



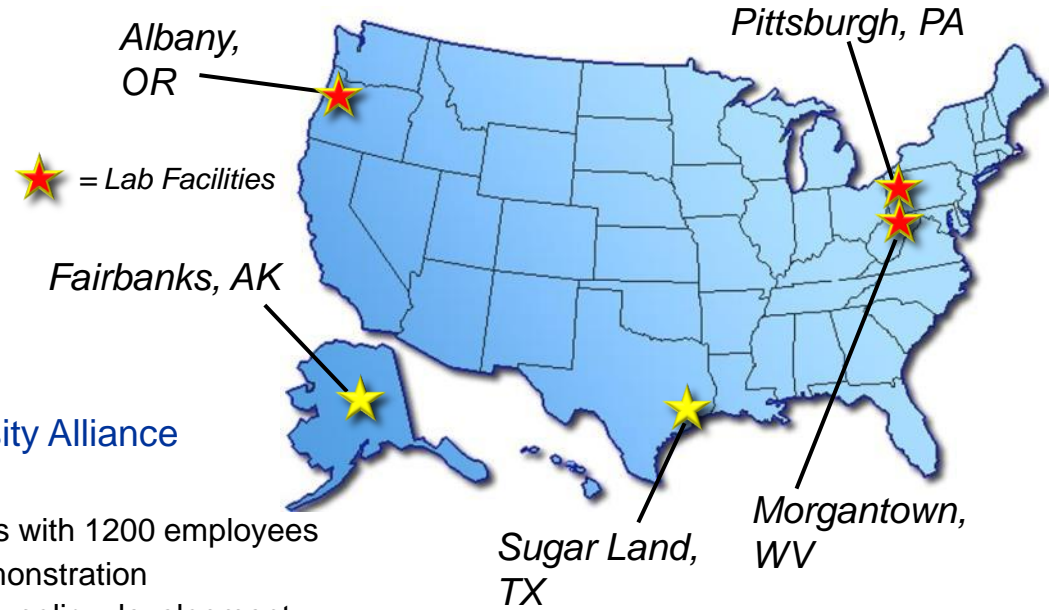
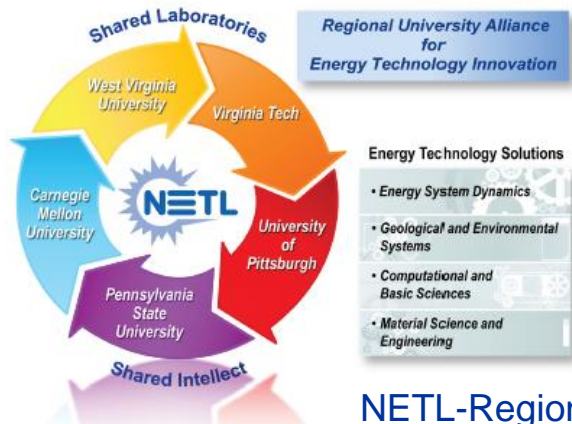
## **The Successful Development of Shale Gas Resources in the United States**

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Daniel J. Soeder, NETL, Morgantown, WV

Presentation for Chesapeake Bay Program STAC  
State College, PA, April 11, 2012

# DOE National Energy Technology Laboratory



- National lab dedicated to fossil energy; 3 sites with 1200 employees
- From fundamental science to technology demonstration
- Onsite research, extramural R&D, and energy policy development



Oregon



Pennsylvania



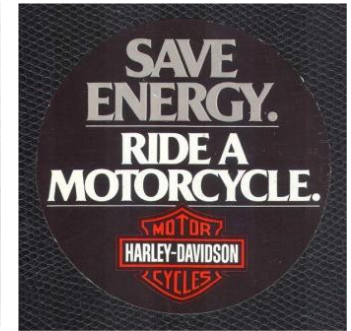
West Virginia

**NATIONAL ENERGY TECHNOLOGY LABORATORY**

# 1973-74 “Energy Crisis”

- **October 6-25, 1973: Yom Kippur War (Arabs vs. Israel)**
  - Rabinovich, Abraham, 2004, *The Yom Kippur War: The Epic Encounter That Transformed the Middle East*. Schocken Books (Random House), New York, NY, 543 p. (ISBN:0805241760)
- **October 20, 1973 to Spring 1974: OPEC oil embargo**
  - Many service stations had no gas; those with gas had long lines
  - Price of gasoline quadrupled in United States (0.40 - \$1.60)
  - At today's prices: \$4.00/gallon to \$16.00/gallon
  - Imports were 40% of U.S. oil use; not all OPEC members signed on
- **Second Energy Crisis: Iran - 1979**
  - Turmoil over fall of the Shah disrupted oil exports
  - Not as severe - Saudi Arabia was able to make up shortfall
  - Yergin, Daniel, 1991, *The Prize: The Epic Quest for Oil, Money, and Power*. Simon & Schuster, New York, NY, 912p. (ISBN: 0671502484)

# Oil Embargo!



- It is hard to overstate the trauma of this event to the American public
- Post WWII: many Americans had moved into new suburban housing
- Suburban life required an automobile for almost every task: work, shopping, school, church, etc.
- Suburbs lacked mass transit options like cities.
- Suburbs were accessed via another new invention, the freeway.
- People felt stuck in the middle of nowhere with a useless car

