An Insight Into Hydrocarbon Extraction From Shale: Definitely Not A Geoscientist’s Bore Nor an Engineer’s Dream

Dr. Iain Bartholomew

Image from Norton et al, CSEG Recorder, 2011 (Progress Energy Resources)
Discussion outline

• Conventional versus unconventional
• Geology is the key to commerciality
• Breakthroughs in predicting the sweet-spots
• Enhancing production
• The North American shale story
• ..... and what about the UK?

Photos from: Hammers et al, AAPG Bulletin, 2011 (Bureau of Economic Geology)
Conventional v’s unconventional gas production

Typical gas recovered per well: 10 – 100 bcf

Typical production rate per well: 10 – 100 million scf/d

Typical gas recovered per well: 0.5 – 10 bcf

Typical production rate per well: 1 – 10 million scf/d (30 day IP rate)

Data source: Drillinginfo

10 mmmscf/d
Shale exploitation

• Typical dimensions
  - 1 to 3km horizontal length
  - Down to 100m spacing
  - 2 to 4km depth
  - Up to 20 horizontal wells per pad
  - Up to 40 frac stages per horizontal well
The early days onshore US: drill, drill, drill!!

- Grab land
- Pattern drill
- Seismic not required
- Horizontal drilling and hydraulic fracking were the technical breakthroughs
- Factory process: drill for minimum cost
- Extend reach
- Decrease spacing (including infill wells)
- More fracs per well
Huge variation in a single play: eg: Haynesville

- Peak gas rates range from 0 – 5 mmscfpd/1,000’
- Single wells produce 2.5 – 4.5 bcf during their life
Only 4 years ago: lack of quantitative data on reservoir properties of shale

• From Aplin and Macquaker, AAPG Bulletin, 2011 (Newcastle University & Memorial University of Newfoundland)

“Although the petrophysical properties of homogeneous mudstones are reasonably well known, the quantitative implications of heterogeneity for petroleum expulsion, retention, petroleum migration, seal capacity, acoustic anisotropy, and identification of shale gas reservoir sweet spots are essentially unexplored.”
Geology is key to unconventional success

- Frackability
  - Brittleness is good (quartz or calcite content)
  - Clay is bad
  - Fracture barriers (good or bad?)
  - Natural fractures
- Hydrocarbon content and maturity
  - High TOC good
  - but high TOC is usually ductile rock (not good)
- Depth (> 5000 feet)
- Energy for production
  - Pressure (small over-pressure is good)
- Structural complexity (simple is good)
  - Understanding of regional stress important
- Regional geological understanding is essential

Photos from the Utica shale, Canada (A primer for understanding Canadian shale gas, National Energy Board, Canada, 2009)
Parameter comparisons for key North American plays

<table>
<thead>
<tr>
<th>Play</th>
<th>Depth (ft)</th>
<th>Thickness (ft)</th>
<th>Quartz (%)</th>
<th>Clay (%)</th>
<th>TOC (%)</th>
<th>Ro</th>
<th>Porosity (%)</th>
<th>Britteness</th>
<th>Pressure Gradient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eagle Ford</td>
<td>6,000-14,000</td>
<td>50-300</td>
<td>5-20</td>
<td>15-25</td>
<td>2-6</td>
<td>1.0-1.6</td>
<td>6-14</td>
<td>Mod</td>
<td>0.5-0.7</td>
</tr>
<tr>
<td>Haynesville</td>
<td>11,000-14,000</td>
<td>150-300</td>
<td>20-35</td>
<td>25-35</td>
<td>1-5</td>
<td>1.3-2.2</td>
<td>6-15</td>
<td>Low</td>
<td>0.7-0.9</td>
</tr>
<tr>
<td>Barnett</td>
<td>6,000-9,000</td>
<td>300-500</td>
<td>40-60</td>
<td>10-30</td>
<td>3-8</td>
<td>1.2-2.0</td>
<td>3-9</td>
<td>High</td>
<td>0.5-0.6</td>
</tr>
<tr>
<td>Marcellus</td>
<td>5,000-8,000</td>
<td>50-350</td>
<td>25-40</td>
<td>20-35</td>
<td>3-14</td>
<td>0.9-3.5</td>
<td>4-11</td>
<td>Low</td>
<td>0.3-0.8</td>
</tr>
<tr>
<td>Horn River</td>
<td>9,000-13,000</td>
<td>200-500</td>
<td>55-80</td>
<td>7-10</td>
<td>2-5</td>
<td>1.6-2.0</td>
<td>3-7</td>
<td>Very High</td>
<td>0.5-0.6</td>
</tr>
</tbody>
</table>

Other important data requirements:
- Young’s modulus, Poisson’s ratio
- Regional and local stress regime
Mudstone diversity: key sedimentological considerations for source, seal, and reservoir properties in petroleum systems

- Mineralogy
- Grain size
- Bioturbation
- Diagenetic changes (pre- and post-compaction)  
  - Including burial and uplift affects
- Depositional setting  
  - Suspension settling out from low-energy buoyant plumes  
  - But dispersed by a combination of waves, gravity-driven processes, and unidirectional currents driven variously by storms and tides  
  - Organised into packages that can be interpreted by sequence stratigraphy

From: Aplin and Macquaker, AAPG Bulletin, 2011  
(Newcastle University & Memorial University of Newfoundland)

Photos from: Hammes et al, AAPG Bulletin, 2011 (Bureau of Economic Geology)
FE-SEM analysis: Woodford shale – lots of pore space!

