Water Management for Enhanced Sustainability and Economics of Shale Gas Development

Arab-American Frontiers
Muscat, Oman
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سلطنة عمان
وزارة التربية والتعليم

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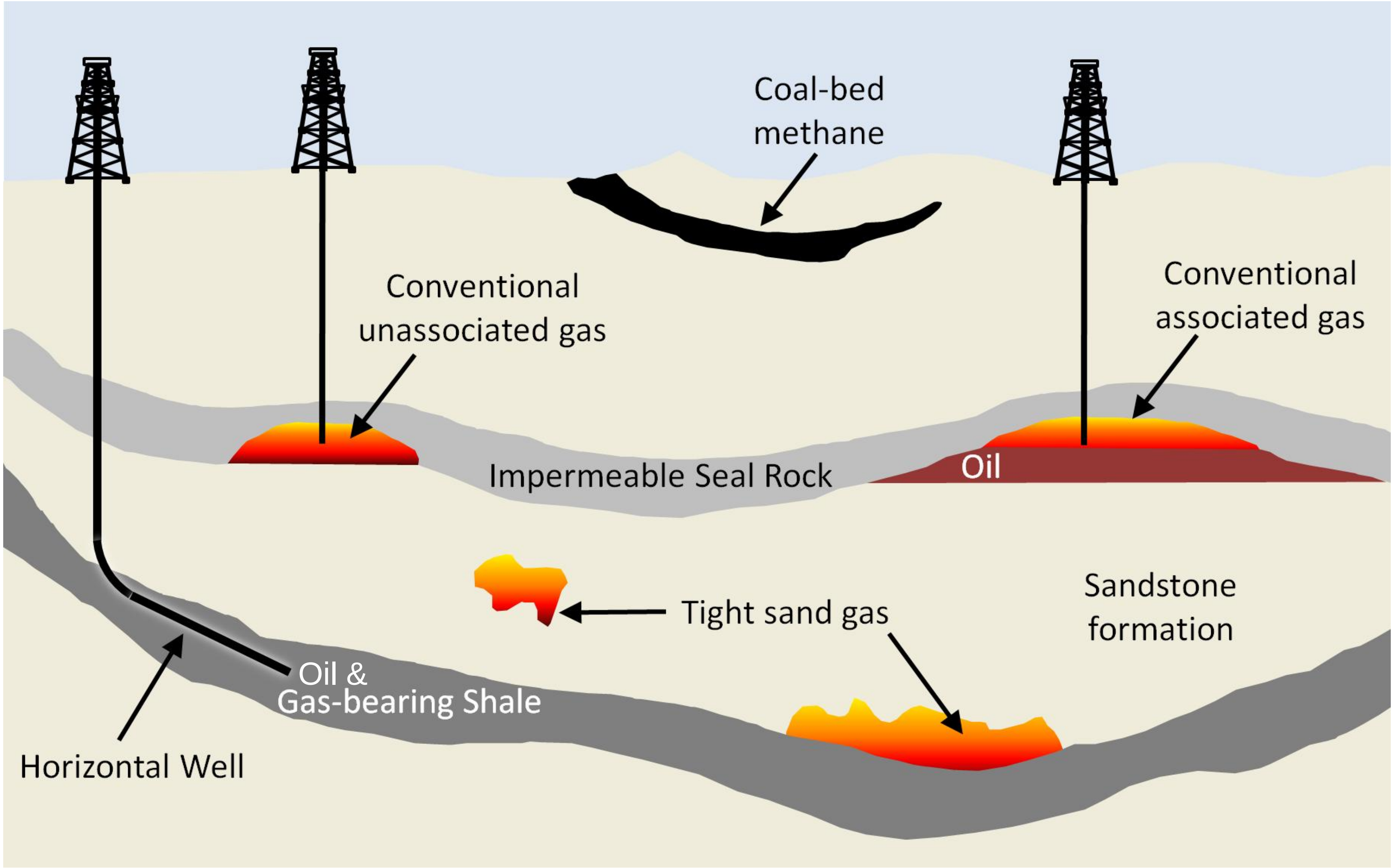
USAID
UNITED STATES AGENCY INTERNATIONAL DEVELOPMENT
FROM THE AMERICAN PEOPLE