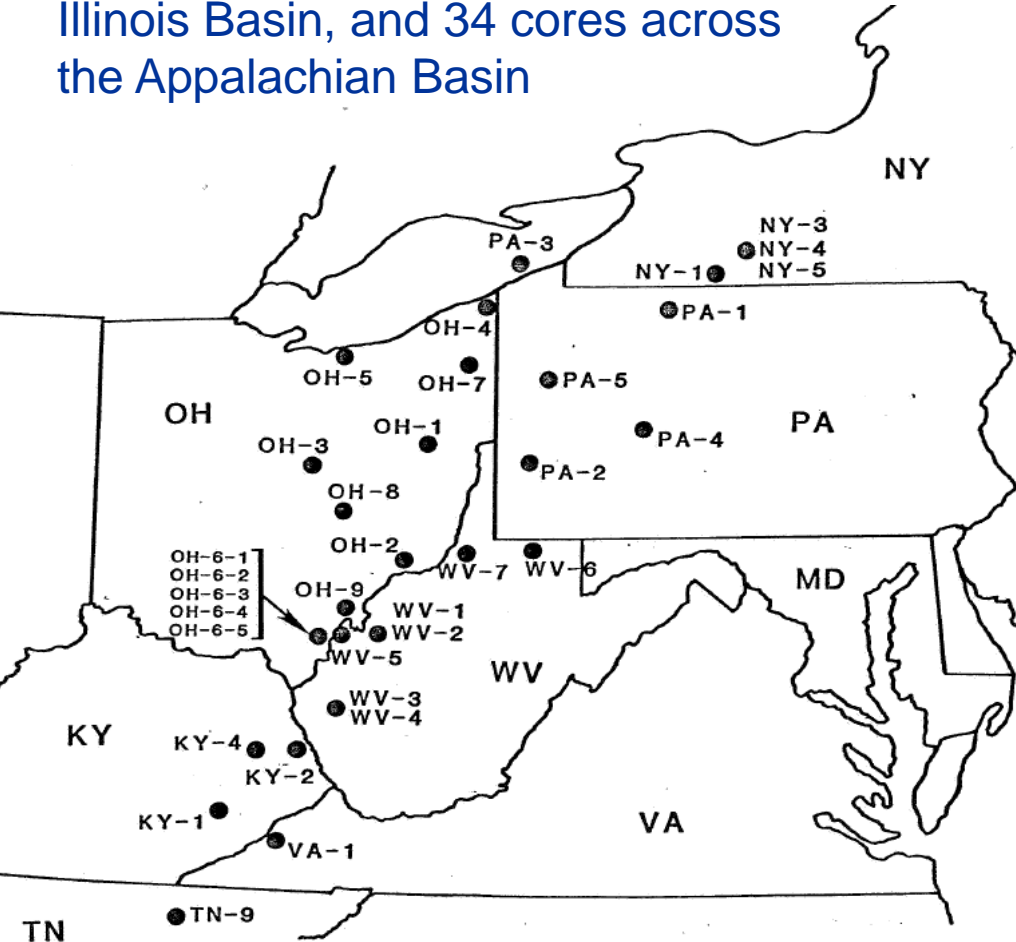


# U.S. DEPARTMENT OF **ENERGY**

- **U.S. Department of Energy created by Carter Administration.**
  - Authorized by Congress on August 4, 1977
  - James R. Schlesinger was the first Secretary of Energy
- **Mission: Encourage the development of domestic sources of energy to replace imports.**
- **A number of natural gas R&D projects were funded by DOE to increase domestic energy supplies**
  - **Eastern Gas Shales**
  - Western Tight Gas Sands
  - Coal Bed Methane
  - Later projects: methane hydrates, E&P research, environmental studies.
- **Components of DOE natural gas energy projects**
  - Resource characterization
  - Development of improved technology and engineering
  - Technology transfer to industry

# DOE Eastern Gas Shales Project 1976-1992

44 total cores, including 3 from the Antrim Shale of the Michigan Basin, 7 from the New Albany Shale of the Illinois Basin, and 34 cores across the Appalachian Basin



# Gas Shale Geology

- ❖ Sedimentary rock formed from mud, composed of fine-grained clay, quartz, organic matter, and other minerals.
- ❖ Shale (mudstone) types:
  - ❖ organic-rich (black)
  - ❖ organic lean (gray or red)
- ❖ Porosity ~ 10%
- ❖ Permeability  $\mu\text{d}$  to  $\text{nd}$ .
- ❖ Small grains = small pores: flat pores between flakes, porosity within minerals, nanopores within the organic matter.
- ❖ Gas occurs in fractures, in pores and adsorbed or dissolved onto organic materials and clays.



