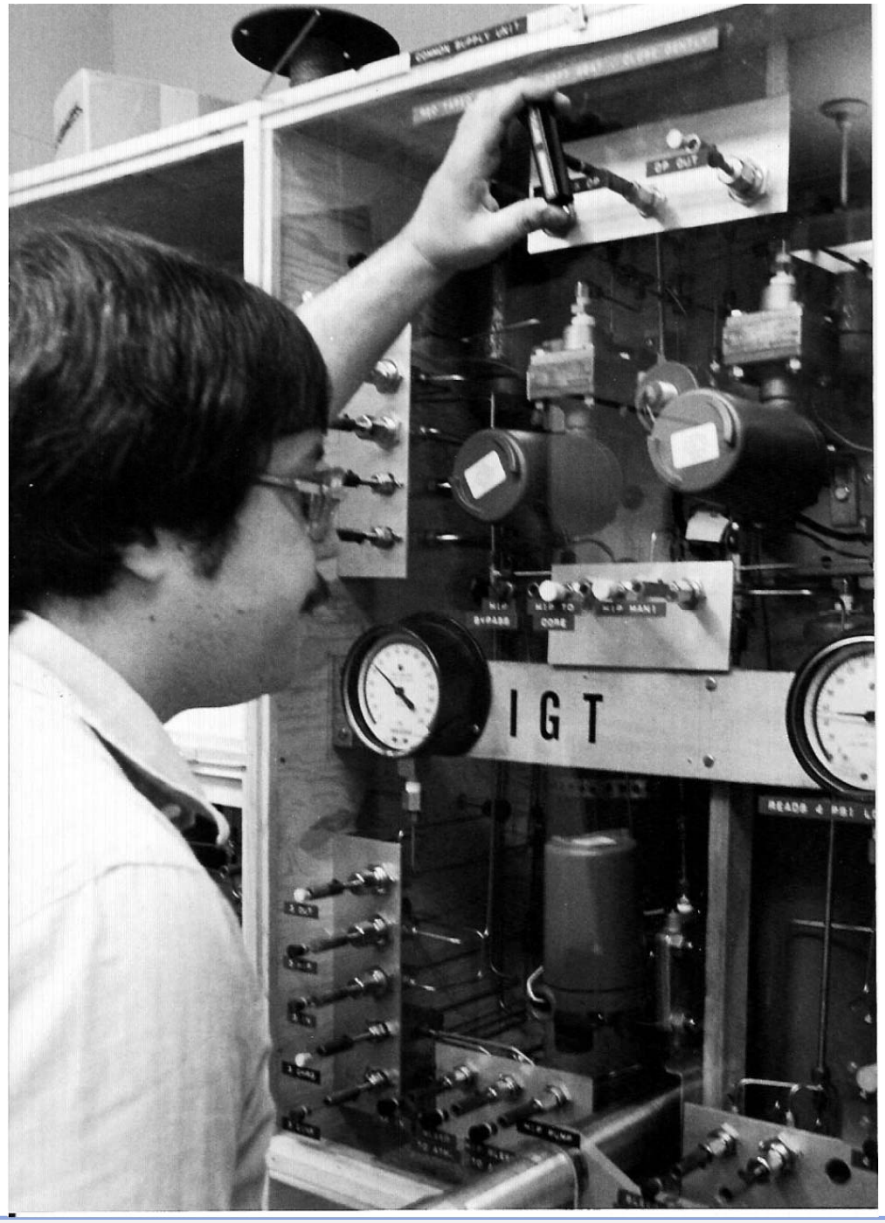
< Gas flow 1 $cm^3/cm^2/sec$

Gas flow 1 $cm^3/cm^2/10^6$ sec >

1 cc of gas/sq cm rock

< 1 sec 11.6 days >

1980's Core Analysis at IGT



Steady-state apparatus developed for ϕ and k on tight rocks

- Temperature control for pressure stability
- Could simulate *in situ* net confining stress and drawdown
- Could measure:
  - steady state k_{gas}
  - pore volume compressibility
  - ϕ to different gases
- Flow limits: 10^{-6} cm^3/sec (at STP)
- Provided research quality data not available from GRI method favored by industry

Designed by IGT for the DOE Multiwell Experiment (MWX) tight sands.

- Devonian shale core analyses in 1984: 7 Lower Huron and 1 Marcellus sample from EGSP
- Results published in 1986 as DOE reports, and in several SPE papers.

IGT and GRI formed GTI in 2000

Randolph, P.L., and Soeder, D.J., 1986, Rock matrix analysis of eastern gas shale and western tight gas sands, final report, DOE/MC/20342-9: Institute of Gas Technology, prepared for U.S. Department of Energy under contract DE-AC21-83MC20342, August, 152 p.

Shale gas was known to be significant in 1988

Porosity and Permeability of Eastern Devonian Gas Shale

Daniel J. Soeder, SPE, Inst. of Gas Technology

Summary. High-precision core analysis has been performed on eight Devonian gas shale samples from the Appalachian basin. Seven of the core samples consist of the Upper Devonian Age Huron member of the Ohio shale, six of which came from wells in the Ohio River valley, and the seventh from a well in east-central Kentucky. The eighth core sample consists of Middle Devonian Age Marcellus shale obtained from a well in Morgantown, WV.

The core analysis was originally intended to supply accurate input data for Devonian shale numerical reservoir simulation. Unexpectedly, the work has identified a number of geological factors that influence gas production from organic-rich shales. The presence of petroleum as a mobile liquid phase in the pores of all seven Huron shale samples effectively limits the gas porosity of this formation to less than 0.2%, and gas permeability of the rock matrix is commonly less than 0.1 μd at reservoir stress. The Marcellus shale core, on the other hand, was free of a mobile liquid phase and had a measured gas porosity of approximately 10%, and a surprisingly high permeability of 20 μd. Gas permeability of the Marcellus was highly stress-dependent, however; doubling the net confining stress reduced the permeability by nearly 70%.

The conclusion reached from this study is that the gas productivity potential of Devonian shale in the Appalachian basin is influenced by a wide range of geologic factors. Organic content, thermal maturity, natural fracture spacing, and stratigraphic relationships between gray and black shales all affect gas content and mobility. Understanding these factors can improve the exploration and development of Devonian shale gas.

Introduction

Organic-rich, Devonian-Age shales in the Illinois, Michigan, and Appalachian basins are considered a major potential source of future domestic natural gas by the U.S. government and the gas industry.[1] As such, both the U.S. Department of Energy (DOE) and the Gas Research Inst. (GRI) have been funding research aimed at encouraging better gas recovery from this resource through improvements in recovery technology and increased understanding of where gas is trapped and how gas is transported within the shale formations.

Most of the difficulties with Devonian shale gas production are related to the fact that the matrix permeability of these rocks is very low, and an extensive natural and/or manmade fracture system is required in the reservoir to move economical quantities of gas to a wellbore. Shale wells generally exhibit a fairly rapid initial decline curve as gas is drained from the fracture system, followed by a slow, gradual decline as gas from the matrix moves into the fractures. This type of reservoir results in a well that produces slowly and steadily over long periods. The typical productive life of a shale gas well is about 40 years, although a few wells in the Appalachian basin have been producing for more than 100 years.[1]

The DOE was trying to model gas production from the Devonian shales using complex numerical simulations. The modelers were encountering difficulties in their simulation attempts because of a number of uncertain or unknown shale gas reservoir properties that resulted in inaccurate input parameters for the computer model. The parameters that caused the modelers the greater problems included measurements of shale gas content that varied with stratigraphy and geographic location (for poorly understood reasons), total gas content determinations that contained an unknown component of adsorbed gas, and matrix porosity and permeability values that were very close to the resolution limits of the equipment used to make the measurements. Other properties, such as the nature of shale pore structure and the effect of confining pressure on shale permeability, were unknown.

To address some of these data uncertainties and provide accurate input parameters for the reservoir modelers, the Inst. of Gas Technology (IGT) measured the porosity, permeability, and other properties of a limited number of Devonian shale samples with recently developed, high-precision core-analysis apparatus. It should be emphasized that porosity and permeability are *not* single numbers to be measured and reported for each sample analyzed in the laboratory. Rather, these are coefficients that appear in the differential equations used to calculate fluid content and movement in porous media. For most high-porosity, high-permeability formations, adequate descriptions of well and reservoir performance can be achieved by assuming that these coefficients are constants. This is not a valid assumption for such tight formations as Devonian shale, however, where the small pore sizes affect fluid flow through the rock matrix on a molecular scale.

