Critical Issues Forum

America’s Increasing Reliance on Natural Gas: Benefits and Risks of a Methane Economy

Wifi network: FWC Wireless
Password: (no password needed)
Session 4:
Drivers of and barriers to natural gas development in North America
Kitty Milliken
Bureau of Economic Geology,
University of Texas
Seeing Reservoir Quality at the Appropriate Scale: A Look at Tools for High-resolution Imaging and Our Evolving Understanding of Pore-Scale Processes in Fine-grained Systems

Kitty Milliken
Exploration for conventional hydrocarbon reservoirs (sandstones and limestones) is a refined scientific endeavor that reduces economic risk.

---

**Porosity model**

- Ajdukiewicz & Lander, 2010

**Large-scale data**

**Depositional model**

**Structural model**

- Chamberlain & Bhattacharjee, 2011

**Small-scale data**

**Original three-tract model**


- From SEPM Strata Website
Shale – Mudrock – Mudstone: Fine-grained Sedimentary Rocks

- A major type of sedimentary rock
- The most abundant type of sedimentary rock: 2/3 of the sedimentary record on Earth.
- Fine-grained: “clay-rich”

“We prefer the straightforward use of mudrock color for classification.” Prothero & Schwab, 2003; p. 108.

Barnett Shale core.

Munsell color system.
Possibly many may think that the deposition and consolidation of fine-grained mud must be a very simple matter, and the results of little interest. However, when carefully studied experimentally, it is soon found to be so complex a question, and the results dependent on so many variable conditions, that one might be inclined to abandon the enquiry, were it not that so much of the history of our rocks appears to be written in this language.


- **Henry Clifton Sorby**
  - "father of petrographic microscopy"
  - Made first preparation of a rock for microscopic study.
  - Published first paper on microscopic examination of rocks (1850s).
 EARLY 1960s

“In a way, shales are the last frontier of sedimentary petrology. . . . .”

EARLY 1970s

“….very little is known about the relative abundances of microcline, orthoclase, and plagioclase in sandstones. **Nothing is known** concerning these species in mudrocks.” Blatt, Middleton, and Murray, 1972, *Origin of Sedimentary Rocks*: Prentice Hall, NJ, 634 p.

EARLY 1980s

“Although they form approximately two-thirds of the stratigraphic column, mudrocks are poorly understood and inadequately studied. Few sedimentary geologists have chosen to study mudrocks......”

EARLY 1990s

“Although shales constitute the bulk of the Earth’s clastic sedimentary rocks, relatively little is known about.......” Issler, 1992, AAPG Bull., v. 76, p. 1170-1189
Late 1990s

“....fine-grained terrigenous clastics (mudstones, shales), the dominant sedimentary rock type, are still “terra incognita” for most geologists.”
Schieber et al. (eds), 1998, *Shales and Mudstones I*: E. Schweizerbart’sche Verlagsbuchhandlung, Stuttgart

Why was the science of mudrocks less advanced than the science of coarser grained systems at the end of the 20\textsuperscript{th} Century?

- Mudrocks are challenging to study because the fundamental components (grains, pores) are so small they cannot be readily observed.

- The occurrence of extractable resources within mudrocks was not expected.

- The more obvious economic importance of sandstones and limestones attracted most of the research interest and funding for study.

- Little funding was directed to mudrocks and few people chose to study mudrocks.
Mudrocks are no longer ignored!

And it’s probably fair to say that we are in the middle of a scientific revolution in our understanding of the most common type of sedimentary rock.

We now know that mudrocks:

- Are a complex class of rocks that displays heterogeneity greater than that of sandstones and limestones.
- Contain abundant clay-size crystals, but are not necessarily dominated by clay minerals nor by clay-size grains.
- As “source, seal, and reservoir” for oil and gas, should be thought of as hosting exploration targets, because assessing mudrock heterogeneity is a solvable problem……
Productivity Tiers of the Barnett Shale; Browning et al., 2013.

“Sweet spots” suggest potential for significant gains in efficiency by application of exploration models that address depositional environments, grain source mixing, and other basic causes of shale heterogeneity.

http://www.beg.utexas.edu/info/sloan_barnett.php
The challenge of mudrocks (shales) in the 19\textsuperscript{th} century and today:

Components in mudrocks (grains, pores) are generally smaller than the thickness of the standard thin section (30 μm) used for light microscopy.

