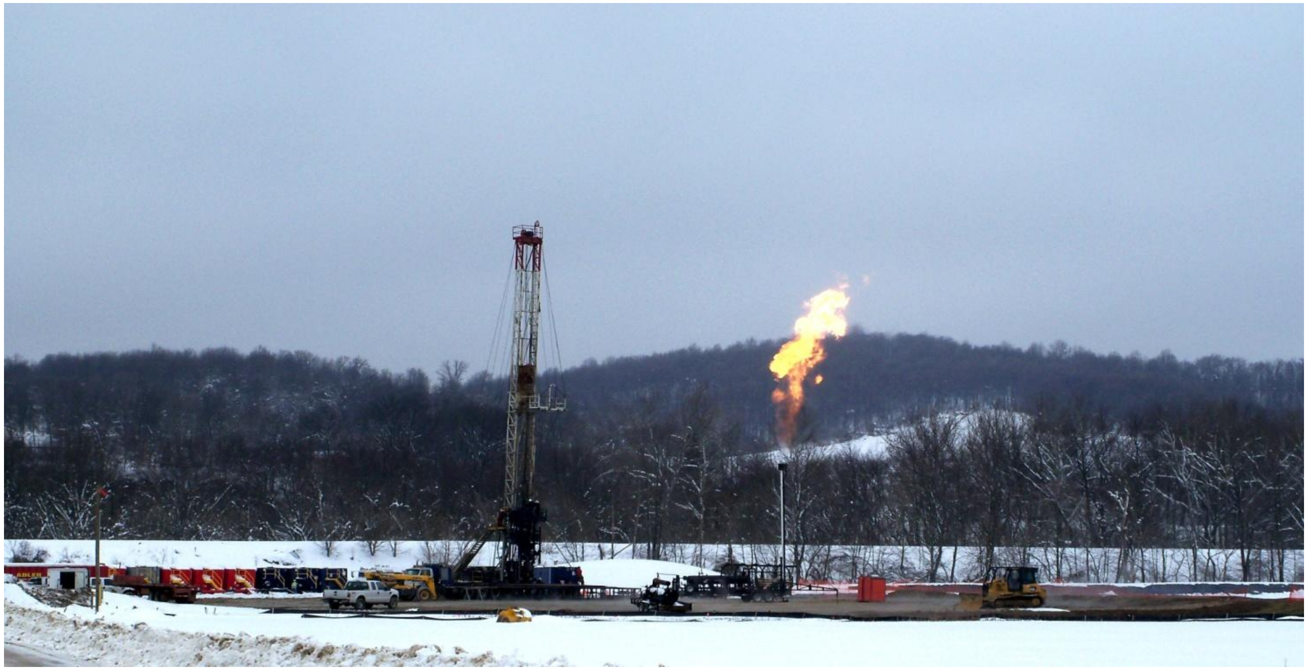
NATIONAL ENERGY TECHNOLOGY LABORATORY



The Successful Development of Shale Gas Resources in the United States

A personal account

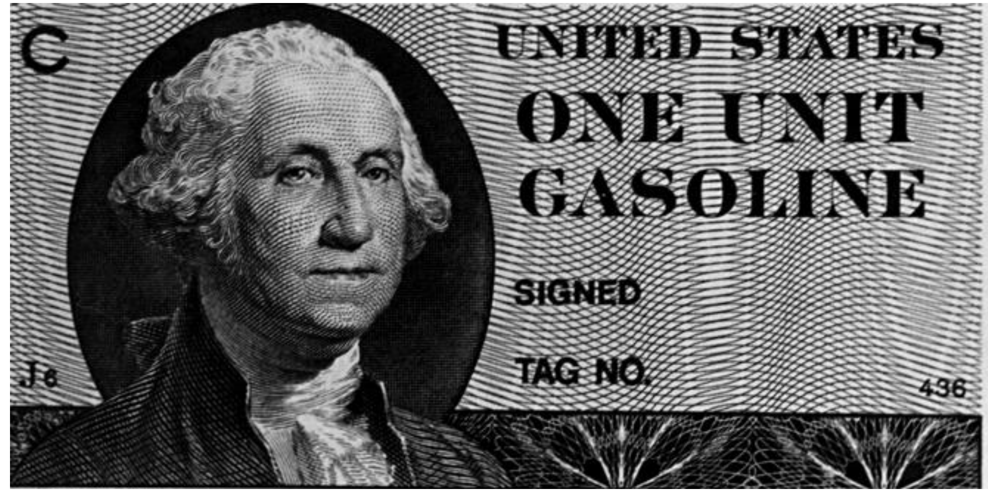
Daniel J. Soeder, NETL, Morgantown, WV

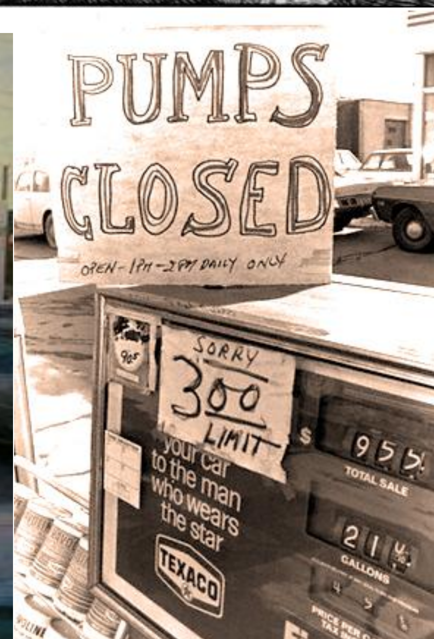
12 October 2011, Minneapolis, Minnesota

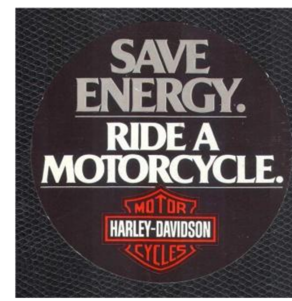
Geological Society of America Annual Meeting

U.S. DEPARTMENT OF ENERGY

Remember the "Energy Crisis"?





