Electrical geophysical and geochemical monitoring of *in situ* enhanced bioremediation

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3) U.S. Geological Survey
4) NAVFAC ESC

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Outline

- Motivation and project objective
- Geophysical monitoring 101
- Resistivity method and premise of approach
- Site description, data processing and amendment injection
- Conceptual model
- Data
- Interpretation
- Conclusion
- Disclaimer

Motivation and project objective

- **Motivation**:
  - Enhanced bioremediation: preferred in situ remedial approach for many contaminated sites
  - Effectiveness depends on ability to deliver amendment to contaminated areas
  - Cost effective tools are needed to verify amendment delivery and subsequent behavior

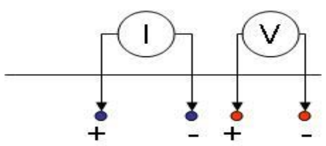
- **Objective** : demonstrate and validate timelapse electrical geophysics as effective tool for monitoring amendment delivery

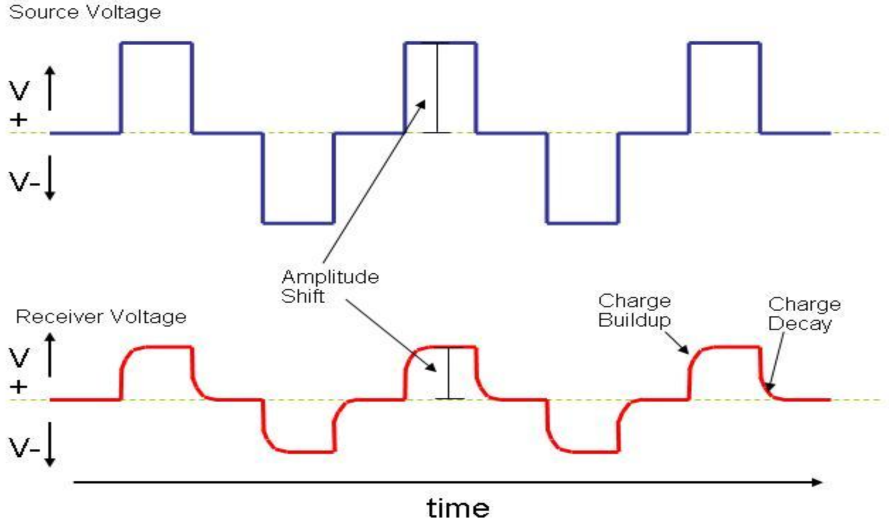
Geophysical monitoring 101

- Collect the same geophysical survey multiple times
- Invert/process the data to yield distribution of physical properties
- Interpret the changes in these physical properties in terms of processes of interest (typically requires use of supporting information)

Geophysical method used:

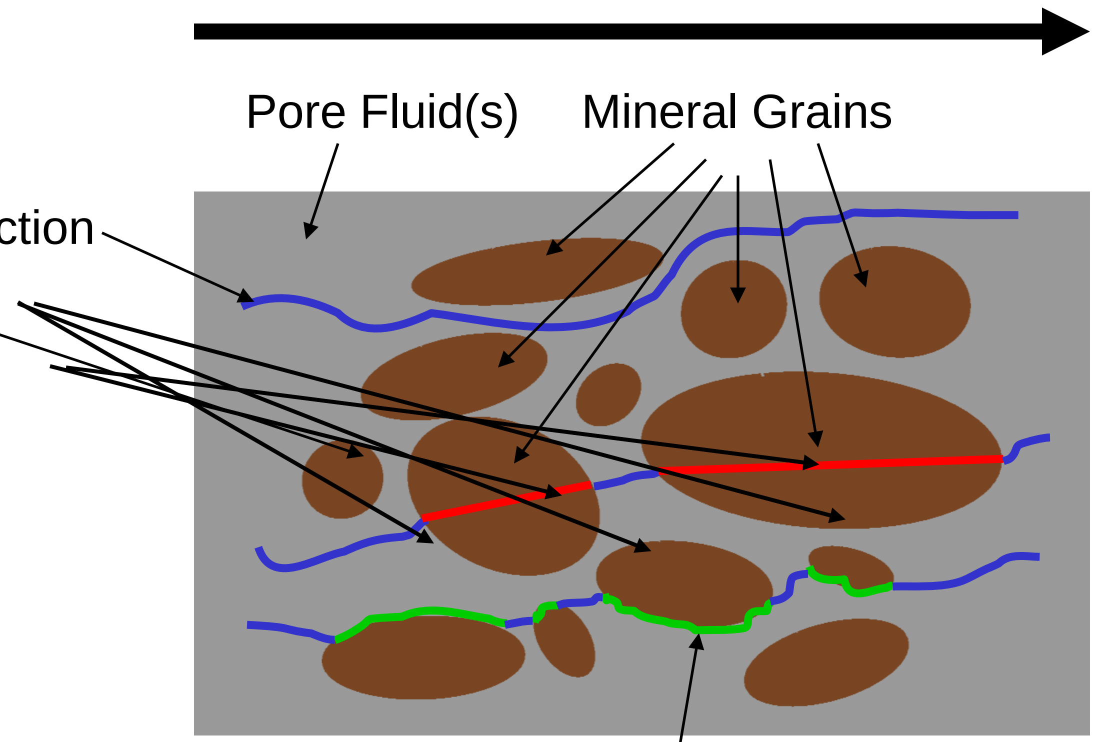
- Resistivity and IP (4 electrode measurement)
  - Inject current into ground
  - Measure resulting potential and chargeability
  - Underlying physical property: electrical conductivity





- Monitoring implementation: permanently emplaced electrodes (~100-700), one survey consists of many (1000-20000) measurements with different combinations of electrodes (Versteeg and Johnson, 2008, TLE)

Pore-scale current conduction



<u>Interfacial Conduction</u> is sensitive to interfacial electrochemistry

<u>Electronic Conduction</u> is sensitive to mineral conductivity

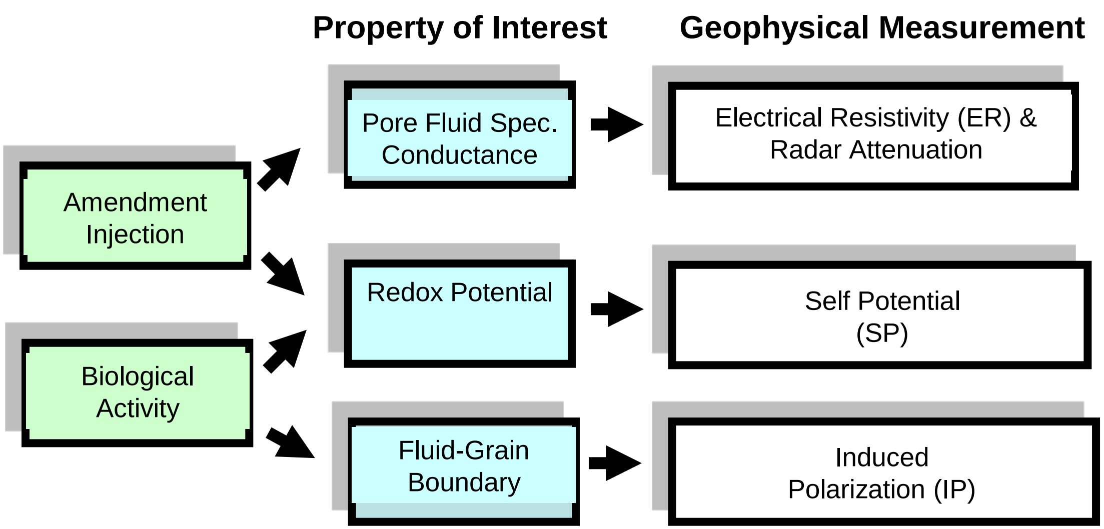
<u>Ionic Conduction</u> is sensitive to:

- Pore fluid conductivity
- Saturation

Total Conductivity = ionic + electronic + interfacial

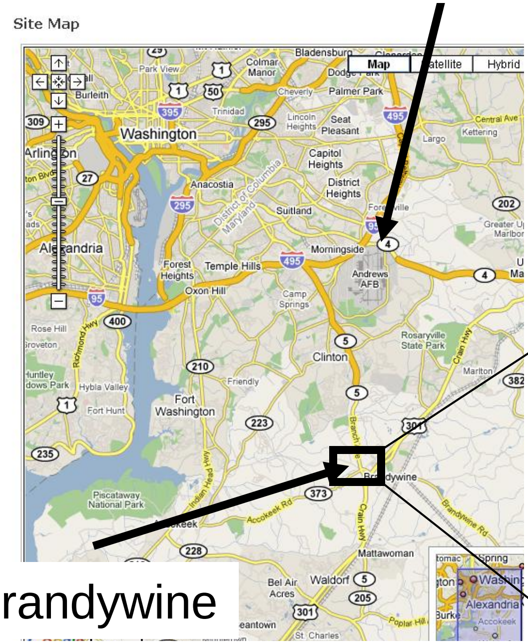
Premise of approach

1) Amendments have different electrical properties than native pore fluids:



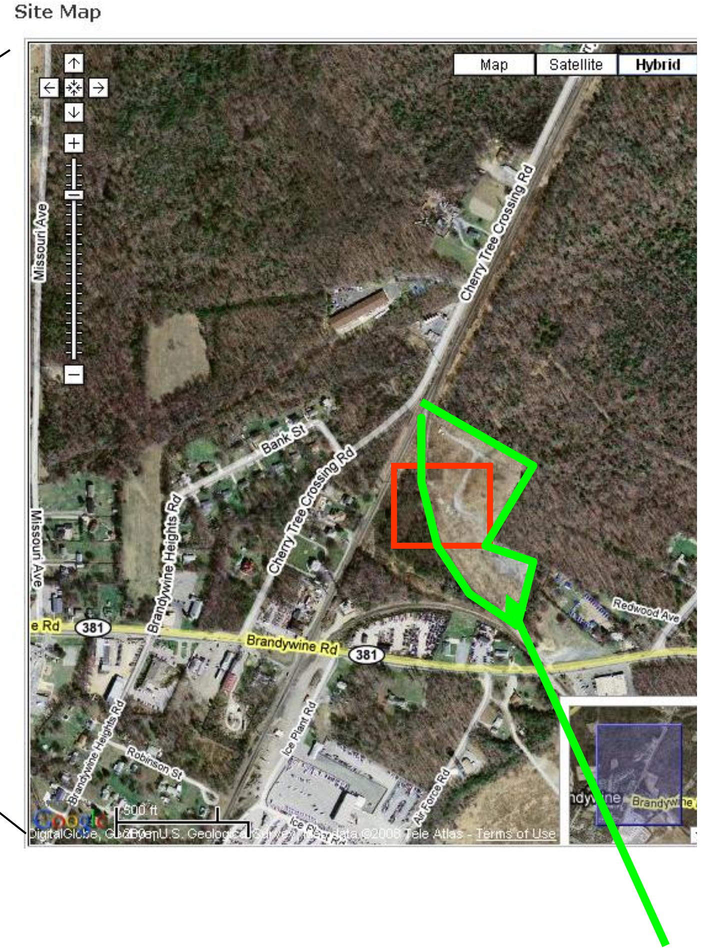
2) Changes in electrical properties post amendment injection, can be interpreted in terms of the behavior of the amendment in subsurface

