Hydrogeological aspects of shale gas extraction in the UK

Marianne Stuart

Groundwater Science
British Geological Survey

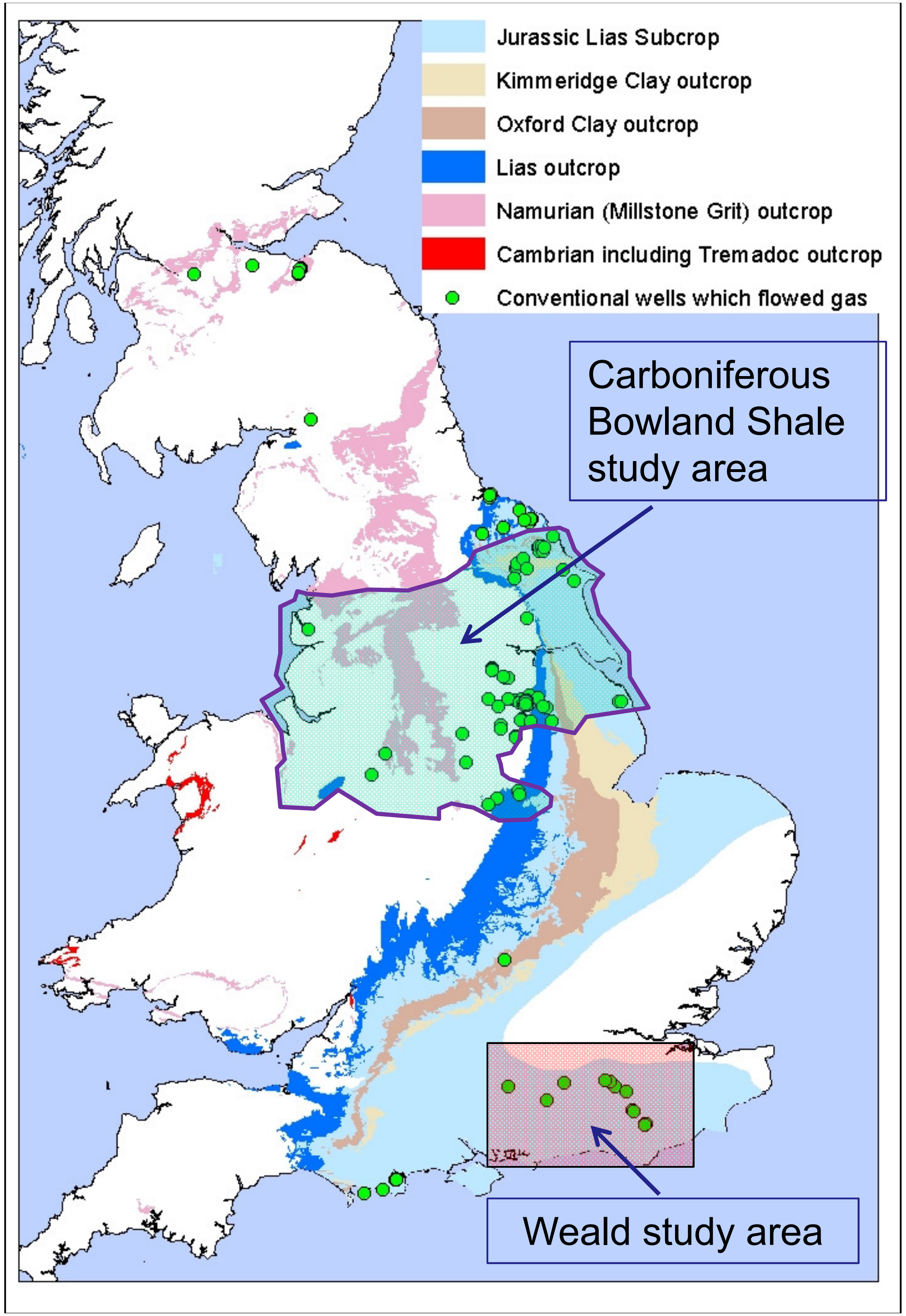
UGAS June 2014

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

A shale gas drilling rig being set up for fracking in Lancashire. Photograph: Alamy

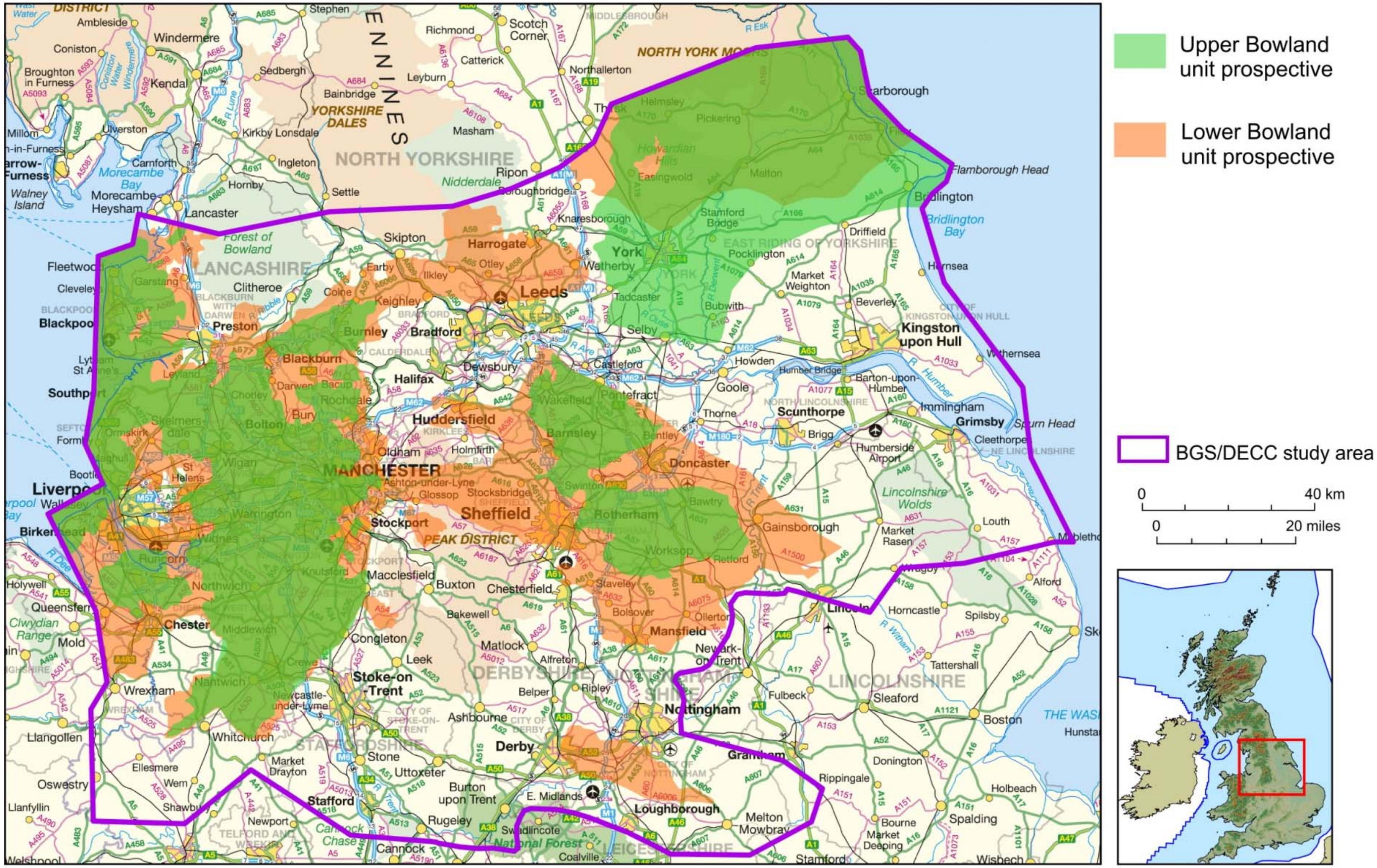
http://www.theguardian.com/environment/2012/may/29/shale-gas-coal-climate-investor



Shale gas in the UK?

- Carboniferous (Namurian): Northern Britain and Ireland
- Jurassic (Upper and Lower): Wessex Basin and The Weald
- Lower Palaeozoic (Silurian, Ordovician, Cambrian): Wales
- Precambrian: Midland Microcraton (?)