10  $\mu\text{m}$

Parallel clay flakes

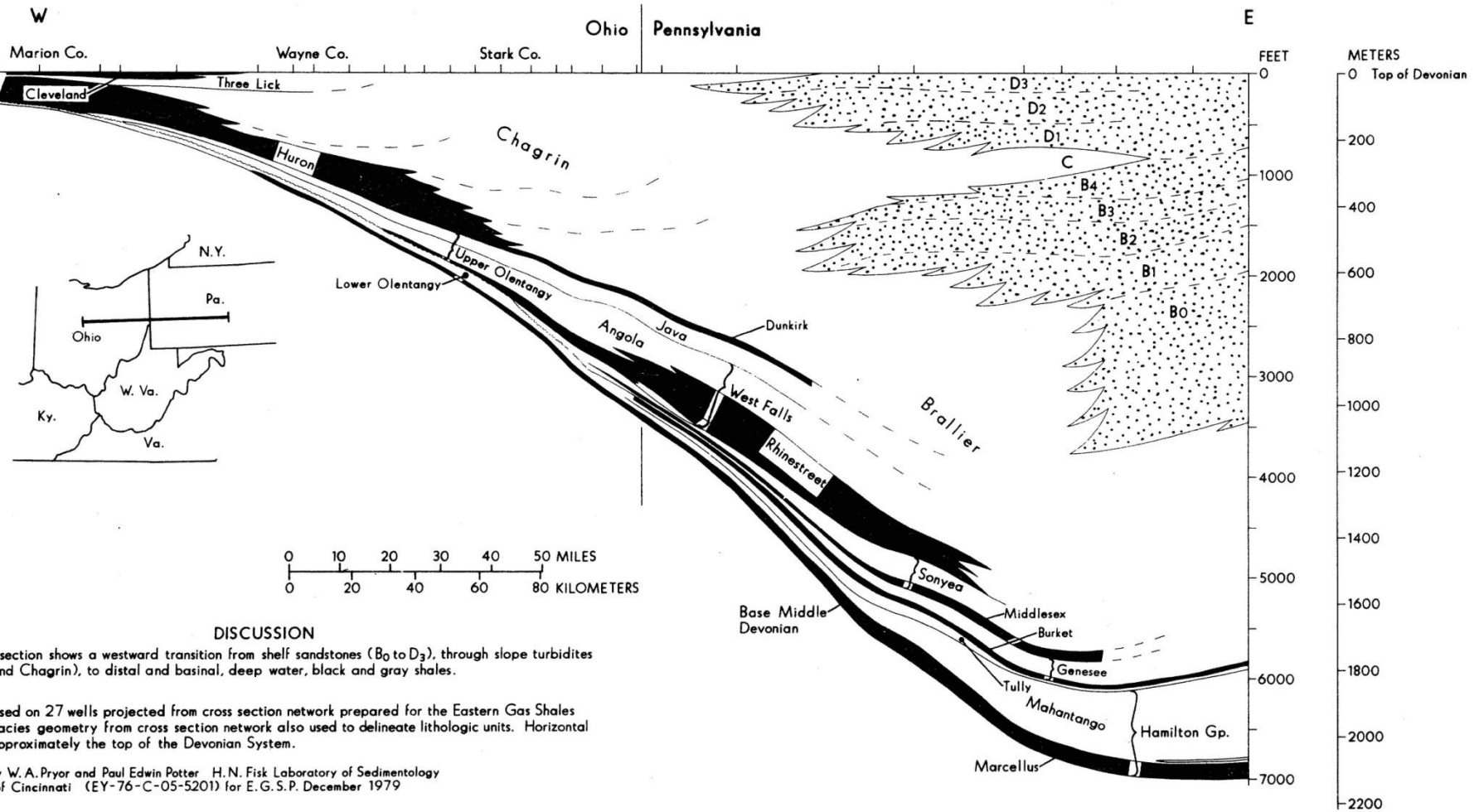
< Microfracture

Woody organic

Pyrite >



# Appalachian Basin Devonian Shale



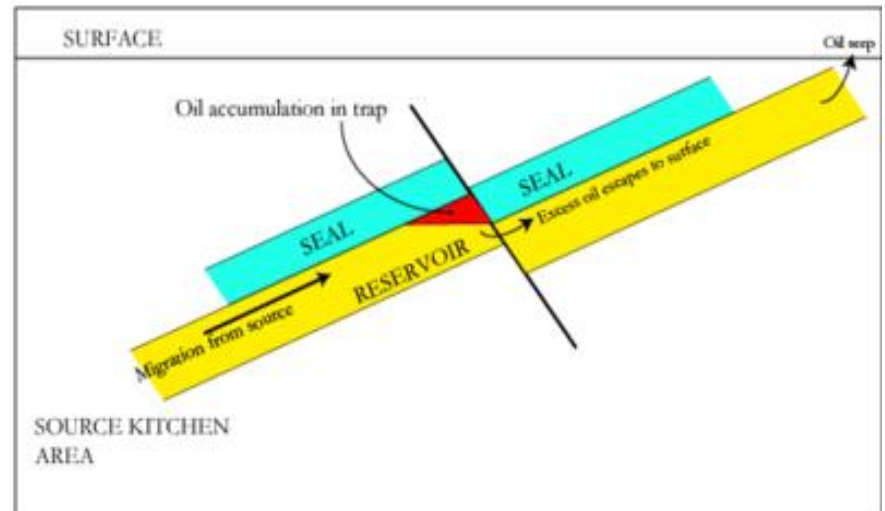
# Petroleum Geology

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

## NEED:

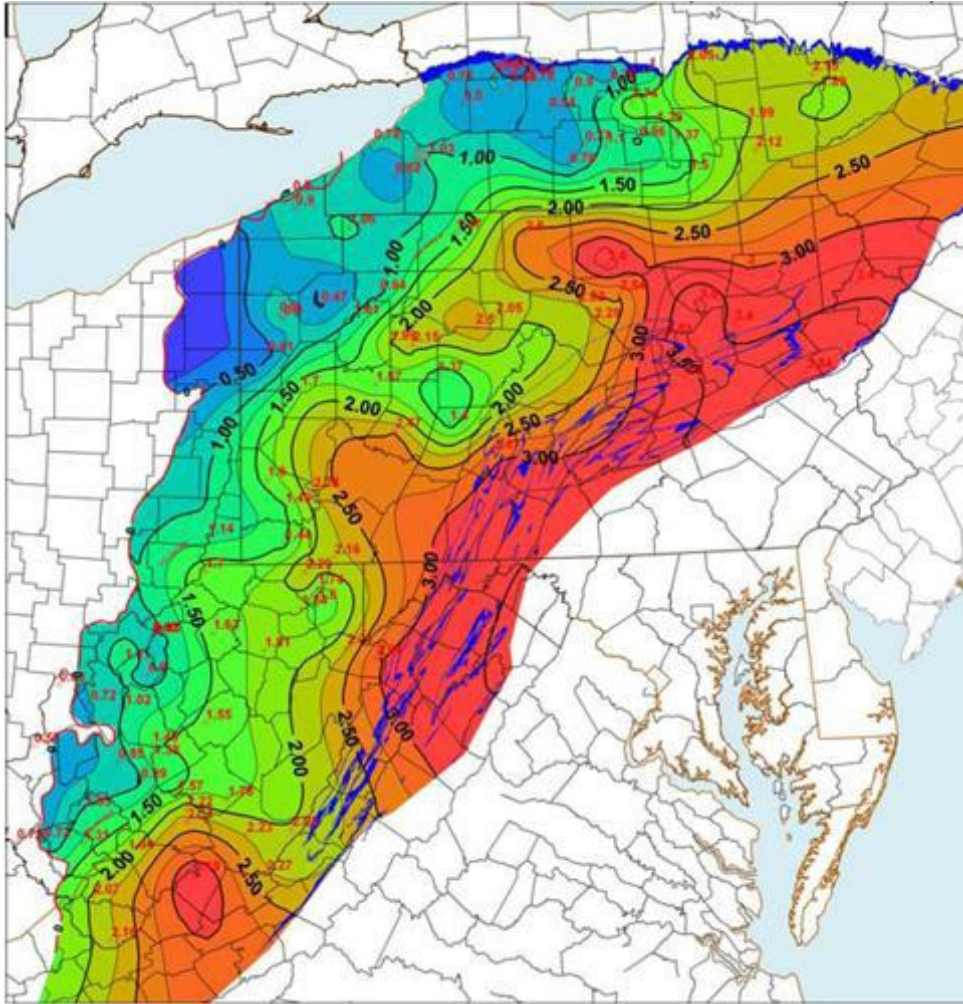
1. Source rock: 1-2% organics (kerogen)
  - a. Types I and II kerogen (petroleum + gas)
  - b. Type III kerogen (coal + gas)
2. Thermal maturity
3. Reservoir rock
4. Trap and Seal
5. Migration pathway

If any one of these is missing,  
no production.

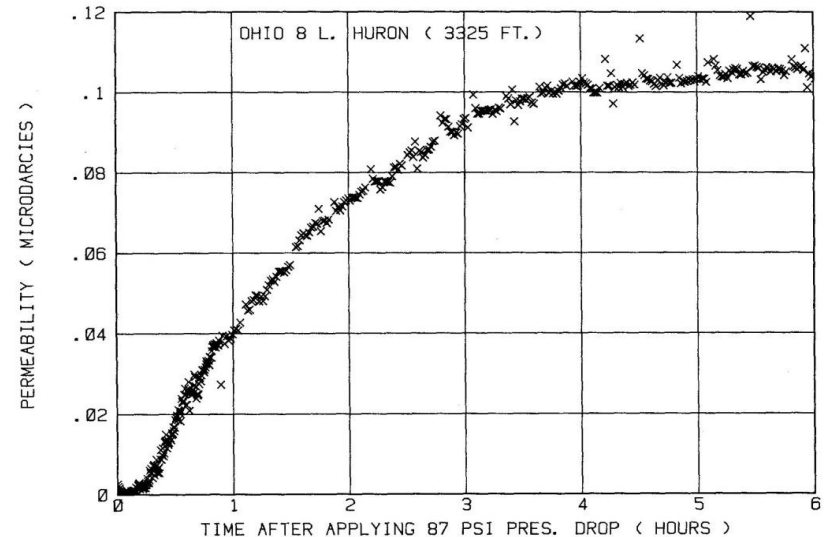
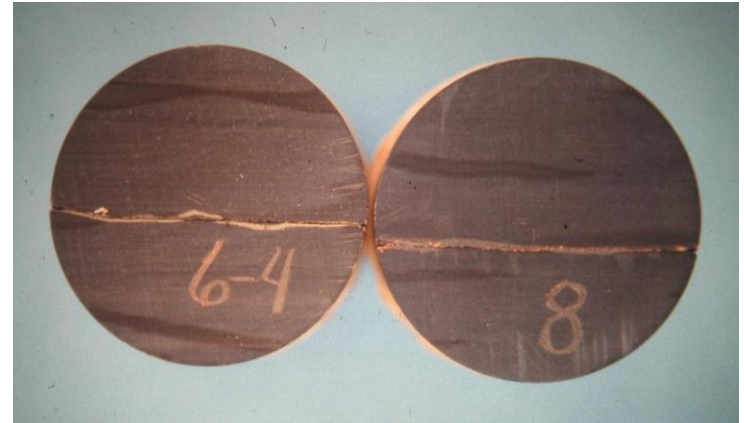


Shale gas is "unconventional": produced directly from thermally-mature high-organic content source rock. No reservoir, trap or seal needed.