Prof. Kelvin B. Gregory

Carnegie Mellon

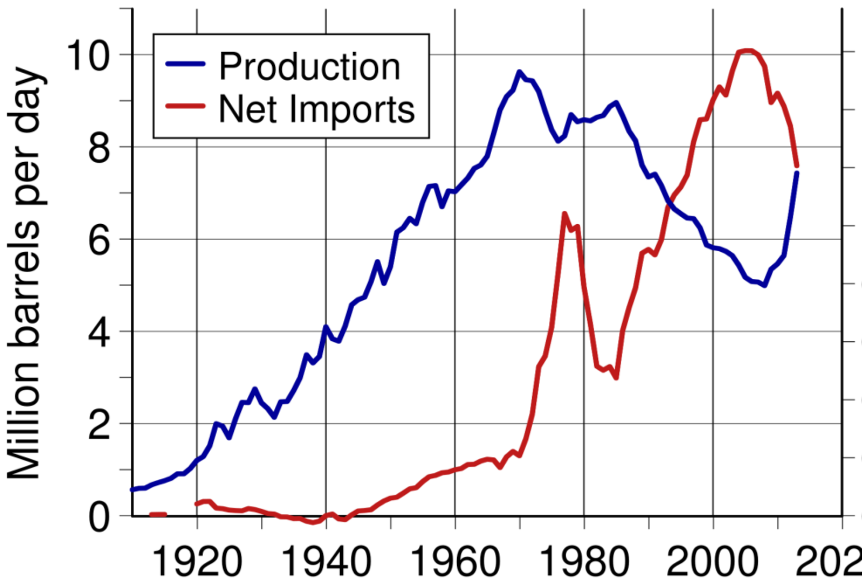
Civil and Environmental ENGINEERING

Unconventional Resources

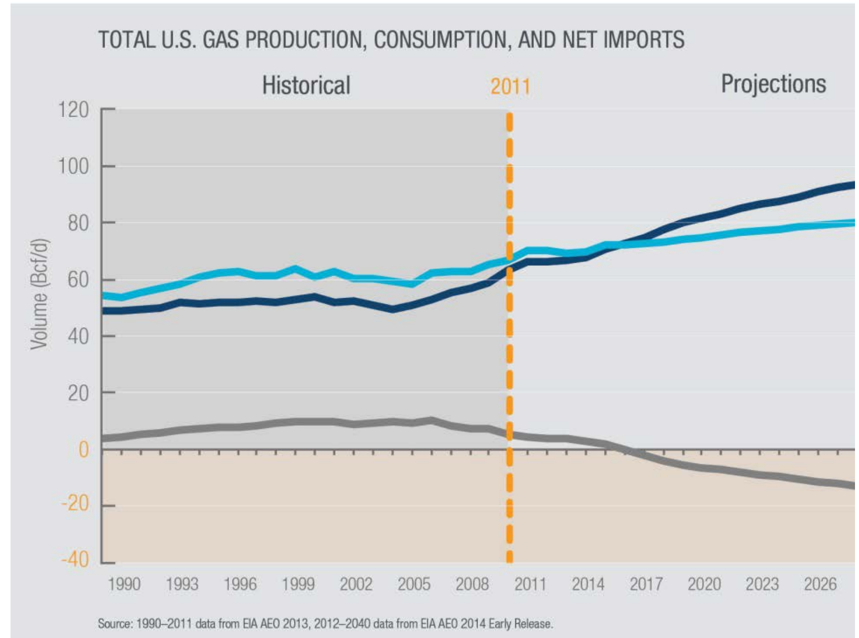


“Game Changer”

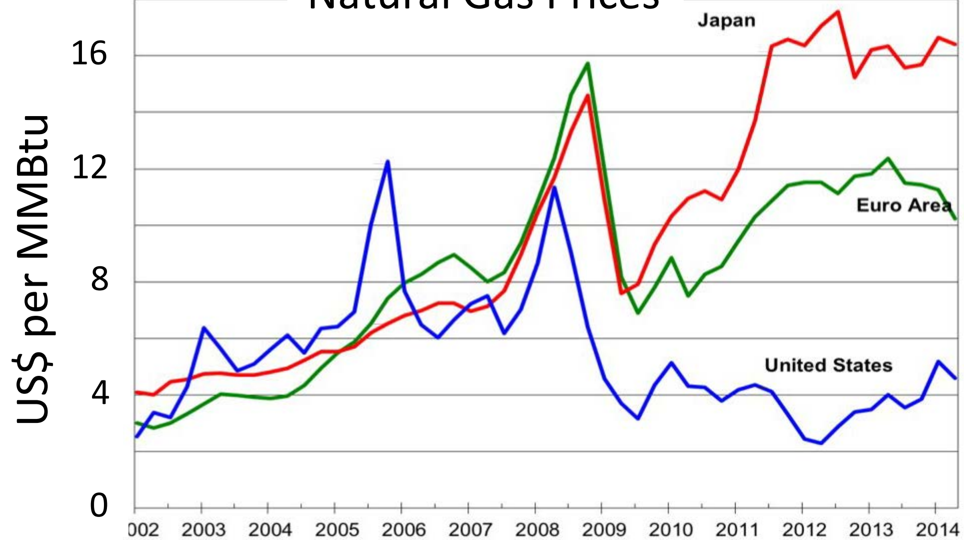
US Crude Oil Production & Imports



US Natural Gas Production & Imports



Natural Gas Prices

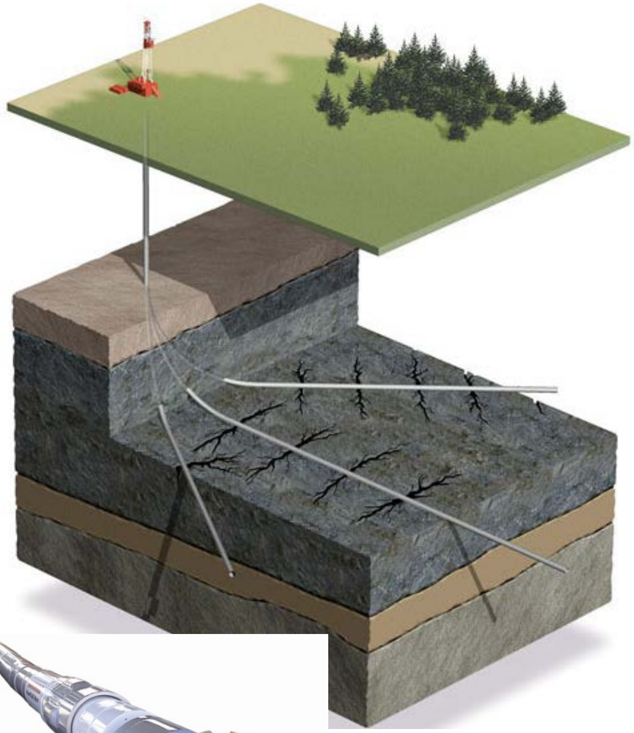


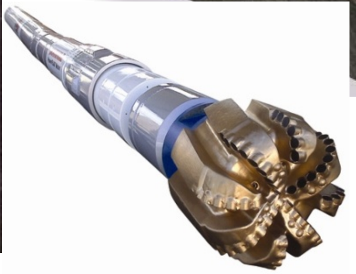
Shale Oil/Gas Plays in US

Natural Gas-bearing Shale

- Gas trapped in pores or adsorbed to surfaces in low permeability (tight) rock.
- Commercial production rates require enhanced permeability: Hydraulic Fracturing
- Economics enabled by <u>Horizontal Drilling</u>