Bowland Shale prospectivity

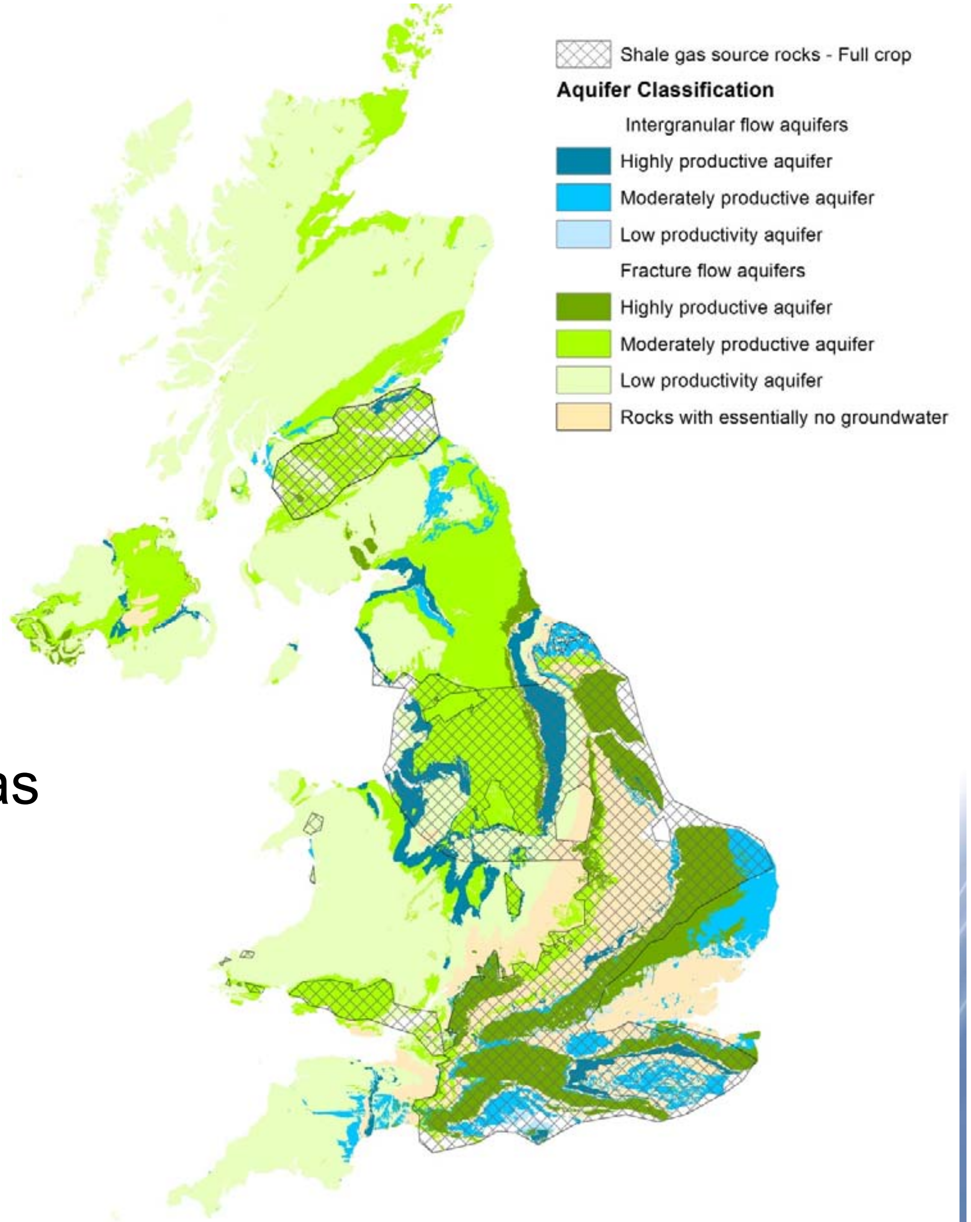


UK experience to date

- 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

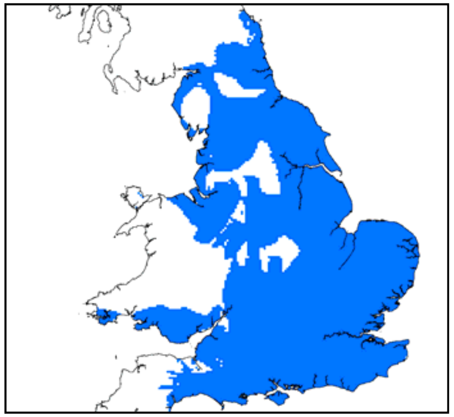
younger

- Crag
- Chalk
- Lower Greensand
- Spilsby Formation
- Kimmeridge & Ampthill Clay
- Corallian limestones
- Kellaways, Oxford Clay & Osgodby
- Oolites
- Lias
- Triassic sandstones
- Magnesian Limestone
- Permian sandstones
- Marros Group
- Bowland & Craven Groups
- Carboniferous Limestone
- Fell Sandstone & Border Group
- Upper Cambrian shales

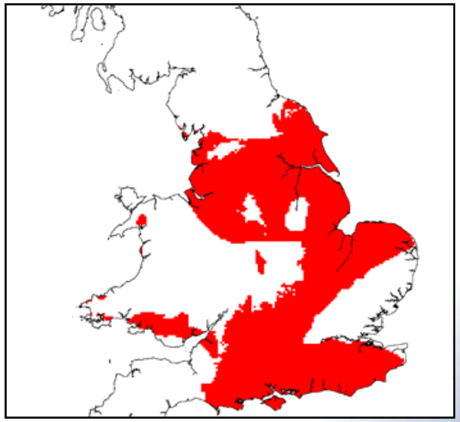
older

	Kimmeridge Clay	Oxford Clay	Lias	Marros	Bowland & Craven	Upper Cambrian
Crag						
Chalk						
Lower Greensand						
Spilsby sandstone						
Corallian						
Oolites						
Permo-Trias sandstones						
Magnesian Limestone						
Appleby Group						
Carb Limestone						
Fell Sst & Border Group						

(pink)	Principal aquifer overlies potential shale gas source rock
(blue)	Potential shale gas source rock overlies Principal Aquifer(s)
(white)	No overlap between Principal Aquifer and potential shale gas source