# Thermal Maturity

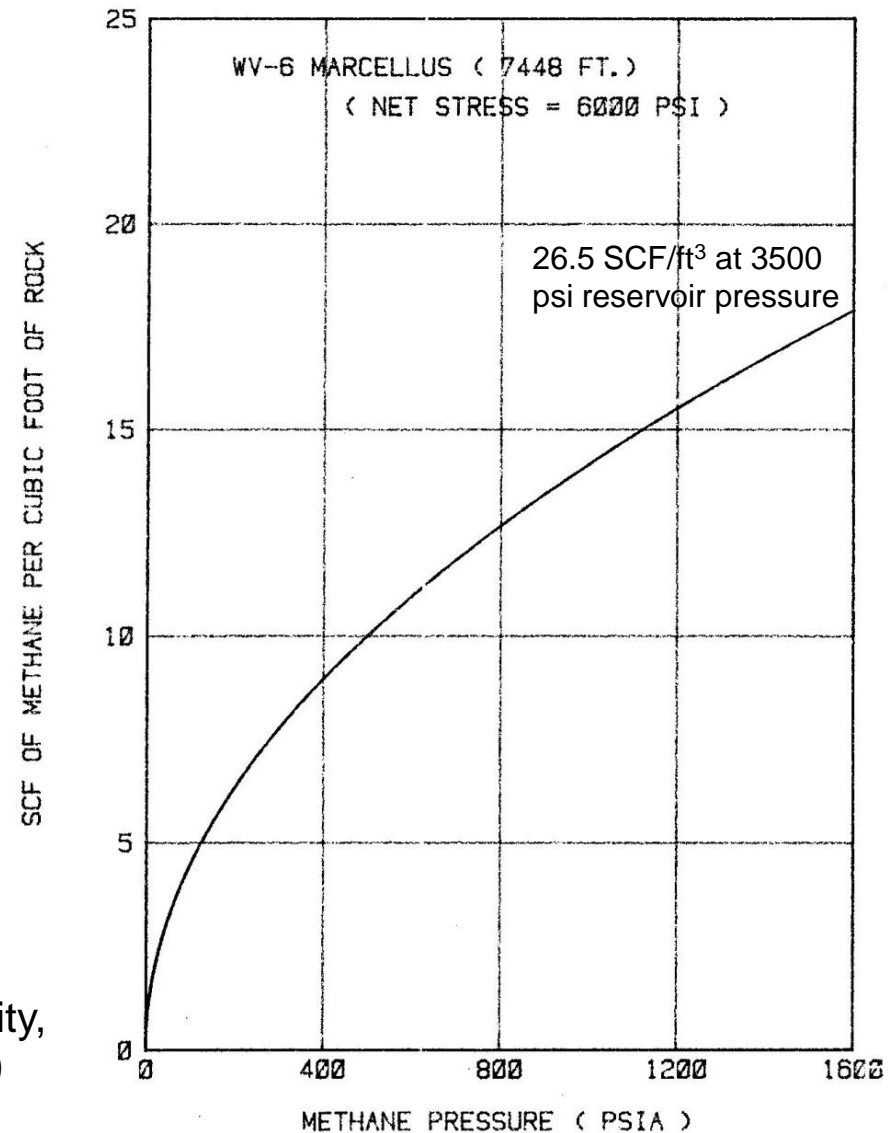
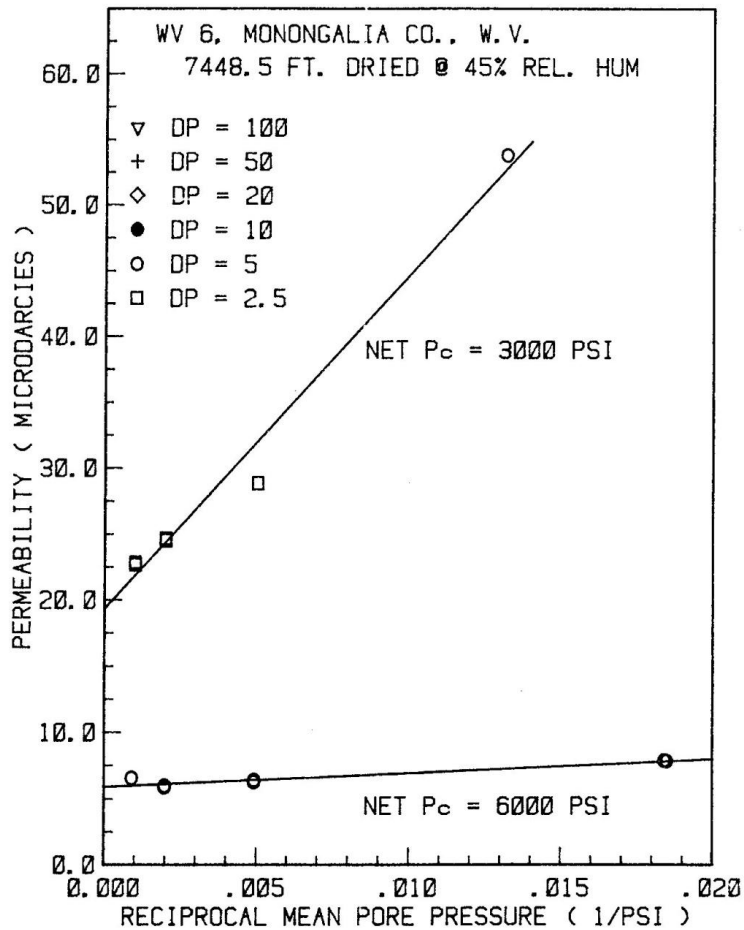


Wrightstone, 2008



Two-phase flow in shale occurs only with great difficulty.

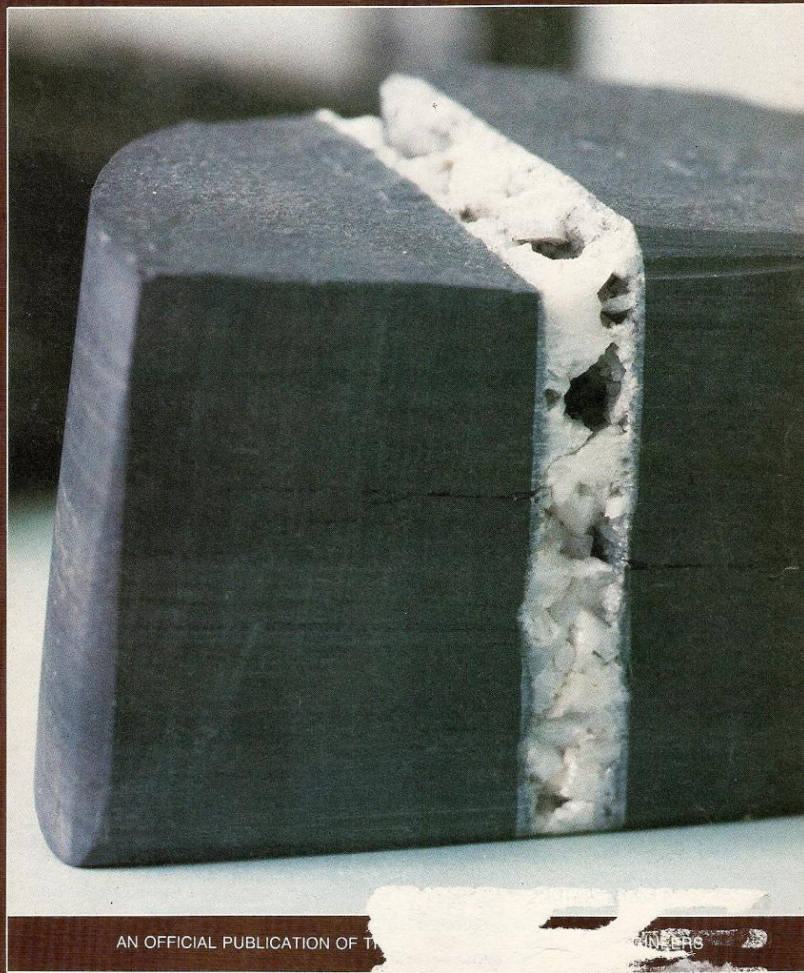
# IGT Core Analysis Results - 1986



Marcellus: strong stress-dependence of permeability, but high gas content (44 to 265X greater than 1980 NPC resource estimates for shale gas)

