Hydrogeological aspects of shale gas extraction in the UK

Marianne Stuart

Groundwater Science
British Geological Survey
Introduction

• Extent of potential shale gas source rocks in UK
• Water resource demands and UK resources
• Contamination issues:
  • Pollutant sources: fracking fluid, flowback water, produced water, storage/transport
  • Pathways: production wells, geological, abandoned wells
  • Receptors: aquifers, abstractions, ecology

http://www.theguardian.com/environment/2012/may/29/shale-gas-coal-climate-investor
Shale gas in the UK?

- Carboniferous (Namurian): Northern Britain and Ireland
- Jurassic (Upper and Lower): Wessex Basin and The Weald
- Lower Palæozoic (Silurian, Ordovician, Cambrian): Wales
- Precambrian: Midland Microcraton (?)
Bowland Shale prospectivity
UK experience to date

- Limited shale gas exploration – Cuadrilla, NW Eng
- Proposals: South Wales, Yorkshire, Somerset, West Sussex, Kent, Northern Ireland, Lincolnshire, Manchester etc
- Extensive UK onshore conventional gas exploration in last 30 years: >2000 wells with ~ 10% fracked
- Examples:
  - Wych Farm (Dorset) – oil field with over 100 production wells and directional drilling up to 10km horizontally
  - Elswick – single production gas well fracked to stimulate gas from sandstone
UK groundwater

- In UK groundwater provides 30% of public water supply
- Important aquifers are the Chalk, Jurassic and Permian limestones, Permo-Triassic sandstones
- Moderately productive Carboniferous aquifers in areas of north England and Midland Valley Scotland
- Poorly productive aquifers locally important for baseflow, wetlands and private supplies
# Aquifer / Shale Gas Stratigraphy

<table>
<thead>
<tr>
<th>Formation</th>
<th>Kimmeridge Clay</th>
<th>Oxford Clay</th>
<th>Lias</th>
<th>Marros</th>
<th>Bowland &amp; Craven</th>
<th>Upper Cambrian</th>
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<tbody>
<tr>
<td>Crag</td>
<td>Red</td>
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<td>Red</td>
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<tr>
<td>Chalk</td>
<td>Red</td>
<td></td>
<td>Red</td>
<td>Red</td>
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<tr>
<td>Lower Greensand</td>
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<tr>
<td>Spilsby Formation</td>
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<td>Kimmeridge &amp; Ampthill Clay</td>
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<tr>
<td>Corallian limestones</td>
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<tr>
<td>Kellaways, Oxford Clay &amp; Osgodby</td>
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<td>Oolites</td>
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<tr>
<td>Lias</td>
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<tr>
<td>Triassic sandstones</td>
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<td>Magnesian Limestone</td>
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<td>Blue</td>
<td>Blue</td>
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<td></td>
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<tr>
<td>Permian sandstones</td>
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<td></td>
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<tr>
<td>Marros Group</td>
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<td></td>
<td>Blue</td>
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<tr>
<td>Bowland &amp; Craven Groups</td>
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<td>Blue</td>
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<tr>
<td>Carboniferous Limestone</td>
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<td>Fell Sandstone &amp; Border Group</td>
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<tr>
<td>Upper Cambrian shales</td>
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<td></td>
<td>Blue</td>
<td>Blue</td>
<td>Blue</td>
<td>Blue</td>
</tr>
</tbody>
</table>

**Notes:**
- Principal aquifer overlies potential shale gas source rock.
- Potential shale gas source rock overlies Principal Aquifer(s).
- No overlap between Principal Aquifer and potential shale gas source.

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**Aquifer formations**

**Shales**
Shale and aquifer mapping
1. Waters characterised using:

- Dissolved concentrations of CH$_4$ and CO$_2$ plus general water chemistry
- DOC
- C and H stable isotopes of CH$_4$, $^{14}$C, stable isotopes of CO$_2$ and DIC
- Trace organics
- Groundwater residence time indicators (CFCs, SF$_6$)
- Microbiological indicators
Hydraulic fracturing water requirements

- Each well may require 250 – 4000 m³ of water to drill, then 7000–23,000 m³ for fracking\(^a\).
- Variation reflects complexity of drilling, geological conditions, total depth/number of fracking stages
- Example of published estimates (per well)\(^b\):