Andrews AFB



Brandywine

Site location



- Primary groundwater contaminant is TCE
- Primary soil contaminants PCB
- Plume has spread from Air force property to residential property
- Contamination resides in upper 30 feet, sandy gravel, aquitard at 30 ft bgs

Brandywine DRMO
(green box)

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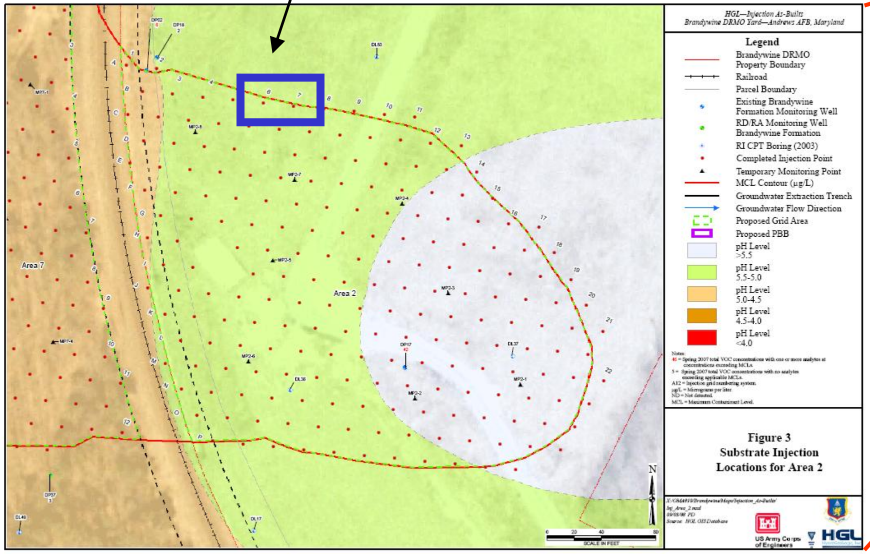
DRMO remedial action

- Amendment injections at ~1000 injection points
- Injection point spacing ~ 20 ft
- Dem/Val effort monitored two of the injections at edge of March/April 2008 treatment area (which comprised several hundreds of injection points)

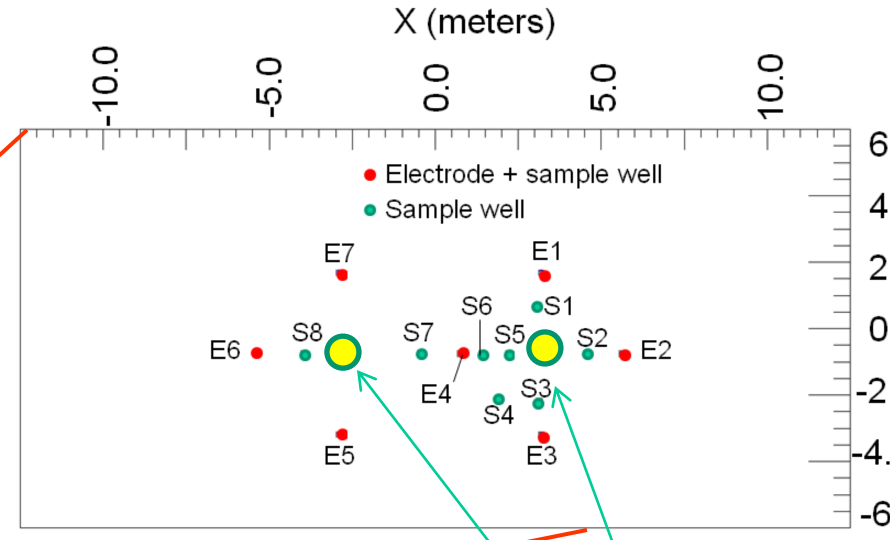
Site location

Dem/Val study area (injections B6 & B7)

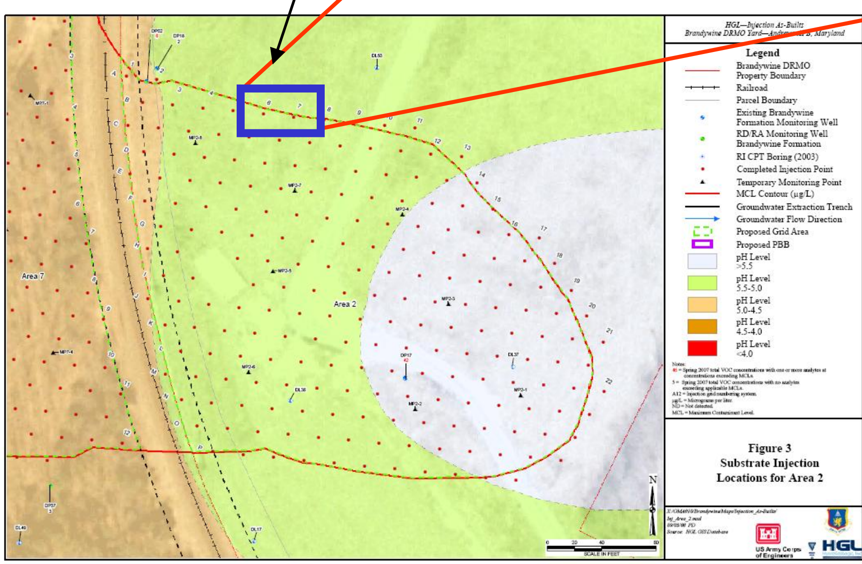


Brandywine DRMO (green box)

Site location



Dem/Val study area
(injections B6 & B7)



Injection
Locations

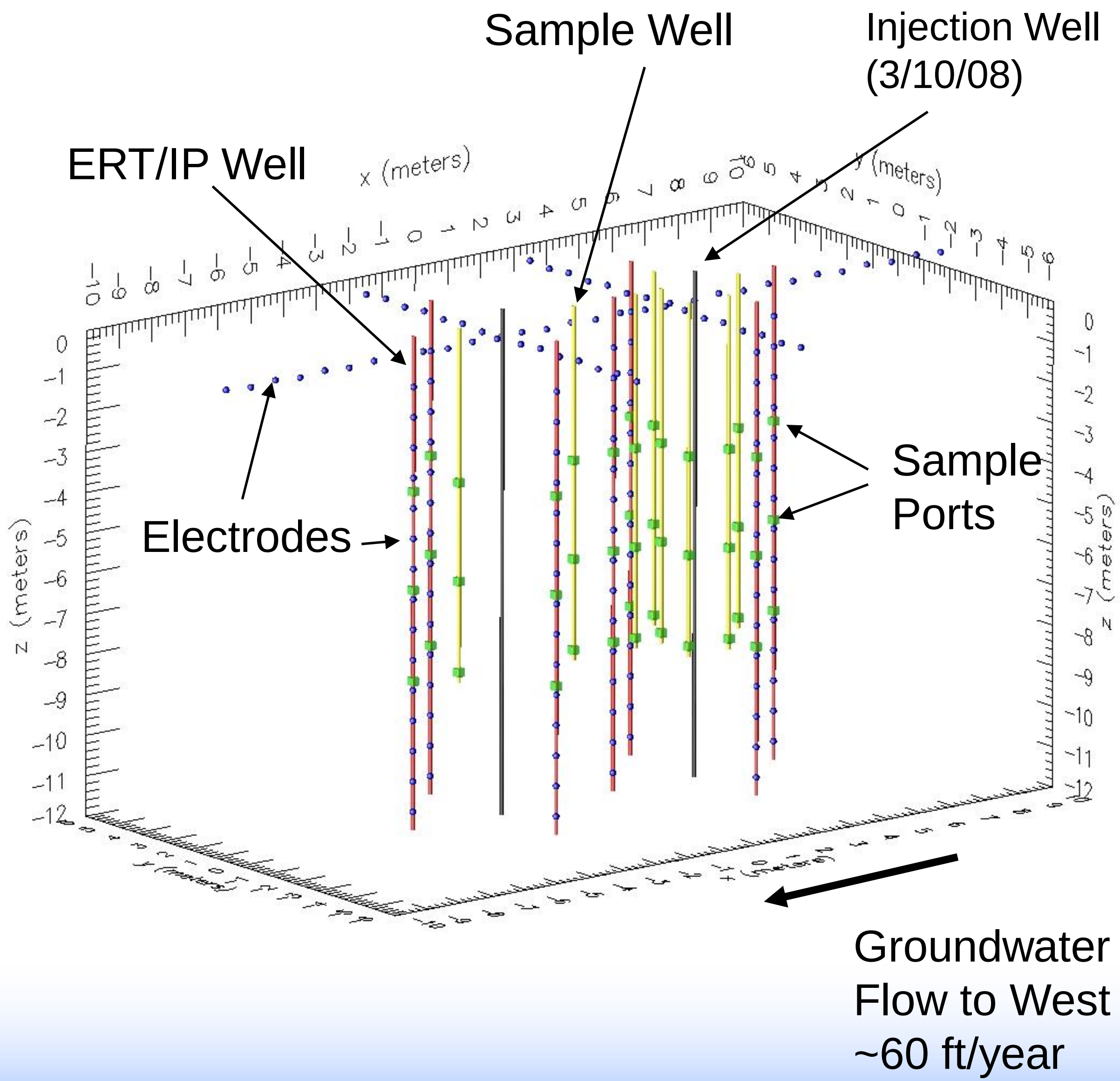
Site Details

- 8 Chem sample wells
- 7 ERT/Chem wells

- ERT wells: 15 electrodes @ 2 feet spacing. 2 inch Sampling ports at 11,19 and 26 feet