# SPE Formation Evaluation

MARCH 1988



AN OFFICIAL PUBLICATION OF THE

NETL-RUA

## 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  $0.1 \mu\text{d}$  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  $20 \mu\text{d}$ . 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.<sup>1</sup> 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.<sup>1</sup>

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 labora-

Copyright 1988 Society of Petroleum Engineers

tory. 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.

### 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).<sup>2</sup> 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  $\text{cm}^3/\text{s}$  to an accuracy of a few percent, and can measure steady-state gas permeabilities with a resolution of  $\pm 0.2$  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.<sup>3</sup>

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.<sup>4,5</sup> 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

# Conventional Gas Shortages

- **The United States was facing significant shortfalls of conventional natural gas production in the late 1990s**
- **Conventional fields in the Gulf Coast had watered out and no new gas fields were being developed.**
- **The Mackenzie Delta in Canada was being assessed for gas resources, as was the North Slope.**
- **A number of distributors constructed import terminals for LNG, like Dominion's at Cove Point.**



# Advanced Technology for Shale Gas

## Directional Drilling

- Turning drill string from surface around curves caused binding.
- Flexible drill pipe called a whipstock introduced in the 1930s.
- Downhole motors turn bit without turning drill string - early models were weak and easily overheated
- Downhole motors powered by mud hydraulic pressure introduced in 1990s - offshore for deep water.
- Curves made with bent pipe or thrust bearings on cutter head.
- Better downhole navigation was needed for borehole with better telemetry to get data to surface
- Sperry-Sun gyroscopes replaced with military grade inertial navigation systems

## Hydraulic Fracturing

- Patented in 1949 by Stanolind Oil.
- Licensed to Halliburton and other service companies in 1953.
- Water pressure exceeds rock strength and produces a crack.
- Fractures have higher permeability than reservoir rocks, creating flowpaths to the well bore.
- Fracs use sand as "proppant" to keep the fractures open.
- Nearly all gas wells, most oil wells and many water wells receive hydraulic fracturing treatment to improve flow.
- Mitchell Energy developed light sand frac, using less proppant
- Slickwater frac helps fluid penetrate rock and reduces friction losses

Old: vertical drilling with a single frac

New: lateral drilling with multiple, (10-15) staged fracs

Land surface



Cost: 2-3X higher; production: 3-4X greater

Younger shales

Kickoff point

Marcellus Shale

100 ft

5000 ft

Onondaga Limestone

Hydraulic fracture zone (fractures every 500 feet)

DJS 05 2011

not to scale

# Shale Gas Production

- **Barnett Shale**, Ft. Worth Basin, Texas: Mitchell Energy adapted offshore technology for economic production of shale gas in the 1990s
  - Directional drilling, long laterals, light sand and slickwater fracs
- **Fayetteville Shale**: 2004, Southwestern Energy, Arkansas
- **Haynesville Shale**: Same period, ArkLaTex area
- **Marcellus Shale**: Range Resources, vertical well to deeper target in 2005; nonproductive, recompleted vertically in Marcellus Shale
  - Several horizontal wells were tried the following year, without success
- Range Resources, Gulla #9 “discovery” well drilled in 2007
  - Drilled horizontally in Washington County
  - Slickwater frac completion with light sand; IP 4.9 MMCFD
- Nearly 8000 Marcellus Shale wells permitted or drilled in PA and WV between January 2008 and January 2012.
- New targets: Woodford Shale, Arkoma Basin, Utica Shale, Appalachian Basin, Eagle Ford Shale, Texas Gulf Coast/Maverick Basin