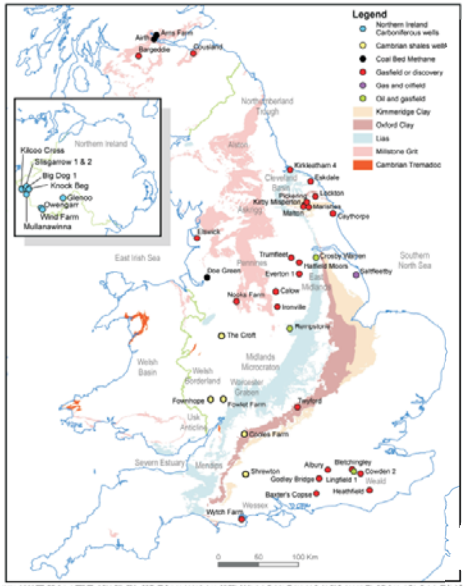


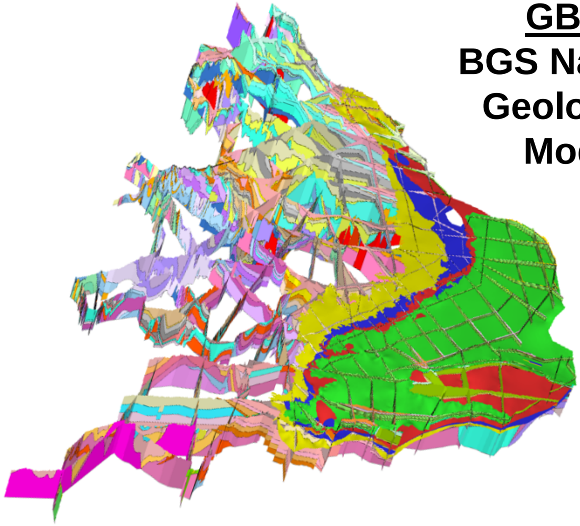
Aquifer formations



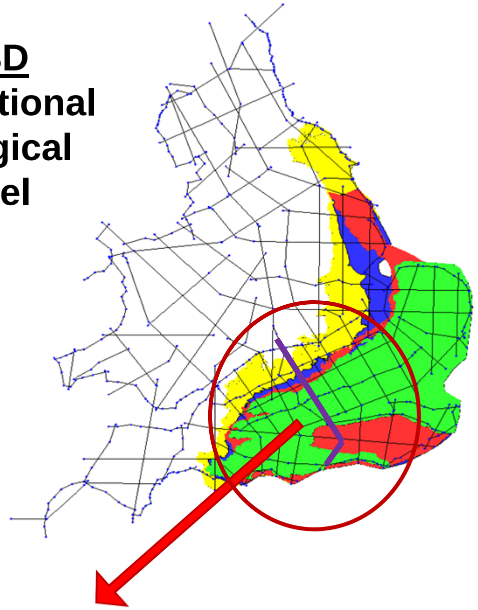
Shales

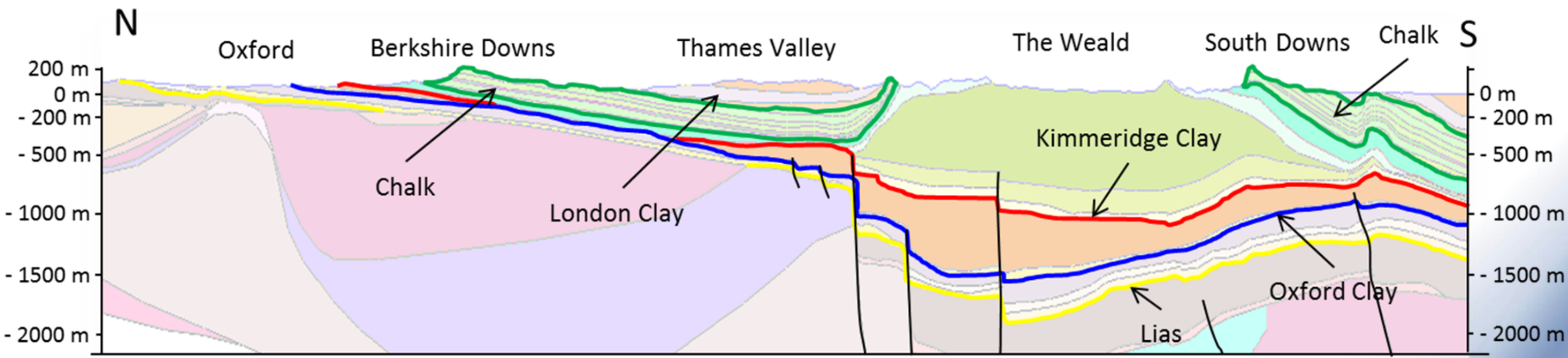
Shale and aquifer mapping

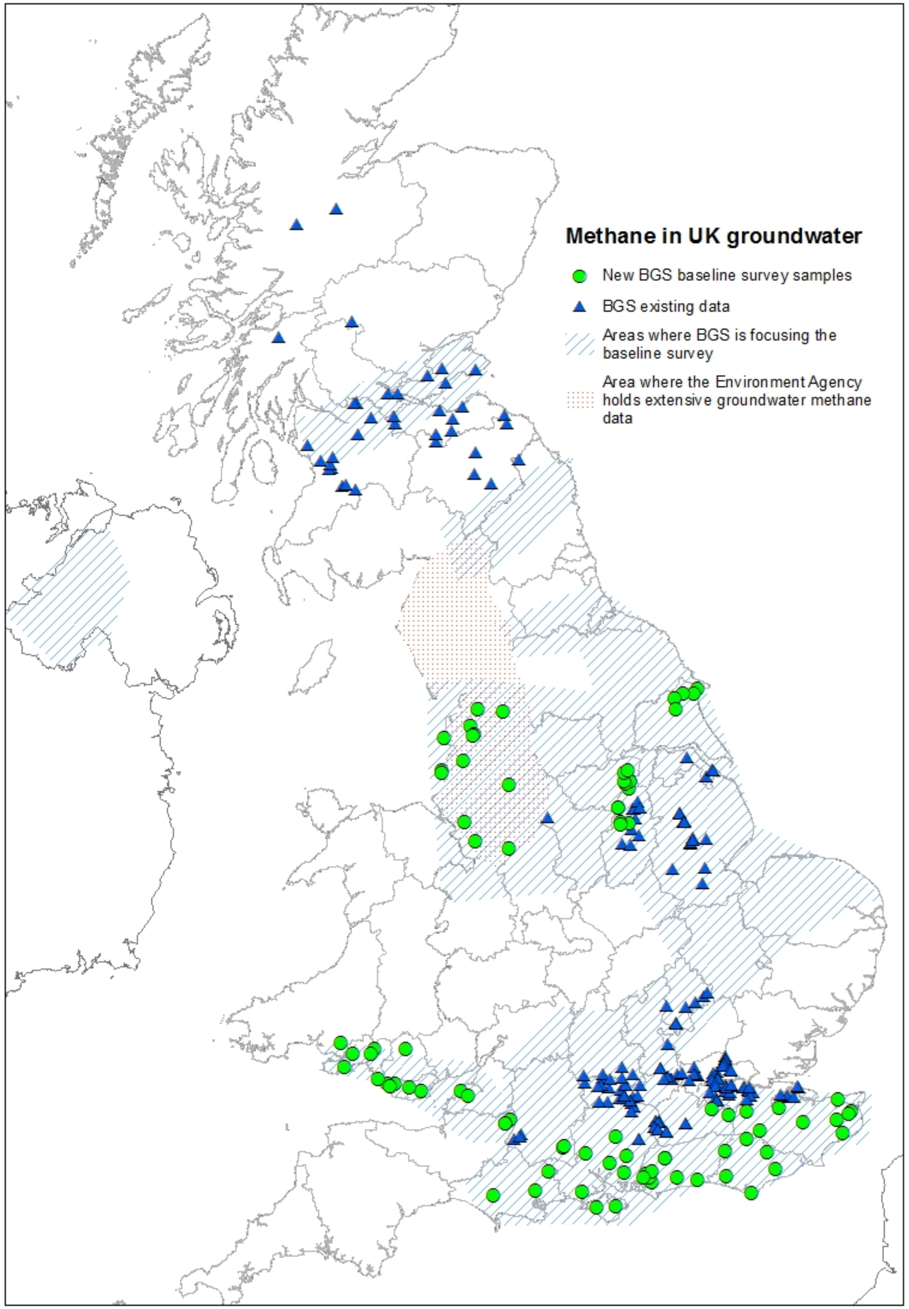




GB3D
BGS National Geological Model







BGS baseline methane survey

Area
West Lancashire and Cheshire basins
Northern Ireland
Stainmore Trough and Cleveland Basin
Wessex & Weald Basins
South Wales coast
Midlands (Edale and Widmerpool Gulf; Gainsborough Trough)
Northumberland Trough

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 – 4000m^3 of water to drill, then 7000–23,000m^3 for fracking[a].
- Variation reflects complexity of drilling, geological conditions, total depth/number of fracking stages
- Example of published estimates (per well)[b]:

Shale Play	Drilling (m^3)	Fracking (m^3)	Total (m^3)
Barnett (US)	950	14000	14950
Haynesville (US)	2300	19000	22300
Fayetteville (US)	250	19000	19250
Marcellus (US)	300	21000	21300
Eagle Ford (US)	500	23000	23500
Bowland Shale (UK)	900	8400	9300

[a] Range obtained from various published sources (mostly US).
[b] University of Texas (2012) and Cuadrilla

Estimated UK water requirement

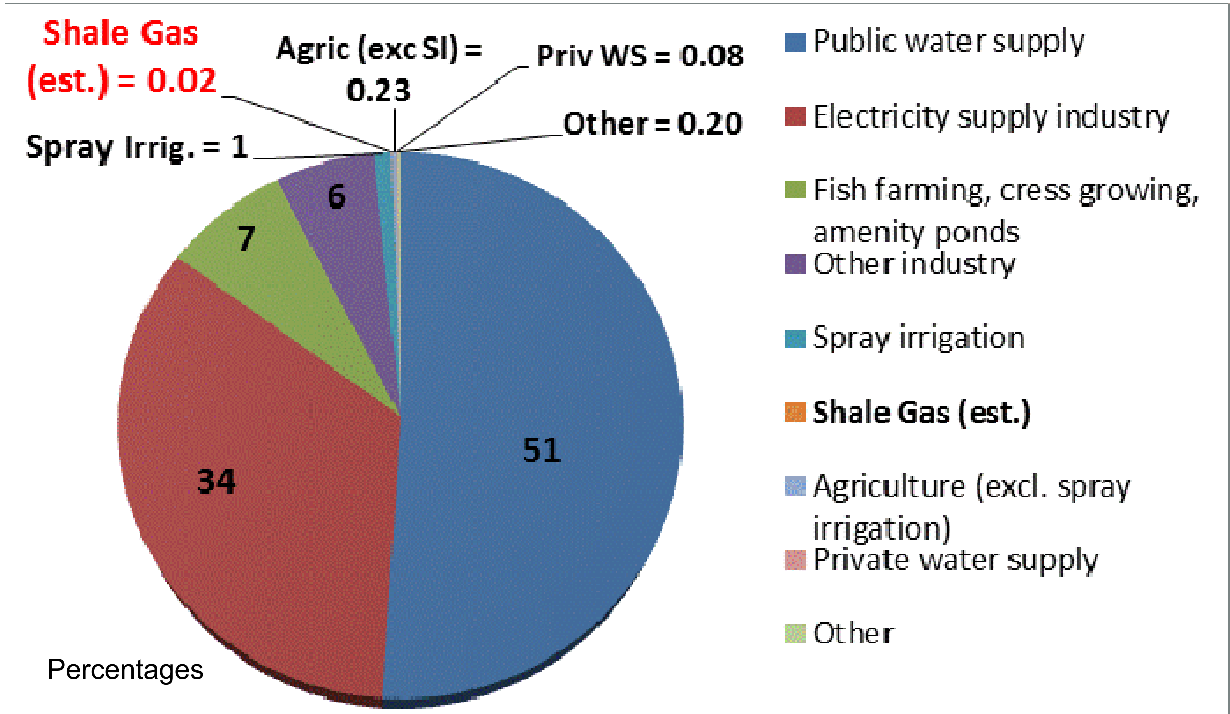
- Strategic Environmental Assessment (SEA)
  - Considers two scenarios – high and low development:
  - Range of number of production wells 180 – 2880
  - Each requiring refracking once
  - Total water requirement 3.6 – 144 million m^3
- My assumptions
  - 100 wells drilled and completed each year
  - Maximum water usage assumed by SEA
  - Water requirement 2.5 million m^3
  - Not all at same time or in same location

https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/273997/DECC_SEA_Environmental_Report.pdf

