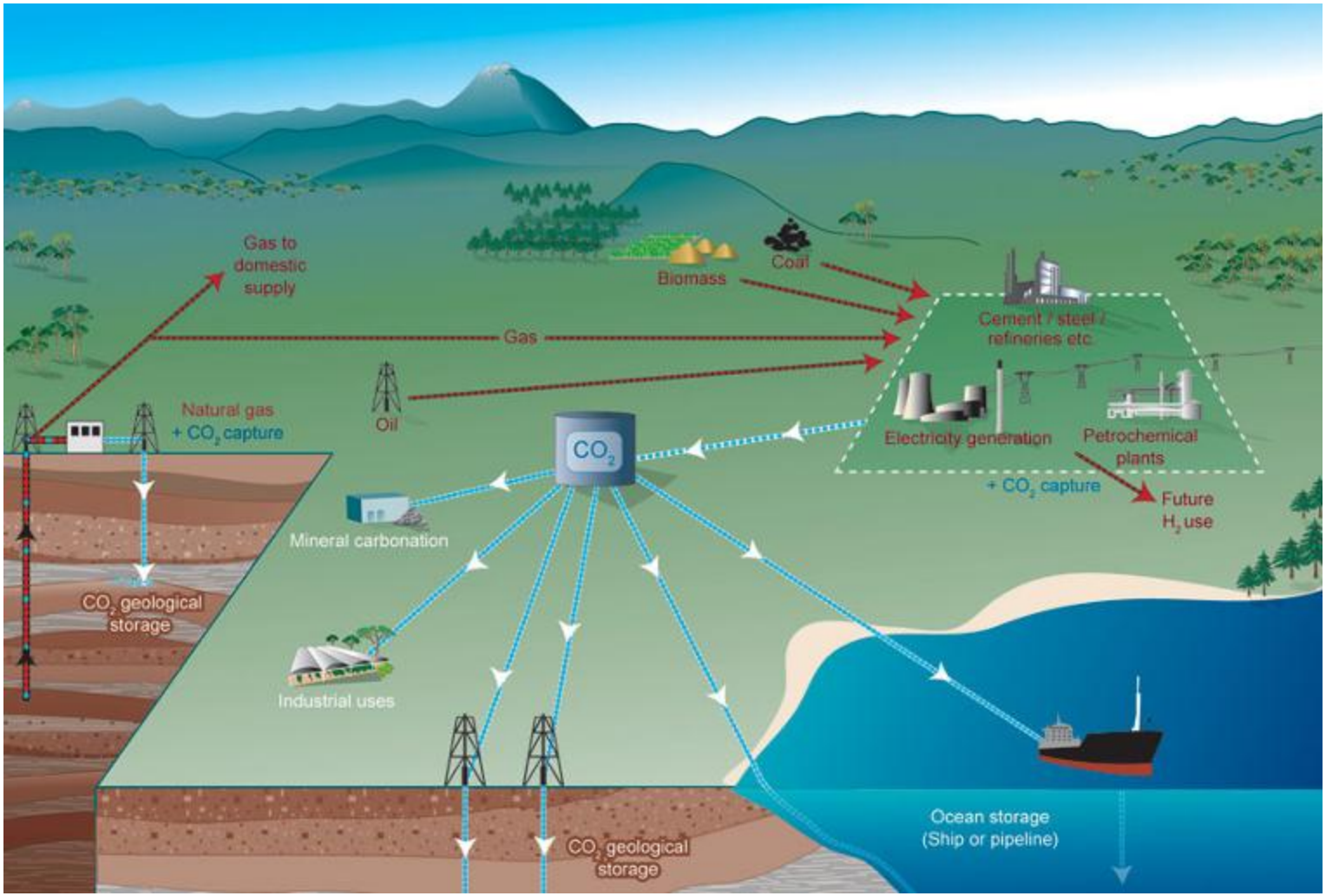
What is CCS (Carbon Capture and Storage)?

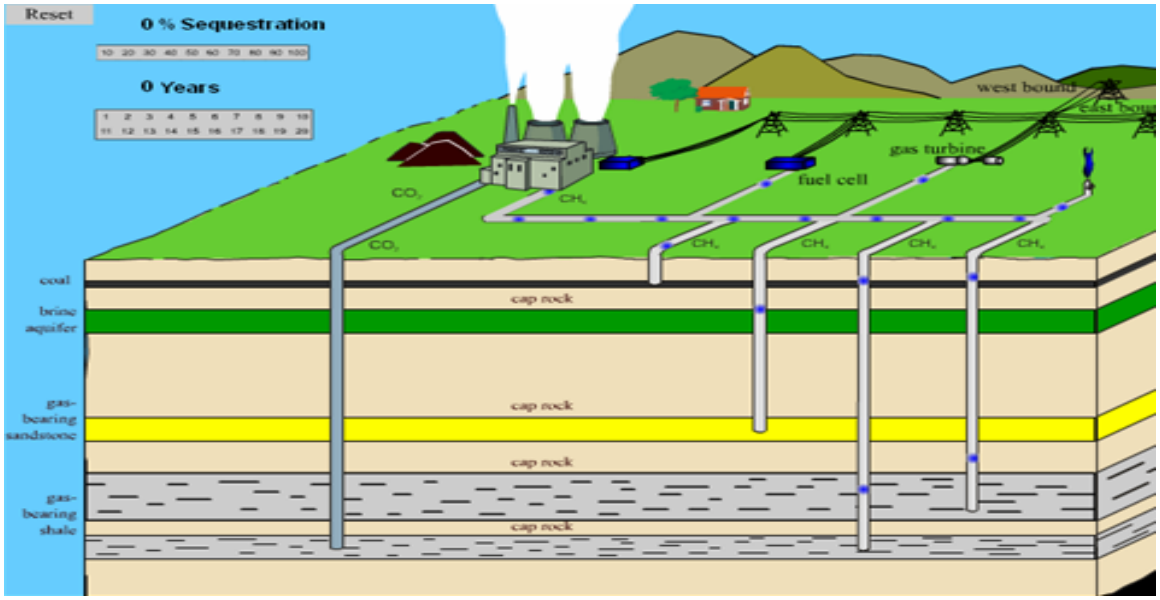


http://www.ipcc.ch/activity/csspm.pdf

Geologic CO_2 sequestration (CCS)

Concept: Reduce global CO_2 emissions by sequestering large quantities (gigatons per year) in deep, secure geological formations

Research Needs: Our DOE EPSCoR project will conduct fundamental an applied research relevant to environmental responses associated with geological carbon storage



A DOE EPSCoR Implementation project in MT which addresses CCS is timely because:

1) MT has 25% of U.S. (6% of the world's) coal reserves

2) Two large CCS projects headquartered at MSU

   Big Sky (DOE) Partnership program (MT,WA,WYO,ND)

   Zero Emissions Research and Technology Center (ZERT)

3) MT now has legislation defining ownership of "pore space" for carbon sequestration

DOE EPSCoR will broaden participation in CCS research across the Montana University System

Environmental Responses to Carbon Mitigation through Geological Storage

A DOE EPSCoR Implementation Grant:
Montana State University (MSU),
The University of Montana (UM), and
Montana Tech of the University of Montana (MTech)

Principal Investigator: Dr. Al Cunningham
Center for Biofilm Engineering, Montana State University, Bozeman Montana 59717

Project Administrator: Dr. Jerry Bromenshenk,
Montana DOE EPSCoR Director, University of Montana, Missoula, MT 59812

Overview

This DOE EPSCoR project will make a significant contribution to CCS.

Both “deep” and “shallow” subsurface questions will be addressed.

The research plan represents a collaboration between three Montana University system campuses and five DOE National Laboratories (LANL, LBNL, PNNL, NETL and LLNL).

Two interrelated research objectives:

Research Objectives

- **Objective 1:** *Determine the influence of CO_2-related injection fluids (ScCO2) on pore structure, material properties, and microbial activity in rock cores from potential geological carbon sequestration sites.* ***(CCS Site characterization)***

- **Objective 2:** *Determine the effects of CO_2 leakage on near-surface microbial and plant ecosystems by conducting field experiments at an outdoor testing facility.* ***(CCS Site leakage detection and impacts)***

Objective 1 (MSU and MTECH)

- High pressure rock core testing MTECH

- Magnetic Resonance Microscopy (MRM) applied to rock cores (MSU)…..Non-invasively measure: tortuosity, permeability, pores size distribution and pore connectivity changes in rock cores subjected to challenges by supercritical CO_2 as well as cores containing biotic and abiotic deposits

- Assess the survivability of microbes (both as biofilms and in suspended cultures) when subjected to supercritical CO_2.

MT Tech EPSCoR Project

At left, Kurt Hibbard (Petroleum Engineering graduate student) demonstrates how to adjust the needle valve on the core holder outlet to maintain back pressure on the system.

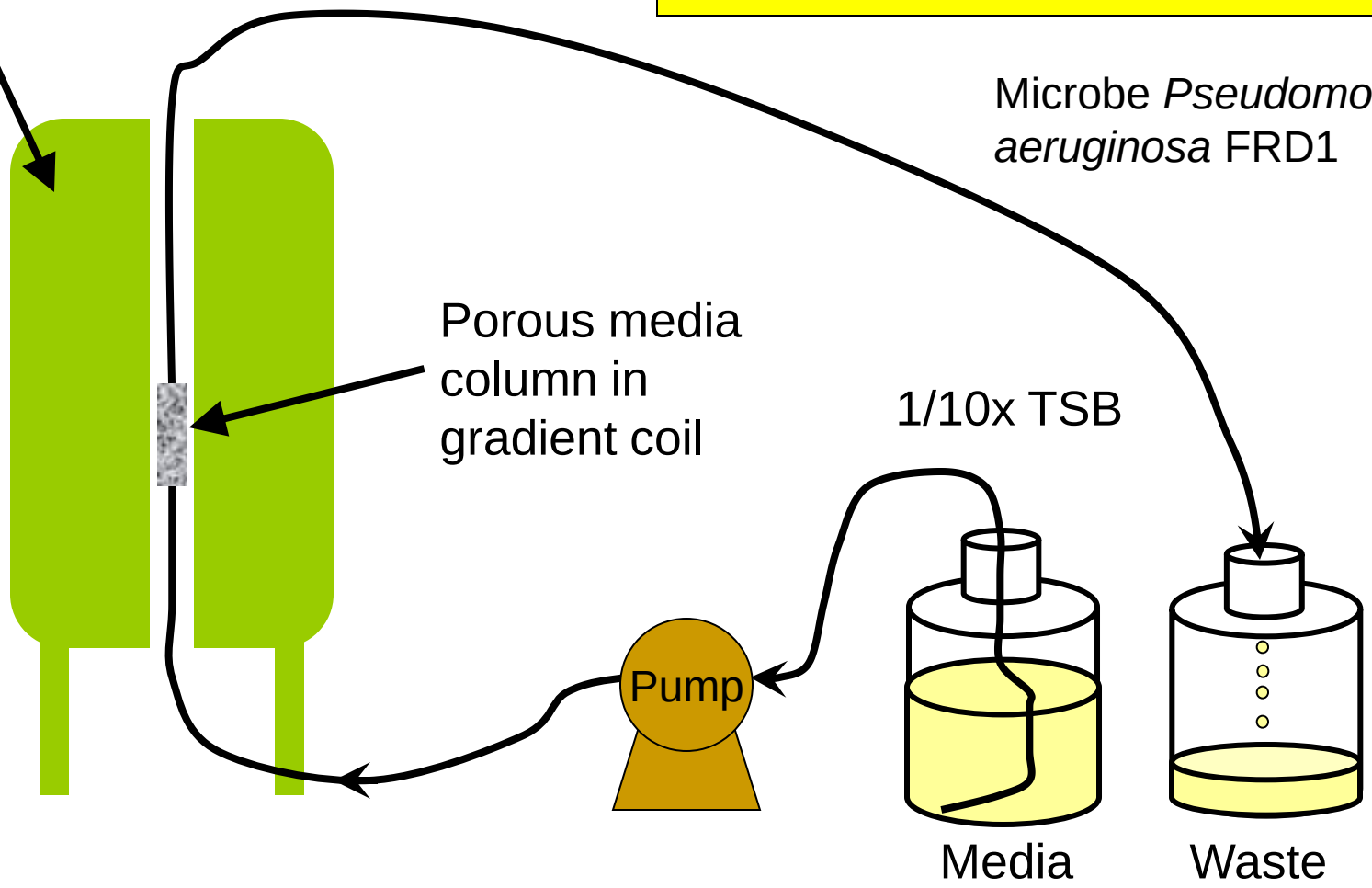
At right, Cameron Shepherd (Petroleum Engineering undergraduate student) monitors the temperatures at the inlet and outlet of the core holder to ensure supercritical fluid conditions are present.

Methodology

- Four rock types challenged with $ScCO_2$ for 48 hours
  - Berea Sandstone (5)
  - Torrey Buff red sandstone (6)
  - Limestone (14)
  - Dolomite (16)
- Five cores of each rock type
- Porosity, permeability, pore volume, grain volume, bulk volume, and bulk density measured

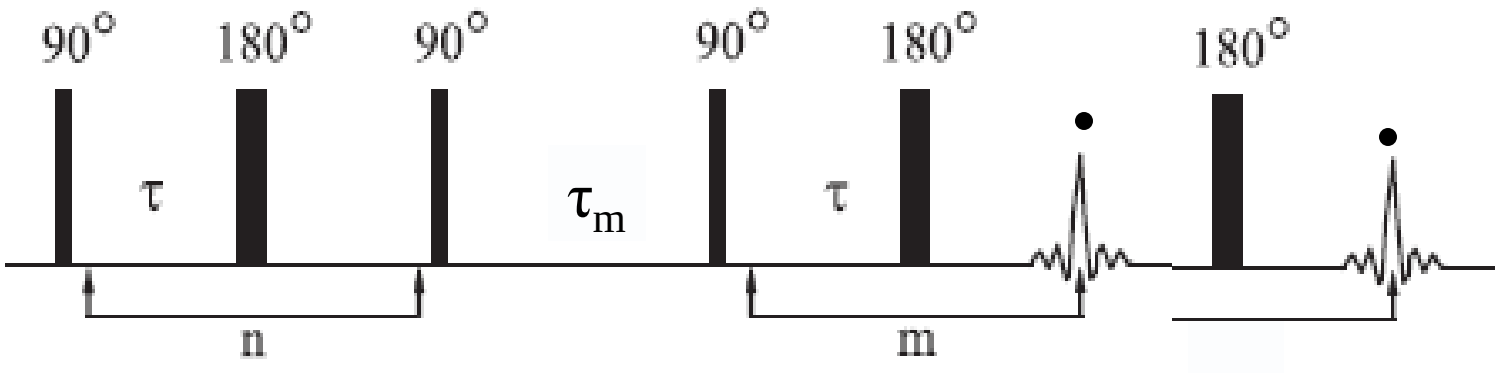
Reynolds number ~ 0.03 – 5

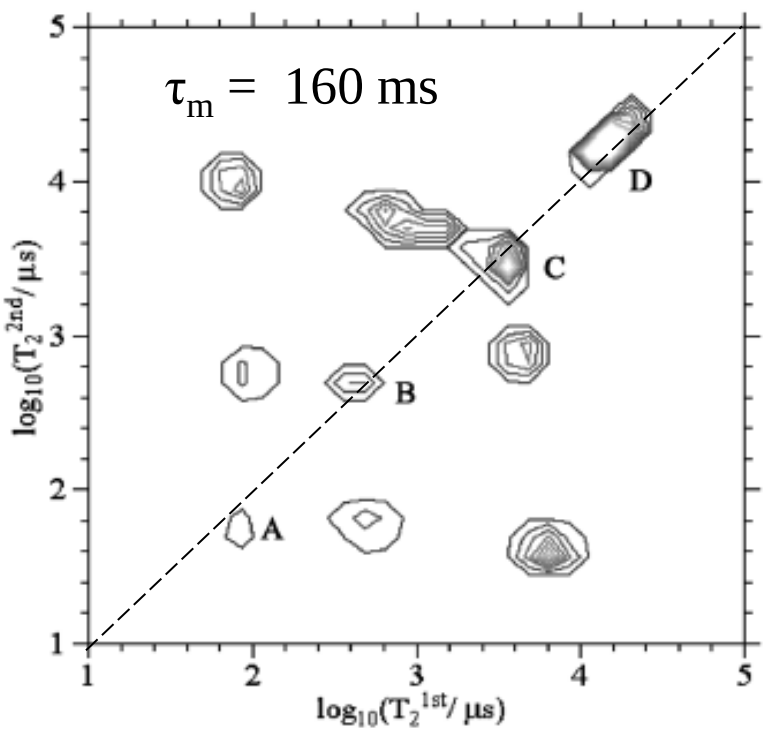
Peclet number ~ 10 - 2000



ARTDECO 2D T_2 Exchange (or 2D Pore Exchange)

[J.H. Lee et al. *JACS* **115** 7761 (1993)]





