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Engineered In-Situ Uranium Precipitation:

An Emerging Approach to Groundwater Remediation

Boyce Clark, Jeff Gillow, Craig Divine, Richard Murphy, John Horst
ARCADIS U.S., Inc.
Baton Rouge, LA ; Denver, CO; Newtown, PA

Application of Anaerobic In-Situ Uranium Bioreduction: Essential Design Elements

- Aqueous geochemistry
  - •Redox conditions
  - •Concentrations of oxidants
  - •Uranium speciation = Inferred from aqueous geochemical parameters
- Hydrologic conditions
  - •Groundwater velocity
  - •Hydraulic conductivity
  - •Infiltration through vadose zone
- Soil geochemistry
  - •Concentration of reducible minerals
  - •Buffer capacity of soil

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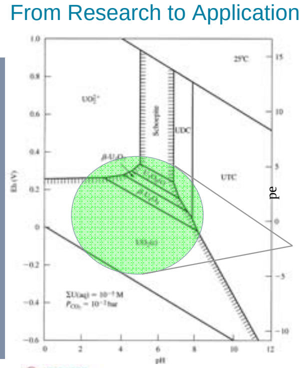
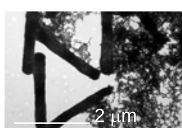
Uranium Bioreduction: From Research to Application





Precipitation of U(IV) by anaerobic bacteria)

$$UO_2^{2+}{}_{(aq)} + 2e^- = UO_{2(c)}$$

- Treats adsorbed uranium mass
- Transforms uranium to stable form found in natural ore bodies
- Creates additional reduced mineral mass to ensure stability over geologic timeframes

Langmuir, 1997

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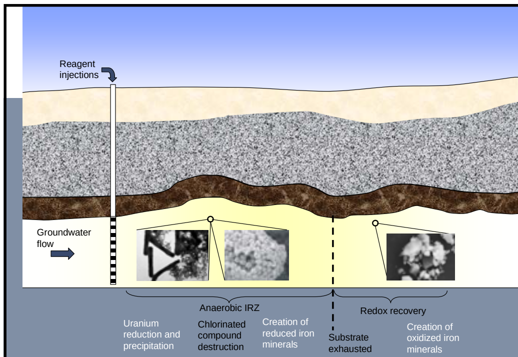

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Anaerobic In-Situ Uranium Bioreduction: Challenges

- Reagent distribution: remediation hydraulics
- Potential for uranium re-oxidation after active remediation phase
- ‘Transient’ hydrologic conditions
- Geochemical modeling
- Regulatory acceptance
  - Held to a higher standard than other technologies (P&T)
  - Application to sites that will be released for unrestricted use
  - Long-term monitoring requirements?

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Remediation Concept

- Addition of e-donor (molasses) results in precipitation of uranium, reduction of iron, and formation of iron sulfide
- Depending upon baseline mineralogy, additional iron and sulfate is added
- Post-remediation aquifer characterization
- Geochemical modeling to simulate the oxidation of reduced iron, creation of iron (hydr)oxides and combination of oxidant scavenging and uranium sorption to maintain uranium below MCL
- Oxidative aging testing to quantify iron transformation

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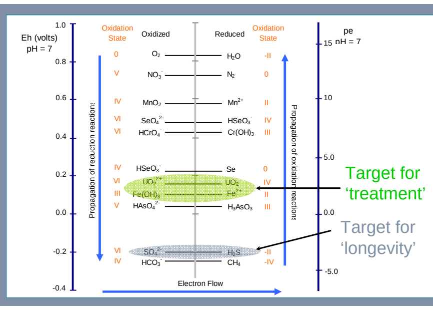
Sequence of Electron Donor Utilization



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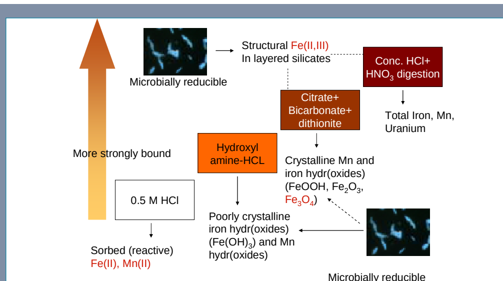
Baseline Characterization: Selective Extraction of Fe, Mn, U from Aquifer Solids



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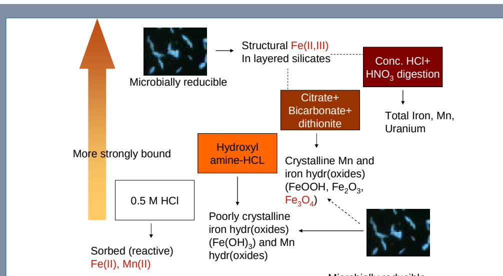
Baseline Characterization: Selective Extraction of Fe, Mn, U from Aquifer Solids