-Sampling wells: sampling ports at 11 and 19 feet. Well screen at bottom (26 feet)
-45 total sampling ports

-ERT data acquisition: repeat 3D survey with 35000 measurements

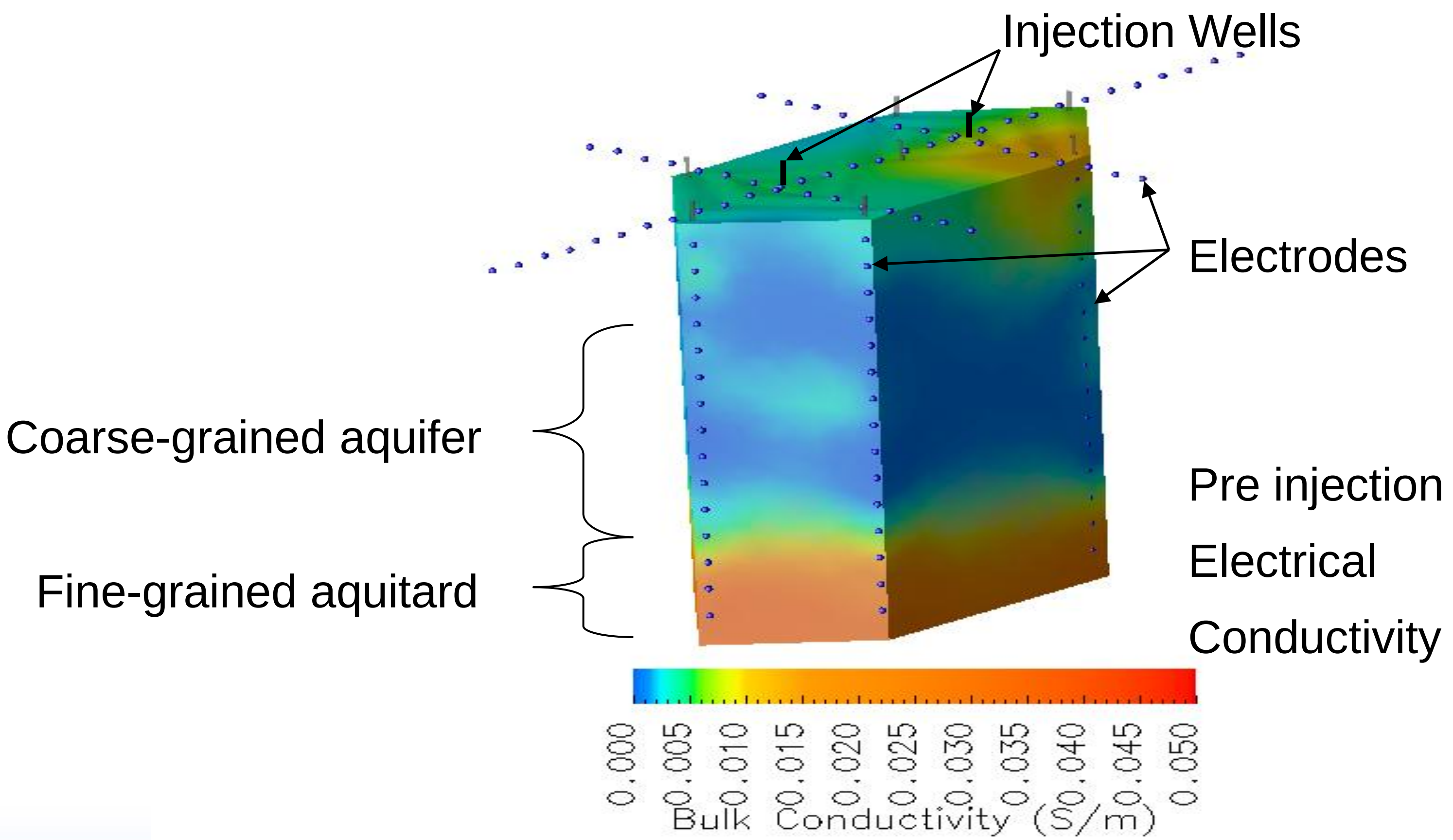


Electrical Geophysical data processing and analysis

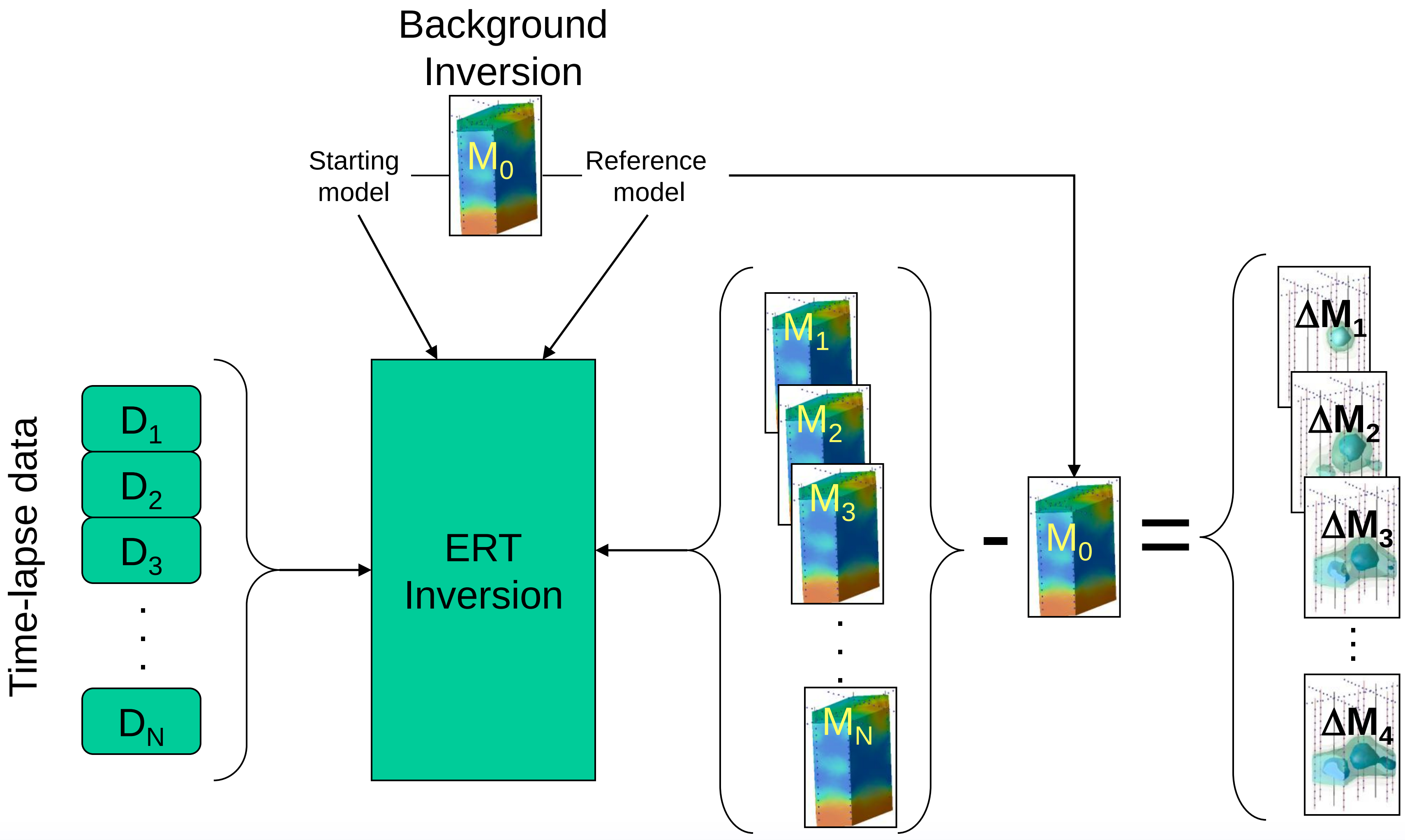
- Standard preprocessing flow (reject poor data, common data filter) applied to each dataset (~35000 individual measurements)
- Inverted with INL's parallel finite element ERT/IP code on INL HPC Cluster (typically ~100 processors, 5 minutes/inversion)
- Each dataset results in a distribution of 3D bulk electrical conductivity
- By differencing distributions, we get <u>changes</u> in bulk electrical conductivity

- Note: inversion process is not unique – typically smoothest solution (see Johnson et al, Geophysics, 2009 for other options) – so bulk electrical conductivity is properly speaking an "estimate"

Background inversion (pre injection)



4D ERT Inversion Flowchart



Amendment Recipe:

- 250 gallons of ABC (Anaerobic Biochem, mixture of lactates, fatty acids, and phosphate buffer)
- 3200 gallons of water
- 466 lbs NaHCO3
- Injectate conductivity 15 mS/cm, pH 8