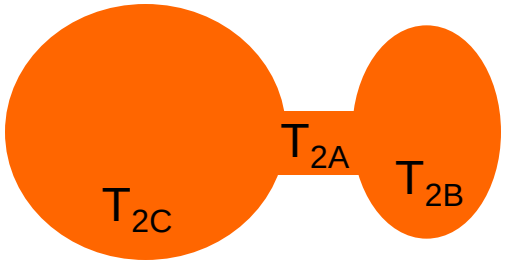
Castelgate sand stone core

T_2 : 0.2; 1.6; 8; 33 ms

τ_{AC} – 21 ms

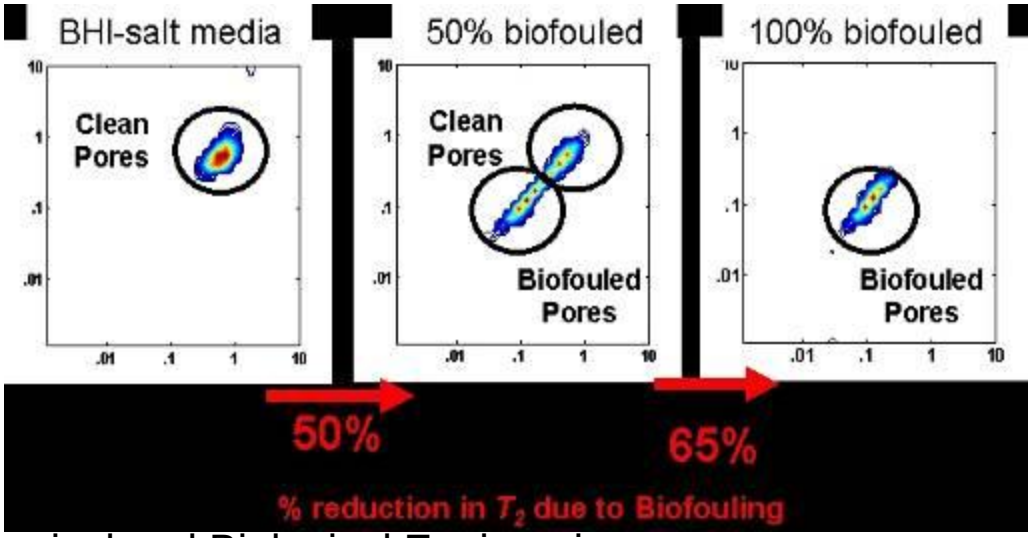
τ_{AB} – 17 ms

τ_{BC} – 43 ms



[Washburn and Callaghan, *PRL* **97**, (2006)]

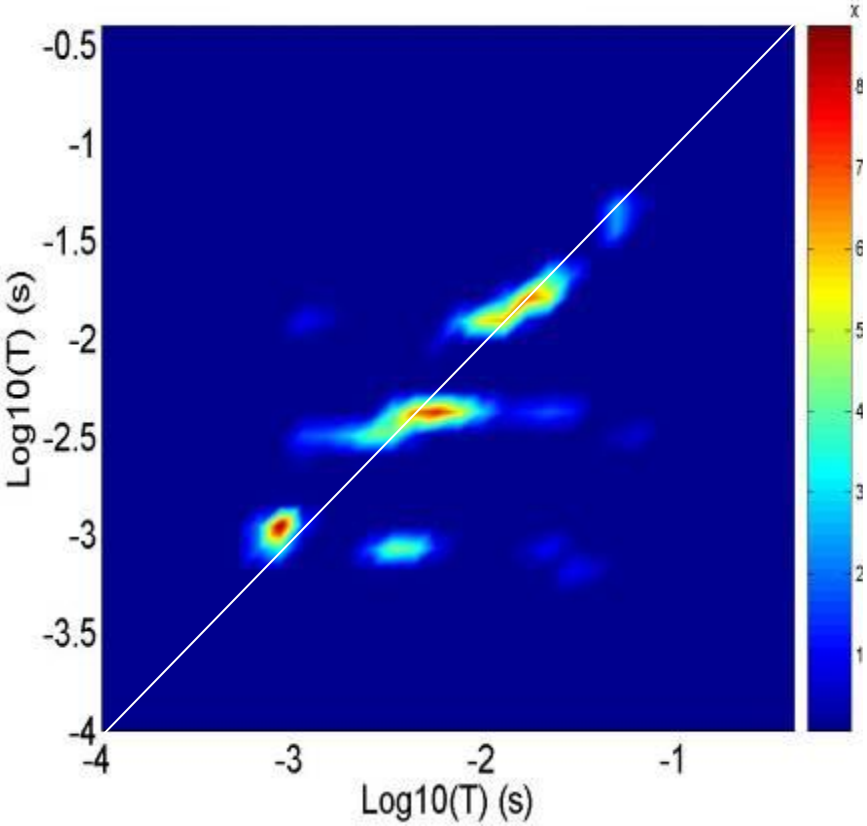
Magnetic Resonance Imaging of biofouled beads



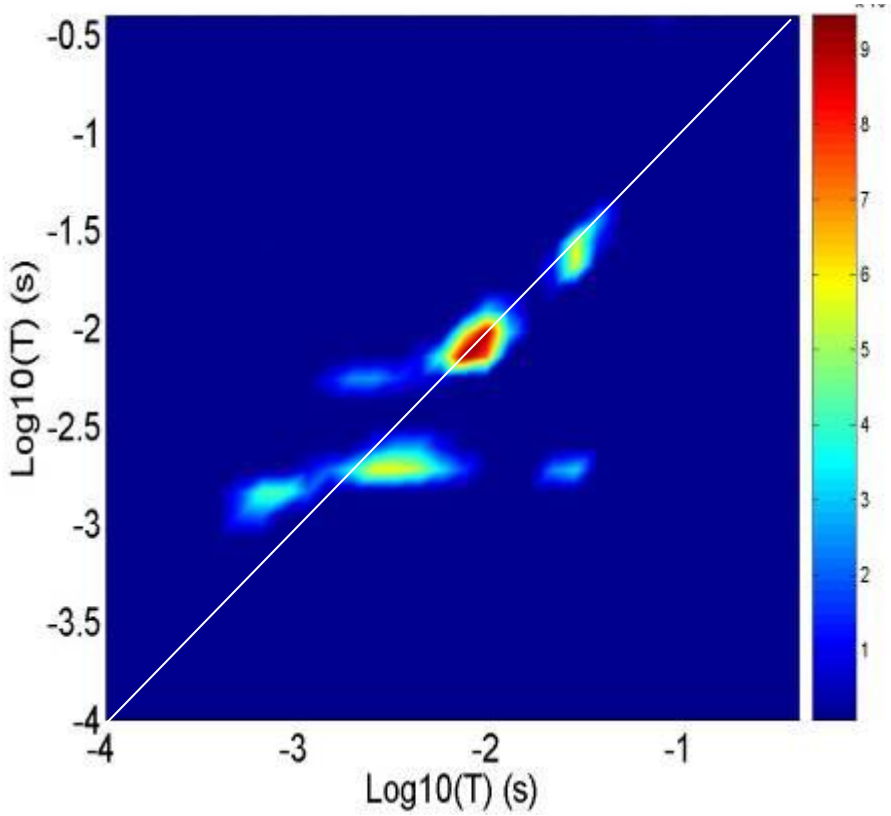
Jennifer Horneman, PhD, Chemical and Biological Engineering

Three *T*2-*T*2 maps for 100 µm borosilicate glass beads in BHI-salt solution media (left), 50% biofouled with *Bacillus mojavensis* (middle), and 100% biofouled (right). The *T*2 value for the main diagonal peaks shifts significantly with biofouling—indicating that water originally present in the free pore space is being sequestered inside the biofilm matrix. This indicates that biofilm has substantially reduced free pore space, porosity and permeability.

Berea core



Same Core after Biofilm Growth



Pore Size Distribution Changed (on diagonal)

Fewer Pore Exchange Peaks (off Diagonal)

ILT Software from P.T. Callaghan and Magritek Limited NZ

Year 1 highlights

- High –pressure core testing system developed and tested at MTECH

- MRM methods developed for measuring porosity and permeability changes in model porous media

Objective 2 (MSU,UM and MTECH)

Since supercritical CO_2 is less dense than water, the potential exists for unwanted upward migration to occur. It is therefore necessary to research environmental responses occurring when CO_2 leakage reaches the ground surface.

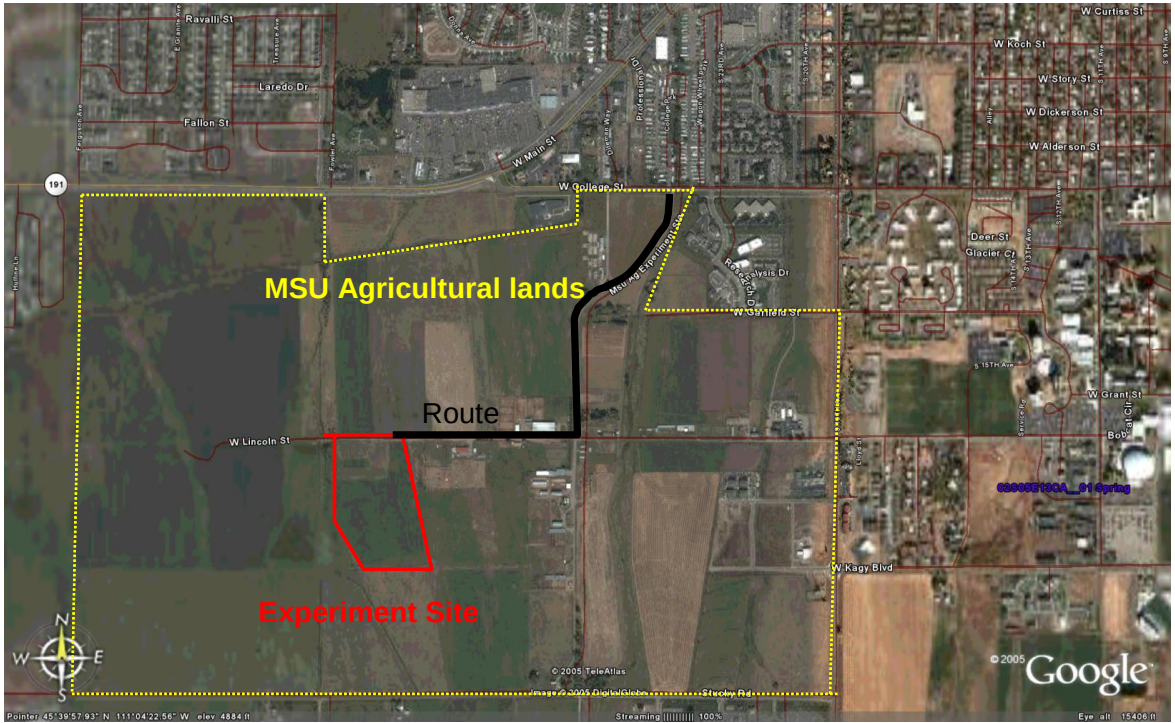
- outdoor field test facility, 5 National Labs

- currently conducting experiments related to CO_2 flux in near-surface soils.

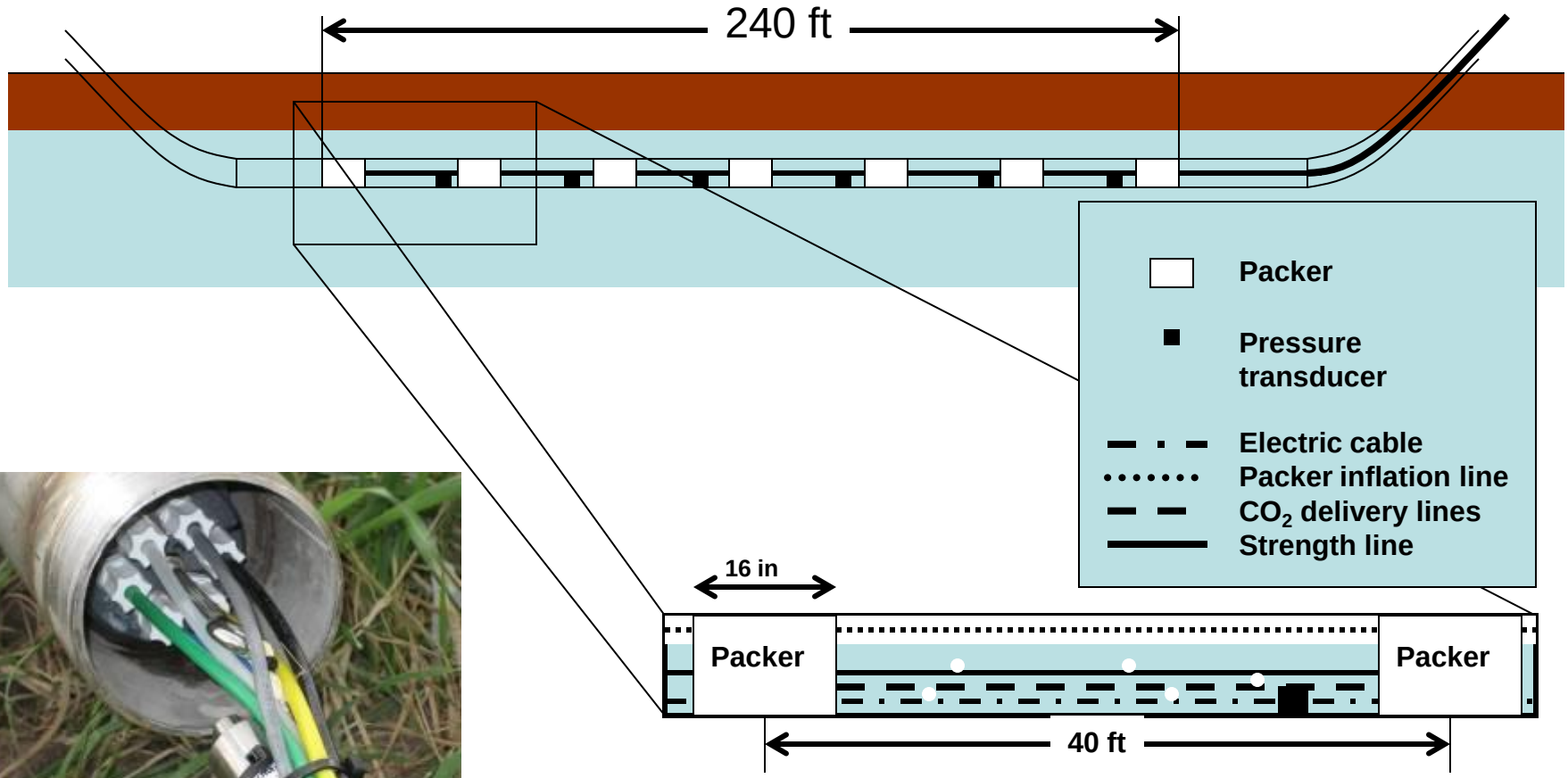
- DOE EPSCoR researchers will measure and quantify the responses of **plant** (MTECH) and soil **microbiological communities** (UM) to controlled releases of CO_2 at the field site.

Field Test Facility at MSU

The facility consists of a 4-inch steel horizontal well approximately 210 feet in length, buried approximately 8 feet below pasture land consisting of alfalfa and native prairie grass. The horizontal well allows CO_2 from a storage tank to be pumped underground and released along the axis of the well—thereby providing a linear source of CO_2 flux which rises up through the overlying soil.