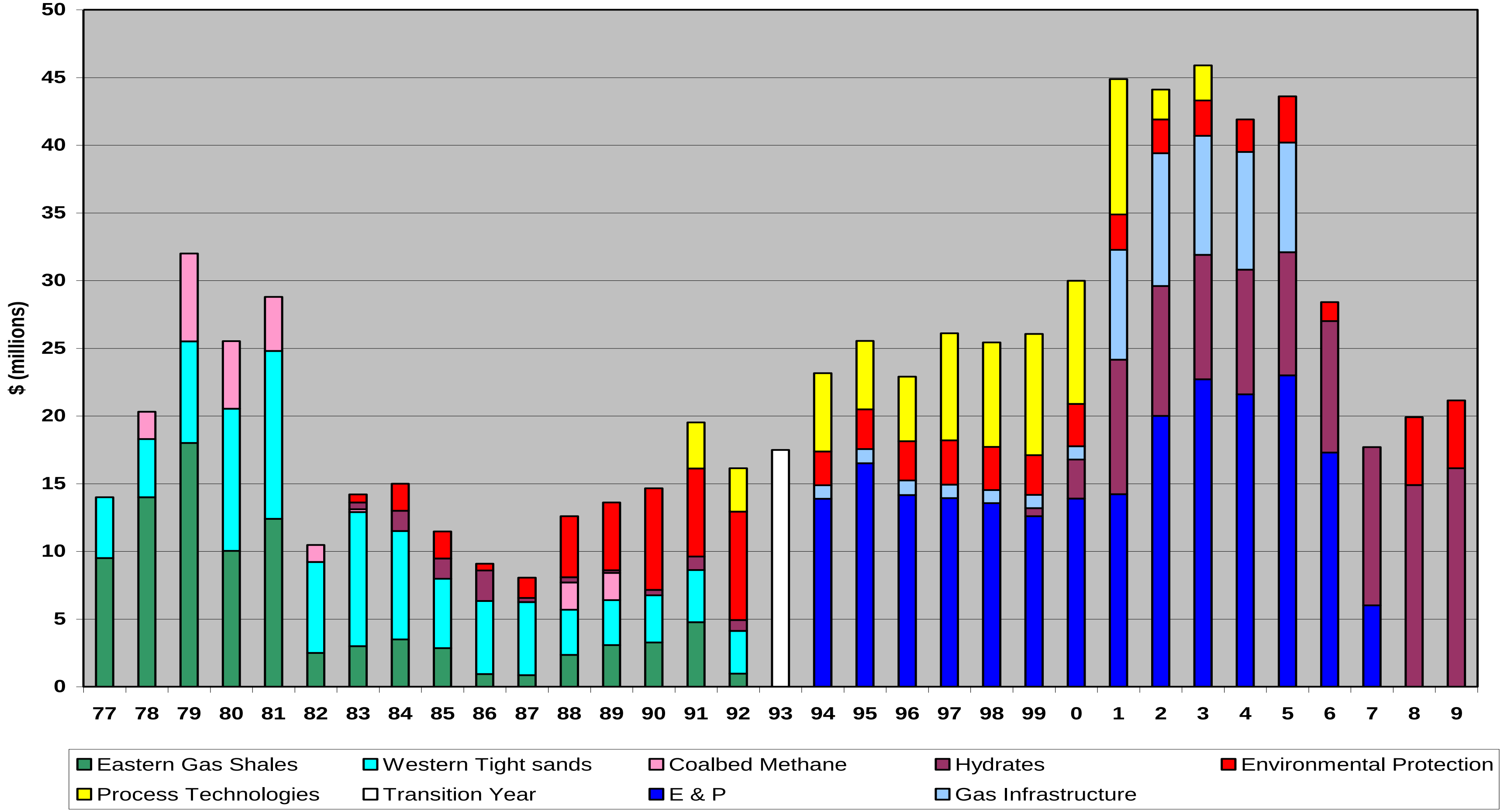


We do…

- **October 6-25,1973: Yom Kippur War (Arabs vs. Israel)**
- **October 20, 1973 to Spring 1974: OPEC oil embargo**
  - Cold War politics and geopolitics – war was only a trigger
  - Result: price of gasoline quadrupled in United States (0.40 - $1.60)
  - Imagine that today: $3.50/gallon to $14.00/gallon
  - Many service stations had no gas; those with gas had long lines
  - People felt stuck in the suburbs with a useless car
- **U.S. Department of Energy formed by Carter Admin.**
  - Created August 4, 1977 to deal with domestic energy
  - James R. Schlesinger was the first Secretary of Energy
- **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
  - U.S. Government printed but never distributed ration coupons

DOE Natural Gas R&D

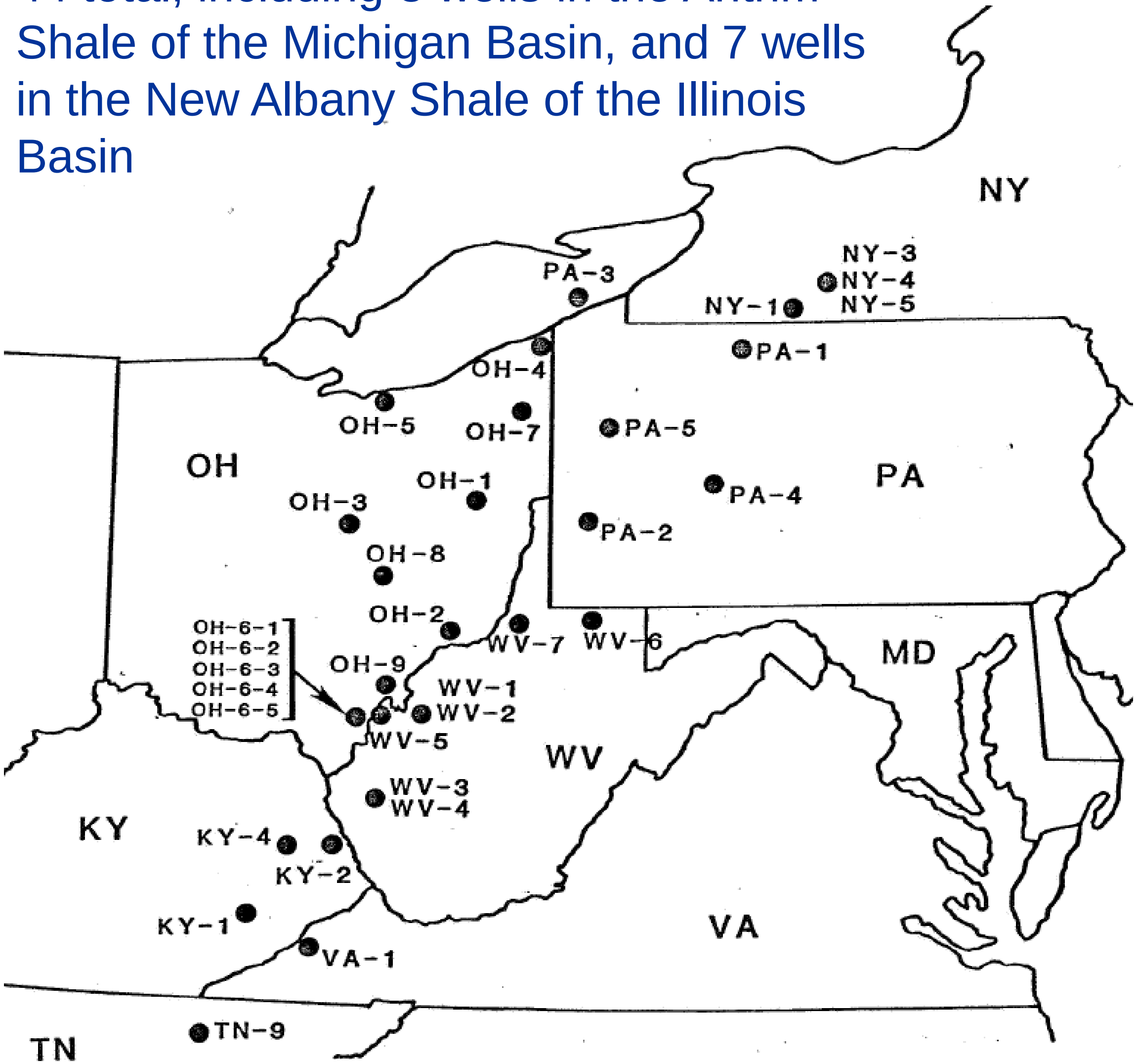
Objective: Encourage responsible production of domestic sources of oil and gas, including resource characterization, development of better technology and engineering, and data transfer to industry.