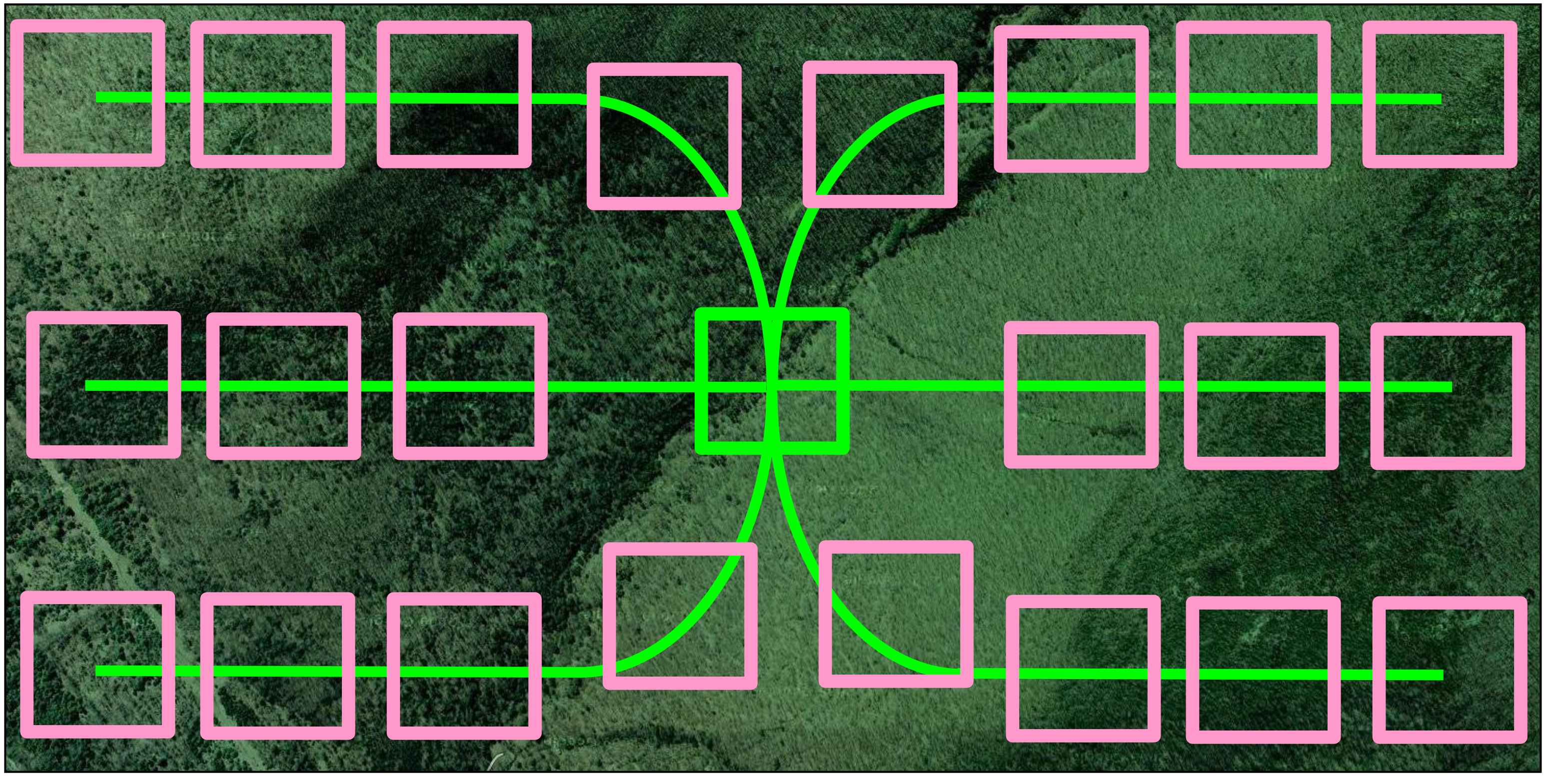
Overview of Horizontal Drilling





“Walking Rig”
Multiple wells on same pad

Economic and Environmental Advantages



Drilling	Pad Sites	Surface Disturbance	Considerations
Vertical	23	19%	Permitting, Construction, Access Roads, Other Infrastructure, Capital Costs
Horizontal	1	2%	

Evolution of Oil and Gas Development

On the banks of the Youghigheny River, Versailles, PA, 1919.
Photo Courtesy: McKeesport Historical Society. Located and Digitized by Prof. Joel Tarr, Carnegie Mellon University.

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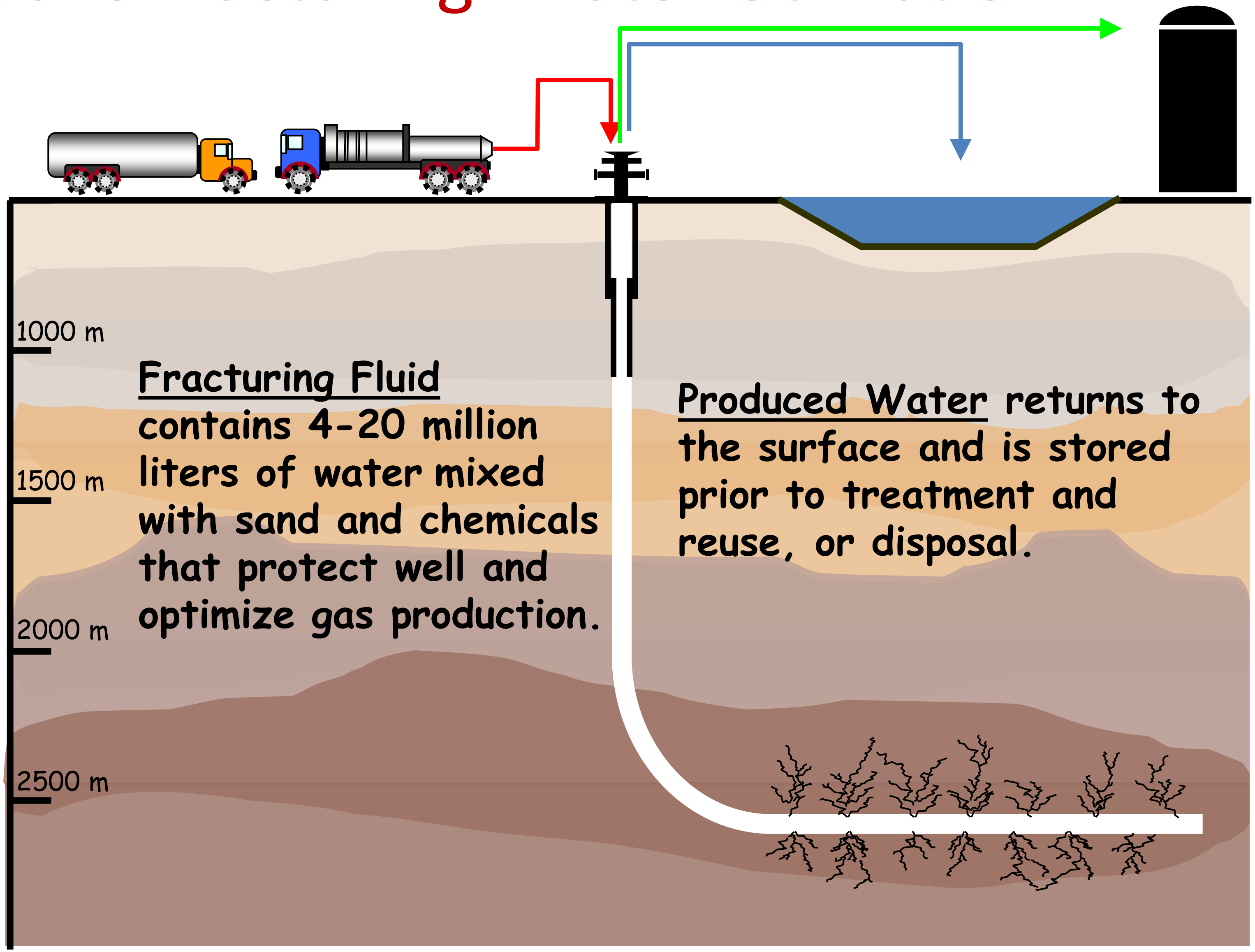
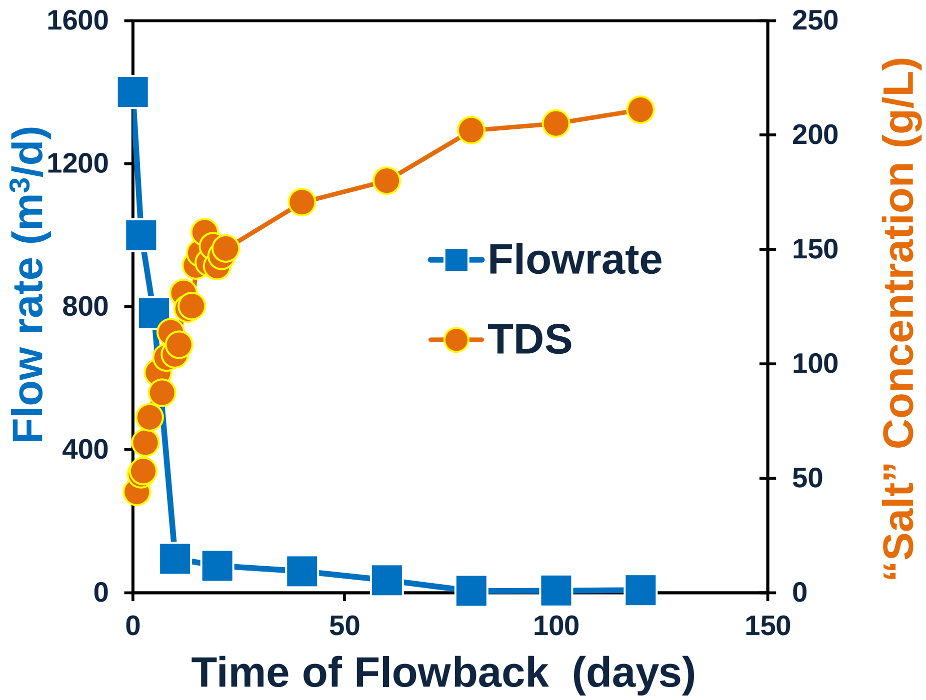
Hydraulic Fracturing: Water Utilization



