Assessing the potential environmental impacts of multi-stage hydraulic fracking on shallow groundwater and surface water

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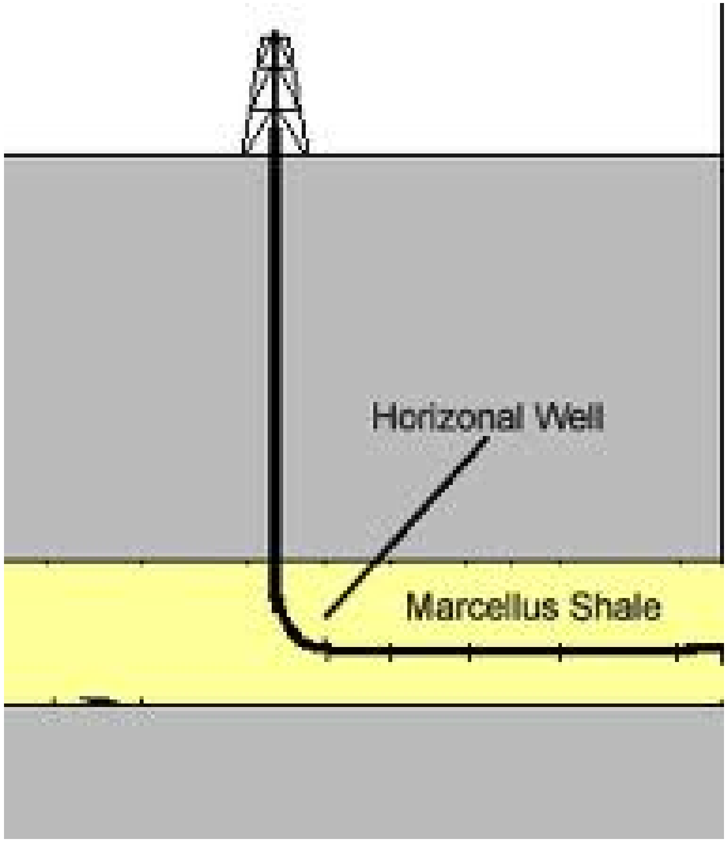
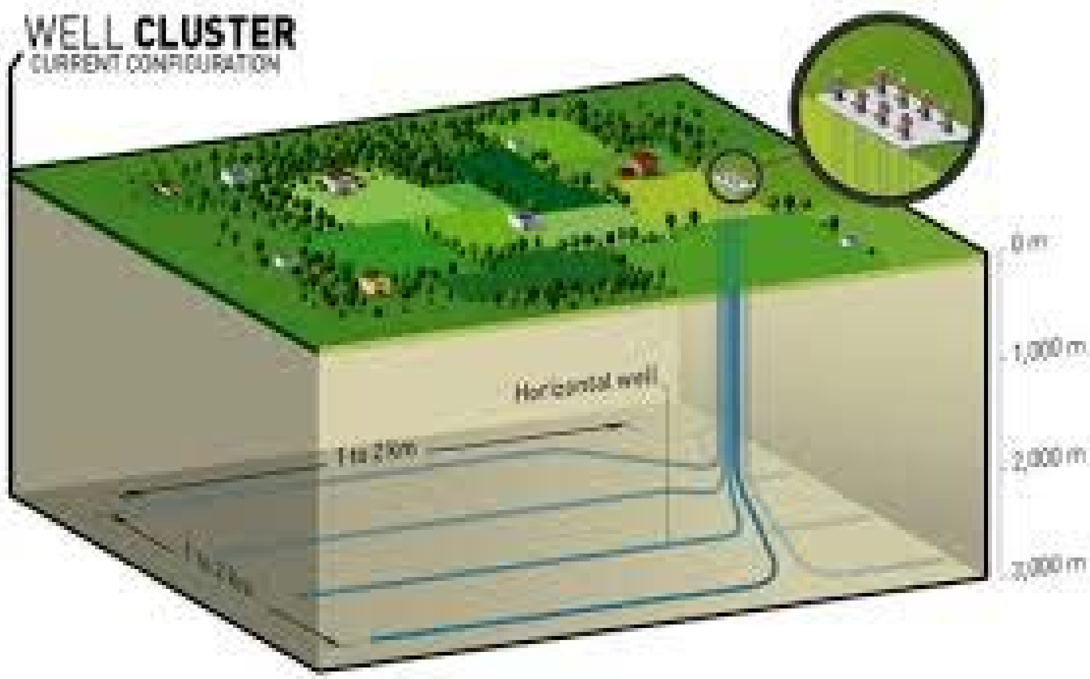
Introduction

The rapid development of shale gas in Canada and the USA has been driven by high gas prices early in the 21th century and by two technical developments:

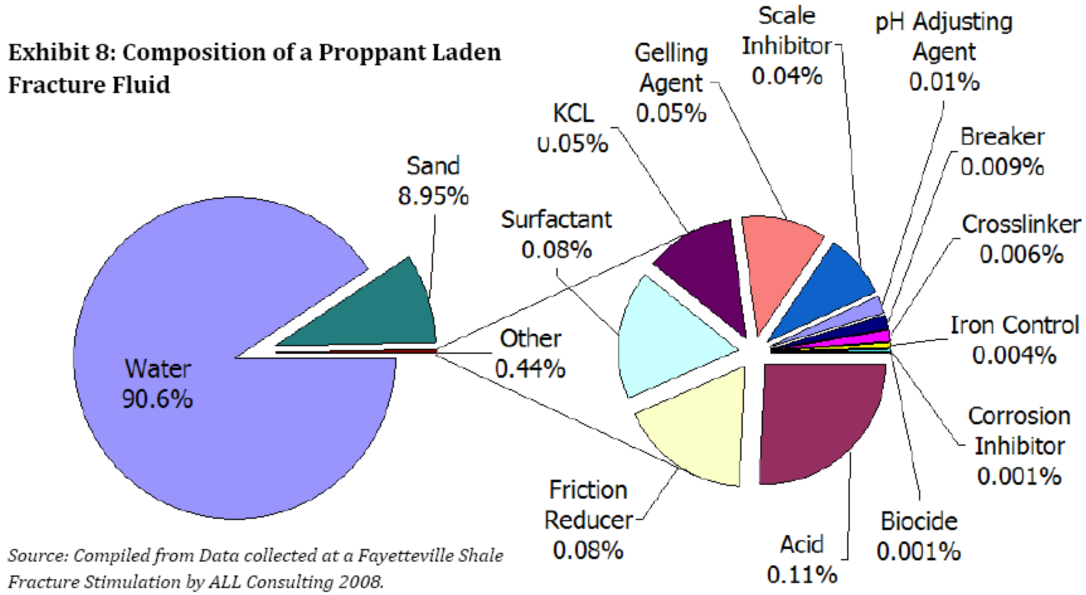
1) horizontal drilling

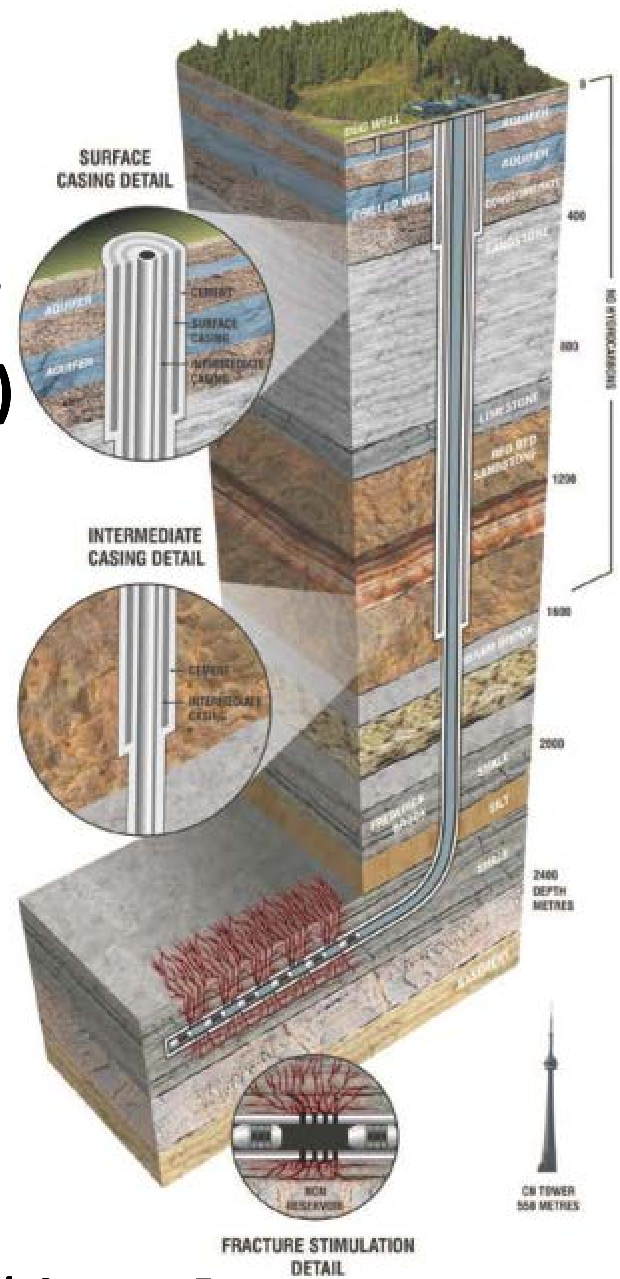




Introduction

… and **hydraulic fracturing or “fracking”**
(= either N_2 (shallow coalbeds) or a mix of fluids, chemicals and sand (in deep shales) are injected) to fracture the reservoir for extraction of natural gas (mainly CH_4)