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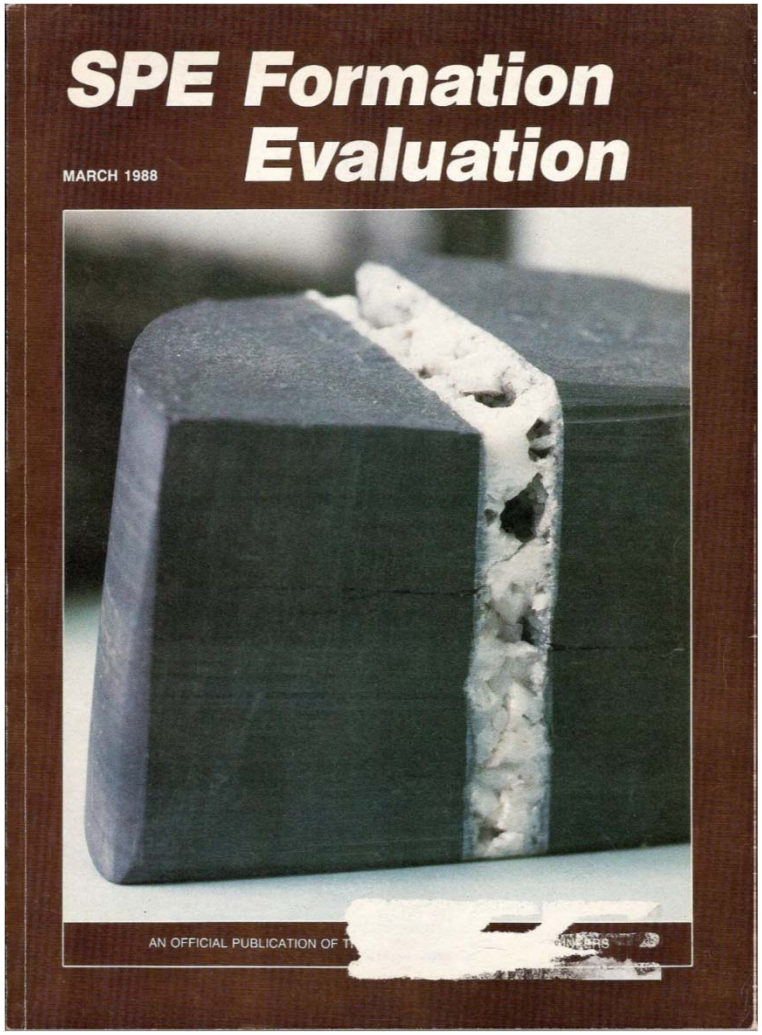
Core-Analysis Procedure

Between 1976 and 1981, the U.S. government cut and retrieved nearly 17,000 ft [5180 m] of Devonian shale drill core under the Eastern Gas Shale Project (EGSP).[2] This large supply of oriented core provided the raw material for the selection of a limited number of samples to be analyzed in our laboratory.

High-precision core analysis at IGT is performed in a device known as the computer-operated rock analysis laboratory (CORAL). CORAL is capable of measuring actual gas flow rates through rock as low as 10^{-6} std cm^3/s to an accuracy of a few percent, and can measure steady-state gas permeabilities with a resolution of ± 0.2 nd. Other rock properties measured by CORAL include gas porosity under stress with a resolution of about $\pm 2\%$ of the measured value, and PV compressibility. A description of the engineering and operational design of CORAL has been presented by Randolph.[3]

Although CORAL was originally designed to perform high-precision core-analysis measurements on western tight gas sandstones, it soon became apparent that the accuracy and high resolution of this equipment would also have applications to other tight gas formations, such as Devonian shale. In the past, there have been several situations where Devonian shale permeabilities were reported from runs in equipment designed for tight sands.[4,5] In both cases reported, the porosity and permeability values measured were near the resolution limits of the equipment, resulting in a significant degree of uncertainty concerning the accuracy of the data. The approach taken toward the Devonian shale core measurements at IGT was to try to understand how the composition and internal pore structure of the rock control gas flow through the matrix into the fracture system, and thereby define the long-term gas production rates in a wellbore.

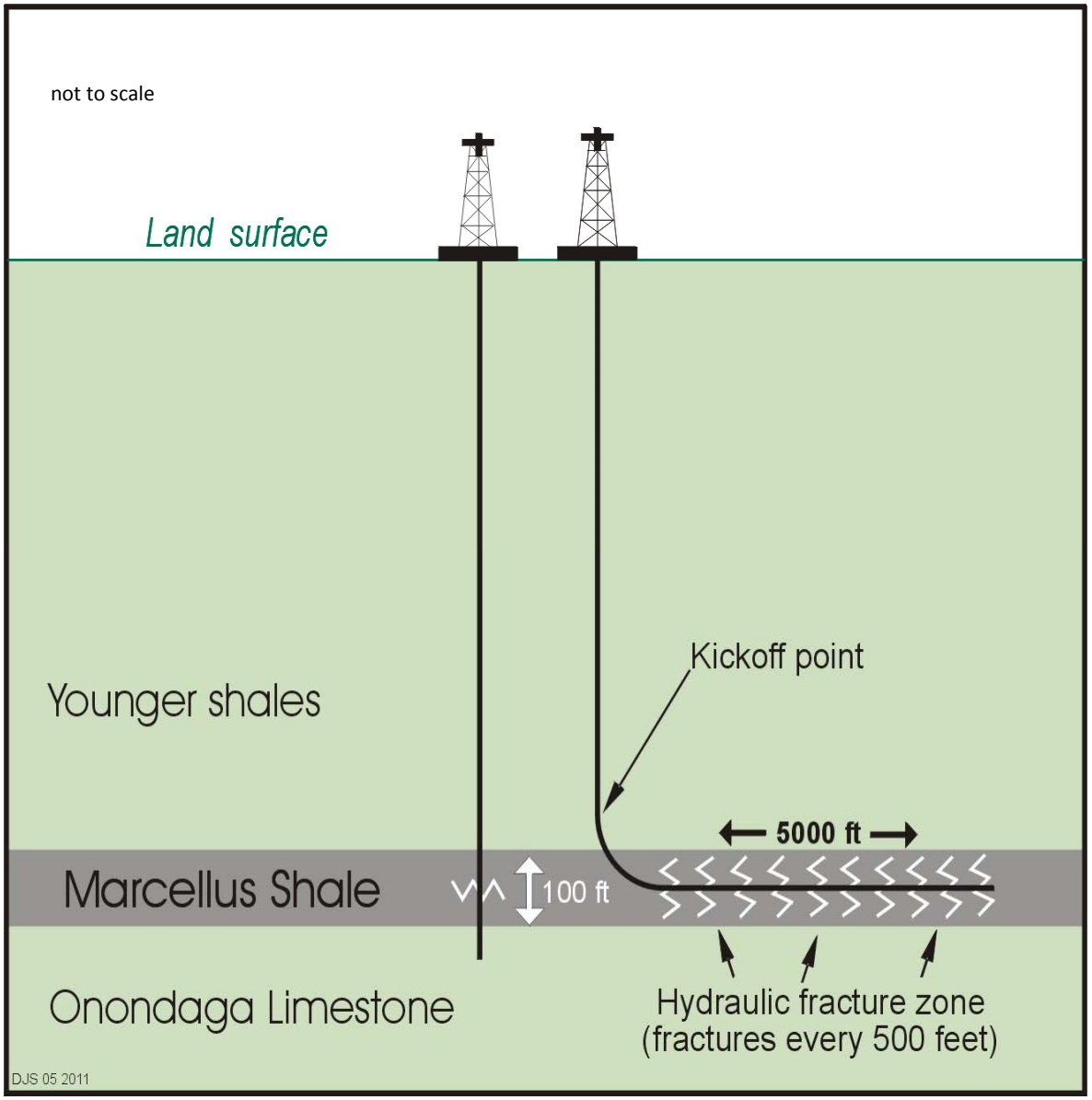
Twenty-eight zones of interest were sampled from 13 EGSP cores selected from a list supplied by DOE. Portions of the shale section



But we lacked the technology to produce it.

Soeder, D. J., 1988, Porosity and permeability of eastern Devonian gas shale: SPE Formation Evaluation, v. 3, no. 2, p. 116-124, DOI 10.2118/15213-PA.