# DIMENSIONS OF A HORIZONTAL WELL

## Central Park, New York

Land surface 110<sup>th</sup> St

Base freshwater 106<sup>th</sup>

Bottom of vertical 85<sup>th</sup>

500 ft curve through softball fields

Lateral: out E 83<sup>rd</sup> St

Top of fracs; E 86<sup>th</sup> St

To scale except for thickness of line depicting wellbore





## Water supply impoundment at frac site





NATIONAL  
CRANE

TITAN  
GENERATOR

18-4400

Tea Master

NATIONAL  
CRANE

SERIES  
1800

# Production Well Pad



Gas-water separator

Stock tanks for produced water



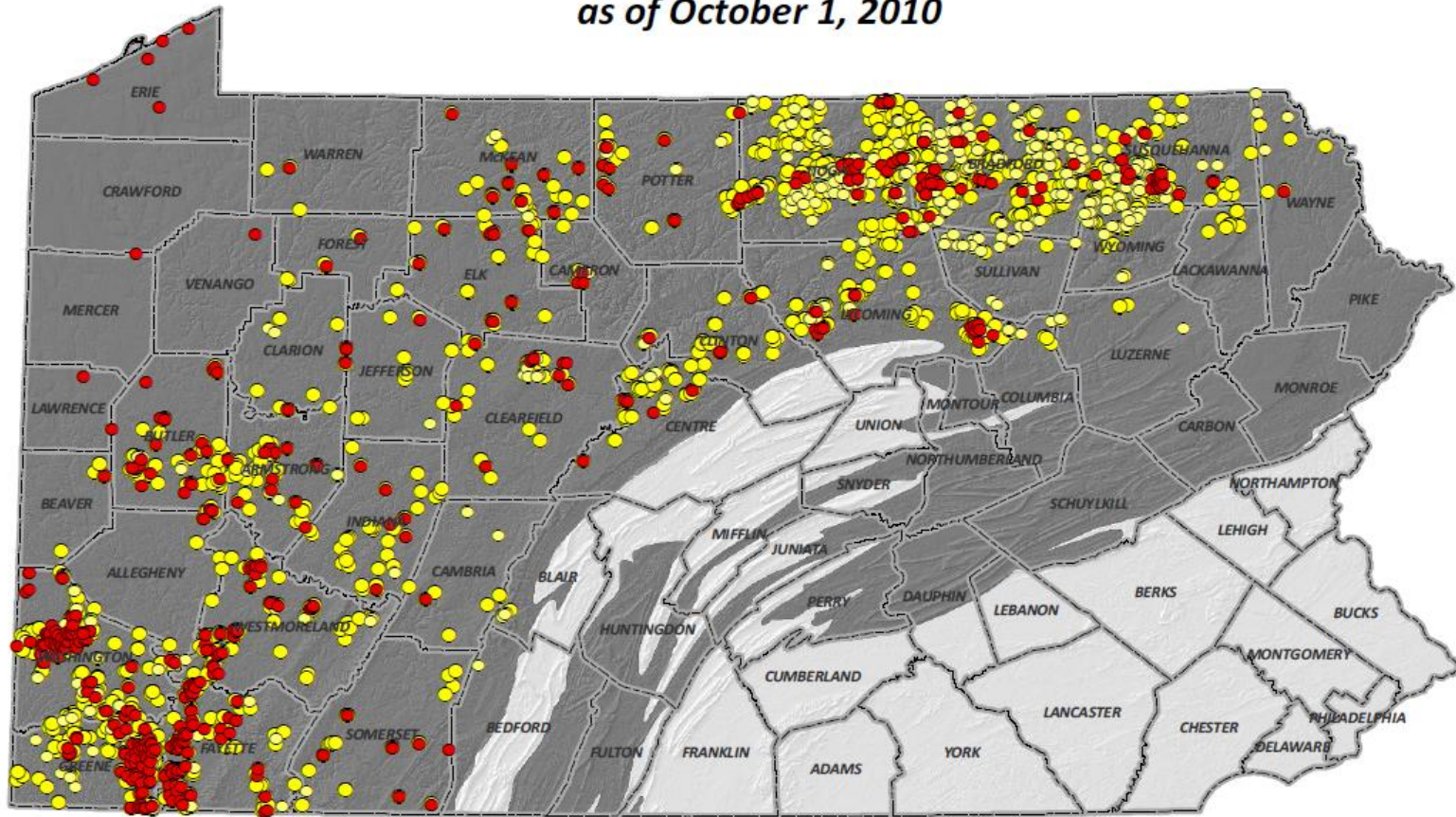
Wellhead



Meter run

# Pennsylvania Marcellus wells

as of October 1, 2010

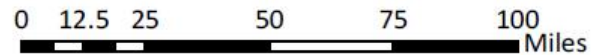


● Active Permits (4510 permits)

● Completion reports received (645 wells)

■ Extent of Marcellus Shale in Pennsylvania

1:2,250,000



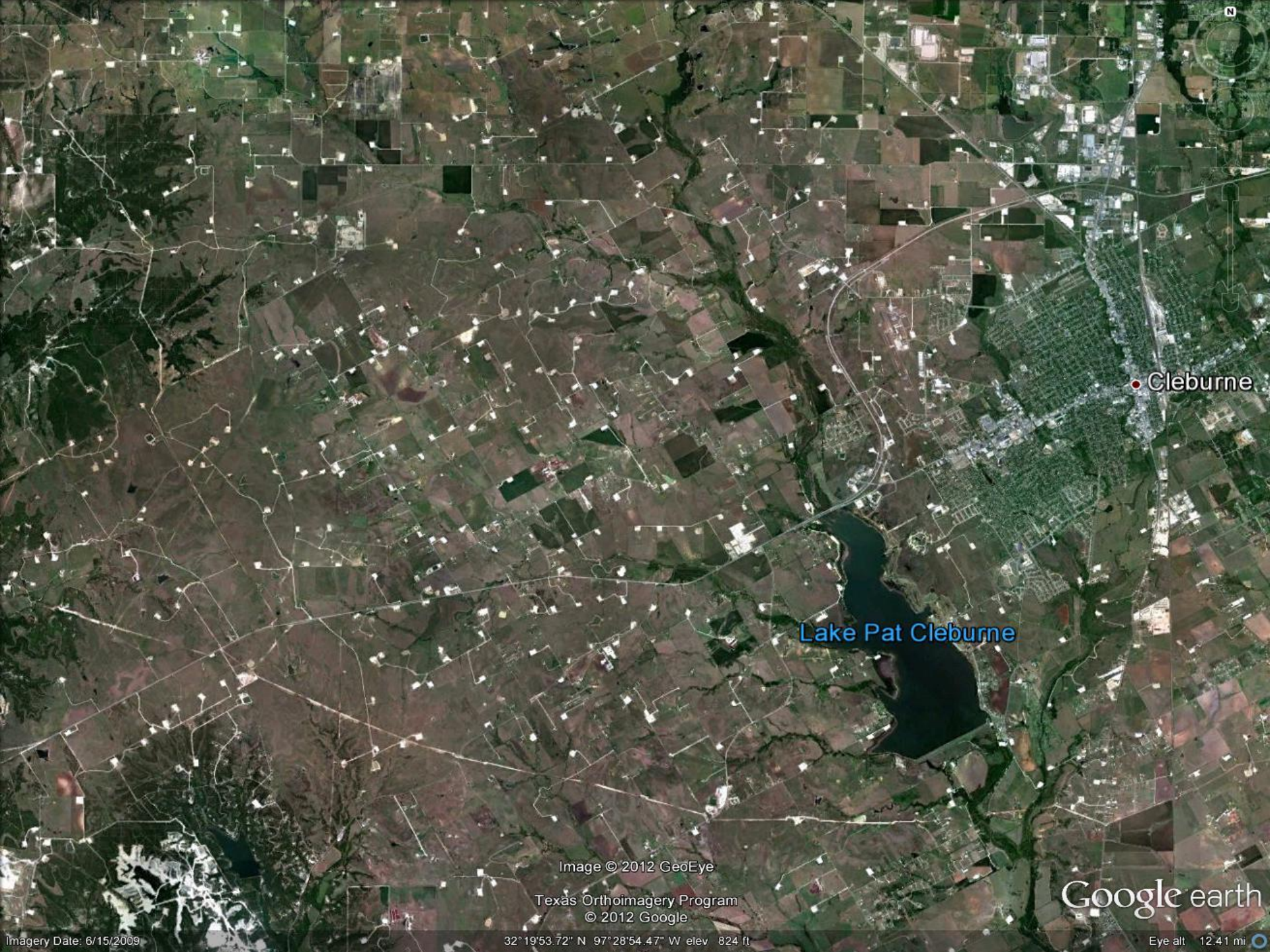
Data Source: Active permits, Pennsylvania Department of Environmental Protection, [www.depweb.state.pa.us](http://www.depweb.state.pa.us), October 2010; Completion reports received, Pennsylvania Geological Survey, October 2010;

\*For Display Purposes Only\*

# Environmental Impacts

- **Potential impacts:**
  - Air, water, landscapes, ecosystems/habitat
  - A major unknown is cumulative impacts, including thresholds (i.e. impervious surfaces)
- **Impacts are short or long term**
  - Short term: construction related (noise, lights, dust)
  - Long term: occupancy related (invasive species)
- **Impacts can be mitigated through regulations and enforcement, however:**
  - Not all known environmental impacts are regulated
  - Not all regulations are fully enforced





Cleburne

Lake Pat Cleburne

Image © 2012 GeoEye

Texas Orthoimagery Program  
© 2012 Google

Google earth

Imagery Date: 6/15/2009

32° 19' 53.72" N 97° 28' 54.47" W elev 824 ft

Eye alt 12.41 mi

# Marcellus Shale

Basal unit of a thick sequence of Devonian shales.

Ranges from 7000 feet deep in central PA to surface outcrops in NY and along Valley & Ridge; thins to a feather edge westward into OH.