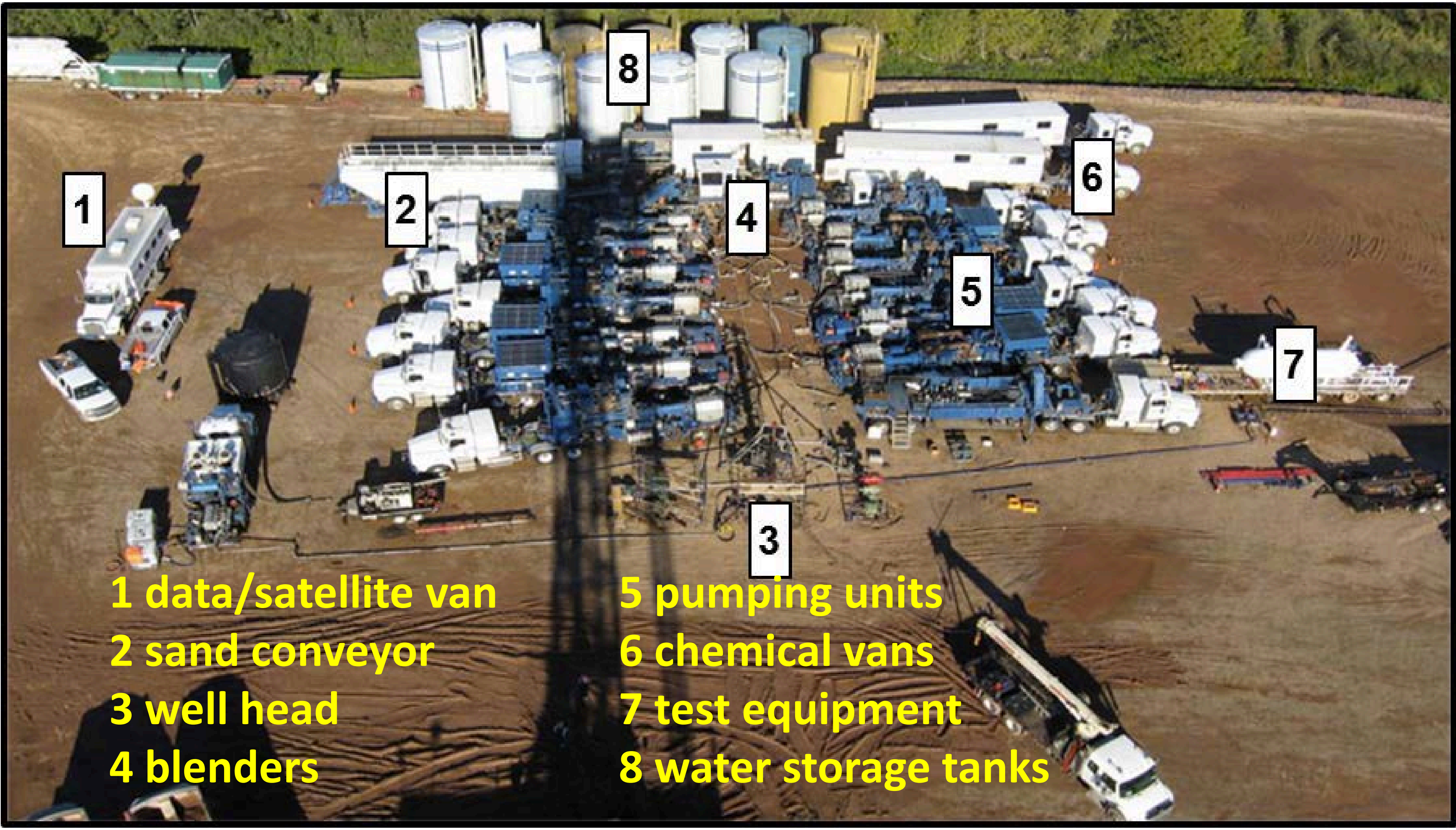


A Schematic Well Construction Diagram for a Shale Gas Well. Source: From http://www2.gnb.ca/content/dam/gnb/Corporate/pdf/ShaleGas/en/3DModelProof.pdf

Introduction

Shale gas development in Canada (and elsewhere) is often affected by the public controversy between the rapidly expanding exploitation of unconventional oil and gas resources by industry facilitated by horizontal drilling and hydraulic fracturing and the fear of landowners and parts of the public that these activities may have a negative impact on the quality of groundwater in shallow aquifers or on surface water.

Hydraulic Fracturing in Action



Hydraulic Fracturing in Action

Hydraulic Fracturing in Action

Introduction

Negative impact on shallow groundwater may occur, among others, from:

- **stray gases (methane etc.)**
- **formation waters (flow-back water)**
- **fracking chemicals used during hydraulic fracturing**

There is an astounding lack of high-quality scientific data in the peer-reviewed scientific literature on groundwater quality in the vicinity of oil and gas wells

Closing this science gap could be highly beneficial for the responsible development of shale gas plays

Objective

to discuss the key components of potential

groundwater and surface water

monitoring programs

that are suitable to generate scientifically

defendable data for testing of impacts,

or the lack thereof,

of shale gas development on the

quality of groundwater in shallow aquifers

Relevant Experience

Since 2006, the Alberta Energy Regulator required a baseline groundwater analysis for each groundwater well within 600 meter radius from a new coalbed-methane well (usually fracked with N_2).

> 10 000 groundwater samples obtained so far

expansion to shale gas plays is under consideration

Unconventional Gas Drilling and Contamination Pathways

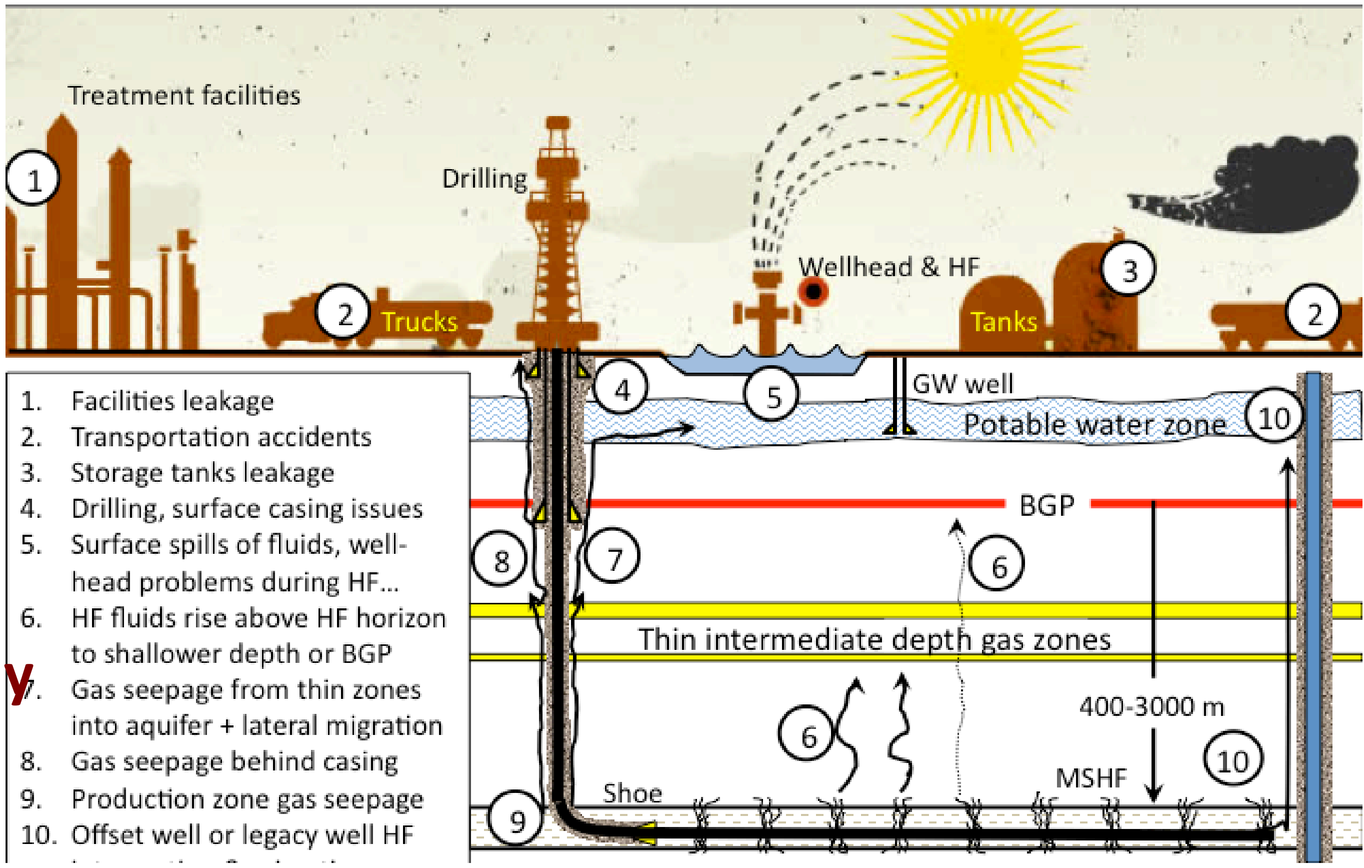
What are the most likely leakage pathways?

From above:

e.g. spills

From below:

most likely leakage pathway is along imperfectly sealed new or old wells



Schematic diagram of potential leakage pathways (from Dusseault et al., submitted)

Well Integrity

If a well is perfectly sealed (cemented), no leakage of gases or fluids will occur.

Essential Components
of a Robust Groundwater Monitoring Program

1. to generate a scientifically defendable baseline prior to drilling and hydraulic fracturing against which future impacts can be compared;

2. to continue groundwater quality monitoring during and regularly after hydraulic fracturing to test for potential detrimental impact on shallow groundwater

Key Questions

1. Which samples should be obtained?
2. How should the samples be obtained?
3. Who should obtain samples?
4. What parameters should be analyzed ?
5. Where to obtain samples?
6. How often should samples be obtained?

… to monitor for potential impacts on shallow groundwater from:

- stray gases (methane etc.)
- formation waters (flow-back water)
- fracking chemicals used during hydraulic fracturing

Which Samples?

