Increasing the Rate and Extent of Microbial Coal to Methane Conversion through Optimization of Microbial Activity, Thermodynamics, and Reactive Transport

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Presentation Outline

- **Project Concept and Background**
- Project objectives
- Project team roles and responsibilities
- Tasks/subtasks
- Key milestones
- Success criteria at key decision points
- Deliverables

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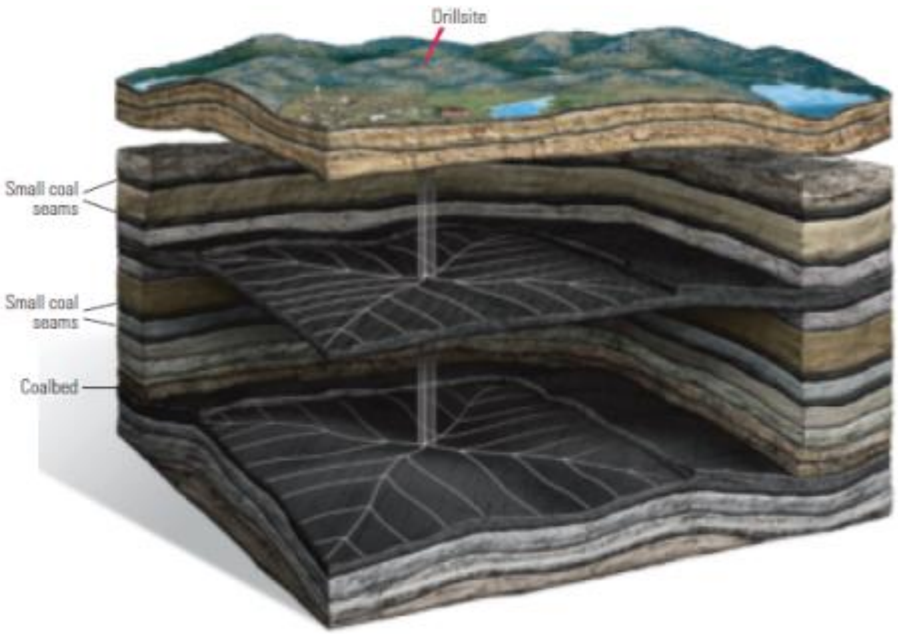
Coal Bed Methane (Natural Gas)

- America has more coal than any other fossil fuel resource. The United States also has more coal reserves than any other single country in the world. In fact, just over 1/4 of all the known coal in the world is in the United States. The United States has more coal than the rest of the world has oil that can be pumped from the ground.



- Methane can be formed through the biotransformation of organic matter (including coal and oil) by bacteria and methane producing microorganisms (*Methanogens*).

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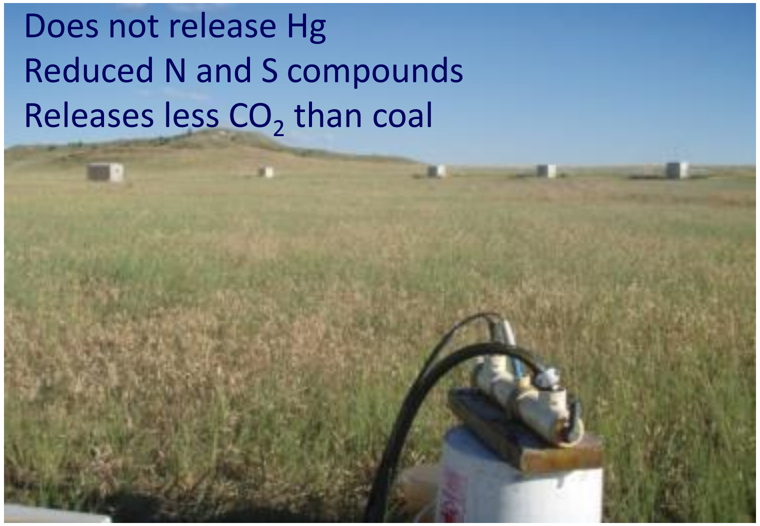
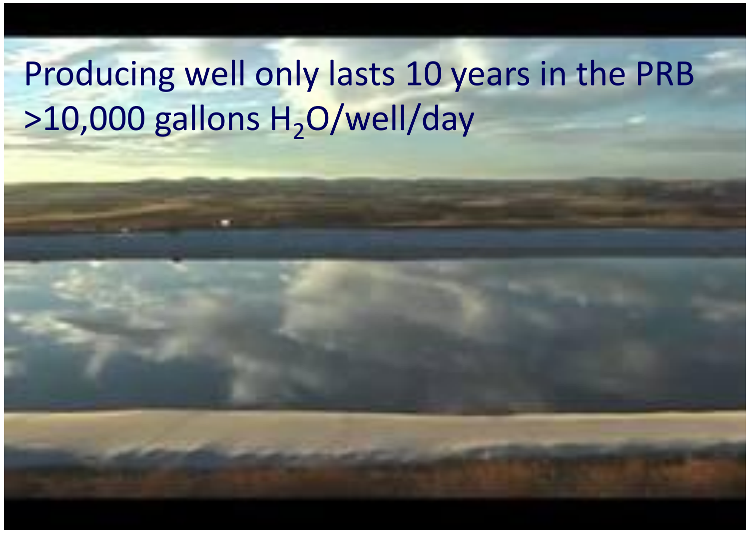
Coal or CBM



Does not release Hg
Reduced N and S compounds
Releases less CO_2 than coal



Producing well only lasts 10 years in the PRB
>10,000 gallons H_2O/well/day

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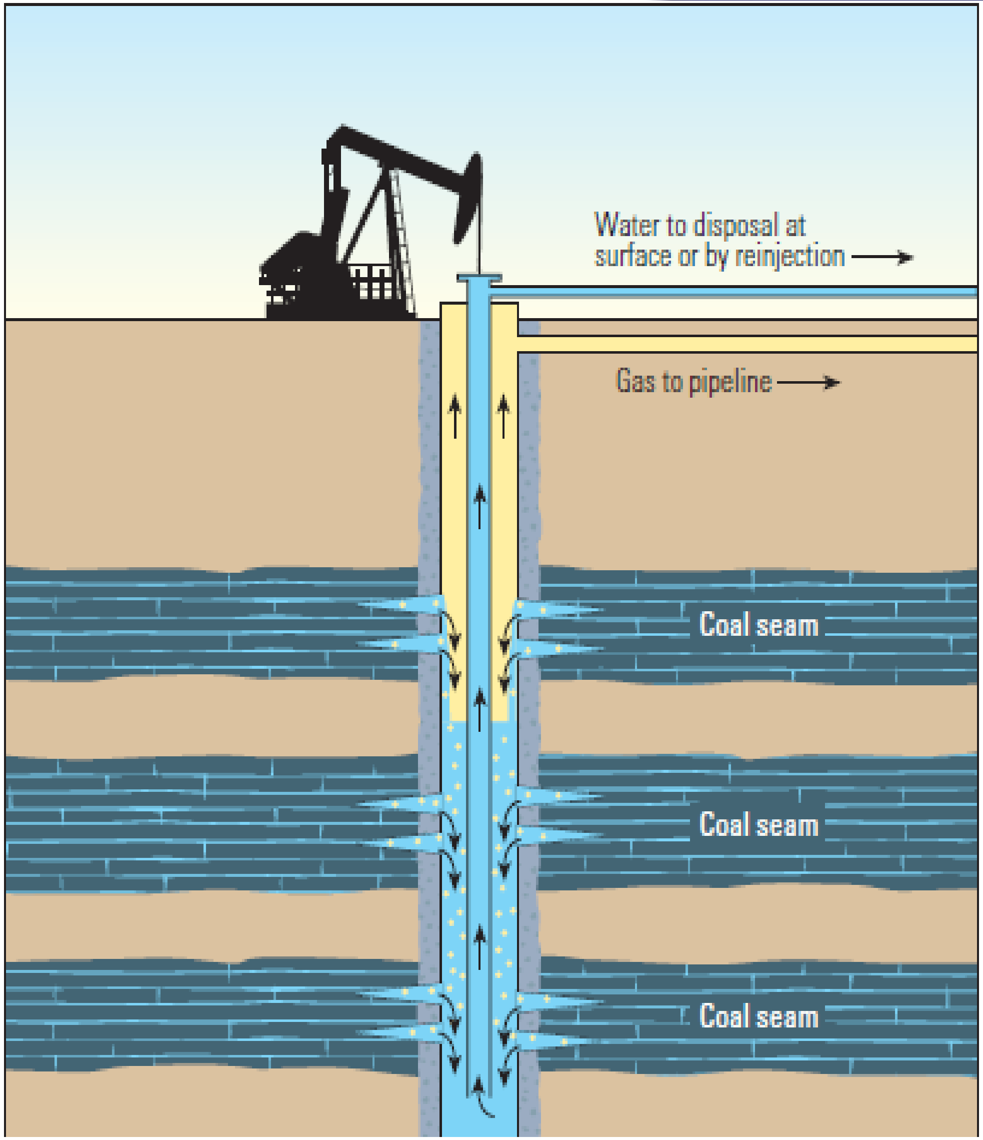
Overall Goal: *Sustainable, Low-Impact, Coal Bed CH_4