Injection procedure

-Prepare amendment in tank

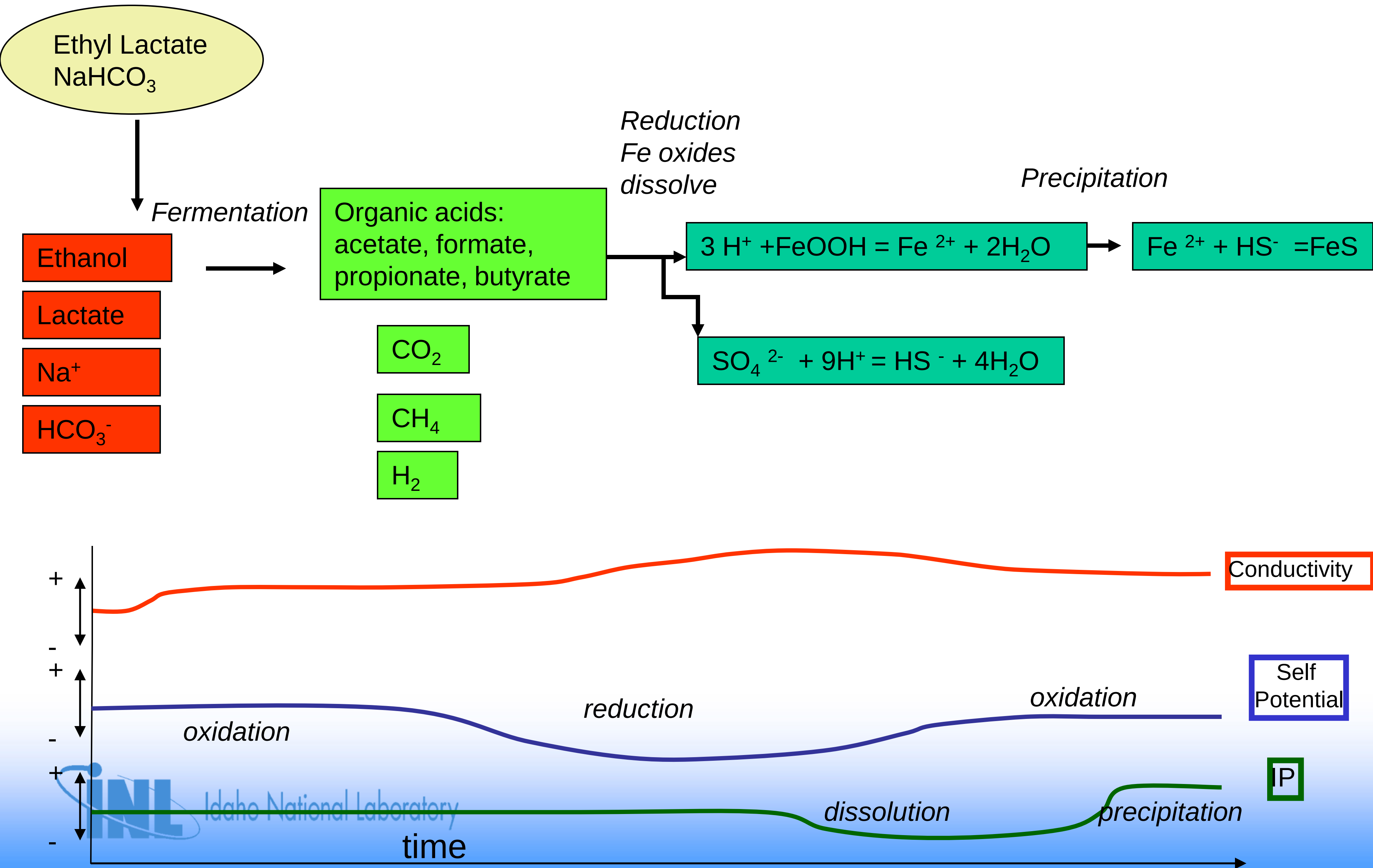
-Direct push injection pipe to 34 feet bgs

-Inject 36 gallons of amendment @ 1 feet intervals

(inject –up 1 feet – inject –up 1 feet) till 8 ft bgs

- Total ~ 950 gallons/location

Conceptual model of Biogeochemical Transformations and expected geophysical response



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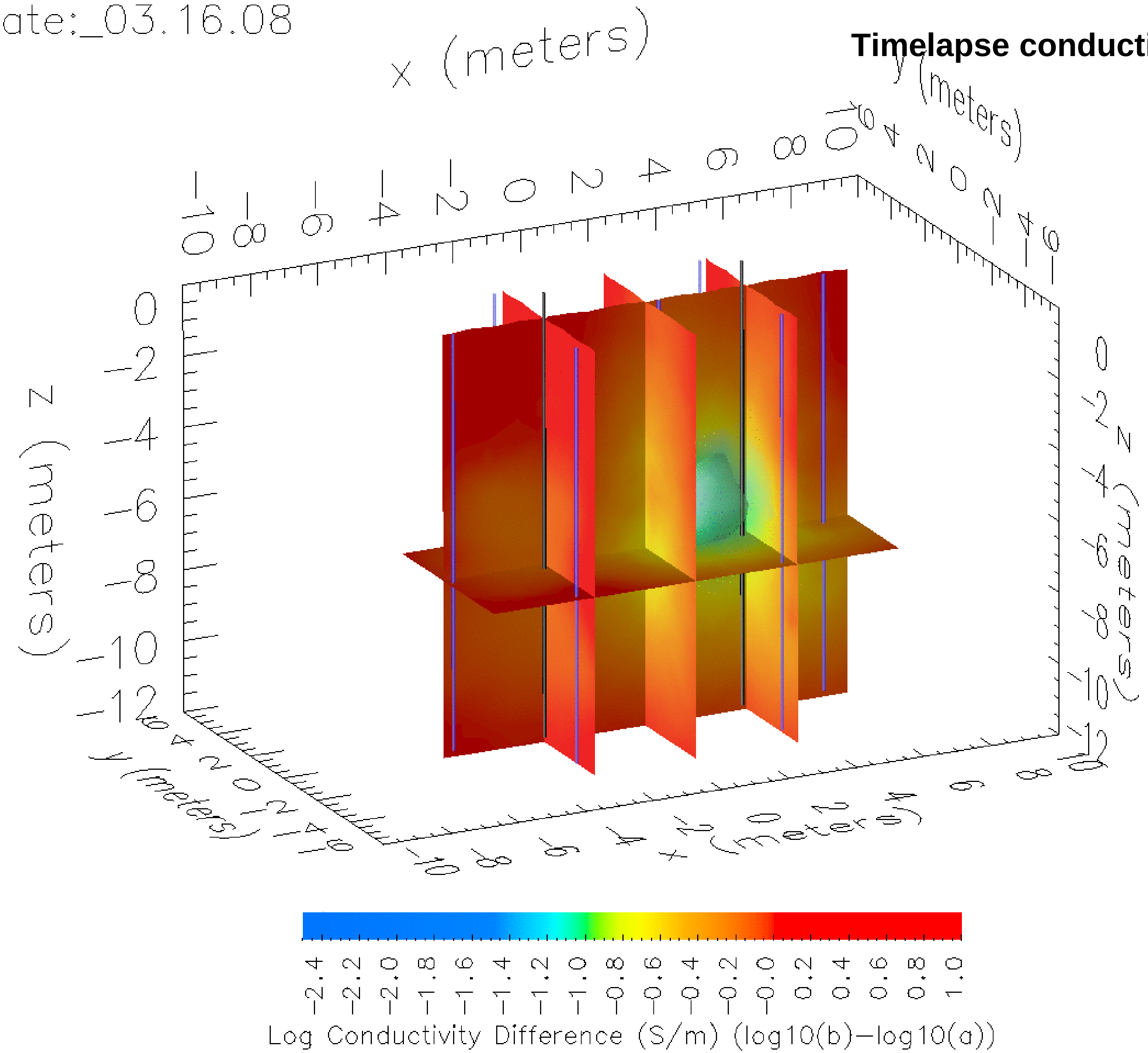
Timelapse conductivity differences

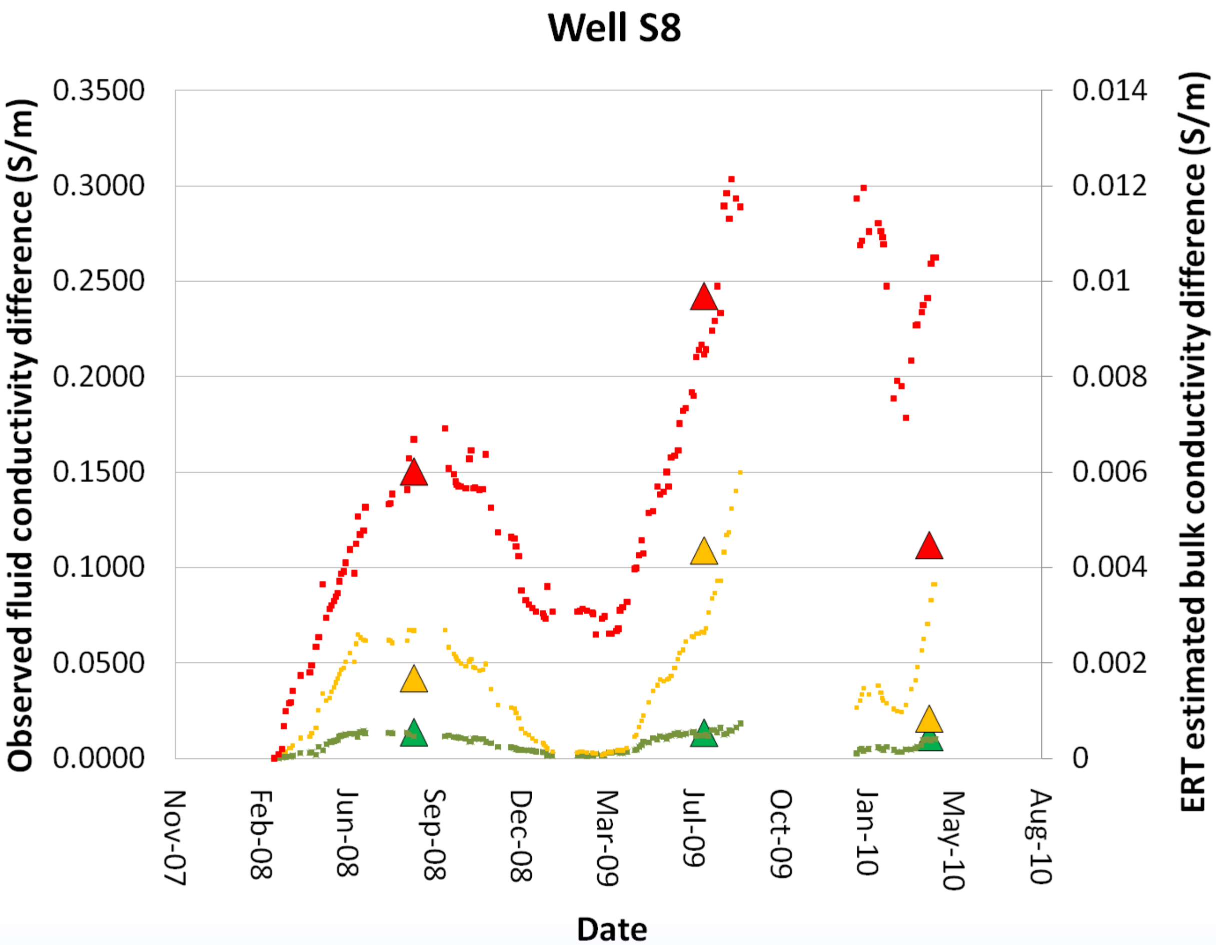


Groundwater sampling events

Injection of 7% ABC (ethyl lactate + fatty acids) + 200mM $NaHCO_3$

	March 2008 (pre-inject) subset	March (post-inject) Subset	April 2008 All wells	August 2008 All wells	July 2009 All wells	April 2010 All wells
pH	X	X	X	X	X	X
Fluid conductivity	X	X	X	X	X	X
Anions	X	X		X	X	
Cations	X	X		X	X	
Organic Acids	X	X		X	X	
VOC	X	X			X	
TOC	X	X		X	X	
Fe^{2+}	X	X			X	
Dissolved O_2	X	X		X	X	
Sulfide	X	X		X	X	