1. Water samples for analyses

2. Gas samples for analyses

Fig.: Sampling at shallow groundwater well (picture provided by Don Jones, AITF)

a. Free gas samples

b. Dissolved gas samples

Under some circumstances, sampling for both may be desirable

CH_4 concentration [mg/L]

over-saturated

sub-saturated

after fracturing

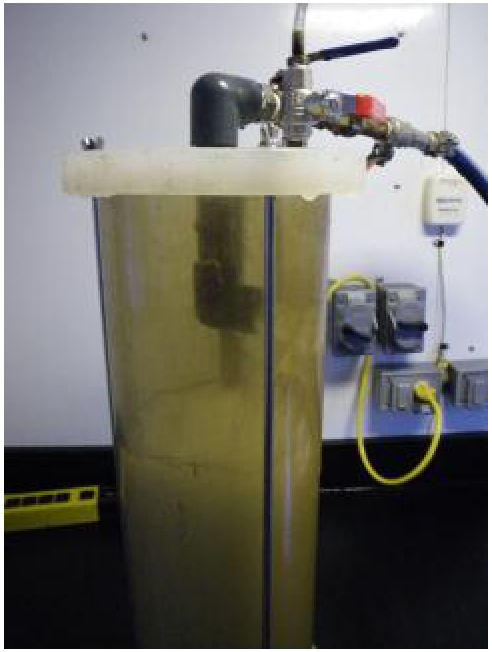
baseline

Fig.: Dissolved gas stability field for methane based on data from Yalowski & He (2003)

Which Samples?

Free gas sampling and analysis

Free gas sampler with Tedlar bag



Free gas sampler in action

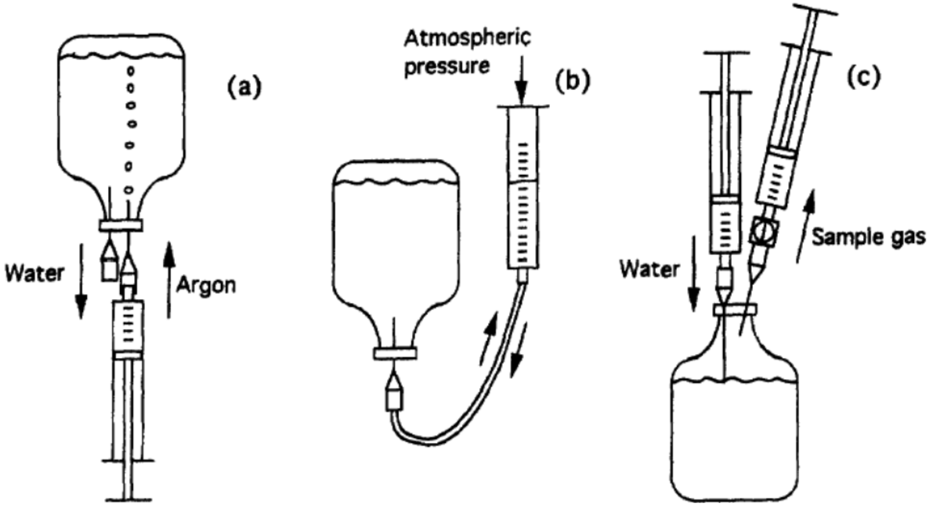
Gas composition analysis @ Vegreville

Isotope measurements at UofCalgary

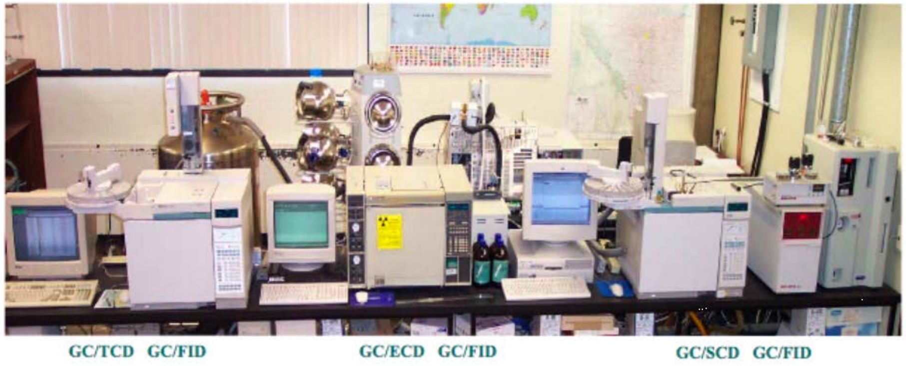
Which Samples?

Dissolved gas sampling and analysis

Sampling for dissolved gases
(photo by. T. Gorody)



Lab procedures for extracting dissolved gas



Gas composition analysis @ Vegreville

Isotope measurements at UofCalgary

Which Samples and Who Takes Them?

a. **Free gas samples**
  - targeted towards risk of explosions in houses etc.
  - different sampling setups may yield different yields/results
  - different consultants may generate different yields/results
  - ensuring comparability of results requires great care

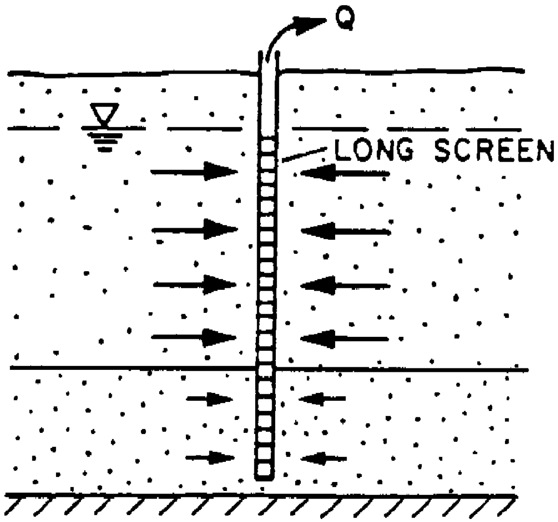
b. **Dissolved gas samples**
  - easier to sample by trained staff
  - analytically more challenging
  - results may be more comparable
  - results only representative for samples at or below saturation

Fig.: Dissolved gas stability field for methane based on data from Yalowski & He (2003)

How to Obtain Samples?

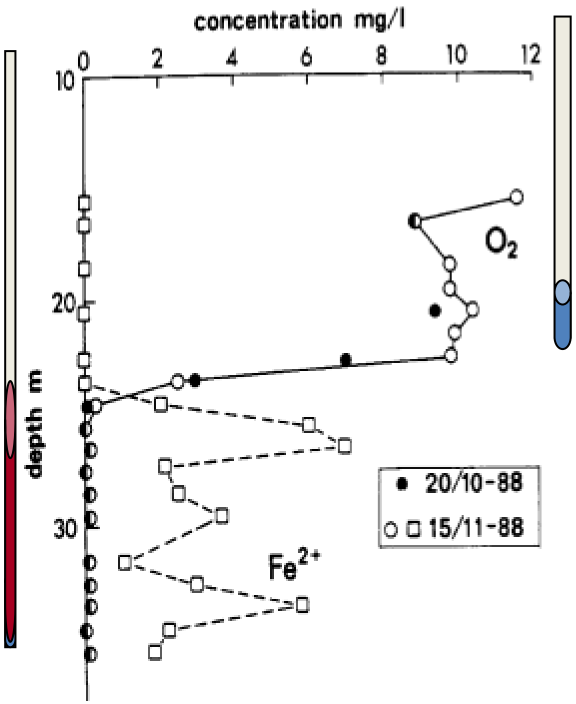
Widely used practice: landowner wells

Rationale: to ensure the landowner that the groundwater quality is not negatively affected

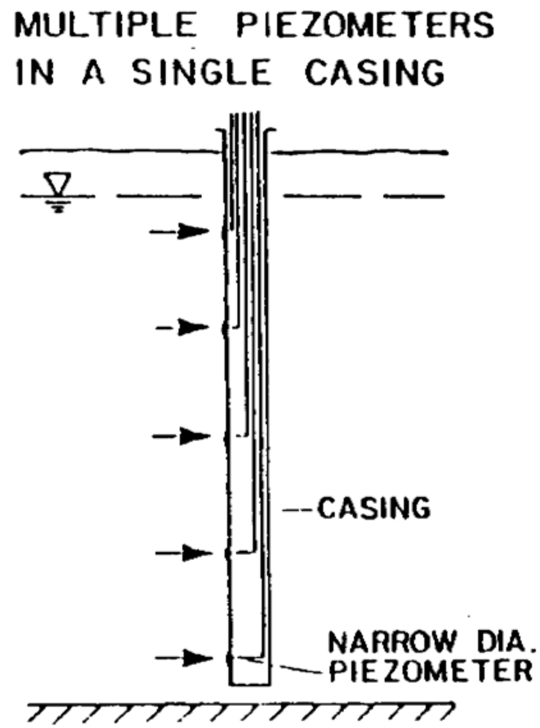


Landowner wells:

- may be poorly maintained
- may have long screen intervals can lead to mixing of groundwater with different chemical compositions
- may result in erroneous data especially for redox-sensitive species



How to Obtain Samples?