New Technology for Shale Gas Production



Directional drilling

- Downhole hydraulic motors
- Non-rotating drill pipe can bend
- Geosteering:
  - Measurement while drilling
  - Inertial navigation
  - Telemetry: better electronics
- 5,000+ ft. laterals (9,000 ft. max)
- Developed for deepwater tension leg platforms
- Applied onshore by Mitchell Energy in Ft. Worth Basin, Texas.

Staged hydraulic fracturing

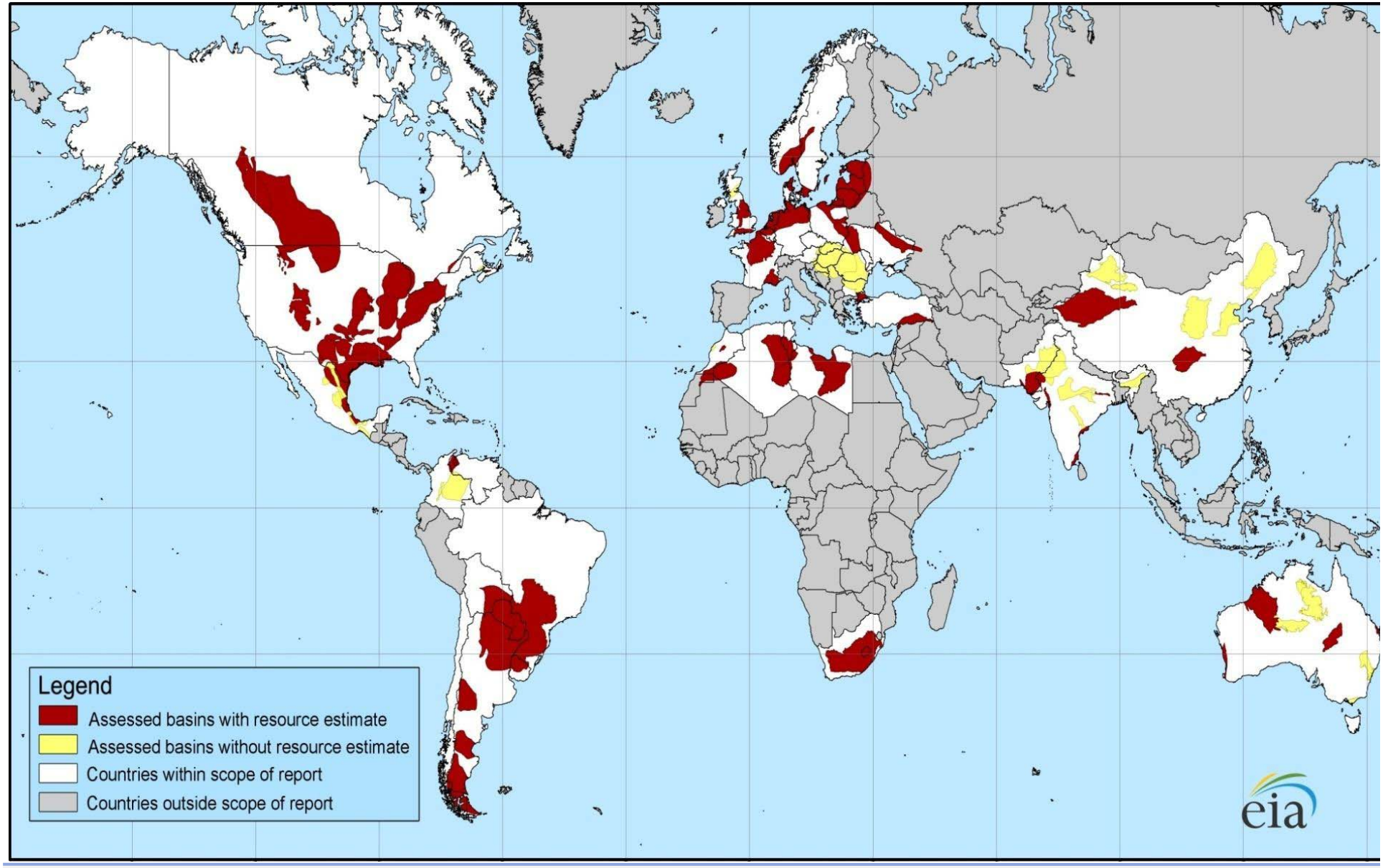
- Light sand frac/slickwater frac
- Up to 30 stages per lateral
- Fast flowpaths in contact with large volume of rock

Barnett Shale: 1997; Mitchell Energy
Fayetteville Shale: 2004; Southwestern
Haynesville Shale: 2004; Chesapeake
Bakken/Three Forks: 2006; EOG
Marcellus Shale: 2007; Range: Gulla #9
Niobrara Formation: 2009 Wattenberg

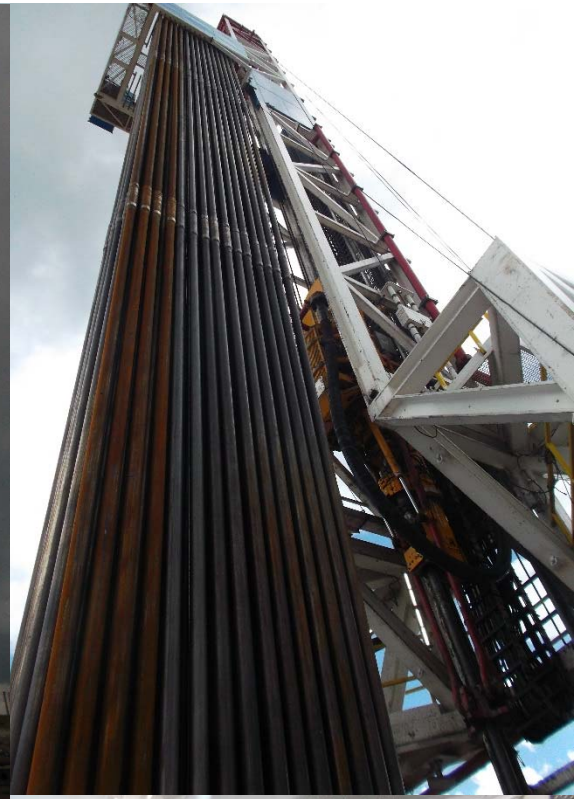
Figure from Soeder, D.J., 2012, Shale gas development in the United States, Chapter 1 in Advances in Natural Gas Technology, Edited by Hamid A. Al-Megren, ISBN 978-953-51-0507-7, InTech Open Access, Rijeka, Croatia, April 11, 2012; DOI: 10.5772/2324, 542 pages.

Source: U.S. Energy Information Administration based on data from various published studies. Canada and Mexico plays from ARI.
Updated: May 9, 2011