Flowback/Produced Water Characteristics



	maximum	average
TDS (mg/L)	345,000	106,390
oil and grease (mg/L)	802	74
TOC (mg/L)	1530	160
SO_4(mg/L)	763	71
Cl (mg/L)	196,000	57,447
Na (mg/L)	117,000	24,123
Ca (mg/L)	41,000	7,220
Ba (mg/L)	13,800	2,224
Sr (mg/L)	8,460	1,695
Fe total (mg/L)	321	76
Ra^{226} (pCi/L)	9,280	623
U^{238}(pCi/L)	497	42

Gregory et al, *Elements* (2011); Barbot et al, *Environ Sci Technol* (2013)

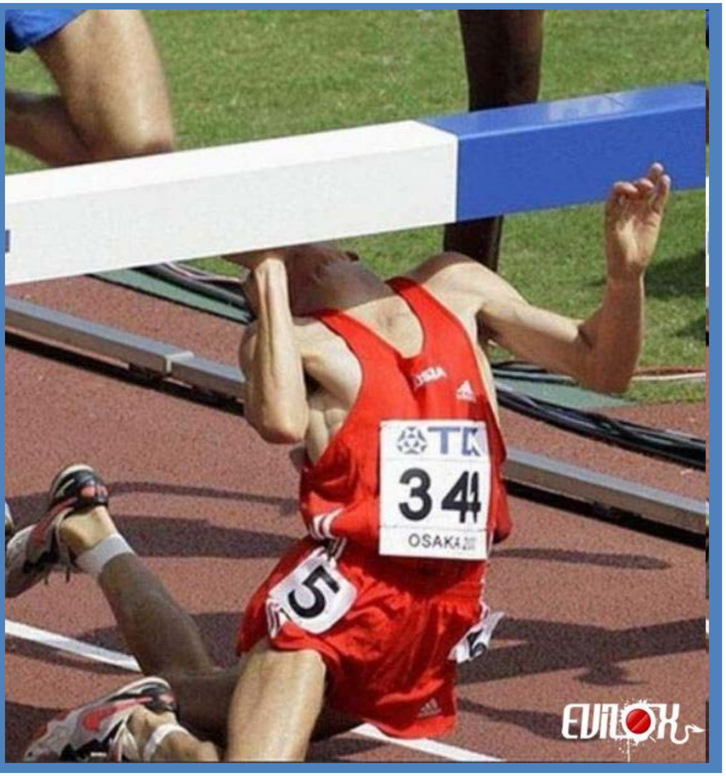
Produced Water Management Hurdles

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



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Local Challenges → Innovation & Local Solutions

Reuse of Produced Water for Hydraulic Fracturing

Hydraulic Fracturing
with Recycled PW

Produced Water to
Impoundment

Dilute to Make-up
volume; add Chems

Low-Quality Water as Make-up and Dilution
(Wastewater, Seawater)

Pretreatment
Remove Solids and M^{2+}.

