United States Environmental Protection Agency

Environmental Geophysics Applied to Site Characterization, Plume Mapping, and Remediation Monitoring

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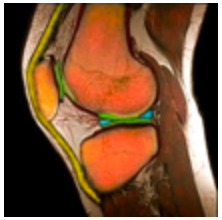
Why geophysics?

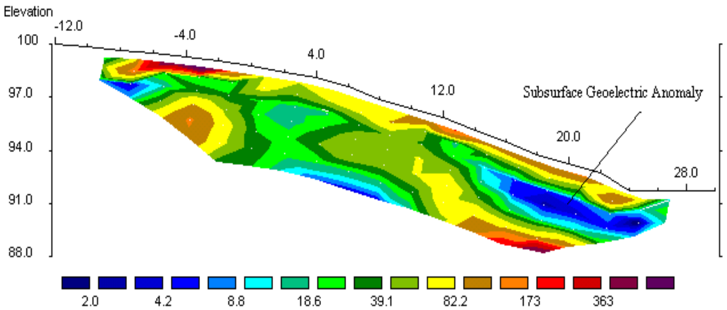
- Prior to expensive and invasive surgery we utilize medical imaging.
- Each medical imaging method is used for specific purposes.


x-ray of knee

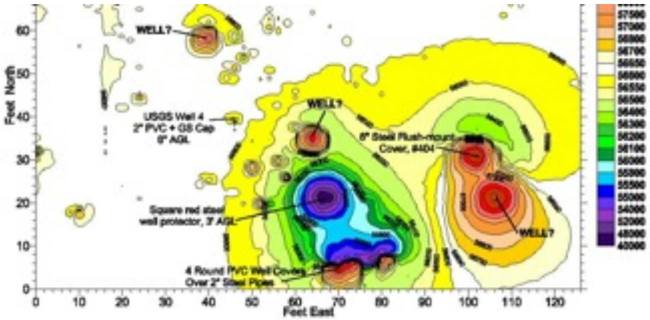

MRI of knee

images credit: Lee Slater

- Prior to expensive earth intrusive investigations (e.g., drilling, excavating, etc.) we can utilize geophysical imaging.
- Each geophysical method is used for specific purposes



Landfill plume mapping



Abandoned well mapping

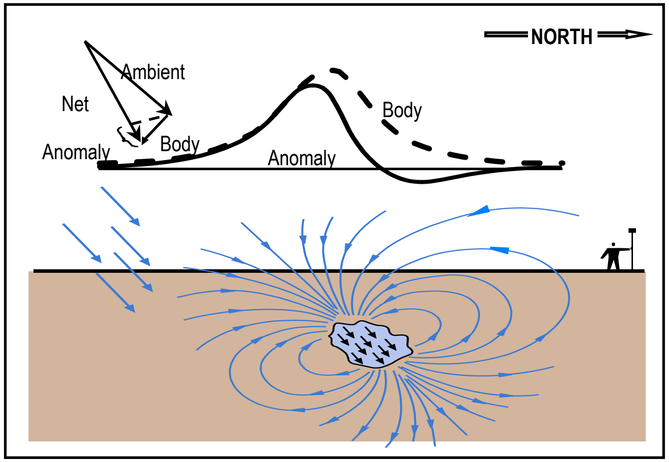
Outline

- Locating subsurface objects and infrastructure
- Plume detection and monitoring
- High resolution characterization and Conceptual Site Model (CSM) Development
- GW/SW Interactions
- Online resources

Geophysical methods include a set of tools in the site investigator's tool box.

Finding USTs & subsurface infrastructure

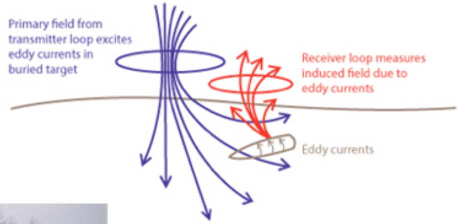
- What are the physical properties of the target, i.e. UST and associated infrastructure?
  - metal?, ferrous metal? fiberglass?
- Any potential interference?



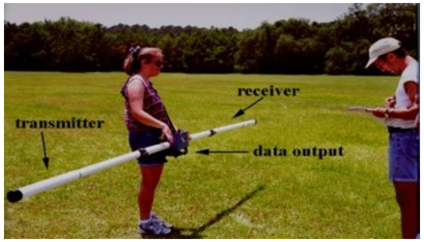
Geometrics G-858 Cesium vapor magnetometer

Likely applicable geophysical methods:

1. Magnetic
2. Electromagnetic
3. Ground Penetrating Radar (GPR)



Geonics EM-61



Geonics EM-31

Geophex GEM2

Mala GPR system

Finding USTs & subsurface infrastructure

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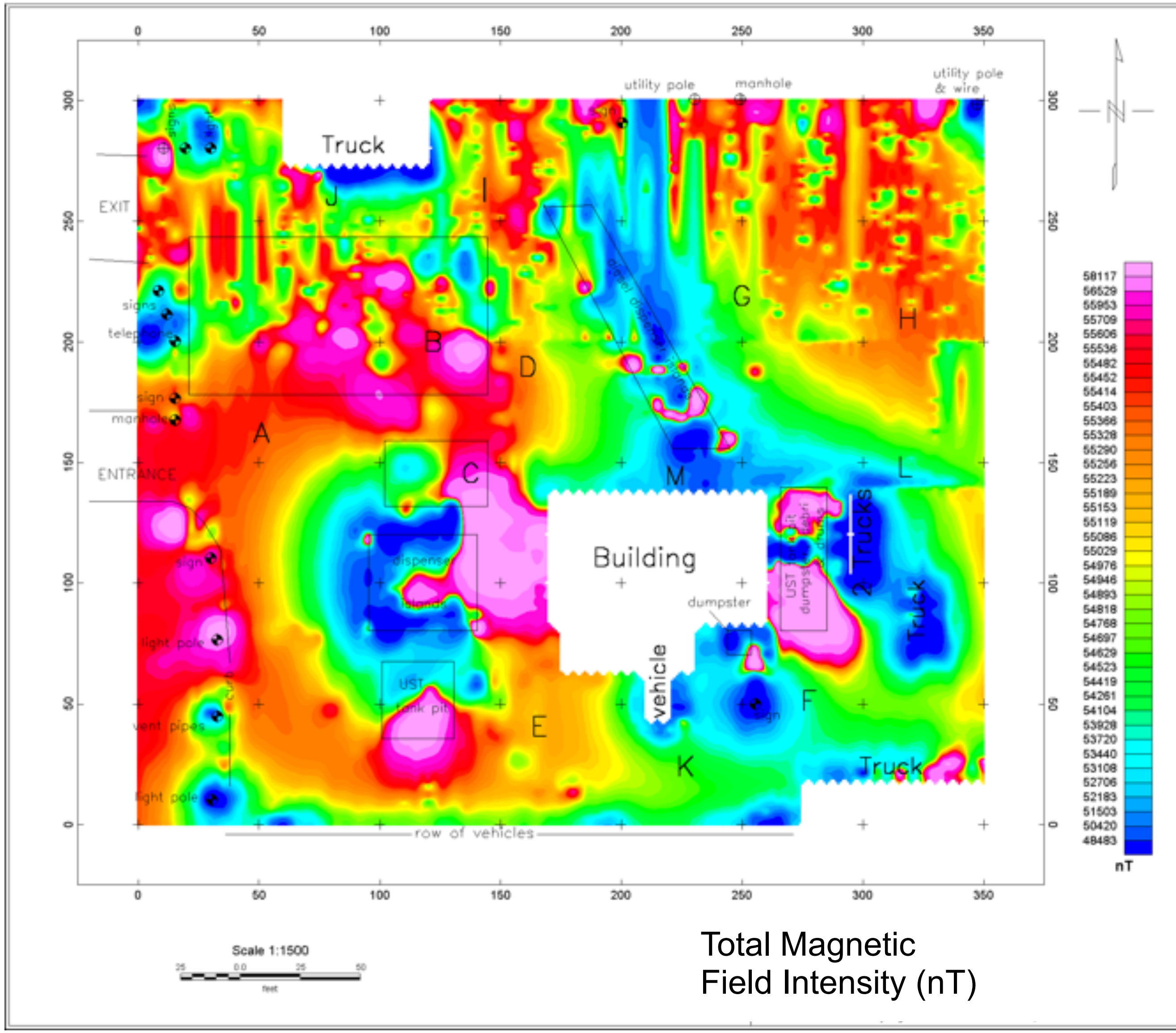
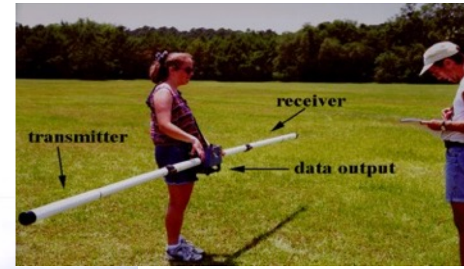
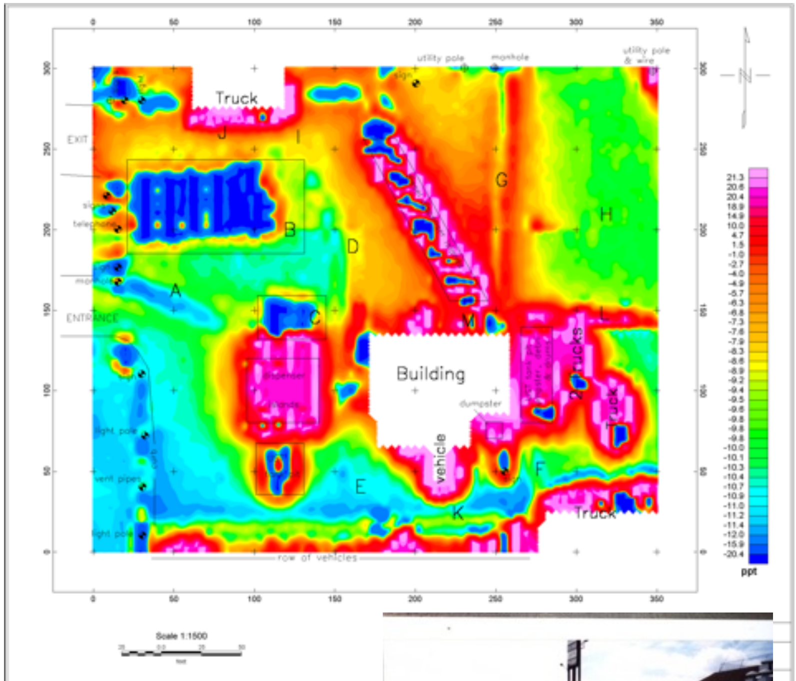
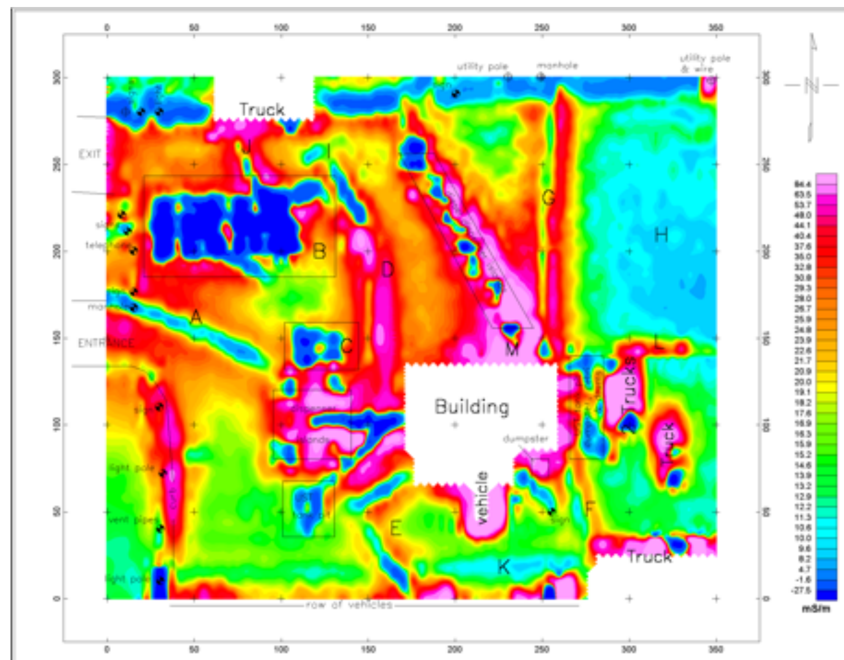


Finding USTs & subsurface infrastructure



Geonics EM-31





EM 31 Quadrature

Finding USTs & subsurface infrastructure

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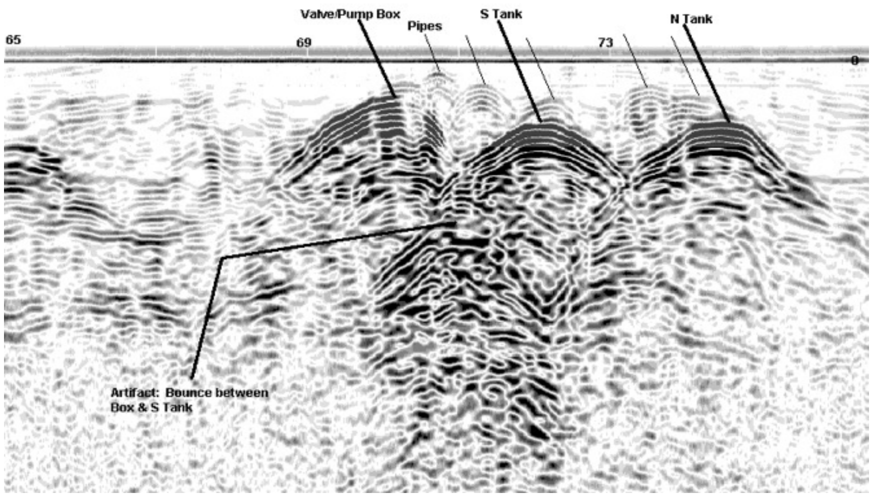
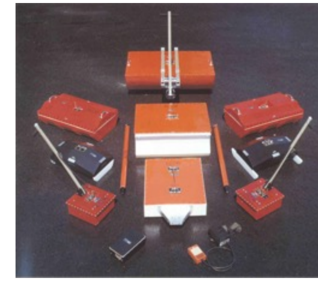
Ground Penetration Radar (GPR) UST and utility examples

500 MHz antenna

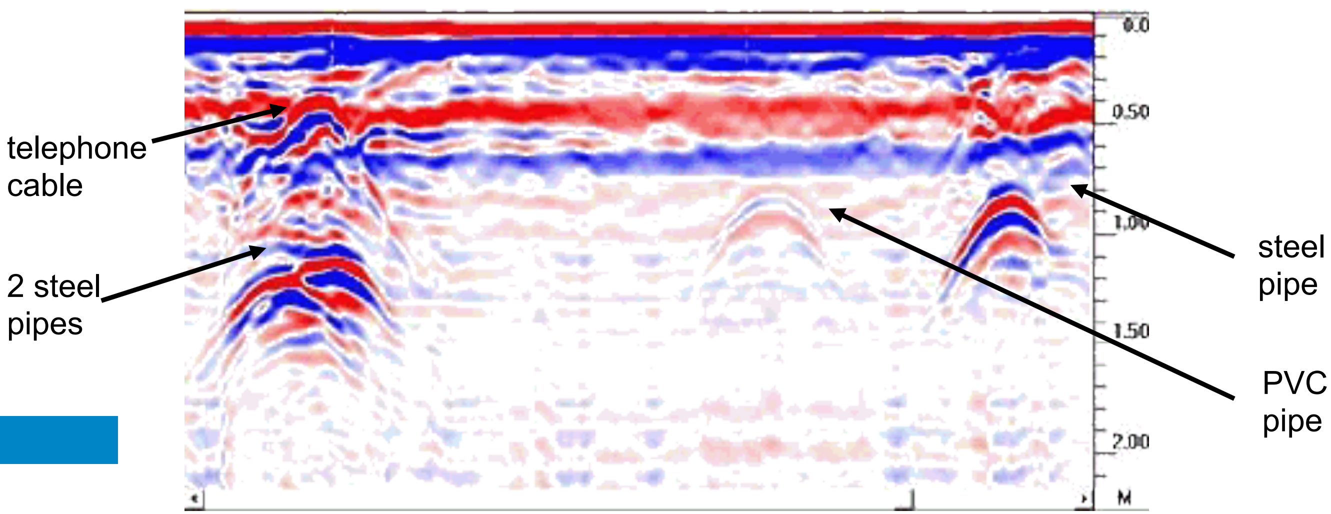




GSSI antenna

- pipes oriented perpendicular to the profile.
- Darker reflections show higher amplitude due to greater electrical property impedance.
- Faint reflections show muted or low amplitude reflections due to the attenuation of the GPR energy from electrically conductive material.