Shale Gas Worldwide



Source: U.S. Energy Information Administration

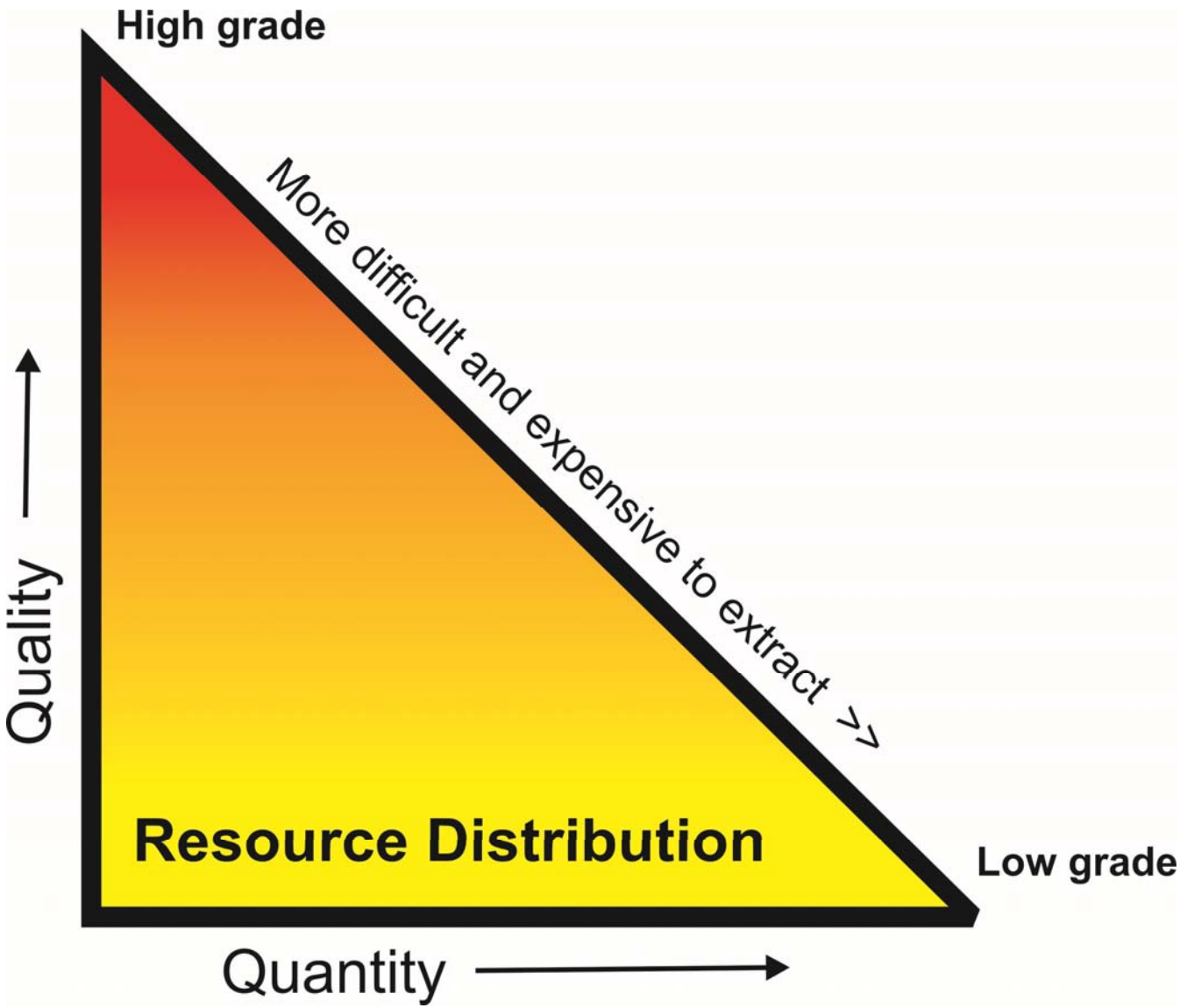


New Technology

High volume hydraulic fracturing is necessary to recover economic amounts of gas.

Photo by Dan Soeder, 2011

Why is the resource so large?

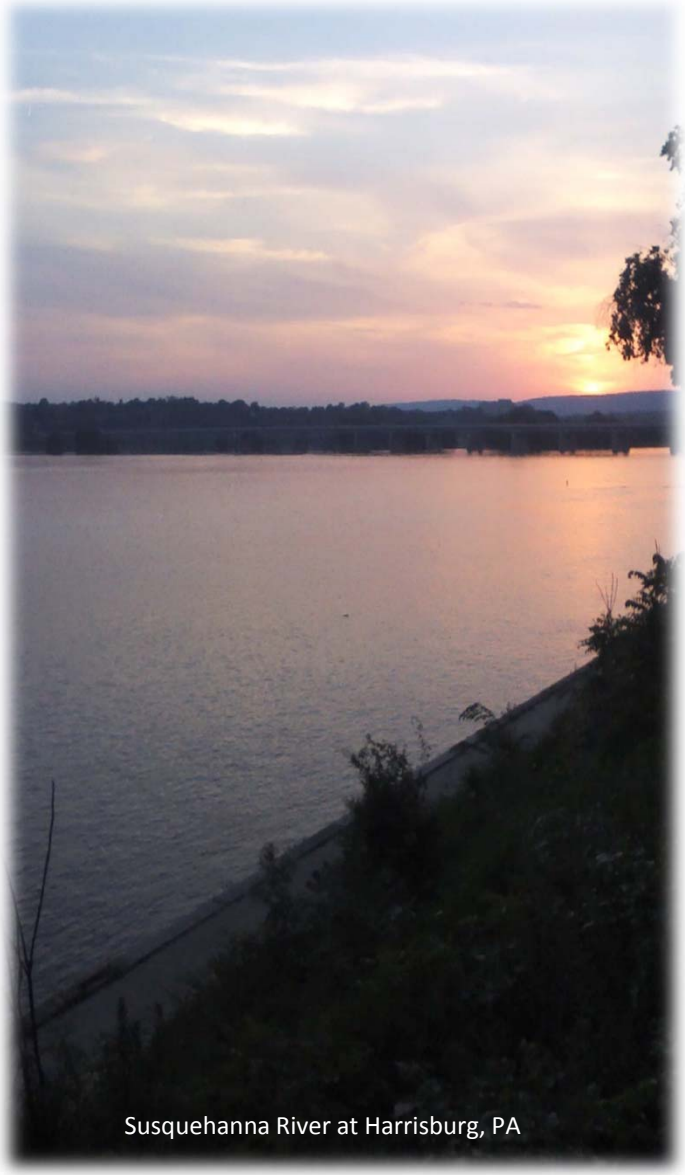


Environmental Concerns

- **Can hydraulic fracturing contaminate shallow groundwater? (GWPC)**
- **Can large volumes of shale cuttings and other solids contaminate groundwater? (NETL)**
- **Does shale gas development cause stray gas migration in shallow aquifers? (NGWA)**
- **How might shale gas development cause detrimental human health effects? (HEI)**
- **Are there legacy environmental data that can provide a pre-drill baseline in areas of shale gas development? (USGS)**

NETL Assessments:

- Fugitive Air Emissions and GHG
- Produced Water Management
- Subsurface Migration of Gas and Fluids
- Induced Seismicity



Susquehanna River at Harrisburg, PA

Soeder, D. J., Sharma, S., Pekney, N., Hopkinson, L., Dilmore, R., Kutchko, B., Stewart, B., Carter, K., Hakala, A., and Capo, R., 2014, An approach for assessing engineering risk from shale gas wells in the United States, International Journal of Coal Geology, Vol. 126, p. 4-19

NETL Engineering Risk Assessments

Engineering Risk

- Mechanism of release: How are contaminants entering the environment?
- Fate and transport: Where are the contaminants going and how fast are they getting there?
- Probability of release: What are the risks at different stages of drilling, stimulation, completion, and production?

Approach

- Field Data to establish baselines and impacts of processes
- Laboratory Data for simulations and confirmation of field data
- Computational Tools to characterize and predict system baselines and behavior

Photograph of Indian Run, WV by Doug Mazer, used with permission

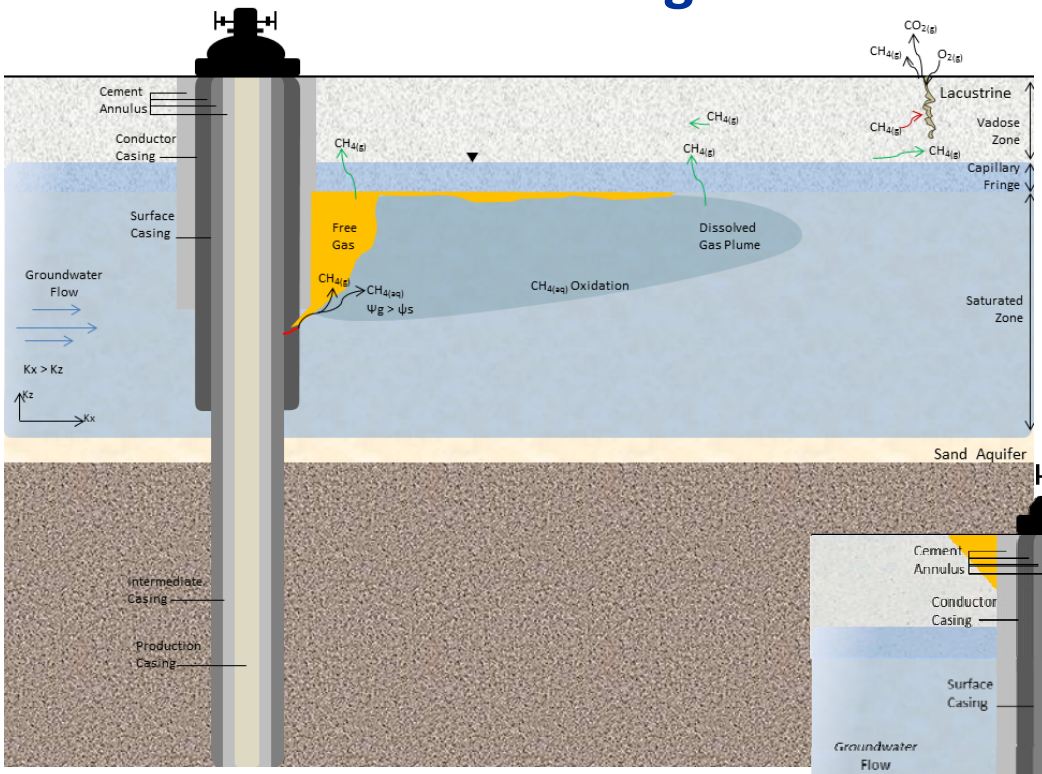
Soeder, D. J., Sharma, S., Pekney, N., Hopkinson, L., Dilmore, R., Kutchko, B., Stewart, B., Carter, K., Hakala, A., and Capo, R., 2014, An approach for assessing engineering risk from shale gas wells in the United States, International Journal of Coal Geology, Vol. 126, p. 4-19