- Once initial methane production is completed the opportunity exists to enhance production of <u>additional</u> methane by stimulating indigenous microbial populations.

- Research aimed at developing <u>sustainable</u> microbial methane production from coal beds.
  - -Microbial Activity
  - -Thermodynamics
  - -Reactive Transport



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MSU CBM Project History

- National Science Foundation, Cold Geobiology, Collaborative Research: Hydrodynamic controls on microbial community dynamics and carbon cycling in coalbeds (PI: J. McIntosh, University of Arizona; co-PIs: M.W. Fields, A.B. Cunningham, MSU)
- Montana Board of Research and Commercialization Technology, Sustainable Coal Bed Methane (CBM) and Biofuel Production (MSU and Montana Emergent Technologies)
- On-going collaborations with U.S. Geological Survey (W. Orem, Reston, VA; A. Clark, Denver, CO)

Approach: Multi-disciplinary work that combines microbiology, ecology, engineering, geochemistry, and hydrology to determine constraints on in situ CBM

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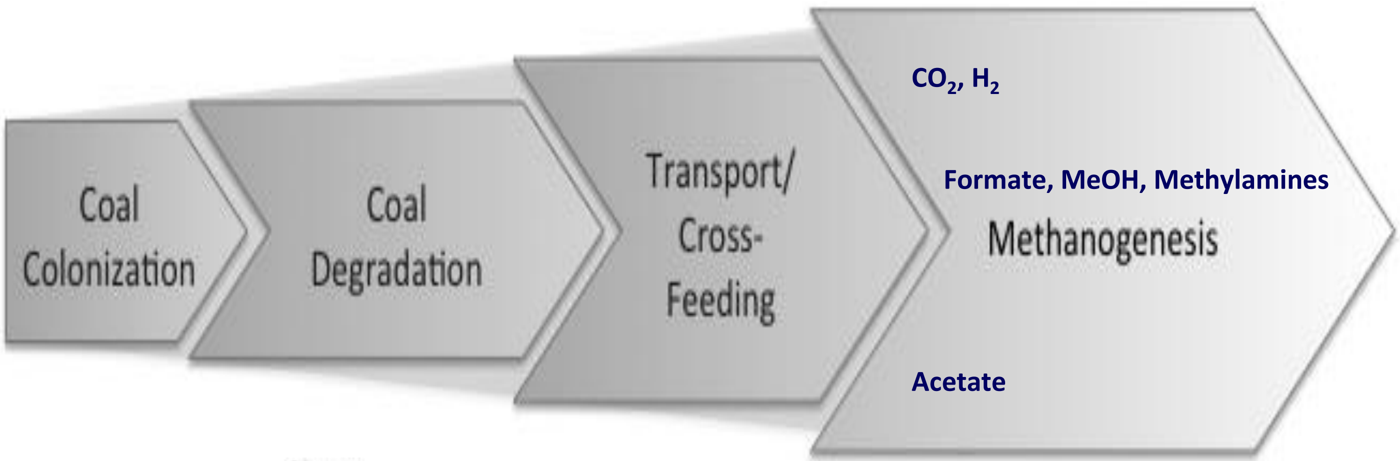
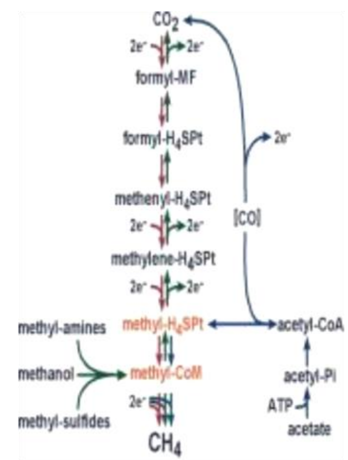
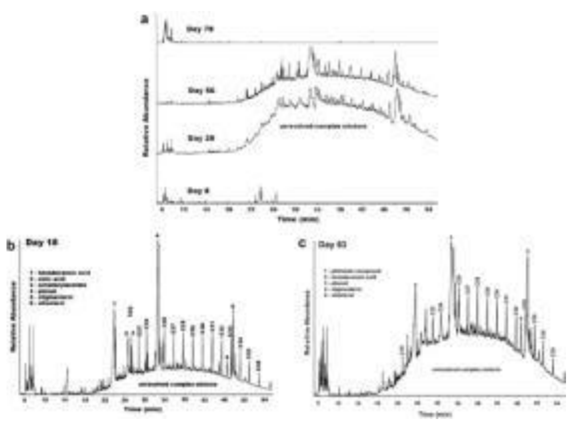
Coal→ Natural Gas (CH_4)

<u>Activity</u>: Coal-dependent growth & conversion
<u>Thermodynamics</u>: Conditions that promote growth & conversion
<u>Reactive Transport</u>: Movement of Nutrients/Organisms/Cross-Feeding