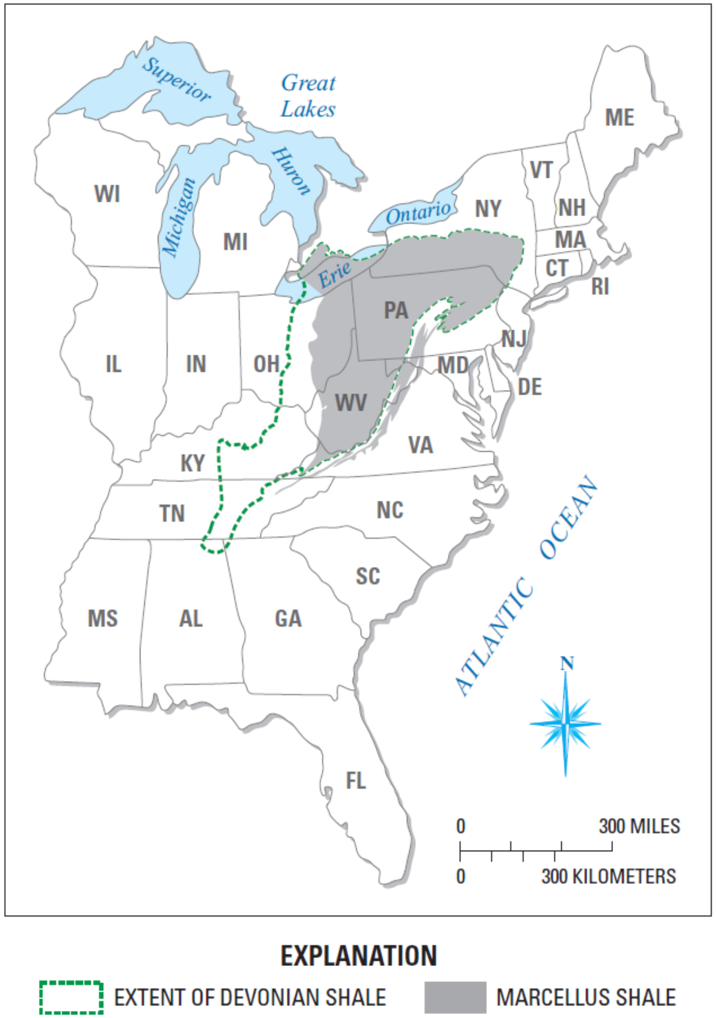


DOE Eastern Gas Shales Project 1976-1992

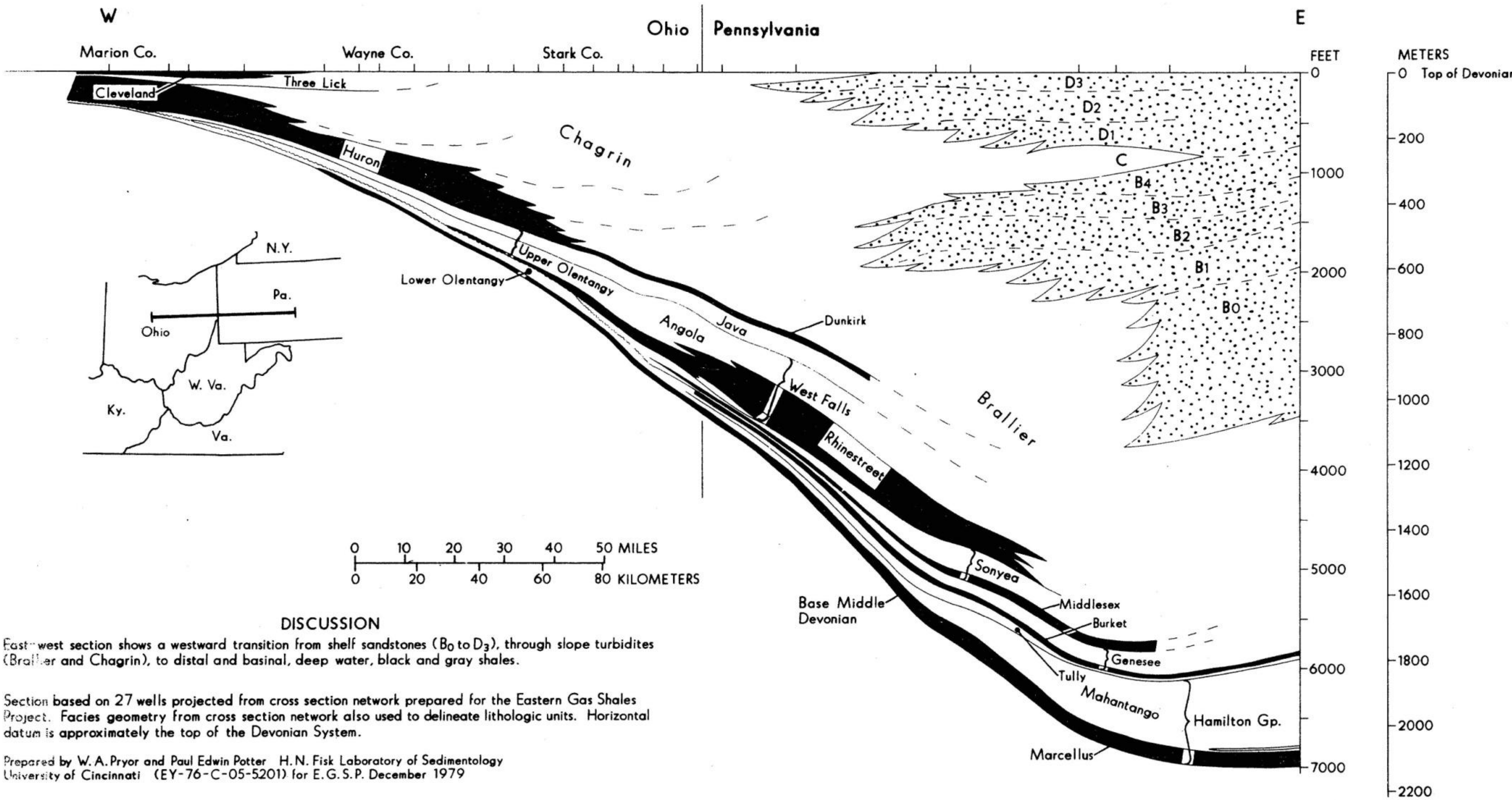
EGSP Cored Well Locations

44 total, including 3 wells in the Antrim Shale of the Michigan Basin, and 7 wells in the New Albany Shale of the Illinois Basin





Appalachian Basin Stratigraphy



DISCUSSION

East-west section shows a westward transition from shelf sandstones (B_0 to D_3), through slope turbidites (Brallier and Chagrin), to distal and basinal, deep water, black and gray shales.

Section based on 27 wells projected from cross section network prepared for the Eastern Gas Shales Project. Facies geometry from cross section network also used to delineate lithologic units. Horizontal datum is approximately the top of the Devonian System.

Prepared by W. A. Pryor and Paul Edwin Potter H. N. Fisk Laboratory of Sedimentology University of Cincinnati (EY-76-C-05-5201) for E. G. S. P. December 1979