400 MHz antenna



Note: Hyperbolic Reflections

GPR sections from Bill Sauck

United States Environmental Protection Agency

Mapping contaminant plumes

Direct Current (DC) Resistivity

Archie's Law for Porous Media w/o clay

$$\rho_e = a\,\phi^{-m} S^{-n} \rho_w$$

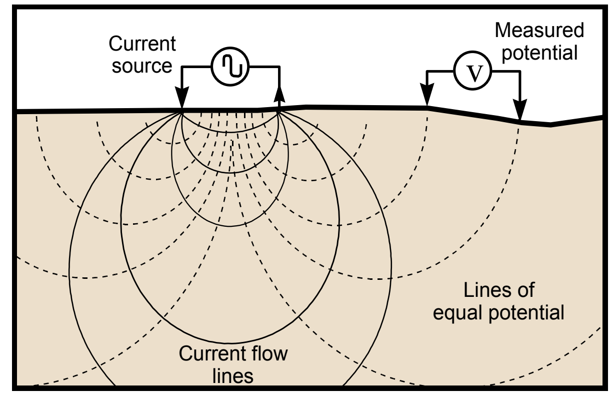
ρ_e = resistivity of the earth

ϕ = fractional pore volume (porosity)

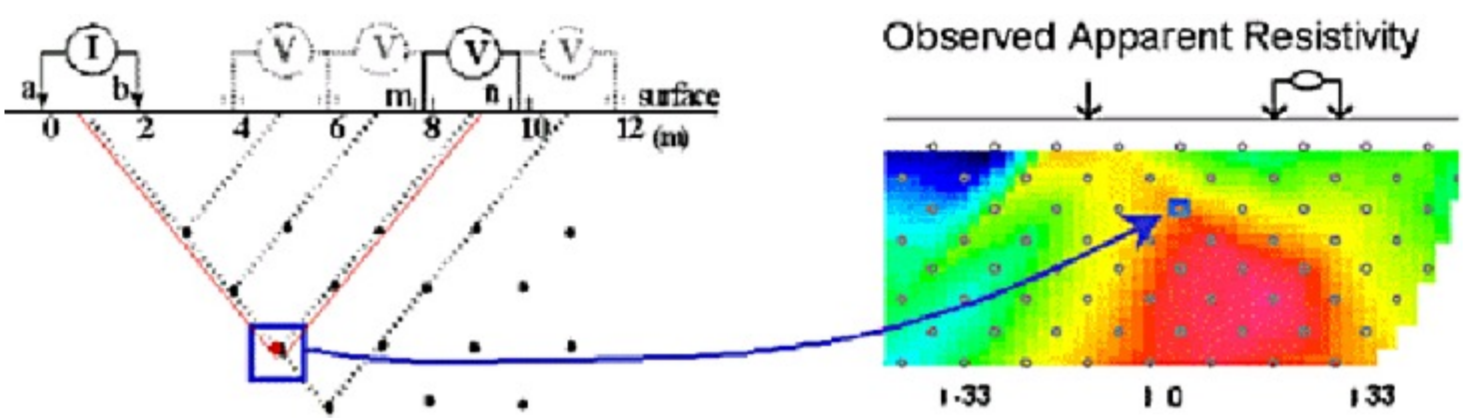
S = fraction of the pores containing fluid

ρ_w = the resistivity of the fluid

n, a and m are empirical constants



Resistivity Surveying

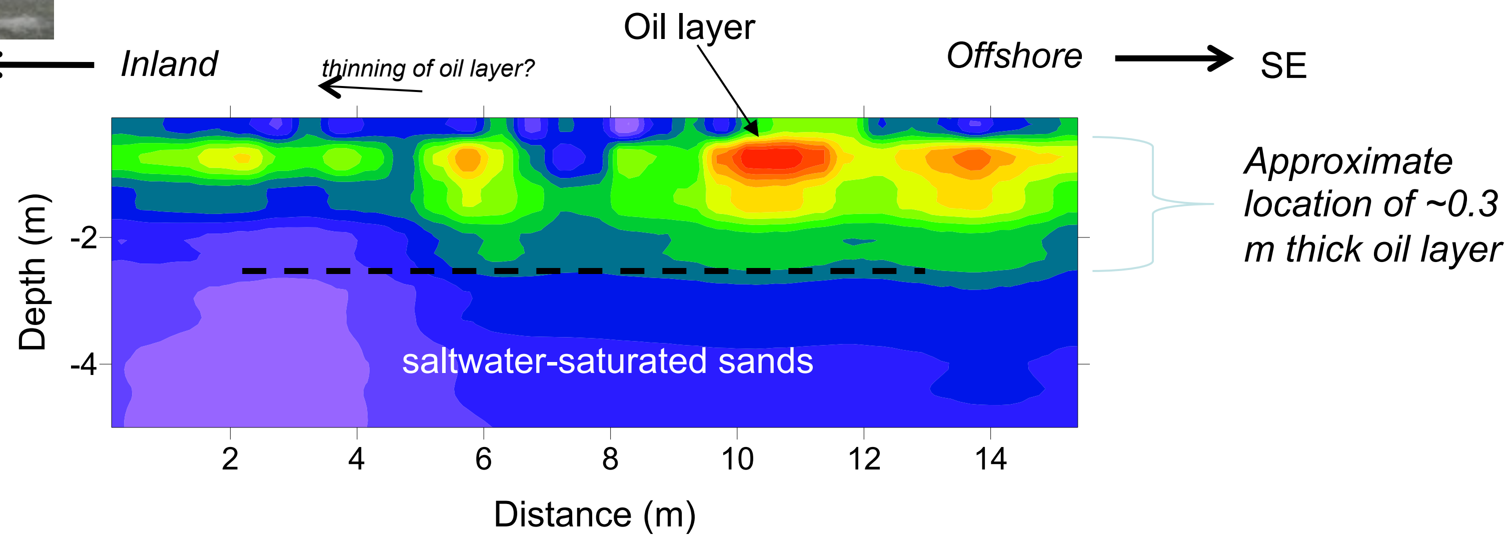


Deep Water Horizon (DWH) , Grand Terre, LA.

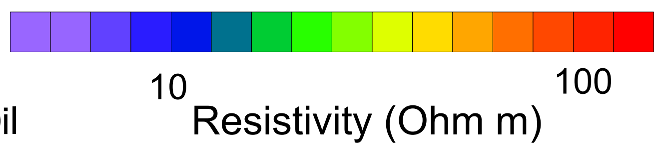
- Uninhabited barrier island impacted by Deepwater Horizon oil spill
- No anthropogenic noise makes it ideal to study the long term fate of the oil contamination
- Oil contamination is located 40-60 cm below the surface and is bounded by sand

DWH Barrier Island Impact DC Resistivity Results

Zone of immature oil contamination imaged as resistive layer



Oil layer

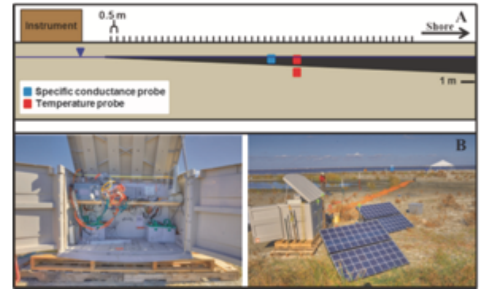


Oil impact thins away from the shoreline

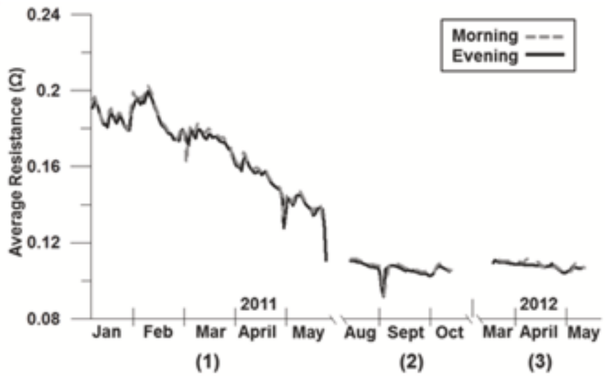
Heenan, J., Slater, L.D., Ntarlagiannis, D., Atekwana, E.A., Fathepure, B.Z., Dalvai, S., Ross, C., Werkema, D.D., and Atekwana, E.A., *Geophysics*, 2014

EPA United States Environmental Protection Agency

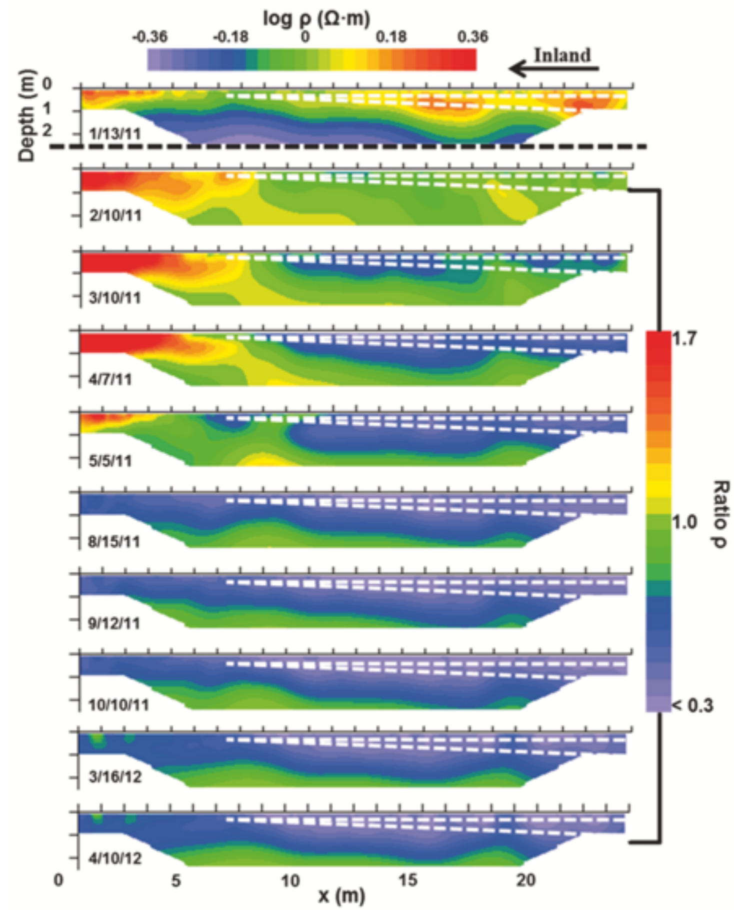
DWH Barrier Island Time-Lapse



Adaptation of field resistivity system to remote solar power acquisition



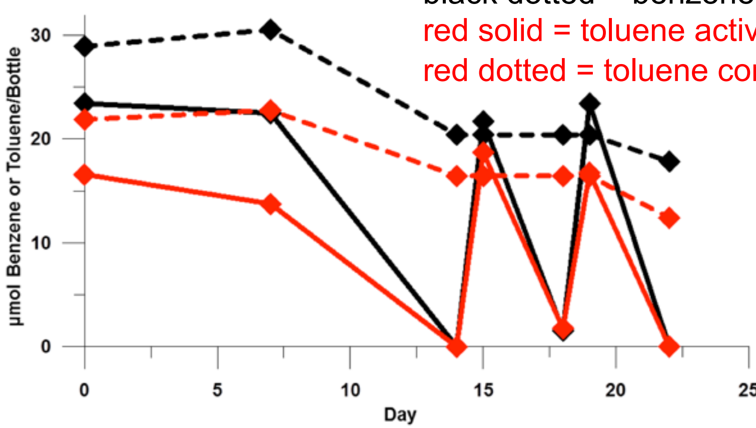
ave. resistance of anomaly vs. time



15 months resistivity

Microcosm experiments using site samples shows rapid and dynamic hydrocarbon degradation

black solid = benzene active
black dotted = benzene control
red solid = toluene active
red dotted = toluene control



Heenan, J., Slater, L.D., Ntarlagiannis, D., Atekwana, E.A., Fathepure, B.Z., Dalvai, S., Ross, C., Werkema, D.D., and Atekwana, E.A., *Geophysics*, 2014

NonAqueous Phase Liquid (NAPL) DC resistivity response

United States Environmental Protection Agency

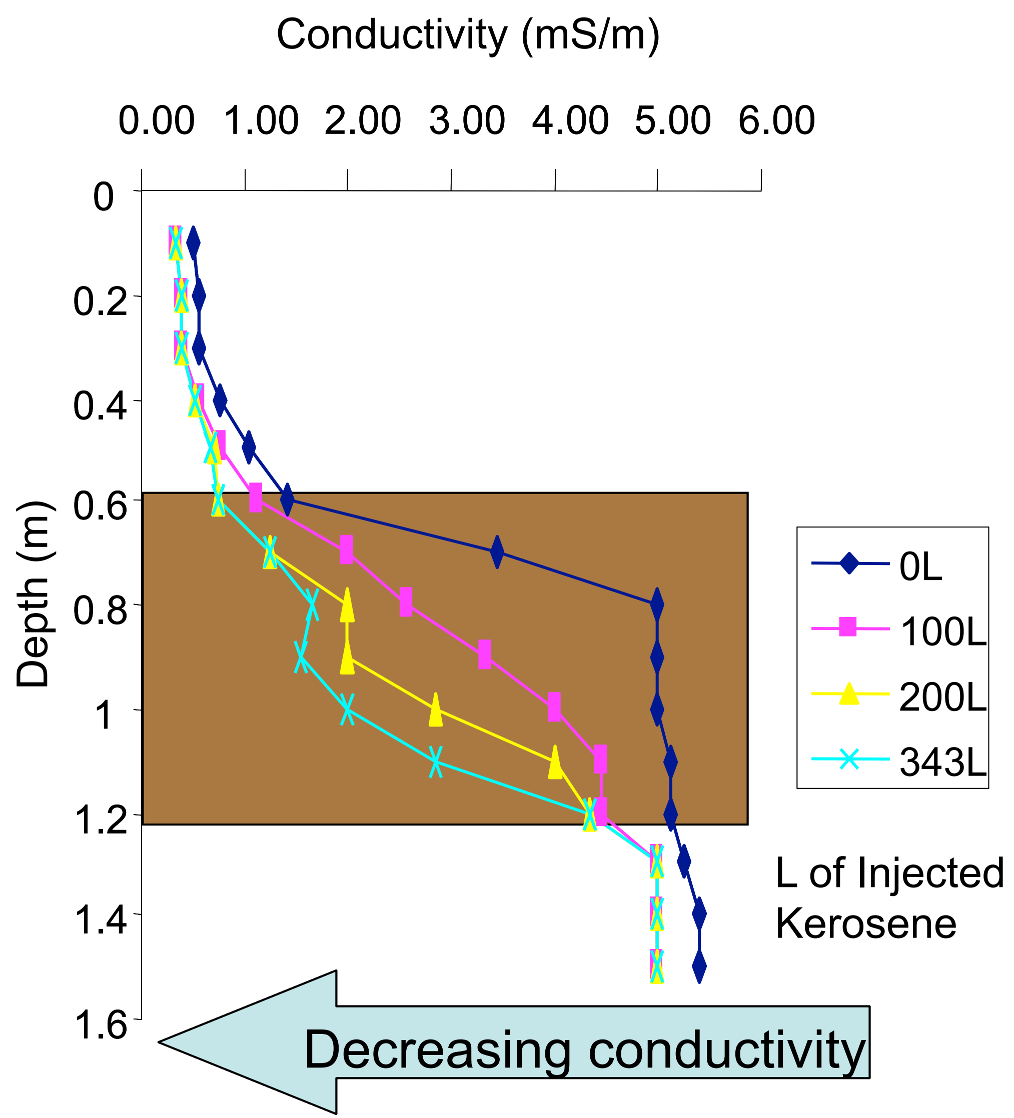
Hydrocarbons are Electrically Resistive (initially)

ARCHIE'S LAW (1942):

$$\rho_e = a\,\phi^{-m}\,S^{-n}\,\rho_w$$

ρ_e = resistivity of the earth
ϕ = fractional pore volume (porosity)
S = fraction of the pores containing fluid
ρ_w = the resistivity of the fluid
n, a and m are constants

Controlled Kerosene Spill

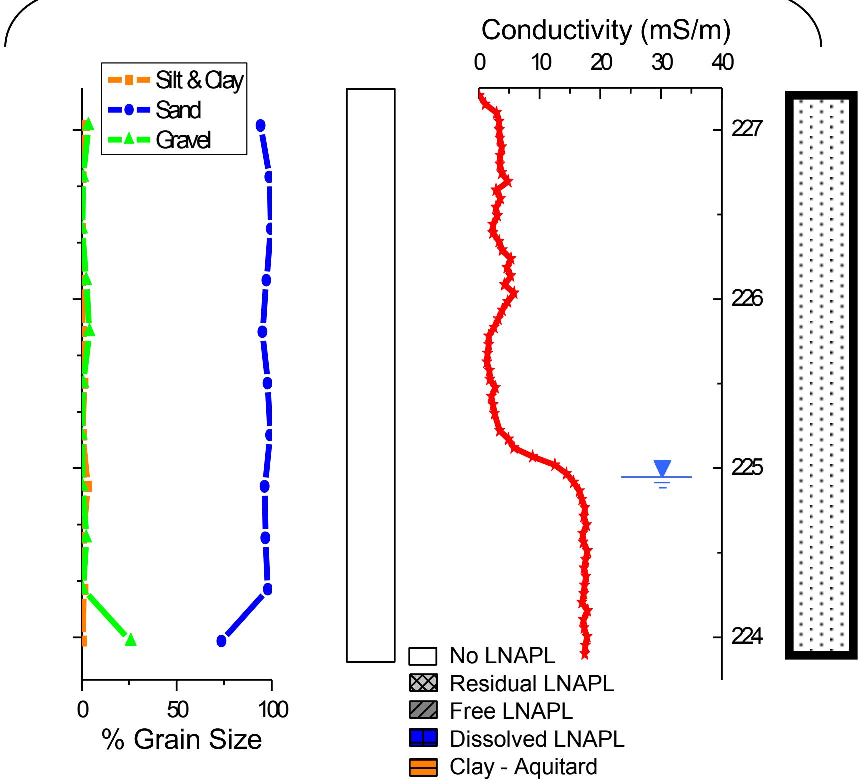


De Ryck et al., 1993

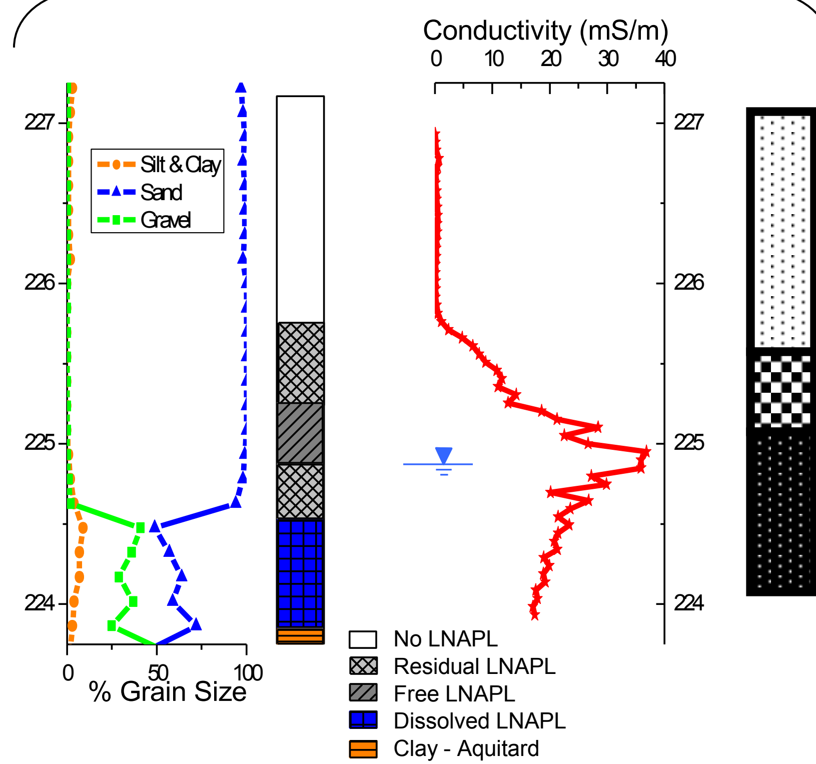
United States Environmental Protection Agency

