Microbial Ecology of Hydraulic Fracturing: Implications for Sustainable Resource Development

Irvine, CA
September 13, 2014
Evolution of Oil and Gas Development

On the banks of the Youghigheny River, Versailles, PA, 1919.

Natural Gas-bearing Shale

- Gas trapped in pores or adsorbed to surfaces in low permeability rock.
- Commercial production requires engineering permeability
- Enabled by: Horizontal Drilling / Hydraulic Fracturing
Overview of Horizontal Drilling

“Walking Rig”
Multiple wells on same pad
Horizontal Drilling: Economic and Environmental Advantages

- Vertical Wells (pink) many pad sites
- Horizontal Well (green) single pad site

Centralized Operations, Less Land Disturbance, Lower Construction Costs
Hydraulic Fracturing: Water Utilization

Fracturing Fluid contains 4-20 million liters of water mixed with sand and chemicals that protect well and optimize gas production.

Produced Water returns to the surface and is stored prior to treatment and reuse, or disposal.
Produced Water Characteristics

**Graph Details:**
- **X-axis:** Time of Flowback (days)
- **Y-axis 1:** Flow rate (m³/d)
- **Y-axis 2:** TDS Concentration (g/L)

**Graph Notes:**
- Flowrate vs. TDS Concentration over time.

**Table:**

<table>
<thead>
<tr>
<th>Substance</th>
<th>Maximum</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDS (mg/L)</td>
<td>345,000</td>
<td>106,390</td>
</tr>
<tr>
<td>oil and grease (mg/L)</td>
<td>802</td>
<td>74</td>
</tr>
<tr>
<td>TOC (mg/L)</td>
<td>1530</td>
<td>160</td>
</tr>
<tr>
<td>SO₄ (mg/L)</td>
<td>763</td>
<td>71</td>
</tr>
<tr>
<td>Cl (mg/L)</td>
<td>196,000</td>
<td>57,447</td>
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<tr>
<td>Na (mg/L)</td>
<td>117,000</td>
<td>24,123</td>
</tr>
<tr>
<td>Ca (mg/L)</td>
<td>41,000</td>
<td>7,220</td>
</tr>
<tr>
<td>Ba (mg/L)</td>
<td>13,800</td>
<td>2,224</td>
</tr>
<tr>
<td>Sr (mg/L)</td>
<td>8,460</td>
<td>1,695</td>
</tr>
<tr>
<td>Fe total (mg/L)</td>
<td>321</td>
<td>76</td>
</tr>
<tr>
<td>Ra²²⁶ (pCi/L)</td>
<td>9,280</td>
<td>623</td>
</tr>
<tr>
<td>U²³⁸ (pCi/L)</td>
<td>497</td>
<td>42</td>
</tr>
</tbody>
</table>

**References:**
Water Management Hurdles in Pennsylvania

**Disposal**
- Deep-Well Reinjection → Few in PA
- Dilution into WWTP → Contamination
- Ag Reuse → Too salty

**Treatment**
- Membrane Technology → $$$
- Thermal Distillation → $$$$$
- Freeze Thaw Evaporation → Bad Climate
- Artificial Wetlands → Too salty

Local Challenges → Innovation & Local Solutions
Hydraulic Fracturing with Recycled PW

Produced Water to Impoundment

Impacted/Low-Quality Water as Make-up and Dilution (Abandoned Mine Drainage)

Pretreatment Remove Solids and M^{2+}

Dilute to Make-up volume; add Chems

Reuse of Produced Water for Hydraulic Fracturing
Centralized Impoundments, Long Storage

Microbial communities
- Thrive on substrates & nutrients in the produced water
- Evolve with time
- Alter the geochemistry in the impoundment and in the well
- Drive management decisions and costs
Microbes and Biogeochemistry of Produced Water

**Microbial Community from Wellhead Introduced to Impoundment**

**Microbial Community from Impoundment Introduced to Next Well During Recycling**

BIOCIDES

- Organics $\leftrightarrow$ CO$_2$
- Fermentation
- $SO_4^{2-} \leftrightarrow S^0 \leftrightarrow H_2S$
- Solubility of Metals
  - $Fe^{3+}(s) \leftrightarrow Fe^{2+}(aq)$
  - $U^{6+}(aq) \leftrightarrow U^{4+}(s)$

**Questions:** Which bacteria are present? Where? When? What can they do?

**Approach:** Next Generation Sequencing for High-resolution Insights
Generating Metrics for Ecological Comparisons

- Cells
  - DNA
  - Gene encoding ribosomal RNA
- Isolate DNA
- PCR
- DNA sequencing
- Sequence analysis
- Compare to Database
  - AGTCGCTAG
  - ATTCCGTTAG
  - AGCGGTAG
- Generate phylogenetic tree