Water resource demand and impact

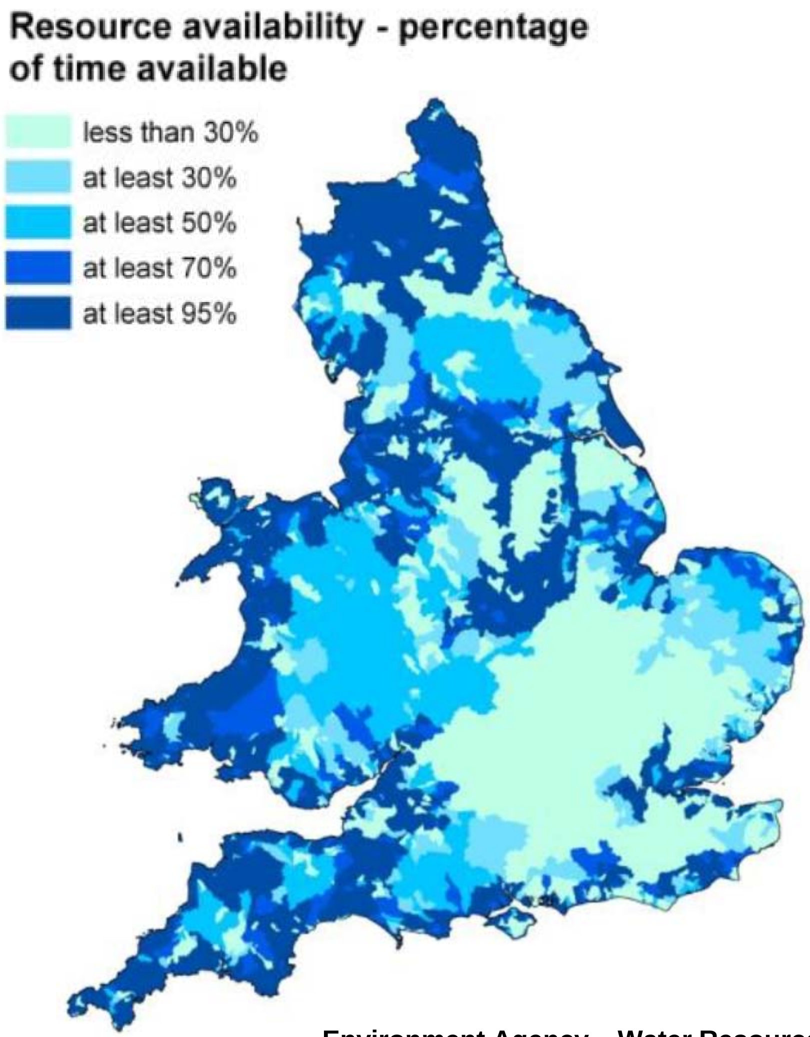
- Total licensed non-tidal abstraction for England and Wales (2011): 11,400 million cubic metres
- Water demand for 100 individual wells per year drilled/stimulated: 1.5 – 2.4 million cubic metres/year
- Challenges come from sourcing in already heavily exploited areas

All freshwater abstraction

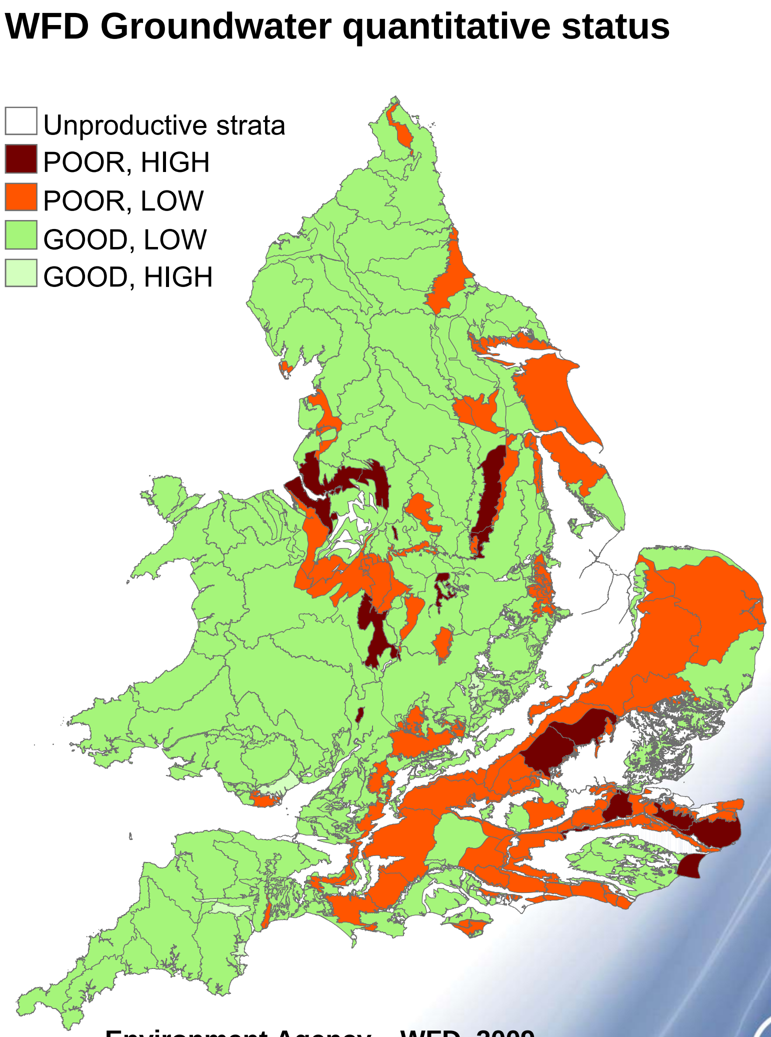


2011, England and Wales
Source: www.gov.uk/government/statistical-data-sets

Water resource availability



Environment Agency – Water Resources Strategy, 2013



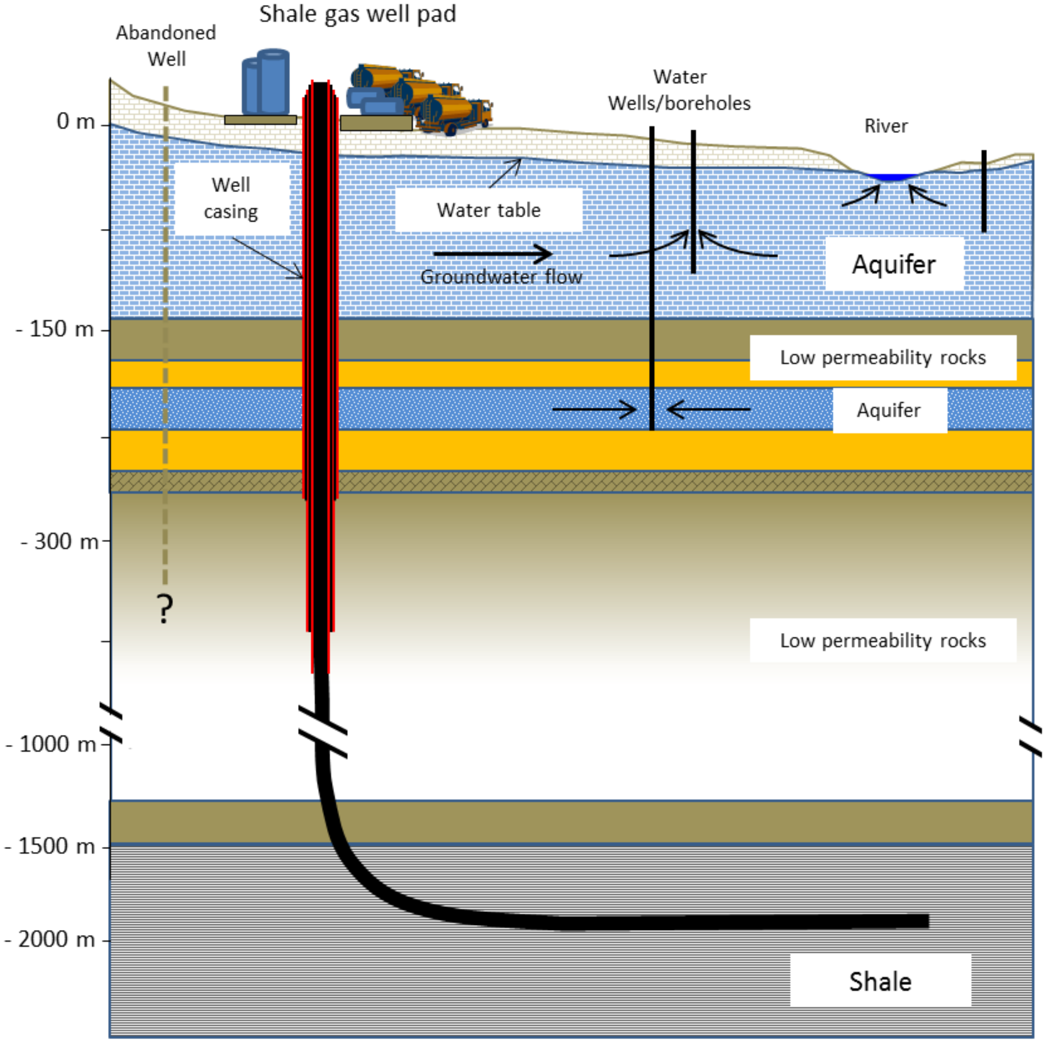
Environment Agency – WFD, 2009

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

Pollutants and exposure pathways



Chemicals, fuel and oils

Shale gas

Formation water and waste (heavy metals, hydrocarbons, NORM)

Exposure pathways

Geological (natural)

Geological (induced)

Well design/failure (shale gas/other)

Surface spills (on site, in transit)