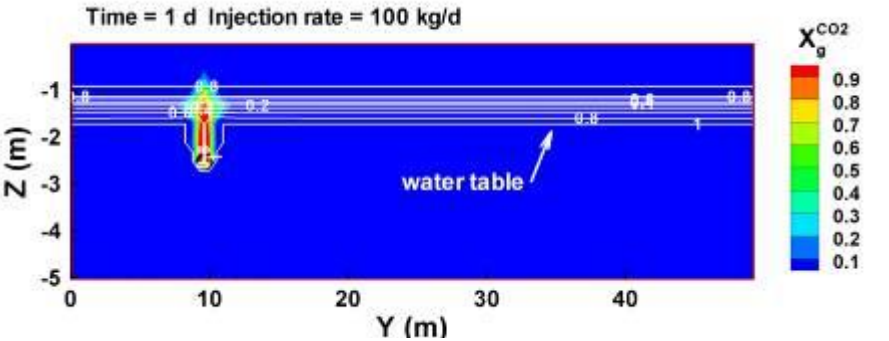
Horizontal Well Installation

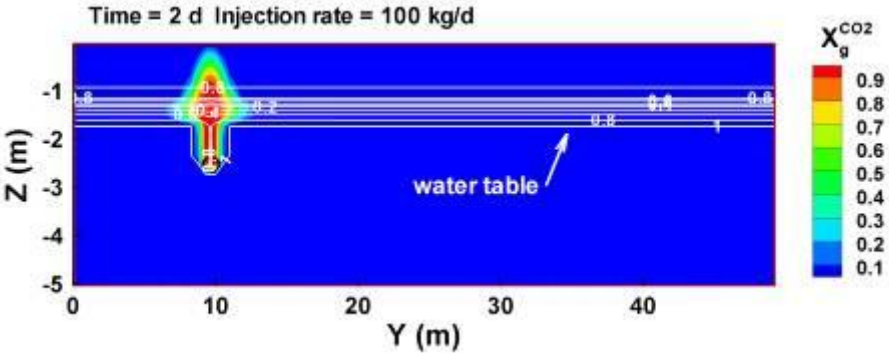


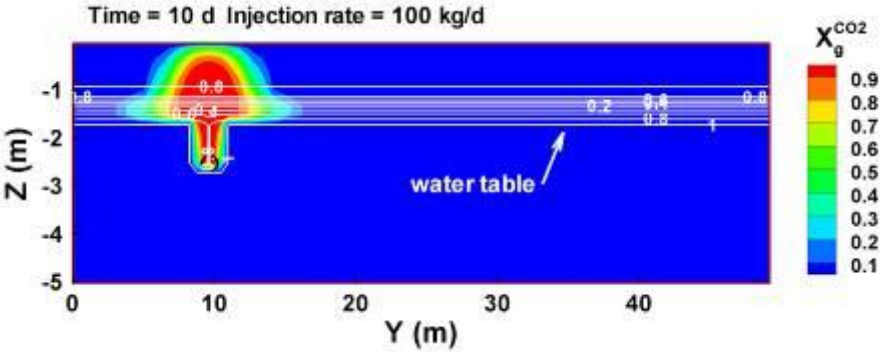
TOUGH2/EOS7CA Model Results of CO_2 Release for Experiment Design

Curtis M. Oldenburg

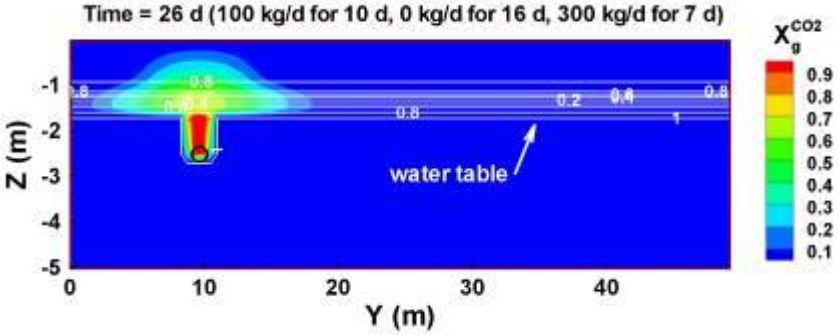
Release 1 (100 kg/d)

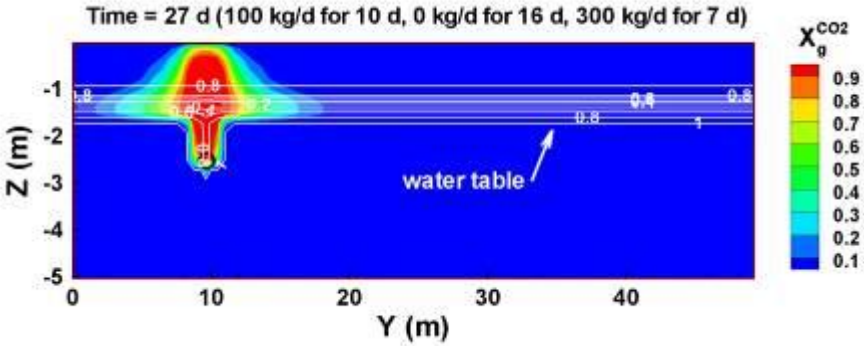


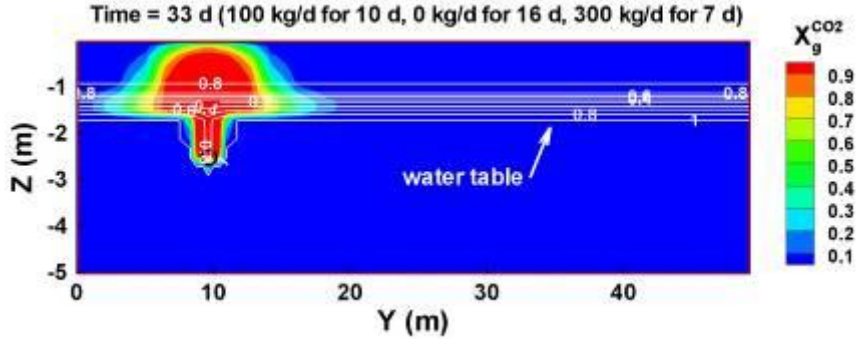


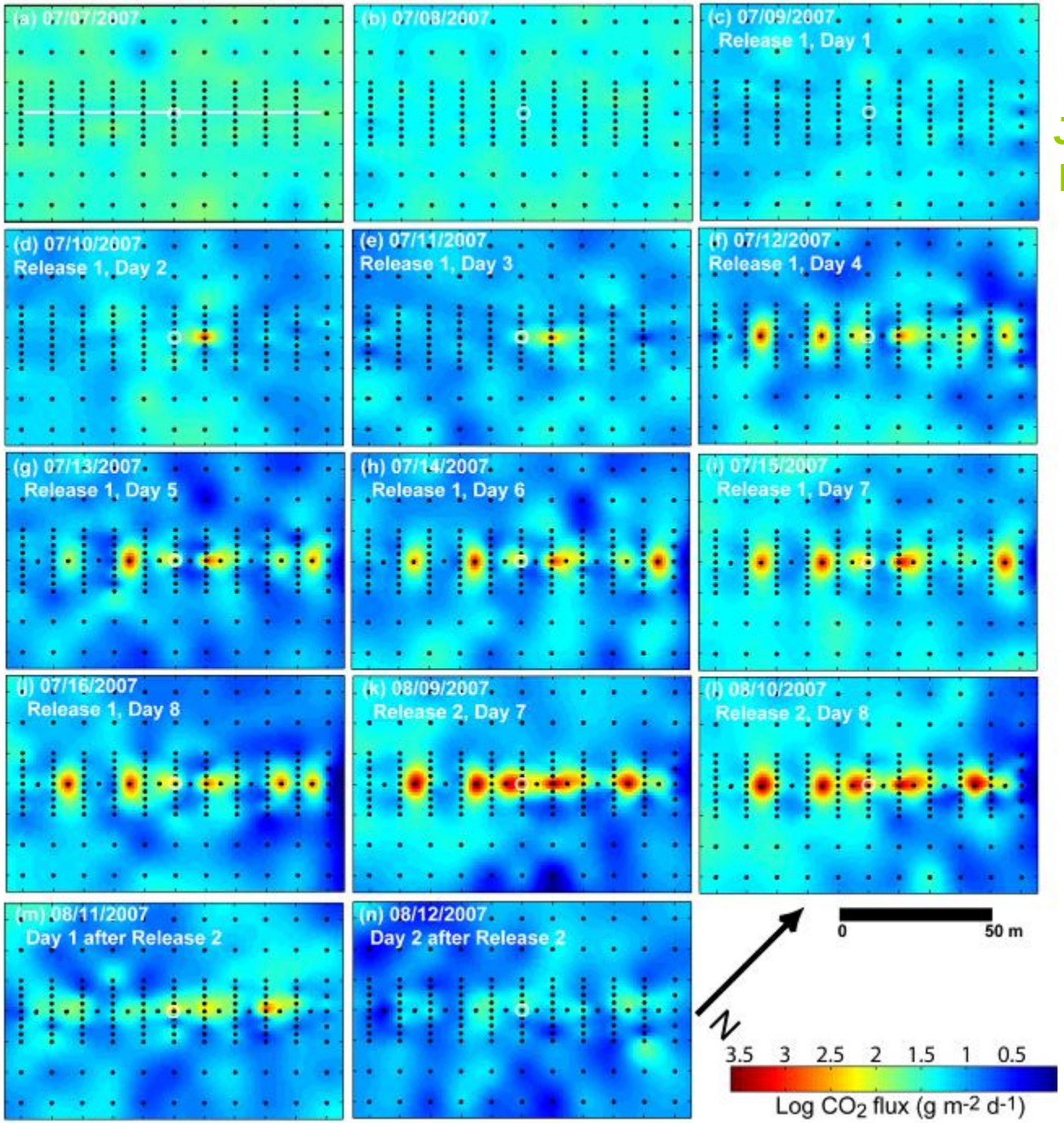


Release 2 (300 kg/d)









Jennifer Lewicki

Large Number of Participants / Methods

MSU – Geotechnical, O2, CO2 (isotope) Lidar

UM – Microbial response

MTECH – Plant response

LBNL – Eddy Covariance, Soil Gas detection, Modeling

LANL – EC, Stable Isotopes Gas & Water

PNNL – Soil gas capture

LLNL – Gas Stable Isotope, Hyperspectral,

NETL – Background Characterization, Tracers

WVU – Water Chemistry

MTECH plant response team installing a root-zone camera at the MSU field site

Plant Response to CO_2 Releases

MARTHA APPLE, XIAOBING ZHOU, and VENKATA LAKKARAJU

The goal of the MTech Plant Responses Research Team is to characterize the physiological, spectral, and growth responses of plants to episodic applications of CO2 over a multi-year time frame.

Important research questions are:

1) What are the impacts of CO2 leaking from the ZERT facility on neighboring plants?

2) Will plants sequester proportionately more carbon into structural tissue when exposed to episodic increases in CO2?

3) Can plants at the ZERT facility be used as remediators of carbon leakages from carbon injections?

UM Microbiologists collecting soil cores at the MSU field site

Sergio Morales Phillip Drummond

Utilizing the bacterial community as an early warning system for elevated CO2 seepage from belowground

UM Research Assistant Professor Sergio E. Morales and Professor William Holben, PhD Student Phillip Drummond

- **prior work has shown that bacterial communities are highly sensitive bio-indicators of environmental perturbation, being about 10X more sensitive than most accepted meso- and macrofauna.**
- **Increased concentrations of CO2 may cause a shift from primarily heterotrophic metabolism to increased autotrophic activity, thereby effecting a change in microbial community composition, respiratory activity and gene expression in near-surface soils.**
- **Findings will determine how microbial community shifts are related to magnitude and duration of CO2 flux.**

Year 1 highlights

- Plant and Soil microbial samples collected from two CO2 releases June 7-16, 2009 and July 15-30, 2009

- Plant response team leader (Martha Apple) co-authored **2 conference presentations** (2008-2009) and **one manuscript** with National Lab colleagues working at the MSU field site

Summary

This research will provide fundamental scientific and engineering-related information which is urgently needed by decision makers dealing with issues surrounding carbon mitigation via geologic sequestration.

Objective 1 will develop methods for characterizing deep aquifer properties related to potential to successfully sequester CO_2.

Objective 2 will assess the impacts of CO_2 releases on surface plant and soil microbial communities

Acknowledgements

US Department of Energy EPSCoR program under grant number DE-FG02-08ER46527. Tim Fitzsimmons program Manager.
Additional support for the MSU Carbon dioxie field testing site is provided by the US Department of Energy Zero Emissions Research and Technology (ZERT) program (DOE Award No. DE-FC26-04NT42262)

Non-Federal Matching funds is being provided by Montana State University, The University of Montana, an Montana Tech of the University of Montana.

Criteria for Success or Effectiveness of Implementation Awards

a) Has awardee made competitive faculty hires and ***retained outstanding faculty*** *within the scope of the implementation award?*

- *Opportunities for several senior faculty (Cunningham,Bromenshenk, Holben) and several junior faculty (Codd, Seymour, Apple, Zhang) to develop a new research topic.*

- *Hired 2 new research faculty (Morales, Parks) with partial support form DOE EPSCoR*

Effectiveness Criteria (continued)

b) *has awardee hired outstanding* ***graduate students*** *and* ***post docs****?*

MSU Department of Chemical and Biological Engineering

Andy Mitchell	Post Doc
Jen Hornemann	PhD
Sarah Vogt	PhD
Logan Schultz	MS
Stacy Parks	MS

MTECH Petroleum Engineering Department

Kurt Hibbard	MS
Cameron Sheperd	MS

MTECH Department of Biological Sciences

Venkata Lakkaraju	MS

UM Division of Biological Sciences

Sergio Morales	Post doc
Phillip Drummond	PhD

Effectiveness Criteria (continued)

c) *Has awardee developed* ***unique infrastructure*** *capabilities that are critical to the advancement of science or technology? Alternatively, are they planning to or making unique contributions to DOE oriented capabilities (e.g., building or developing* ***unique capabilities for a DOE experiment or facility****)?*

- MSU CO_2 Research field test facility
- MSU Magnetic Resonance Microscopy (MRM) Laboratory
- MTECH High Pressure Rock Core testing system

Effectiveness Criteria (continued)

d) *are the grantees on track to a* ***sustained leadership position*** *in their discipline(s)?*

- Research publication/presentations on track for year 1

- (at least 5) new proposals submitted

- Theme area for NSF EPSCoR proposal established in CCS—DOE EPSCoR faculty are in leadership positions

Effectiveness Criteria (continued)

e) *are the grantees effectively* ***leveraging DOE funding*** *and capabilities with* ***local and regional*** *resources*

MSU Field site (attracting interest from non-DOE sources)

MTECH Petroleum Engineering Contacts in Petroleum Industry

MSU Center for Biofilm Engineering Industrial Associates Program

How has the jurisdiction's EPSCoR Committee planned to and what actions have they taken to ***maximize the long-term impact*** *of the award?*

Montana's EPSCoR Committee chose this proposal for submission to DOE EPSCoR because of fit with Montana's long-term plan for energy research development. A similar choice was recently made for submission to NSF EPSCoR.

Future work Objective 1

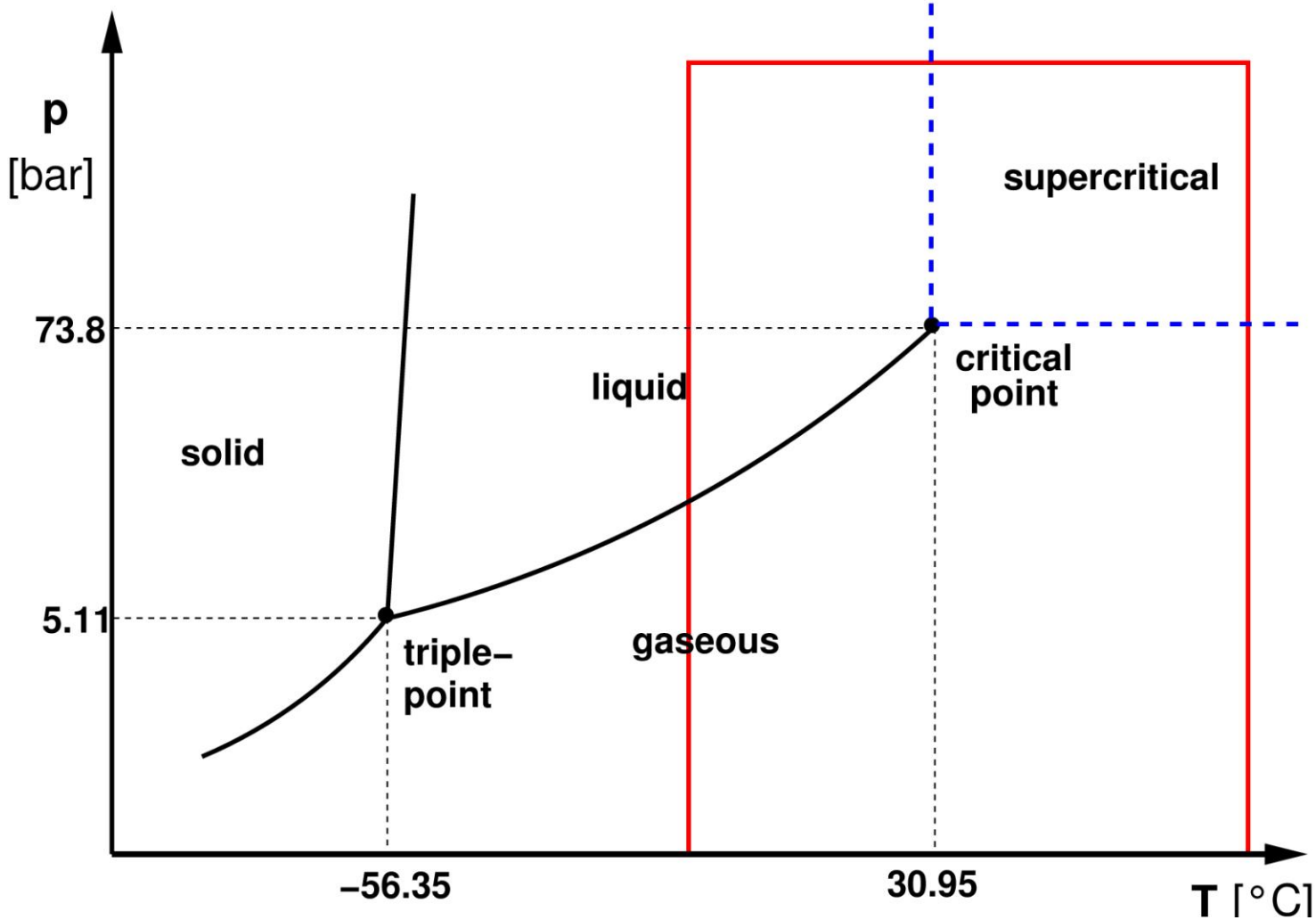
- Conduct ScCO2 challenges through various rock cores and assess changes in properties (MTECH)
- Apply MRM to rock cores (MSU)
- Assess Microbial survivability after ScCO2 exposure (MSU)