30 microns = 30,000 nm!
Barnett Shale seen in transmitted polarized light microscopy.
Claystones exist but are NOT the most common type of mudrock.

Back-scattered electron image.

Oligocene Frio Formation, South Texas, USA.
Mudstones (mudrocks, shales) contain abundant:

- silt-size and sand-size grains
- non-clay minerals
- detrital and authigenic components
- fossils

- Dolomite (authigenic?)
- Pyrite (authigenic)
- Organic matter
- Quartz or feldspar (detrital)
- Agglutinated foraminifer
- Phosphate clast
- Clay aggregate

Barnett Shale, Wise County, Texas, USA
X-ray mapping by Energy-Dispersive Spectroscopy (EDS)

X-ray signal can be used qualitatively for element ID or mapping, or quantitatively for analysis.
Multi-element map:

Nova NanoSEM 430

<5 nA

15 KV

10 minutes

0.05 micron/pixel (approx)

Marcellus Formation, Pennsylvania
Mudrocks contain complex grain assemblages.

DETTRITAL, mostly extrabasinal grains:

- albite
- dolomite
- calcite
- K-mica
- quartz
- organic matter

Barnett Shale, Ellis County, Texas, USA

X-ray map
Scanned Cathodoluminescence Imaging

Visible light emitted in response to electron beam excitation.

Sensitive to trace element and defect variations.

Images subtle chemical differences that are invisible in other techniques.

after Oxford Instruments, 1993
SE/BSE image

Barnett Shale, Wise County, Texas
Angular silt with variable CL color & brightness

“matrix” quartz with dark CL:
- former opal?
- former organic matter?
Barnett Shale: siliceous lithology

- extrabasinal quartz grain
- organic matter
- microquartz cement
- extrabasinal quartz grain
- mica
- clay mineral matrix

Barnett Shale, Ellis County, Texas
Barnett Shale sample:

Polished thin section

Ion-milled surface.
Mineral-hosted pores

Eagle Ford Formation, South Texas.
Secondary pores within pore-filling residual hydrocarbon.

Eagle Ford Formation, South Texas
Something to think about:

Pores in mudrocks are generally smaller than the wavelength of light. Mudrocks are *natural nanomaterials*. 

![Image of pores in mudrocks](image)

![Graph of green light wavelength](graph)
If we had exploration models for fine-grained systems what would we want them to predict?

Bulk properties:
- Porosity (storage)
- Permeability (flow)
- Organic content (source)
- Mechanical moduli (“frackability”)
Textural heterogeneity: silt content, silt size

Barnett Shale, Ellis County, Texas, USA
Variations in grain assemblages can be assessed by CL and X-ray mapping.

X-ray maps

Silt-bearing mudstone          Chert-cemented mudstone

Barnett Shale                  Milliken, 2013
Variations in grain assemblages can be assessed by CL and X-ray mapping.

CL maps

Silt-bearing mudstone
Barnett Shale
Cathodoluminescence images

Chert-cemented mudstone
“matrix-dispersed authigenic microquartz”
Milliken, 2013
Variations in grain assemblages can be assessed by CL and X-ray mapping.

*Organic matter: terrigenous vs marine vs residual hydrocarbon.*

Silt-bearing mudstone

Chert-cemented mudstone

Milliken et al., 2012
Four-component mixing system for sediments in the Barnett Shale

<table>
<thead>
<tr>
<th>Extrabasinal debris</th>
<th>Silt-size components</th>
<th>Clay-size components</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>quartz, feldspar, mica</td>
<td>clay, quartz, feldspar</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Intrabasinal particles</th>
<th>Silt-size components</th>
<th>Clay-size components</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>bio-siliceous allochems, glauconite</td>
<td>bio-siliceous allochems</td>
</tr>
</tbody>
</table>

Quartz may dominate in 3 of these, even in a single sample.

Milliken et al., 2012
Declining extrabasinal content

Porous Permeable Brittle Oil-prone

Model best reservoir quality where:
- extrabasinal influx is minimal
- marine OM is highest
- siliceous fossils react to form brittle mudstones.

Milliken et al., 2012
Future Exploration Model?

“Detrital Clay is the New Sand”

Theoretical idea for mudrock compositional variation across stratigraphy needs to be tested.
Transformative Technologies for Micro-Imaging:

- Light microscopy
- X-ray mapping & CL imaging
  - Grain assemblages in mudrocks
- CL-imaging
  - Integrated chemical-mechanical history
- FE-SEM
  - Ar-ion cross-section polishing
  - Pore systems in mudrocks: correlating pore evolution to thermal maturity
Apparent homogeneity of shales as seen by visual inspection is misleading......