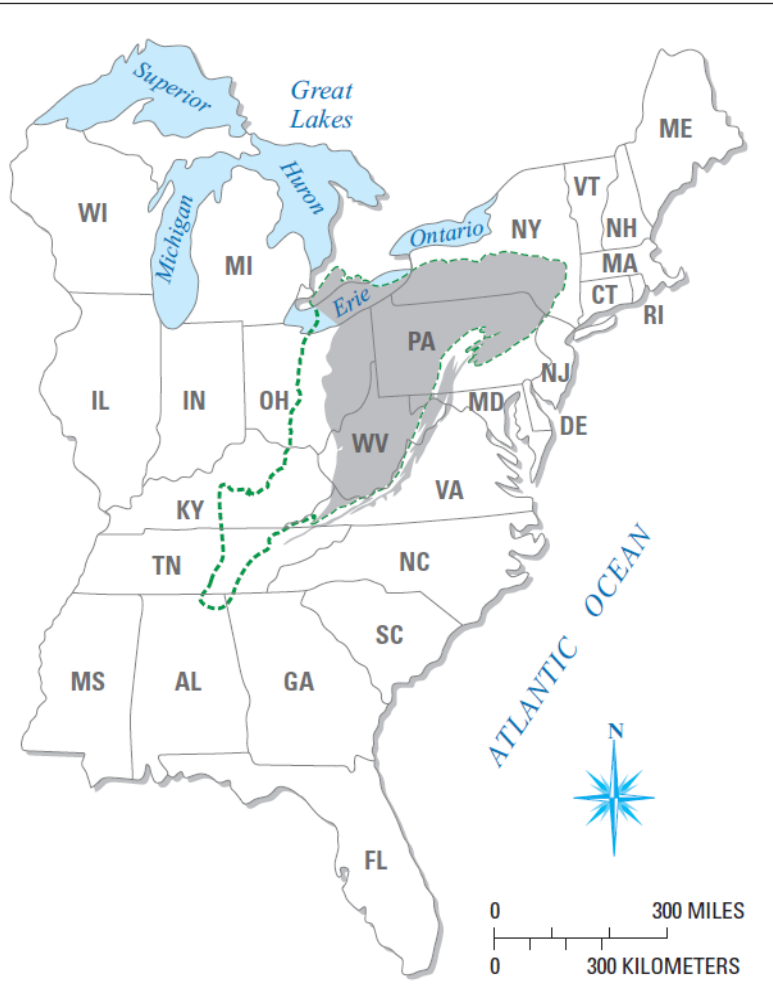
The type locality is an outcrop a mile south of the town of Marcellus, New York, in Onondaga County; named for Marcus Claudius Marcellus (268–208 BC), a famous Roman general.

Thickest in NE Pennsylvania and Southern Tier of NY; subdivided into a lower and upper shale separated by a limestone.



Six lithotypes linked to facies identified in WV.

Merges with other shales in southern WV and VA – becomes part of a compressed black shale sequence known as the Millboro Shale.

Map from U.S. Geological Survey Fact Sheet 2009–3032



## EXPLANATION

 EXTENT OF DEVONIAN SHALE     MARCELLUS SHALE

## Early to Middle Devonian Section

# Hanson Aggregates New York, Oriskany Falls Quarry



# Marcellus Shale in Hanson Quarry, NY

Oatka Creek Member

Cherry Valley LS

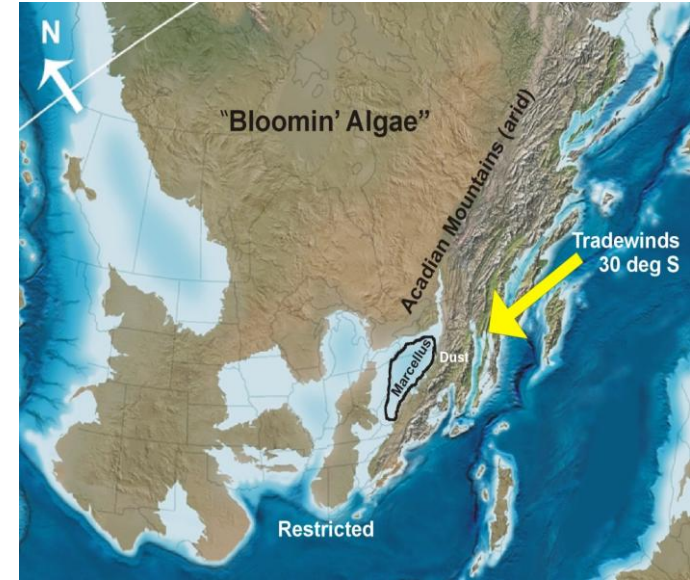
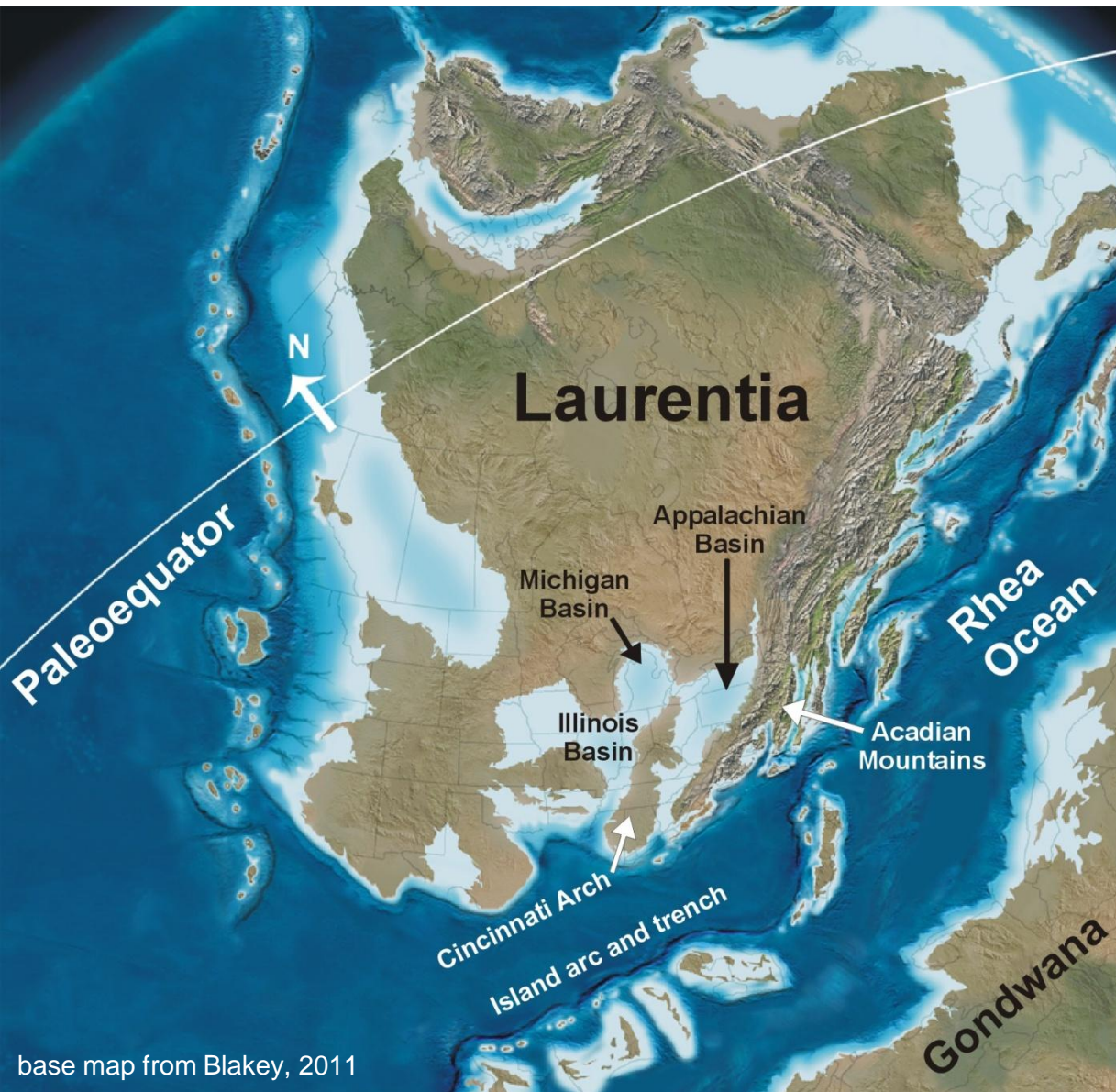
Union Springs Member