<table>
<thead>
<tr>
<th>Shale Play</th>
<th>Drilling (m³)</th>
<th>Fracking (m³)</th>
<th>Total (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barnett (US)</td>
<td>950</td>
<td>14000</td>
<td>14950</td>
</tr>
<tr>
<td>Haynesville (US)</td>
<td>2300</td>
<td>19000</td>
<td>22300</td>
</tr>
<tr>
<td>Fayetteville (US)</td>
<td>250</td>
<td>19000</td>
<td>19250</td>
</tr>
<tr>
<td>Marcellus (US)</td>
<td>300</td>
<td>21000</td>
<td>21300</td>
</tr>
<tr>
<td>Eagle Ford (US)</td>
<td>500</td>
<td>23000</td>
<td>23500</td>
</tr>
<tr>
<td>Bowland Shale (UK)</td>
<td>900</td>
<td>8400</td>
<td>9300</td>
</tr>
</tbody>
</table>

\(^a\) Range obtained from various published sources (mostly US).
\(^b\) University of Texas (2012) and Cuadrilla
Estimated UK water requirement

• Strategic Environmental Assessment (SEA)
  • Considers two scenarios
    – high and low development:
  • Range of number of production wells 180 – 2880
  • Each requiring refracking once
  • Total water requirement 3.6 – 144 million m³

• My assumptions
  • 100 wells drilled and completed each year
  • Maximum water usage assumed by SEA
  • Water requirement 2.5 million m³
  • Not all at the same time or in the same location

Water resource demand and impact

- Total licensed non-tidal abstraction for England and Wales (2011): 11,400 million cubic metres
- Water demand for 100 individual wells per year drilled/stimulated: 1.5 – 2.4 million cubic metres/year
- Challenges come from sourcing in already heavily exploited areas

![Pie chart showing percentages of freshwater abstraction]

2011, England and Wales
Source: www.gov.uk/government/statistical-data-sets

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Water resource availability

Resource availability - percentage of time available

- less than 30%
- at least 30%
- at least 50%
- at least 70%
- at least 95%

WFD Groundwater quantitative status

- Unproductive strata
- POOR, HIGH
- POOR, LOW
- GOOD, LOW
- GOOD, HIGH


Environment Agency – WFD, 2009
Water resource availability
England and Wales

• Concerns related to over-abstraction of water
• UK has developed and mature groundwater legislation and management/ protection policies
• All potentially polluting industries regulated

Managing water abstraction,
http://a0768b4a8a31e106d8b0-50dc802554eb38a24458b98ff72d550b.r19.cf3.rackcdn.com/LIT_4892_20f775.pdf, date accessed 5/2/2014

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Pollutants and exposure pathways

- Shale gas
- Chemicals, fuel and oils
- Formation water and waste (heavy metals, hydrocarbons, NORM)
- Geological (natural)
- Geological (induced)
- Well design/failure (shale gas/other)
- Surface spills (on site, in transit)
- Contamination of groundwater
- Contamination of aquifers
- Contamination of surface waters
Potential contamination sources from fracking

- Fracking fluid
  - Additives
  - Transport infrastructure

- Flowback / produced water
  - Salinity
  - Heavy metals
  - Naturally occurring radioactive material (NORM)
  - Fracking fluid additives

- Shale gas
  - Methane and other light hydrocarbons
  - Carbon dioxide, hydrogen sulphide, noble gases
Hydraulic fracturing fluid

- Additives: 0.1 – 2.0%
- Continued development
- Greater openness now in the US
- UK requires prior authorisation – substances controlled by WFD/GWD

Fate of injected fluids:
- 20-80% returns as flowback
- Remainder stays in formation
## Hydraulic fracturing fluid