- Bacteria
  - Proteobacteria
  - Cyanobacteria
  - Planctomyces
  - Bacteroides
  - Cytophaga
  - Thermotoga
  - Aquifex
- Archaea
  - Green Filamentous bacteria
  - Spirochetes
- Eukarya
  - Entamoeba
  - Slime molds
  - Animals
  - Fungi
  - Plants
  - Ciliates
  - Flagellates
  - Trichomonads
  - Microsporidia
  - Diplomonads

You Are Here
Your Breakfast was Here
Wellheads
Dynamic Populations in Wellhead Samples

- Diversity sharply decreases
- Anaerobic, fermentative and sulfur-reducing populations emerge
- At the expense of the aerobic and phototrophic
- Dominant species in PW is present in source water

Functional Metagenome Reveals How Capabilities of Community is Changing

<table>
<thead>
<tr>
<th>Level 2 functional categories (Level 1)</th>
<th>SW</th>
<th>PW day 1</th>
<th>PW day 9</th>
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<tbody>
<tr>
<td>alpha-proteobacterial cluster of hypotheticals (CS)</td>
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<tr>
<td>Organic Carbon</td>
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<tr>
<td>Carbohydrates</td>
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<tr>
<td>Sugars</td>
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<tr>
<td>Polysaccharide</td>
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<tr>
<td>Amino Sugar</td>
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<tr>
<td>Metabolism</td>
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<td>Glycoside hydrolases (C)</td>
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<tr>
<td>Selenoproteins (PM)</td>
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<tr>
<td>CRISPs (DNA)</td>
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<tr>
<td>Sodium ion coupled energetics (R)</td>
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<tr>
<td>Oxidative Stress</td>
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<tr>
<td>Heat Shock</td>
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<tr>
<td>Osmotic Stress</td>
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<tr>
<td>Periplasmic stress (SR)</td>
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<tr>
<td>Acid Stress</td>
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<td>Inorganic Sulfur Metab.</td>
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</tr>
<tr>
<td>Organic Sulfur Metab.</td>
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</tr>
</tbody>
</table>

Adapting towards organisms that are tough and optimized for survival and proliferation in PW
Impoundments
Impoundments and Sampling

- Surface
- Middle
- Bottom

- Untreated
- Biocide Amended
- Aerated
### Chemical Constituents of Water Samples (mg/L)

<table>
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<tr>
<th>Analyte</th>
<th>Untreated</th>
<th>Biocide Amended</th>
<th>Aerated</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>SUF</td>
<td>MID</td>
<td>BOT</td>
</tr>
<tr>
<td>Ba(^{2+})</td>
<td>277</td>
<td>339</td>
<td>418</td>
</tr>
<tr>
<td>Ca(^{2+})</td>
<td>6150</td>
<td>8818</td>
<td>8679</td>
</tr>
<tr>
<td>Total Fe</td>
<td>0.3</td>
<td>4.4</td>
<td>64.9</td>
</tr>
<tr>
<td>K(^+)</td>
<td>190</td>
<td>224</td>
<td>261</td>
</tr>
<tr>
<td>Na(^+)</td>
<td>14250</td>
<td>20910</td>
<td>20410</td>
</tr>
<tr>
<td>Sr(^{2+})</td>
<td>894</td>
<td>1296</td>
<td>1256</td>
</tr>
<tr>
<td>Cl(^-)</td>
<td>35100</td>
<td>51000</td>
<td>50900</td>
</tr>
<tr>
<td>Br(^-)</td>
<td>371</td>
<td>552</td>
<td>549</td>
</tr>
<tr>
<td>I(^-)</td>
<td>5.6</td>
<td>9.8</td>
<td>10.3</td>
</tr>
<tr>
<td>NO(_3^-)</td>
<td>ND (^b)</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>SO(_4^{2-})</td>
<td>15.1</td>
<td>25.7</td>
<td>16.5</td>
</tr>
<tr>
<td>Acetate</td>
<td>ND</td>
<td>32.6</td>
<td>75.9</td>
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</tbody>
</table>

*Geochemical Characteristics/Stratification*

Bacterial Communities in Impoundments

Take Home Message and Discussion

- Unique microbial communities arise that are selected for sulfur (not sulfate) metabolism

- Industry tests to determine sulfide producing potential will yield false negatives

- The chemistry of produced water selects for tough bacteria that are well-adapted for survival

- Recycling of produced water carries over tough bacteria into the next frac and may accelerate the onset of well souring
Thoughts on Shale Resources & Water Stress

Development competes with local municipal, industrial, agricultural, and environmental water resource needs.

Recycling of produced water may enable oil/gas development in new regions.

Solutions arise locally that can have global impacts.
Research Frontiers: Microbial Control

Engineered Microbial Communities in Subsurface: Optimize Beneficial Populations while Eliminating Detrimental Ones

‘Botique” biocides that target specific populations while leaving others unharmed

Engineered functionality of existing microbial community: introduction of desired genes into the tough population

Design of hydraulic fracturing fluid with the endpoint, desired microbial community in mind
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- Rick Hammack
  NETL

- Angela Hartsock
  NETL