Contamination of groundwater

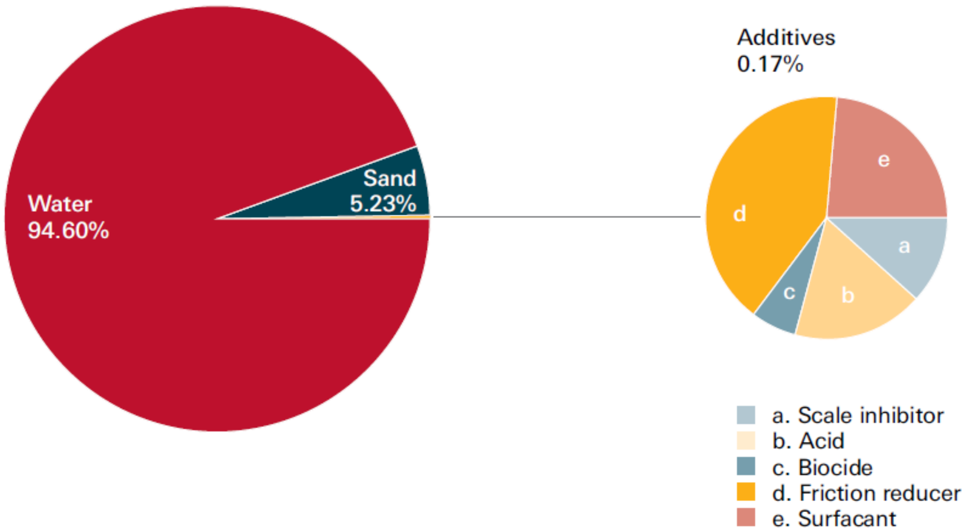
Contamination of groundwater/ aquifers

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

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

***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

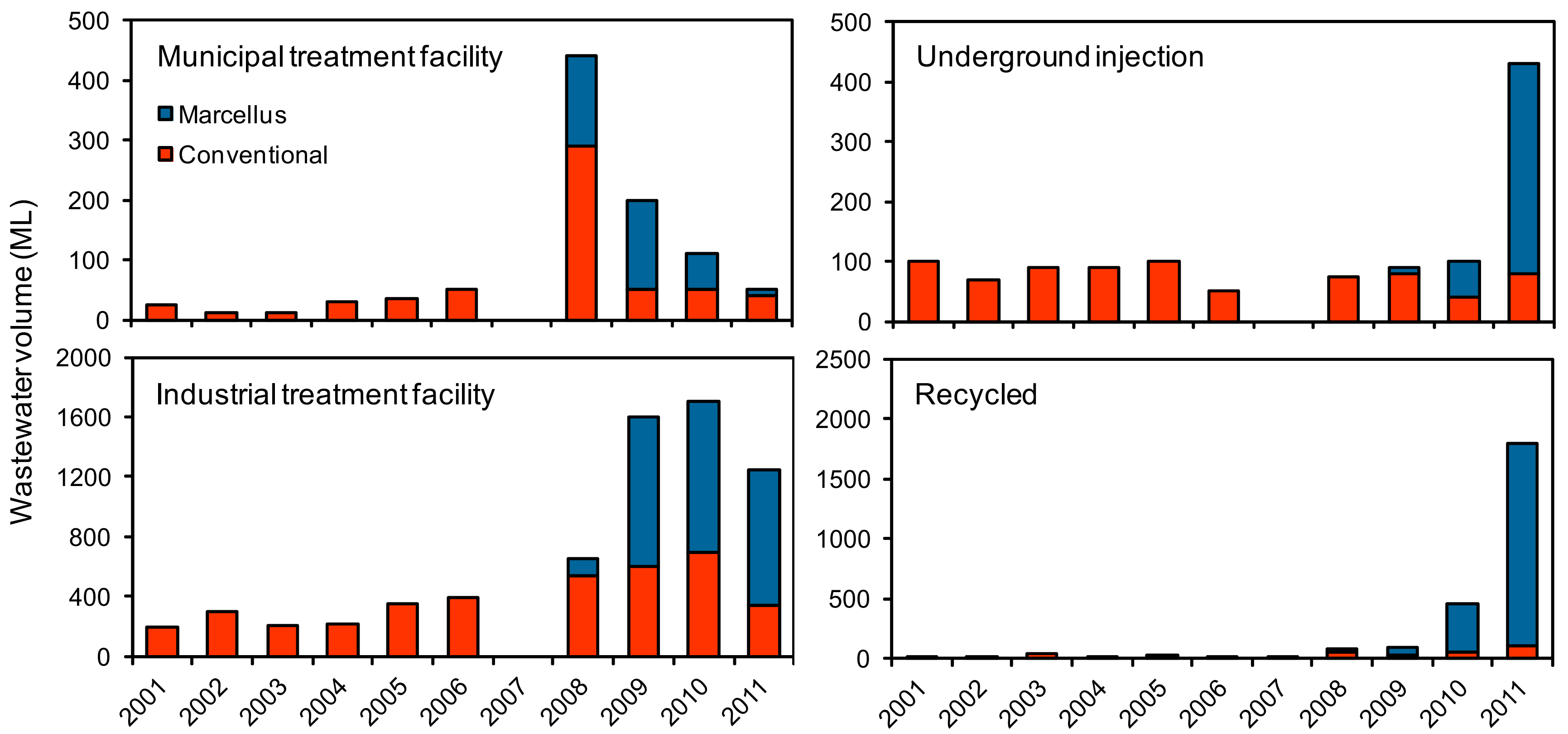
Flowback/produced water

- **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

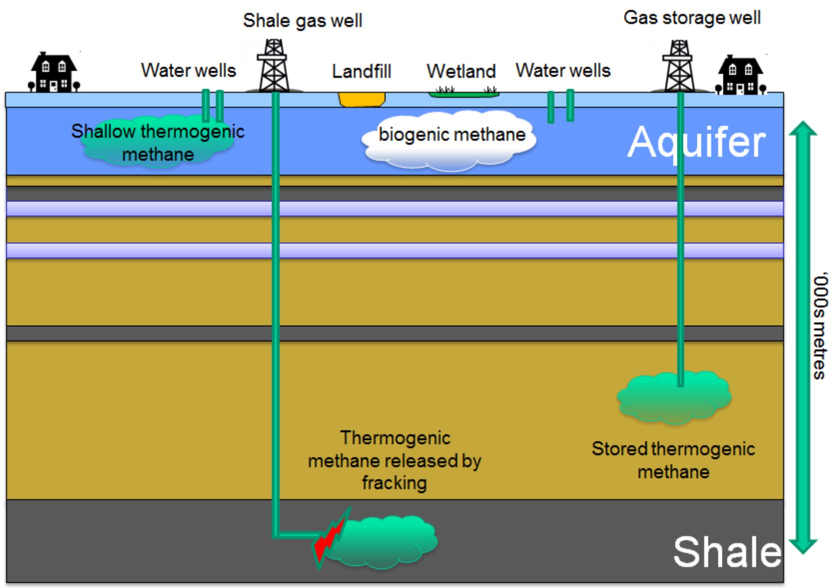
Development of wastewater management methods



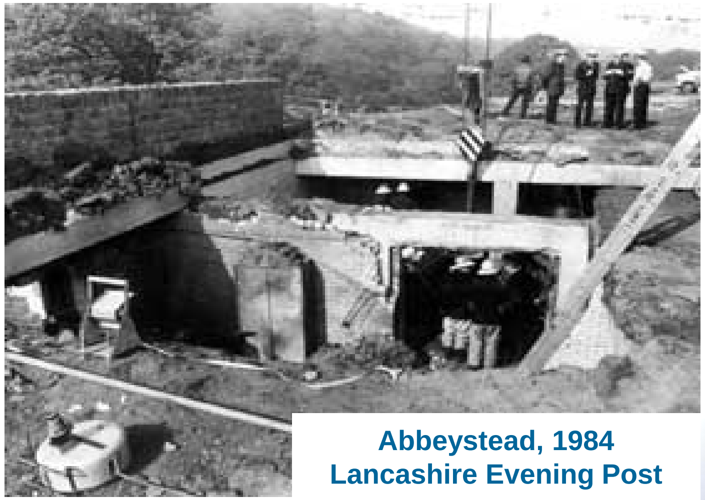
Lutz et al. (2013) Generation, transport, and disposal of wastewater associated with Marcellus Shale gas development, *Water Resources Research, 49, 647-656*

Shale gas

Name	Formula	Typical content (%)
Methane	CH_4	70–90
Ethane	C_2H_6	0–20
Propane	C_3H_8	
Butane	C_4H_{10}	
Carbon dioxide	CO_2	0–8
Oxygen	O_2	0–0.2
Nitrogen	N_2	0–5
Hydrogen sulphide	H_2S	0–5
Rare gases	Ar, He, Ne, Xe	Trace



Loscoe, 1986
Derby Evening Telegraph

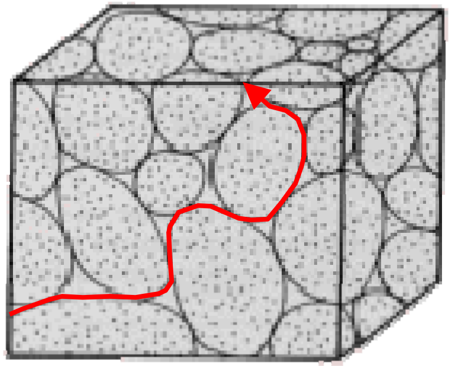


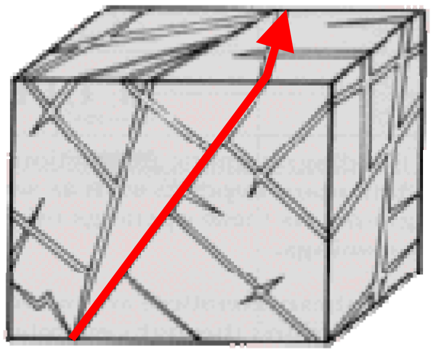
Abbeystead, 1984
Lancashire Evening Post