Relating changes in bulk conductivity to changes in geochemistry



~3.5 m bgs

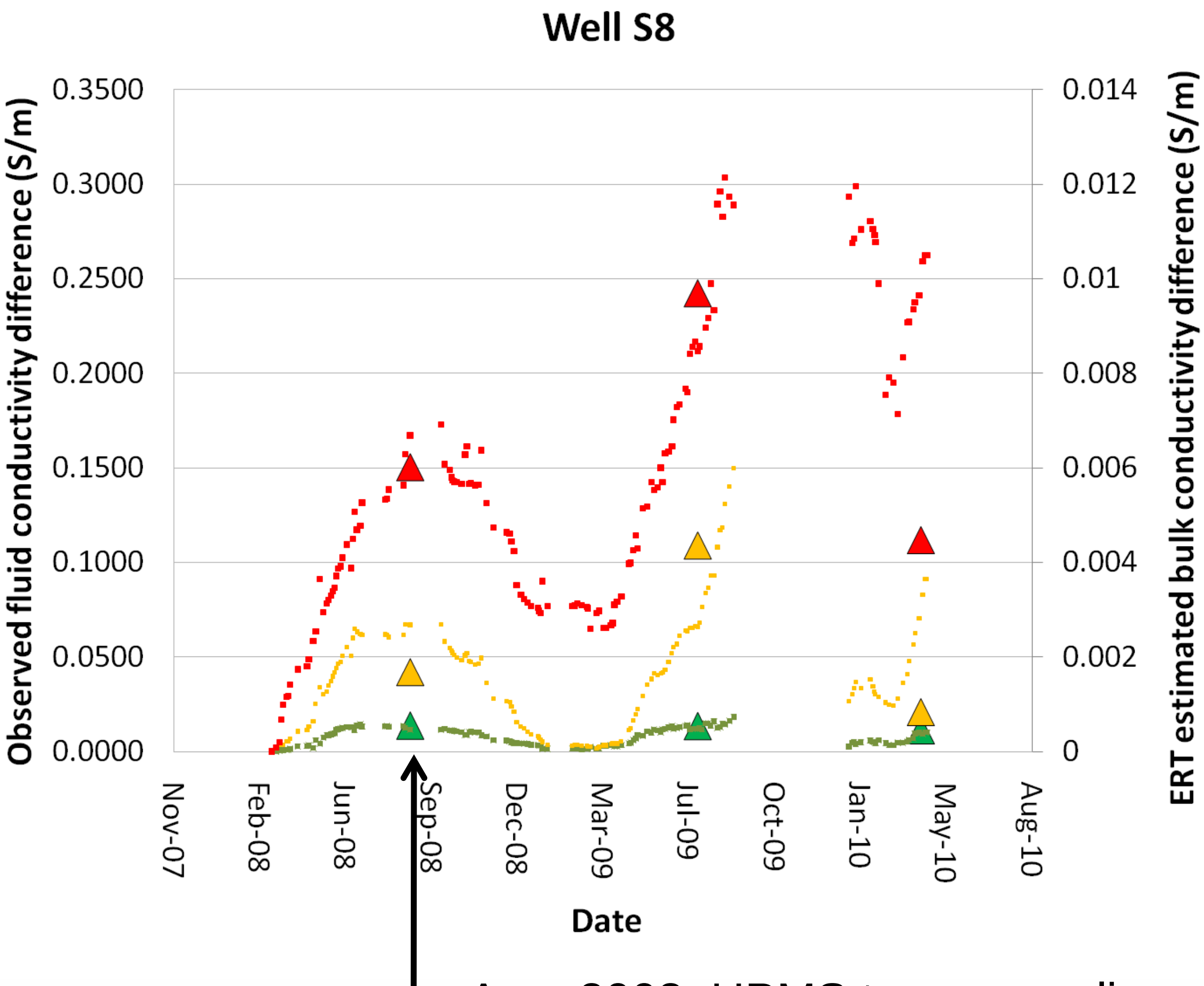
~6.0 m bgs

~8.5 m bgs

Note:

- Dots are ERT inversion results at sample ports.
- Triangles are fluid conductivity measurements taken at sample ports

August 2008 sampling event



Aug. 2008: HPMS team sampling event
- large increase in sodium in lower ports
- modest increase in iron, large increase in sulfate
- slight increase in organic acids, pH
- fermentation beginning slowly

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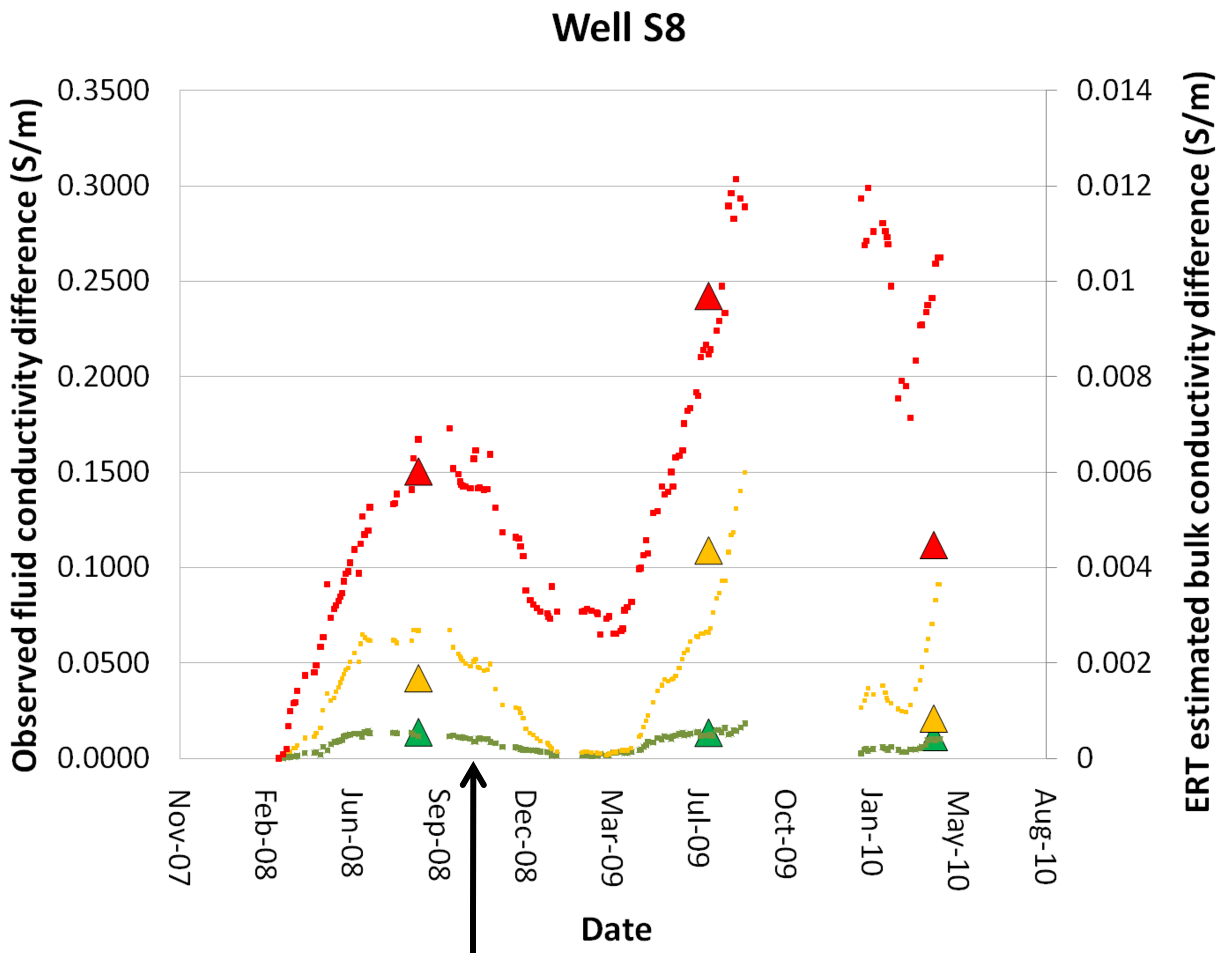
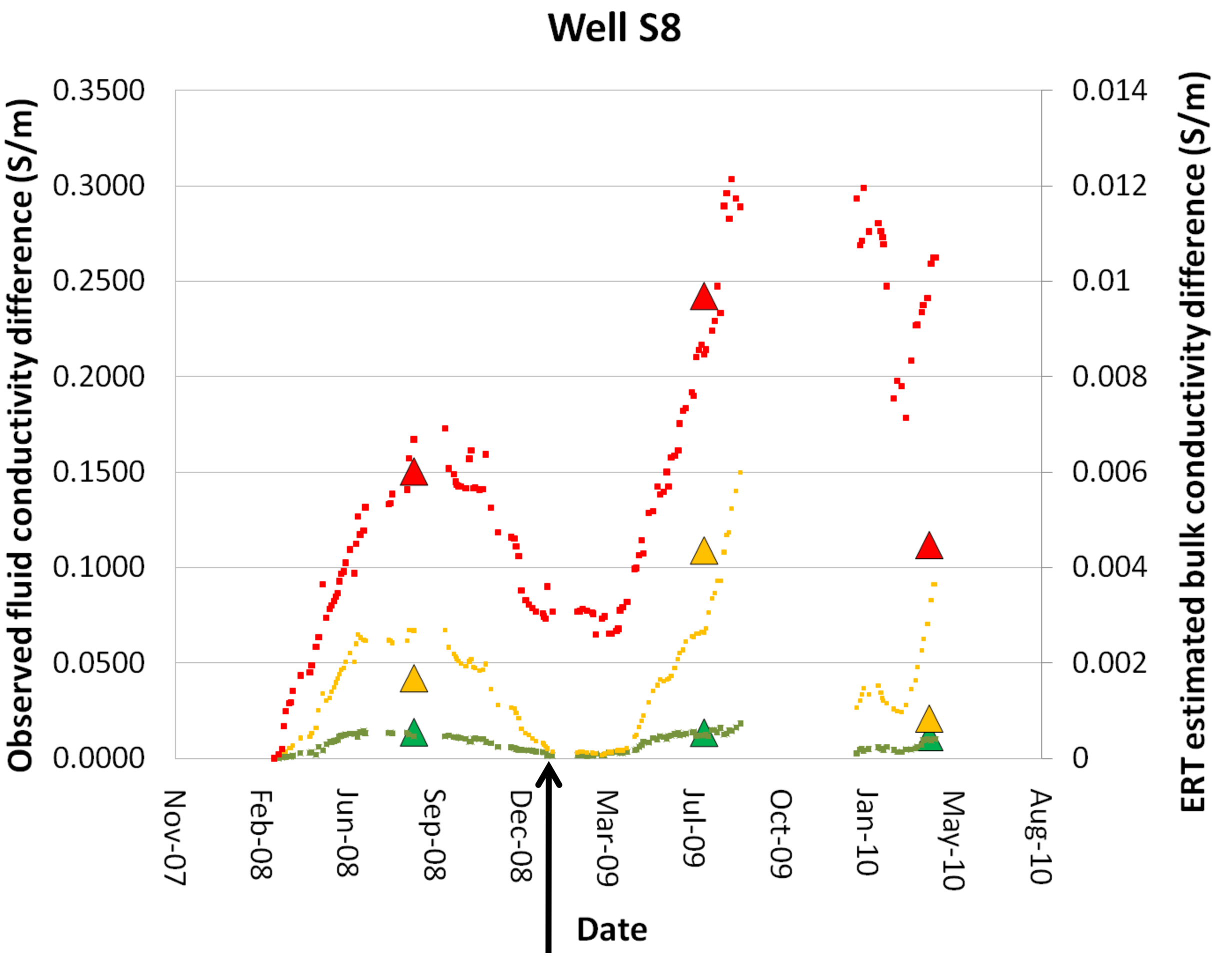
October 2008 sampling event