Field Site: Bulk Conductivity Profiles in-situ resistivity probes

Uncontaminated location



Contaminated location



Acidobacteria = Common soil bacteria

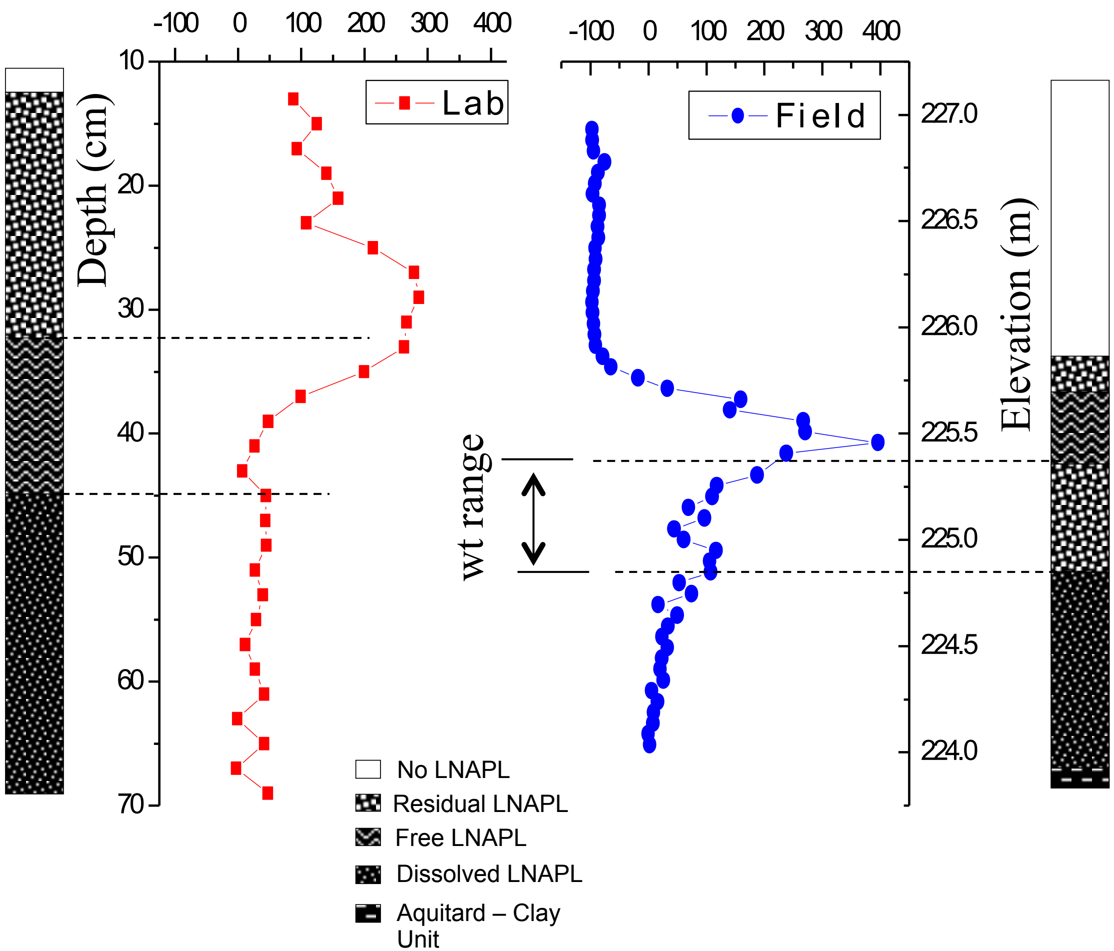
Methylotrophs + Aromatic Hydrocarbon Degraders

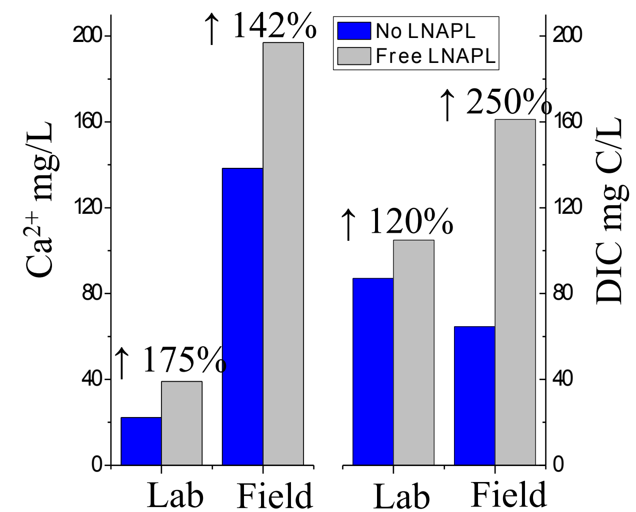
Iron and sulfur reducers & Hydrocarbon degrading fermenters

Werkema Jr., D.D., Atekwana. E.A., Endres, A., Sauck, W.A. and Cassidy. D.P., *Geophysical Research Letters*, 2003

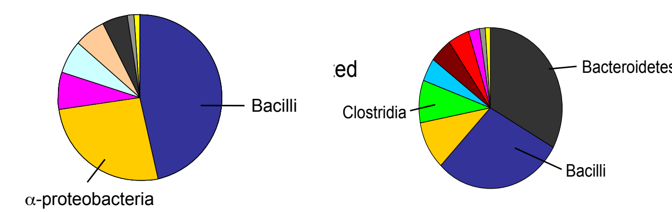
DC Resistivity of mature LNAPL plume

% change conductivity contaminated - clean





% change of Ca^{2+} and DIC



16S rRNA gene community composition

Geophysical response is coincident with microbiology and geochemical changes

Werkema Jr., D.D., Atekwana. E.A., Endres, A., Sauck, W.A. and Cassidy. D.P., *Geophysical Research Letters*, 2003

Induced Polarization (IP) and Spectral Induced Polarization (SIP)

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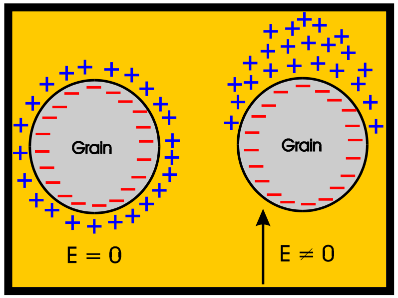


SIP (frequency domain):

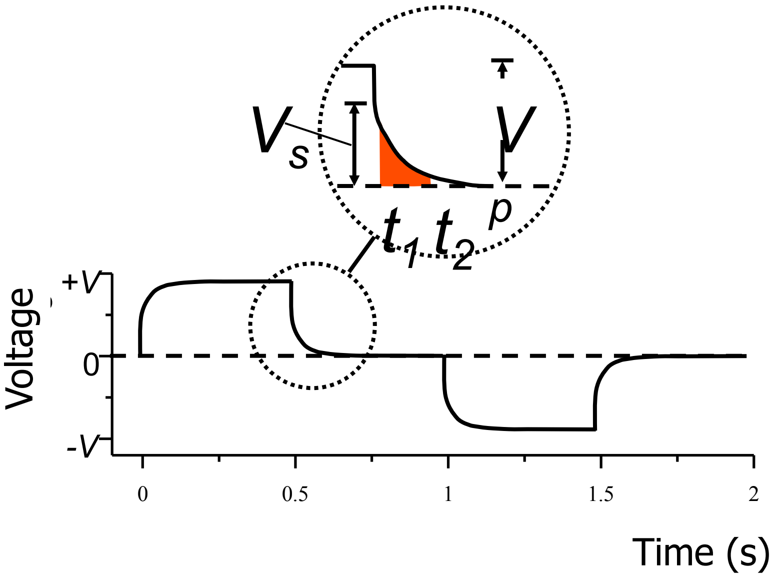
Real or In-phase: (σ ' = |σ| cos φ)

- fluid chemistry,
- electrolytic conduction, and
- interfacial component

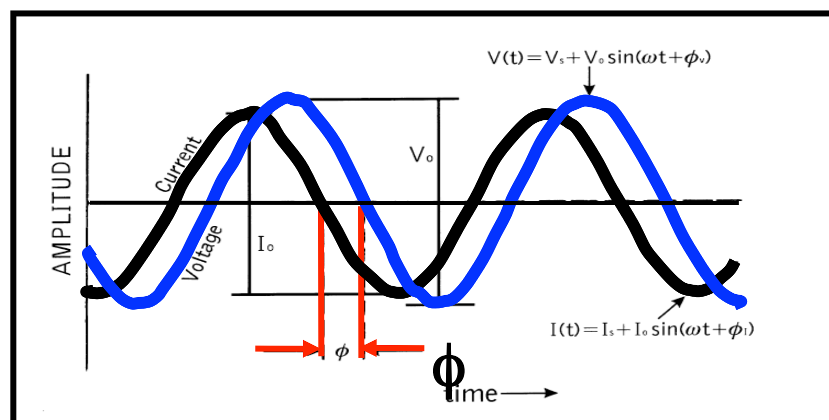
Imaginary, out-of-phase, or quadrature (σ " = |σ| sin φ)

- physicochemical properties at fluid-grain interface
- surface charge density,
- ionic mobility,
- surface area, and
- tortousity

IP (time domain):



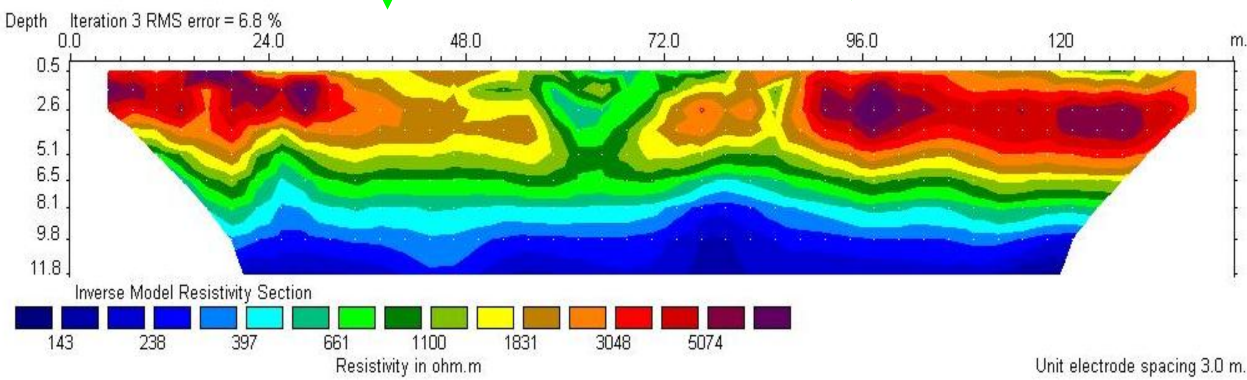
Chargeability = $M = \frac{1}{V_p}\int_{t_1}^{t_2} V(t)\,dt$



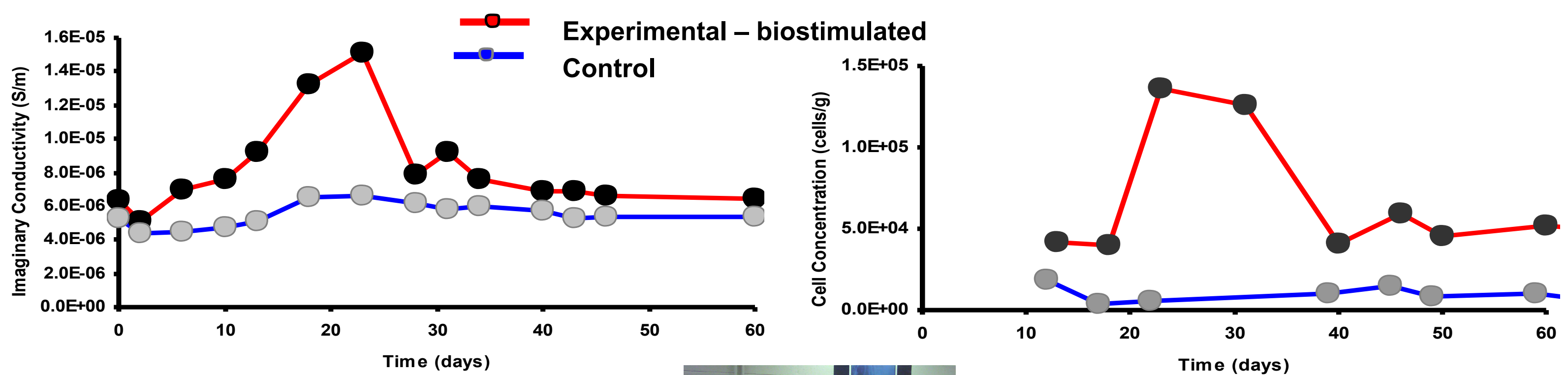
Slide credit: Lee Slater

MNA Field Example with core sample measurements

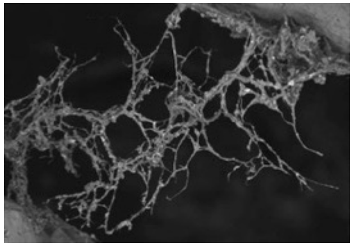
zone of hydrocarbon impact

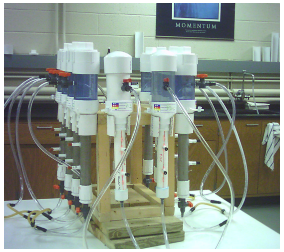


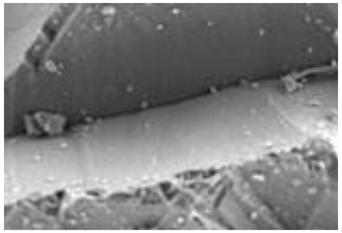
Lab SIP



Lab cells/g





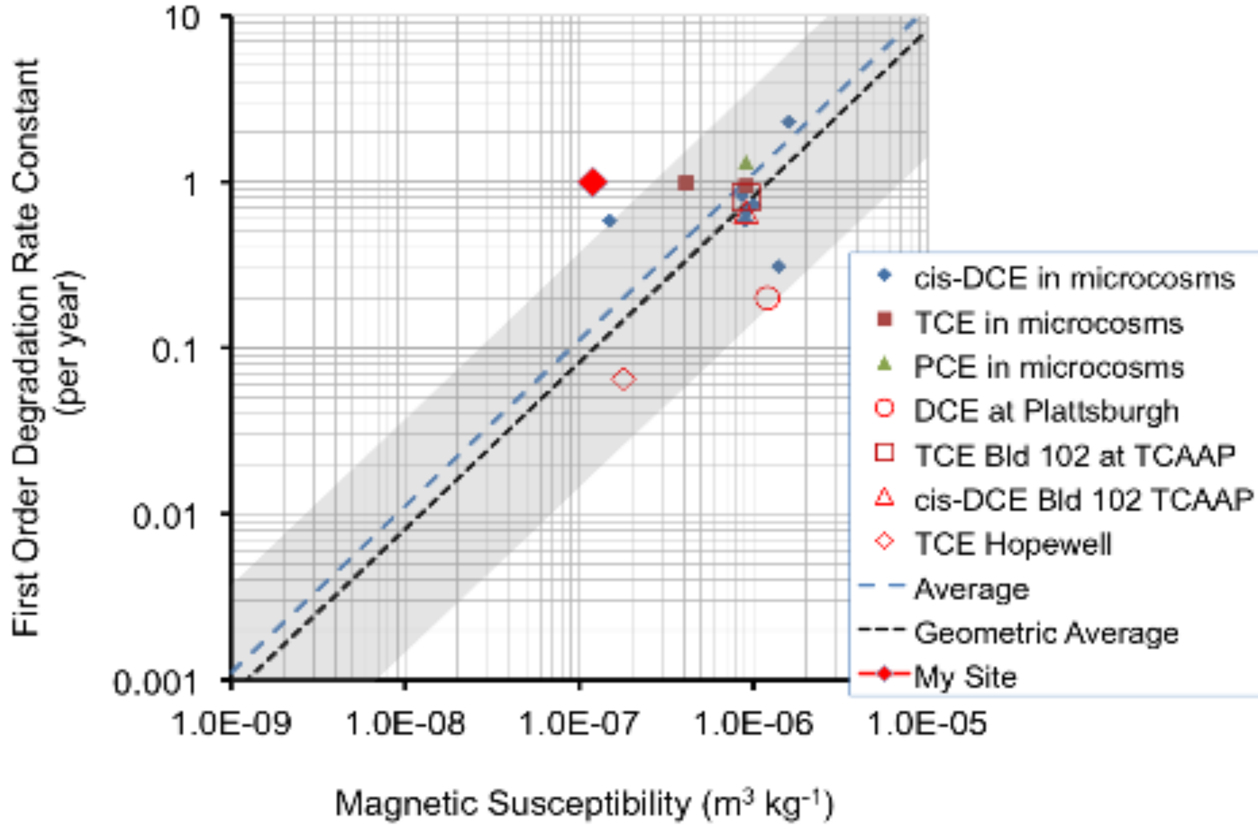


SEM: Day 23 experimental column

SEM: Day 23 control column

Abdel Aal, G. Z., Atekwana, E. A., Rossbach, S., and Werkema Jr., D.D., *Journal of Geophysical Research*, 2010