Future work Objective 2

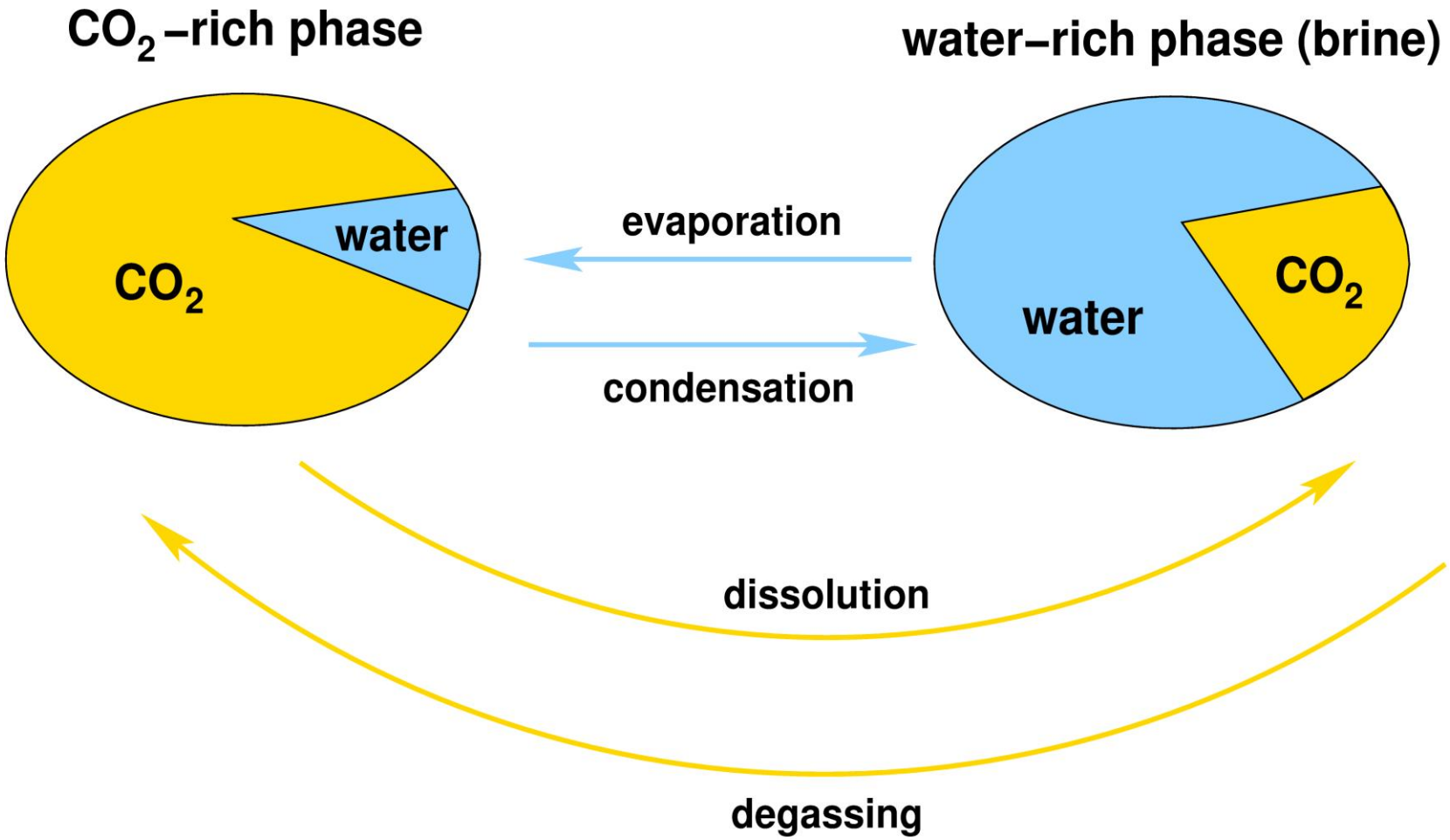
- Microbial population shifts due to CO2 exposure--early warning system

- What are the impacts of CO2 leaking from the ZERT facility on neighboring plants?

Model: Phase Diagram of CO_2



Model Concept: Two-Phase Two-Component



Properties of Supercritical CO_2

- Density S.G. 0.8 (20C) – 0.3 (40C)
- Viscosity ~0.1 of water @ 40C, 100bar
- Sparingly soluble (~4%)
- Enthalpy highly nonlinear with pressure **(Non-isothermal)**

Used as a solvent in Enhanced Oil Recovery

Objective 1 (MSU and MTECH)

Objective 1 will combine state-of-the art high pressure rock core testing with Magnetic Resonance Microscopy (MRM) to measure tortuosity, permeability, pores size distribution and pore connectivity changes in rock cores subjected to challenges by supercritical CO_2 as well as cores containing biotic and abiotic deposits--thereby providing unique data related to the ability of rock formations to sequester CO_2. Objective 1 will also assess the survivability of microbes (both as biofilms and in suspended cultures) when subjected to supercritical CO_2.

Overview

This DOE EPSCoR project will make a significant contribution to the study of carbon mitigation through geological storage. Both “deep” and “shallow” subsurface questions will be addressed through research directed at understanding the **environmental responses** associated with injection of CO_2 into geologic formations.

The research plan, which represents a collaboration between three Montana University system campuses and five DOE National Laboratories (LANL, LBNL, PNNL, NETL and LLNL), has two interrelated objectives:

Outline for talk

Title of talk

Overview CCS

Project abstract

Background….why this project is well suited to MT

Anticipated benefits of project (improved intra-campus coordination, new proposals, career development, collaboration with industry, etc.)

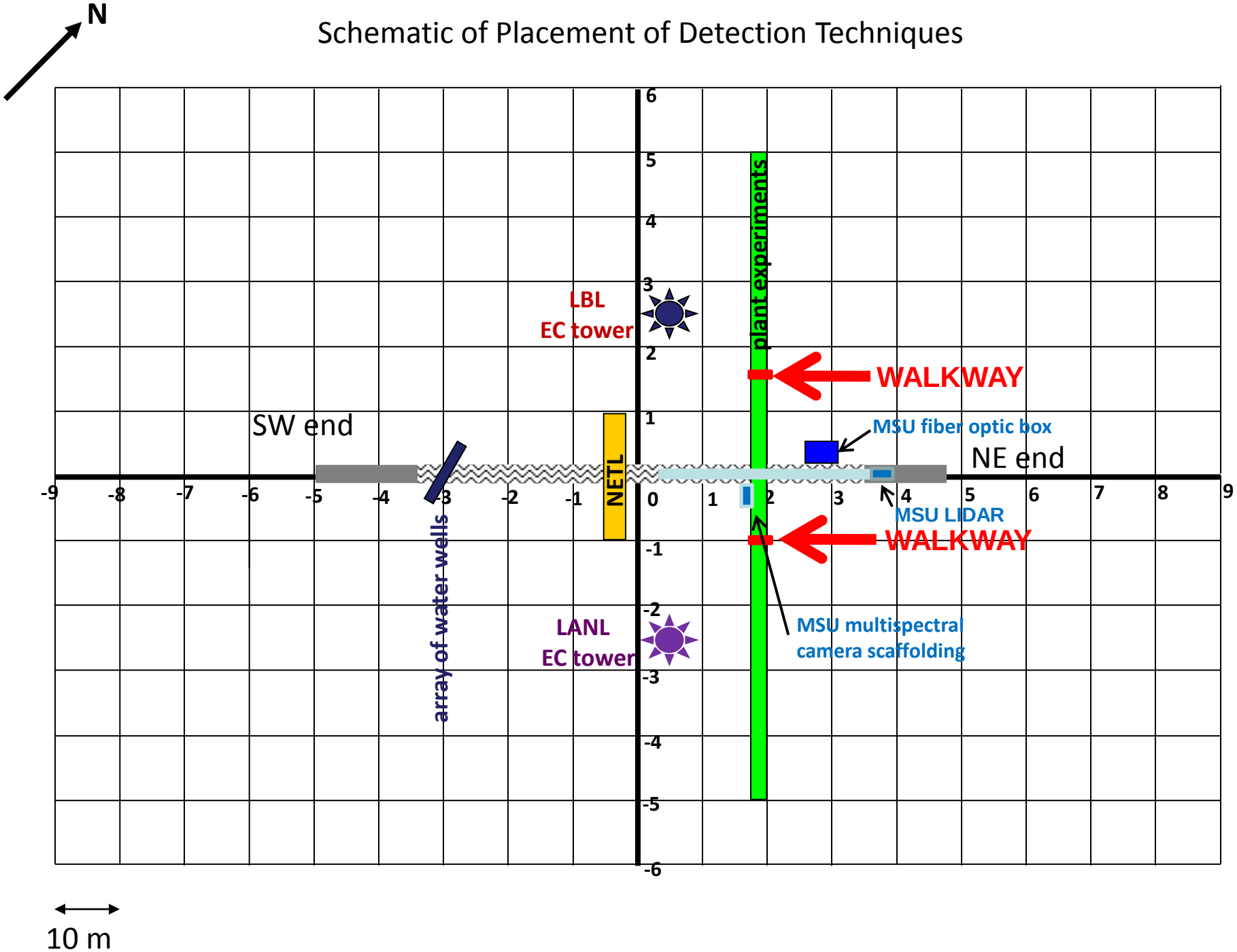
Project summary (objectives, overview)

Project summary (Objective 1 MSU UM-MTECH, highlights yr1, expected yr 2)

Project summary (Objective 2 UM, UM-MTECH,MSU, highlights yr1, expected yr2)

Review questions

Schematic of Placement of Detection Techniques



Pump

- Teledyne Isco 500D syringe pump
  - Constant flow or constant pressure injection
  - High pressure
  - Corrosion resistant
  - Tracking of injection pressure, total volume delivered, and run time

Core Holder

- Temco HCH-1
  - Bi-axial core holder
  - Floating distribution plug/injector
  - Working pressure of 2,500 psi
  - Variable core length

Core Sleeve

- Viton, PVC, Buna-N nitrile, neoprene, rubber, and Tygon tubing incompatible with $ScCO_2$
  - Significant reaction with $ScCO_2$ and sleeve
  - Diffusion of $ScCO_2$ through sleeve

Core Sleeve

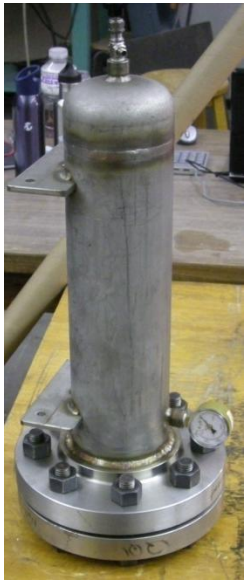
- Compatible materials
  - Polypropylene
  - Kynar® (PVDF)
  - Teflon® (PTFE)
- Too rigid
- Solution
  - Tygon core sleeve
  - Core wrapped in aluminum foil

Incubator

- VWR 1555 General Purpose Incubator
  - Temperature control
  - Safety
    - Enclosed high pressure system
    - Glass doors
  - 11.25 cu. ft. capacity allows for expansion

Batch Test Cylinder

- Static Batch Tests
  - High pressure steel cylinder (3,000+ psi)
  - Static exposure
  - More realistic of far reservoir conditions



Summary

- No statistically significant changes in porosity, permeability, or pore volume in sandstone cores challenged with $ScCO_2$ ($\alpha = 0.05$)
  - No bulk density changes
  - Small decrease in grain volume in Berea sandstone cores injected
    - Minor pore volume increase
    - No porosity or permeability increase
  - Statistical analysis shows changes due to instrumentation and random chance

Summary

- No statistically significant changes in porosity, permeability, or pore volume in carbonate cores challenged with $ScCO_2$ ($\alpha = 0.01$)
  - No bulk density changes
  - Small permeability, porosity, and pore volume, changes
    - Decrease in grain volume in injected carbonate cores
    - No significant change in pore volume, porosity, or permeability
  - Statistical analysis shows changes due to instrumentation and random chance

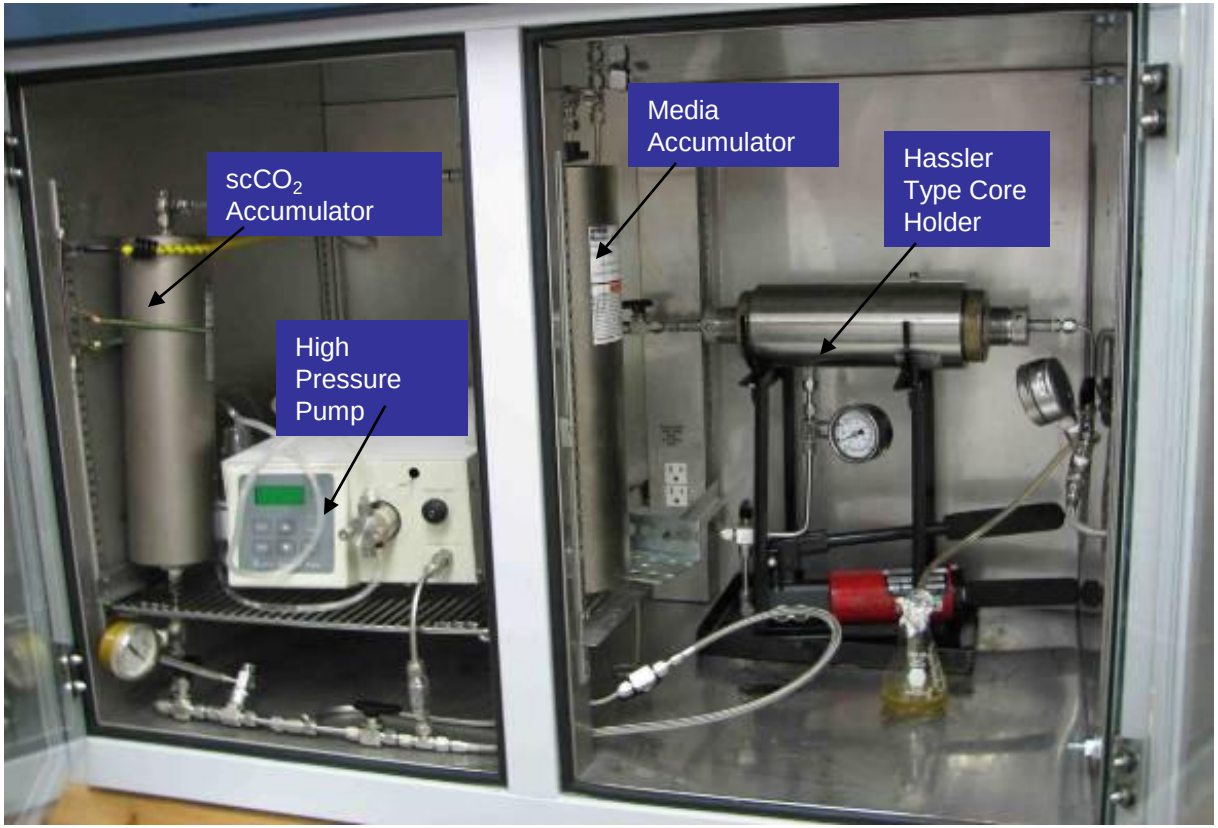
Conclusions

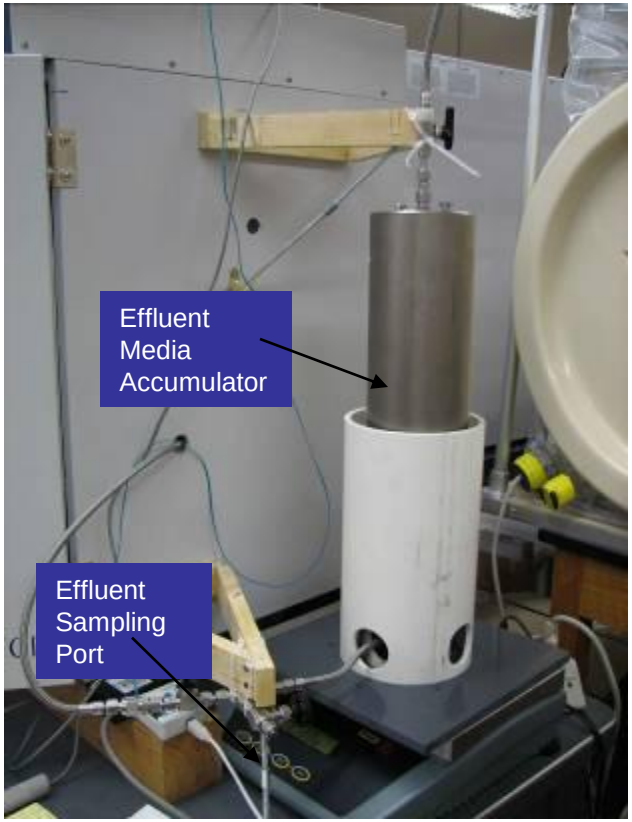
- Succeeded in design and setup of injection apparatus
  - Maintain constant temperature conditions
  - Capable of handling high pressure $ScCO_2$
  - Expandable for future work
- Obtained baseline data
  - No significant flow property changes in sandstone, limestone, and dolomite core samples due to short term exposure to $ScCO_2$