Groundwater Risk per Production Phase

Production Activity	Potential GW Risks
initial spud-in	air/fluid infiltration into aquifer, methane migration
set surface casing; drill vertical well	well integrity: annular migration of fluids from open hole
set intermediate casing; drill lateral	low risk to groundwater
set production casing; complete well	frac chemicals on site; surface spills, potential leakage
hydraulic fracturing	abandoned wells, faults; frac chemicals on site; P-wave through aquifer
flowback and produced waters	frac chemicals and high TDS waters on site; surface spills, potential leakage
long-term gas production	well integrity: casing/cement deterioration; potential weathering of cuttings

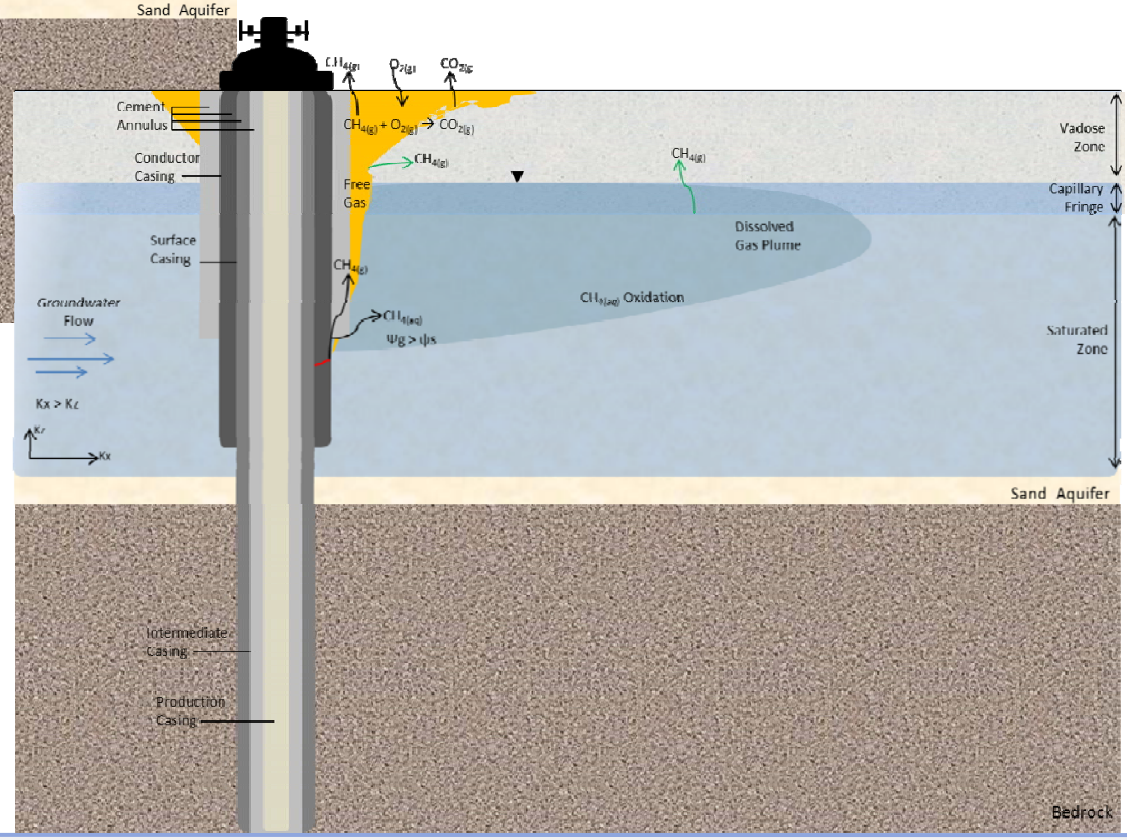
Source: Soeder, D. J., Sharma, S., Pekney, N., Hopkinson, L., Dilmore, R., Kutchko, B., Stewart, B., Carter, K., Hakala, A., and Capo, R., 2014, An approach for assessing engineering risk from shale gas wells in the United States, International Journal of Coal Geology, Vol. 126, p. 4-19

Gas Migration and Wellbore Integrity



< Conceptual model of gas migration from wellbore leakage into a confined aquifer.

Transport mechanisms for dissolved gas include diffusion, dispersion, or advection. Free gas moves as bubbles or a slug.

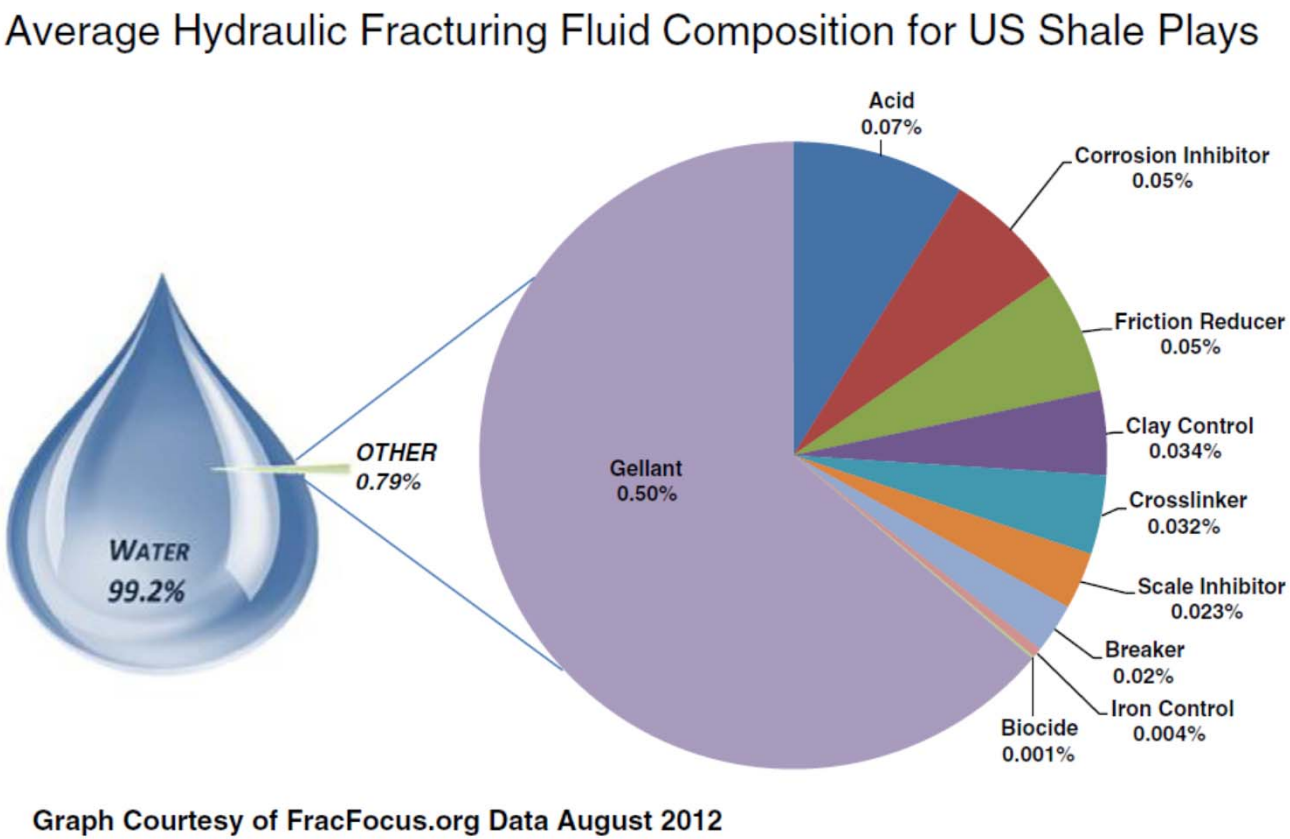


Conceptual model of gas migration from wellbore leakage into an unconfined aquifer. >

Could transmission of frac pressure through cement-filled annulus cause cracking/de-bonding when released, creating micro-annuli?