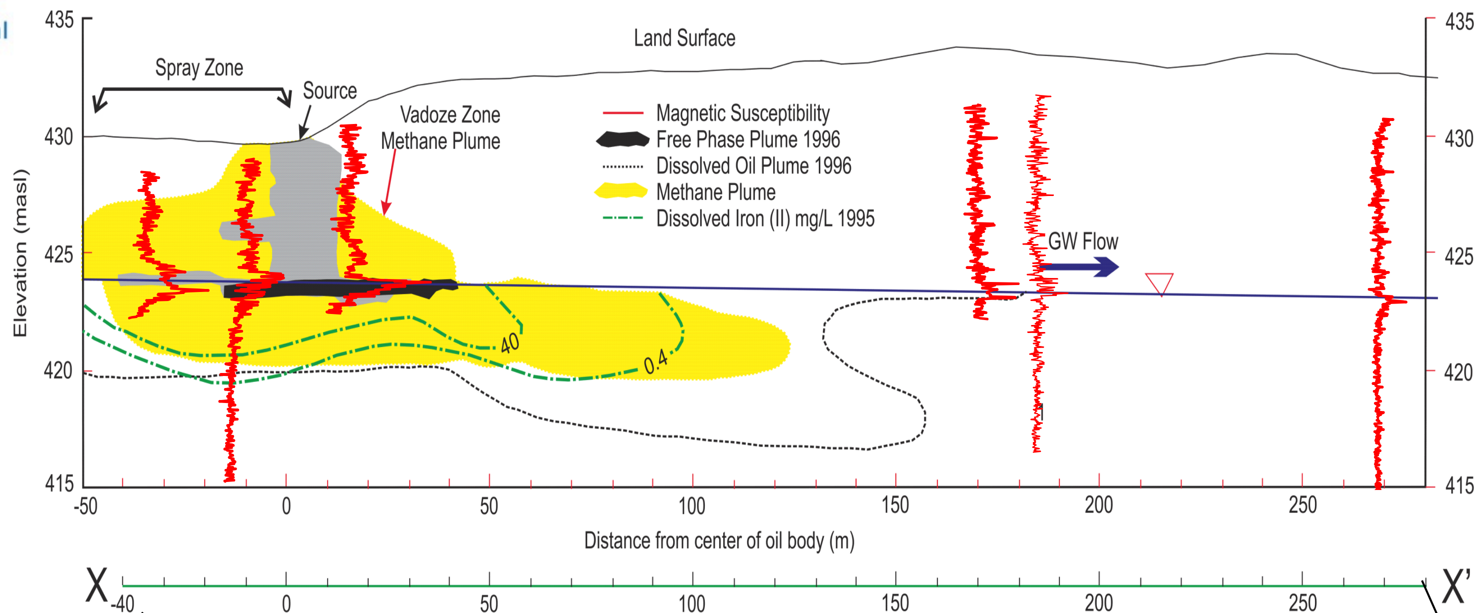
Relationship of Chlorinated Solvent (CS) abiotic degradation rates and Magnetic Susceptibility



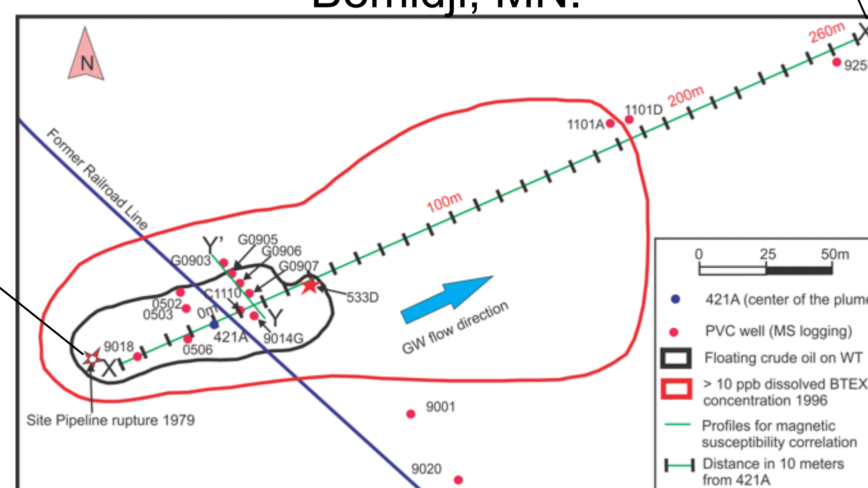
- *CS abiotic degradation rates in saturated soil vs. Magnetic Susceptibility*
- *Wilson has suggested that MS should be measured at all chlorinated solvent sites to identify abiotic degradation rates. (Wilson, PM, 2013)*

Magnetic Susceptibility (MS) at Bemidji, MN

United States Environmental Agency



Bemidji, MN.



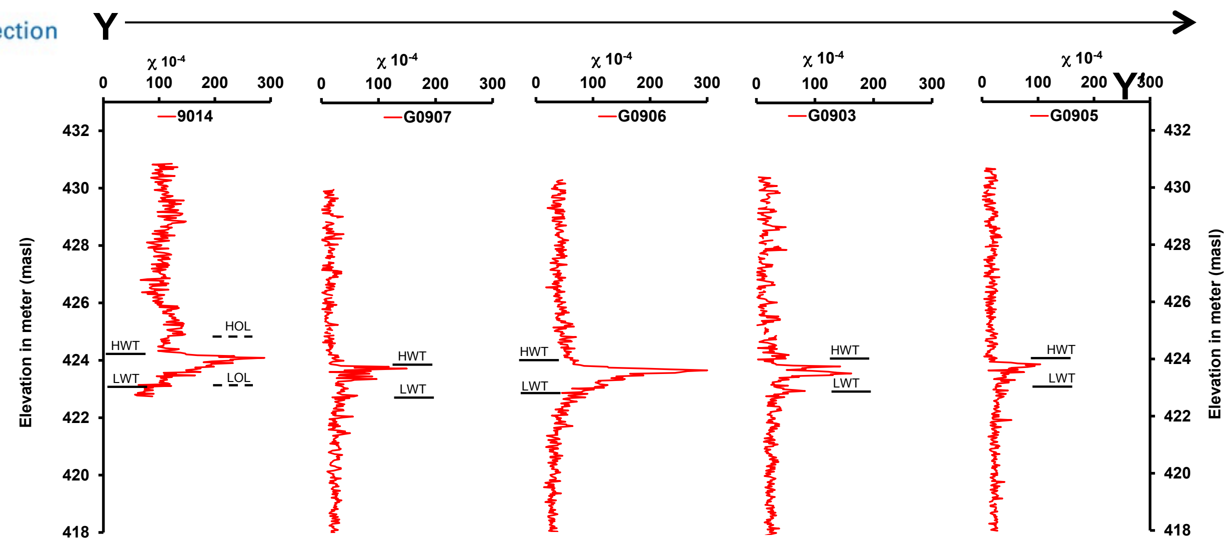
Proxy (MS) measurements of the accumulation of magnetite may be adopted as a non-invasive technology for monitoring long-term natural attenuation of crude oil in the subsurface?

Atekwana, Mewafy, Abdel Aal, Werkema, Revil and Slater, Journal of Geophysical Research, 2014

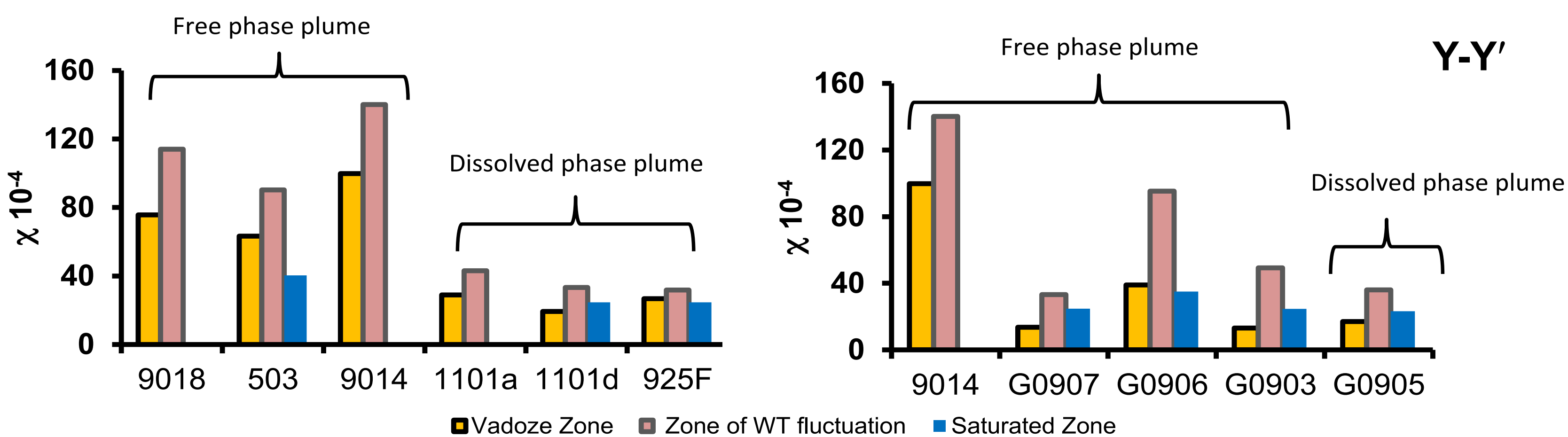
Magnetic Property Enhancement

free phase plume (FPP)

dissolved phase plume (DPP)



X-X′



FPP MS higher vs. DPP MS values

Vadose zone MS above FPP higher vs. locations above DPP

Water table fluctuation zone is the most biogeochemical active

Slide credit: Estella Atekwana

Summary

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Microbial Growth & Metabolism in Porous Media

Microbes + Organic Carbon + Nutrients + Mineral Substrate

Production of Biomass

Microbial Cells
Extracellular Polysaccharides (EPS)
Biofilms
Proteinaceous Appendages

Generation of Metabolic Byproducts

Organic Acids
Biogenic Gases
Biosurfactants

Microbial-Mediated Electrochemical Processes

Redox Reactions
Biomineralization

Can Lead to Physical/Chemical Changes…

Porosity/Permeability
Surface Area/Roughness
Pore Throat Geometry
Tortuosity

Changes in Pore Fluid Chemistry
Enhanced Mineral Dissolution
Increased Porosity/Permeability
Increased Pore Pressure
Changes in Wettability

Reduced Species
Redox Gradients
Enhanced Mineral Precipitation

Changes in Petrophysical Properties

Electrical Resistivity, Induced Polarization, Spontaneous Potential, Seismic, GPR, Magnetic Susceptibility

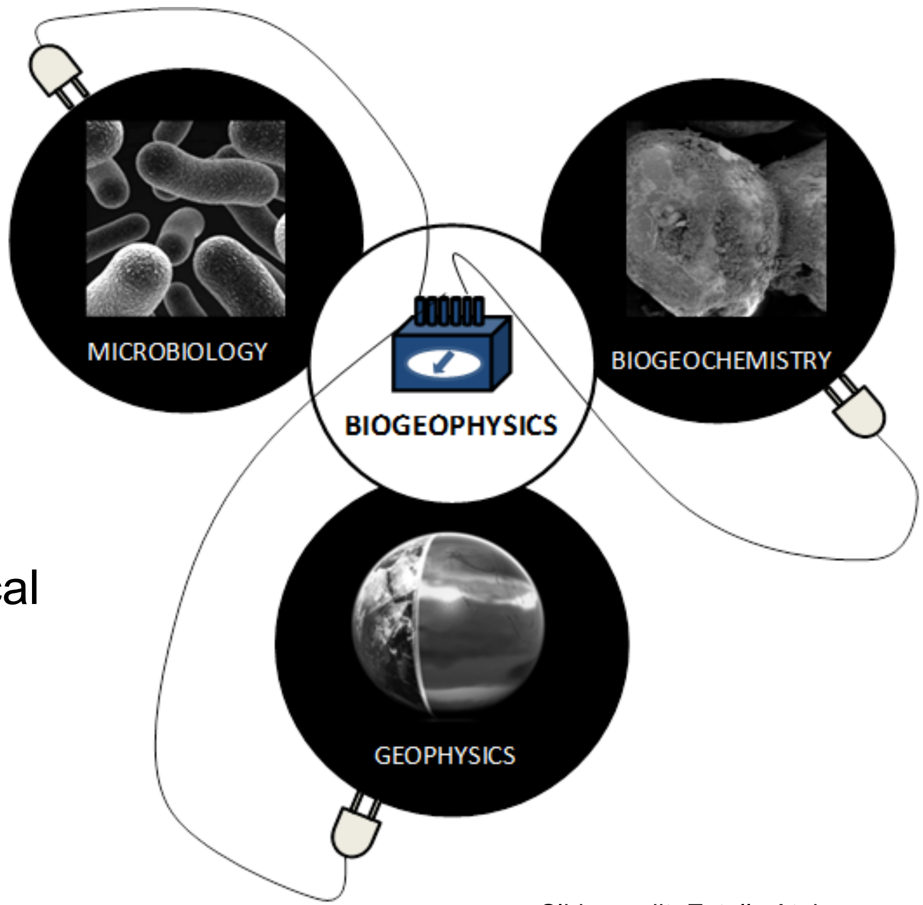
Slide credit:
Estella Atekwana

Biogeophysics

"The geophysical investigation of microbial processes/interactions in the earth"

Atekwana and Slater, 2009, Biogeophysics: A new frontier in Earth science research: Rev. Geophys., 47, RG4004, doi:10.1029/2009RG000285

- Geophysical methods to detect/monitor microbial activity & their by-products or presence in the subsurface
- Optimization of remediation programs
- Assess redox transformations and biogeochemical cycling of elements
- Guide microbial sampling in biogeochemical hot zones



Slide credit: Estella Atekwana

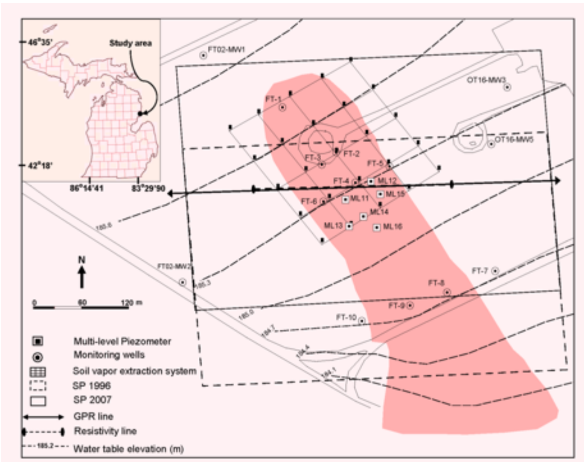
Soil Vapor Extraction (SVE) monitoring using Self-Potential (SP)

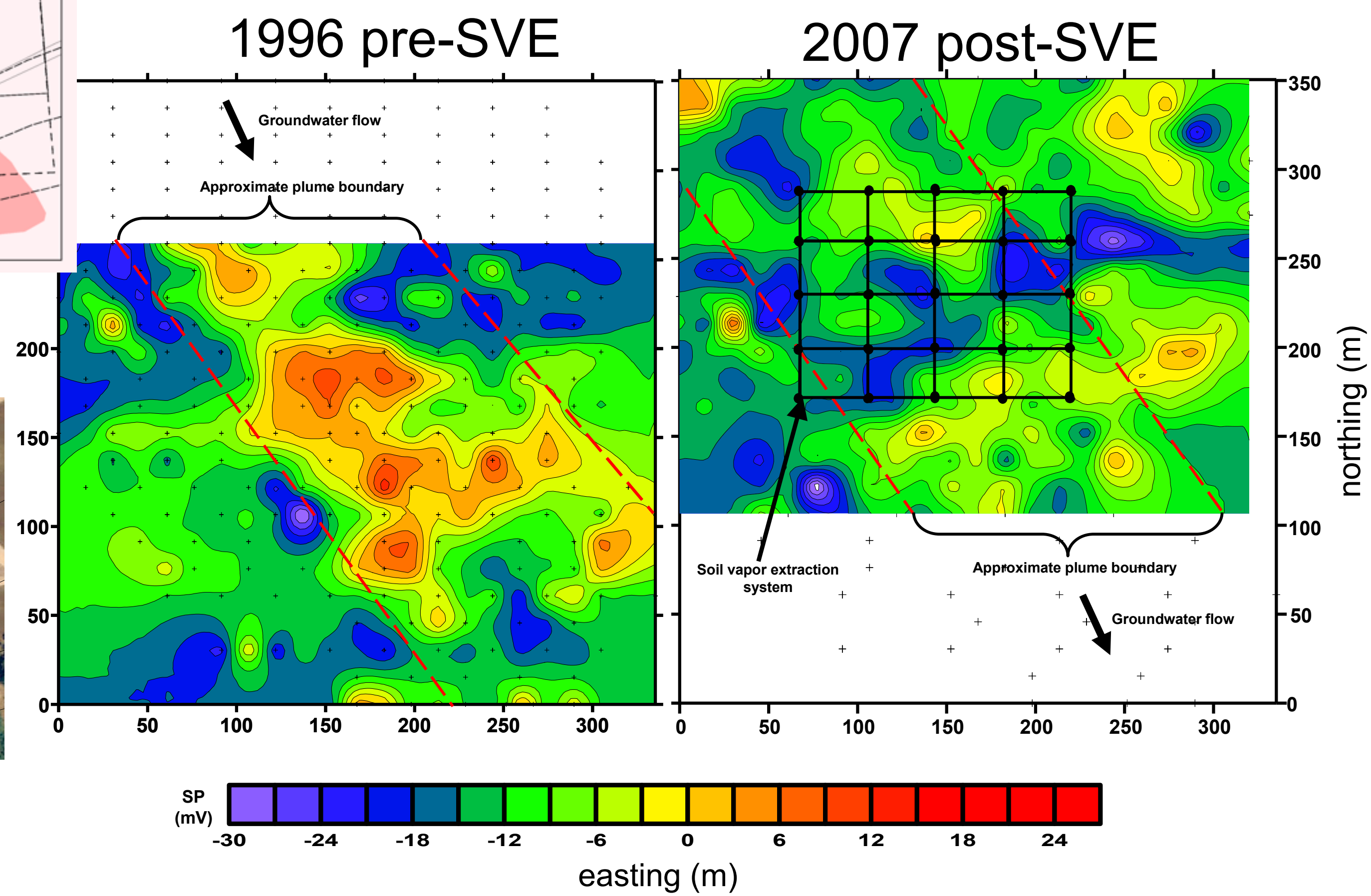
United States Environmental Protection Agency

Former fire training facility, Oscoda, Michigan

Large quantities of fuel were burned.