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Composition (% by vol)</th>
<th>Example</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water and sand</td>
<td>99.50</td>
<td>Sand suspension</td>
<td>“Proppant” sand grains hold microfractures open</td>
</tr>
<tr>
<td>Acid</td>
<td>0.123</td>
<td><strong>Hydrochloric acid</strong></td>
<td>Dissolves minerals and initiates cracks in the rock</td>
</tr>
<tr>
<td>Friction reducer</td>
<td>0.088</td>
<td><strong>Polyacrylamide</strong> or mineral oil</td>
<td>Minimizes friction between the fluid and the pipe</td>
</tr>
<tr>
<td>Surfactant</td>
<td>0.085</td>
<td>Isopropanol</td>
<td>Increases the viscosity of the fracture fluid</td>
</tr>
<tr>
<td>Salt</td>
<td>0.060</td>
<td>Potassium chloride</td>
<td>Creates a brine carrier fluid</td>
</tr>
<tr>
<td>Gelling agent</td>
<td>0.056</td>
<td>Guar gum or hydroxyethyl cellulose</td>
<td>Thickens water to suspend the sand</td>
</tr>
<tr>
<td>Scale inhibitor</td>
<td>0.043</td>
<td>Ethylene glycol</td>
<td>Prevents scale deposits in pipes</td>
</tr>
<tr>
<td>pH-adjusting agent</td>
<td>0.011</td>
<td>Sodium or potassium carbonate</td>
<td>Maintains effectiveness of chemical additives</td>
</tr>
<tr>
<td>Breaker</td>
<td>0.01</td>
<td>Ammonium persulphate</td>
<td>Allows a delayed breakdown of gel polymer chains</td>
</tr>
<tr>
<td>Crosslinker</td>
<td>0.007</td>
<td>Borate salts</td>
<td>Maintains fluid viscosity as temperature increases</td>
</tr>
<tr>
<td>Iron control</td>
<td>0.004</td>
<td>Citric acid</td>
<td>Prevents precipitation of metal oxides</td>
</tr>
<tr>
<td>Corrosion inhibitor</td>
<td>0.002</td>
<td>n,n-dimethyl formamide</td>
<td>Prevents pipe corrosion</td>
</tr>
<tr>
<td>Biocide</td>
<td>0.001</td>
<td><strong>Glutaraldehyde</strong></td>
<td>Minimizes growth of bacteria that produce corrosive and toxic by-products</td>
</tr>
<tr>
<td>Oxygen scavenger</td>
<td>-</td>
<td>Ammonium bisulphite</td>
<td>Removes oxygen from the water to prevent corrosion</td>
</tr>
</tbody>
</table>

*Used in the UK for shale gas fracking - ENDS Special Report “UK shale gas and the environment”*
Hydraulic fracturing fluid development

- Historically a wide range of chemicals used in addition to water and proppant
- Fracking fluid and flowback/produced water can contain:
  - BTEX, phenols, dioxanes, glycols, aldehydes, PAH, phthalates, chlorinated solvents, heterocyclics
- Now move to use less hazardous and simpler mixtures possibly using food and household product constituents:
  - enzymes, ethoxylated sugar-based fatty acid esters, hydrogenated vegetable oils, sulphonated alcohols and polysaccharides
Flowback/produced water

- **Flowback** – reflects fracking fluid composition modified by residual material from drilling/fracking, and some formation water

- **Produced water** increasingly reflects formation water over time. This may include: metals (e.g. zinc, chromium, nickel), arsenic, sodium, calcium, magnesium, chloride, and NORM (U, Ra)

- Safe handling, storage and disposal of wastewaters is required by EA:
  - Small volumes – industrial wastewater treatment plants
  - Larger volumes – specialist processing for disposal and/or re-use
Wastewater disposal

- Recycling
- On-site treatment and solids disposal to treatment works:
  - Hydrocarbons, toxic metals, organic compounds
  - Inhibition of biological denitrification
  - Impact on settlement properties of activated sludge
  - Inhibition of anaerobic digestion
  - Unacceptable effluent and sludge quality
- Discharge to surface water
- Deep reinjection
Development of wastewater management methods

### Shale gas

<table>
<thead>
<tr>
<th>Name</th>
<th>Formula</th>
<th>Typical content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>CH₄</td>
<td>70–90</td>
</tr>
<tr>
<td>Ethane</td>
<td>C₂H₆</td>
<td>0–20</td>
</tr>
<tr>
<td>Propane</td>
<td>C₃H₈</td>
<td>0–20</td>
</tr>
<tr>
<td>Butane</td>
<td>C₄H₁₀</td>
<td></td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>CO₂</td>
<td>0–8</td>
</tr>
<tr>
<td>Oxygen</td>
<td>O₂</td>
<td>0–0.2</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>N₂</td>
<td>0–5</td>
</tr>
<tr>
<td>Hydrogen sulphide</td>
<td>H₂S</td>
<td>0–5</td>
</tr>
<tr>
<td>Rare gases</td>
<td>Ar, He, Ne, Xe</td>
<td>Trace</td>
</tr>
</tbody>
</table>
Pathways and receptors

• Runoff from leaks and spills at the surface during transport and operations
• Uncontrolled release of drilling muds into non-target geological formations containing aquifers
• Migration of high-pressure drilling muds or fracking fluids along natural faults and fractures
• Creation of interconnected fractures beyond the intended zone (induced fractures)
• Well failure arising from poor construction or loss of integrity during operation/damage from induced seismicity
• Existing infrastructure - abandoned wells, mine workings-providing pathway
Natural pathways