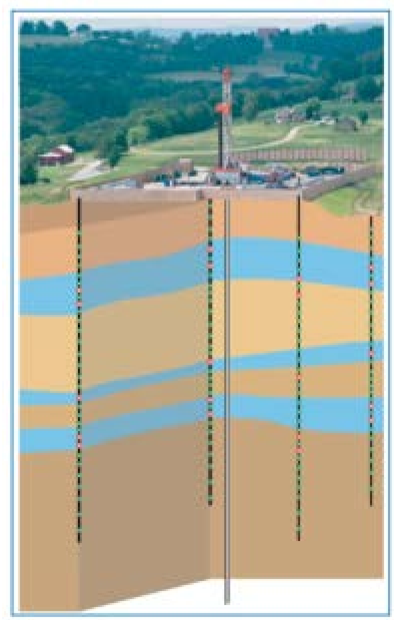


For truly scientific purposes:

- **multi-level piezometers in shallow aquifers appropriately placed based on thorough aquifer characterization**

- **Where possible, observation wells in the intermediate zone (e.g. Westbay systems)**

Figures from:
Jackson, Geofirma



What Parameters: Water

Groundwater, but also formation water, flow-back water

Field parameters:	temperature, pH, electr. conduct., Eh, dissolved oxygen (DO), turbidity, total alkalinity
Laboratory analyses:	
major cations:	Ca, Mg, Na, K, NH_4
major anions:	Cl, HCO_3, SO_4, NO_3, F
minor ions and trace metals:	Fe, Mn, As, Ba, B, Cr, Se, U etc.
organics + dissolved gases:	BTEX, $C_1 – C_5$
Calculated parameters:	total dissolved solids, ion balance

What Parameters: Water

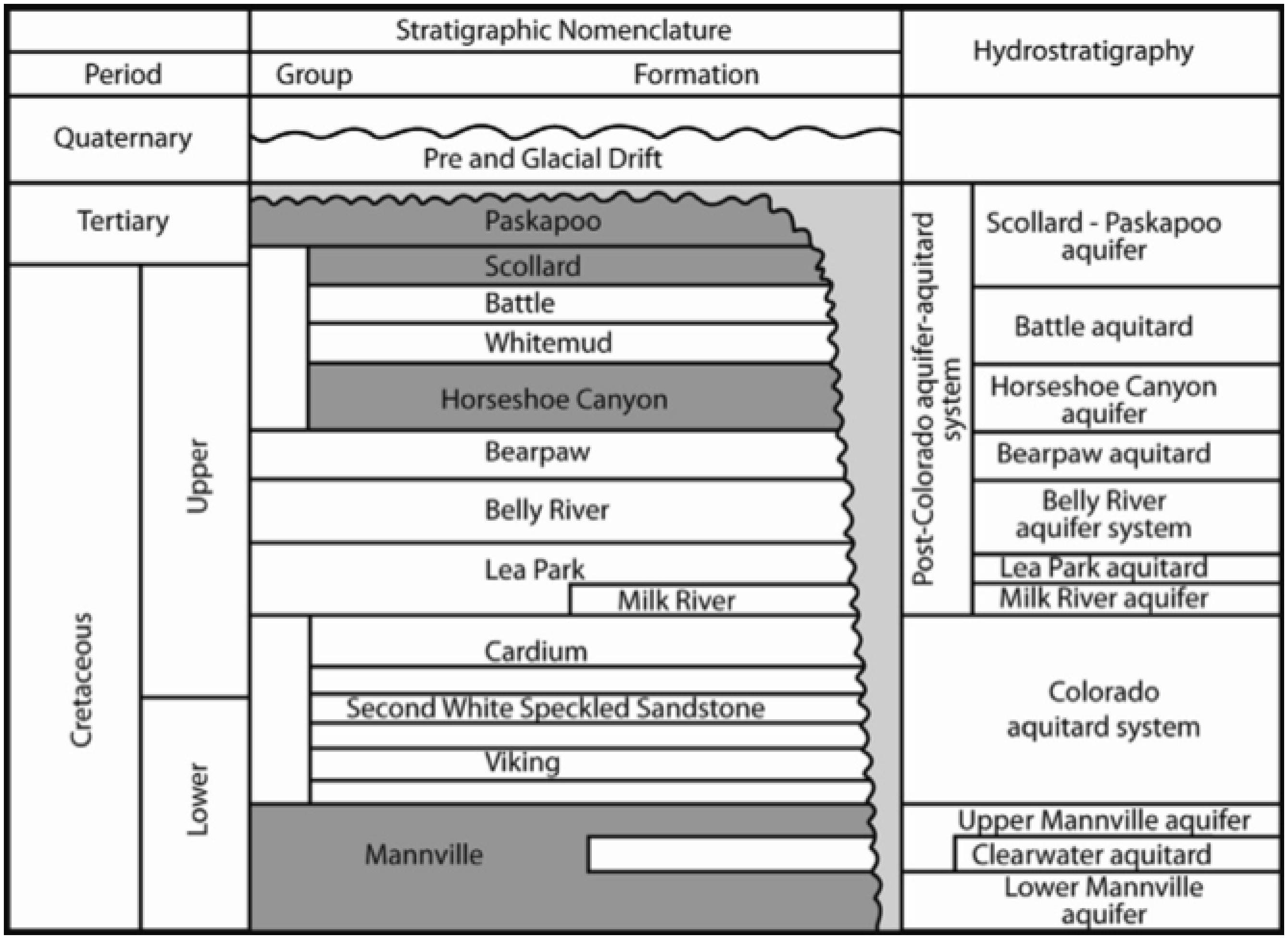
Chemical composition of water samples from selected shale gas plays compared to "average" Alberta groundwater.

Analytes (mg/L)	Formation: Fayetteville	Formation: Marcellus	Formation: Barnett	Alberta Groundwater
Na	5363	24445	12453	378
Mg	77	263	253	80
Ca	256	2921	2242	26
Sr	21	347	357	0.4
Ba	0.8	679	42	0.1
Mn	0.5	3.9	44	0.1
Fe	28	26	33	0.5
SO_4	149	9.1	60	185
HCO_3	1281	261	289	735
Cl	8042	43578	23798	77
TDS	15,219	72,533	39,570	1037
Sp Gravity	1.01	1.05	1.03	1.00
Depth (m)	300-2000	1200-2600	2000-2600	<100

Due to the often much higher TDS in formation waters, its potential impact on shallow groundwater is easily detectable

What Parameters: Alberta Waters

Hydro-Stratigraphy of Western Canadian Sedimentary Basin



Shallow groundwater

Horseshoe Canyon Fm
CBM play

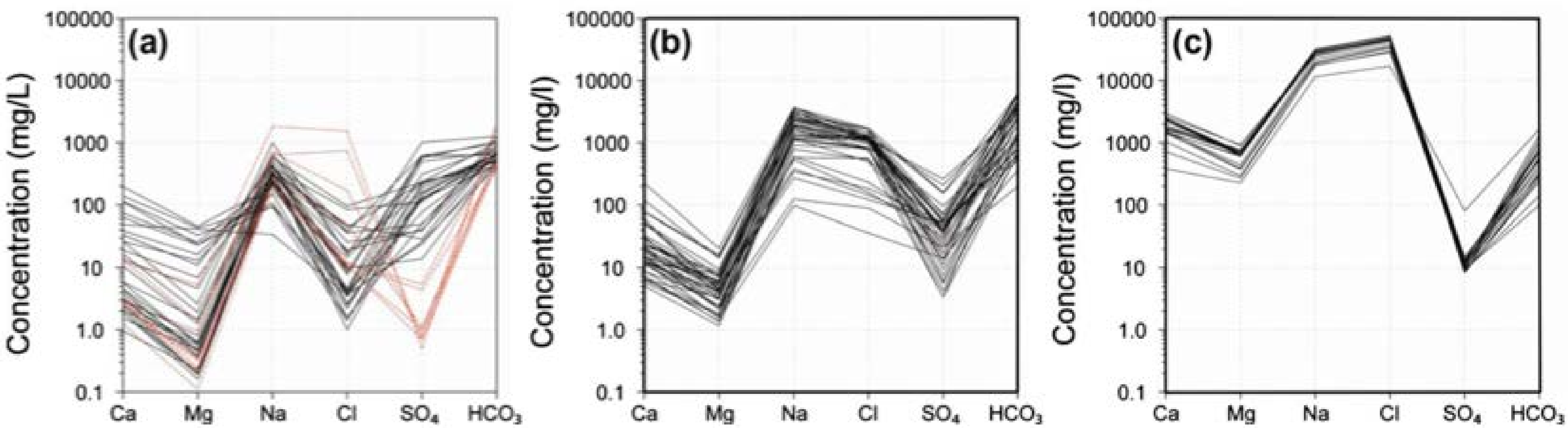
Mannville Formation
CBM play

Most shale plays (Montney, Horn River, Duvernay) stratigraphically below (Triassic, Devonian)

What Parameters: Water

Different chemical compositions of shallow groundwater and formation waters in Alberta (from Cheung et al., 2010)

Shallow groundwater | Horseshoe Canyon Fm | Mannville Formation



Shallow groundwater is mainly of Na-HCO_3 type;
Formation water is mainly of Na-Cl type;

Water type is a good indicator of formation water impact on shallow groundwater

What Parameters: Gases

composition of gases: CH_4, C_2H_6, C_3H_8 etc. CO_2, N_2 …

wetness parameter:

$$\frac{\text{Concentration of } CH_4}{\text{Concentrations of } C_2H_6 + C_3H_8 + \text{etc.}}$$

isotopic composition:

$\delta^{13}C$ of methane, ethane, propane

$\delta^{13}C$ of butane and pentane (if available in sufficient concentrations)

$\delta^{2}H$ of methane

What is an Isotope?

$$^{N+Z}_{Z}\text{E}_{\text{lement}}$$

Z = number of protons (or atomic number)

N = number of neutrons

A = N+Z = mass number

Stable Isotopes for Applications in Geology and Environmental Sciences

Element	Isotopes	Z	N	Atomic Mass	Abundance [%]
Hydrogen	^{1}H	1	0	1.0078	99.984
	^{2}H	1	1	2.0141	0.0156
Carbon	^{12}C	6	6	12.0000	98.892
	^{13}C	6	7	13.0034	1.108

Delta (δ) Notation

Stable isotope ratios of a sample are always measured with respect to a reference material; by measuring relative differences, the highest precision can be achieved;

$$\delta^{13}C\ [‰] = \left(\frac{{}^{13}C/{}^{12}C_{\text{sample}}}{{}^{13}C/{}^{12}C_{\text{reference}}} - 1 \right) \times 1000$$

$$\delta^{2}H\ [‰] = \left(\frac{{}^{2}H/{}^{1}H_{\text{sample}}}{{}^{2}H/{}^{1}H_{\text{reference}}} - 1 \right) \times 1000$$