Orem, W. et al., 2010. *Organic Geochem.*

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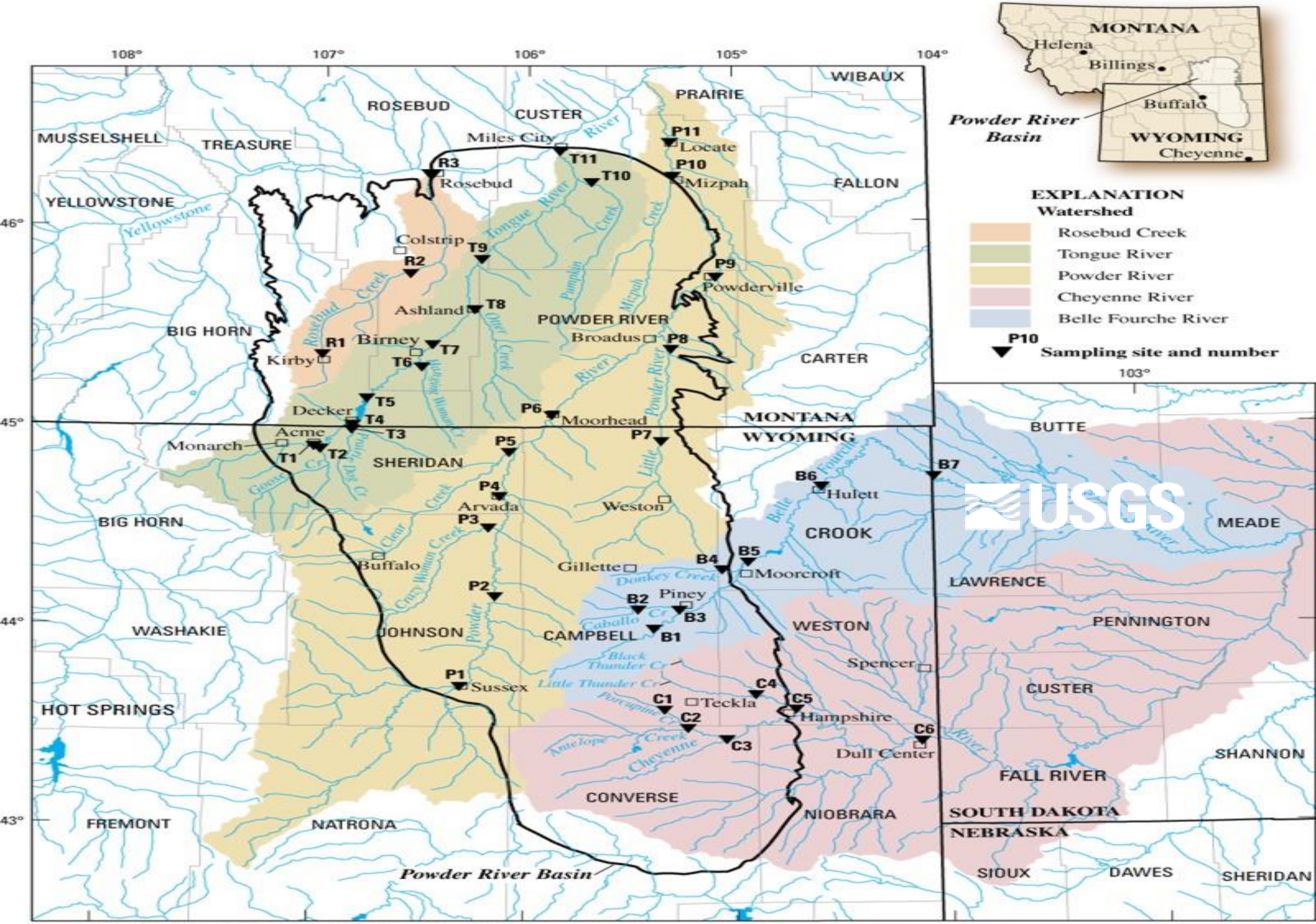
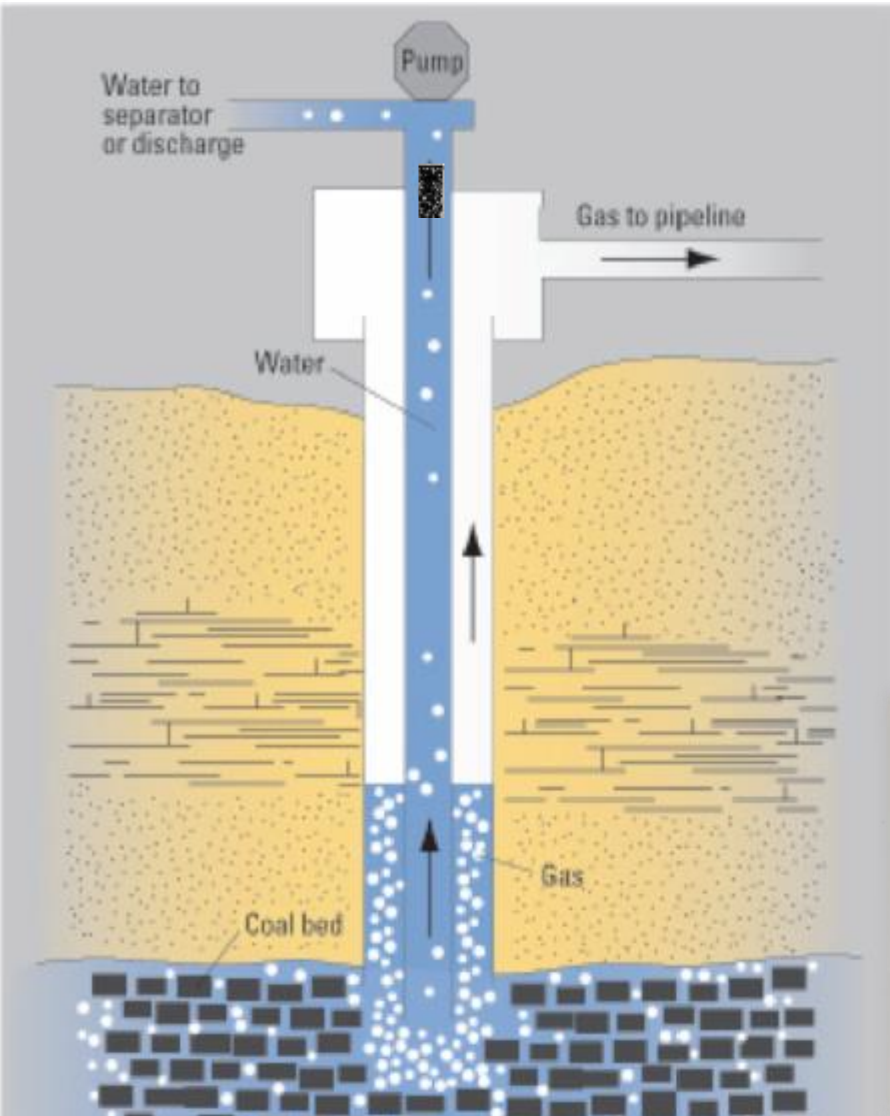
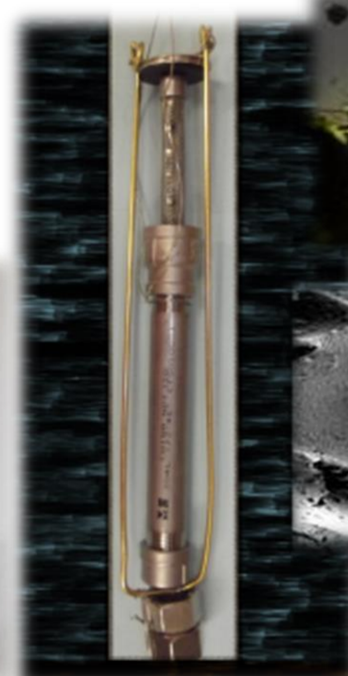


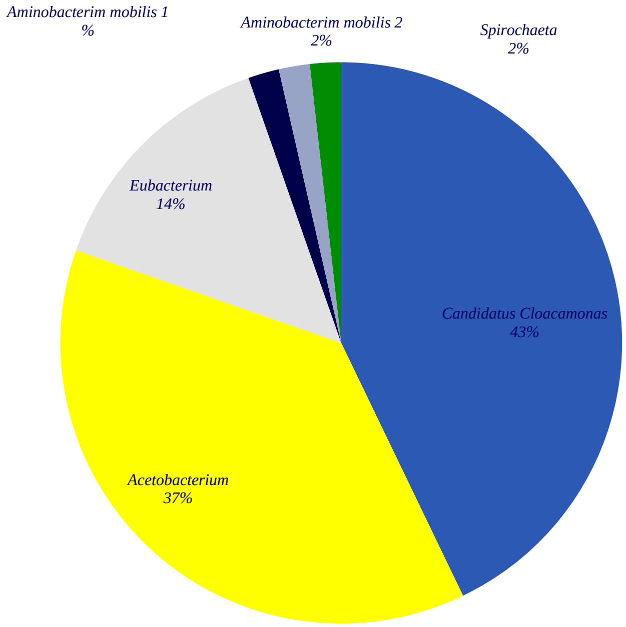
Base modified from Digital Chart of the World digital data, 2003
Drainage basins modified from USGS Hydrologic Unit Boundaries, 1999
Albers Equal-Area projection, standard parallels 20° and 60°, central meridian -105°30′