- Advective transport through rock matrix:
  - Slow movement 10s of 1000s of years

- Preferential movement through fractures and discontinuities:
  - Rapid movement 10s or 100s of years

- Characterised by:
  - Aperture
  - Tortuosity
  - Connectivity

- In UK knowledge below 100 m depth very sparse

Induced fractures

- Data collated from major shale gas plays in US and compared to natural hydraulic fractures
- Maximum upwards propagation 588 m
- Estimated probability of fracture extending > 350 m:
  - Stimulated fracture ~ 1%
  - Natural fracture ~ 33%

Well installation and integrity

- Shale gas well design principals same as other oil/gas well design
- Industry standards: API, BS:ISO, HSE
- Loss of drilling fluids, blowout & surface spills
- Considerable variation in well failure rate
  - 50% within 15 years\(^1\)
  - 6-7% of new wells\(^2\)
  - 2.9-75% of wells in Pennsylvania\(^3\)

\(1\) Schlumberger. 2003. From mud to cement - building gas wells. *Oilfield review, Autumn, 62-76*; \(^2\) CIWEM. 2013. Shale gas and water. An independent review of shale gas exploration and exploitation in the UK with a particular focus on the implications for the water environment. \(^3\) Davies et al. Oil and gas wells and their integrity: Implications for shale and unconventional resource exploitation Marine and Petroleum Geology.
Casing integrity

- Aim to isolate the well from geological formations/aquifers
- Steel casing: conductor/surface/intermediate/production
- Cement: to fill each annulus/complete well
- CBL/VDL used to check quality
- Cement plugs part of site abandonment
- Materials can degrade over time: corrosion, cracking, deform

Source: Alberta Energy Utilities Board
Fracture propagation

- Data collated from major shale gas plays in US and compared to natural hydraulic fractures
- Estimated probability of fracture extending > 350m:
  - Stimulated fracture ~ 1%
  - Natural fracture ~ 33%
- No fractures > 600m

Surface releases

• 1-2 months of intense activity at wellhead:
  • Re-fuelling of diesel tanks
  • Bulk chemical transport and storage
  • Cleaning and maintenance
  • Leaking pipework
  • Mud/cement mixing areas
  • Wastewater storage and transport
Methane in groundwater

- Contamination of groundwater considered biggest concern with multiple examples in literature
- Interpretation of the data should consider all possible sources and pathways

Source differentiation

- Biogenic/bacterial (e.g. wetland, landfill):
  - high $C_1/C_{2+}$ ratio
  - low $\delta^{13}C$ and $\delta^{2}H$ values (more negative)
  - Measurable $^{14}C$
- Thermogenic (e.g. natural gas, coalbed):
  - low $C_1/C_{2+}$ ratio
  - higher $\delta^{13}C$ and $\delta^{2}H$ values (less negative)
  - No $^{14}C$


Pavillion, Wyoming

Example of Poor well location, design and construction (USEPA, 2011)

Figure 20. Lithologic cross-section along transect illustrating production wells (with evaluation of CBL/VDLs), domestic wells, and blowout location. Red arrows denote depths of hydraulic fracturing of unknown areal extent. Sandstone units are undifferentiated between fine, medium and coarse-grained units.
Endocrine disruptors

- Measured endocrine disruption in water in densely-drilled area of Colorado catchment

- Activity measured in water samples:
  - Estrogenic - 89%
  - Anti-estrogenic - 41%
  - Androgenic - 12%
  - Anti-androgenic - 46%

Kassotis et al 2014 Estrogen and androgen receptor activities of hydraulic fracturing chemicals and surface and ground water in a drilling-dense region. *Endocrinology, 155.*
Conclusions

• UK shale gas exploitation currently at a very early stage. Potentially significant quantities but resource not yet proven

• In the UK a number of the potentially exploitable shale areas are below important aquifers

• Water demand for shale gas production is projected not to be significant relative to other uses but local needs must be considered carefully

• Extraction will use/mobilise chemicals/substances that are potential pollutants. Risks must be fully assessed and managed effectively – from exploration to post abandonment

• From exploitation at depth the most significant risks will be from surface activities, followed by poor well design/completion and pre-existing artificial pathways

• Once in production, the long term well integrity is critical

• Baseline and on-going monitoring is essential

• We need to learn from the US but only what is relevant and reliable!