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

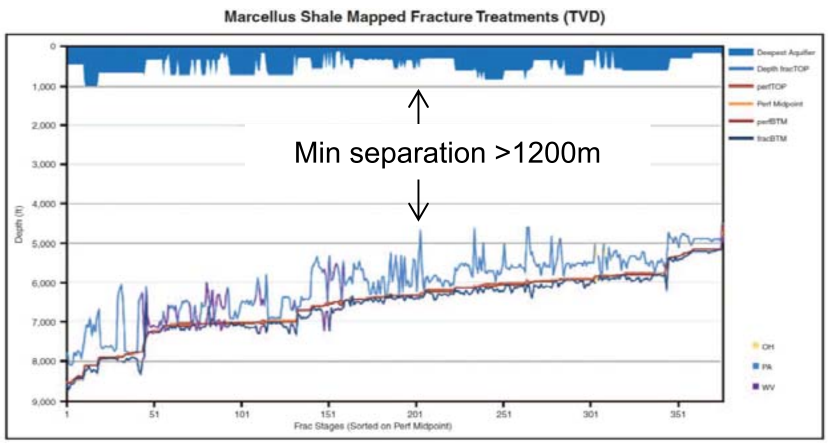


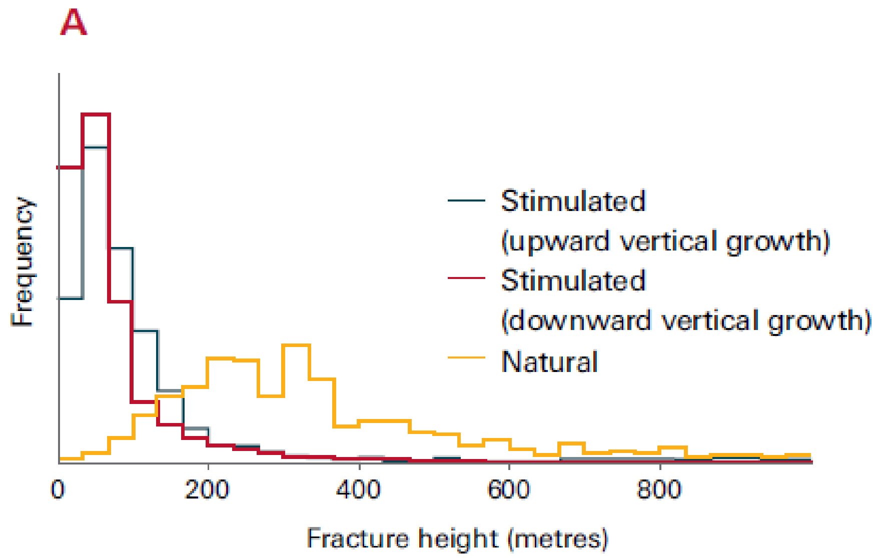


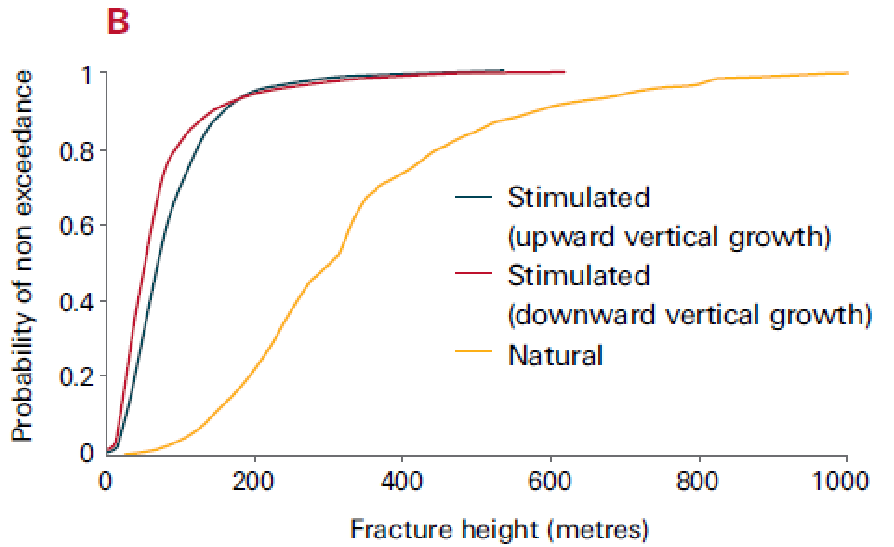
- Advective transport through rock matrix:
  - Slow movement 10s of 1000s of years
- Preferential movement through fractures and discontinuities:
  - Rapid movement 10s or 100s of years
- Characterised by:
  - Aperture
  - Tortuosity
  - Connectivity
- In UK knowledge below 100 m depth very sparse

Myers (2012) Potential contaminant pathways from hydraulically fractured shale to aquifers. *Ground Water, 50, 872-882.*

Induced fractures





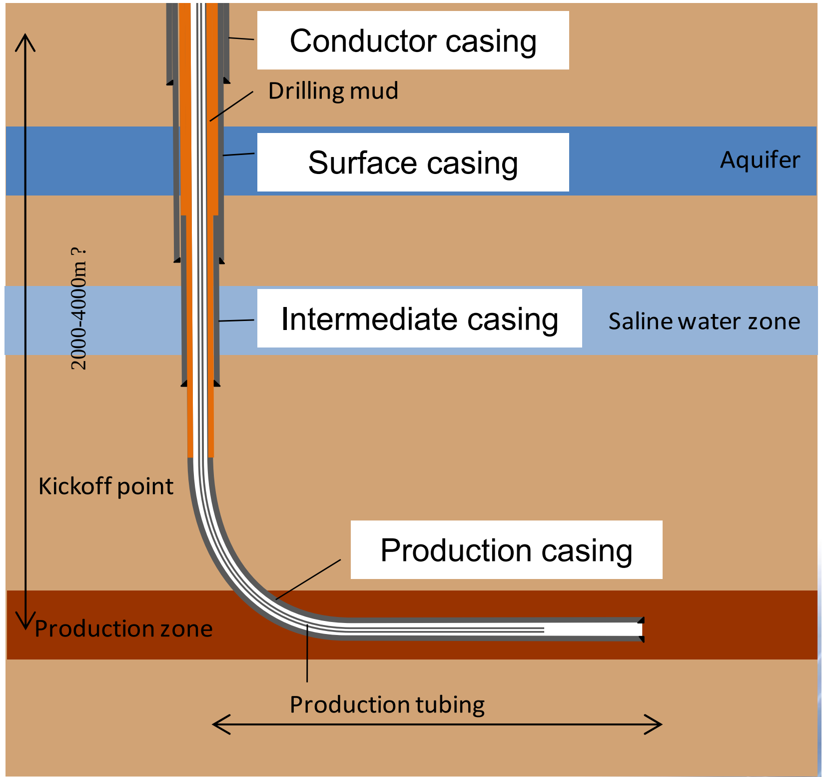


- Data collated from major shale gas plays in US and compared to natural hydraulic fractures
- Maximum upwards propagation 588 m
- Estimated probability of fracture extending > 350m:
  - Stimulated fracture ~ 1%
  - Natural fracture ~ 33%

Davies et al . 2012. Hydraulic fractures: How far can they go? *Marine and Petroleum Geology, Vol. 37, 1-6.*