Isotopic Fingerprinting of Methane

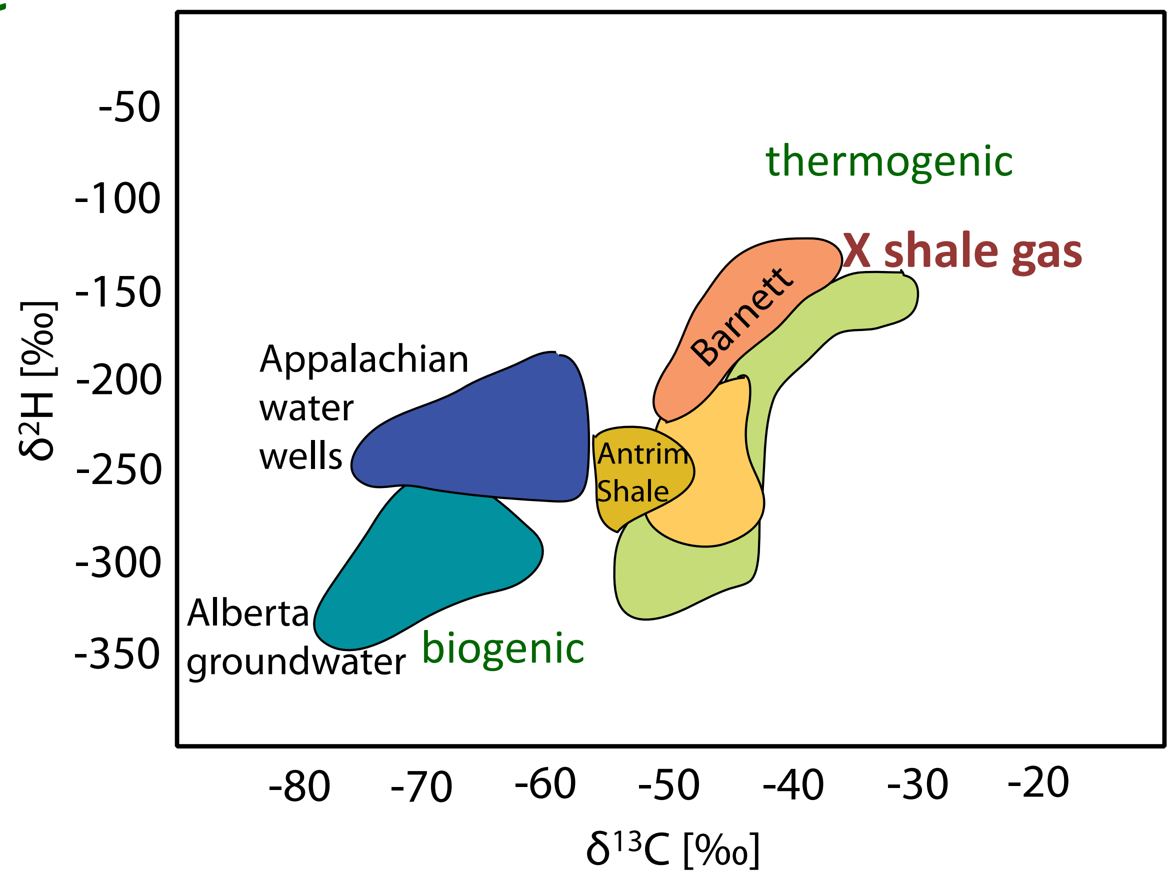
Biogenic Methane

$\delta^{13}C$ between
-110 and -55 ‰

$\delta^{2}H$ between
-170 and -400 ‰

Thermogenic Methane:

$\delta^{13}C$ between
-60 and -25 ‰

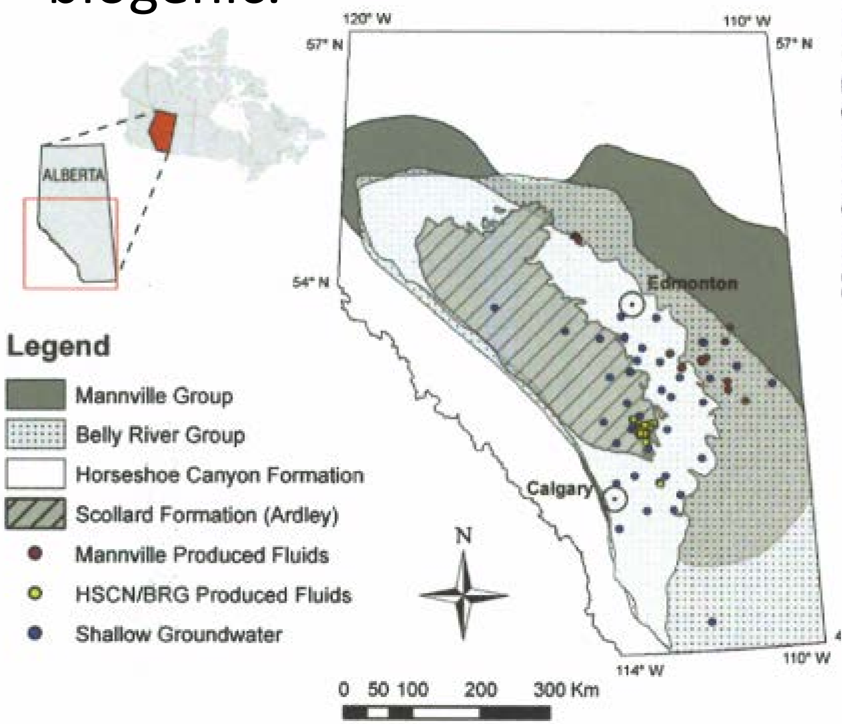


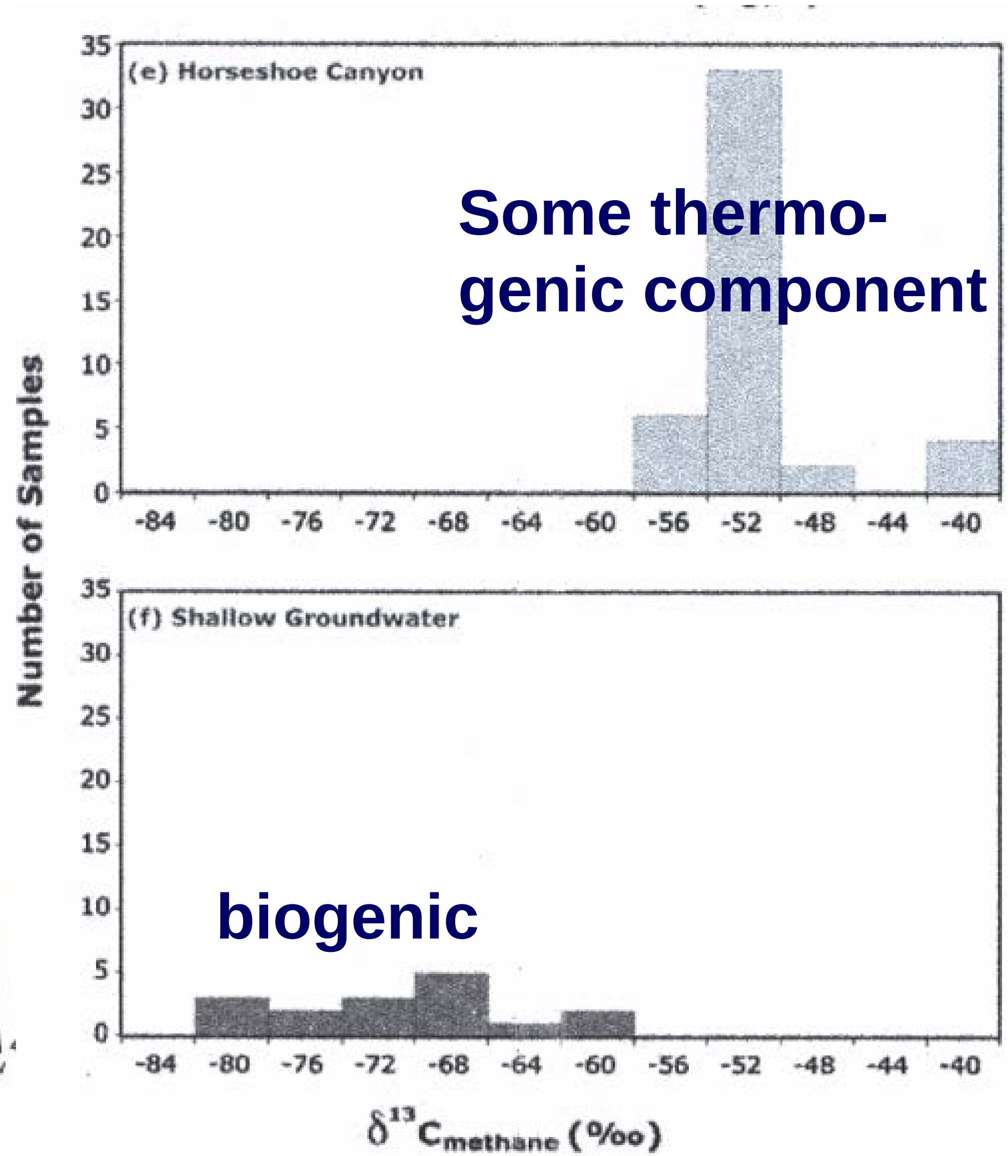
The isotopic composition of methane in shallow groundwater and selected natural Gas plays (from: Jackson et al., 2013)

Methane in Alberta Groundwater

GW in Alberta often contains methane (CH_4)

$\delta^{13}C$ values indicate this methane is usually biogenic.