Sampling: Water vs. Coal Matrix



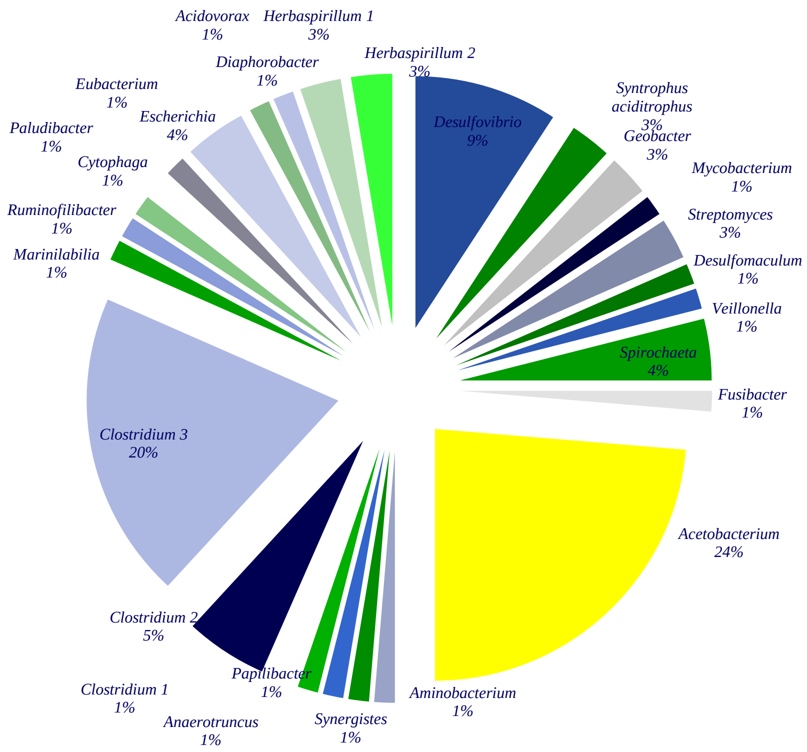


Bacterial Enrichments – With and Without Coal



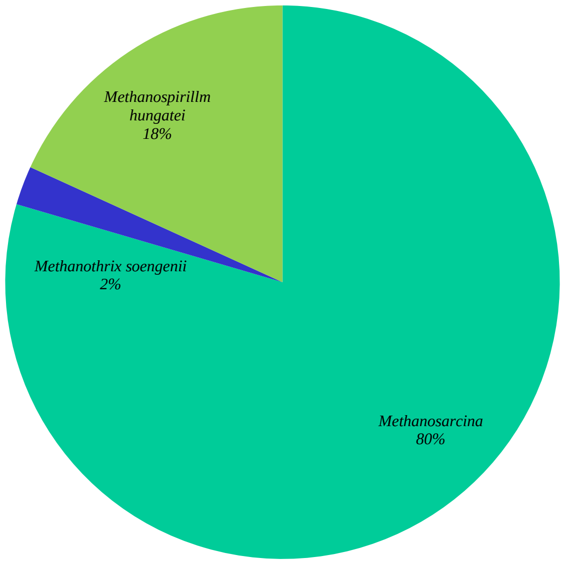
Bacterial 16S
No coal

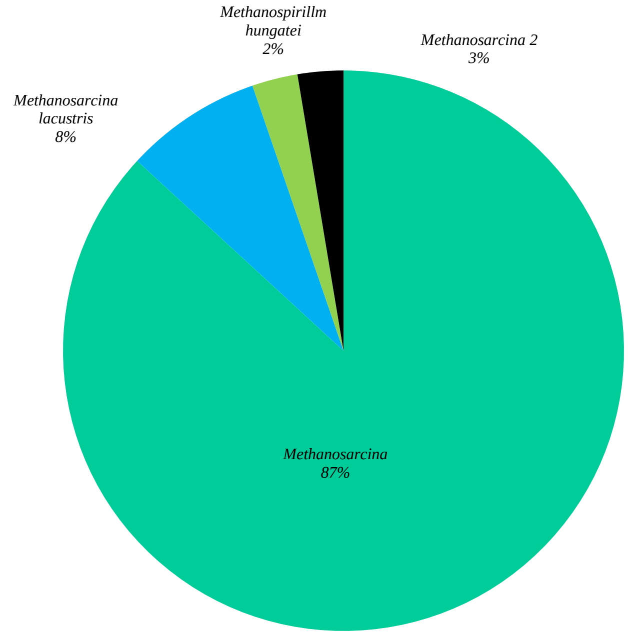
Bacterial 16S
Coal



Archaeal Enrichments – With Coal

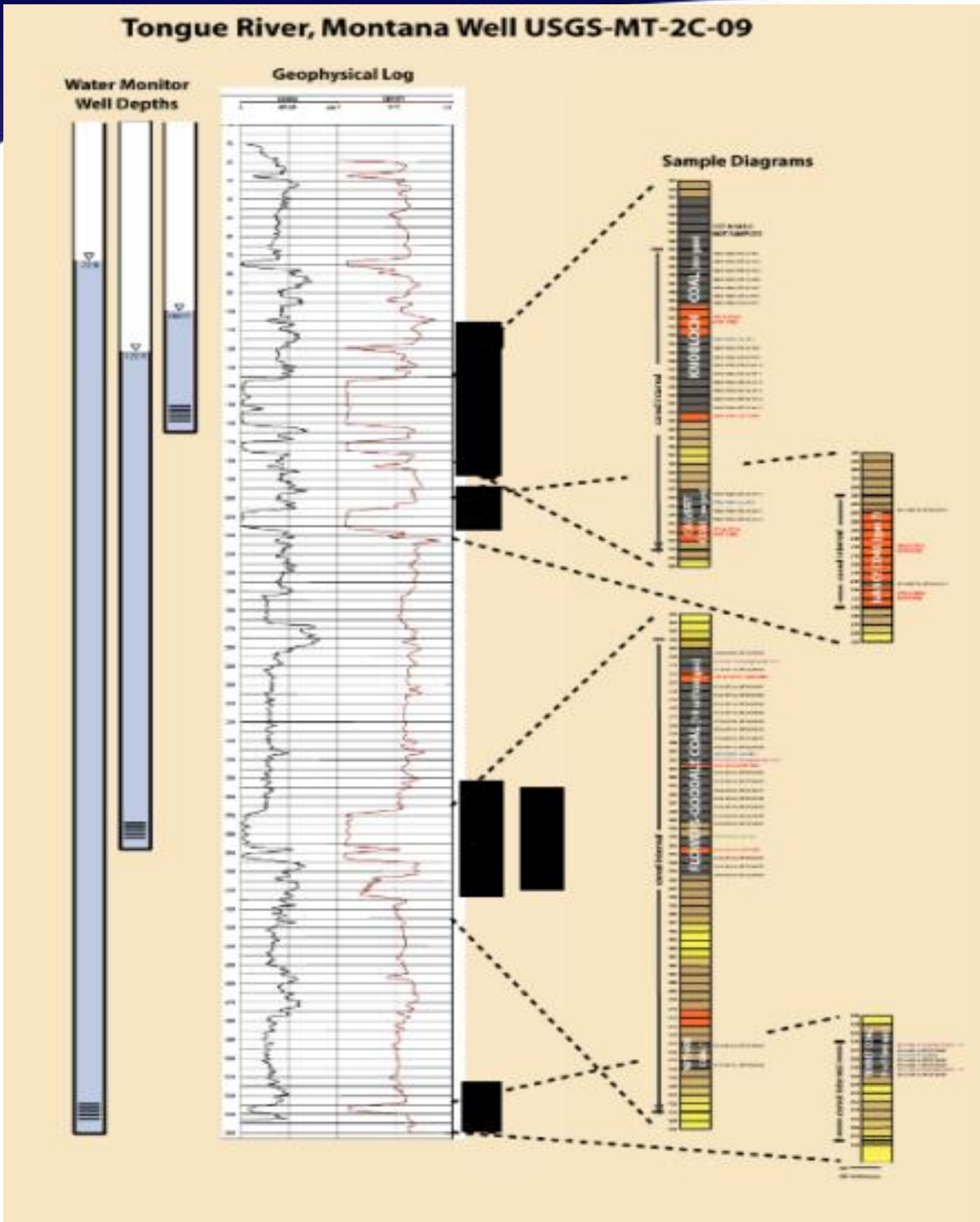
Archaeal 16S





Archaeal *mcr*A

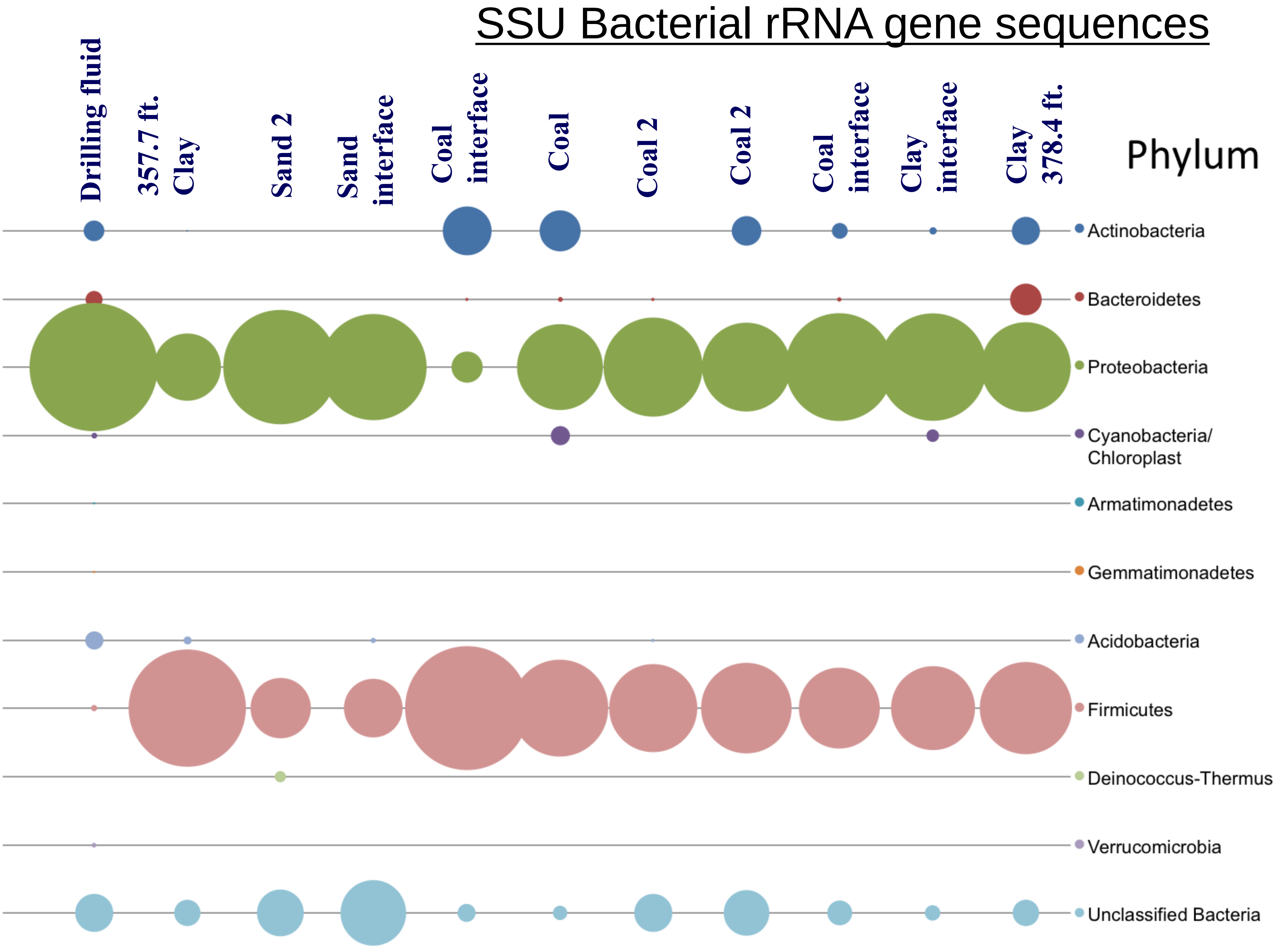
Native Microbial Community of Coal



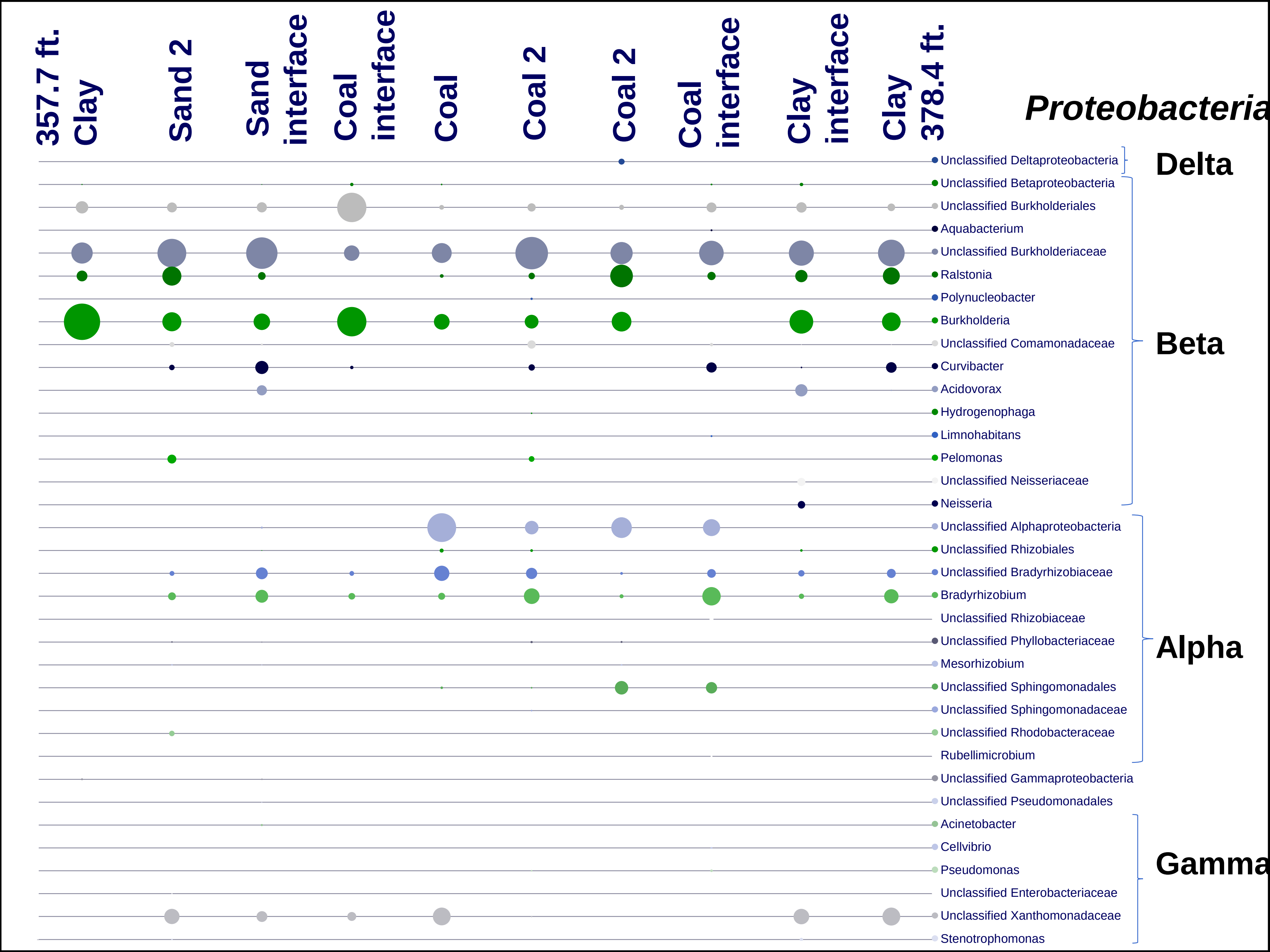
Flowers-Goodale cores

11 samples analyzed to date

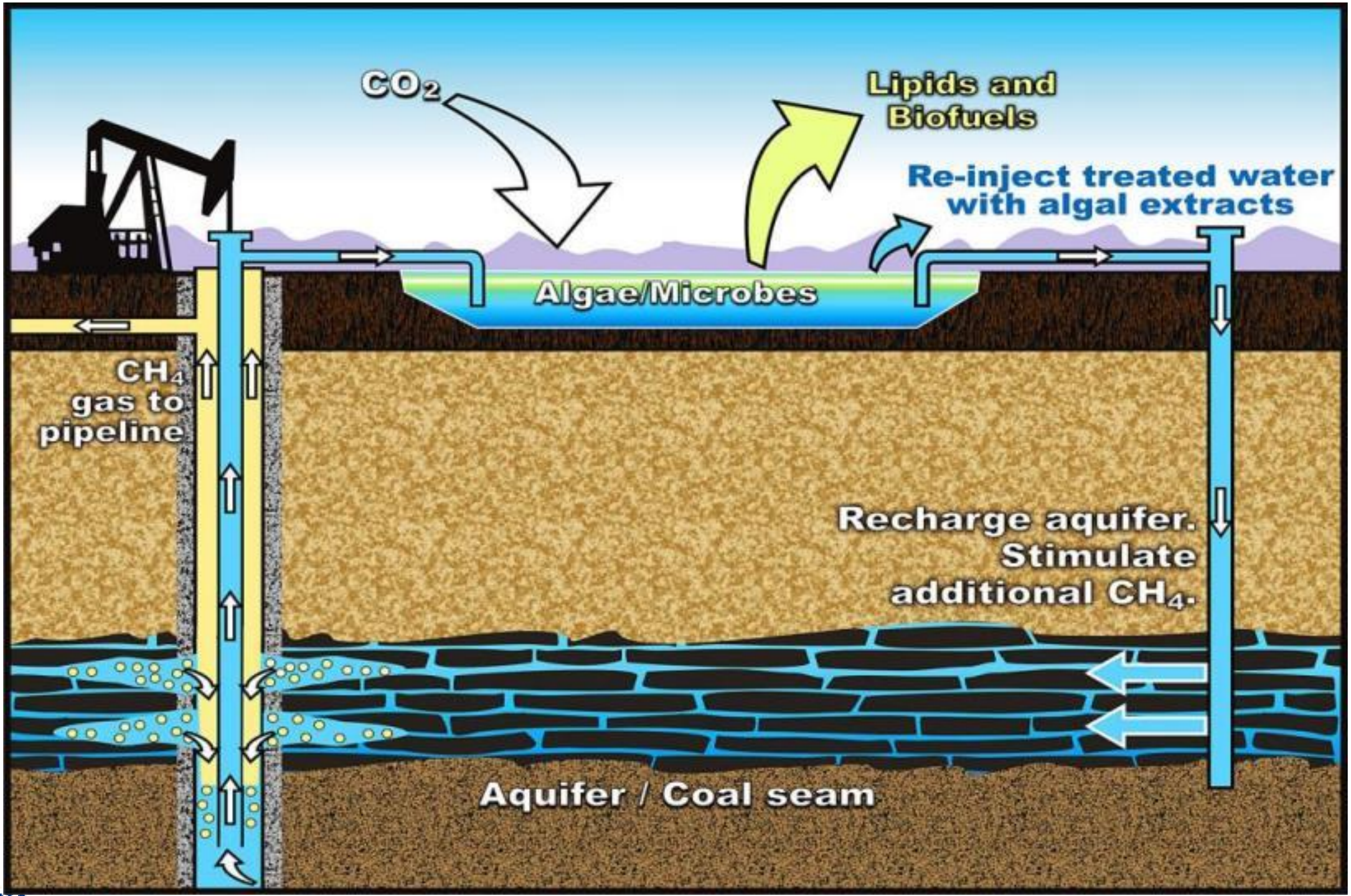
- 3 above coal seam
- 5 within coal seam
- 2 below coal seam
- Drilling fluid



SSU Bacterial rRNA gene sequences
Drilling fluid
357.7 ft. Clay
Sand 2
Sand interface
Coal interface
Coal
Coal 2
Coal 2
Coal interface
Clay interface
Clay 378.4 ft.
Phylum
Actinobacteria
Bacteroidetes
Proteobacteria
Cyanobacteria/ Chloroplast
Armatimonadetes
Gemmatimonadetes
Acidobacteria
Firmicutes
Deinococcus-Thermus
Verrucomicrobia
Unclassified Bacteria


357.7 ft.
Clay
Sand 2
Sand
interface
Coal
interface
Coal
Coal 2
Coal 2
Coal
interface
Clay
interface
Clay
378.4 ft.
Proteobacteria