Centralized Impoundments, Long Storage

Impoundment for Single Well Pad

Centralized Impoundments for Multiple Well Pads

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

Organics ↔ CO_2

Fermentation → Malodorous Compounds

SO_4^{2-} ↔ S^0 ↔ **H_2S**

Solubility of Metals

$Fe^{3+}_{(s)}$ ↔ $Fe^{2+}_{(aq)}$

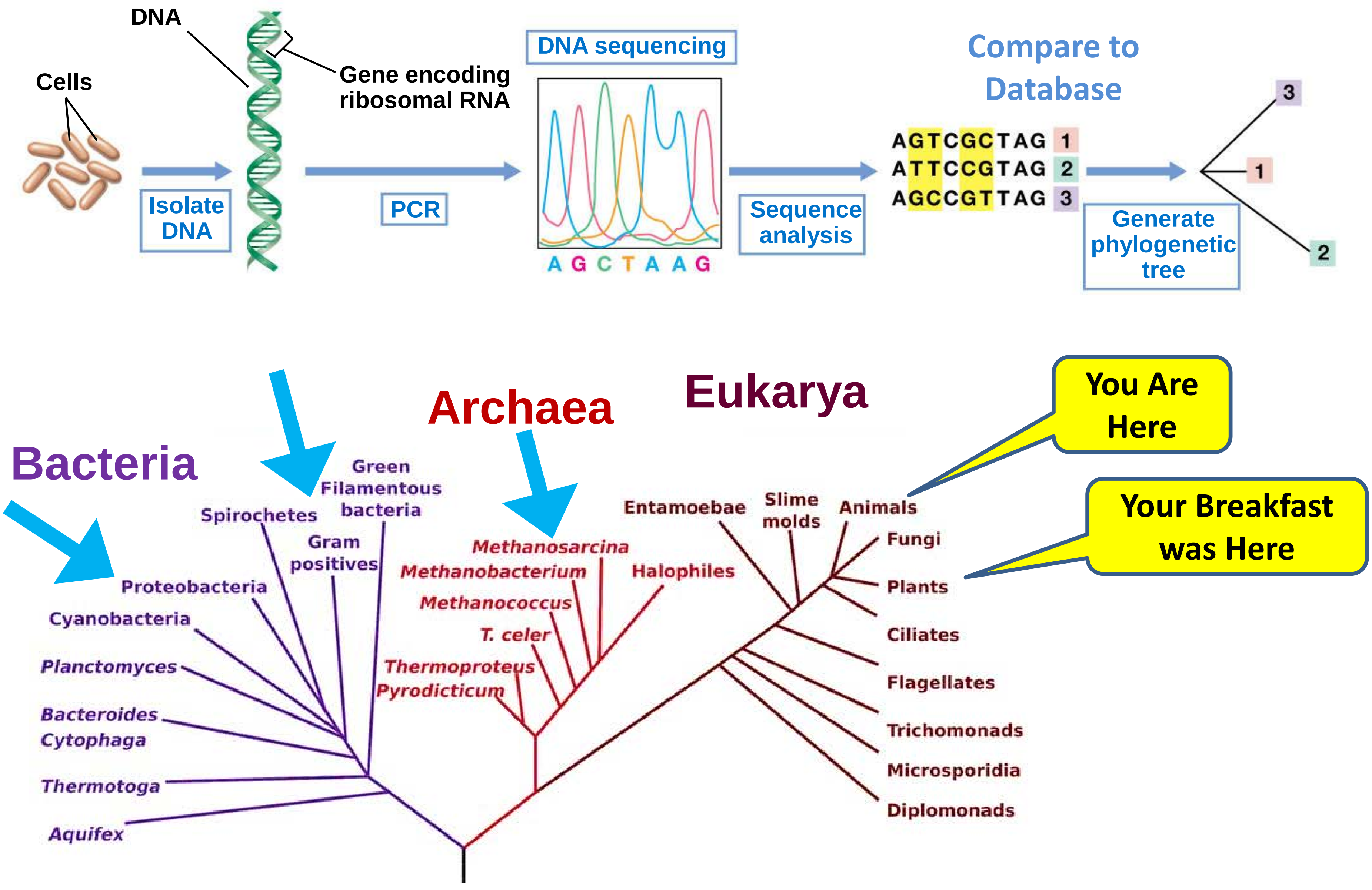
$U^{6+}_{(aq)}$ ↔ $U^{4+}_{(s)}$

Biocorrosion

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

Approach: Next Generation Sequencing for High-resolution Insights

Generating Metrics for Ecological Comparisons



Wellheads

Dynamic Populations in Wellhead Samples

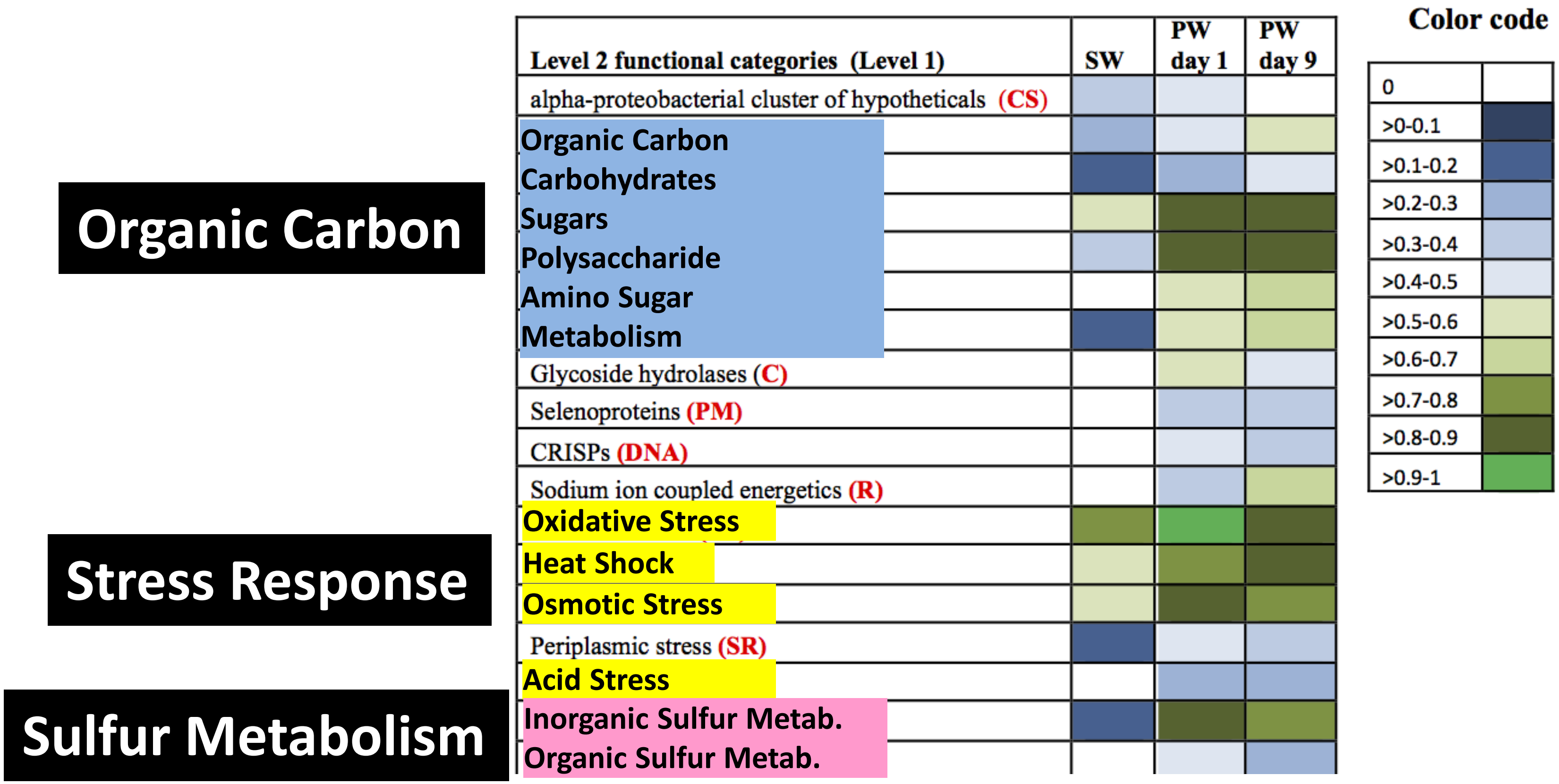
Order (Class)	Sample name					
	SW	FF	FB1	FB7	FB9	PW
Rhodobacterales (Alphaproteobacteria)	>10-20%	>20-30%	>20-30%	>0 - 5%	>0 - 5%	0%
Sphingomonadales (Alphaproteobacteria)	>0 - 5%	>0 - 5%	>0 - 5%	>0 - 5%	>0 - 5%	0%
Caulobacterales (Alphaproteobacteria)	>10-20%	>5-10%	>0 - 5%	0%	0%	0%
Rhodospirillales (Alphaproteobacteria)	>5-10%	>0 - 5%	>0 - 5%	0%	0%	0%
Pseudomonadales (Gammaproteobacteria)	>20-30%	>30-50%	>10-20%	>0 - 5%	>0 - 5%	>0 - 5%
Vibrionales (Gammaproteobacteria)	>0 - 5%	>0 - 5%	>0 - 5%	>10-20%	>20-30%	0%
Alteromonadales (Gammaproteobacteria)	>0 - 5%	>0 - 5%	>5-10%	>5-10%	>10-20%	0%
Chromatiales (Gammaproteobacteria)	>5-10%	>0 - 5%	>0 - 5%	>0 - 5%	0%	0%
Campylobacterales (Epsilonproteobacteria)	>0 - 5%	>0 - 5%	>5-10%	>10-20%	>10-20%	0%
Burkholderiales (Betaproteobacteria)	>0 - 5%	>0 - 5%	>0 - 5%	>0 - 5%	>0 - 5%	0%
Thermoanaerobacterales (Clostridia)	0%	0%	>5-10%	0%	0%	0%
Halanaerobiales (Clostridia)	>0 - 5%	>0 - 5%	>0 - 5%	>5-10%	>10-20%	>99%
Clostridiales (Clostridia)	>0 - 5%	>0 - 5%	>0 - 5%	>5-10%	>0 - 5%	0%
Bacteroidales (Bacteroidetes)	>0 - 5%	>0 - 5%	>5-10%	>20-30%	>10-20%	0%
Flavobacteriales (Flavobacteria)	>0 - 5%	>0 - 5%	>10-20%	>0 - 5%	>0 - 5%	>0 - 5%
Fusobacteriales (Fusobacteria)	>0 - 5%	>0 - 5%	>0 - 5%	>5-10%	>5-10%	0%
Bacillales (Bacilli)	0%	>0 - 5%	>0 - 5%	>5-10%	>0 - 5%	0%
Lactobacillales (Bacilli)	>0 - 5%	>0 - 5%	>0 - 5%	>0 - 5%	>0 - 5%	>0 - 5%