Gas Shale Geology

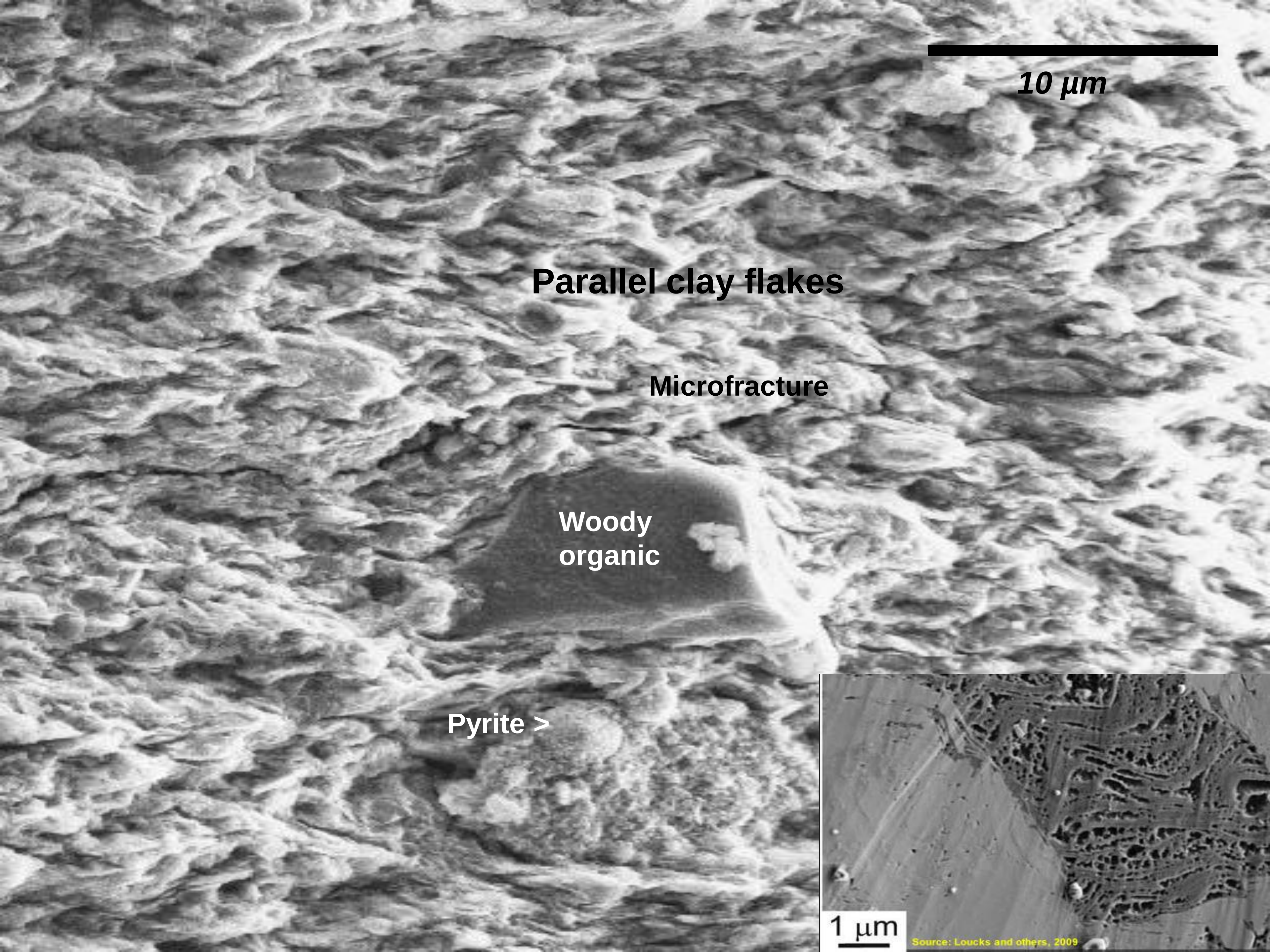
- Sedimentary rock formed from mud, composed of fine-grained clay, quartz, organic matter, and other minerals.

- Shale types from a gas perspective:
  - organic-rich (black)
  - organic lean (gray or red)

- Shale porosity ~ 10%
- Shale permeability μd to nd.

- Small grains = small pore spaces; there are also nanopores within the organic matter.

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



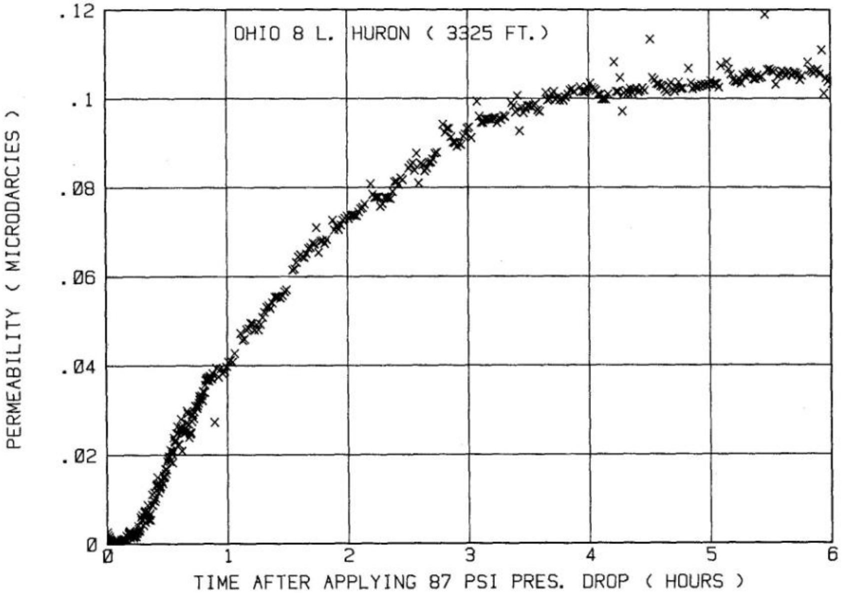
10 µm
Parallel clay flakes
Microfracture
Woody
organic
Pyrite >
1 µm
Source: Loucks and others, 2009