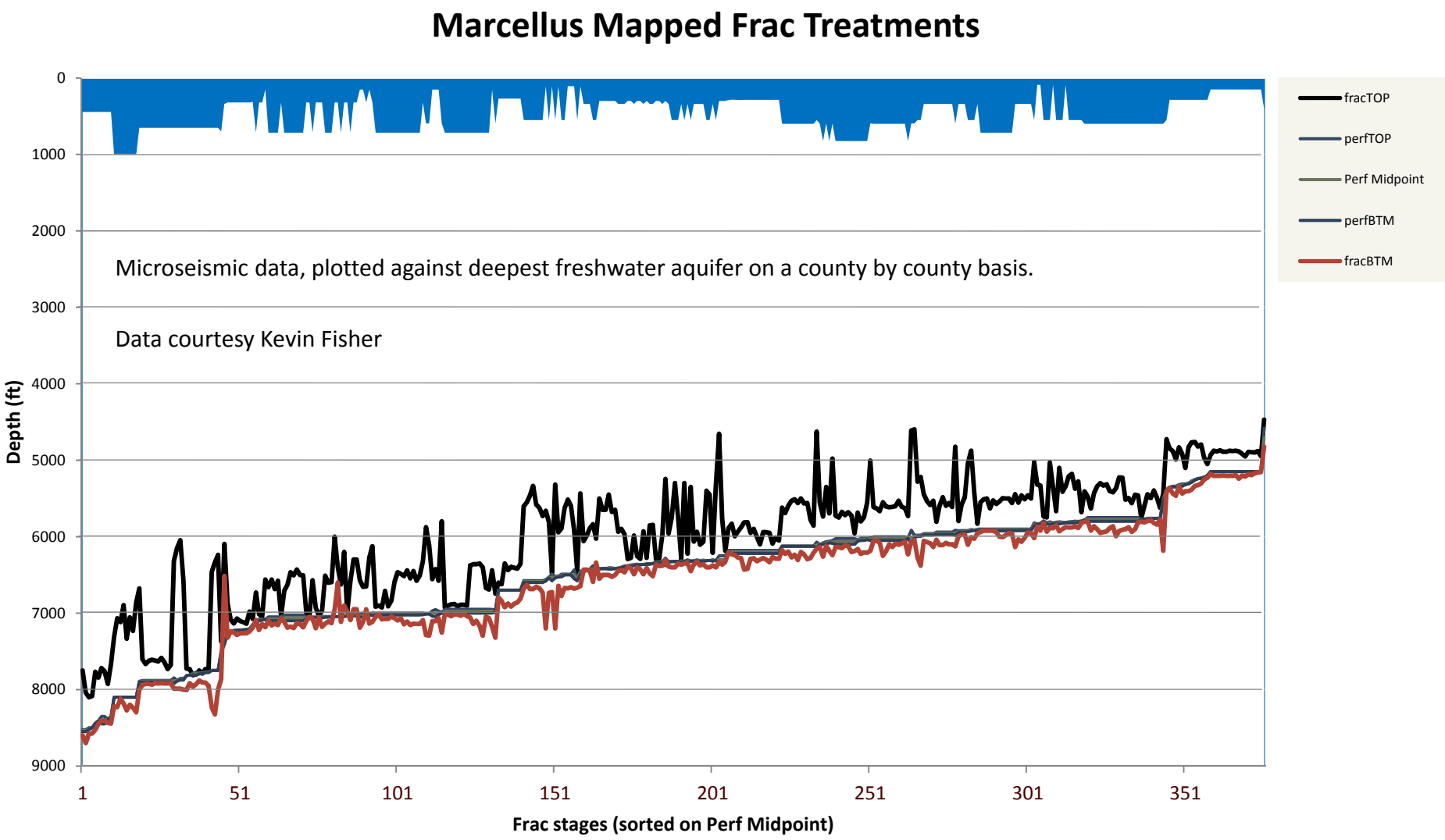
Source: Canadian Water Network, adapted from Vidic, R., Brantley, S.L., Vandenbossche, J.M., Yoxtheimer, D., and Abad, J.D., 2013, Impact of shale gas development on regional water quality: Science 340, 1235009. (DOI: 10.1126/science.1235009)

Frac Fluid Chemicals



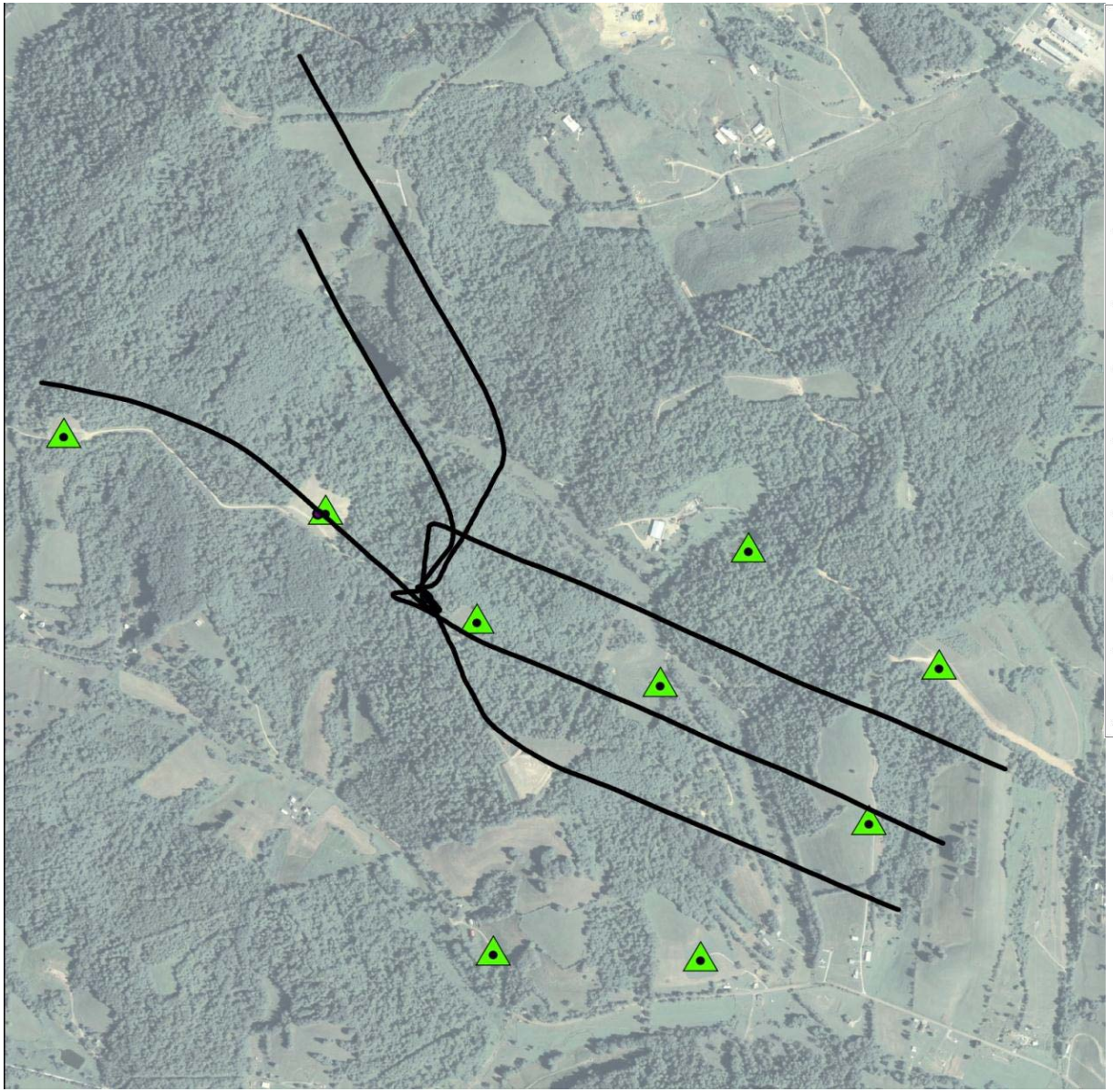
Source: Ground Water Protection Council, 2012, FracFocus well records: January 1, 2011 through February 27, 2012: accessed on-line at http://www.fracfocus.org