1990s, the free product 0.3 m thick and > 200 m down gradient





Vukenkeng C.A., Atekwana Estella.A., Atekwana, Eliot, A., Sauck, W.A., Werkema Jr., D.D., *Geophysics*, vol. 74, 2009

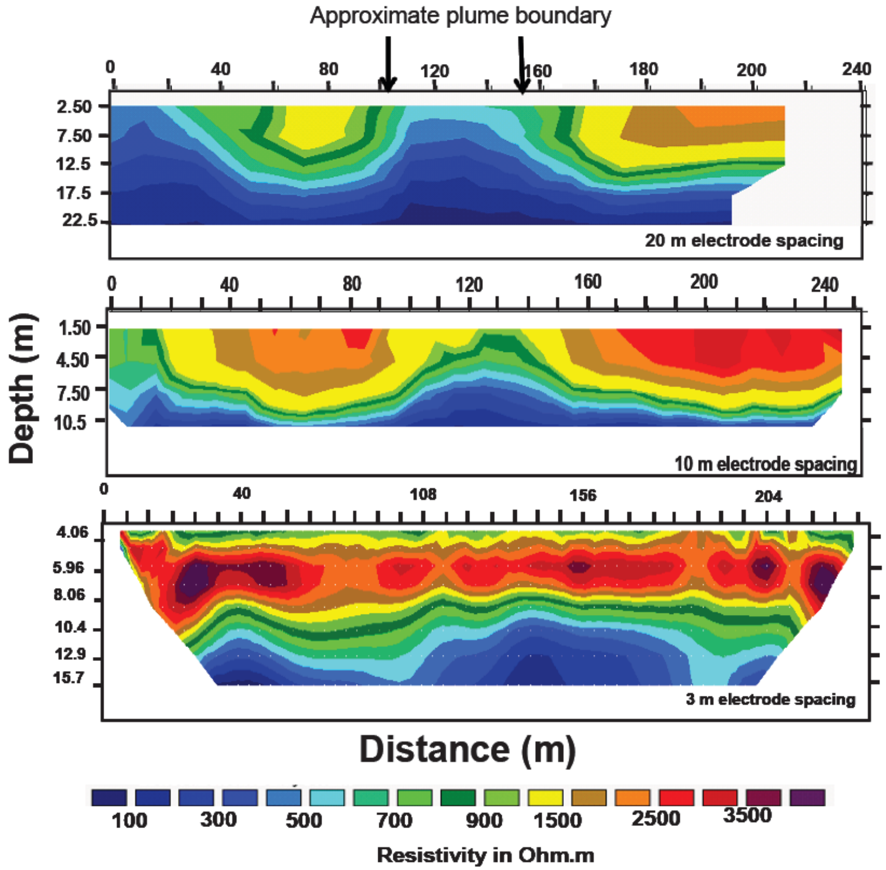
DC Resistivity response to SVE system

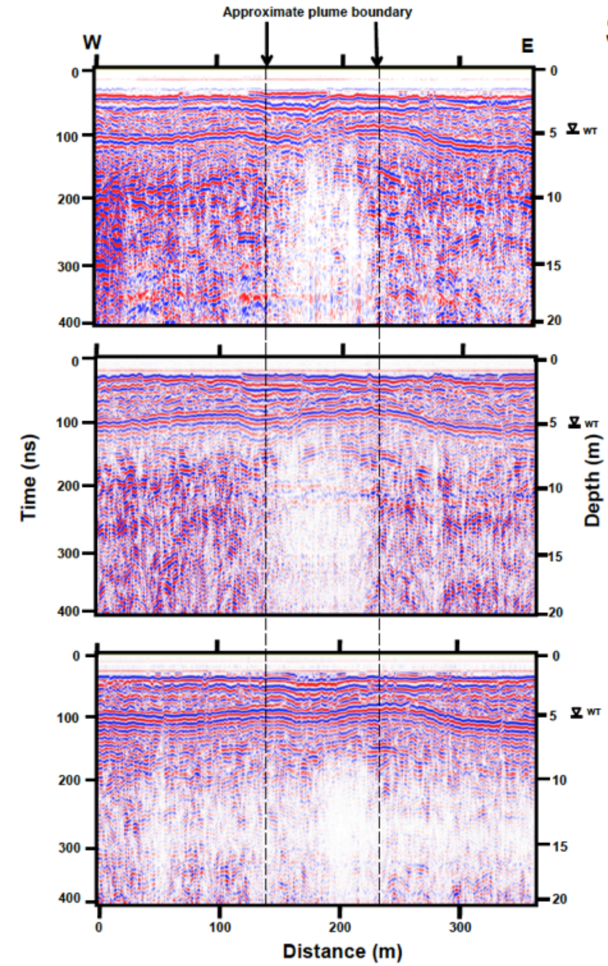
GPR Response to SVE System

1996

2003

2007





1996

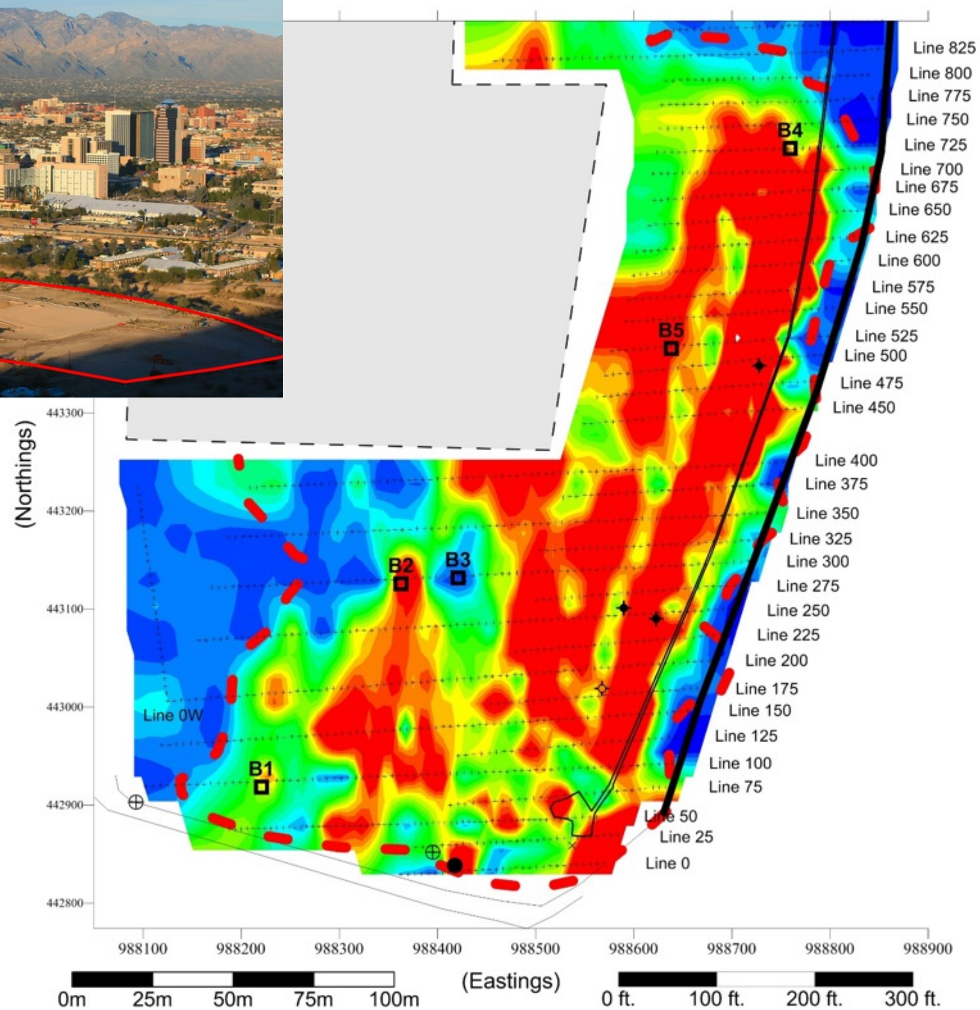
2003

2007

Vukenkeng C.A., Atekwana Estella.A., Atekwana, Eliot, A., Sauck, W.A., Werkema Jr., D.D., *Geophysics*, vol. 74, 2009

Landfill investigations using Induced Polarization (IP)

Tucson, AZ



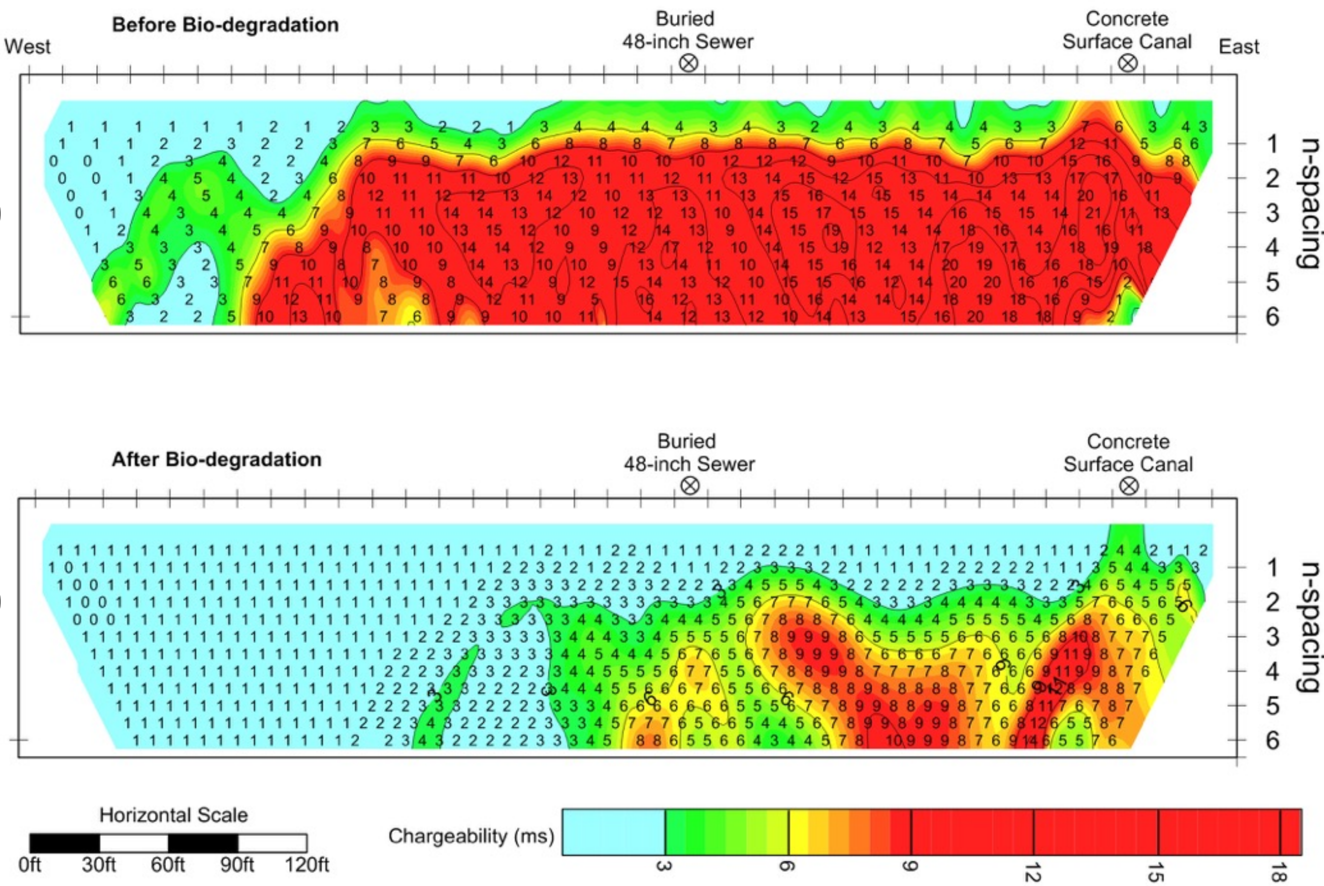
Slide credit: Norm Carlson

United States Environmental Protection Agency

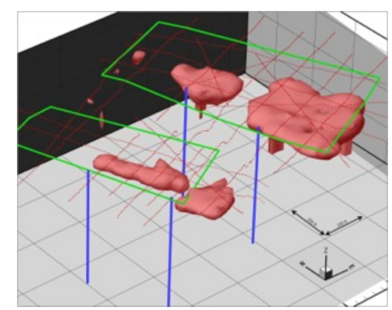
IP surveys map the landfill extent & breakdown

1999

2009



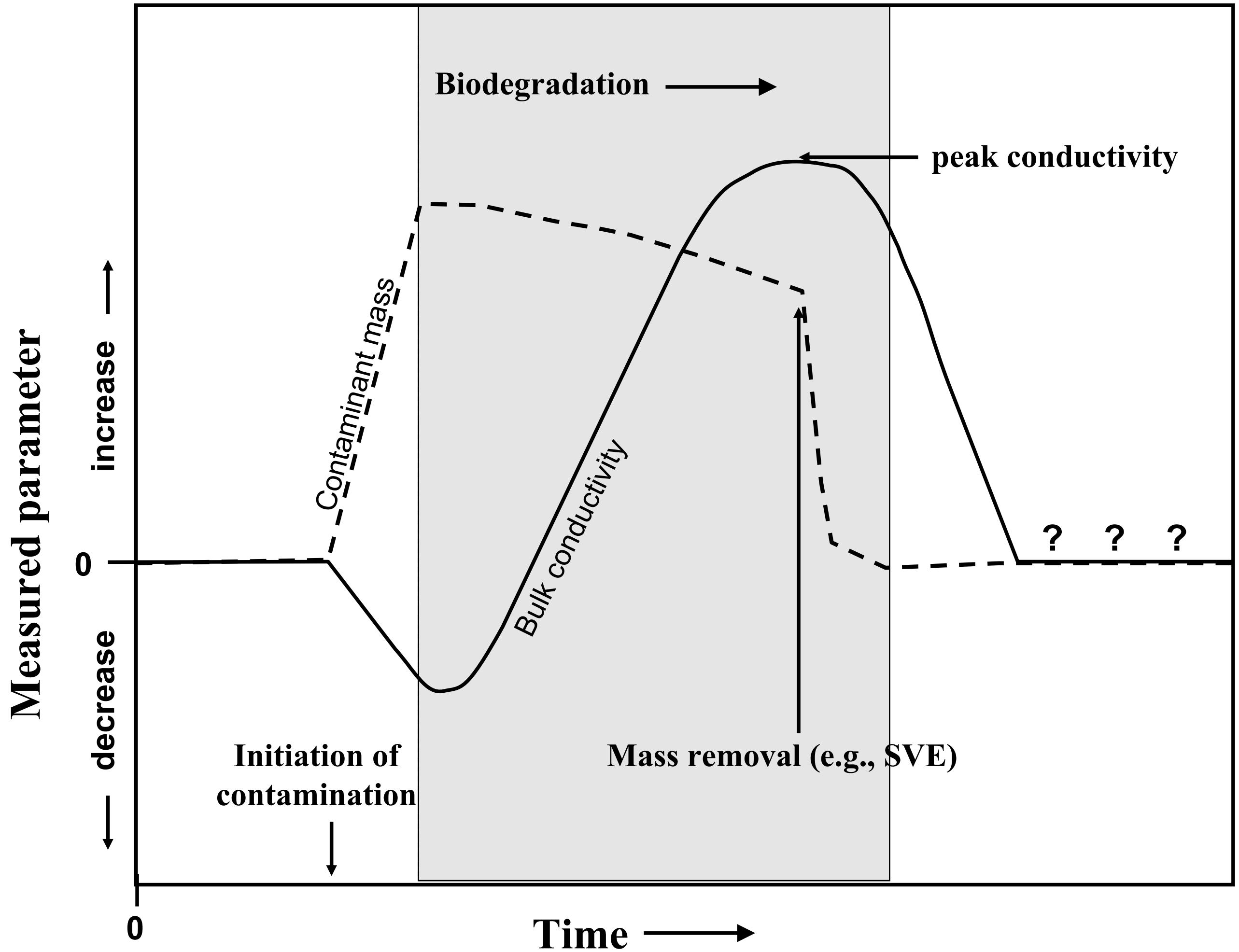
3D mapping



- Air and water injected to enhance microbial activity
- Flows adjusted to maintain optimum temperatures

Slide credit: Norm Carlson

Conceptual model illustrating the temporal behavior of bulk electrical conductivity due to natural attenuation (biodegradation)

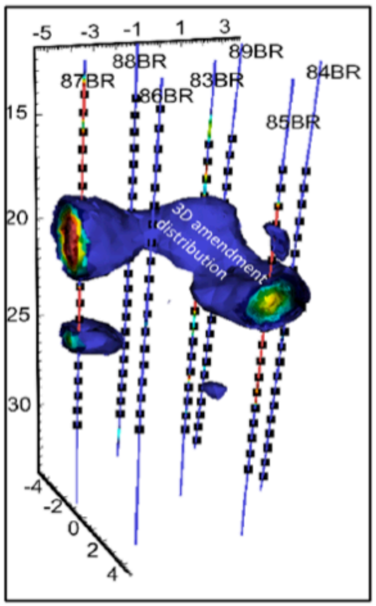


Atekwana E.A., Atekwana E.A., Werkema Jr., D.D., Allen, J.P., Smart, L.A., Duris, J.W., Cassidy, D.P., Sauck, W.A., and Rossbach. S., 2004

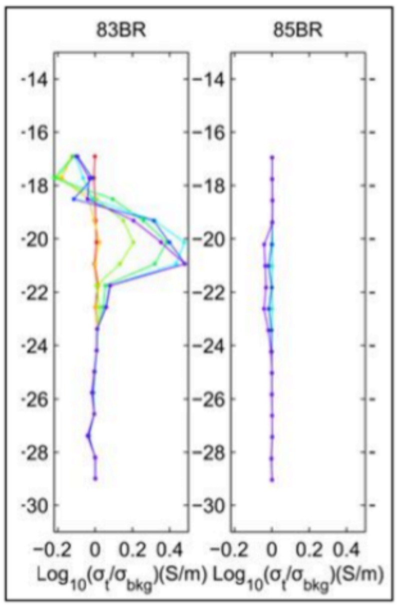
High Resolution Characterization

United States Environmental Protection Agency

Electrical Resistance Tomography (ERT) Imaging



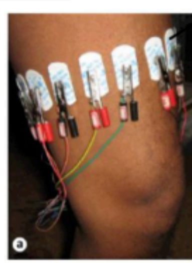
Vertical Profiling

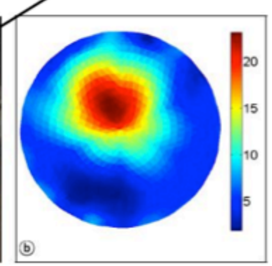


2D, 3D, and 4D

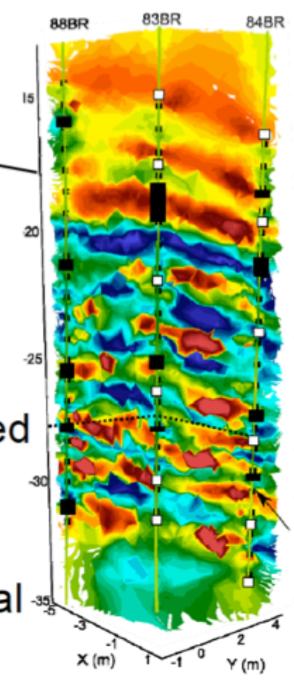
Method: Electrical Resistivity Tomography (ERT)