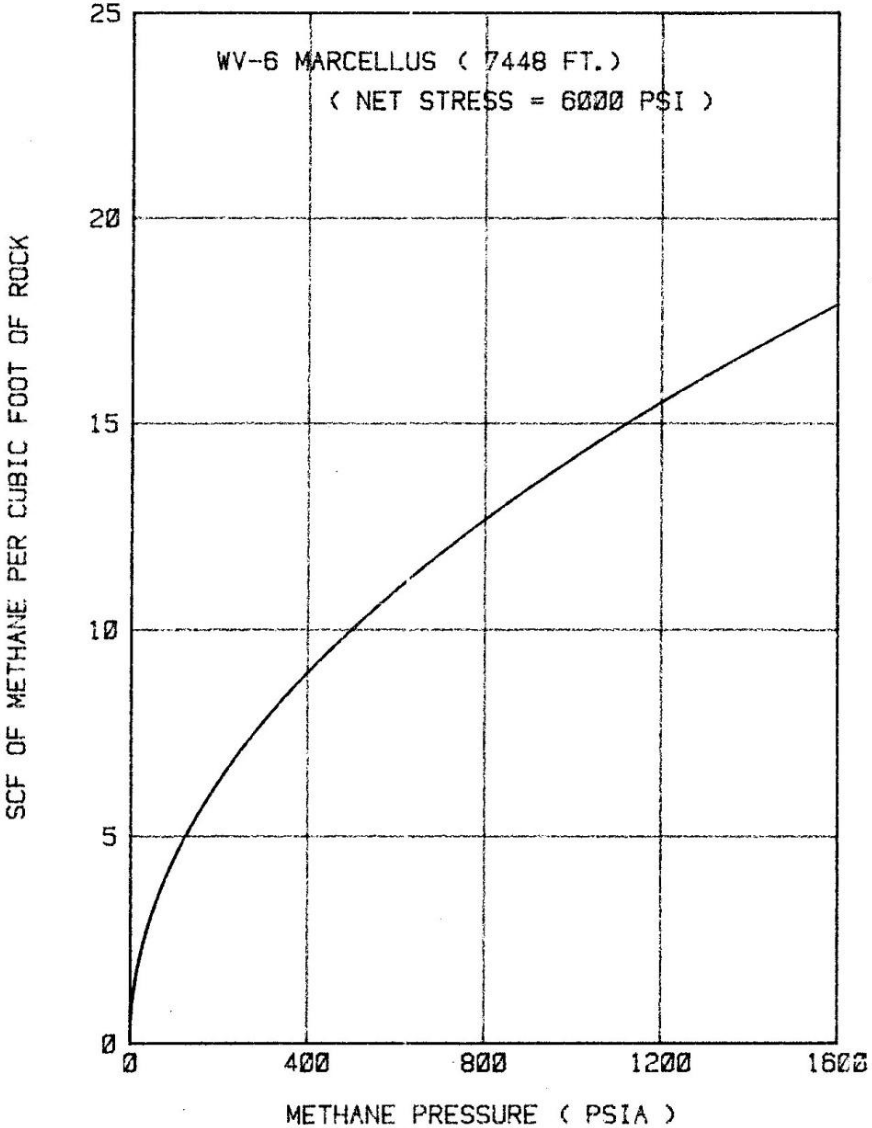
IGT Core Analysis Results

EGSP shale samples analyzed in 1986: 7 Lower Huron and 1 Marcellus

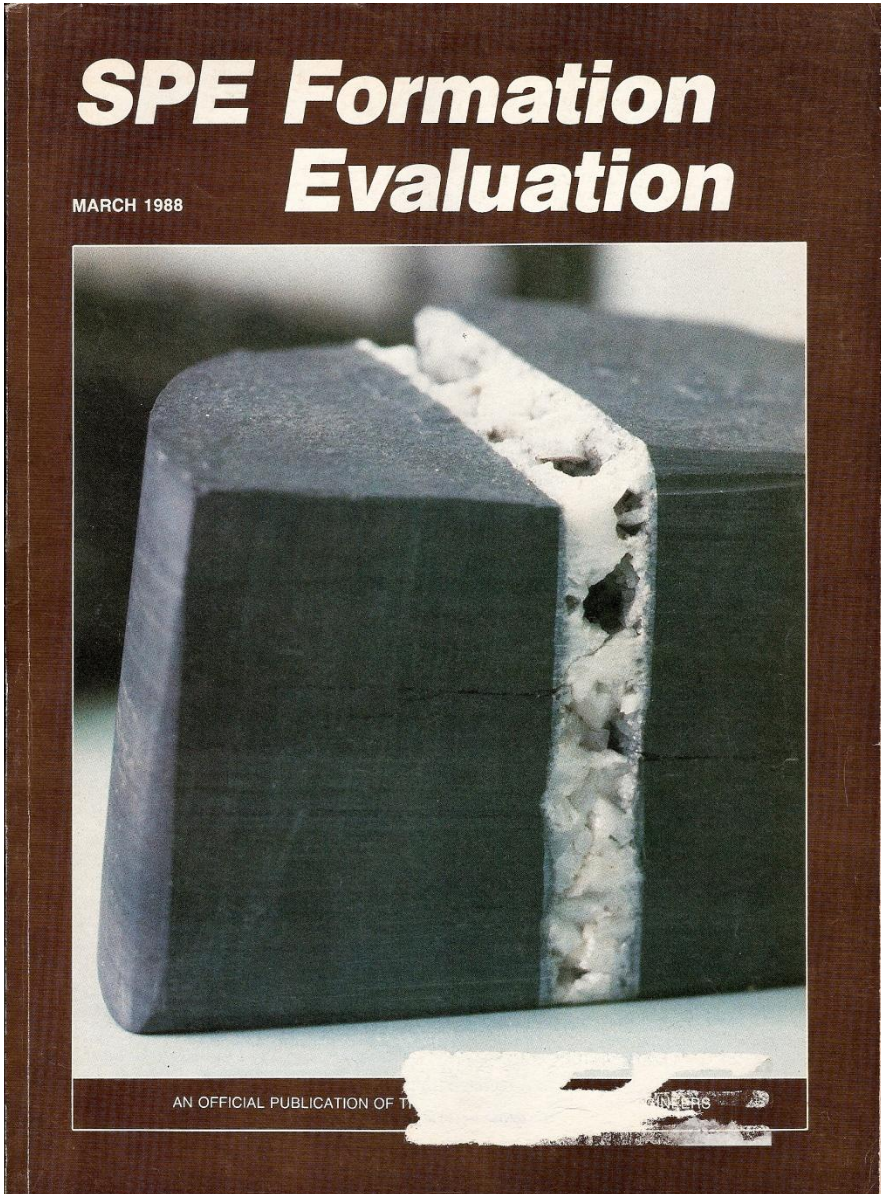
Marcellus: 26.5 SCF/ft^3 at 3500 psi reservoir pressure, compared to1980 NPC resource estimates for shale: 0.1 to 0.6 scf gas/ft^3 (44 to 265 X greater)

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





Published 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.

Core-Analysis Procedure

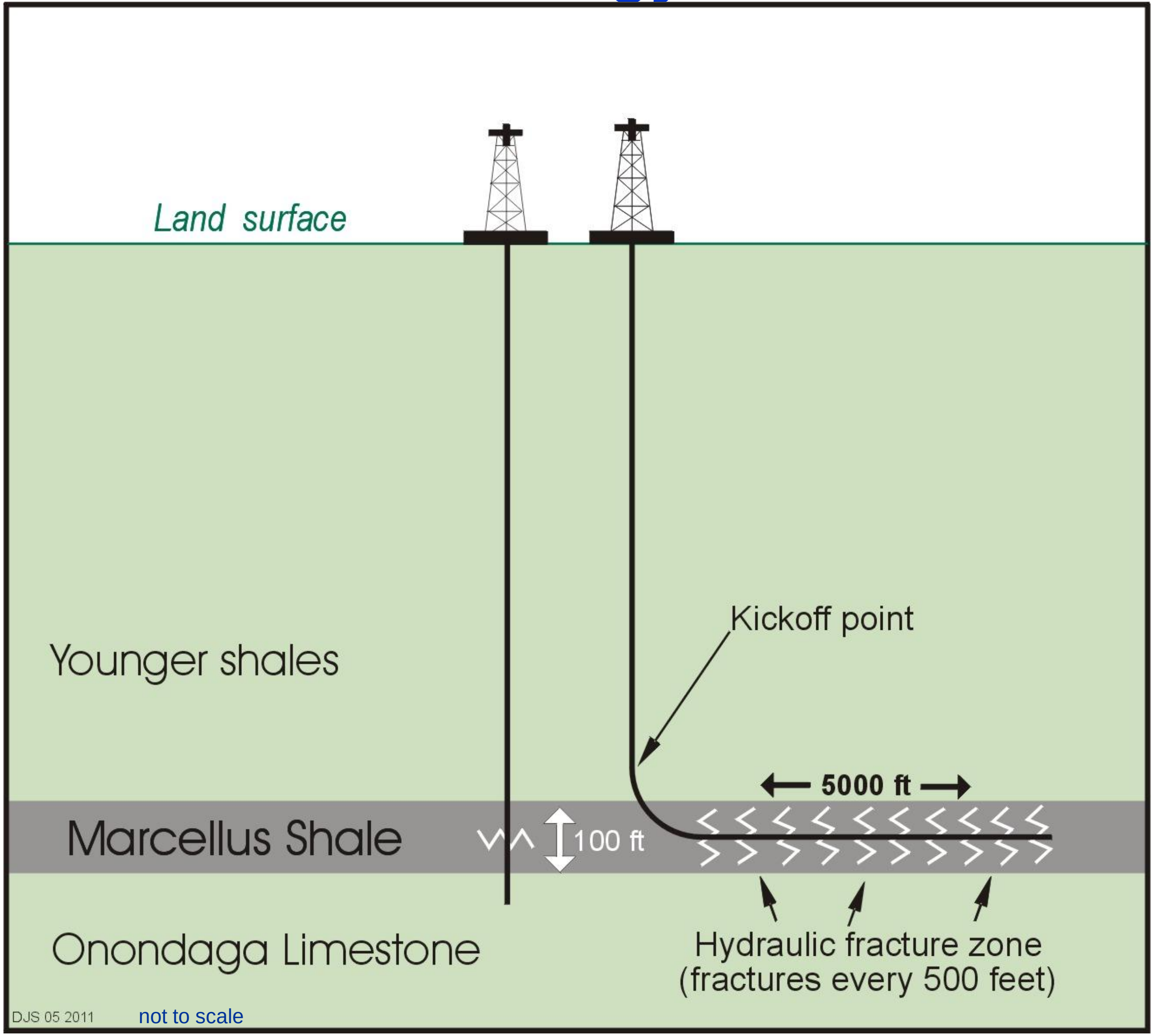
Between 1976 and 1981, the U.S. government cut and retrieved nearly 17,000 ft [5180 m] of Devonian shale drill core under the Eastern Gas Shale Project (EGSP).[2] This large supply of oriented core provided the raw material for the selection of a limited number of samples to be analyzed in our laboratory.