0%	
>0 - 5%	
>5-10%	
>10-20%	
>20-30%	
>30-50%	
>99%	

- 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

Murali Mohan et al, Environ Sci Technol (2013)

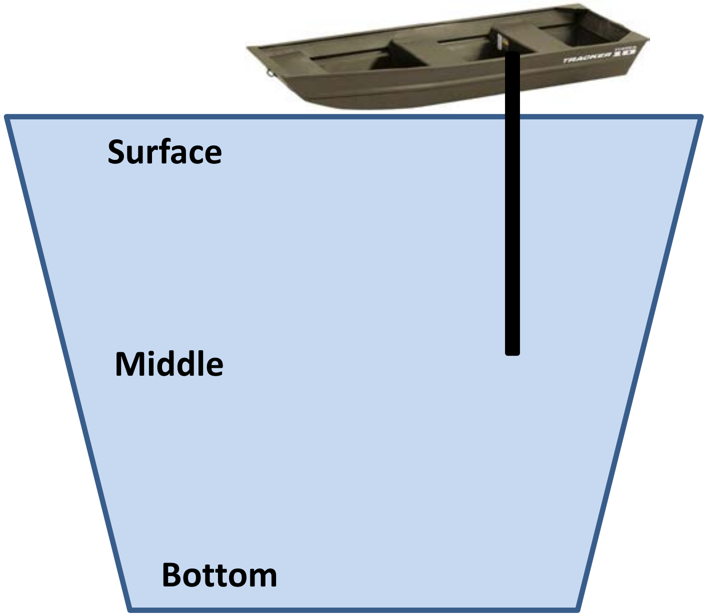
Functional Metagenome Reveals How Capabilities of Community is Changing