High Pressure Rock Core Testing System

~1500 psi (100 bar) supercritical fluids

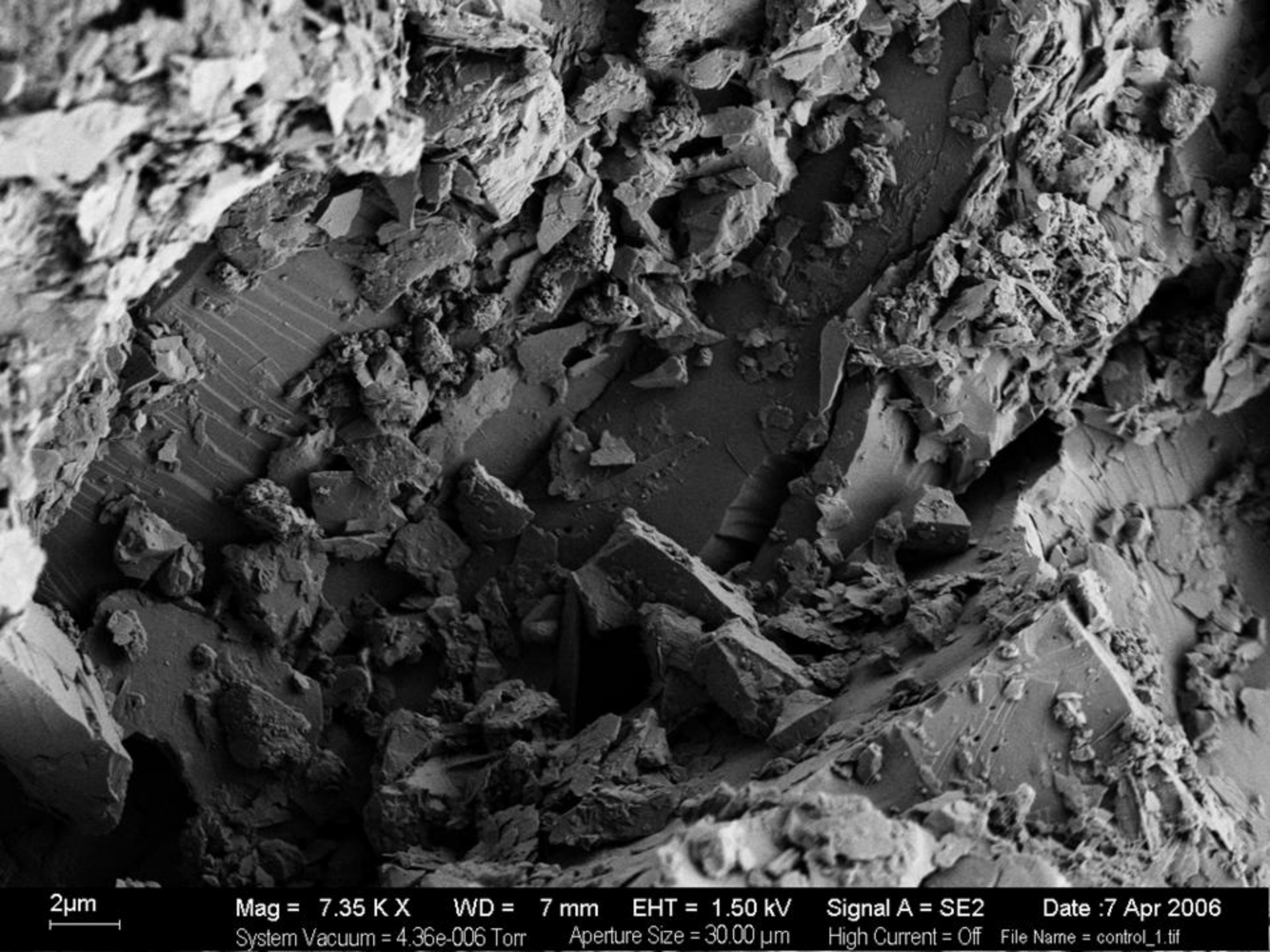
~65 degrees C Objective 1





Finding #3 Biofilm Accumulation

- **Destructive sampling of the Berea sandstone core**
- **Thin sections cut off core**
- **Image Analysis:**
  - Field Emission SEM Zeiss® Supra 55VP (Montana State University ICAL)
  - Stain w/ Syto 9® (Molecular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Mag = 7.35 K X
WD = 7 mm
EHT = 1.50 kV
Signal A = SE2
Date :7 Apr 2006
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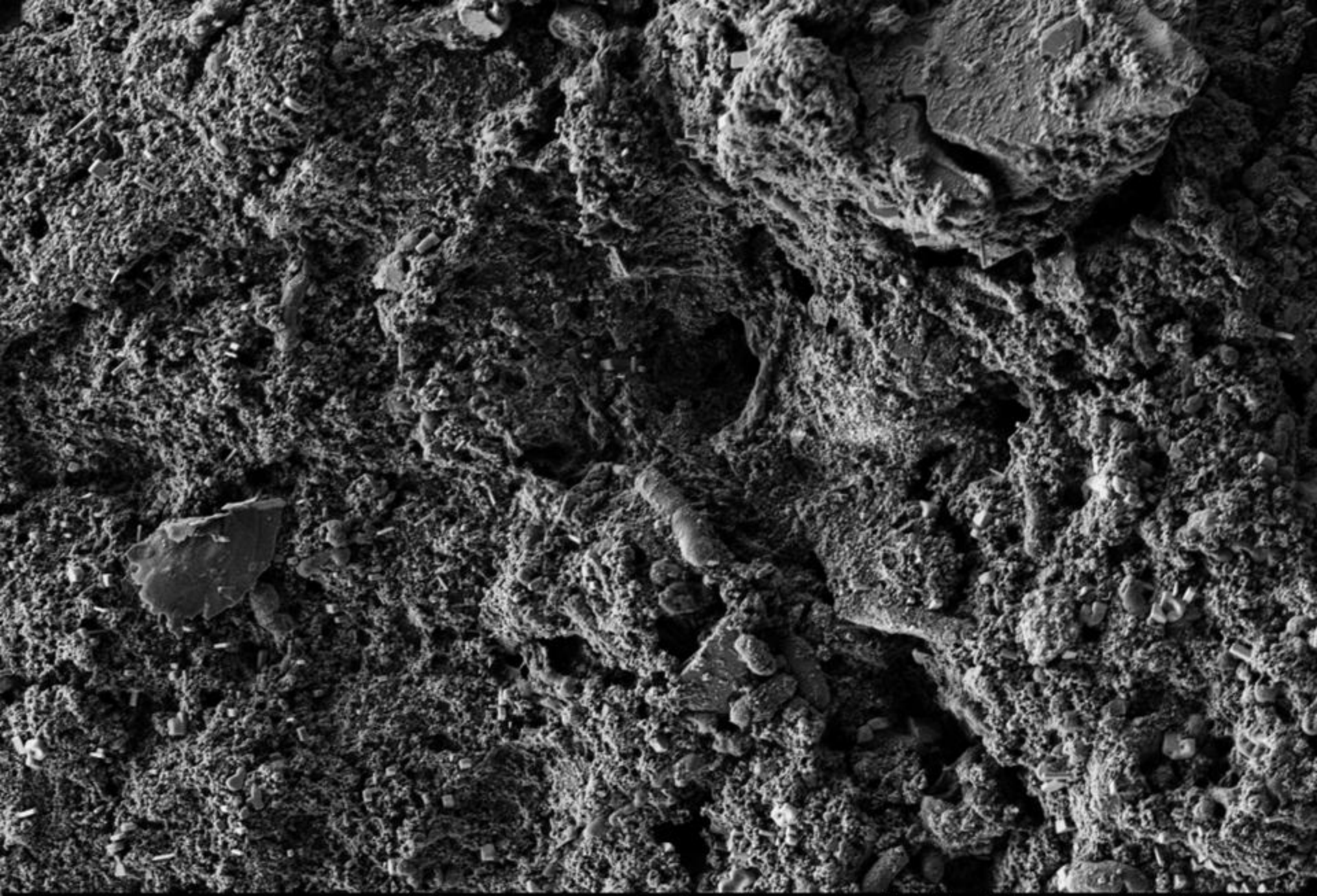
Aperture Size = 30.00 µm
High Current = Off
File Name = control_1.tif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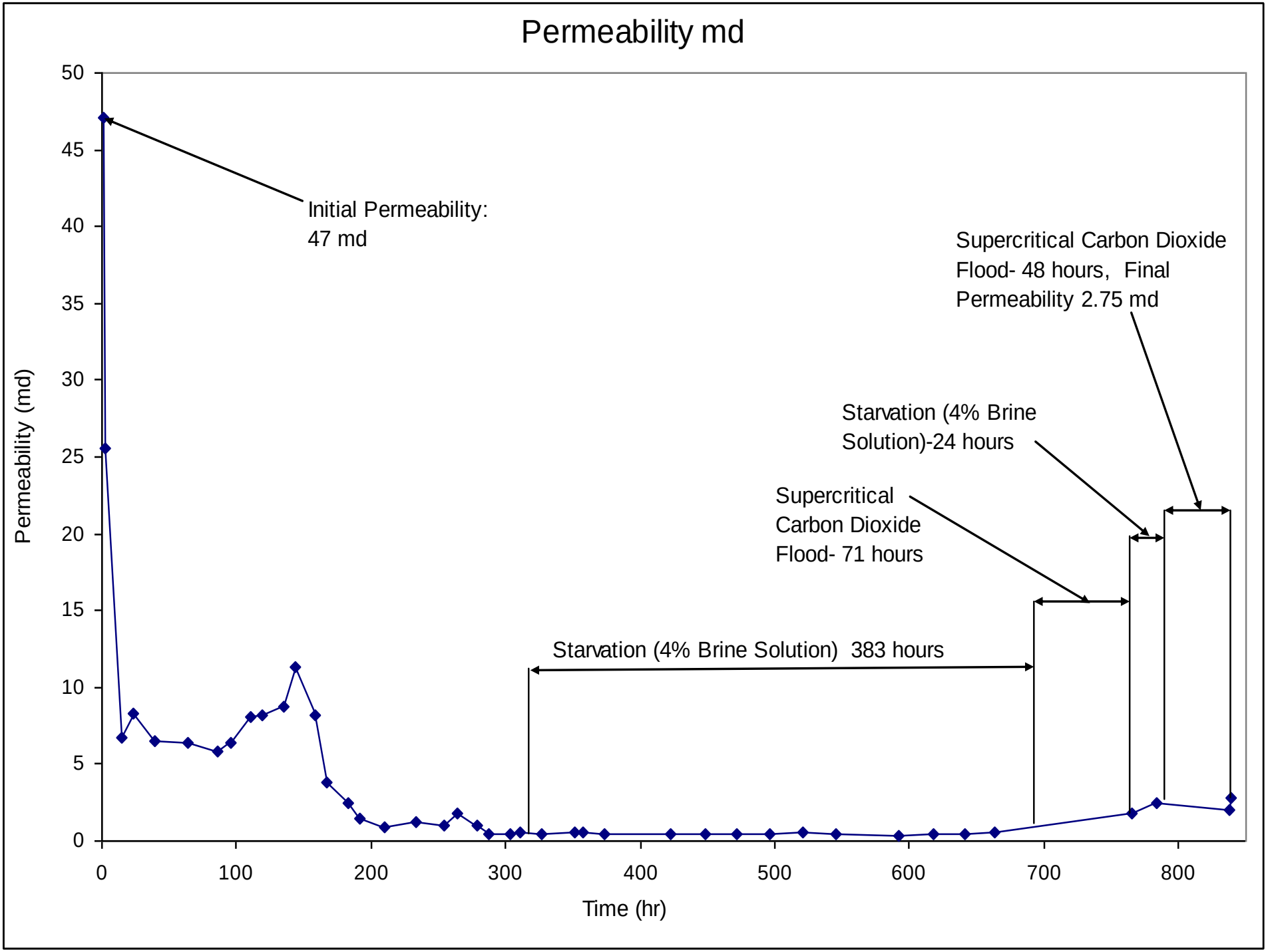
Permeability md
Permeability (md)
Time (hr)
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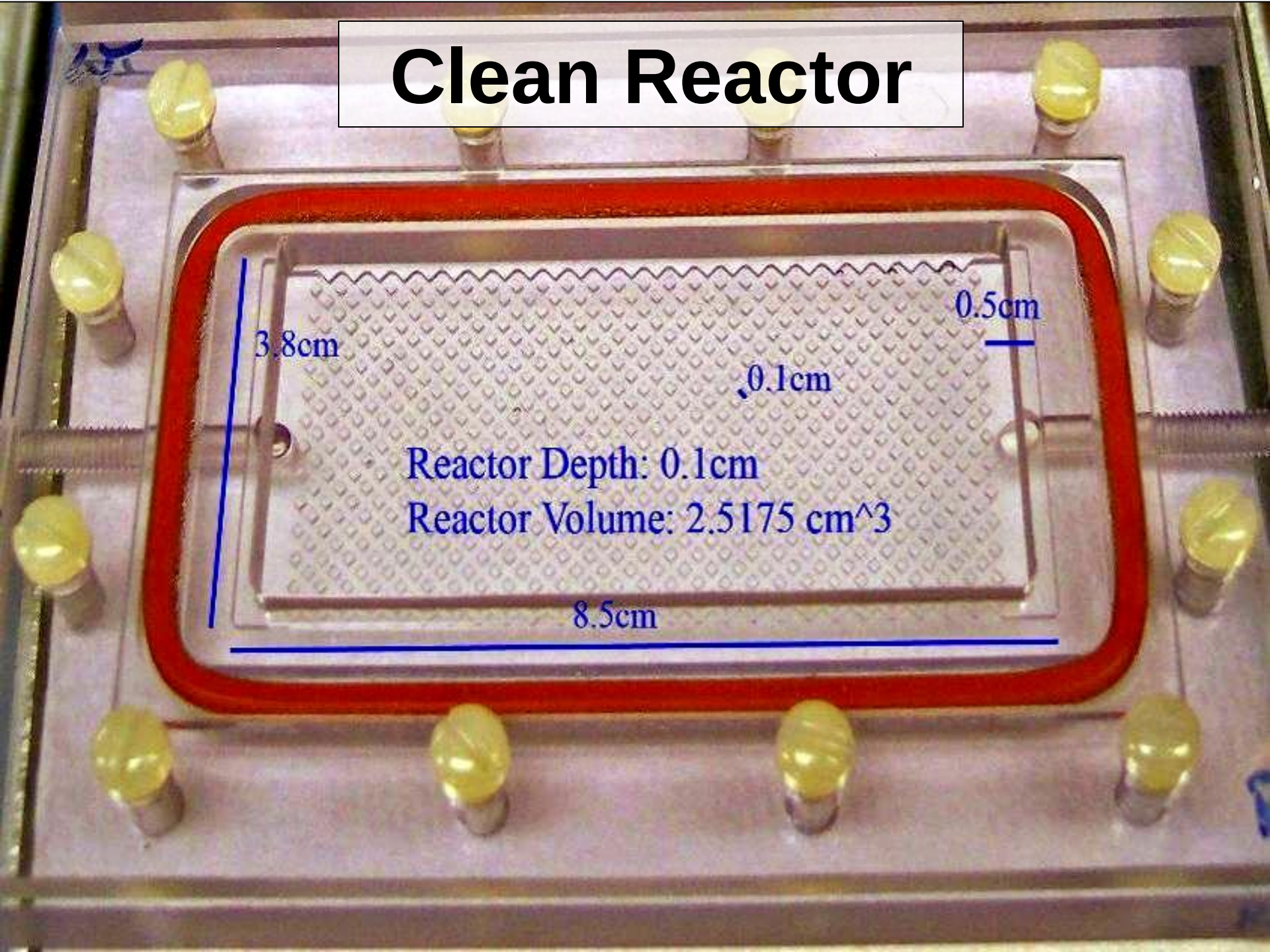
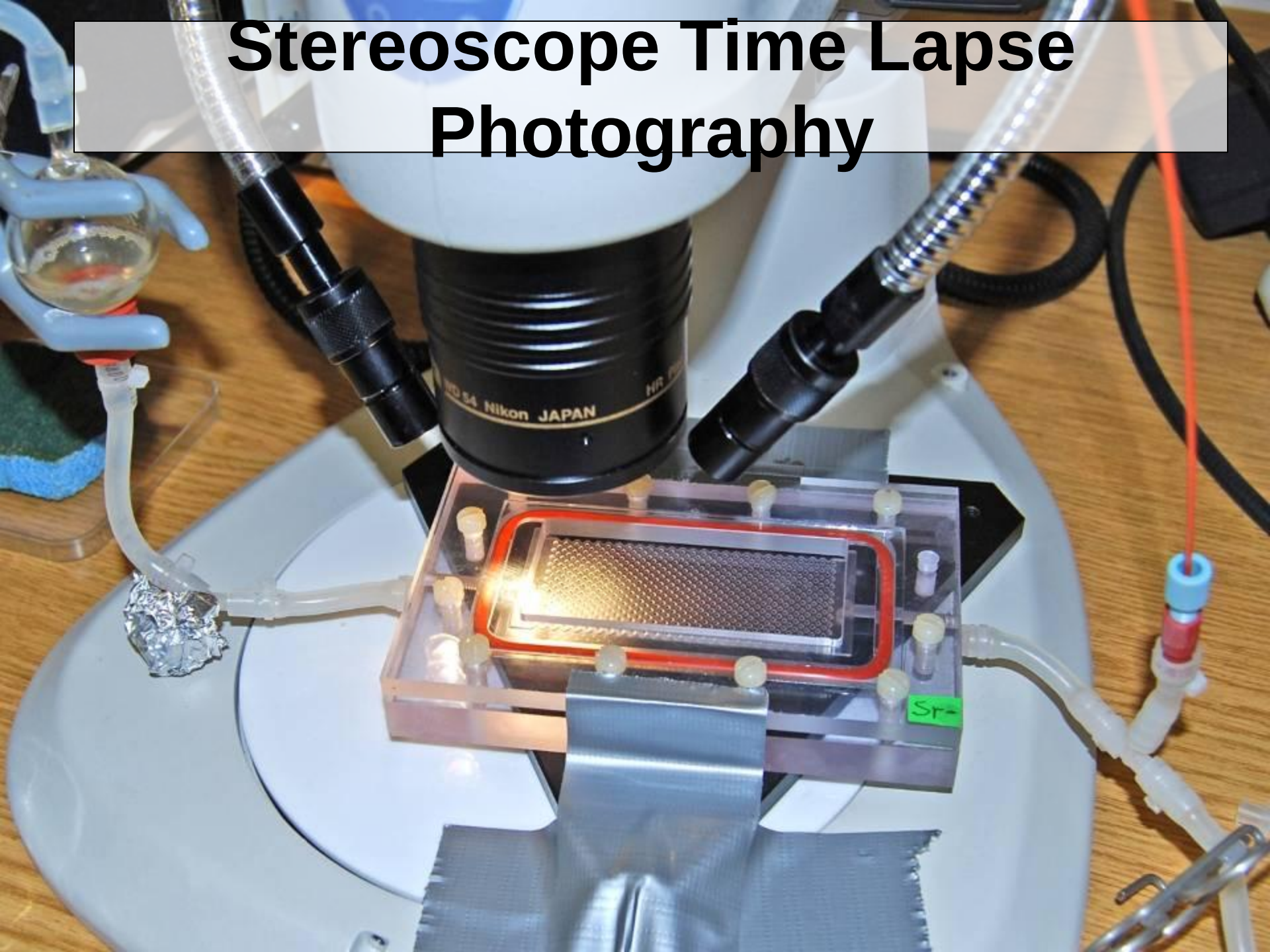
10
15
20
25
30
35
40
45
50
0
100
200
300
400
500
600
700
800
Initial Permeability:
47 md
Supercritical Carbon Dioxide
Flood- 48 hours, Final
Permeability 2.75 md
Starvation (4% Brine
Solution)-24 hours
Supercritical
Carbon Dioxide
Flood- 71 hours
Starvation (4% Brine Solution) 383 hours