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

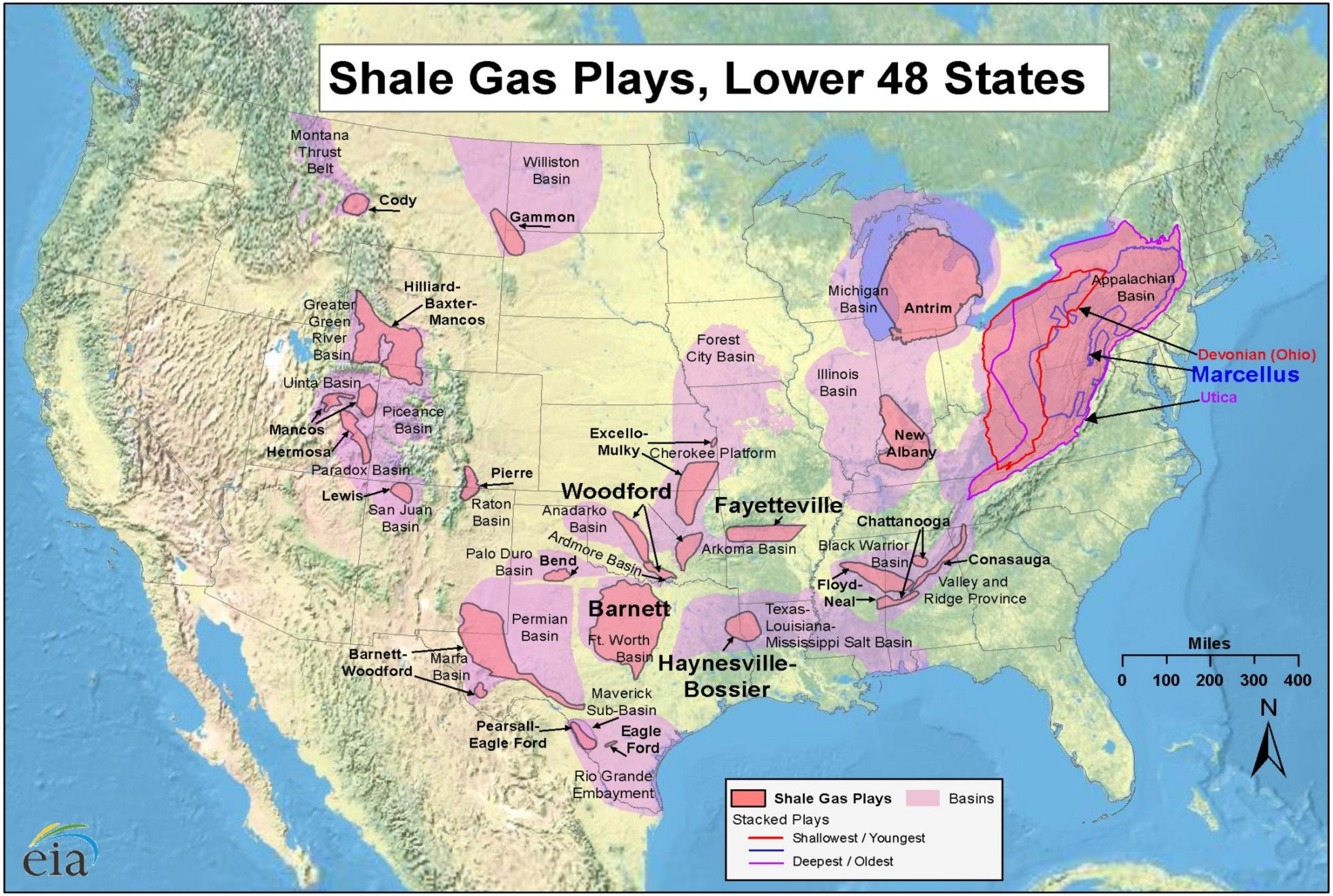
New Technology Needed for Shale Gas



- Directional drilling
- Downhole hydraulic motors
- Measurement while drilling
- Better inertial navigation
- Better telemetry: mud pulse and electronic
- 5000 ft laterals
- Light sand frac
- Slickwater frac

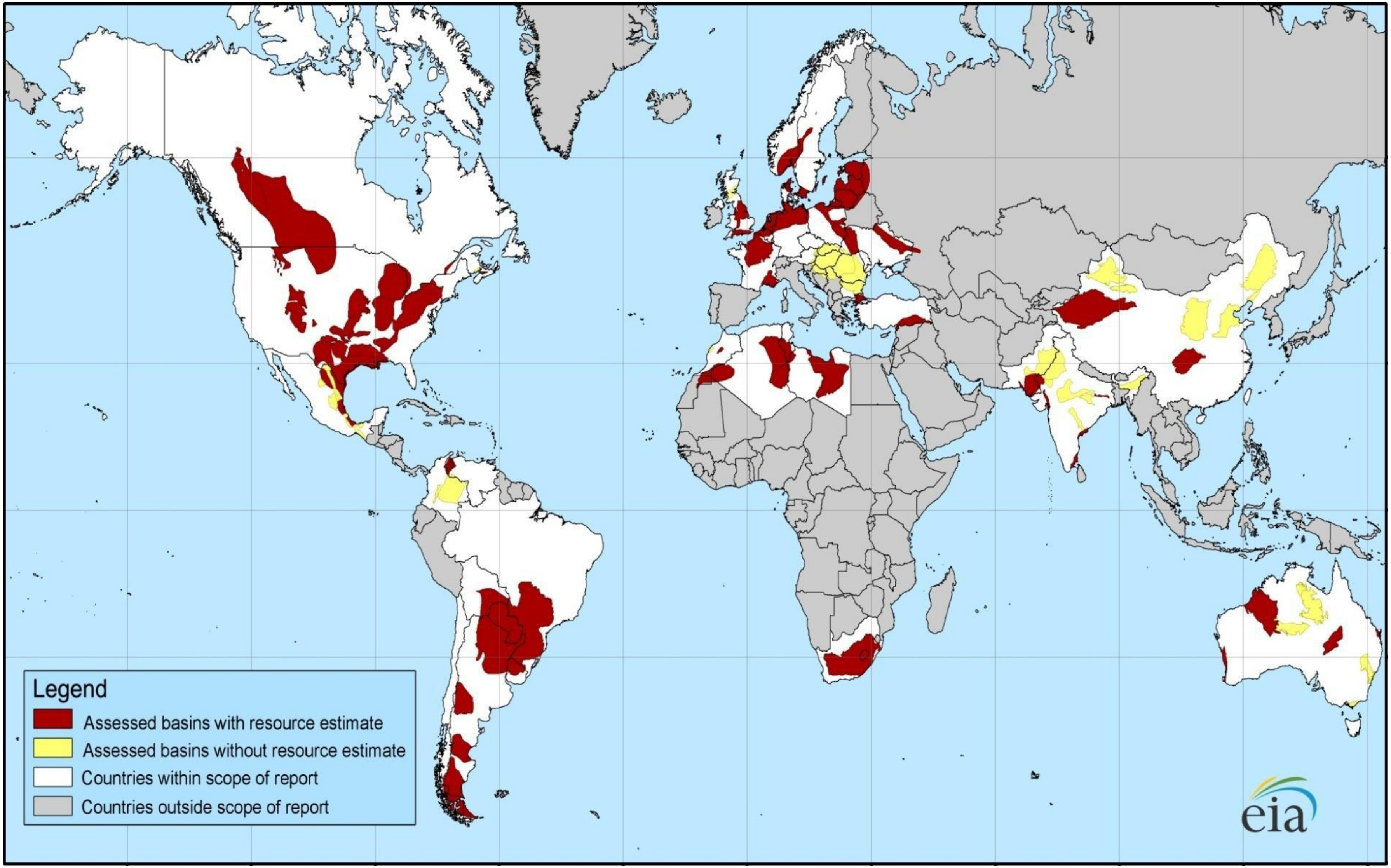
Shale Gas Production

- Barnett Shale, Ft. Worth Basin, Texas: Mitchell Energy adapted new technology for economic production of shale gas in the 1990s
  - Directional drilling, long laterals & light sand fracs
- Fayetteville Shale: 2004, Southwestern Energy, Arkansas
- Haynesville Shale: Same period, ArkLaTex area
- Marcellus Shale: Range Resources, vertical well to Lockport Dolomite in Washington Co., PA in 2005; 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
- 3157 Marcellus Shale wells drilled in PA between January 2008 and June 2011; 2900 Marcellus wells permitted in WV as of 2010.
- New targets: Woodford Shale, Arkoma Basin, Utica Shale, Appalachian Basin, Eagle Ford Shale, Texas Gulf Coast/Maverick Basin
- Energy value of U.S. natural gas may be double the oil in Saudi Arabia.