Unclassified Deltaproteobacteria
Delta
Unclassified Betaproteobacteria
Unclassified Burkholderiales
Aquabacterium
Unclassified Burkholderiaceae
Ralstonia
Polynucleobacter
Burkholderia
Unclassified Comamonadaceae
Curvibacter
Acidovorax
Hydrogenophaga
Limnohabitans
Pelomonas
Unclassified Neisseriaceae
Neisseria
Beta
Unclassified Alphaproteobacteria
Unclassified Rhizobiales
Unclassified Bradyrhizobiaceae
Bradyrhizobium
Unclassified Rhizobiaceae
Unclassified Phyllobacteriaceae
Mesorhizobium
Unclassified Sphingomonadales
Unclassified Sphingomonadaceae
Unclassified Rhodobacteraceae
Rubellimicrobium
Alpha
Unclassified Gammaproteobacteria
Unclassified Pseudomonadales
Acinetobacter
Cellvibrio
Pseudomonas
Unclassified Enterobacteriaceae
Unclassified Xanthomonadaceae
Stenotrophomonas
Gamma

Lab to Field



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Summary of Current MSU Work

Key Findings

- Hydrogenotrophic methanogens are present under non-stimulated laboratory conditions
- Acetoclastic methanogens appear under stimulated laboratory conditions
- Yeast extract enhances CBM production from native PRB microbes when coal is also present
- Coal enriches a diverse bacterial community in the presence of coal
- Coal-dependent populations can be identified
- Increasing sulfate *in situ* corresponds to decreasing archaeal diversity

Future Plans

- Biochemical parameters limiting coal-dependent methanogenesis
- Thermodynamic and reactive transport in coal systems
- Optimize microbial coal-dependent methanogenesis in column-flow reactors

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Objectives

The parameters that constrain microbial coal conversion to natural gas include many physical, chemical, and biological variables. The project will investigate and determine the impact of surface area, pH, nutrients, and transport on overall methanogenesis. The three main objectives of the project are to:

Objective 1: Determine the chemical and biological parameters limiting methane production from coal.

Objective 2: Develop strategies for the optimization of the MECBM (microbially-enhanced coal bed methane) technology based on thermodynamic and reactive transport considerations.

Objective 3: Scale up laboratory microcosms to optimize microbial coal-to-methane production in column flow reactors.