Figures from Cheung et al., Applied Geochemistry, 2010

Methane in Alberta Groundwater

Biogenic CH_4 has usually a wetness parameter >1000 and $\delta^{13}C$ values < -60 ‰

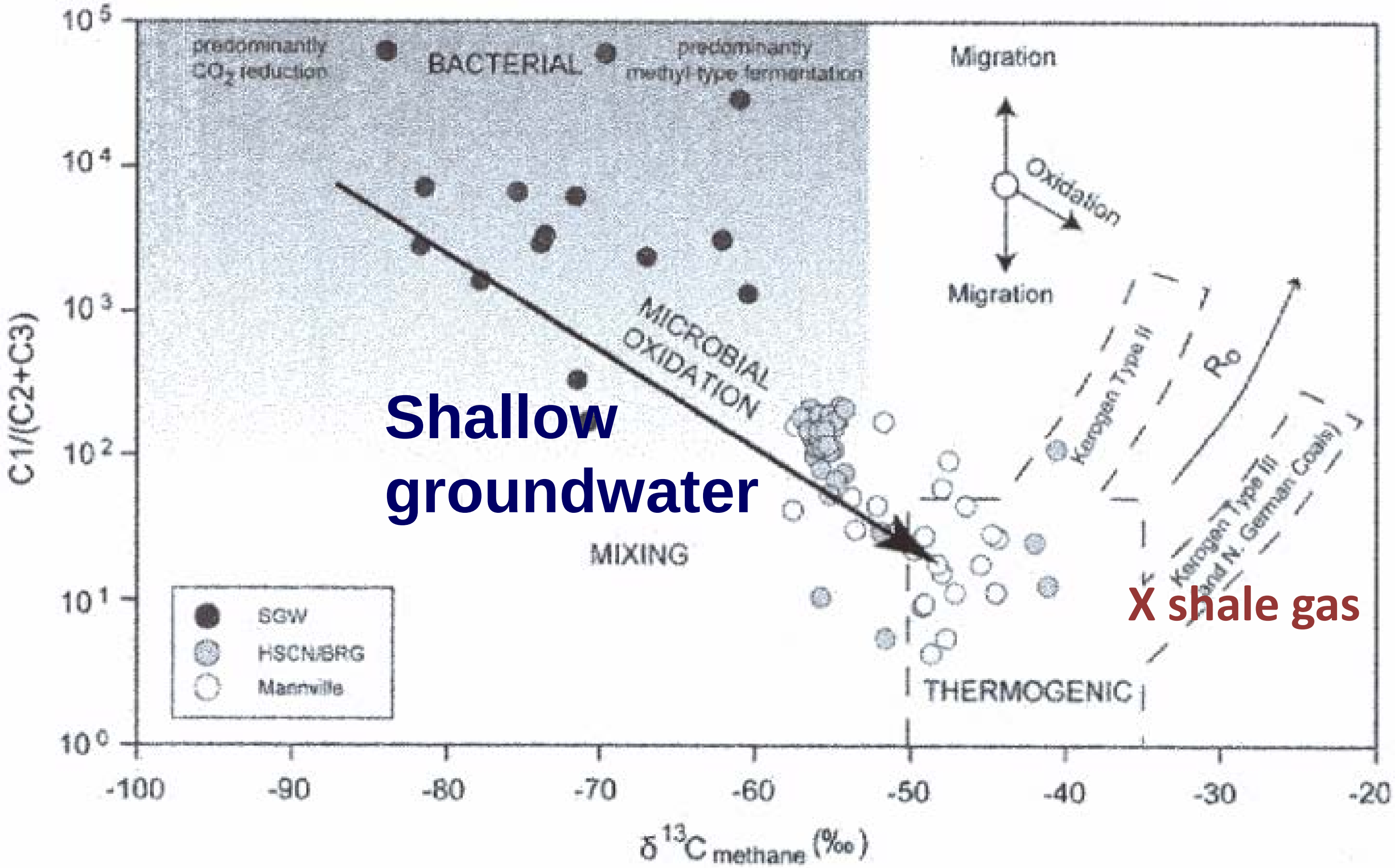


Figure from: Cheung et al., Appl. Geochem., 2010

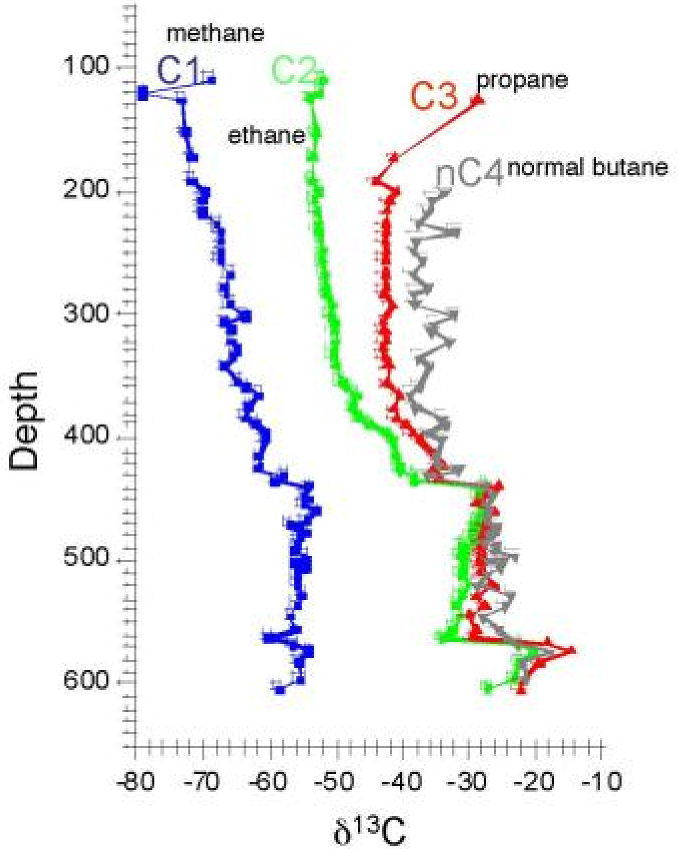
Impact of stray gases on shallow groundwater can be detected by combining wetness and isotopic parameters

What Parameters: Gases

To detect the exact source of stray gases impacting shallow groundwater, gas samples for chemical and isotopic analyses are needed from:

- **shallow groundwater**
- **mud logs (see diagram)**
- **the producing formation**

Determining source of migrating gas: Start with Mudlog (NE Alberta)



Example: $\delta^{13}C$ values for methane, ethane, propane and butane for mudlog samples drilled in Alberta (from Muehlenbachs, Gussow presentation 2012)

Tracing Leakage of Natural Gas

$\delta^{13}C$ of C_1 (methane), C_2 (ethane) and C_3 (propane) in 3 shallow groundwater samples, surface casing gases, and oil & gas wells

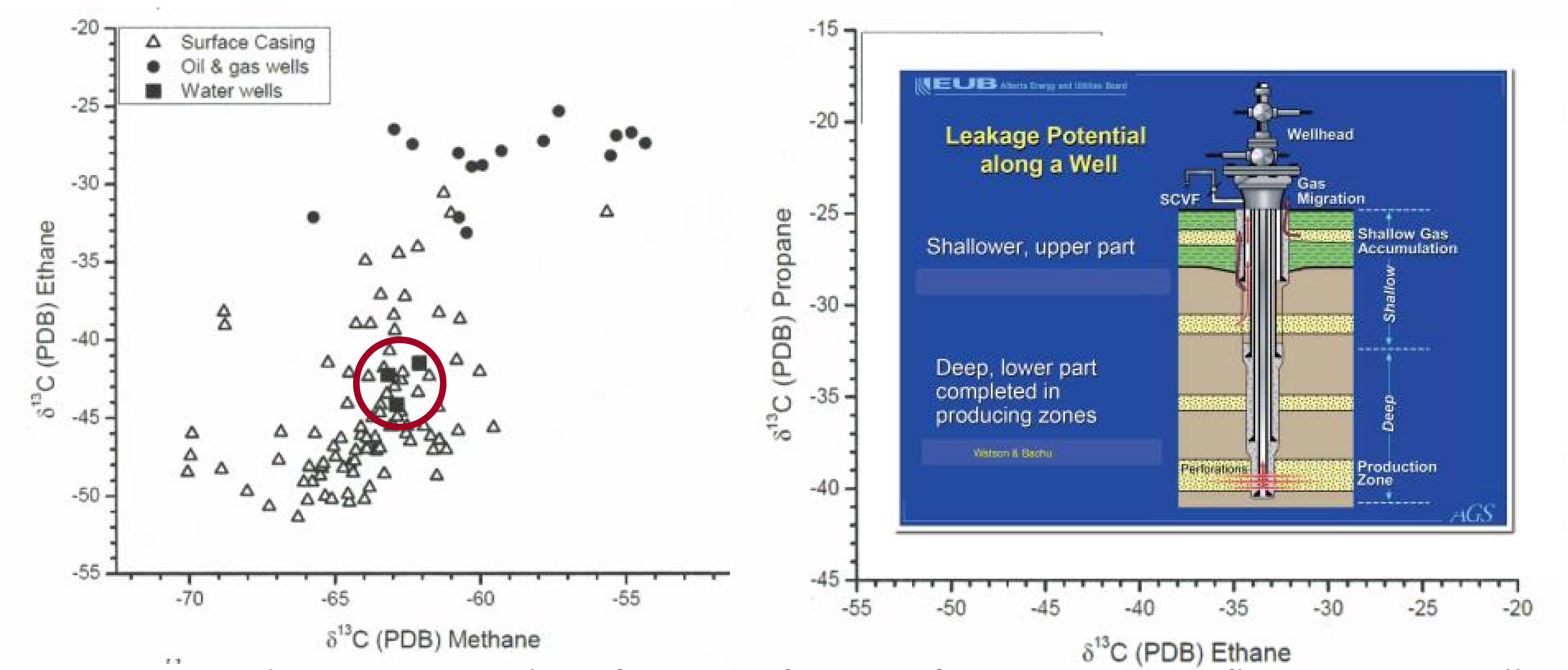


Figure: Carbon isotope values for gases from surface casing vent flows, water wells, and production zones in the Wildmere heavy oil field, east-central Alberta (from: Tilley & Muehlenbachs, 2011)

Tracing Leakage of Natural Gas

Isotopic fingerprinting of C_1 (methane), C_2 (ethane) and C_3 (propane)

C isotope data suggest that gas leakage originates in 500 meter depth, ~ 100 meter above the producing zone