Source: Energy Information Administration based on data from various published studies.
Updated: March 10, 2010

Shale Gas Worldwide

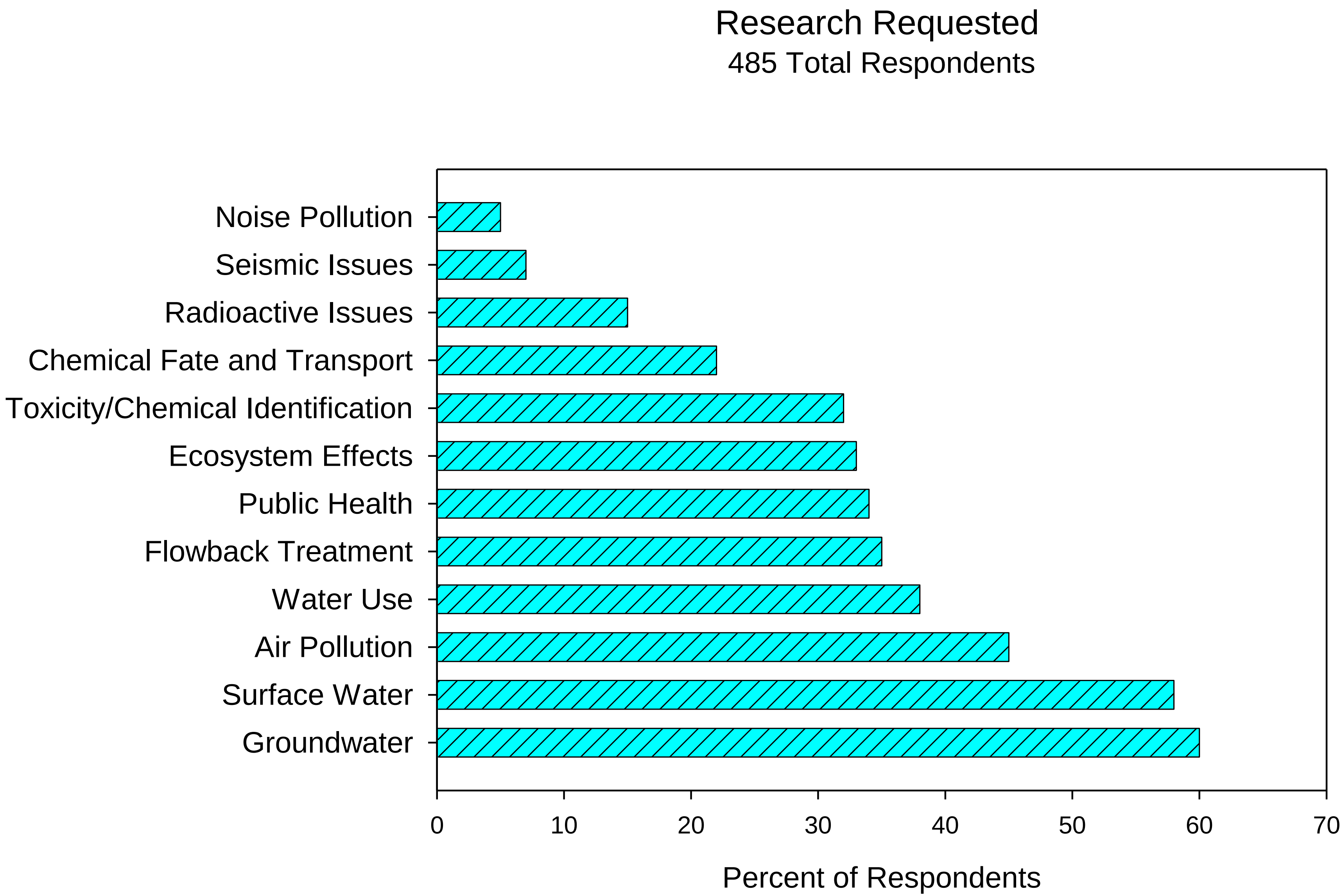


Source: U.S. Energy Information Administration

NETL Office of Research and Development

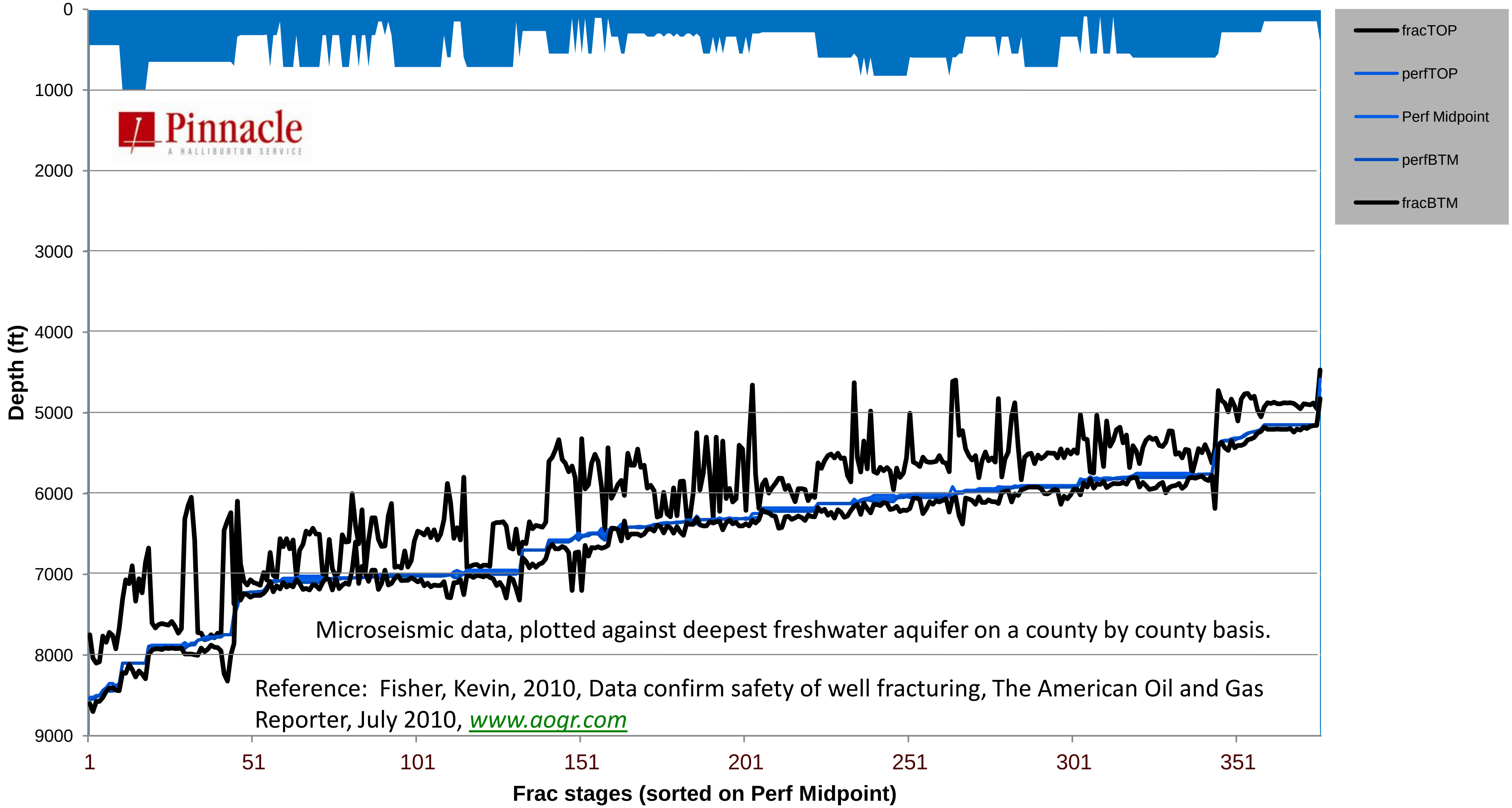
- Direction from Secretary of Energy in 2011: Assess risk from oil and gas production
- Program Technical Areas:
  - Ultra-Deep Offshore/Frontier Regions
  - Unconventional Resources, primarily shale gas
- Focus Areas for Risk Assessment:
  - Reservoirs and Resources
  - Wellbores and Drilling
  - Water Resources
  - Natural Systems Monitoring
  - Fluid-Rock Geochemistry
  - Fluid-Rock Geophysics
  - Geomaterials Science
  - Integrated Assessment Modeling