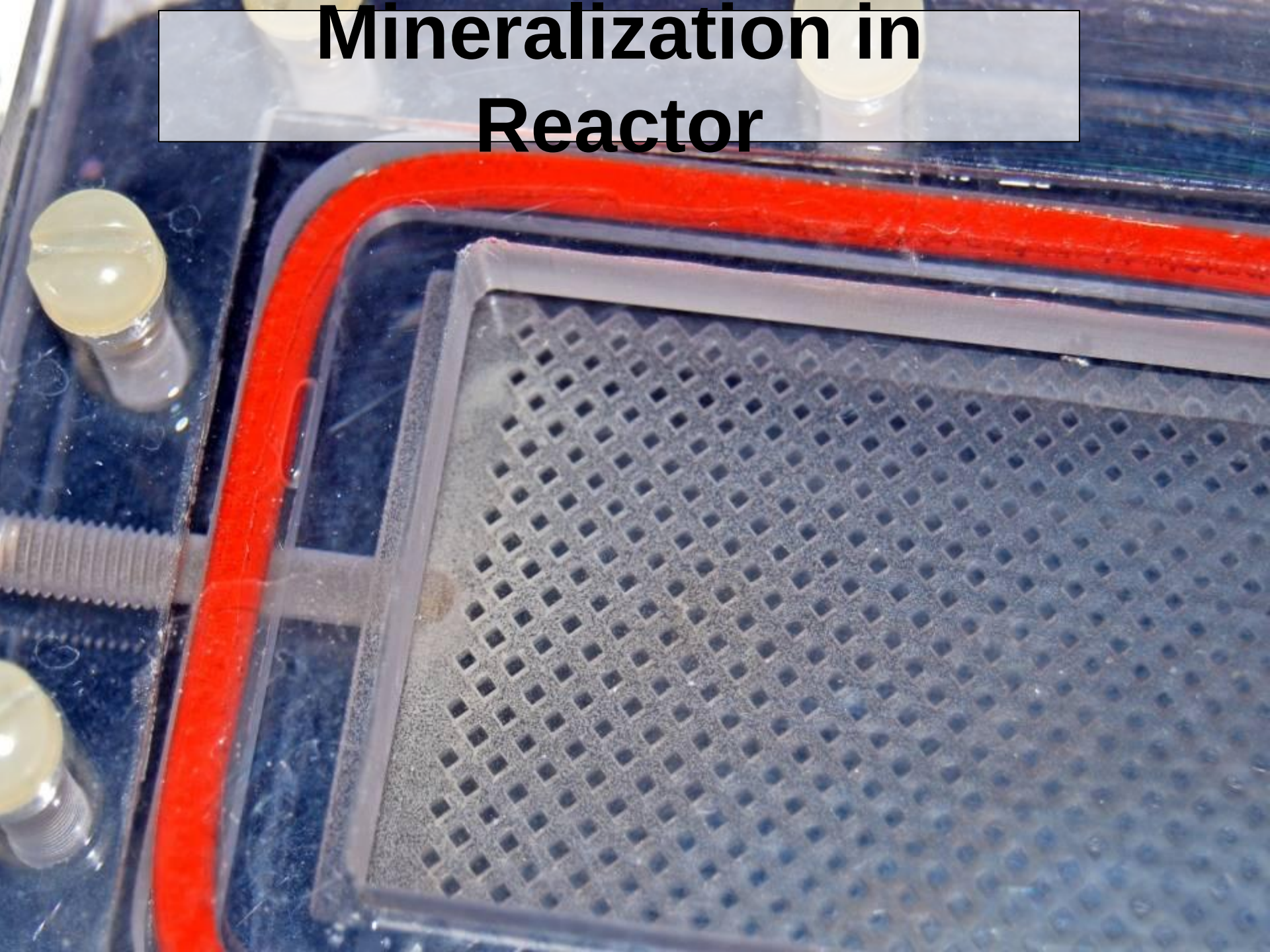
Clean Reactor



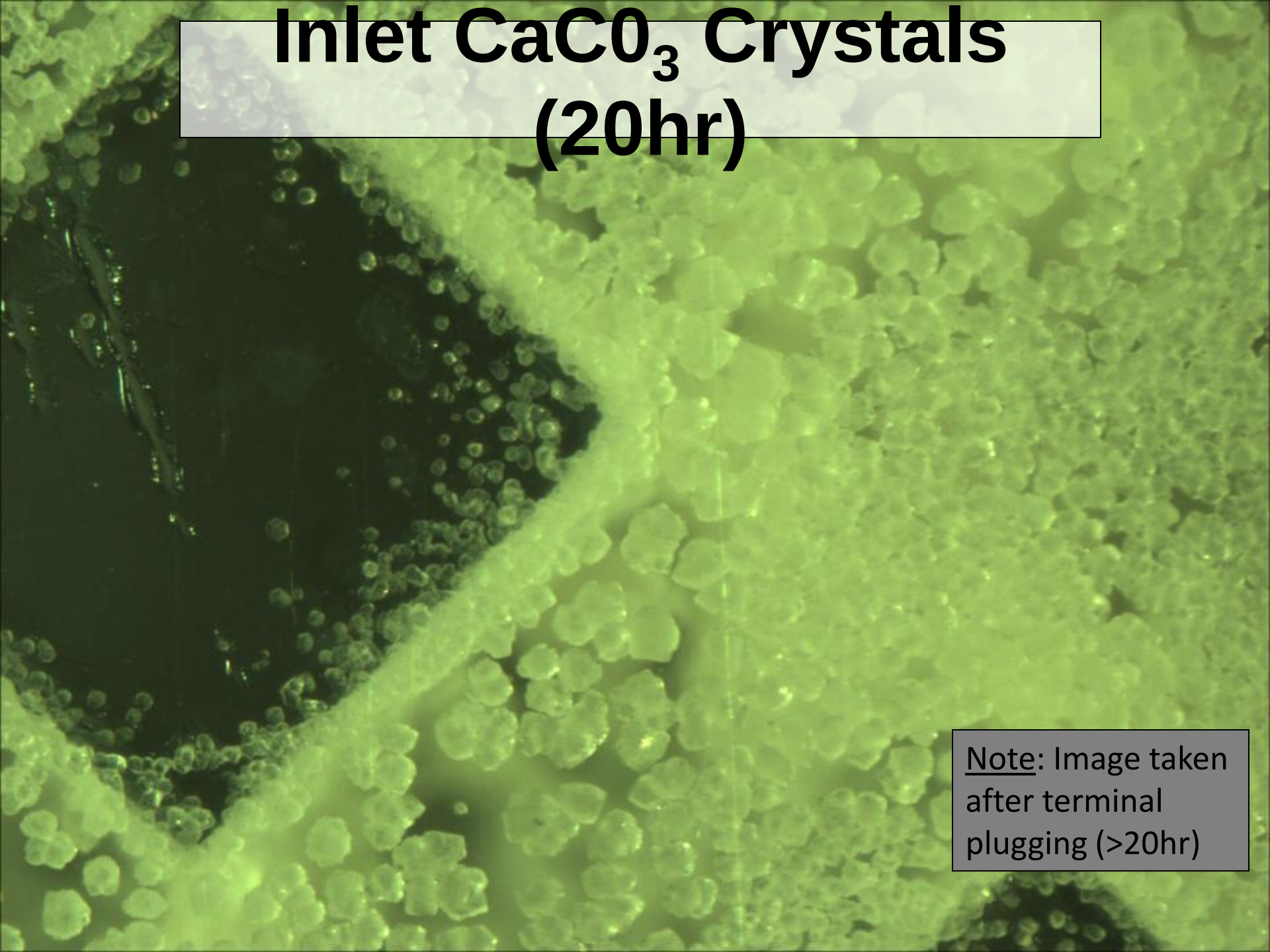
Stereoscope Time Lapse Photography



Mineralization in Reactor

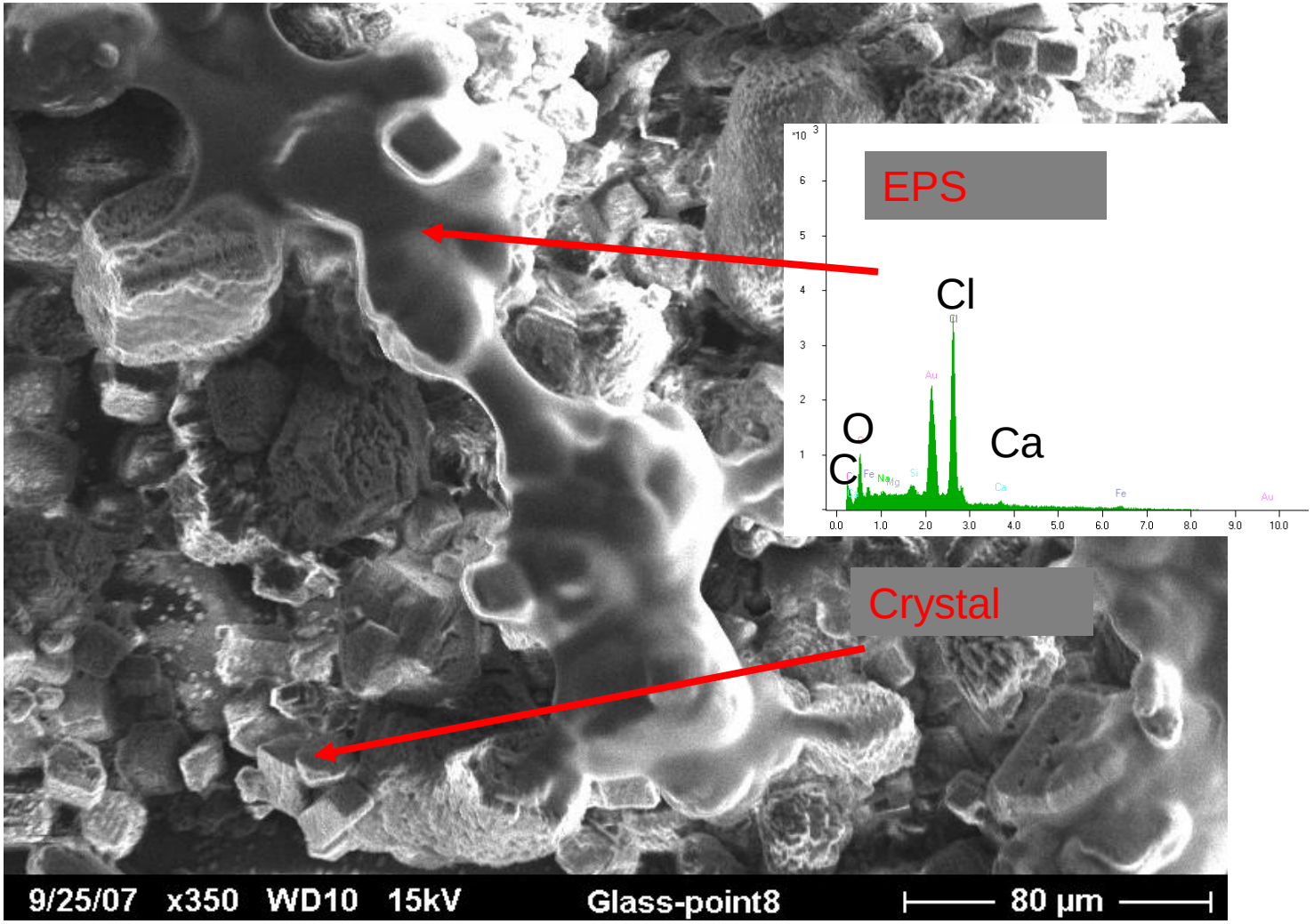


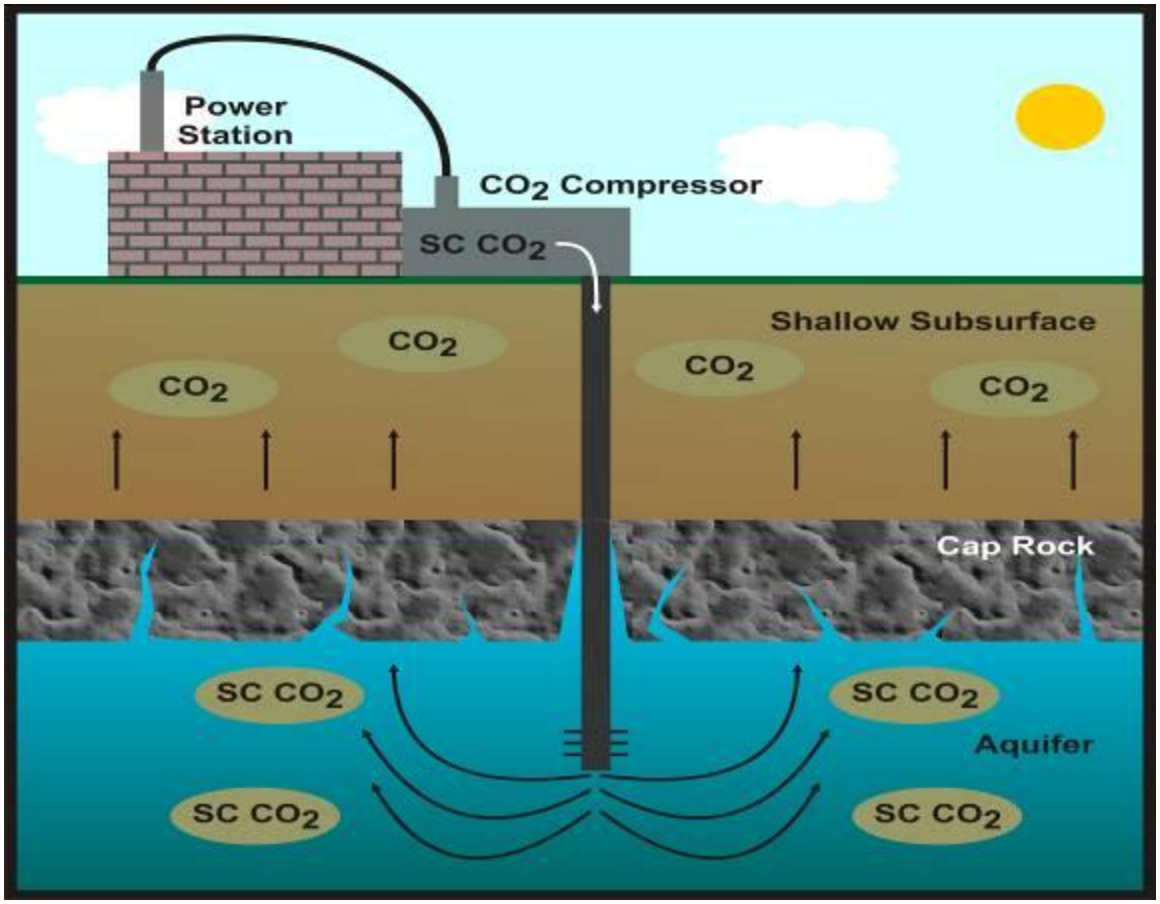
Inlet $CaC0_3$ Crystals (20hr)