Field emission scanning electron microscope images. Slides C, D and E show mesopores concentrated in the kerogen aggregate next to clay. Slide F shows fracture surfaces.

From Chalmers et al, AAPG Bulletin, 2012 (University of British Columbia)
Quantification of pore space in shale using nanometer-scale resolution imaging

- Shales are quite different and their microstructures are highly variable and complex
- Understanding pore connectivity is key

From Curtis et al, AAPG Bulletin, 2012 (University of Oklahoma)
Example of bioturbation enhancing reservoir quality

Core slab of bioturbated mudstone facies from Rosario Formation, Mexico (Mm = mudstone matrix; Bc = burrow core composed of mineralogically altered clay minerals; Bh = burrow halo composed of silt and sand grade minerals (mainly quartz).

3-D model of phycosiphoniform burrows from the Upper Cretaceous Rosario Formation, Mexico

From: Bednarz and MaIlroy, AAPG Bulletin, 2012 (Memorial University of Newfoundland)
Marcellus shale lithofacies modelling

Figure 22. Bubble map of monthly average Marcellus Shale gas production (mmcf) for the first 6 months of production from horizontal wells in Pennsylvania and West Virginia overlain on the Marcellus Shale isopach of modeled composite organic-rich lithofacies (A) and the composite brittle lithofacies (B). The filled color and the radius indicate the values of average gas production; the lower color bar is for production data and the unit is mmcf/month; the upper color bar is for isopach maps.

From Wang and Carr, AAPG Bulletin, 2013 (West Virginia University)
Hybrid and stacked plays

- Hybrid plays contain organic rich shale intervals interbedded with gas charged silty layers.
- This is the case of the Montney formation in Western Canada, which contains a gradation of facies ranging from coastal sand to offshore shale and fine grained turbidites.
- The deposition and preservation of organic matter in the sediments is a key element of the hydrocarbon system.

From Pflug, NECA Conference, 2009 (TransCanada)
Simultaneous deposition of organic-rich carbonate and clastic sediments in an anaerobic basin results in hydrocarbon-rich, interbedded, conventional and unconventional reservoirs.

From: Pioneer Natural Resources Investor Presentation, 2015
Use of seismic data to predict reservoir quality in unconventional plays

- The two key properties derived from seismic for estimating ‘fracability’ are Young’s modulus and Poisson’s ratio.
- Azimuthal inversion and AVO can be used to determine both the principal stresses and the differential horizontal stress ratio.
- Faults and fracture identification from 3D volumes.
- These data enable:
  - Sweet spot identification
  - Well location optimization
  - Completions optimization

From Ouenes, CSEG Recorder, 2011 (Sigma3)
Micro-seismic monitoring

Microseismic basic principle (vertical well)

Combined results from a 3 well fracking completion programme from Montney shale, Canada

Near-surface array design in the Horn River Basin. This array was used to monitor 253 fracking completions on a 10 well pad over a 90 day period.

From Snelling and Taylor, CSEG Recorder, 2013 (Microseismic Inc and Encana) and Norton et al, CSEG Recorder, 2011 (Progress Energy Resources)
Reservoir performance prediction from seismic: an example from the Montney shale, Canada

Poisson’s Ratio minimum map. Hot colours are low PR values (more porous and less ductile) and cool colours high PR values (less porous and more ductile)

Ant-Tracker results at the reservoir interval showing larger and smaller-scale faults

From Norton et al, CSEG Recorder, 2011 (Progress Energy Resources)
Reservoir performance prediction from seismic: micro-seismic data results from the Montney shale – evidence of fracture barriers

Map combining the PR minimum display with Ant-Tracker results at the reservoir interval, and the micro-seismic measurements from fracking (circle sizes indicate magnitude of seismic event)

From Norton et al, CSEG Recorder, 2011 (Progress Energy Resources)
Better prediction of reservoir properties enables ‘informed’ production enhancement

- Infill Drilling
- Optimisation of well spacing
- Drilling longer laterals
- Offsets from existing laterals
- Optimising number of frac stages
- Simul fracs/Zipper fracs
- Refracs
- Managing drilling fluid chemistry
  - avoid formation damage
  - enhance brittleness and effectiveness of stimulation (including hydraulic fracturing)

Photos from American Oil & Gas Reporter, 2015
Unconventional oil and gas resources: the US story
The North American shale story: huge resource

• Huge recoverable resource: > 1,000 TCF plus > 26 billion barrels recoverable
• Assuming 25 TCF/year US consumption then there is enough gas resource for >40 years

North American production from unconventional plays:

<table>
<thead>
<tr>
<th></th>
<th>Produced by end 2013 TCF</th>
<th>Billion BBL</th>
<th>Total recoverable TCF</th>
<th>Billion BBL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shale</td>
<td>42</td>
<td>0.3</td>
<td>1182</td>
<td>26.3</td>
</tr>
<tr>
<td>Hybrid</td>
<td>84</td>
<td>2.1</td>
<td>547</td>
<td>51.1</td>
</tr>
<tr>
<td>CBM</td>
<td>26</td>
<td>0</td>
<td>94</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>152</td>
<td>2.4</td>
<td>1823</td>
<td>77.4</td>
</tr>
</tbody>
</table>

* Based on Wood Mackenzie and EIA data
The US shale story: its evolution

• **Big tax incentives early on**
  – Federal Tax Section 29 nonconventional fuels production tax credit (on ‘tight’ wells drilled between 1980 – 1992)

• **Lots of experimentation early on**
  – Antrim Shale: first development in 1965: 1,200 wells drilled in tax credit period (natural fractures)
    ➢ 3.3 TCF produced to date
    ➢ 13 TCF produced to date

• **Technological breakthroughs**
  – Horizontal drilling
  – Hydraulic fracturing
The US shale gas revolution

- Dependency on shale gas to meet demand
- 45% of gas production in US is now from shale
- In 2014 US gas consumption was 26 TCF. 26 TCF was produced (13 TCF from shale)
- 46 TCF produced to end 2013; 665 TCF remaining technically recoverable*

*Note: ARI estimates U.S. shale oil resources at 48 billion barrels and U.S. shale gas resources at 1,161 trillion cubic feet.
Source: United States: EIA and USGS; Other basins: ARI.
...closely followed by oil from shale

- >50% of oil production in US is now from shale (~5.2 million barrels per day)
- In 2013 US oil consumption was 18.9 million barrels per day
- 58 billion barrels remaining technically recoverable*

*Note: ARI estimates U.S. shale oil resources at 48 billion barrels and U.S. shale gas resources at 1,161 trillion cubic feet. Source: United States: EIA and USGS; Other basins: ARI.
US shale: scale of operations

• Huge scale of operation
  – 1,700 land rigs in operation in US in early 2014: <1,000 in early 2015
  – 36,000 wells drilled in 2013
  – Over 30,000 wells are currently on production from shales
    ✓ For oil on average each well produces 315 barrels oil per day
    ✓ For gas on average each well produces 1.6 million standard cubic feet per day

• Very high level of drilling must continue in order to sustain production as individual wells only have 1-5 year economic life

• Over 1 million wells required to produce unconventional resource in North America. 124,000 have already been drilled.
Where does it all come from?

- 64 key shale plays
- 28 are ‘pure shale’
- 36 are ‘hybrid’
- Huge variation in liquids content

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
Some plays have huge resources

Ultimate recoverable reserves and produced reserves per play in Nth Am

- **Shale gas plays**: Marcellus, Haynesville, Horn River, Fayetteville, Barnett, Liard
- **Liquid-rich shale plays**: None
- **Hybrid gas plays**: Eagle Ford, Duvernay, Three Forks
- **Hybrid liquid-rich plays**: Montney, Bakken

- **425 TCFE**
- **180 TCFE**
- **160 TCFE**
- **140 TCFE**
- **120 TCFE**
- **100 TCFE**
- **80 TCFE**
- **60 TCFE**
- **40 TCFE**
- **20 TCFE**
- **0 TCFE**

- **Ultimately recoverable**
- **Produced to end 2013**

- **Ultimate recoverable reserves**
- **Produced to end 2013**
BUT only a few plays have production

- 6 shale plays are bulk of production*
- They have already produced 126 TCF and 2.4 billion barrels by end 2013*
- These plays alone have potential to still produce 800 TCF and 13 billion barrels

* Includes Bakken which is a ‘hybrid’ play

Sources: LCI Energy insight gross withdrawal estimates as of January 2013 and converted to dry production estimates with EIA-calculated average gross-to-dry shrinkage factors by state and/or shale play.
Canada? Huge resources but needs LNG export
Impact of the oil price crash
Oil price crash has materially impacted the number of active onshore drilling rigs

Active US Onshore Rigs

From Evercore ISI Investment Conference, 2015 (Pioneer Natural Resources)

Baker Hughes

U.S. Shale Crude and Condensate Production (MMB/D)

Source: EIA

Average LLS (2013 $/Bbl)
Individual well productivity is enabling the industry to survive in a low price environment.

From EIA, Drilling Productivity Report, May 2015
The UK Opportunity
The UK: setting the scene

UK net gas production and net gas imports, 2000-2030

- Net gas imports
- Net gas exports
- UK net gas production

UK – US area comparison
UK: how do we compare?

- Very small areas compared to North America
- Structurally complex basins
- Much thicker shale sequences and therefore volumes could still be interesting
  - BGS/DECC estimate ~1,300 TCF GIIP for Bowland (P50)
    - BUT ??? recovery factor and commerciality
- In the UK we are still very much in the **EXPLORATION** stage – we will have to wait and see
- We can learn a huge amount from North America

ANY QUESTIONS?