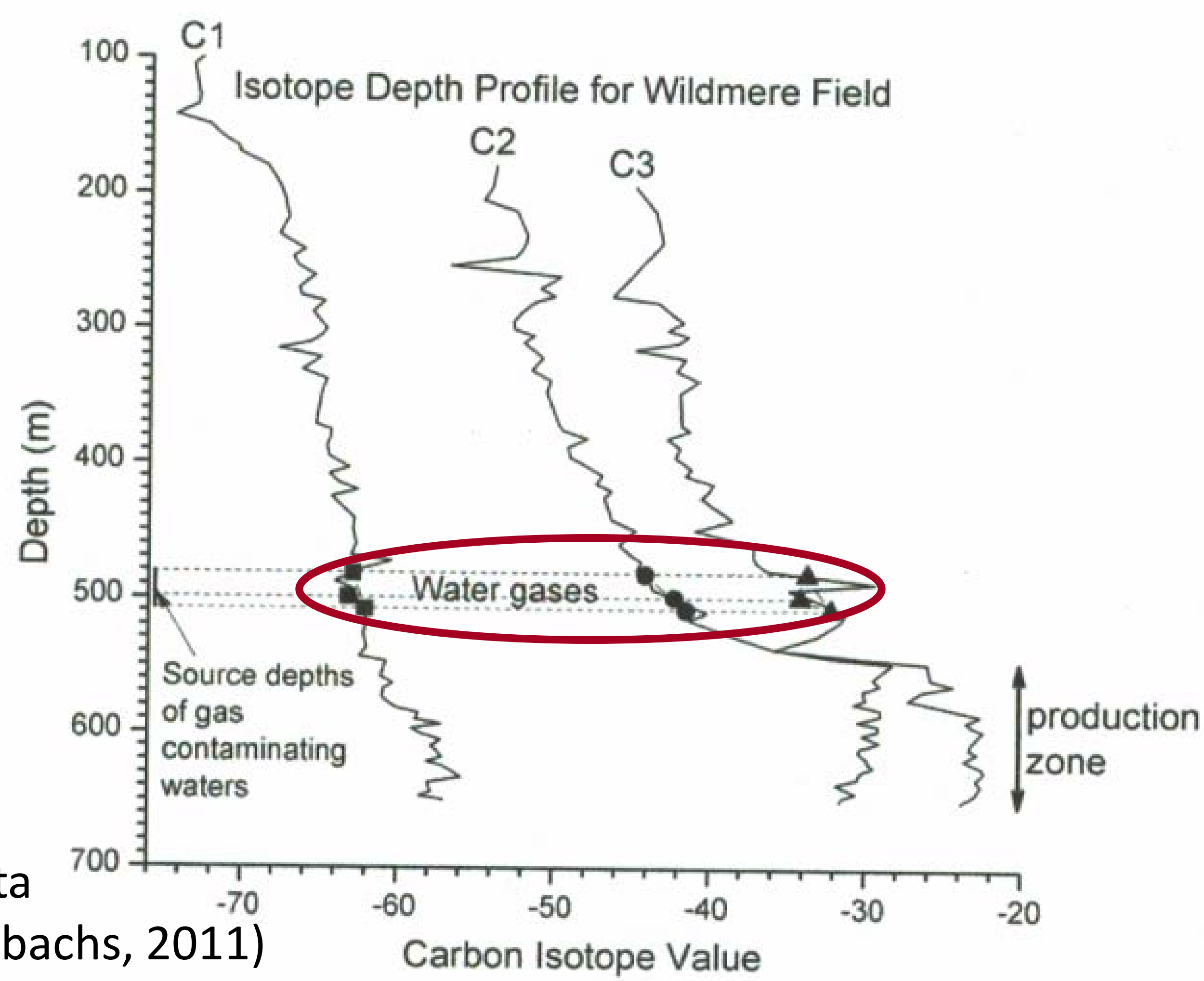
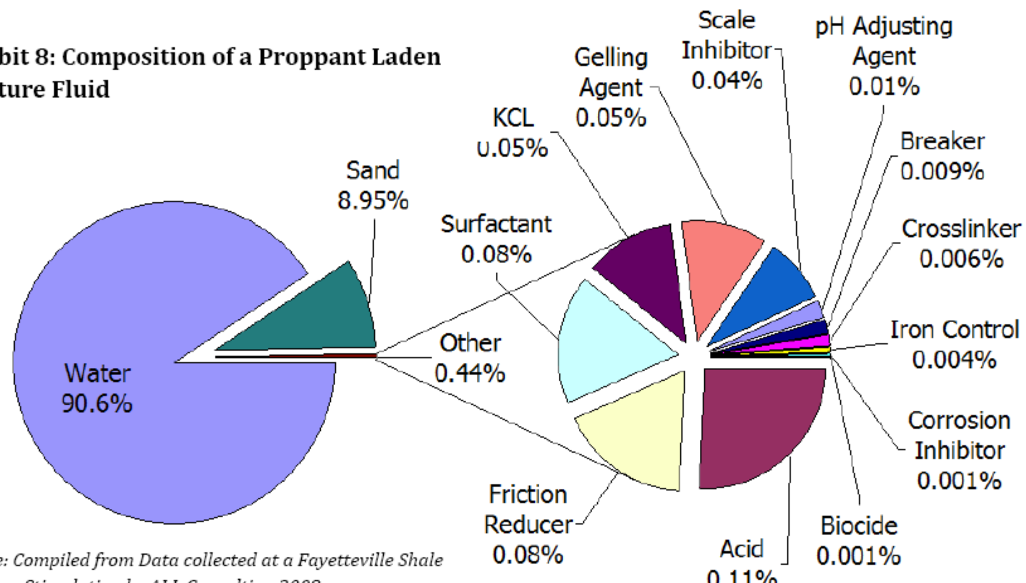


Figure: Carbon isotope values for gases from the Wildmere heavy oil field, east-central Alberta (from: Tilley & Muehlenbachs, 2011)

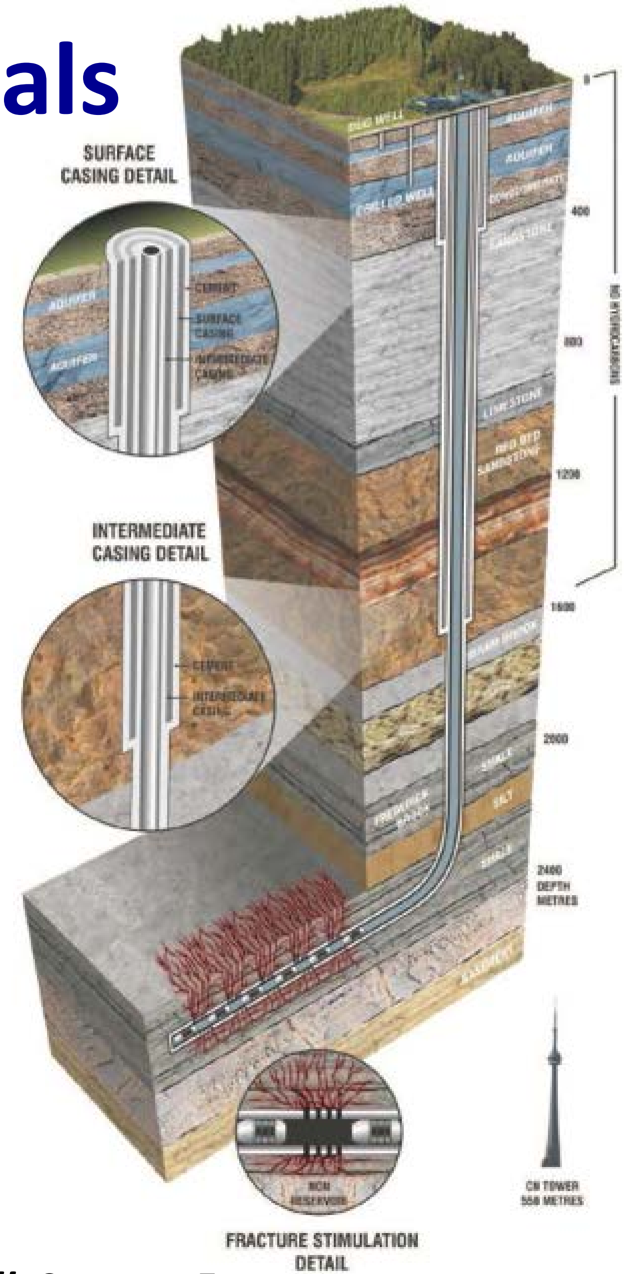
Fracking Chemicals

… often a mix of fluids, chemicals and sand to fracture the reservoir for extraction of natural gas (mainly CH_4);

Exhibit 8: Composition of a Proppant Laden Fracture Fluid



Source: Compiled from Data collected at a Fayetteville Shale Fracture Stimulation by ALL Consulting 2008.