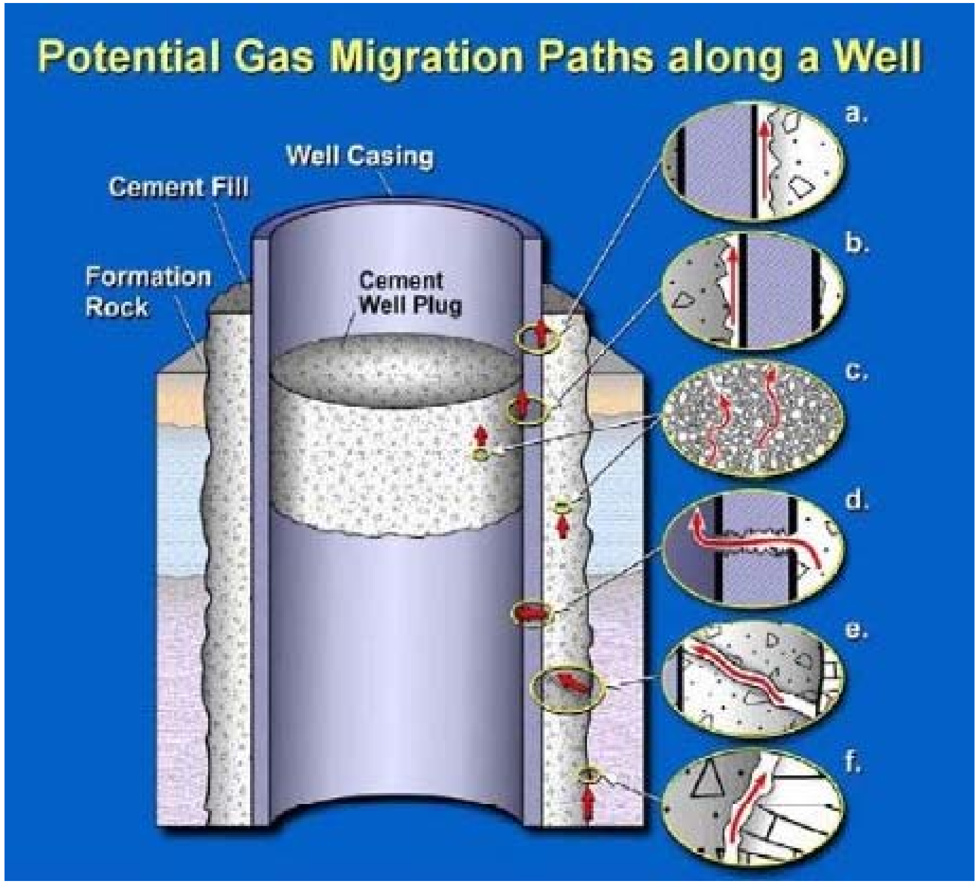
Well installation and integrity

- 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,

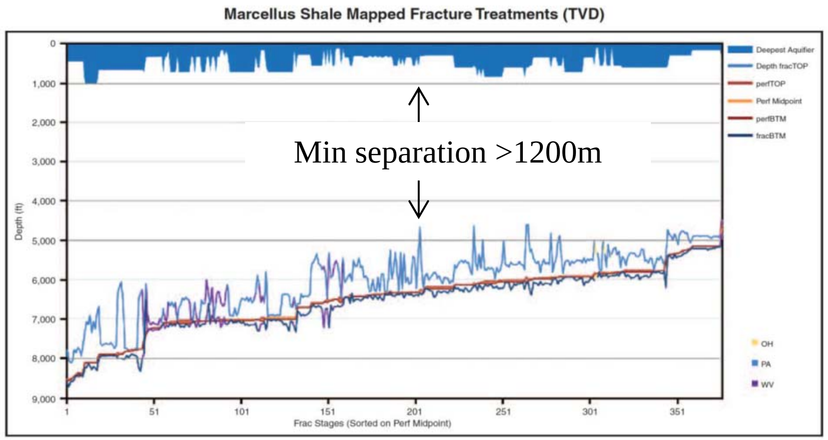
Casing integrity

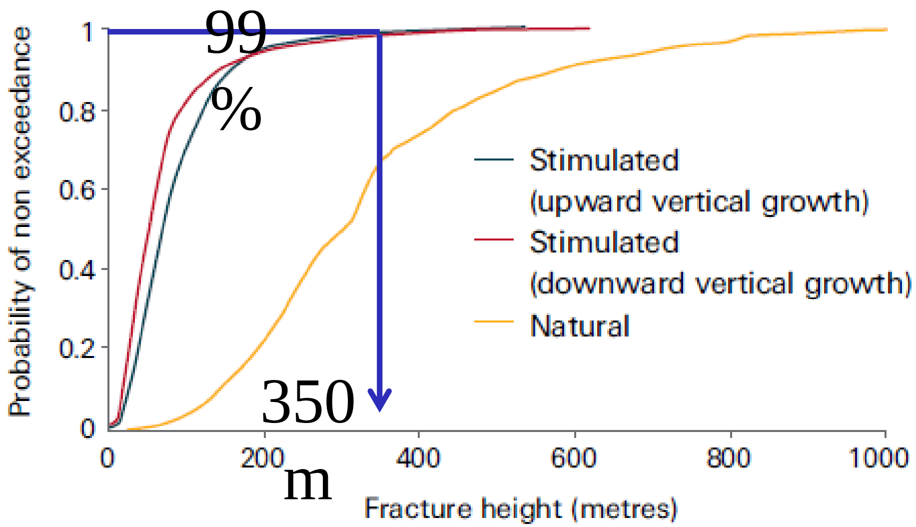


Source: Alberta Energy Utilities Board

- 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

Fracture propagation





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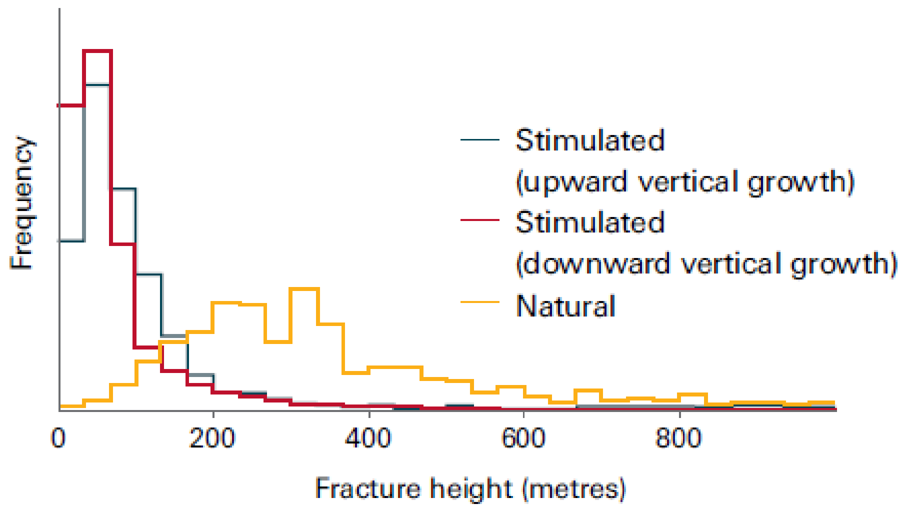


- Data collated from major shale gas plays in US and compared to natural hydraulic fractures
- Estimated probability of fracture extending > 350m:
  - Stimulated fracture ~ 1%
  - Natural fracture ~ 33%
- No fractures > 600m

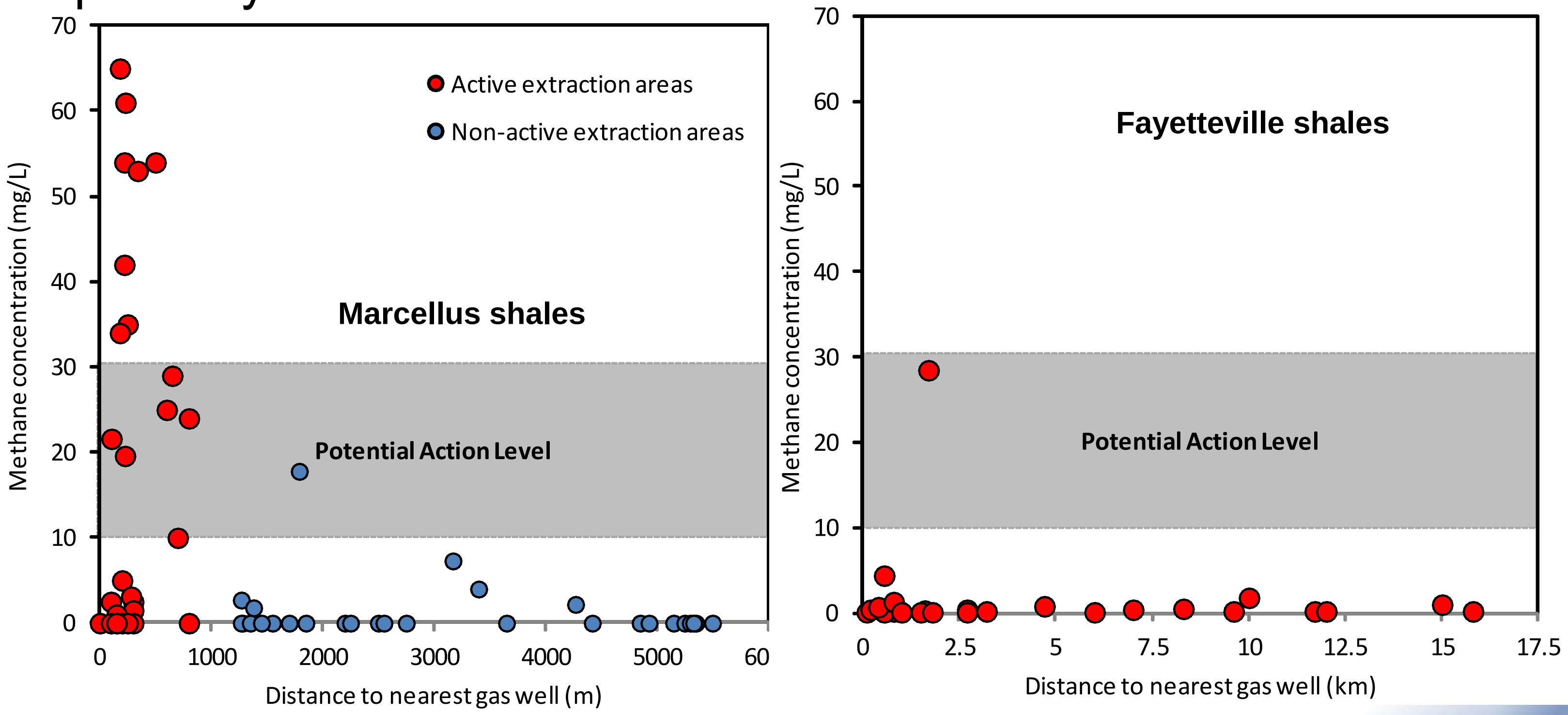
Davies, R.J. et al. 2012. Hydraulic fractures: How far can they go? *Marine and Petroleum Geology*, 37, 1-6

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



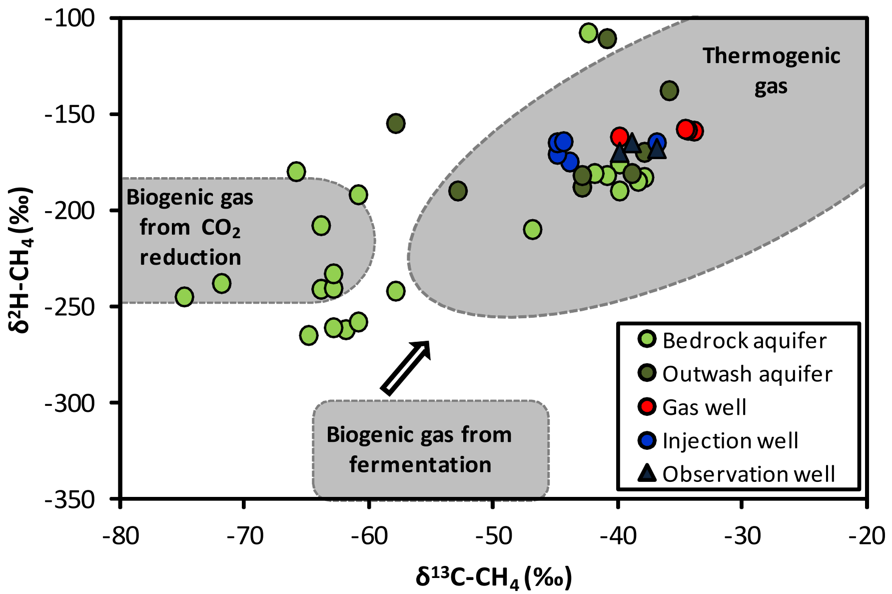
Osborn 2011 Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. *Proceedings of the National Academy of Sciences, 108, 8172-6.* Warner 2013 Geochemical and isotopic variations in shallow groundwater in areas of the Fayetteville Shale development, north-central Arkansas. *Applied Geochemistry, 35, 207-220.*