At high magnifications, we learn that most shales don’t look like this:

But rather, like:

Barnett Shale Examples
Building exploration models for fine-grained depositional systems: What does it take?

- **Training (undergraduate and graduate levels)**
  - Basic chemistry, physics, biology, mathematics
  - Basic geoscience
  - Sedimentology and stratigraphy
  - Mineralogy and geochemistry
  - Petrology
  - Paleontology

- **Working environment**
  - Interdisciplinary
  - Multi-scale: basinal to nanometer

- **Tools**
  - High-quality log suites
  - Core descriptions
  - Micro-imaging
    - Light microscope
    - X-ray mapping
    - CL imaging
    - High-resolution pore imaging
    - Many affiliated techniques

**Drivers:**
- Economic motivations
- Technologies
- Scientific understanding

**Needs:**
- Education in rock-based studies
- Integration across disciplines and scales
- Cores (please share!)
- Time (Research takes time.....)

http://www.fei.com/natural-resources/oil-gas/
Terrigenous and Volcanic Grains

EXTRABASINAL:
Terrigenous-argillaceous = TARL

INTRABASINAL:
Calcareous-argillaceous = CARL
Siliceous-argillaceous = SARL

Classification of Fine-grained Sedimentary Rocks

Average particle size < 62 micrometers

From Milliken, in press, JSR.
Randy Randolph
Southern Gas Association
AGI Critical Issues Forum

America’s Increasing Reliance on Natural Gas: Benefits and Risk of a Methane Economy

“Politics & Public Opinion”

The Natural Gas Conundrum

L. C. (Randy) Randolph Jr.
Southern Gas Association
Who We Are...

- 106 year old natural gas trade association
- 160 natural gas company members
- 300 associate members
- 500+ member volunteers
- 60 live & 50 virtual events per year
SGA Member Service Areas
Outline

• Geographic Changes in Nat Gas Supply
• Nat Gas & Liquid Hydrocarbon Connection
• US Refining Capacity
• Economic Contributions
• Regional Responses
• Technology
Natural Gas Production Geography Keeps Evolving

Units = Bcfd
Basins Sized Relative to Rockies 2010 Prod

- Rockies: 15.2 Bcfd
- Anadarko: 5.4 Bcfd
- Barnett: 5.2 Bcfd
- Haynesville: 4.7 Bcfd
- Eagle Ford: 0.6 Bcfd
- Permian: 4.5 Bcfd
- Fayetteville: 2.5 Bcfd
- Marcellus: 2.6 Bcfd
- GOM: 6.8 Bcfd

Source: Ponderosa Advisors & HPDI
Marcellus/Utica Transforming The Natural Gas Market

<table>
<thead>
<tr>
<th>Basin</th>
<th>2010 Prod</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rockies</td>
<td>13.0</td>
<td></td>
</tr>
<tr>
<td>Anadarko</td>
<td>7.5</td>
<td>6.3</td>
</tr>
<tr>
<td>Permian</td>
<td>6.3</td>
<td>5.3</td>
</tr>
<tr>
<td>Eagle Ford</td>
<td>7.1</td>
<td></td>
</tr>
<tr>
<td>Haynesville</td>
<td>2.9</td>
<td>4.3</td>
</tr>
<tr>
<td>Fayetteville</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>GOM</td>
<td>16.4</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Source: Ponderosa Advisors HPDI
Marcellus/Utica Will Transform The Natural Gas Market

2020

Units=Bcfd
Basins Sized Relative to Rockies 2010 Prod

Source: Ponderosa Advisors & HPDI
Marcellus/Utica Production Dominates NA Flow Patterns Straining Pipeline Assets

Units = Bcfd
Basins Sized Relative to Rockies 2010 Prod

Marcellus/Utica Production Dominates
NA Flow Patterns Straining Pipeline Assets

Source: Ponderosa Advisors & HPDI
North America Natural Gas Supply and Demand

N. America Supply vs. Demand

North America is poised to become a net LNG exporter

* N. America: U.S. and Canada only
Dry Gas Declines Have Been Offset By Associated Gas Production

Gross Gas Production By GPM

Assoc Gas Definition: Onshore Production Areas With GPM > 1.15, Data through 8/2014