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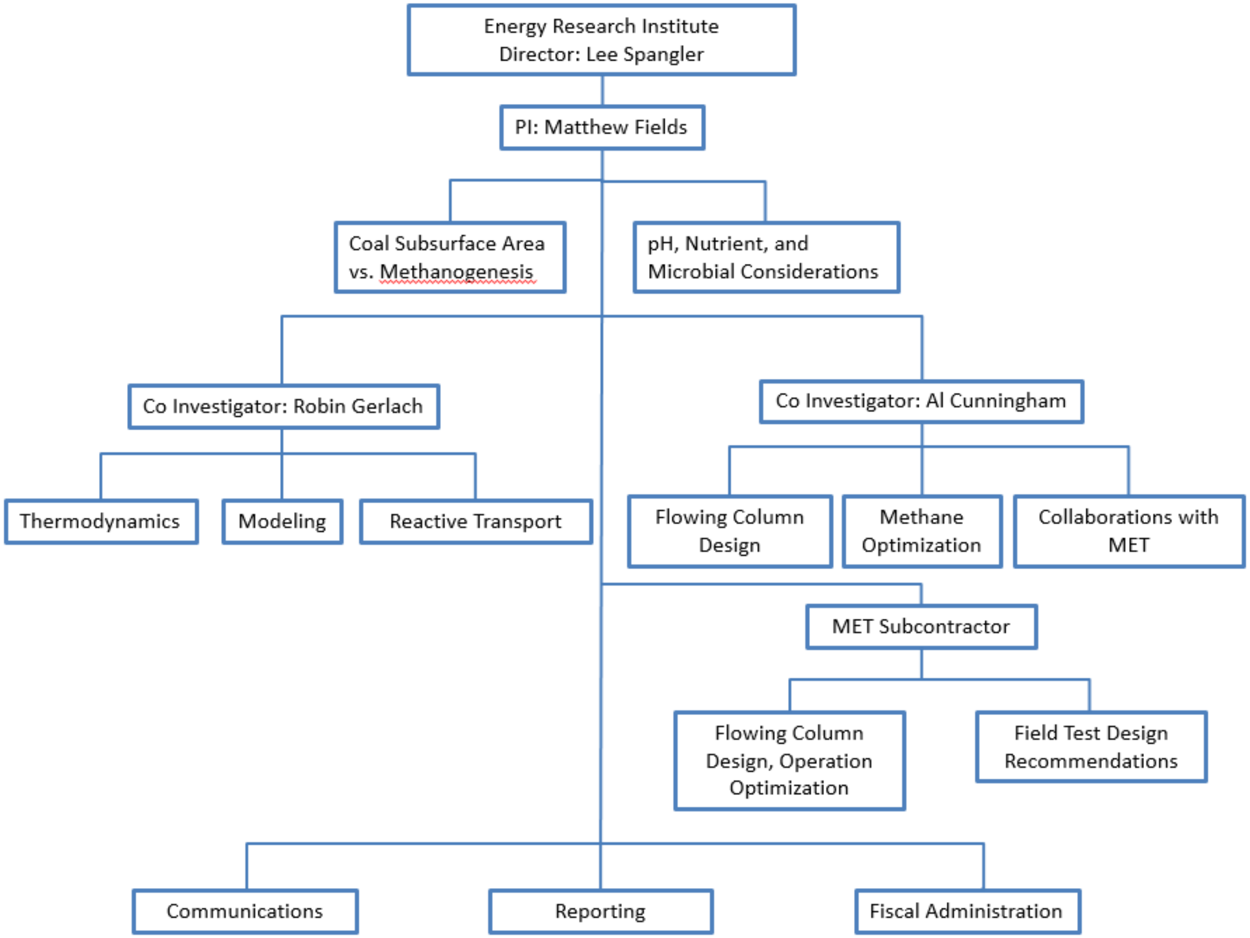
Team Roles & Responsibilities



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Task & Subtasks: Summary

Task 1.0 Project Management, Planning and Reporting: In accordance with the PMP

Task 2.0 Characterization of chemical and biological parameters that limit methane production from coal

Subtask 2-1 Assess Surface Area Impacts on Microbial Coal Conversion

Subtask 2-1.1 Surface area impacts on coal colonization and methanogenesis

Subtask 2-1.2 Surface area impacts on coal degradation

Subtask 2-2 Evaluation of the effect of pH and nutrient supplementation on coal-dependent methanogenesis

Subtask 2-2.1 pH effects on coal-dependent methanogenesis

Subtask 2-2.2 Nutrient transport and stimulation

Subtask 2-3 Biological considerations (colonization, degradation, and microbial interactions)

Subtask 2-3.1 Biological considerations (colonization, degradation, and microbial interactions)

Subtask 2-3.2 Microbial interactions and cross-feeding

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Task & Subtasks: Summary

Task 3.0 Developing an understanding of the thermodynamic, reaction and transport considerations necessary for technology development and scale-up

Subtask 3-1 Thermodynamics

Subtask 3-2 Reactive transport considerations

Subtask 3-2.1 Subtask 3-2.1 Determination of Reaction Kinetics

Subtask 3-2.2 Determination of Reaction-Transport Relationships

Subtask 3-3 Reactive transport modeling in coal bed cleats

Task 4.0 Scale up laboratory microcosms to optimize microbial coal-to-methane production in column flow reactors

Subtask 4-1 Column reactor design and fabrication

Subtask 4-1.1 Design and fabricate column reactors

Subtask 4-1.2. Develop suitable Oxidation-Reduction Potential conditions

Subtask 4-2 Develop coal-to-methane conversion protocol

Subtask 4-3 Adjust column operation to optimize methane production

Subtask 4-4 Design of field demonstration at the USGS Powder River Test site

Subtask 4-4.1 Design field demonstration project

Subtask 4-4.2 Perform economic analysis

Subtask 4-4.3. Evaluate Potential Ecological Hazards

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Tasks & Subtasks

Subtask 2-1.1 Surface area impacts on coal colonization and methanogenesis.

- *Enrichments from field samples (three different coal seams) are in progress to develop inoculum for surface area experiments*

- *Chosen particle size ranges based on preliminary results:*

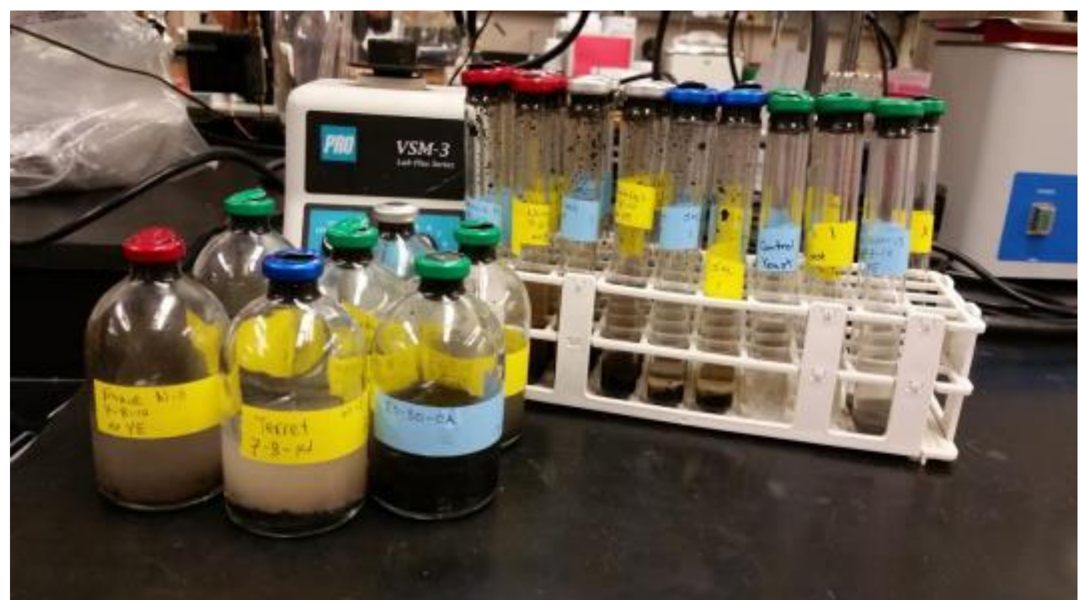
  4 fractions, duplicates, w/ and w/o 0.1g/L yeast extract:

  0.1 - 0.3 mm

  0.6 - 1.2 mm

  3.4 – 4.8 mm

  6.3 - 9.5 mm



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Tasks & Subtasks

Subtask 2-2.1 pH effects on coal-dependent methanogenesis.