Oct. 2008: contractor sampling event

- Low methane
- slight increase in iron and manganese
- slow fermentation

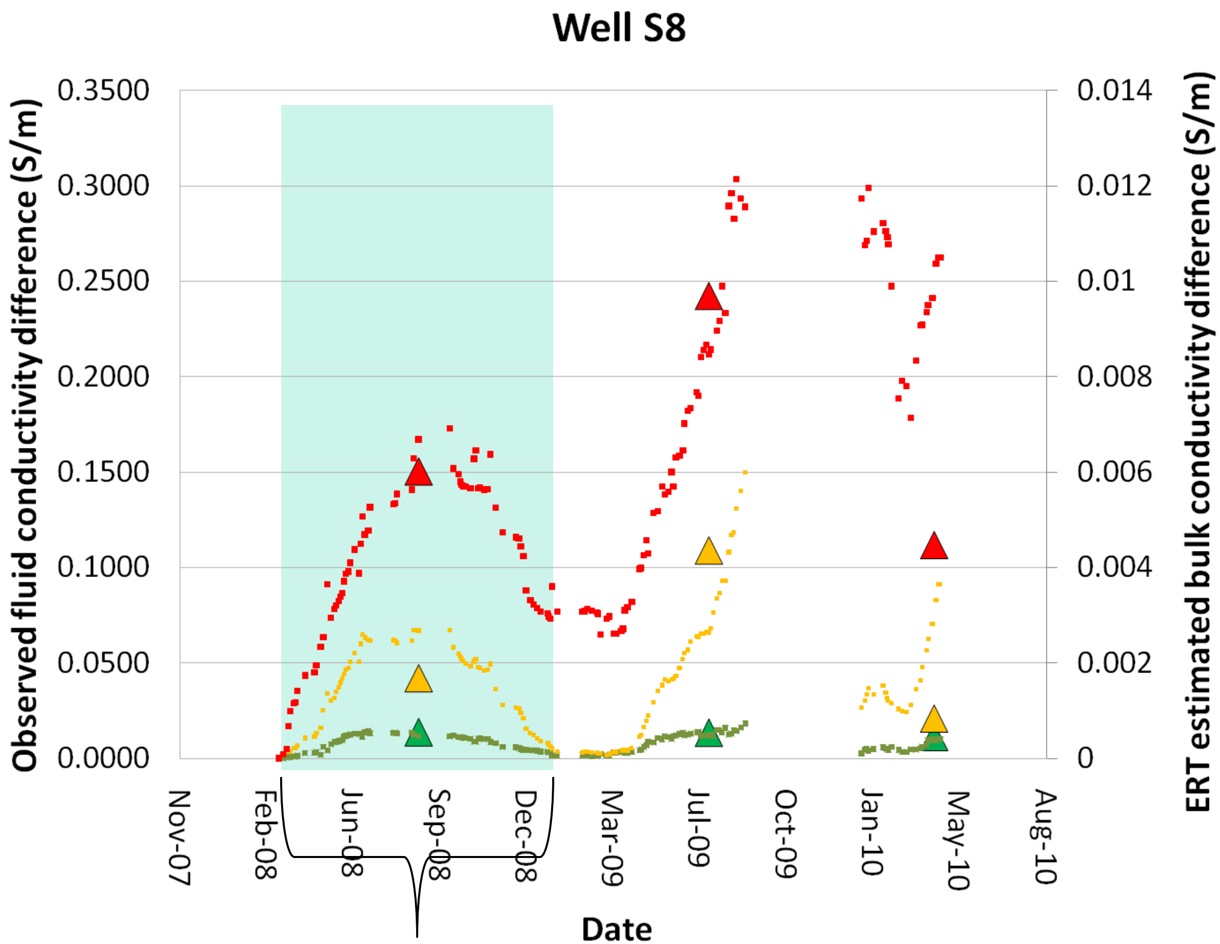
January 2009 sampling event



Jan 2009: contractor sampling event

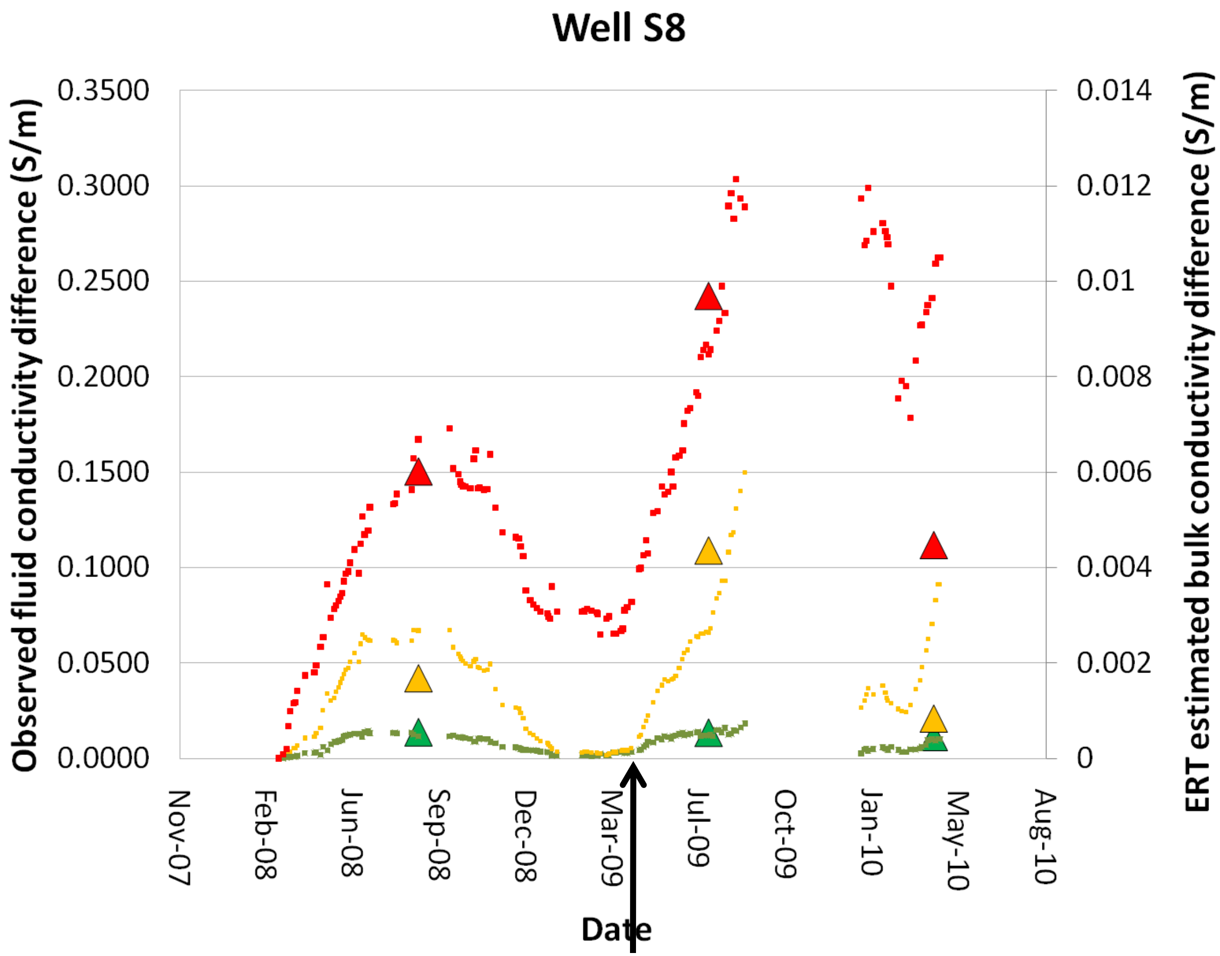
- Similar to October sampling.
- Low methane
- slowly progressing fermentation

March 2008 to January 2009 summary



March 2008 to Jan. 2009 summary:
- Little microbial activity
- Rise and fall in bulk conductivity due primarily to sodium transport and subsequent dilution.