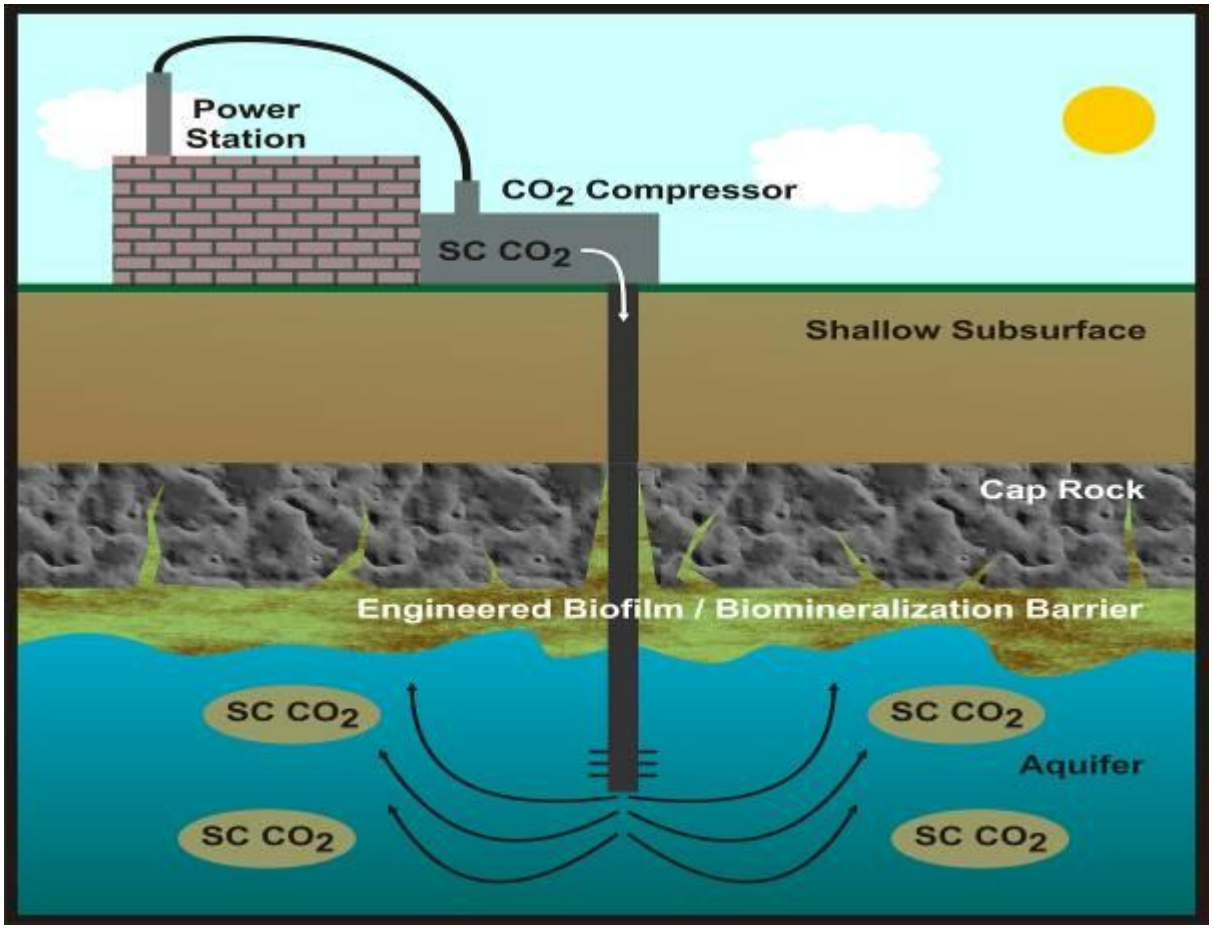


Note: Image taken after terminal plugging (>20hr)

Biomineralizing Biofilms




Power Station
CO_2 Compressor
SC CO_2
Shallow Subsurface
CO_2
CO_2
CO_2
CO_2
Cap Rock
SC CO_2
SC CO_2
Aquifer
SC CO_2
SC CO_2


Power Station
CO_2 Compressor
SC CO_2
Shallow Subsurface
Cap Rock
Engineered Biofilm / Biomineralization Barrier
SC CO_2
SC CO_2
Aquifer
SC CO_2
SC CO_2

Finding #3 Biofilm Accumulation

- **Destructive sampling of the Berea sandstone core**
- **Thin sections cut off core**
- **Image Analysis:**
  - Field Emission SEM Zeiss® Supra 55VP (Montana State University ICAL)
  - Stain w/ Syto 9® (Molecular

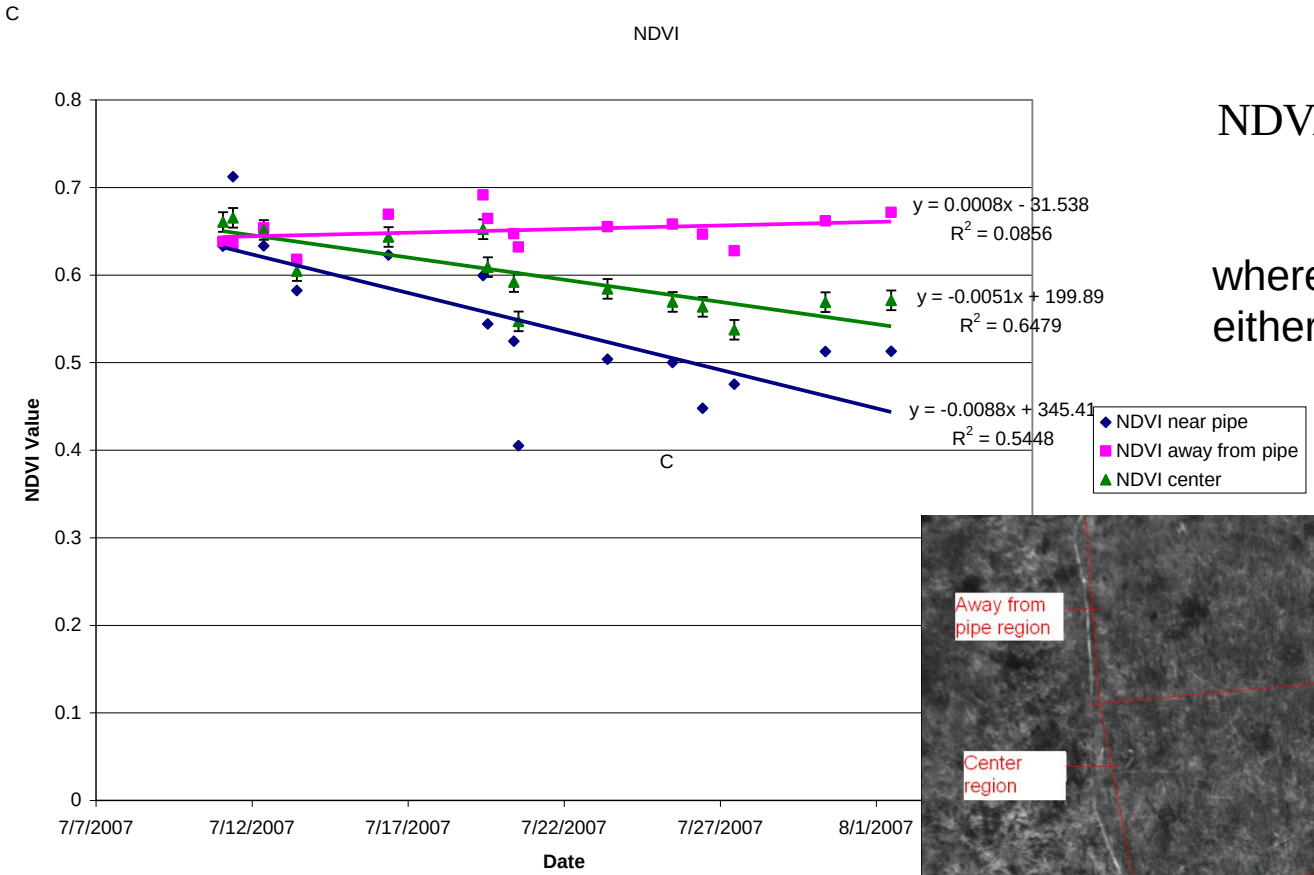
Engineered Biofilm/Biomineralization Barriers

Injection of fluids and nutrients into subsurface formations can cause the formation of thick microbial biofilms, along with biomineralization deposits, which plug free pore space, reduce porosity and permeability, and modify activity (i.e. formation plugging, and engineered (reactive) biofilm barriers)

Vertical Injection Site

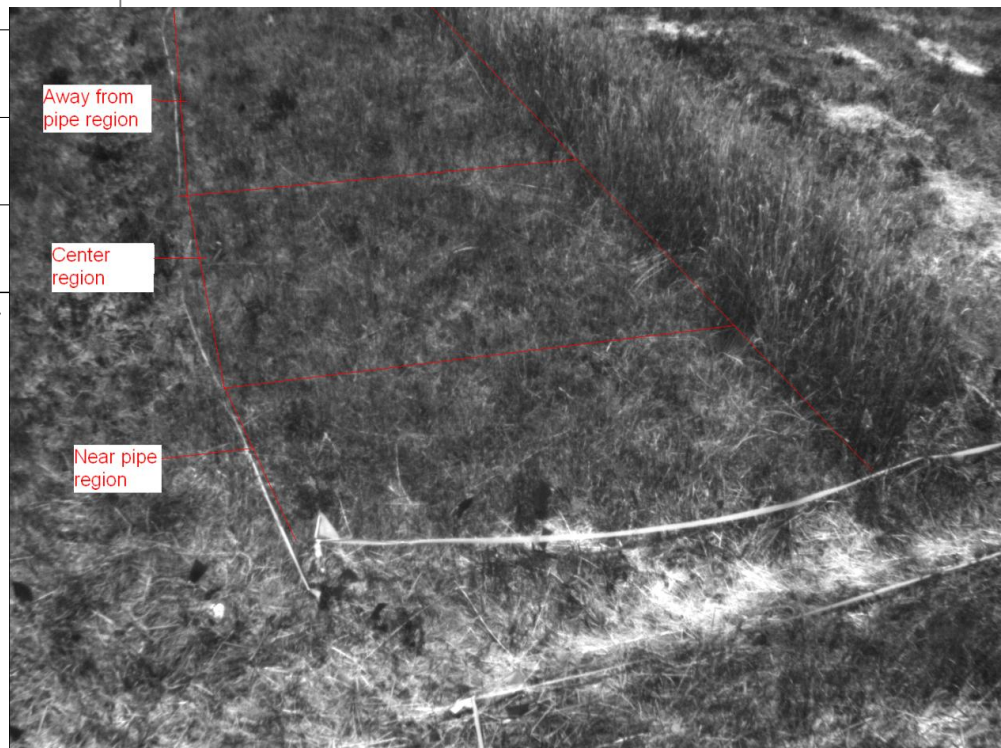
NDVI from Multi-spectral Imaging

Joe Shaw



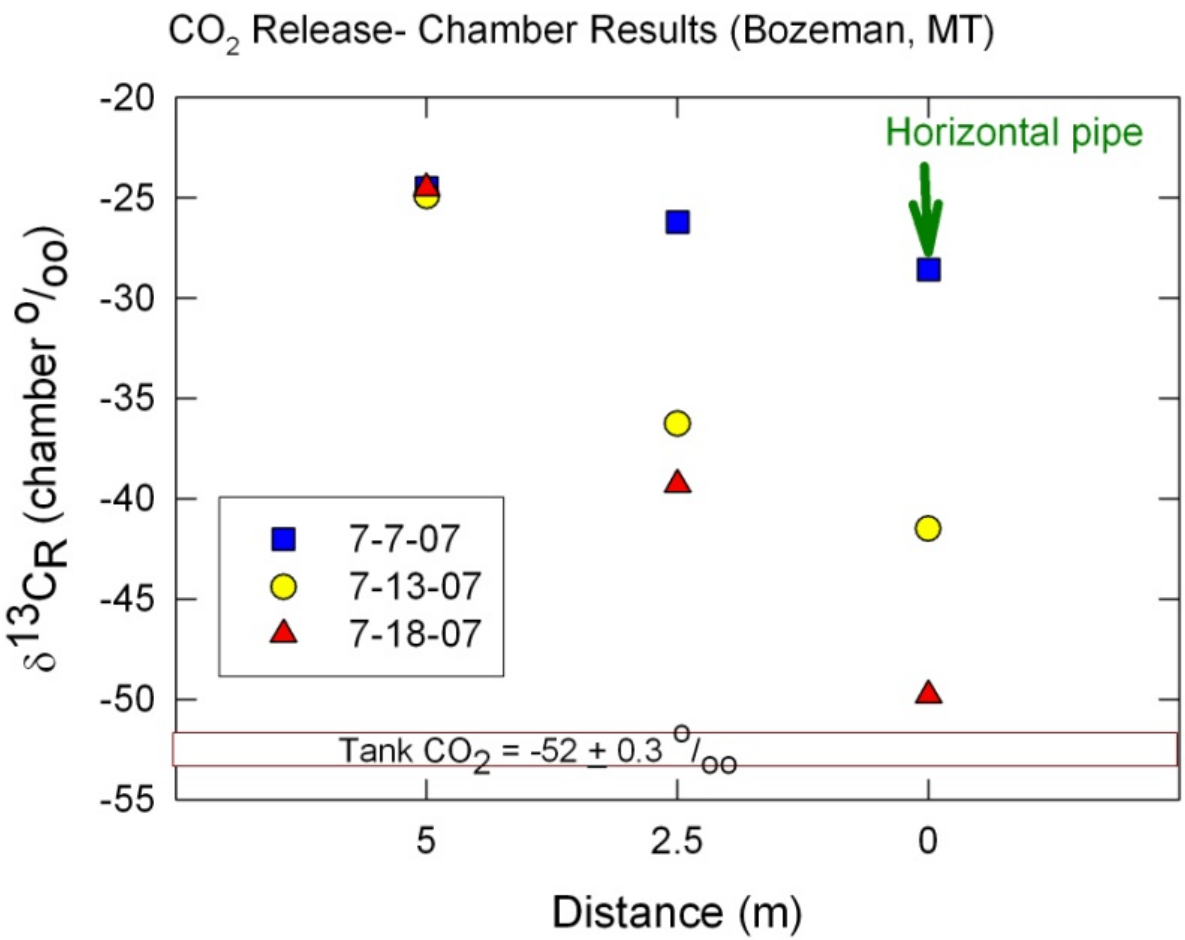
$$\mathrm{NDVI} = \frac{\rho_{\mathrm{NIR}} - \rho_{\mathrm{red}}}{\rho_{\mathrm{NIR}} + \rho_{\mathrm{red}}},$$

where ρ is the reflectance for either the NIR or red band.