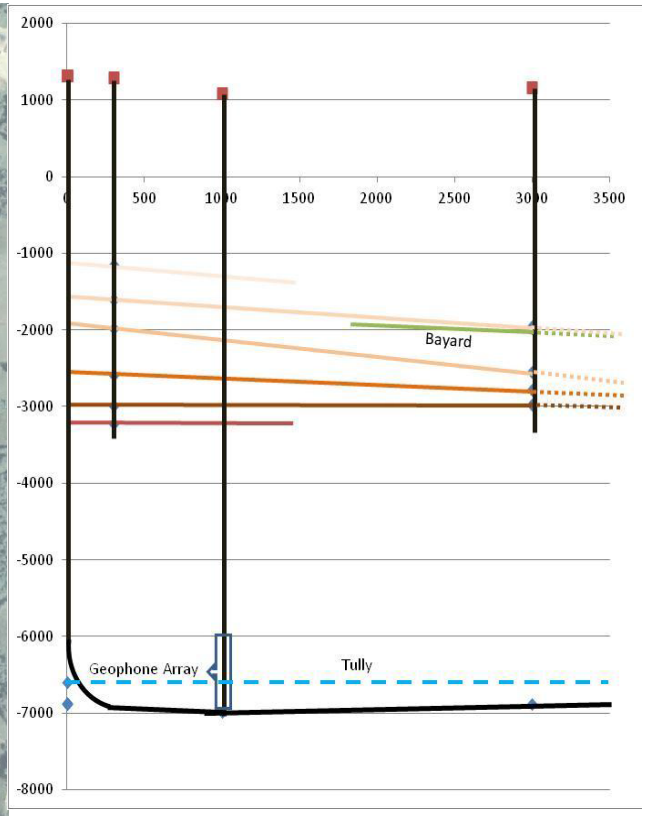
Out of Zone Fractures



Fisher, Kevin, 2010, Data confirm safety of well fracturing, The American Oil and Gas Reporter, July 2010, www.aogr.com

Greene County Well Site





Marcellus horizontal well drilled below existing Upper Devonian production sands.

Pre-existing vertical Marcellus well between laterals.

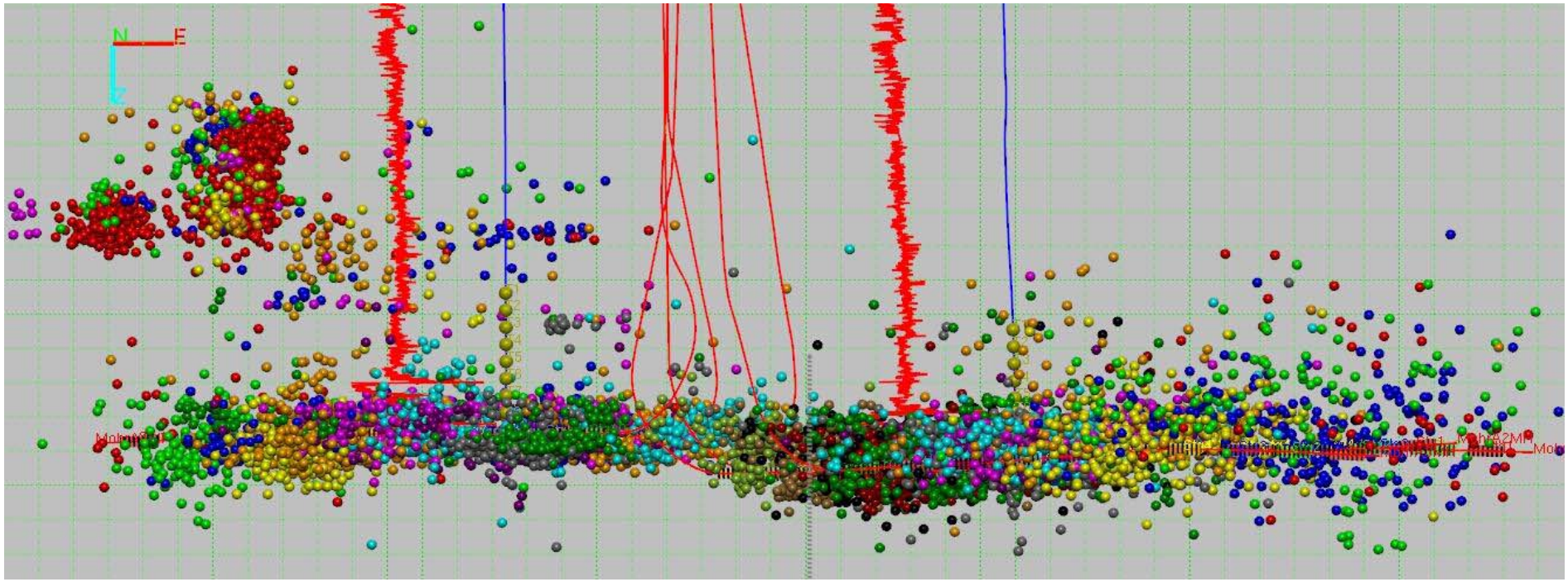
PFC tracers in frac fluid to detect gas migration.

Microseismic monitoring during frac

Hammack, R., Harbert, W., Sharma, S., Stewart, B., Capo, R., Wall, A., Wells, A., Diehl, R., Blaushild, D., Sams, J., Veloski, G., 2014, An Evaluation of Fracture Growth and Gas/Fluid Migration as Horizontal Marcellus Shale Gas Wells are Hydraulically Fractured in Greene County, Pennsylvania; NETL-TRS-3-2014; EPAct Technical Report Series; U.S. Department of Energy, National Energy Technology Laboratory: Pittsburgh, PA, 76 p.

Greene County Tracer Study

- **Goal: determine if gas from the Marcellus Shale was migrating upward into the overlying Upper Devonian sandstone after the hydraulic fracture treatment.**
- **Perflurocarbon (PFC) tracer added to frac fluid during injection.**
- **PFC volatilizes and migrates with the natural gas.**
- **Post-frac pressure and chemical monitoring; production well from Upper Devonian sand sampled monthly.**
- **Reservoir model realizations suggest 8+ years migration time.**



Zhang, Liwei, Anderson, Nicole, Dilmore, Robert, Soeder, Daniel J., and Bromhal, Grant, 2014, Leakage Detection of Marcellus Shale Natural Gas at an Upper Devonian Gas Monitoring Well: A 3-D Numerical Modeling Approach: Environ. Sci. Technol., August 2014, V.48, p. 10795−10803; dx.doi.org/10.1021/es501997p.

Types of Accessible Gas Wells

Research Well

Non-commercial well drilled for research purposes.

Driller is paid up-front for cost of well; does not need to produce it for revenue.

Greatest freedom for researchers, but also the most expensive option.

Transparent Well

Commercial well drilled on university or government land.

Agency/university owns mineral rights; driller must produce well for revenue.

Terms of the lease agreement require the driller to allow various environmental monitoring programs to take place during well development.

Commercial Well

Investor-owned well drilled on a commercial lease.

Driller must produce well for revenue to cover costs.

Research access is at the discretion of the driller, and the landowner holding the lease.

Other options include piggy-back coring operations, formation water sampling, additional geophysics and logging, etc., usually for the cost of rig time.