- *Preliminary results have demonstrated that coal has buffering capacity in CBM production water.*

- *Near-term experiments will include pH determinations in CBM water post-algal growth.*

Subtask 2-2.2 Nutrient transport and stimulation. Methods to optimize the use nutrients to produce methane from coal in laboratory biofilm reactors will be developed under this subtask.

- *Prototype up-flow column reactors are being tested.*

Subtask 2-3.1 Biological considerations (colonization, degradation, and microbial interactions).

Subtask 2-3.2 Microbial interactions and cross-feeding.

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Tasks & Subtasks

Subtask 3-1 Thermodynamics. In this task, a spreadsheet based tool that will be created to allow for the calculation of the free energy available for the different methanogenic reactions and for the range of environmental (p, T) and geochemical (concentrations of reactants, pH value) conditions.

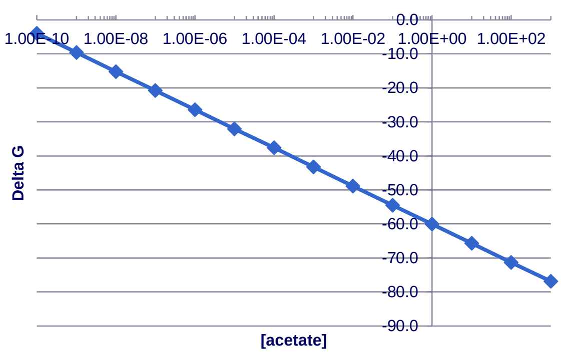
Reactant/Product	(kJ/mol)
$CH_3COOH_{(aq)}$	-396.6
$CO_{2(g)}$	-394.4
H^+	0
$H_{2(g)}$	17.74
H_2O	-237.2
$CH_{4(g)}$	-50.75
$CH_3OH_{(l)}$	-166.4

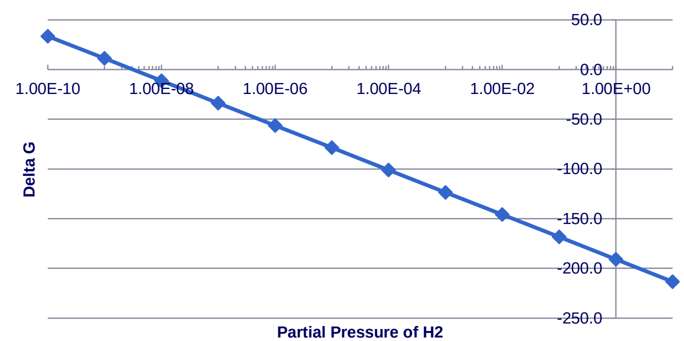
1. Hydrogenotrophic
   $CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O$
2. Acetoclastic
   $CH_3COOH \rightarrow CH_4 + CO_2$
3. Methylotrophic
   (a) $4\ CH_3OH \rightarrow 3\ CH_4 + CO_2 + 2\ H_2O$
   (b) $CH_3OH + H_2 \rightarrow CH_4 + H_2O$
   (c) $4\ CH_3R + 2\ H_2O \rightarrow 3\ CH_4 + CO_2 + 4\ RH$

(where R can be NH_2, SH or similar)

Reactant/Product	Activity
$CH_3COOH_{(aq)}$	7.0E-6 mol
$CO_{2(g)}$	1.0E-2 atm
$H_{2(g)}$	1E-6 atm
$CH_{4(g)}$	8.8E-1 atm
$CH_3OH_{(l)}$	1E-6 atm

Reactants in red were not measured. It is assumed that they have low activities and therefore a value of 1E-6 was used.





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Tasks & Subtasks

Subtask 3-2 Reactive transport considerations

Subtask 3-2.1 Determination of Reaction Kinetics.

- *Establish baseline conditions in Objective 2.*

Subtask 3-2.2 Determination of Reaction-Transport Relationships.

- *Establish reactors in Task 4.0.*

Subtask 3-3 Reactive transport modeling in coal bed cleats

- The model will be calibrated and validated using the batch and column experiments described in tasks 2 and 4 and will ultimately be used as the basis for the field scale demonstration preparations.

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Tasks & Subtasks

Task 4.0 - Scale up laboratory microcosms to optimize microbial coal-to-methane production in column flow reactors.

Subtask 4-1.1 Design and fabricate column reactors.

•*Prototype reactors are being tested.*

Subtask 4-1.2 Develop suitable Oxidation-Reduction Potential (ORP) conditions in reactors.

Subtask 4-2 Develop coal-to-methane conversion protocol.

Subtask 4-3 Adjust column operation to optimize methane production

Subtask 4-4.1 Design field demonstration project.

•*Baseline characterization of USGS field site in collaboration with USGS.*

Subtask 4-4.2 Perform economic analysis.

Subtask 4-4.3 Evaluate Potential Ecological Hazards.

•*Baseline microbial community characterization is underway with Diffusive Microbial Samplers.*

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Deliverables

Periodic topical and final reports will be submitted in accordance with the "Federal Assistance Reporting Checklist". A Project Management Plan (PMP) shall be maintained and submitted, with the initial PMP due 30 days after award. Revisions to the PMP shall be submitted, as requested, by the Project Officer.

The techno-economic analysis and summary report on the evaluation of potential ecological hazards will be provided to the Project Officer as stand-alone topical reports. These reports should be submitted within 30 days of the completion of their associated tasks and/or sub-tasks.

Milestones

Milestone Number	Budget Period	Task	Fiscal Year & Quarter	Milestone Description	Planned Completion	Verification Method
1	1	1.0	FY2015 Q1	Updated Management Plan	11/30/2014	Project Management Plan file
2	1	1.0	FY2015 Q1	Kickoff meeting	12/09/2014	Presentation
3	1	4.1	FY2015 Q2	Complete coal-to-methane flowing column design and fabrication	03/31/2015	Progress Report
4	1	3.1	FY2015 Q3	Complete development of a spreadsheet tool to predict rate and extent of methanogenesis	6/30/2015	Progress report
5	2	2.1	FY2016 Q2	Complete experiments on surface area impacts on coal colonization and methanogenesis	03/31/2016	Progress report
6	2	4.4	FY2016 Q3	Complete design recommendations field pilot project at the USGS Powder River test site	06/30/2016	Progress report

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Decision Points & Success Criteria

This is a "single phase" project intended to evaluate and further develop the potential for the commercial implementation of microbially enhanced coal bed methane (MECBM) production through a combination of laboratory experiments, modeling, scale-up and field test design.

There are no "go/no-go" decision points associated with the project schedule. At the conclusion of the project the results will be evaluated to determine overall effectiveness of nutrient amendment, geochemical manipulation, and engineering strategies to enhance the rate and extent of biological coal-to-methane conversion in the field.

Our target metric is to achieve at least a three-fold increase in methane production from coal that has undergone nutrient stimulation relative to unamended controls. The overall success of project results will be evaluated with the help of feedback from all project collaborators which include MSU, MET, the Reston Office of the U.S. Geological Survey as well as DOE-NETL.

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Schedule Budget

CATEGORY	Budget Period 1 Costs	Budget Period 2 Costs	Total Costs	Project Costs %
a. Personnel	$149,535	$102,824	$252,359	40.4%
b. Fringe Benefits	$43,412	$35,264	$78,676	12.6%
c. Travel	$8,000	$8,000	$16,000	2.6%
d. Equipment	$0	$0	$0	0.0%
e. Supplies	$33,090	$23,637	$56,727	9.1%
f. Contractual				
Sub-recipient	$25,000	$25,000	$50,000	8.0%
Vendor	$0	$0	$0	0.0%
FFRDC	$0	$0	$0	0.0%
Total Contractual	$25,000	$25,000	$50,000	8.0%
g. Construction	$0	$0	$0	0.0%
h. Other Direct Costs	$17,400	$8,700	$26,100	4.2%
Total Direct Costs	$276,437	$203,425	$479,862	77%
i. Indirect Charges	$78,138	$67,000	$145,138	23.2%
Total Project Costs	$354,575	$270,425	$625,000	100%

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