Site remediation equivalent of medical tomography





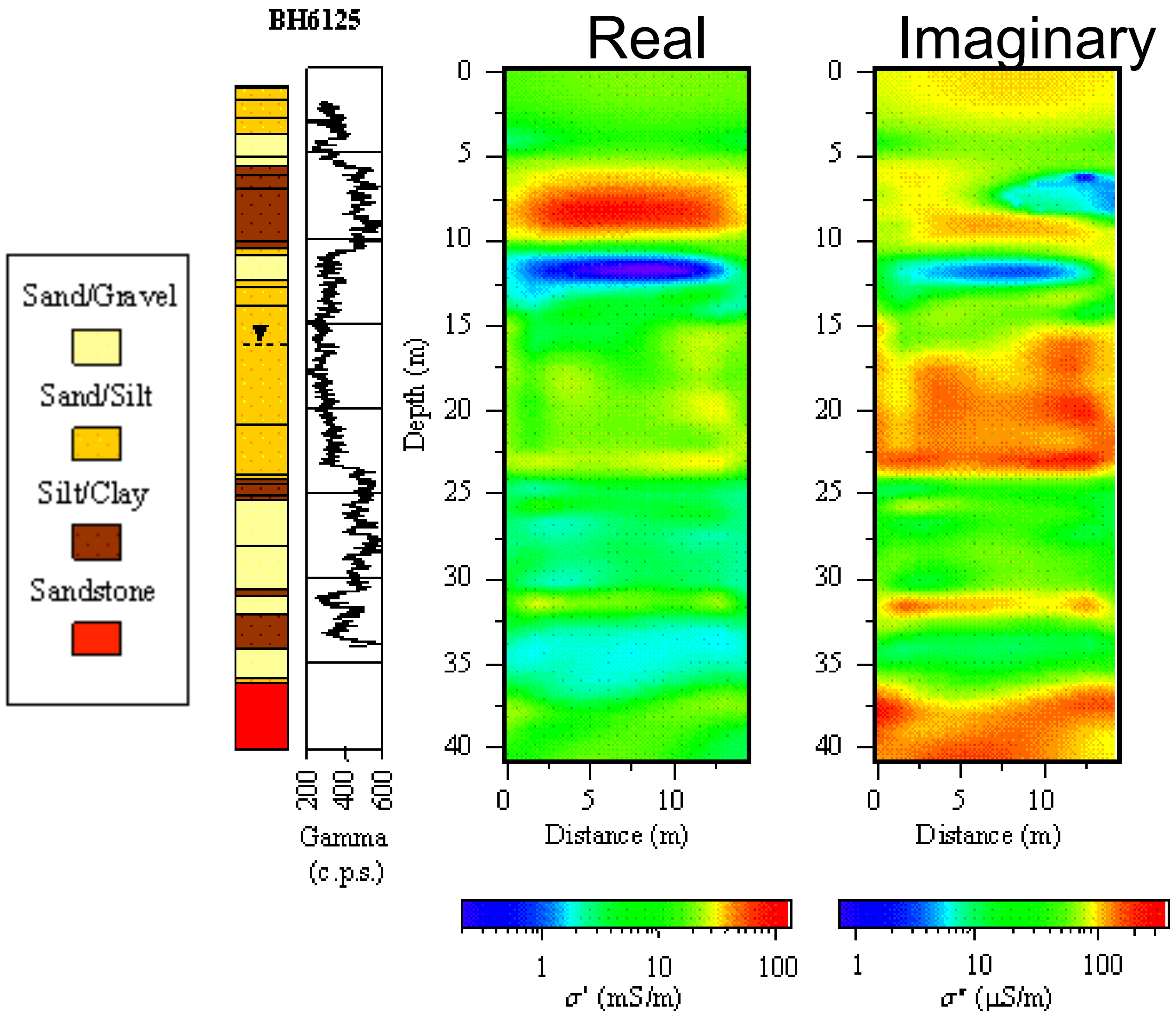
- Electrodes in boreholes are used to image volume bounded by boreholes
- Relies on electrical conductivity contrasts



Slide credit: Lee Slater

IP for lithologic imaging

- Sensitivity of IP to surface area makes it well-suited for imaging lithology
- Lithologic boundaries are sharper in the imaginary response

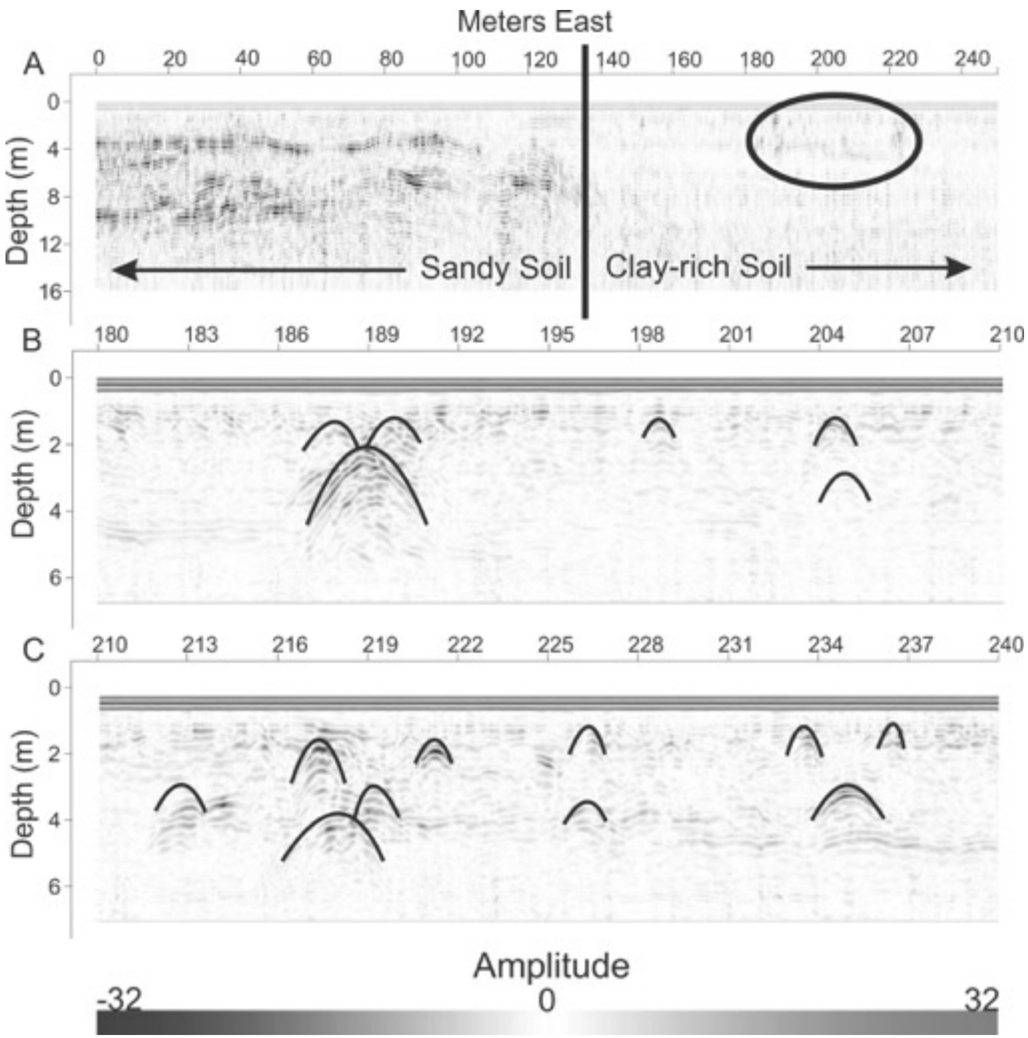


Kemna et al., 2004, *Geophysics*

Slide credit: Lee Slater

High Resolution CSM development

GPR detection and mapping of animal burrows



Cutter ant burrow GPR image with 100 MHz antenna

A) the transition from sandy to clay-rich soils (vertical line) and inactive cutter ant burrows (rectangle).

B) zoomed-in view of the inactive cutter ant burrows from 180E to 240E.

C) Zoom in from 210 to 240

B) & C) Hyperbolic reflections related to the burrow system are traced in bold.

The relative permittivity is estimated at 5 for all profiles in this figure, indicating a velocity of 0.13 m/ns.

Sherrod, L., Sauck, W., Simpson, E., Werkema, D., Swiontek, J., Case histories of GPR for animal burrows mapping and geometry, Journal of Environmental and Engineering Geophysics, In press, 2018

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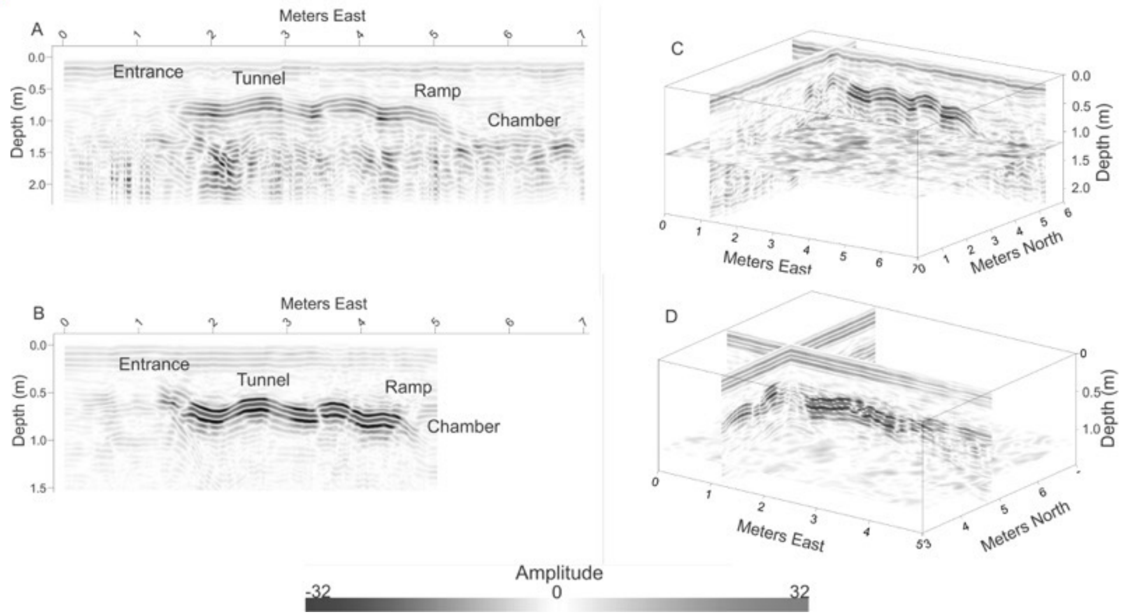
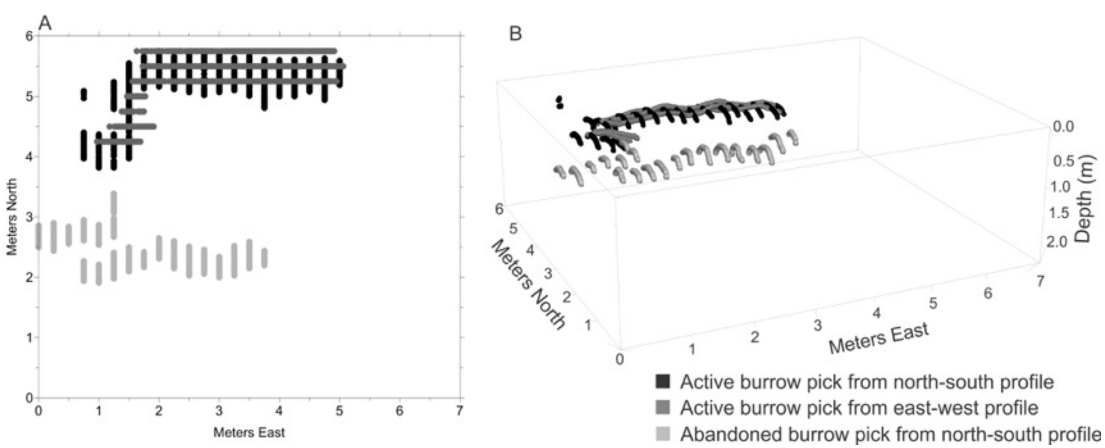
GPR detection and mapping of animal burrows

400 MHz

900 MHz



Groundhog burrow GPR image depicting the entrance shaft, tunnel, ramp, and chamber imaged with the 400 MHz antenna and the 900 MHz antenna.



Manual picks chosen for the identification of the groundhog burrow system through hyperbolic reflections in the 400 MHz data.

Sherrod, L., Sauck, W., Simpson, E., Werkema, D., Swiontek, J., Case histories of GPR for animal burrows mapping and geometry, Journal of Environmental and Engineering Geophysics, In press, 2018

Using Geophysics for Groundwater Surface Water Investigations: Environmental Applications

FO-DTS: Fiber-Optic Distributed Temperature Sensor Technology

Optical Time Domain Reflectometry - OTDR

- A narrow laser pulse is sent into the fiber and the backscattered light is detected and analyzed by the system
- The time it takes the backscattered light to return to the detection unit is used to determine the location of the temperature event.
- This is completed along the length of the cable enabling the generation of temperature profiles
- Diurnal variability is removed

Control Unit:
AC 115V house power
30-40 W on average, peak ~70 W.
Run from laptop

Slide credit: Marty Briggs

Groundwater – surface water interactions

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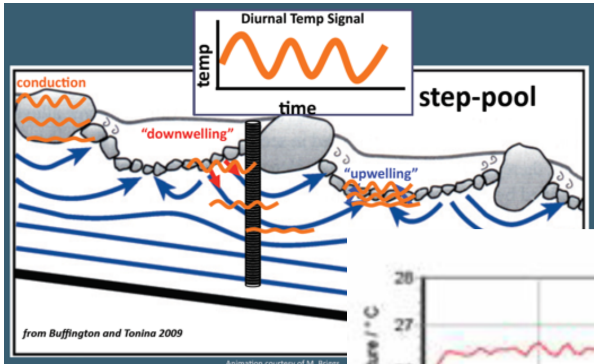
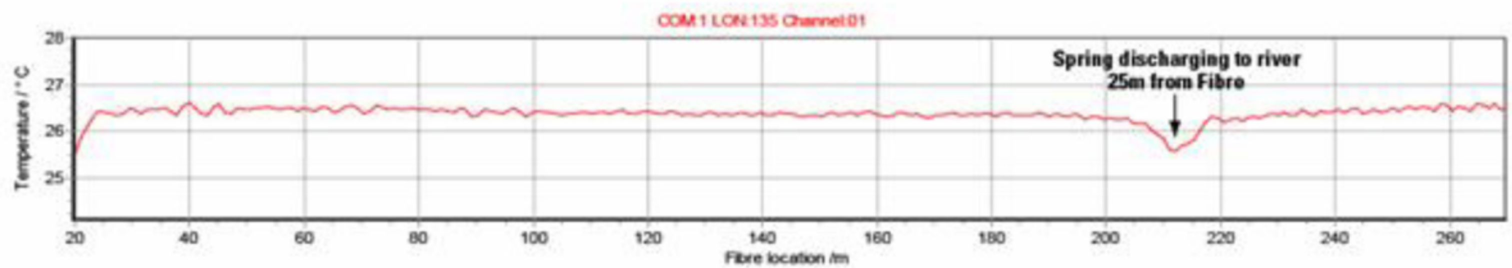
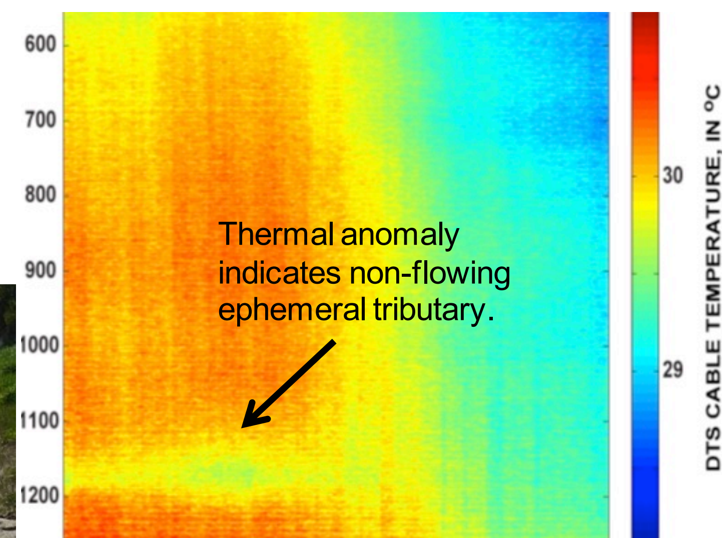
Fiber Optic Distributed Temperature System (FoDTS)







Voytek, E.B., Drenkelfuss, A., Day-Lewis, F.D., Healy, R., Lane, Jr., J.W. and Werkema, D., 2013