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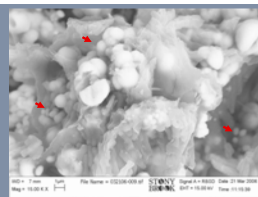
Baseline and Post-Remediation Characterization: Secondary Mineralization of Ferrihydrite (Biogenic Mineral Formation) with Glucose

Prior to Microbial Activity: SEM of ferrihydrite ("2-line ferrihydrite" $Fe_5HO_8{\cdot}4H_2O$; surface area: 331± 2 m^2/g; 592 ± 1 ug Fe/mg)



After Microbial Activity: SEM analysis shows magnetite spherules (Fe_3O_4 (mixed-valent iron)), bacterial cells and exopolymer. Bacteria were grown on glucose.

Gillow, 2006, in-prep.

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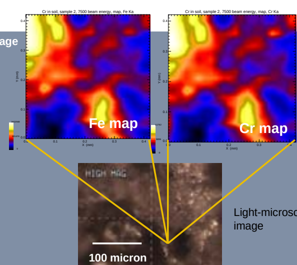
Post-Remediation Characterization

Advanced solid-state analyses for remediation end-points

x-ray fluorescence image

100 micron



Light-microscope image

Fe/Mn-rich (w/ trace Cr)

- X-ray fluorescence microprobe of sand shows Fe and Cr co-located indicating that Cr is bound with iron and Fe(II) may react to form Cr(III)

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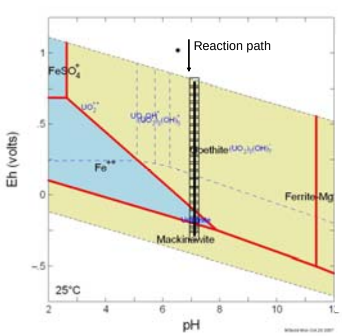
Geochemical Modeling: Bioreduction



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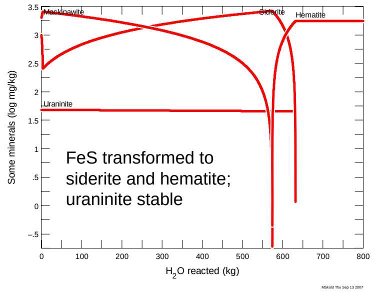
Geochemical Modeling: Reoxidation



• Mineral dissolution and precipitation during re-oxidation of the aquifer
• One kg of reacted water represents one pore volume

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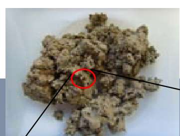
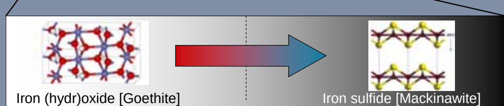


IRON MINERALOGY TESTING:
Soil samples obtained under anoxic conditions;
During and after active treatment



<1% 50% 100%
[Percent of target iron sulfide concentration]

Iron sampling performed to characterize the conversion of iron (hydr)oxide to reactive iron minerals (mixed valent iron, iron sulfide) and the accumulation of these phases during in-situ treatment.

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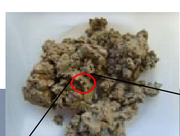
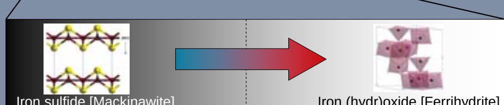


OXIDATIVE AGING:
Soil samples obtained under anoxic conditions;
Packed into columns and flushed with oxygenated water.



[Conversion of iron sulfide after oxidizing conditions are established]

Oxidative aging sampling performed to characterize the conversion of reactive iron minerals to amorphous iron (hydr)oxide with oxidizing conditions.

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Gaining regulatory acceptance

- NRC regulatory timeframe is 1,000 years.
- 'Resident farmer' criteria implies unrestricted groundwater use.
- Compliance demonstration requires:
  - Meeting treatment target
  - Maintaining treatment target
- Regulatory acceptance based upon
  - Robust remediation approach
  - Comprehensive baseline characterization
  - Geochemical modeling to guide remediation
  - Post-remediation characterization
  - Compliance demonstration testing and monitoring

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Application of the ARCADIS Approach

- NRC-regulated sites
  - Nuclear fuel processing facilities
  - Closure of ISL operations
- DOE – Environmental Management sites
  - Hanford UP200-1-S-SX groundwater plume
    - Nitrate, Cr(VI), Tc-99 (FY2008-2011)

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