Perceived Risks: EPA Stakeholder Survey

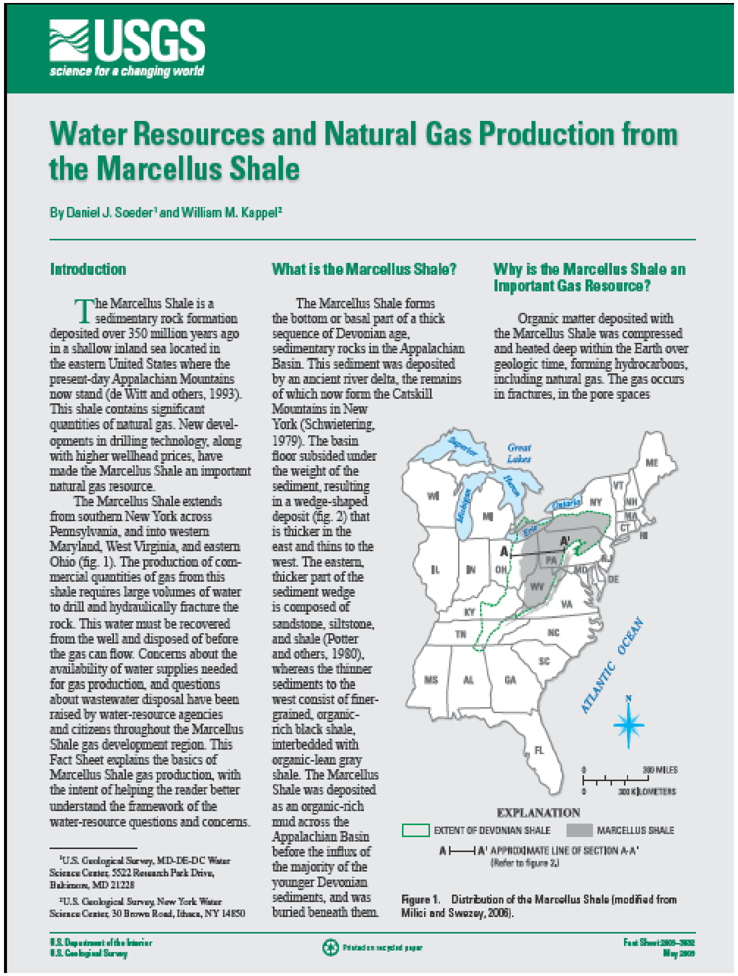


Hydraulic Fracture Heights and Aquifers

Marcellus Mapped Frac Treatments



Water Resource Concerns



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Water Resources and Natural Gas Production from the Marcellus Shale

By Daniel J. Soeder[1] and William M. Kappel[2]

Introduction

The Marcellus Shale is a sedimentary rock formation deposited over 350 million years ago in a shallow inland sea located in the eastern United States where the present-day Appalachian Mountains now stand (de Witt and others, 1993). This shale contains significant quantities of natural gas. New developments in drilling technology, along with higher wellhead prices, have made the Marcellus Shale an important natural gas resource.

The Marcellus Shale extends from southern New York across Pennsylvania, and into western Maryland, West Virginia, and eastern Ohio (fig. 1). The production of commercial quantities of gas from this shale requires large volumes of water to drill and hydraulically fracture the rock. This water must be recovered from the well and disposed of before the gas can flow. Concerns about the availability of water supplies needed for gas production, and questions about wastewater disposal have been raised by water-resource agencies and citizens throughout the Marcellus Shale gas development region. This Fact Sheet explains the basics of Marcellus Shale gas production, with the intent of helping the reader better understand the framework of the water-resource questions and concerns.

What is the Marcellus Shale?

The Marcellus Shale forms the bottom or basal part of a thick sequence of Devonian age, sedimentary rocks in the Appalachian Basin. This sediment was deposited by an ancient river delta, the remains of which now form the Catskill Mountains in New York (Schwietering, 1979). The basin floor subsided under the weight of the sediment, resulting in a wedge-shaped deposit (fig. 2) that is thicker in the east and thins to the west. The eastern, thicker part of the sediment wedge is composed of sandstone, siltstone, and shale (Potter and others, 1980), whereas the thinner sediments to the west consist of finer-grained, organic-rich black shale, interbedded with organic-lean gray shale. The Marcellus Shale was deposited as an organic-rich mud across the Appalachian Basin before the influx of the majority of the younger Devonian sediments, and was buried beneath them.

Why is the Marcellus Shale an Important Gas Resource?

Organic matter deposited with the Marcellus Shale was compressed and heated deep within the Earth over geologic time, forming hydrocarbons, including natural gas. The gas occurs in fractures, in the pore spaces

Figure 1. Distribution of the Marcellus Shale (modified from Milici and Swezey, 2006).

[1]U.S. Geological Survey, MD-DE-DC Water Science Center, 5522 Research Park Drive, Baltimore, MD 21228

[2]U.S. Geological Survey, New York Water Science Center, 30 Brown Road, Ithaca, NY 14850

U.S. Department of the Interior
U.S. Geological Survey

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Fact Sheet 2009–3032
May 2009

http://pubs.usgs.gov/fs/2009/3032/

- **Supply**
  - 3 to 4 million gallons per well
  - Only 1/4 to 1/3 is recovered/reused
  - Permits are not always required
- **Watersheds & Headwater Streams**
  - Transportation of water, sand and chemicals to well locations
  - Impacts of drilling on small watersheds
- **Disposal**
  - Recycling, injection wells, wastewater treatment for TDS
- **Water Quality Concerns**
  - Long-term leaching of drill cuttings
  - Infiltration of chemicals/spills into shallow groundwater
  - Potential for gas migration
  - Fate of fluids underground

New Uses for Natural Gas

- **Electric power generation**
  - Cleaner than coal to extract, combust and exhaust.
  - No arsenic, selenium, mercury or sulfur in flue gas, no ash disposal
- **Automobile fuel**
  - Current gasoline powered vehicles can run on compressed natural gas (CNG) with a simple conversion: dual-fuel; CNG has less range
  - CNG is cleaner-burning than gasoline; cheaper than gasoline
- **Each year, approximately 5 billion barrels of oil, or 2/3 of our total annual use, are imported.**
  - Replacing this energy with the equivalent amount of natural gas requires 13.1 TCF
  - Current national gas use is about 23 TCF/year; increasing it to 36 TCF/year will replace oil imports
  - The 360 TCF estimated recoverable from the Marcellus Shale alone could supply the Nation for a decade.

DOE Environmental Risk Assessment

Goals

Assess short/long term environmental impacts of shale gas production.

Investigate scientific concerns

Outcomes

Rigorous study with conclusions supported by well-documented data

Benefits

Public information to create a more informed environmental debate.

Improved management practices for shale gas production.

Environmental indicators for focused regulatory monitoring.