# Marcellus Shale features



# Paleogeography of Appalachian Devonian Shales



Wrightstone (2011): planktonic marine algae were fertilized by mineral-laden dust blown into the basin by trade winds off the arid Acadian Mountains to the east.

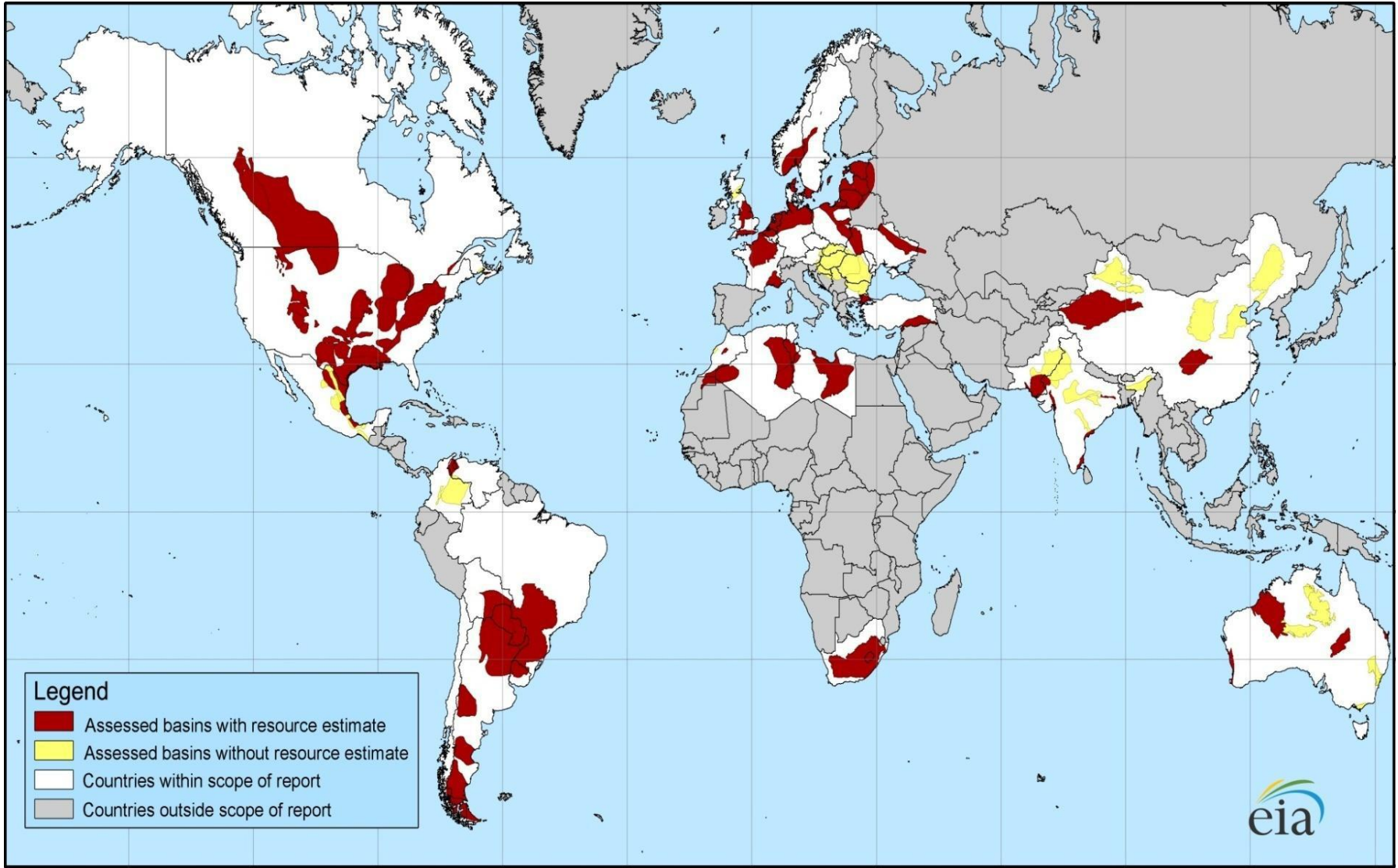
# North American shale plays (as of May 2011)



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

# Why Natural Gas?

**Potentially very abundant:** black shales, coal seams, tight sandstones, deep brine aquifers, methane hydrates, biomass.

**Energy independence:** domestic resource, difficult to import. U.S. shale gas production has solved the "energy crisis," and can replace all imported oil.

**Many uses:** electricity, industrial heat, chemical feedstock

Automobile fuel: lower cost per BTU than oil, 13 TCF of gas replaces 5 bbl oil (3.5 bbl imported) used annually for transportation fuel.

**Methane** is a stronger GHG than CO<sub>2</sub>; natural gas must be considered valuable enough to warrant sealing leaks in systems.

## Advantages over other fuels:

- A national infrastructure already exists
- Onshore gas drilling is less risky than offshore, Arctic or ultradeep drilling.
- Gas is the cleanest fossil fuel when burned:
  - No sulfur, no mercury, no ash in combustion products
  - No cracking or refining – essentially pure methane; use as-is.
  - Low NOx and ozone, no complex HC to create photochemical smog
  - Lower carbon dioxide emissions per BTU when burned



# U.S. DEPARTMENT OF ENERGY

## Websites for additional information:

American Petroleum Institute (hydraulic fracturing info., how it is done): <http://www.api.org/>

EPA hydraulic fracturing & drinking water info:  
<http://water.epa.gov/type/groundwater/uic/class2/hydraulicfracturing/index.cfm> (or go to epa.gov and do a search)

Environmentally friendly drilling research & engineering:  
<http://www.efdsystems.org/>

FracFocus: Ground Water Protection Council and Interstate Oil & Gas Compact Commission website for hydrofracture chemical info: <http://fracfocus.org/>

Marcellus Shale Coalition (industry site; drilling process video):  
<http://marcelluscoalition.org/>

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