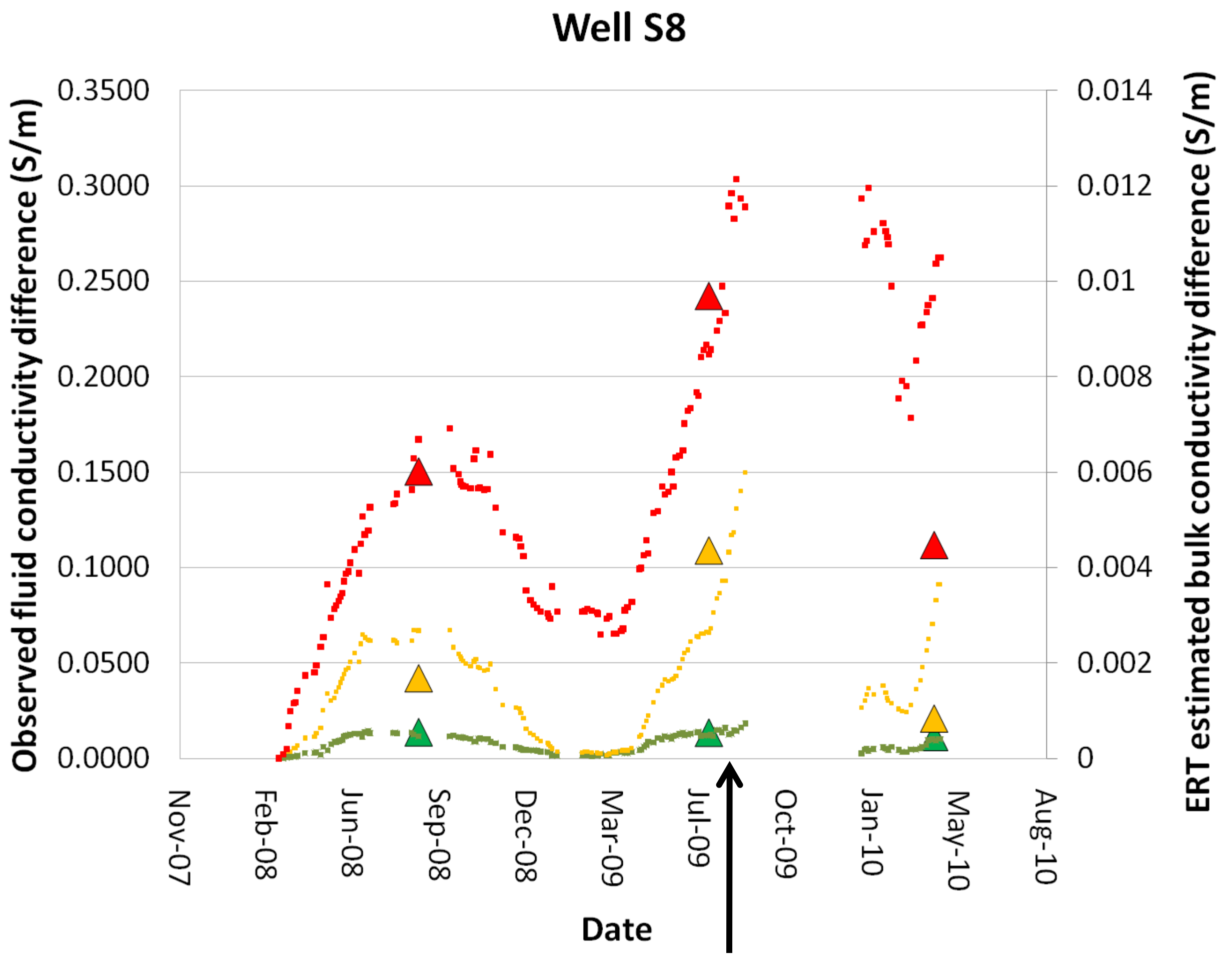
April 2009 sampling event



April 2009: contractor sampling event

- Significant development of reducing conditions since January.
- High methane production
- low DO and ORP

August 2009 sampling event



August 2009: HPMS team sampling event

- Decrease in sodium since Aug. 2008
- Large increase in iron and organic acids
- Large decrease in sulfide and pH
- Iron sulfide precipitation likely

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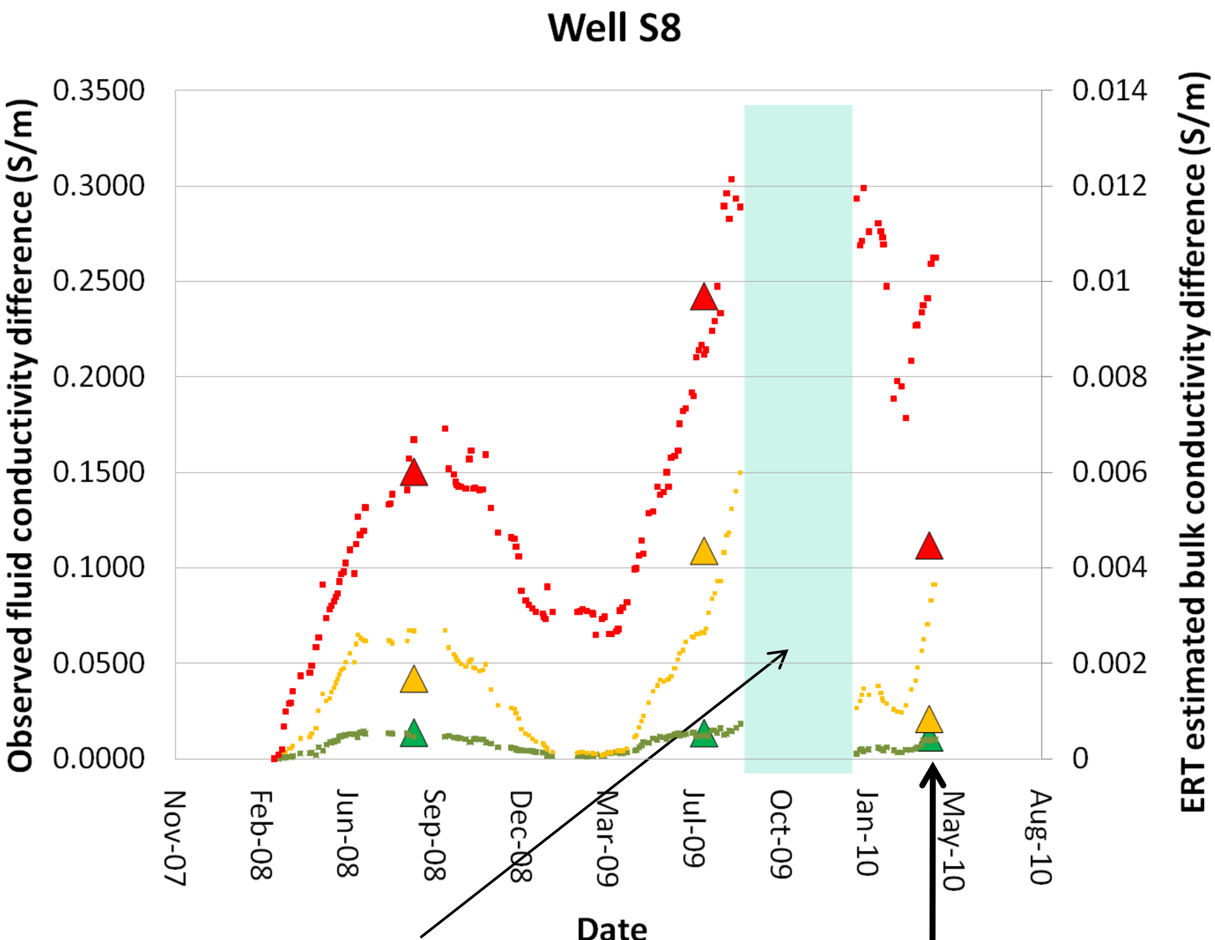
April 2010 sampling event