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

Impoundments

Impoundments and Sampling



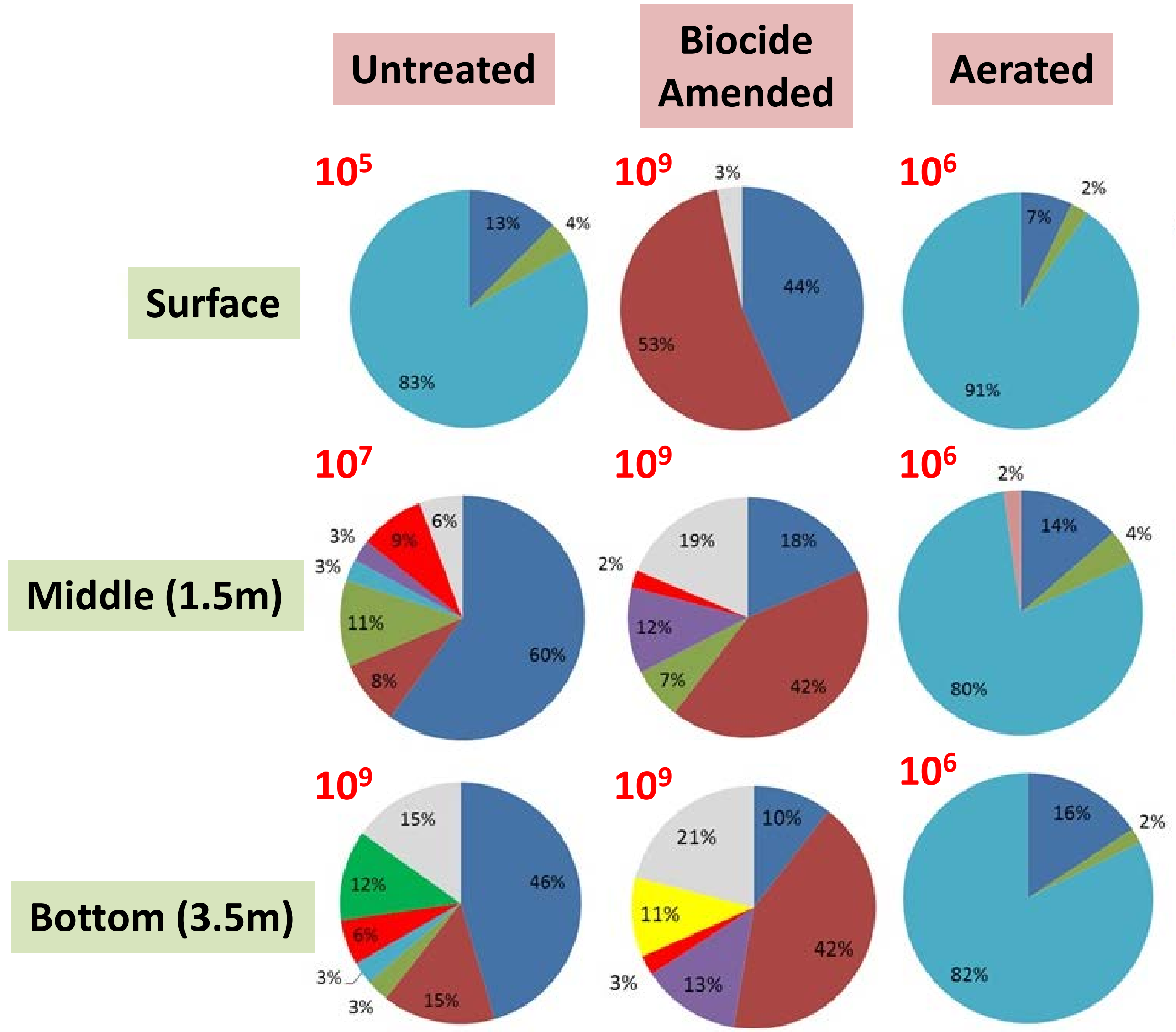
Geochemical Characteristics/Stratification

Chemical Constituents of Water Samples (mg/L)

	Untreated			Biocide Amended			Aerated		
Analyte	SUF	MID	BOT	SUF	MID	BOT	SUF	MID	BOT
Ba^{2+}	277	339	418	63	175	228	10	9.5	9.5
Ca^{2+}	6150	8818	8679	7526	10790	8167	5780	5733	5253
Total Fe	0.3	4.4	64.9	21.6	14.9	14.2	0.1	0.1	0.1
K^{+}	190	224	261	351	410	420	161	188	201
Na^{+}	14250	20910	20410	19930	26500	17590	12810	12940	11120
Sr^{2+}	894	1296	1256	1058	1493	1082	800	803	707
Cl^{-}	35100	51000	50900	43500	55400	56800	32300	32100	32500
Br^{-}	371	552	549	461	597	615	345	344	346
I^{-}	5.6	9.8	10.3	7.2	9.1	9.3	4.4	4.4	4.4
NO_3^{-}	ND[b]	ND	ND	ND	ND	ND	ND	ND	ND
SO_4^{2-}	15.1	25.7	16.5	43.7	49.9	37.3	234	234	236
Acetate	ND	32.6	75.9	39.4	46.5	62	ND	ND	ND

Murali Mohan et al, *Microb Ecol* (2013)

Bacterial Communities in Impoundments



Phototrophs
Aerobic Metab.

Fermentative
Sulfur-utilizing
Spore-forming

Facultative, Aerobic
Anaerobic

Not sufficiently
similar to known
Bacteria

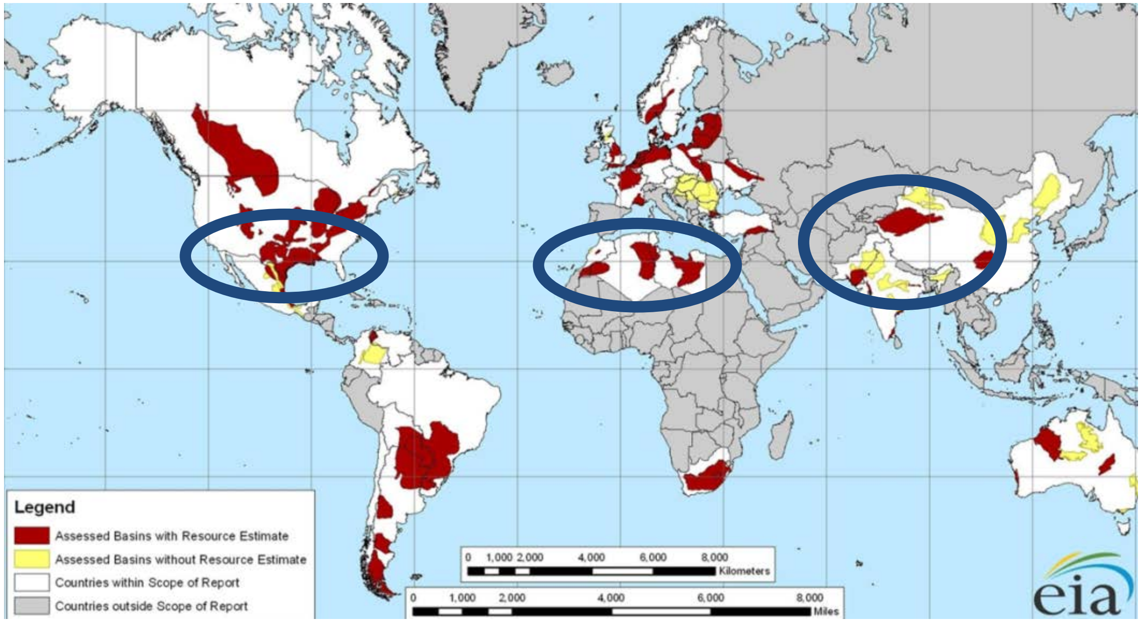
Methane-producing
Archaea at bottom
of untreated and
biocide only