A Schematic Well Construction Diagram for a Shale Gas Well. Source: From http://www2.gnb.ca/content/dam/gnb/Corporate/pdf/ShaleGas/en/3DModelProof.pdf

What Parameters: Fracturing Chemicals

not all fracs are water-based

chemicals used vary from play to play and with time

often of highest concern to the public

From: Jackson et al., (2003)

Component and Purpose	Chemical
Carrier or 'make-up' fluid	Water, N_2, CO_2, LPG, foams, emulsions
Proppants – designed to keep fractures open after fracking fluid pressure decreases	Sand, resin-coated sand, sintered bauxite, alumina, ceramics, and silicon carbide
Clean up damage from initial drilling, initiate fracturing	HCl, other acids
Additives to adjust frack fluid viscosity, and form gels – designed to keep proppants suspended in frack fluid so it will enter and 'prop open' new fractures	Viscosity adjusters: Guar gum, cellulose-based derivatives. Gel formation: Cross-linking agents (borate compounds or metal complexes)
Viscosity 'breakers' (reducers) designed to decrease viscosity after frack fluid has reached its target zone	Ammonium persulfate, sodium peroxydisulfate
Stabilizers to delay the action of breakers, biocides, fluid-loss additives, friction reducers	latex polymers or copolymers of acrylamides, and acid corrosion inhibitors, e.g. alcohols
Acid corrosion or scale inhibitors	isopropanol, methanol, formic acid, acetaldehyde
Friction reducers for low-viscosity 'slickwater' fracking where proppants penetrate more deeply into fractures	Surfactants, polyacrylamide, ethylene glycol
Biocides to inhibit sulfate reducers	Aldehydes, amides
Surfactants to improve relative gas permeability	Isopropanol
Clay stabilizer to prevent clay flocculation	KCl (for clays)
Other	Glycols, amines, defoamers

What Parameters: Fracturing Chemicals

Unless spilled from the surface, fracturing chemicals will be introduced into shallow aquifers via flow-back water

→ Monitor for contamination from flow-back & formation water first; if detected test for fracturing chemicals more specifically;

Knowledge of the fracturing chemicals that are actually used at the site is essential for selecting appropriate monitoring parameters

What Parameters: Fracturing Chemicals

Potential parameters for regular monitoring that may indicate impact from fracturing fluids:

- **Some cations or anions (NH_4, K, possibly SO_4^{2-})**
- **TOC as bulk parameter for organic contaminants**
- **possibly selected organic compounds (e.g. BTEX, glycols etc.)**

Once impact of fracturing chemicals on shallow groundwater is suspected, more detailed analysis for fracturing chemicals (borate compounds, acrylamides, isopropanol, methanol, surfactants, biocides etc.) and their degradation products should be initiated on a site-specific basis.

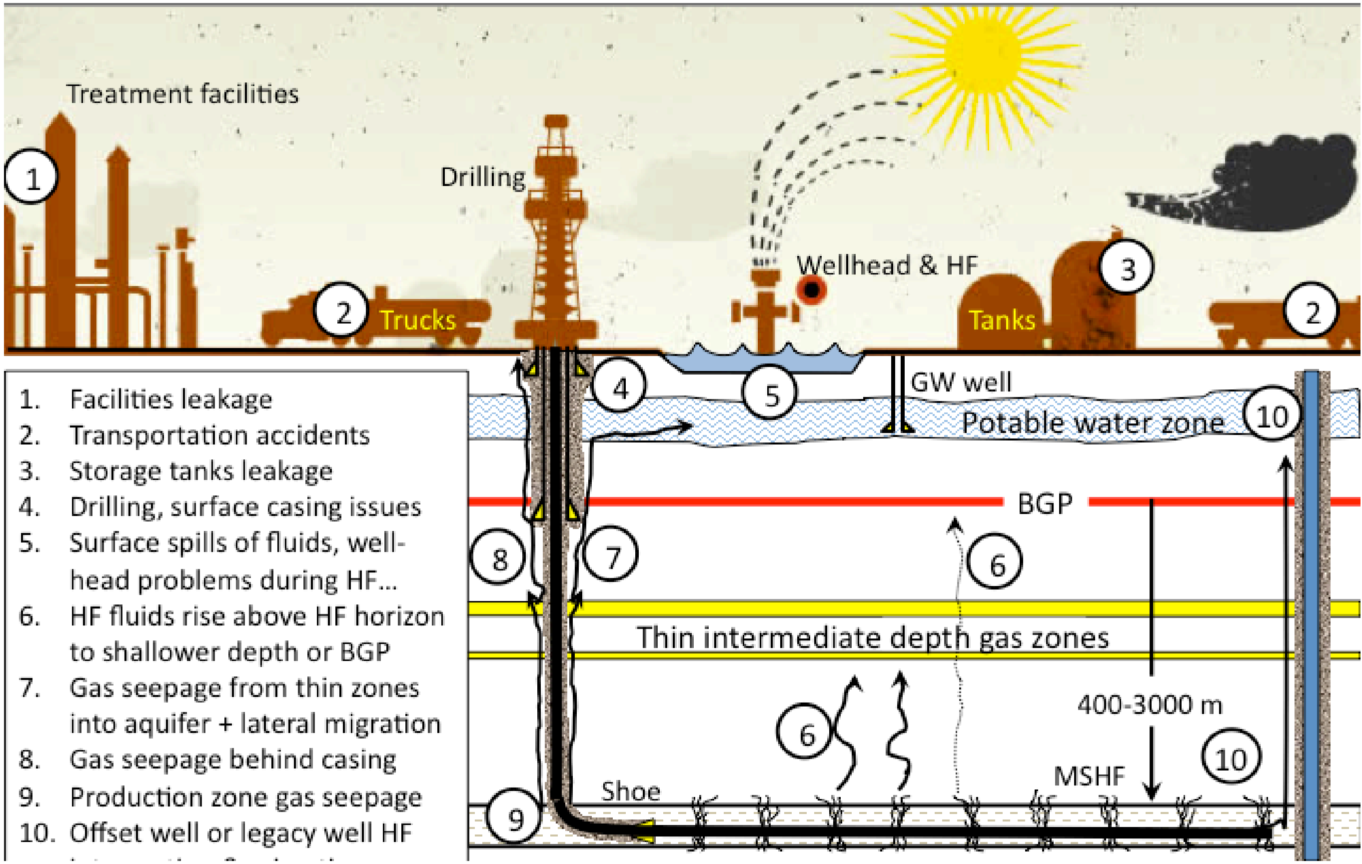
Where to Obtain Samples?

What are the most likely leakage pathways?

From surface

From subsurface

- **Shale gas well**
- **Offset wells**
- **Abandoned wells**



Schematic diagram of potential leakage pathways
(from Dusseault et al., submitted)

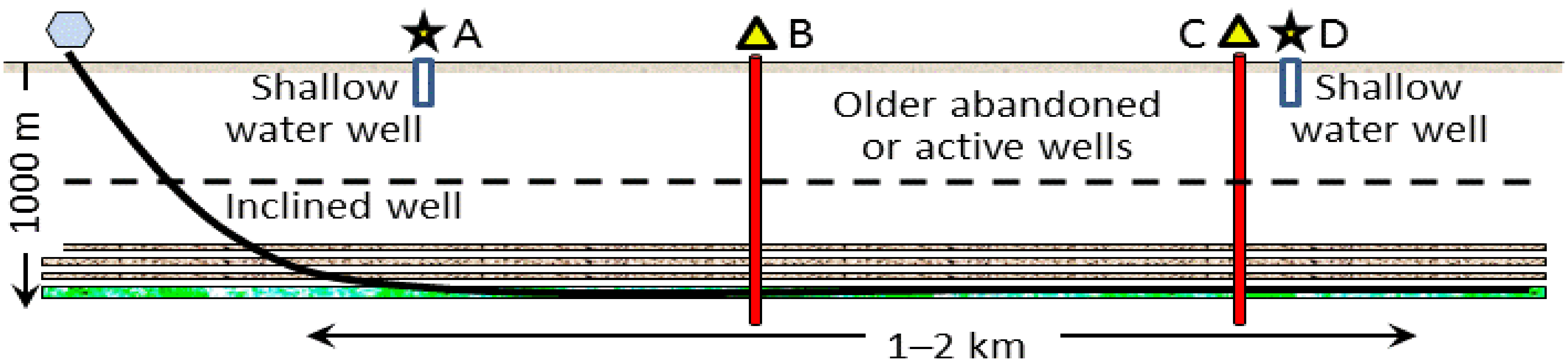
Where to Obtain Samples?

The question of testing radius around potential leakage sites (e.g. wells) is difficult to answer without proper aquifer characterization

Distance and even direction of impact may be different for stray gases and formation waters affecting shallow aquifers

For landowner wells, distances of up to 600 meter or ½ mile are often used (not based on solid scientific data)

For newly installed scientific sampling wells, properly selected sampling sites can be chosen based on aquifer characterization



Schematic diagram of shale gas well (from Dusseault et al., submitted). B,C are off-set energy wells. A, D are landowner wells included in monitoring program.

How Often to Obtain Samples?

Depends on specific objective

Minimum sampling frequency:

- **Baseline sampling**
- **Sampling during hydraulic fracturing**
- **Sampling during production (after hydraulic fracturing) frequency: depends on objective**

Leakage may occur many years after well construction and hydraulic fracturing

Long-term monitoring desirable

Conclusions

It is feasible to develop groundwater monitoring programs that are suitable to generate scientifically defendable data for testing of impacts, or the lack thereof, of shale gas development on the quality of groundwater in shallow aquifers

Establishing such programs requires, among others:

- **Willingness to design a scientifically sound monitoring program**
- **Collaboration between industry, academia & regulators;**
- **Sufficient funds to conduct this task thoroughly**
- **A long-term commitment to maintain the program for years**

Outcome & Benefits

The beneficiaries will include:

- **Regulators who are responsible for ensuring land-owners and the public that the groundwater quality is protected;**
- **Industry that will have data on groundwater quality that demonstrate the extent of impacts on shallow groundwater; and**
- **The public that will be assured that scientific data are being collected that are suitable to monitor the quality of its freshwater resources in aquifers.**

References Used

CHEUNG, K., KLASSEN, P., MAYER, B., GOODARZI, F. & ARAVENA, R. (2010): Major ion and isotope geochemistry of fluids and gases from coalbed methane and shallow groundwater wells in Alberta, Canada. – Applied Geochemistry, 25(9): 1307-1329.

Tilley, B., and K. Muehlenbachs (2011): Fingerprinting of Gas Contaminating Groundwater and Soil in a Petroliferous Region, Alberta, Canada. In *Proceedings, International Network of Environmental Forensics*, Cambridge, UK, July 25-27, 10 pages

JACKSON, R. E., GORODY, A. W., MAYER, B., ROY, J. W., RYAN, M. C. & VAN STEMPVOORT, D. R. (2013): Groundwater protection and unconventional gas extraction: the critical need for field-based hydrogeological research. – Ground Water, 51(4): 488-510. doi:10.1111/gwat.12074

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