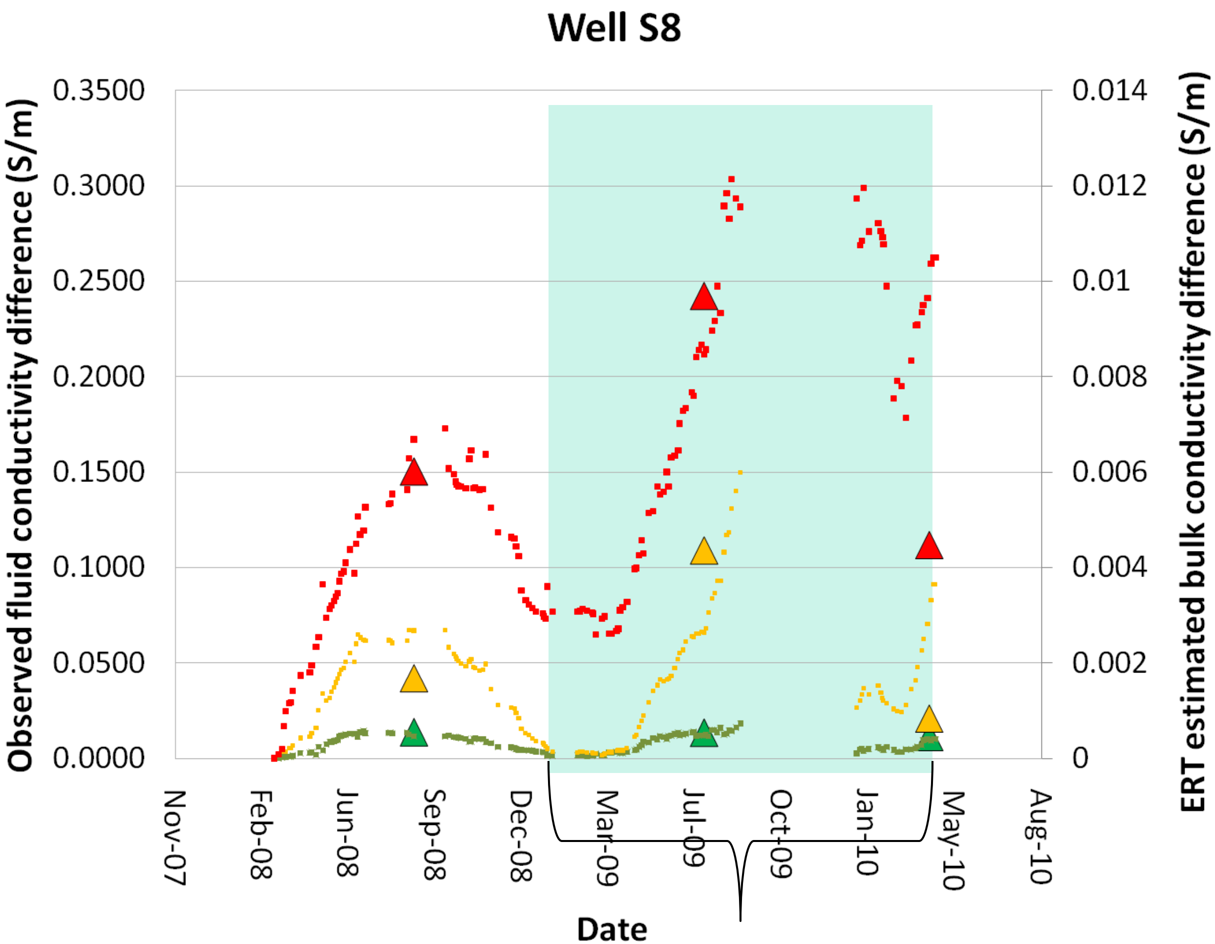


Monitoring system out of order

April 2010: HPMS team sampling event

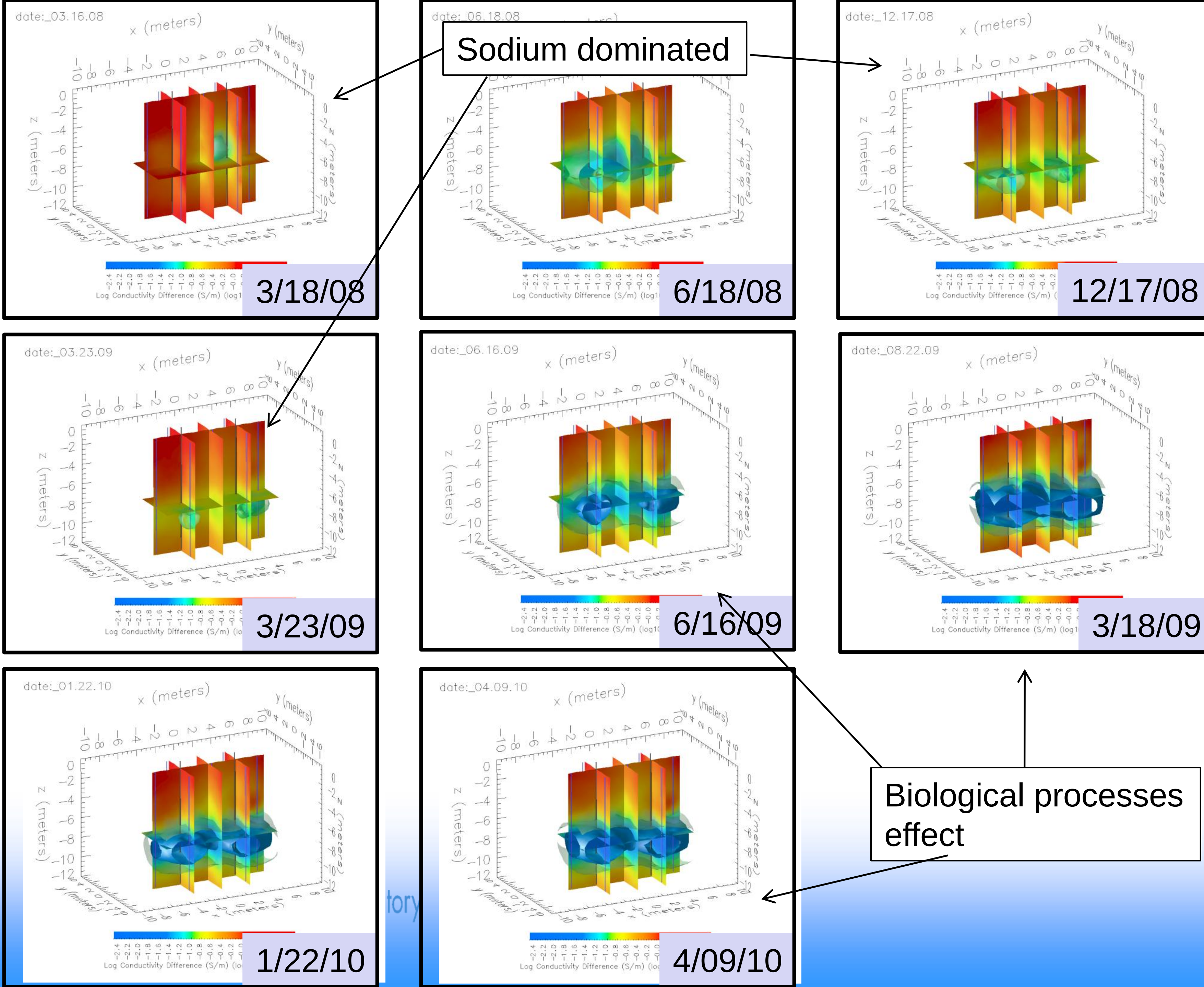
- Fluid conductivity sampled only
- Decrease in fluid conductivity everywhere since August 2009.

January 2009 to April 2010 summary



Jan 2009 to April 2010 summary

- Geochemical data suggest vigorous microbial activity
- Fluid conductivity decreases, bulk conductivity increases - suggesting increase in interfacial conductivity (sensing iron-sulfide precipitation ?)
- Most activity occurs just above confining unit (corresponding to amendment distribution)


Sodium dominated
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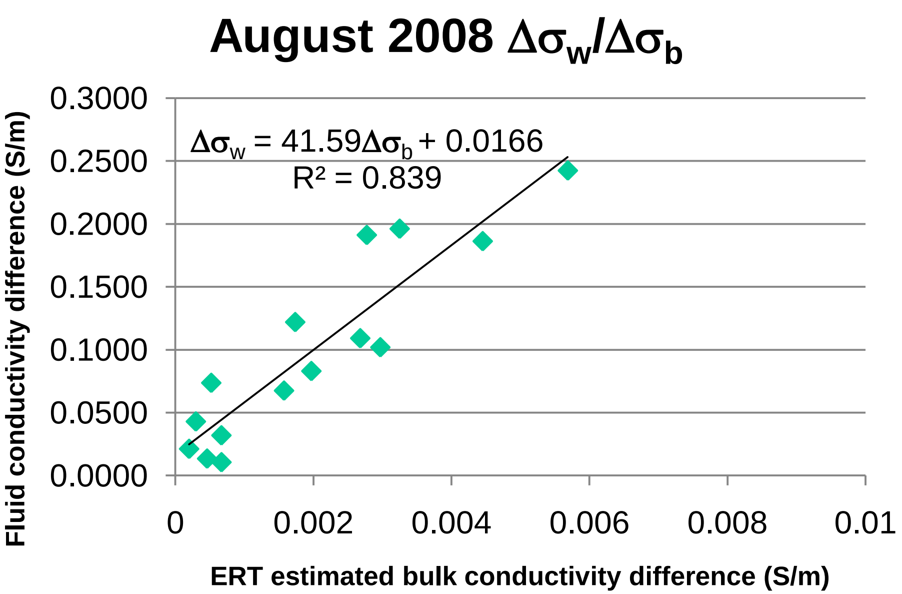
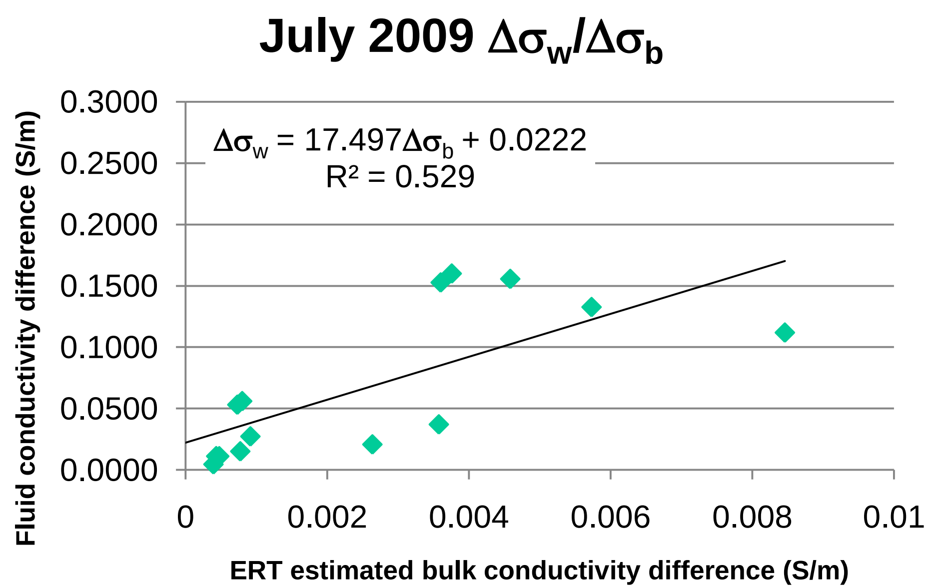
Biological processes effect

Further evidence for changes in interfacial conduction





High correlation : ERT response primarily due to change in fluid conductiivity
Lower correlation : ERT response caused by changes in interfacial conductivity mineral precipitation)

Summary I – Experiment and future work

- Changes in subsurface electrical conductivity obtained from the ERT inversion coupled with the sparse geochemical data can be interpreted with high confidence in terms of spatiotemporal information about the amendment behavior and associated subsurface biogeochemical processes.
- We successfully demonstrated/validated our approach
- Future work
  - ESTCP has funded follow up injection of molasses at same site
  - Will occur in August 2010
  - Interested parties (biogeochemical monitoring) welcome (contact authors)
  - Coupled modeling/inversion

Summary II - Method

- Timelapse geophysical imagery obtained from continuous geophysical monitoring data provides details on system behavior which can not be captured by periodic, sparse point sampling

- Knowledge of, and access to a geophysical monitoring toolbox can benefit geochemists, hydrologists and microbiologists

- However – read the disclaimer before using the toolbox

Geophysical toolbox

DISCLAIMER: geophysical data DOES NOT directly sense (changes in) microbiology, geochemistry and/or hydrology.

Geophysical data is sensitive to (changes in) macroscopic physical properties such as bulk electrical conductivity, dielectric permittivity and density.

To the extent that (changes in) microbiology, geochemistry and/or hydrology impact these physical properties through clearly understood mechanisms timelapse geophysical data can be interpreted in terms of information on subsurface properties and processes of interests.

Use with caution. Misuse can cause serious heartburn.