Isotopic Studies

Julianna Fessenden

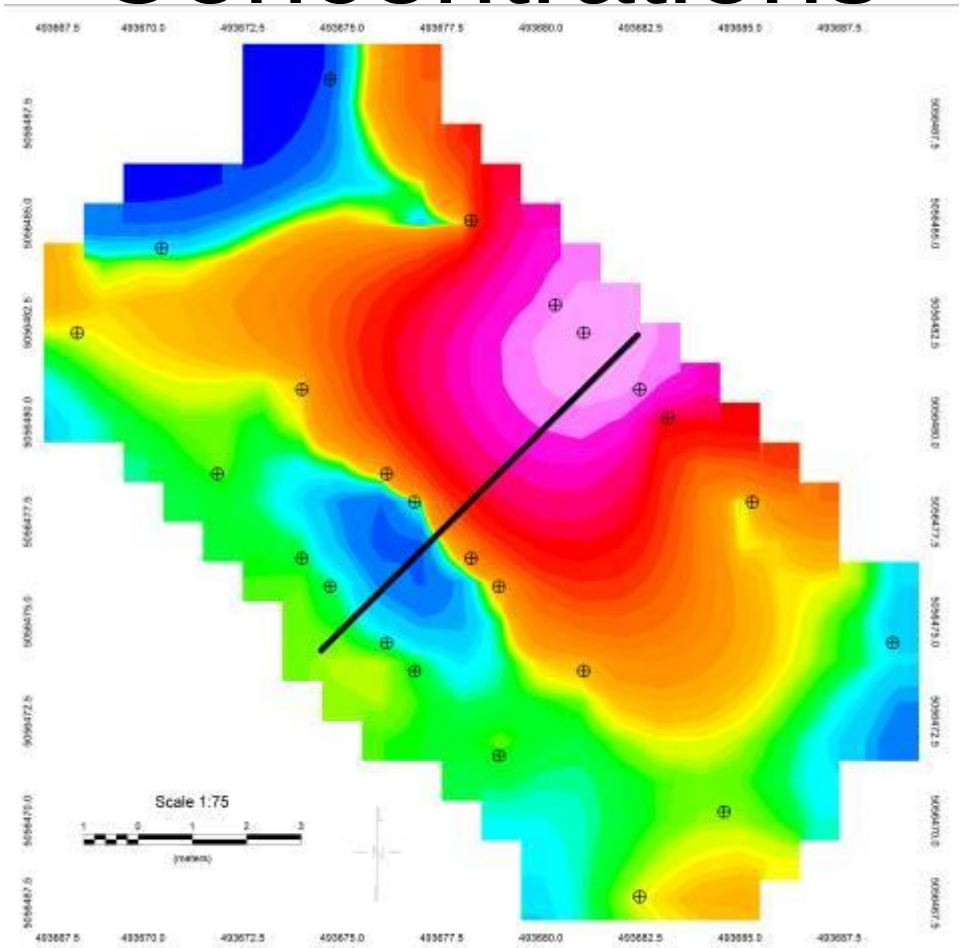


Isotopes measured on CO_2 from chambers collected on July 7, 13, and 18, 2007. Keeling plot results (intercept values of $\delta^{13}C$ vs. 1/[CO2] measured from CO2 in chamber air.

MONTANA STATE UNIVERSITY

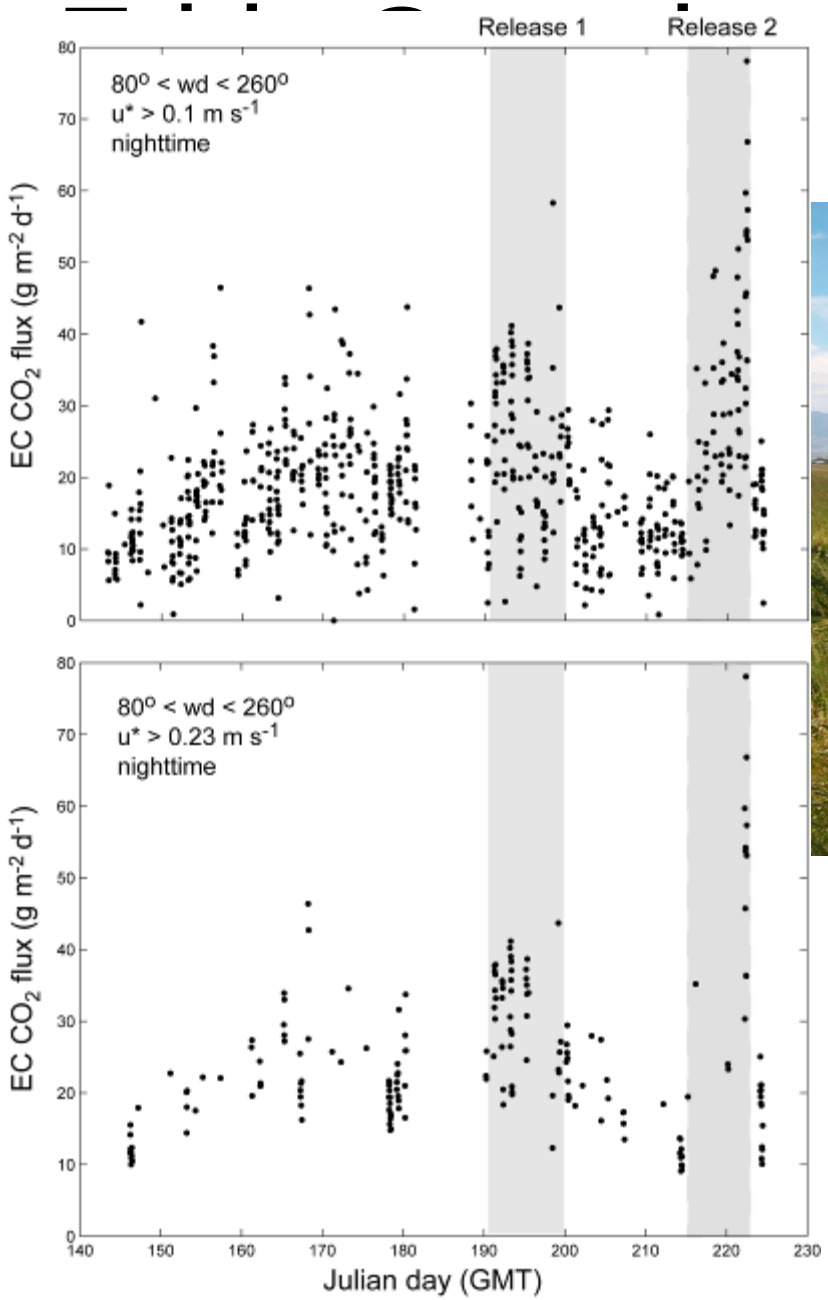
ZERT Horizontal Well Tracer Concentrations

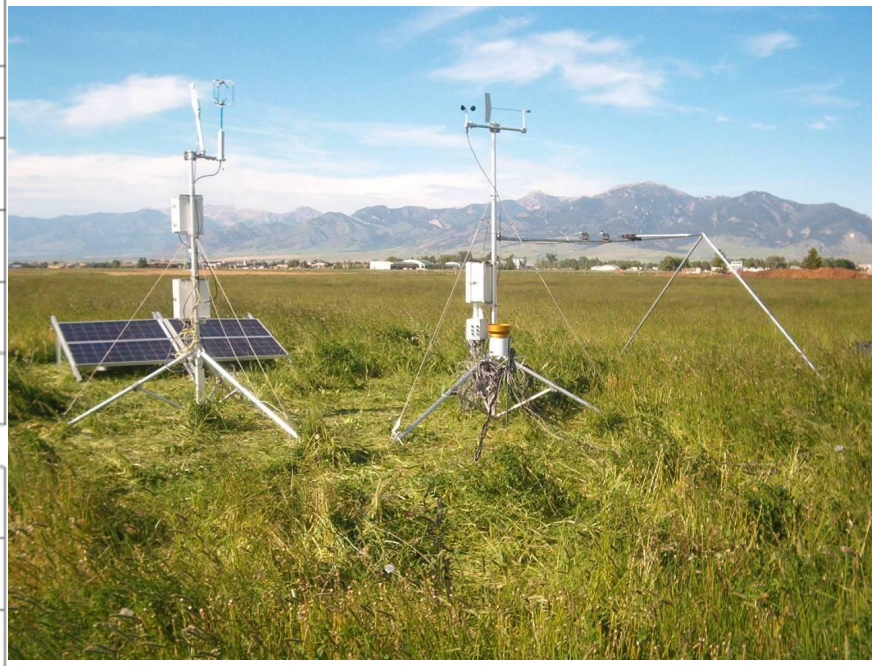
Art Wells



ce Method

Jen Lewicki

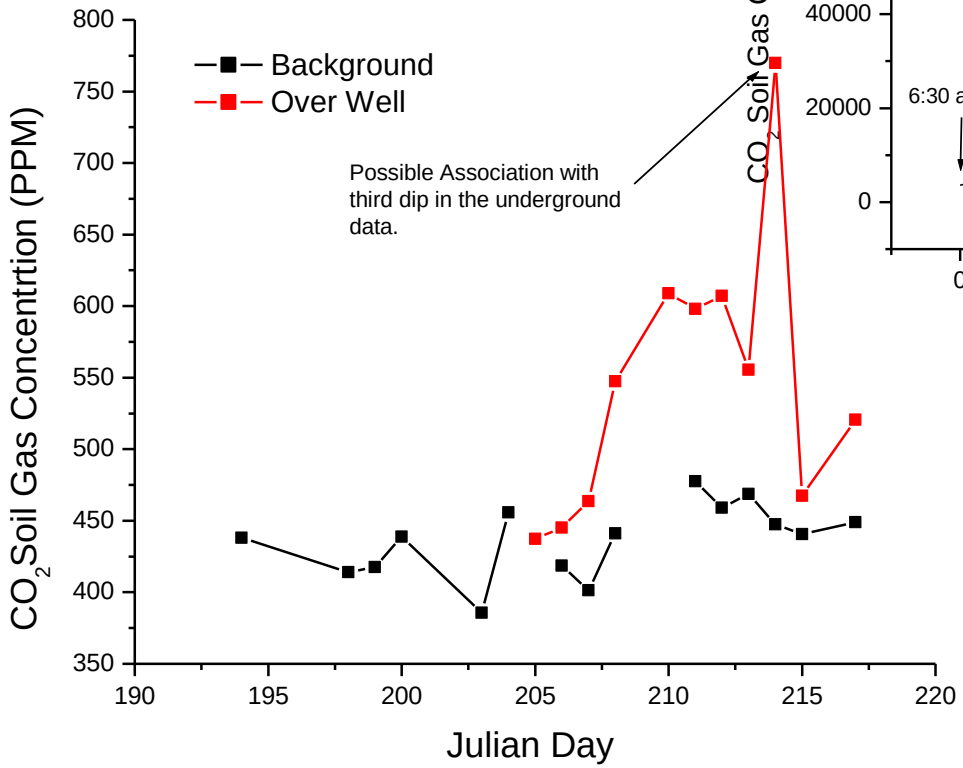


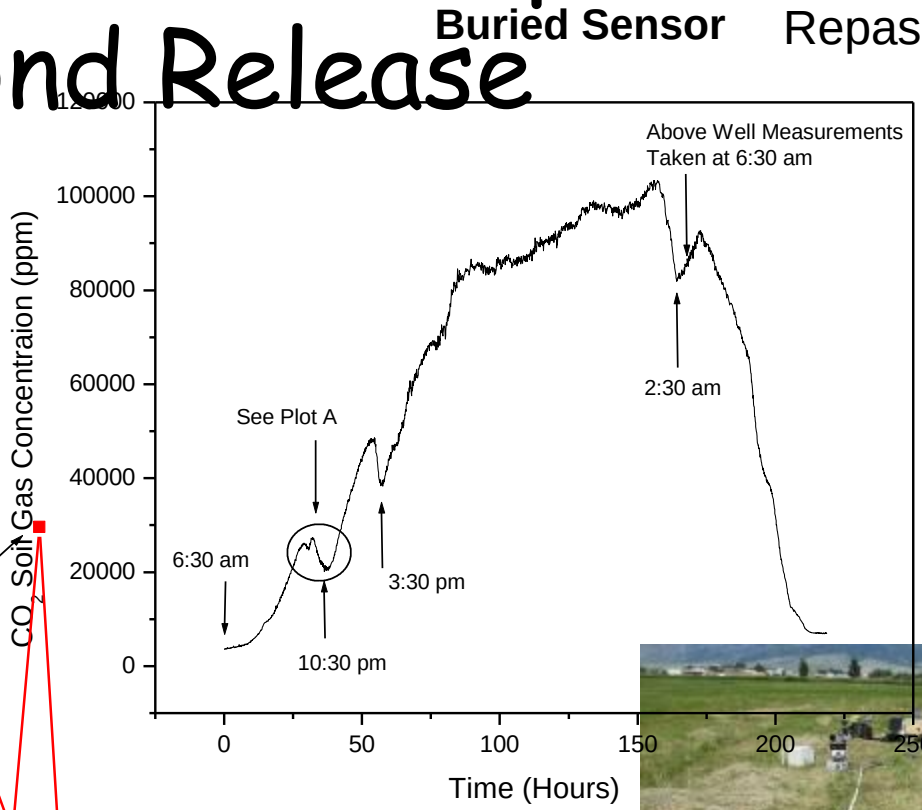


Flux Tower

Laser Soil Gas Atm Comparison - Second Release

Repasky





Conclusions

- Future work
  - Various injection rates, injection volumes, and exposure times
  - Material property changes
  - Brine, oil, or combinations of oil/brine saturated core injections
  - Other rock types
  - Chemical/polymer flooding
  - MEOR flooding
  - Geological sequestration studies

Utilizing the bacterial community as an early warning system for elevated CO2 seepage from belowground

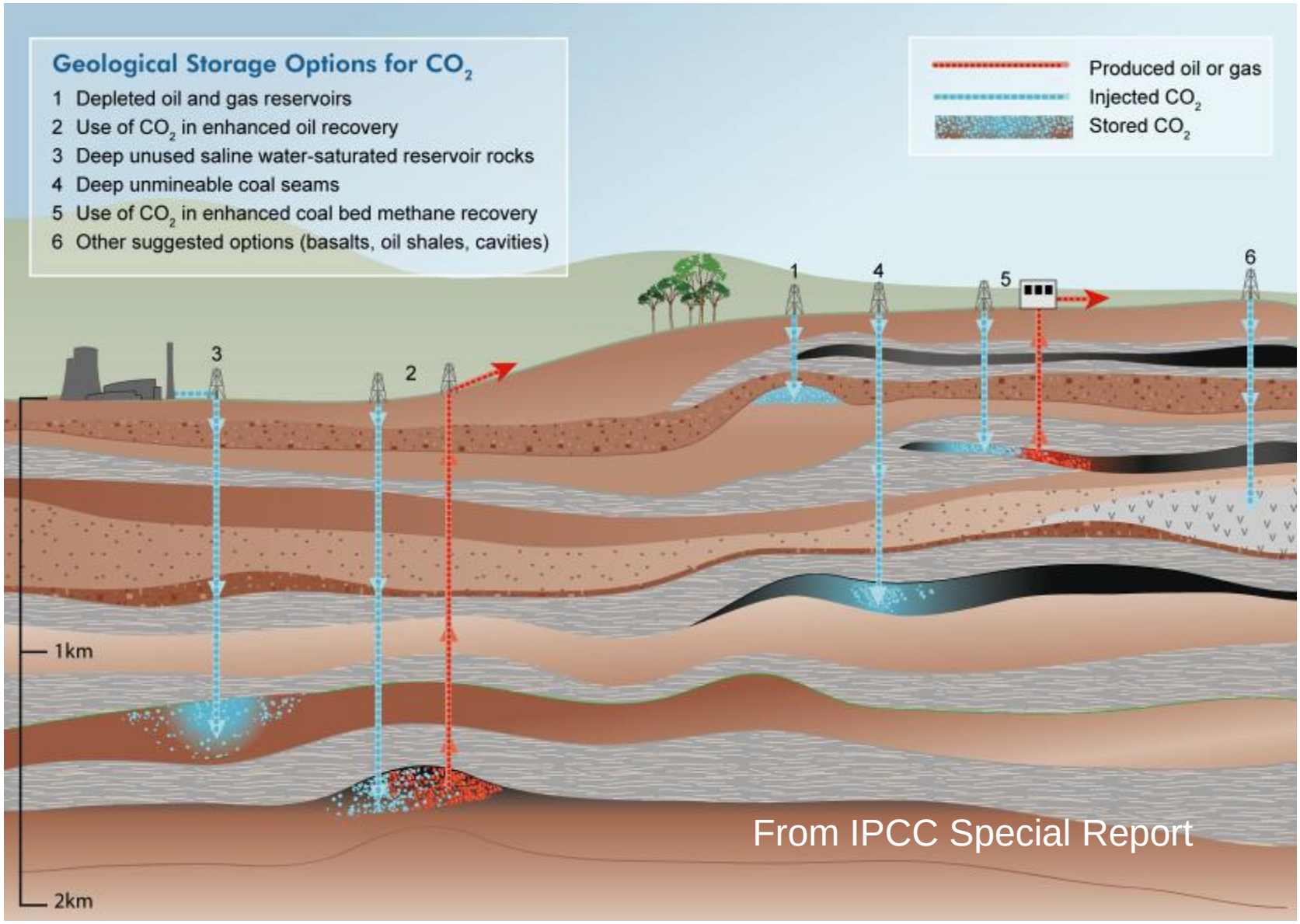
Research Assistant Professor Sergio E. Morales and Professor William Holben
The University of Montana

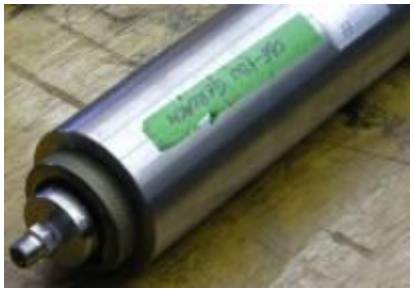
The UM Microbial Ecology Group is investigating the effects of CO2 on microbial community biomass, composition and activity on samples from the ZERT facility

Soil samples will be analyzed for bacterial abundance by fluorescence microscopy, and nucleic acids will be extracted for use in quantitative PCR for measurements of gene abundance (DNA copy number) and gene expression (RNA copy number) within the soils

Anticipated benefits

Options for Geological Storage



From IPCC Special Report

Experimental Design