Source: Ponderosa Advisors, HPDI, FERC
¹Utilization Rate: 90%
²Foreign Owned Capacity: 1.4 MMb/d
³Canadian Imports: 3.1 MMb/d
US Refining Capacity Will Slow Production Growth

Source: Ponderosa Advisors, HPDI, FERC

¹Utilization Rate: 90%
²Foreign Owned Capacity: 1.4 MMB/d
³Canadian Imports: 3.1 MMB/d
United States Oil & Gas Key Industry Statistics

**EMPLOYMENT**

<table>
<thead>
<tr>
<th>Year</th>
<th>Employment</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>830,800</td>
</tr>
<tr>
<td>2010</td>
<td>835,500</td>
</tr>
<tr>
<td>2011</td>
<td>906,400</td>
</tr>
<tr>
<td>2012</td>
<td>982,000</td>
</tr>
<tr>
<td>2013</td>
<td>1,012,800</td>
</tr>
</tbody>
</table>

**WAGE COMPARISON**

Annual Average in 2013

- **Private Sector**: $49,700
- **Oil & Gas**: $103,400
- **Professional Services**: $83,400
- **Manufacturing**: $61,100
- **Construction**: $53,200

Source: U.S. Bureau of Labor Statistics
All data is for 2013 except where noted.
California Oil & Gas Key Industry Statistics

**EMPLOYMENT**

2009-2013

- 2009: 44,200
- 2010: 44,000
- 2011: 45,200
- 2012: 46,600
- 2013: 46,400

**WAGE COMPARISON**

Annual Average in 2013

- Private Sector: $56,600
- Oil & Gas: $138,200
- Professional Services: $97,600
- Manufacturing: $77,900
- Construction: $58,200

Source: U.S. Bureau of Labor Statistics

All data is for 2013 except where noted.
Colorado Oil & Gas Key Industry Statistics

**EMPLOYMENT**

<table>
<thead>
<tr>
<th></th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>22,800</td>
<td>23,200</td>
<td>26,100</td>
<td>27,600</td>
<td>28,200</td>
</tr>
</tbody>
</table>

**WAGE COMPARISON**

Annual Average in 2013

- Private Sector: $51,100
- Oil & Gas: $111,700
- Professional Services: $84,800
- Manufacturing: $62,400
- Construction: $51,100

Source: U.S. Bureau of Labor Statistics

All data is for 2013 except where noted.
Texas Oil & Gas Key Industry Statistics

**EMPLOYMENT**

<table>
<thead>
<tr>
<th>Year</th>
<th>Employment</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>304,500</td>
</tr>
<tr>
<td>2010</td>
<td>307,300</td>
</tr>
<tr>
<td>2011</td>
<td>345,200</td>
</tr>
<tr>
<td>2012</td>
<td>388,500</td>
</tr>
<tr>
<td>2013</td>
<td>411,600</td>
</tr>
</tbody>
</table>

**WAGE COMPARISON**

Annual Average in 2013

- Private Sector: $52,100
- Oil & Gas: $118,900
- Professional Services: $83,900
- Manufacturing: $68,900
- Construction: $55,700

Source: U.S. Bureau of Labor Statistics
All data is for 2013 except where noted.
UT Austin Energy Survey

35 years old and younger
• 68% would likely vote for candidates that support carbon emission reductions
• 56% are willing to pay much higher prices to protect the environment
• 72% strongly support subsidies for renewable energy
• 39% are familiar with hydraulic fracturing for hydrocarbon fuel extraction
• 37% support the use of hydraulic fracturing

65 years old and older
• 50% would likely vote for candidates that support carbon emission reductions
• 20% are willing to pay much higher prices to protect the environment
• 58% strongly support subsidies for renewable energy
• 52% are familiar with hydraulic fracturing for hydrocarbon fuel extraction
• 52% support the use of hydraulic fracturing
Building Creditability & Relationships

• Education – Public, Customers & Employees
• Advocacy Training
• Local Community Engagement
• Workforce Training & Development
• Public Forum Participation
• Safety - Public, Customer and Employee
• Communications
Contact

L. C. (Randy) Randolph Jr.
Vice President
rrandolph@southerngas.org
713-299-9414

Find Us Online

www.southerngas.org
www.gmrc.org
http://twitter.com/SouthernGas
www.linkedin.com/company/Southern-Gas-Association
Lawrence Bengal
Arkansas Oil and Gas Commission
American Geosciences Institute
Critical Issues Forum
Forth Worth, Texas
November 19-20, 2014