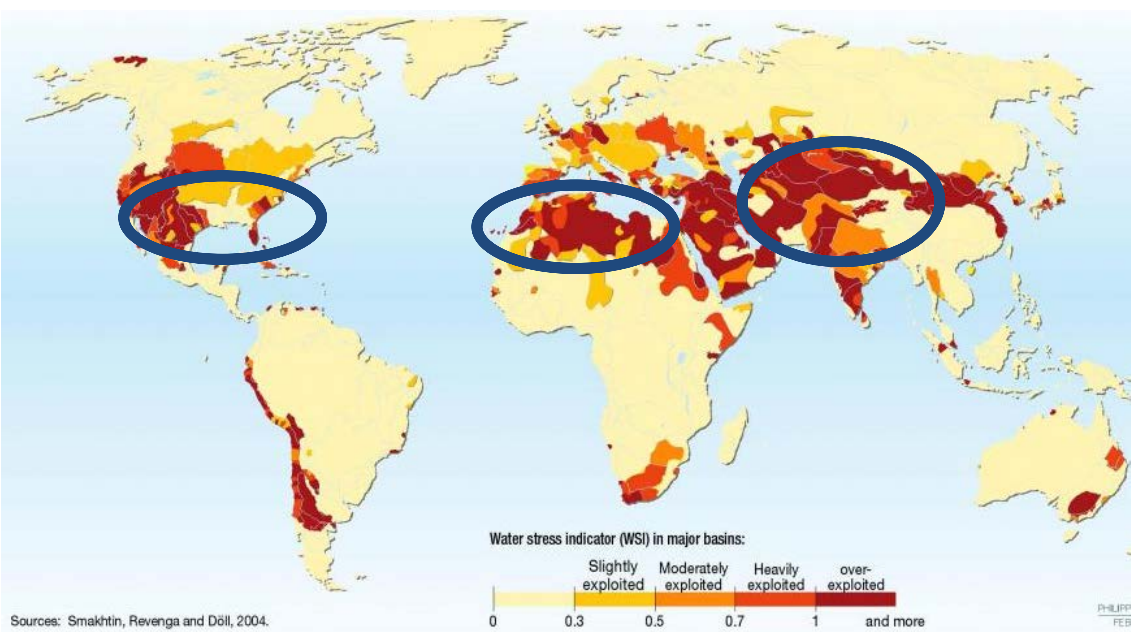
Murali Mohan et al, *Microb Ecol* (2013)

Messages 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 with deleterious metabolisms into the next frac
- Recycling may lead to accelerated onset of well souring

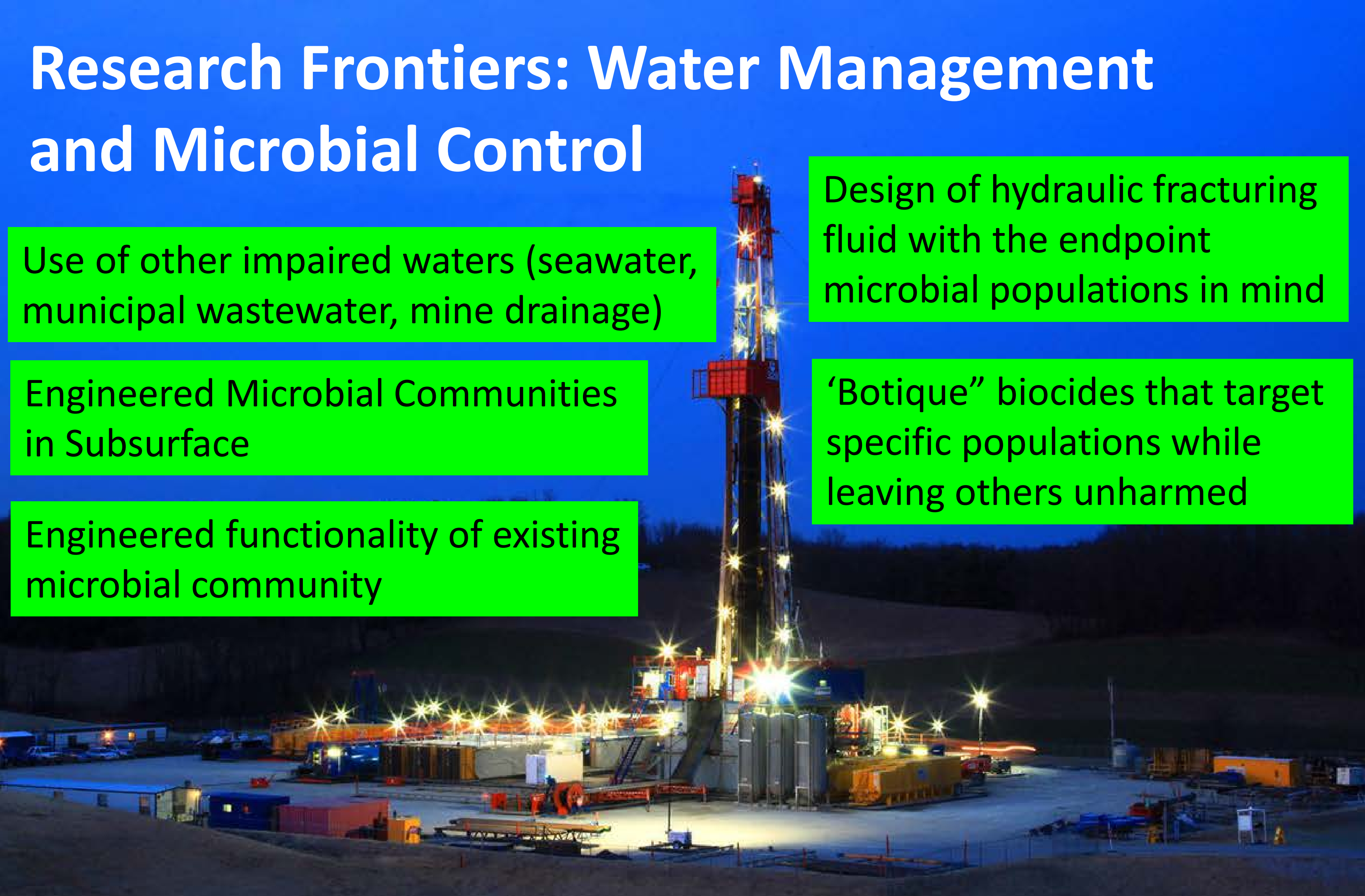
Thoughts on Shale Resources & Water Stress





- Water management challenges are local
- Development competes with municipal, industrial, agricultural, and environmental water resource needs.
- Recycling of produced water and use of low-quality water will enable a sustainable oil/gas development in water stressed regions

Research Frontiers: Water Management and Microbial Control



Use of other impaired waters (seawater, municipal wastewater, mine drainage)

Engineered Microbial Communities in Subsurface

Engineered functionality of existing microbial community

Design of hydraulic fracturing fluid with the endpoint microbial populations in mind

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