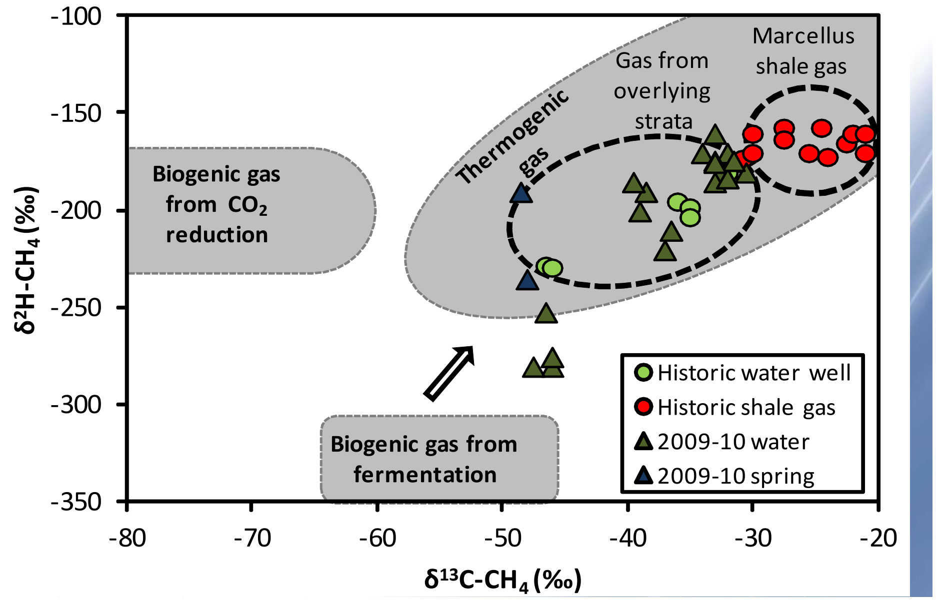
Source differentiation

- 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

Révész et al. 2010. Carbon and hydrogen isotopic evidence for the origin of combustible gases in water-supply wells in north-central Pennsylvania. *Applied Geochemistry, 25, 1845-59.*

Molofsky et al. 2012. New geochemical data show methane in N.E.Pennsylvania water wells unrelated to hydraulic fracturing. *Houston Geological Society Bulletin, 54, 27.*





Pavillion, Wyoming

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

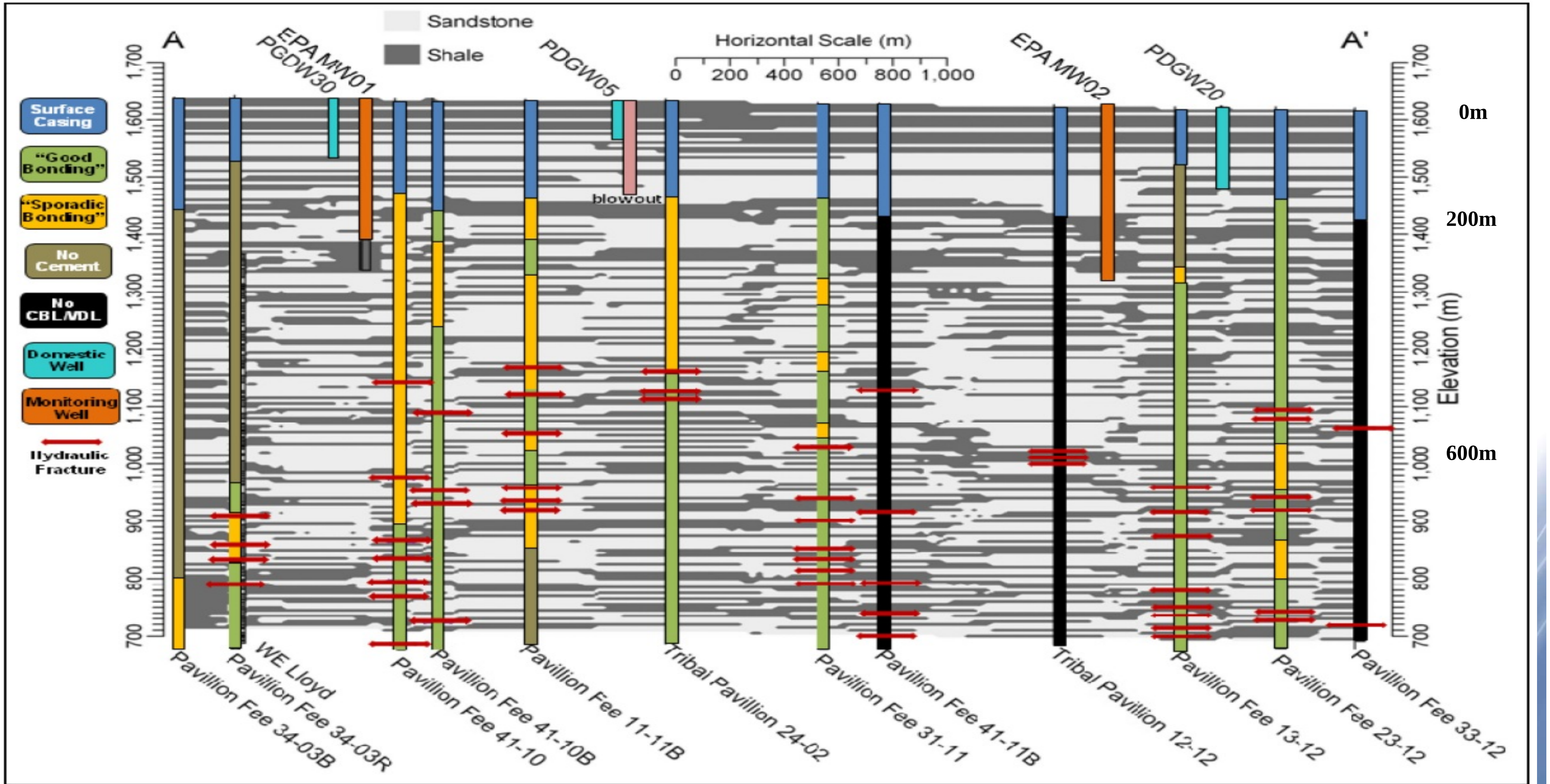
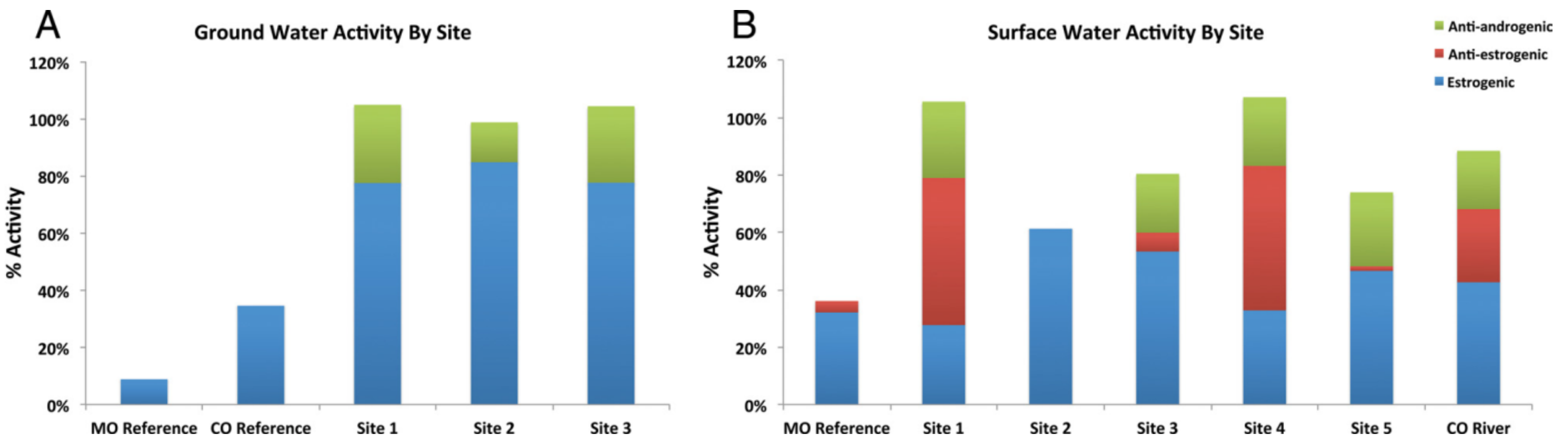


Figure 20. Lithologic cross-section along transect illustrating production wells (with evaluation of CBL/VDLs), domestic wells, and blowout location. Red arrows denote depths of hydraulic fracturing of unknown areal extent. Sandstone units are undifferentiated between fine, medium and coarse-grained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