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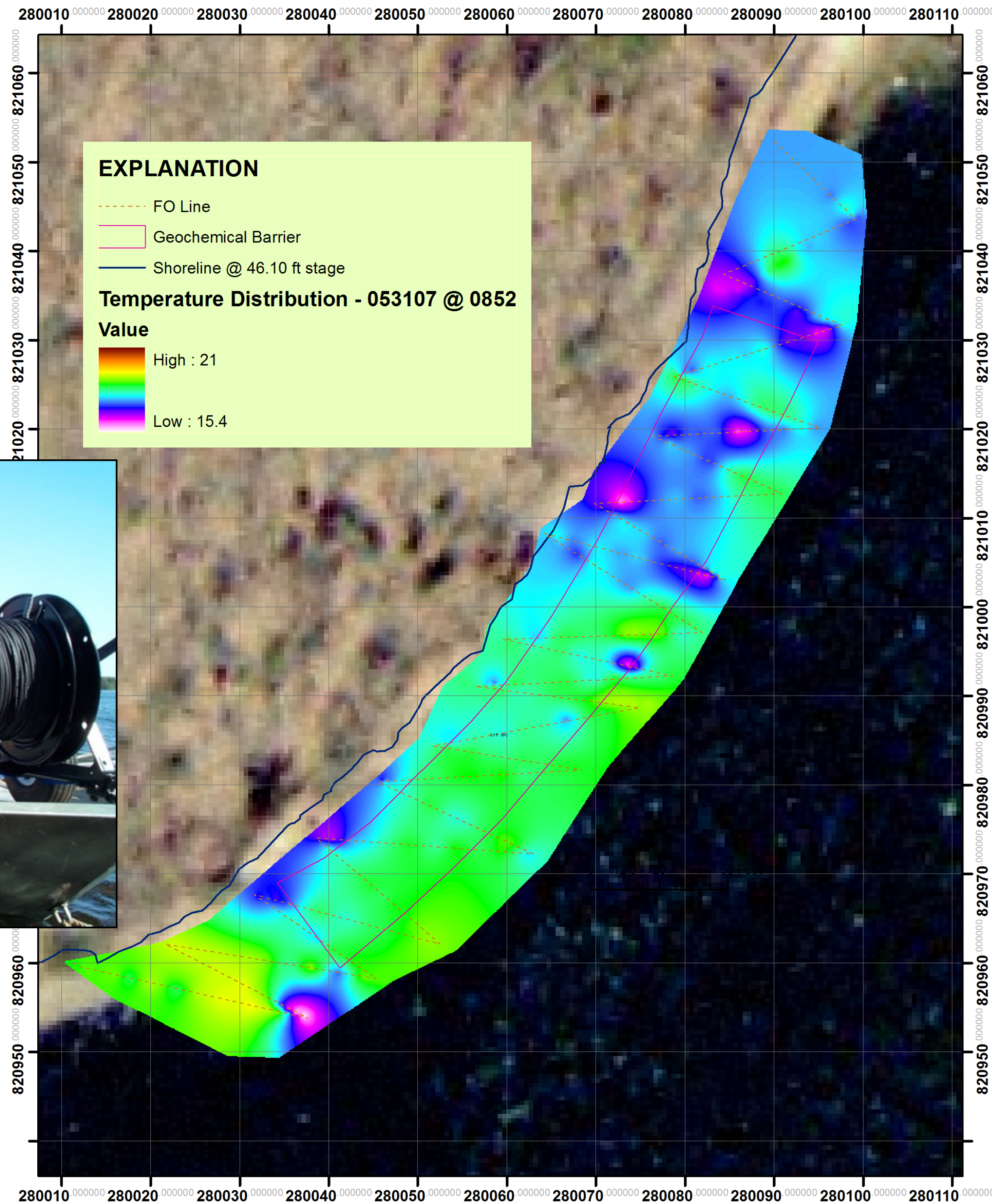
FO-DTS Monitoring



Slide images credit: Marty Briggs

Recent advances in UAV-based infrared

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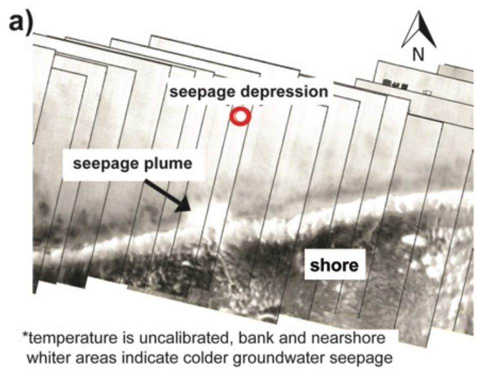
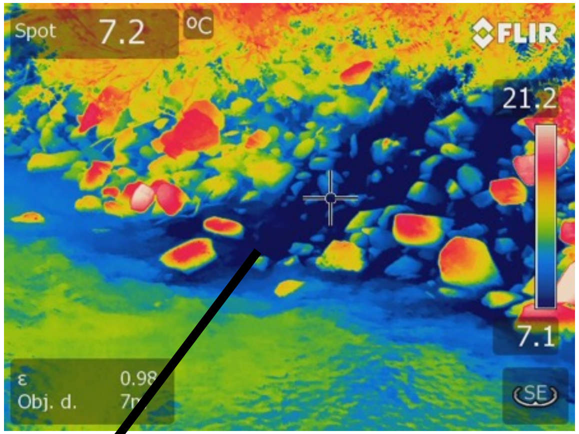




Handheld FLIR

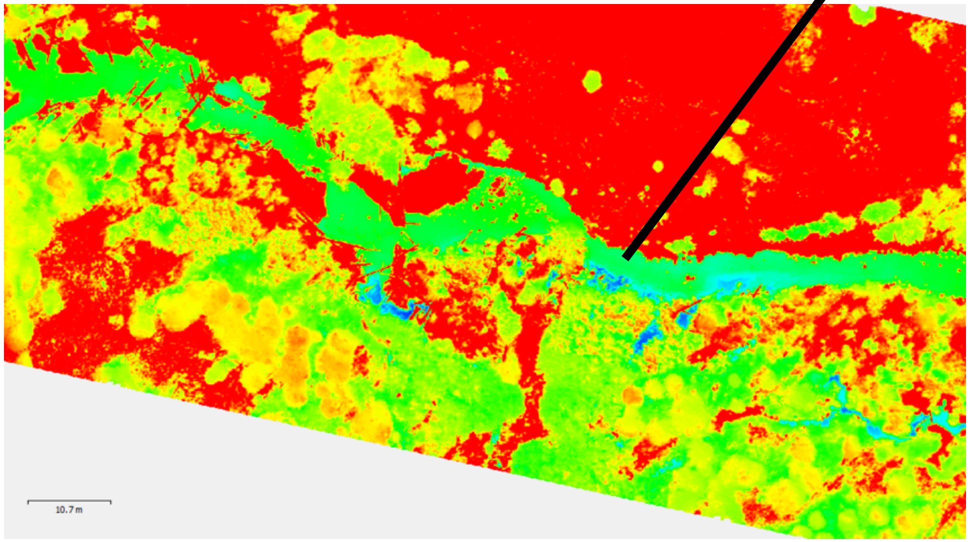
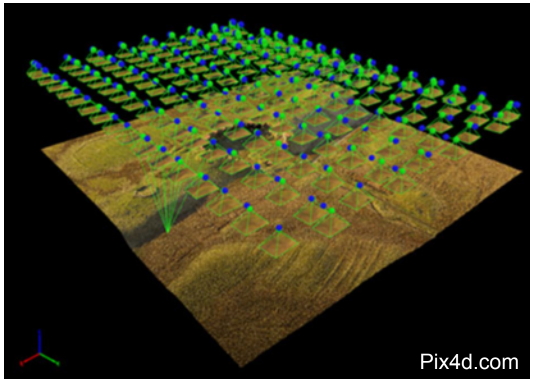


image compiled by C. Holmquist-Johnson,
preliminary (not reviewed)

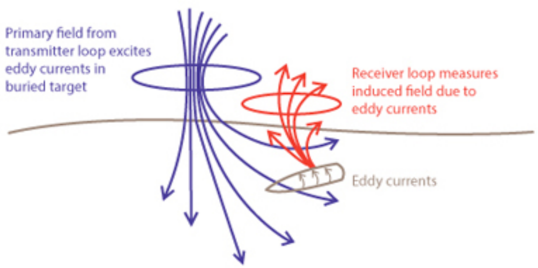


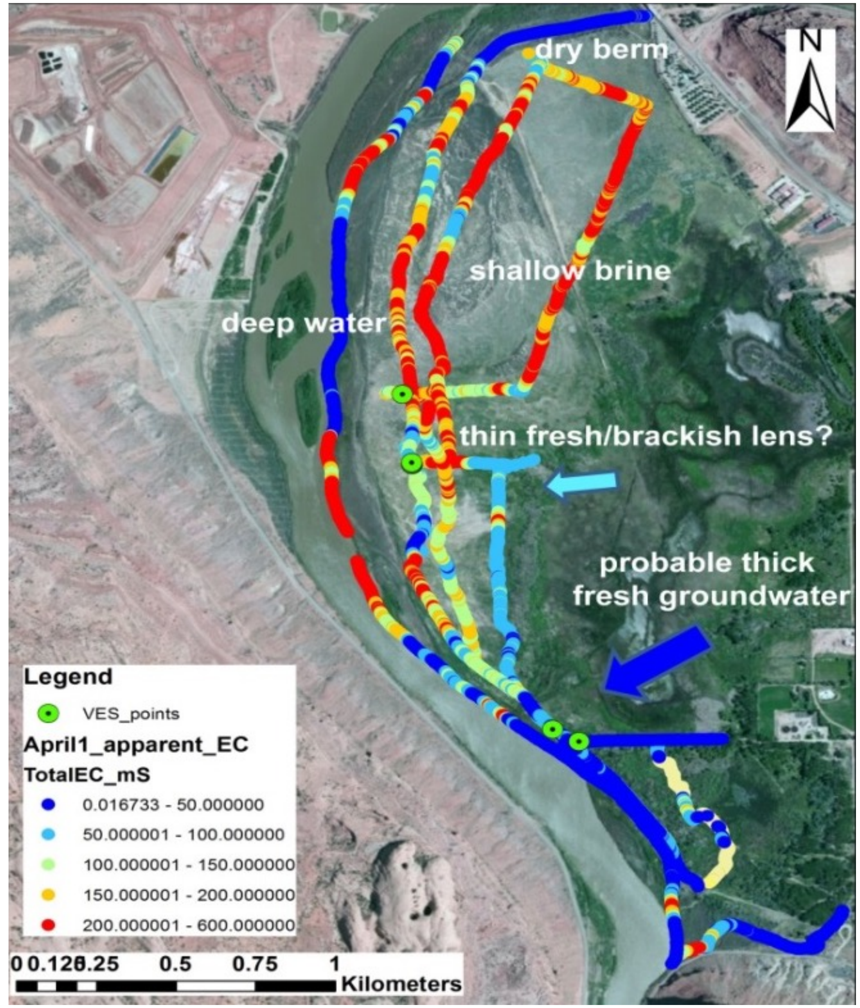
UAV photogrammetry for topography; e.g. Pix4D

Slide images credit Marty Briggs

Stream Electromagnetic Induction

United States Environmental Protection Agency





Moab, UT

EMI allows the characterization of many km/day over land and shallow water

Slide credit: Marty Briggs

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Environmental Geophysics web presence: tech transfer, assistance, guidance, and decision support tools

ONLINE RESOURCES

Environmental Geophysics explores the physics of the earth related to environmental problems. This site includes technical scientific content, decision support tools, predictive models, and data interpretation models to facilitate the proper use, application, and interpretation of geophysics to environmental problems.

About

- Overview
- Geophysical Methods
- Applications

Tools

- Decision support
- Forward models
- Inverse models

Related Links

- Professional societies
- Journals
- Equipment
- Other Feds
- Universities

Publications and Research

- EPA publications
- Ongoing research

Resources

- Surface Methods
- Borehole Methods
- Marine Methods
- Geophysical Properties
- Inversion
- Terms
- References

Once finalized this will be found at:

www.epa.gov/environmental-geophysics

Beta version: https://clu-in.org/characterization/technologies/geophysics/

Models & Decision Support

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Environmental Geophysics

CONTACT US SHARE

- Home
- Geophysical Methods
  - Borehole Geophysical Methods
  - Marine Geophysical Methods
  - **Surface Geophysical Methods**
    - Electrical Methods
    - Electromagnetic Methods
    - Nuclear Methods
    - Potential Field Methods
    - Seismic Methods
  - Inversion
- Geophysical Properties
  - Density
  - Electrical Conductivity and Resistivity
  - Geomechanical (Engineering) Properties
  - Magnetic Susceptibility
  - Porosity
  - Reflectivity
  - Seismic Velocities (VS,VP)

Surface Geophysical Methods

This section covers most of the commonly used surface geophysical methods.

- Electrical Methods
  - Equipotential and Mise-a-la-Messe Methods
  - Induced Polarization
  - Resistivity Methods
  - Self-Potential (SP) Method
- Electromagnetic Methods
- Nuclear Methods
- Potential Field Methods
- Seismic Methods

Contact Us to ask a question, provide feedback, or report a problem.

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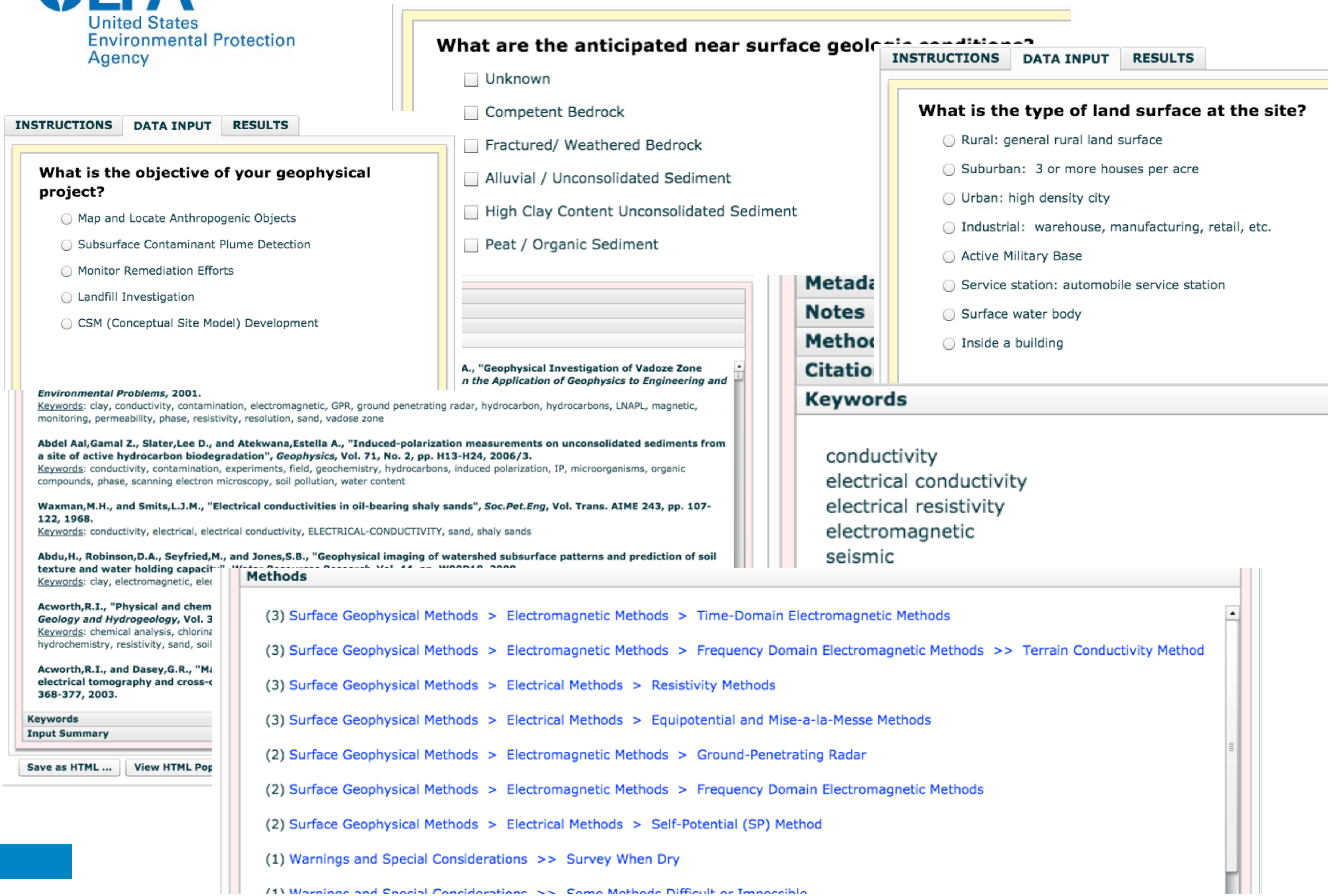
Geophysical Decision Support System (GDSS)

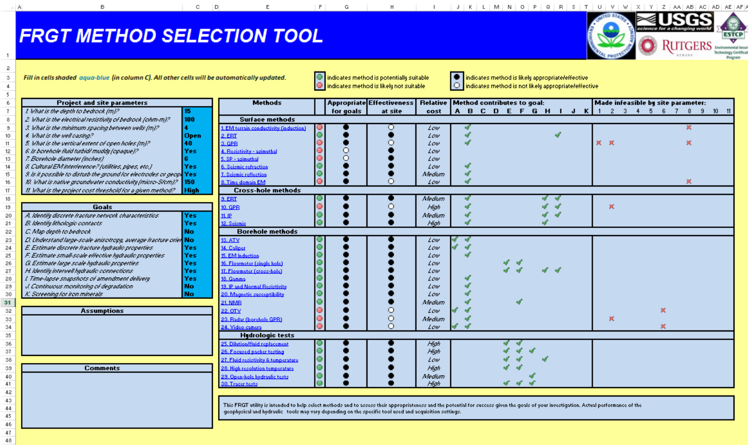


https://clu-in.org/characterization/technologies/geophysics/

Werkema Jr., D.D., Jackson, M., and Glaser, D., EPA/600/C-10/004, 2010

Forward and Inverse Models

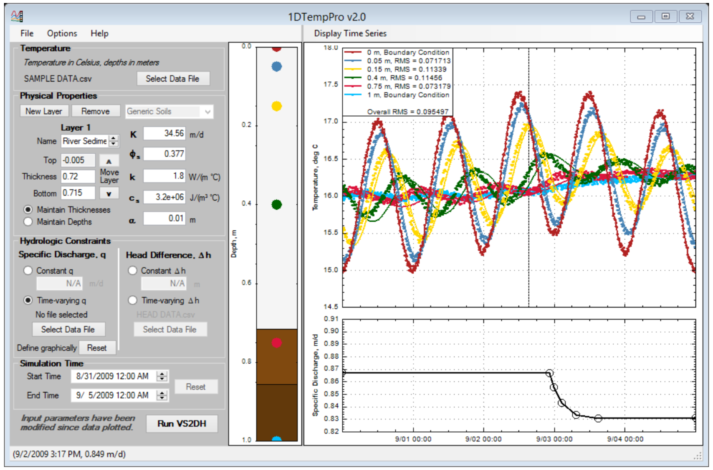
Fractured rock geophysical selection tool