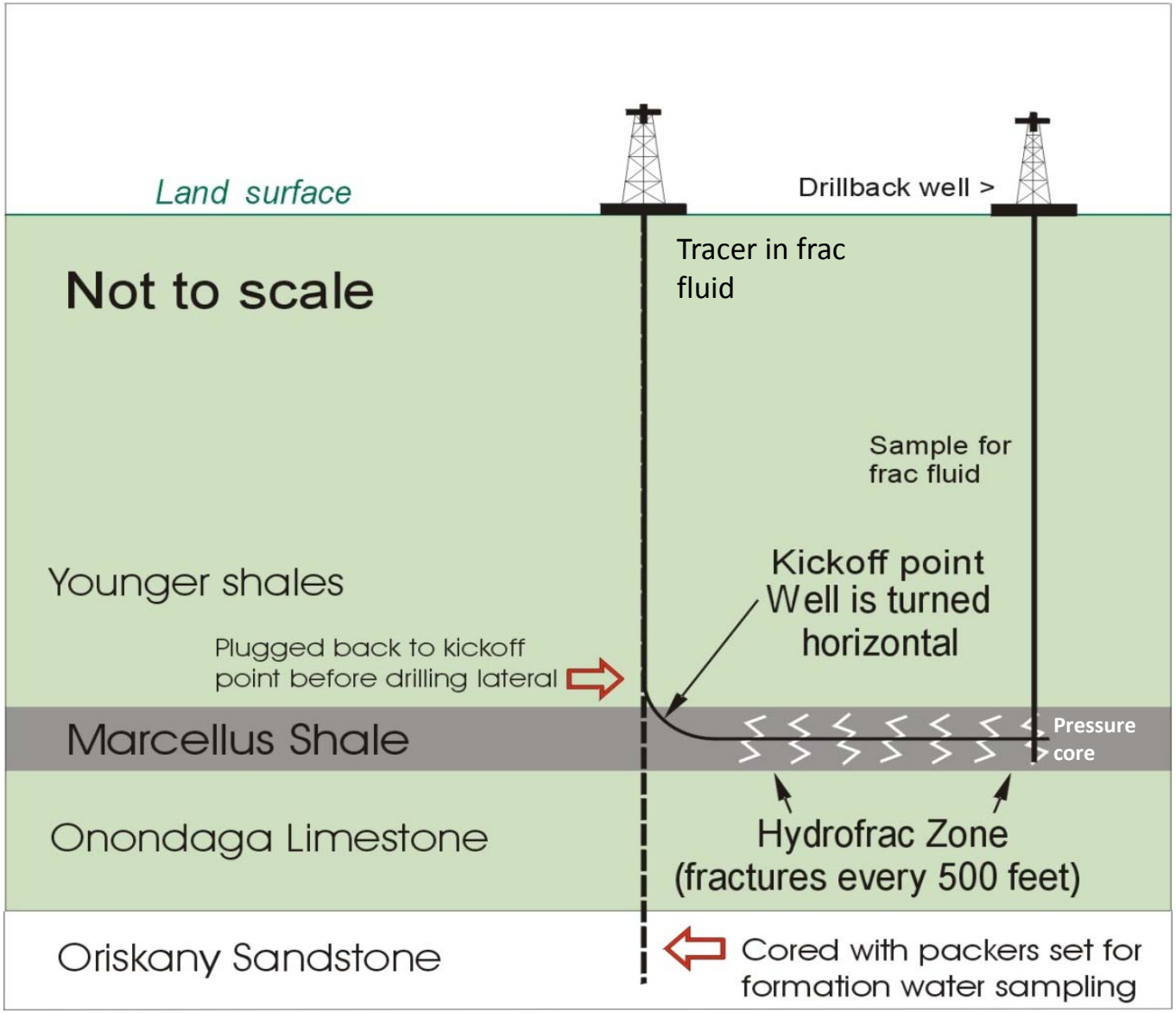
West Virginia University Study Site

- **Marcellus Shale wells on existing wellpad in Westover industrial park.**

- **First two wells on site were drilled/fracked in 2012; next 2 wells in 2015.**
- **NETL is funding WVU and Ohio State to carry out wide range of scientific studies**
- **Driller has provided access to drill core, sidewall core, well logs, drilling data, downhole fluids, geophysical data, and air monitoring.**
- **Drilling schedule defined by need to supply gas to Morgantown by winter.**
- **Land access is held by industrial park; owners have refused to allow any groundwater monitoring wells to be installed for this study.**

Photo: Northeast Natural Energy drillpad with wells in Westover, West Virginia. Photo by Dan Soeder

Schematic of a possible research well



By Dan Soeder, concept first drawn 2010

Questions?

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References Cited:

Soeder, D.J., 2012, Shale gas development in the United States, Chapter 1 in Advances in Natural Gas Technology, Edited by Hamid A. Al-Megren, ISBN 978-953-51-0507-7, InTech Open Access, Rijeka, Croatia, April 11, 2012; DOI: 10.5772/2324, 542 pages

Schrider, L. A. and Wise, R.L., 1980, Potential new sources of natural gas: Journal of Petroleum Technology, April 1980, p. 703-716

Soeder, D. J., 1988, Porosity and permeability of eastern Devonian gas shale: SPE Formation Evaluation, v. 3, no. 2, p. 116-124, DOI 10.2118/15213-PA.

Potter, P.E., Maynard, B., and Pryor, W.A., 1980, Final report of special geological, geochemical, and petrological studies of the Devonian shales of the Appalachian Basin: University of Cincinnati, prepared for U.S. Department of Energy under contract EY-76-C-05-5201, January, 94 p.

Horton, A. I., 1981, A comparative analysis of stimulations in the eastern gas shales, report DOE/METC 145: U.S. Department of Energy, Morgantown Energy Technology Center, 120 p.

Charpentier, R.R., and Cook, T.A., 2011, USGS Methodology for Assessing Continuous Petroleum Resources: U.S. Geological Survey Open File Report 2011–1167, 75 p.

Engelder, T., and Lash, G.G., 2008, Marcellus Shale play's vast resource potential creating stir in Appalachia: The American Oil and Gas Reporter, May, p. 7.

Soeder, D. J., Sharma, S., Pekney, N., Hopkinson, L., Dilmore, R., Kutchko, B., Stewart, B., Carter, K., Hakala, A., and Capo, R., 2014, An approach for assessing engineering risk from shale gas wells in the United States, International Journal of Coal Geology, Vol. 126, p. 4-19

Vidic, R., Brantley, S.L., Vandenbossche, J.M., Yoxtheimer, D., and Abad, J.D., 2013, Impact of shale gas development on regional water quality: Science 340, 1235009. (DOI: 10.1126/science.1235009)

Fisher, Kevin, 2010, Data confirm safety of well fracturing, The American Oil and Gas Reporter, July 2010 (follow up paper in *SPE Production & Operations, 2012, v. 27, no. 1, p. 8-19.*

Hammack, R., Harbert, W., Sharma, S., Stewart, B., Capo, R., Wall, A., Wells, A., Diehl, R., Blaushild, D., Sams, J., Veloski, G., 2014, An Evaluation of Fracture Growth and Gas/Fluid Migration as Horizontal Marcellus Shale Gas Wells are Hydraulically Fractured in Greene County, Pennsylvania; NETL-TRS-3-2014; EPAct Technical Report Series; U.S. Department of Energy, National Energy Technology Laboratory: Pittsburgh, PA, 76 p.

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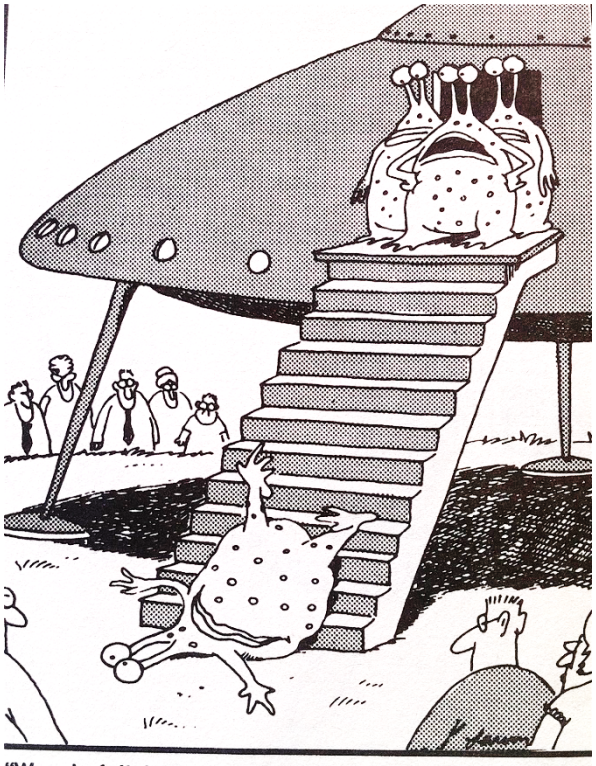

"Wonderful! Just wonderful! . . . So much for instilling them with a sense of awe."