America’s Increasing Reliance on Natural Gas: Benefits and Risks of a Methane Economy

Session 4 – Drivers of and Barriers to Natural Gas Development in North America
Figure 1. U.S. Natural Gas Production by Source (Historic and Projected)

480,000 Miles of Existing Natural Gas and HL Pipelines In-Place Facilitating Shale Production
Most U.S. Unconventional Shale Resources Occurred in States With Existing Conventional Oil and Gas Regulatory Frameworks In-Place
Key Points: State Oil and Gas Regulation

- Diversity of geology, topography, work force, culture make states logical oil and gas regulators
- States have historically been the primary regulators of oil and gas development
- States are innovative, flexible, can rapidly respond to changes in technology
- States work collaboratively as oil and gas resources cross state boundaries
Primary Barriers to and Drivers of Natural Gas Development Challenge States

Public Policy

Regulatory

Technology

Environment

Economic
States are rising to these challenges as laboratories for creative solutions and regulatory innovation ......
States First Initiative

Governors’ letter of support

Sincerely,

Mary Fallin
Jack Dalrymple
Steve Bullock
Governor of Montana

Robert Bentley
Governor of Alabama
2013 IOGCC Chairman

Gary R. Herbert
Governor of Utah

Sean Parnell
Governor of Alaska

Mary Fallin
Governor of Oklahoma

Tom Corbett
Governor of Pennsylvania

Phil Bryant
Governor of Mississippi

John Hickenlooper
Governor of Colorado

Jack Dalrymple
Governor of North Dakota
Partnership between IOGCC and GWPC

States First Initiative

Shaping the STATE of our energy future together.

Collaboration, Solutions, Regulatory Leadership
Interstate Oil and Gas Compact

- Established by Congress in 1935
- Governors of oil and gas producing states
- Collectively representing the States
- State led, Chaired by governors
  - Governor Robert Bentley (Alabama) 2013
  - Governor Phil Bryant (Mississippi) 2014
  - Governor Gary Herbert (Utah) 2015
- Promote conservation and efficient recovery of oil & gas while protecting health, safety and the environment
IOGCC 38 Member States

Note: Six Canadian Provinces are Affiliate Members
The national association of state groundwater protection programs
What is States First?

- Partnership between IOGCC and GWPC
- Platform demonstrating states continuing regulatory improvements
- Initiated by 14 IOGCC member Governors
- Announced by 2013 IOGCC Chairman Alabama Governor Bentley
- Approved by IOGCC and GWPC governing bodies
PURPOSES OF THE INITIATIVE

1. Recognition of the state’s continuing regulatory improvements.

2. Provide a platform for open communication and sharing between state’s.

3. Develop best practices.

4. Assist states efficiently develop and implement regulatory solutions.

5. Contribute to Nation’s economic growth, national security and energy independence.
STATES FIRST INITIATIVE

Promoting and Documenting Continuous Regulatory Improvement

- Underground Injection Control
- Hydraulic Fracturing
- Inspector Training & Certification
- Effective Regulation through SOGRE
- Science, Technology and Information Transfer
STATES FIRST INITIATIVE

UNDERGROUND INJECTION CONTROL

- Peer Reviews of State Class II Regulatory Programs
- Consultation with States on Regulatory Improvements

EFFECTIVE REGULATION THROUGH SOGRE

- Peer Reviews and Consultations of Oil and Gas Regulatory Programs
- State to State Issue Focused Workshops and Forums – **Utah Horizontal Well Spacing Workshop**
- Stakeholder Forums
STATES FIRST INITIATIVE

INSPECTOR TRAINING AND CERTIFICATION

- State Oil and Gas Inspector Training Program (Affiliated With Universities')
- State Oil and Gas Inspector Certification Program

INFORMATION, TECHNOLOGY AND SCIENCE TRANSFER

- Recently created Seismicity Task Force
- New report on state regulations to protect groundwater.
HYDRAULIC FRACTURING

• Chemical Disclosure through Frac Focus
GOALS

• Continuous Improvement
• Build Public Confidence
• Open Communications For States and Federal Agencies
• Empower states
• Educate Congress
• Inform Industry
Questions
Critical Issues Forum

America’s Increasing Reliance on Natural Gas: Benefits and Risks of a Methane Economy

Wifi network: FWC Wireless
Password: (no password needed)