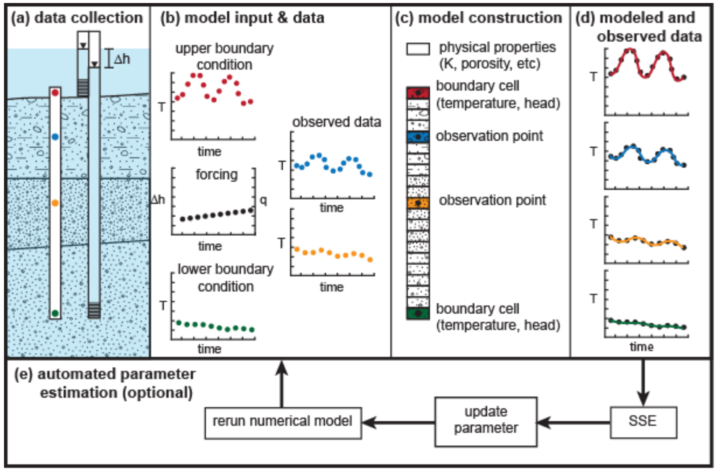


- user enters site parameters and objectives
- output table indicates feasible methods

Day-Lewis, et. al., Groundwater, 2016

1DTempPro V2





Parameter input, model estimation

- Temperature data collection
- Model construction and generation

Koch, et. al., Groundwater, 2015

SEER – Scenario Evaluator for Electrical Resistivity

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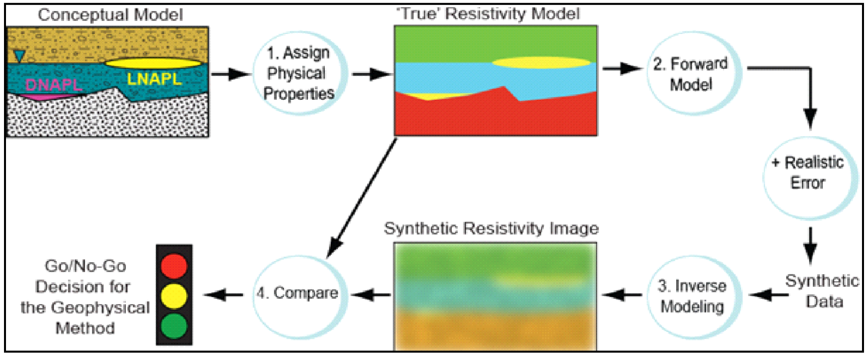
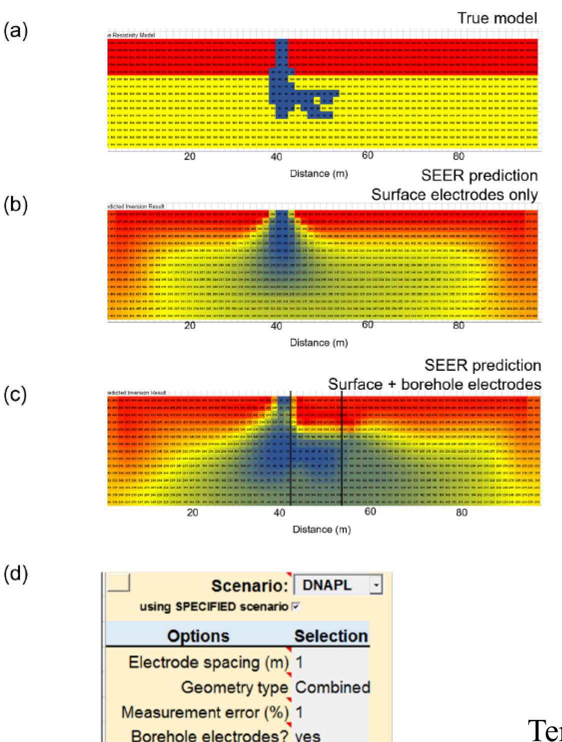
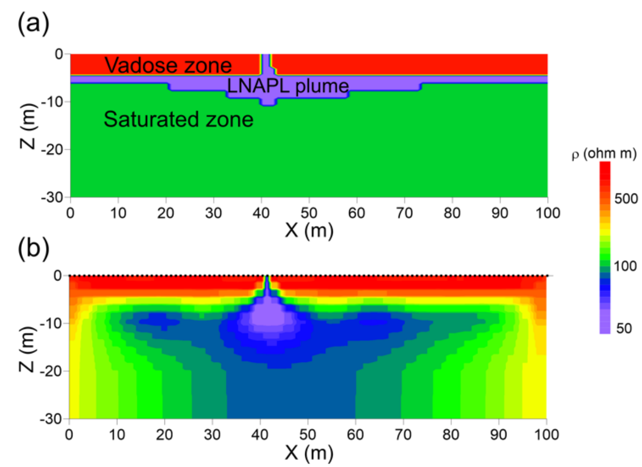
SEER is a simple spreadsheet tool for rapid visualization of the likely outcome of 2D electrical resistivity surveys.







(a) hypothetic target consisting of a mature LNAPL plume on the water table, and electrodes with 1-m spacing at land surface

(b) the resultant electrical resistivity tomogram, assuming normally distributed random standard errors of 3%.

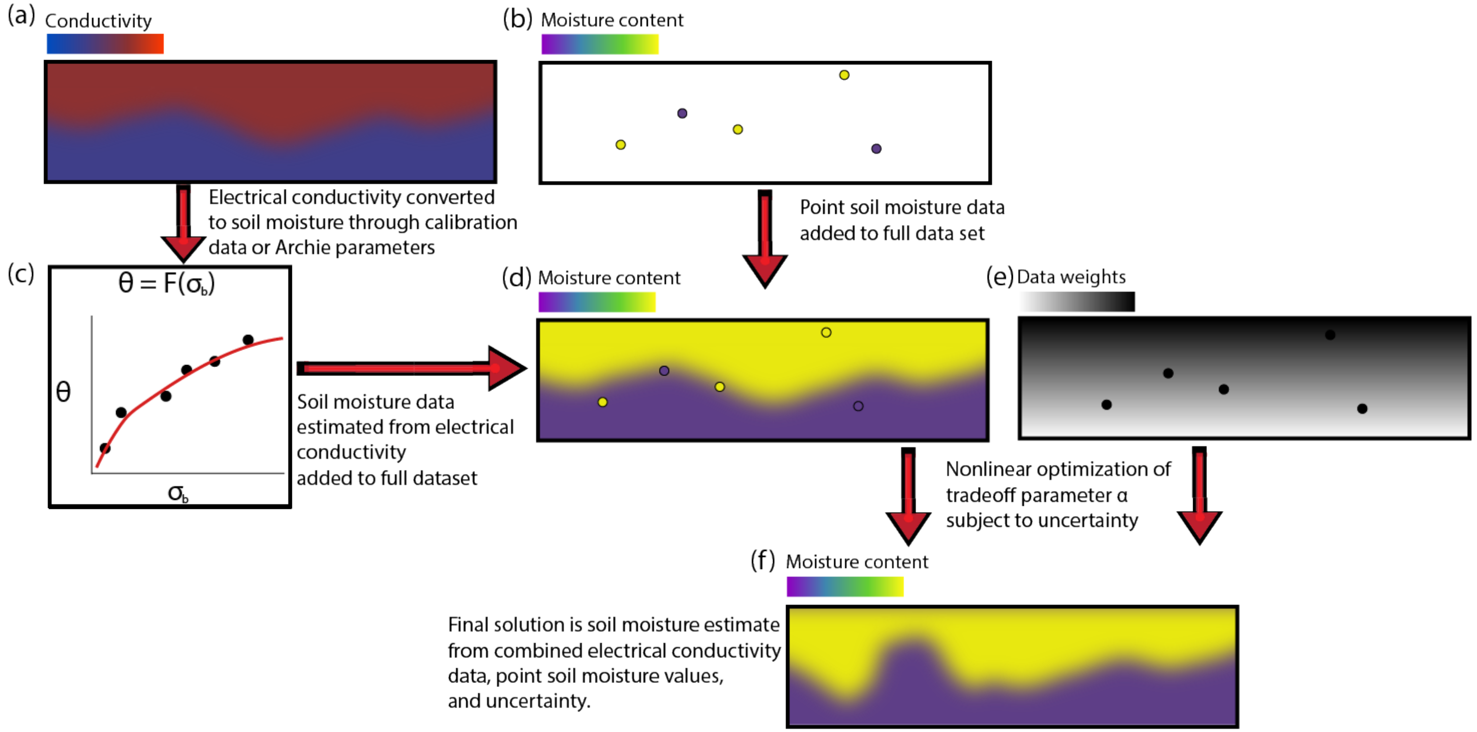
Terry, N., Day-Lewis, F., Robinson, J., Slater, L., Halford, K., Binley, A., Lane Jr., J., Werkema, D., 2017

Model Development example: Landfill Long Term Cell Performance

A critical factor to understand landfill performance, degradation, and containment is knowledge of ***landfill moisture content and distribution***

1. Mapping Soil-Moisture using Electromagnetic Induction
   - calibrate EM data with NMR (Nuclear Magnetic Resonance)
   - generate model/code to determine water content from surface EM data
2. Software and Field Approaches for Landfill Moisture Characterization: A Landfill Module for the Geophysical Toolbox Decision Support System (GTDSS)

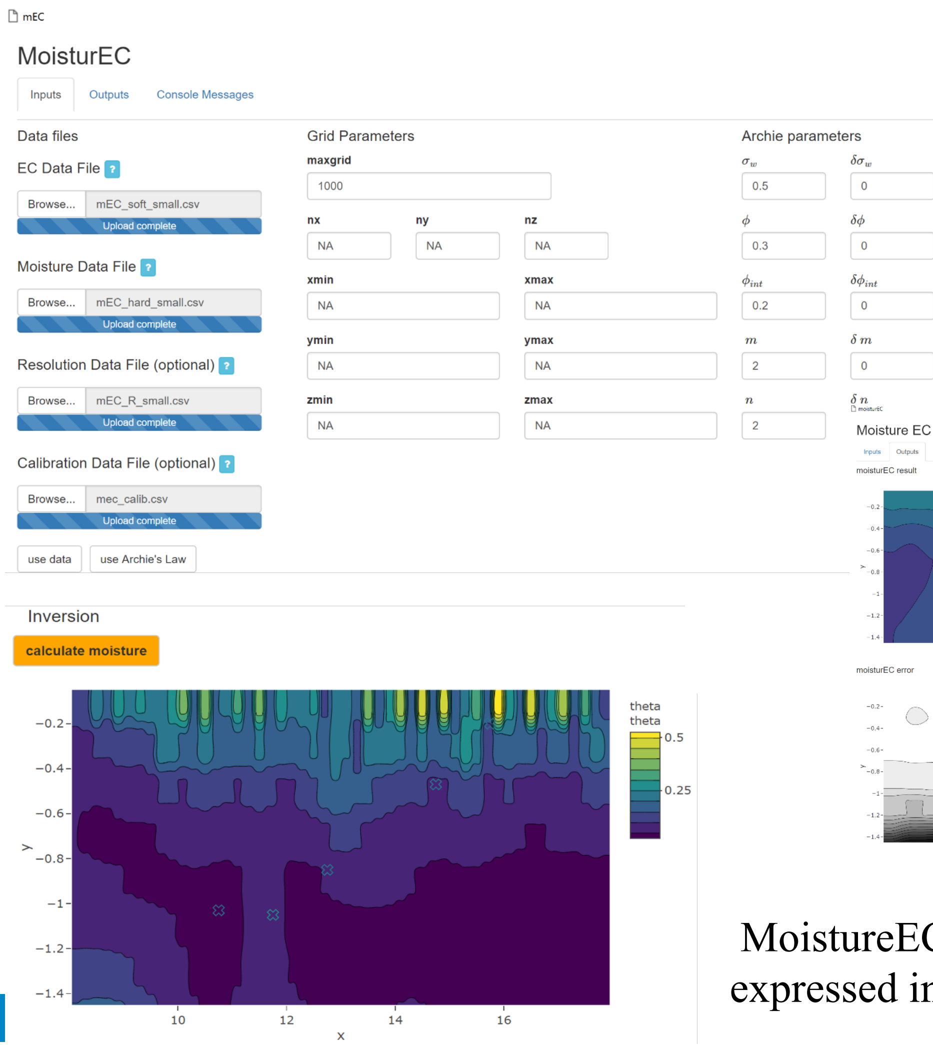
MoistureEC - flowchart



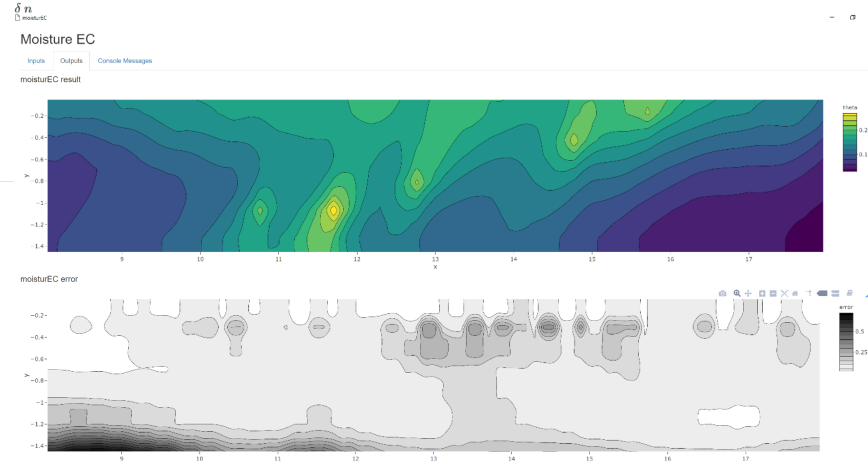
a) Electrical conductivity (EC) data
b) Moisture content values used to calibrate transform function
c) Petrophysical transform function converts EC data to
d) moisture
e) Data are weighted
f) Final moisture estimate using all data, errors, and generates an optimal data fit and smoothing

Terry,N., Day-Lewis, F.D., Werkema,D., Lane Jr., J.W., *Groundwater*, 2017.

MoistureEC GUI



- GUI inputs
- plot of the input data – EC data form the background contour plot



MoistureEC GUI 2D moisture estimate and propagated error, expressed in terms of moisture content.

Terry,N., Day-Lewis, F.D., Werkema,D., Lane Jr., J.W., *Groundwater*, 2017.

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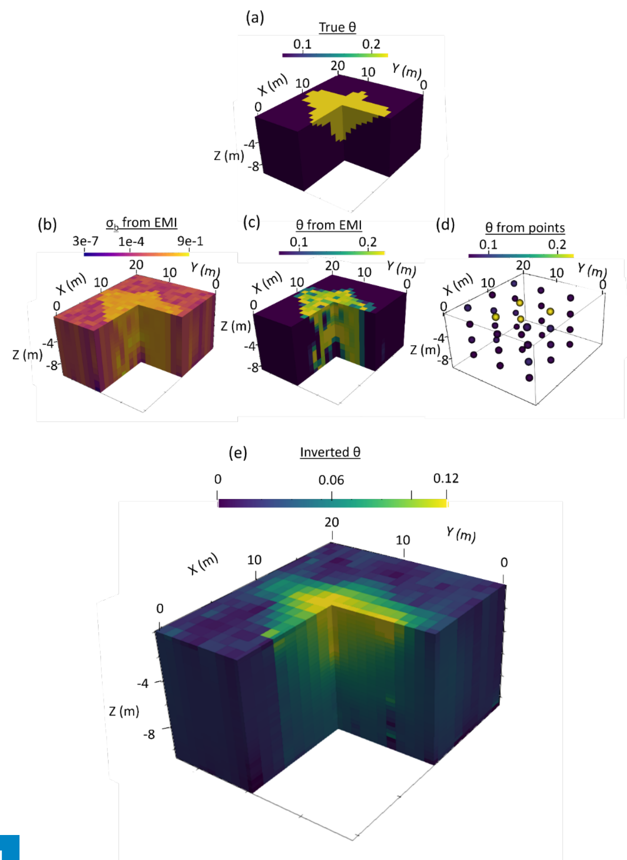
Moisture EC – synthetic 3D example



(a) true moisture model;
(b) inverted electromagnetic induction data collected over true moisture model;
(c) moisture estimate based on electrical conductivity using an Archie parameterization;
(d) point moisture data locations and values;
(e) resulting moisture estimate from MoisturEC.

Terry,N., Day-Lewis, F.D., Werkema,D., Lane Jr., J.W., *Groundwater*, 2017.

Summary

Geophysical methods can be used to characterize and monitor:

1. Subsurface objects; e.g., tanks, utilities
2. Direct detection of some contaminants
3. Active and passive remediation detection and monitoring
4. Biogeochemical reactions and interactions
5. CSM development and high resolution characterization
6. Dynamic Hydrogeologic processes, GW/SW interaction
7. Forward models and decision support systems help reduce uncertainty of results and inform stakeholders

The geophysical response is a function of the geology, hydrogeology, biology, and chemistry of the subsurface.

- Look for physical property contrasts, understand the mechanism of that contrast and if geophysical methods have the requisite resolution to detect the contrast.

What are the physical property contrasts?

Are these contrasts geophysically detectable?

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Acknowledgements & Collaborators

- John Lane, Fred Day-Lewis, Marty Briggs, Carole Johnson, Eric White, Terry Neal: *USGS and University of Connecticut*
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- Andre Revil: *Colorado School of Mines*
- Barbara Luke: *University Nevada-Las Vegas*
- Bill Sauck & Silvia Rossbach: *Western Michigan University*
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  - *Rutgers*: Jeff Heenan, Yves Robert-Personna, Sina Saneiyan, Sundeep Sharma, Angelo Lamousis,
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  - *Colorado School of Mines:* Marios Karaoulis

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Questions?

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