Geophysical Applications for Mine Waste Investigations

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Outline

- Mine waste site investigations - OBJECTIVES
- WHY GEOPHYSICS? What role does it serve for mine waste investigations?
- GEOPHYSICS BASICS – methods applicable to mine waste are objective dependent
  - Waste pile characterization
  - Leachate/run off
  - Groundwater – surface water connections
- SUMMARY

Some Typical Mine Waste Investigation Objectives

1. Tailings Characterization: saturated slurry, slurry pile stability, tailings pile characterization
2. Acid mine drainage: where does the mine impacted groundwater go?
3. Mine impacted groundwater interaction with surface water

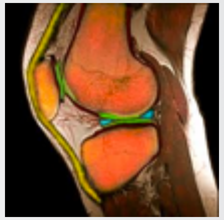
Clearly define the objectives in order to pick the correct geophysical tools/methods for the task

- Physical property mapping
- Anomalies, trends, hot spots
- Analysis, modeling, interpretation

Why Geophysics – what role does it serve?

- 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

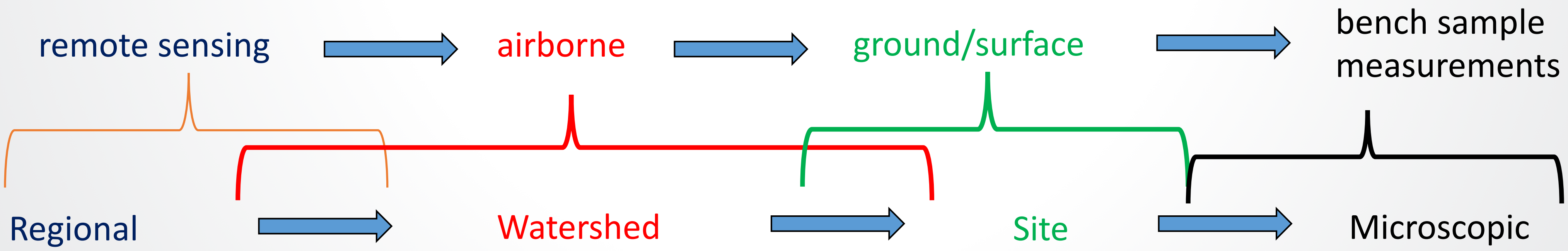
images credit: Lee Slater

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

- What mine site investigative objectives can geophysics help with?
  1. Mapping the 3D extent of the piles
  2. Mapping acid mine drainage (AMD) – ground water plumes or the interactions with native materials
  3. Mapping the geology – traditional geophysical exploration
  4. Locating and monitoring groundwater – surface water interactions; when AMD reaches surface water features

Geophysical surveys are scale dependent

- <u>REMOTE SENSING</u>: Satellite, high altitude
- <u>AIRBORNE</u>: Electromagnetic Induction (EMI), magnetic, radiometric
- <u>GROUND/SURFACE</u>: Ground Penetrating Radar (GPR), seismic, gravity, electrical methods, EMI



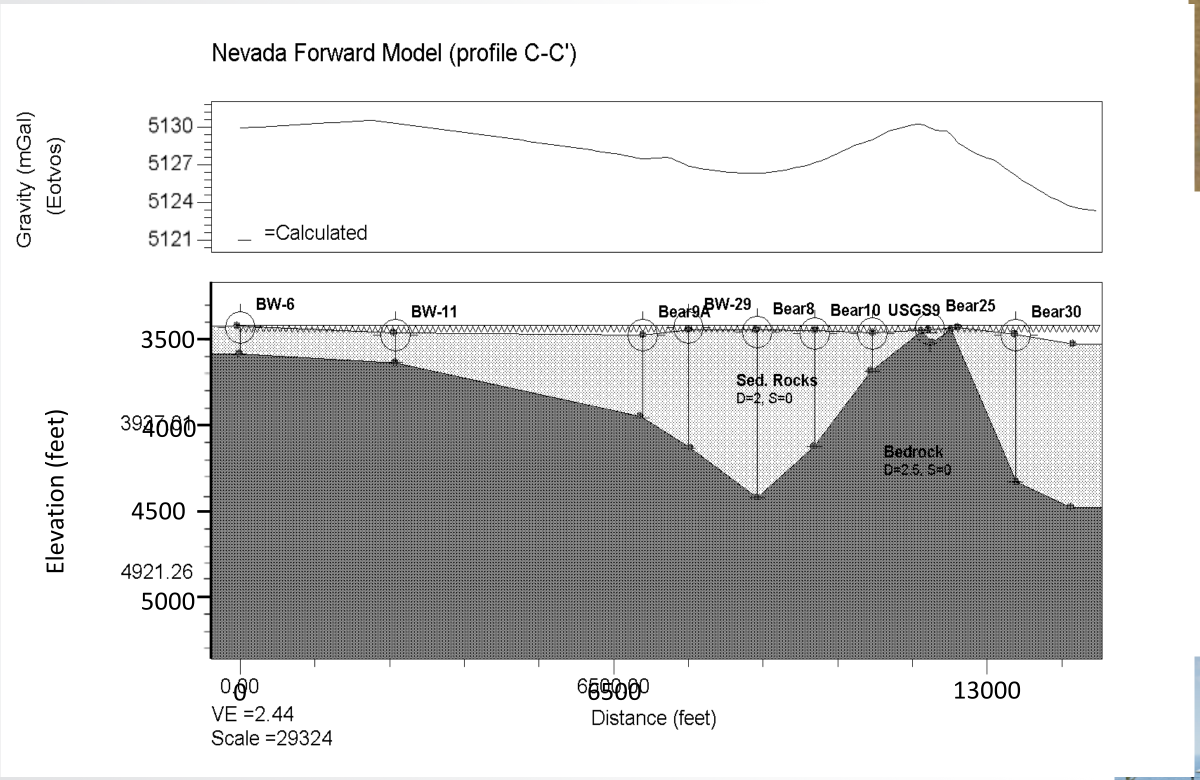
1. Map 3D extent of tailings piles

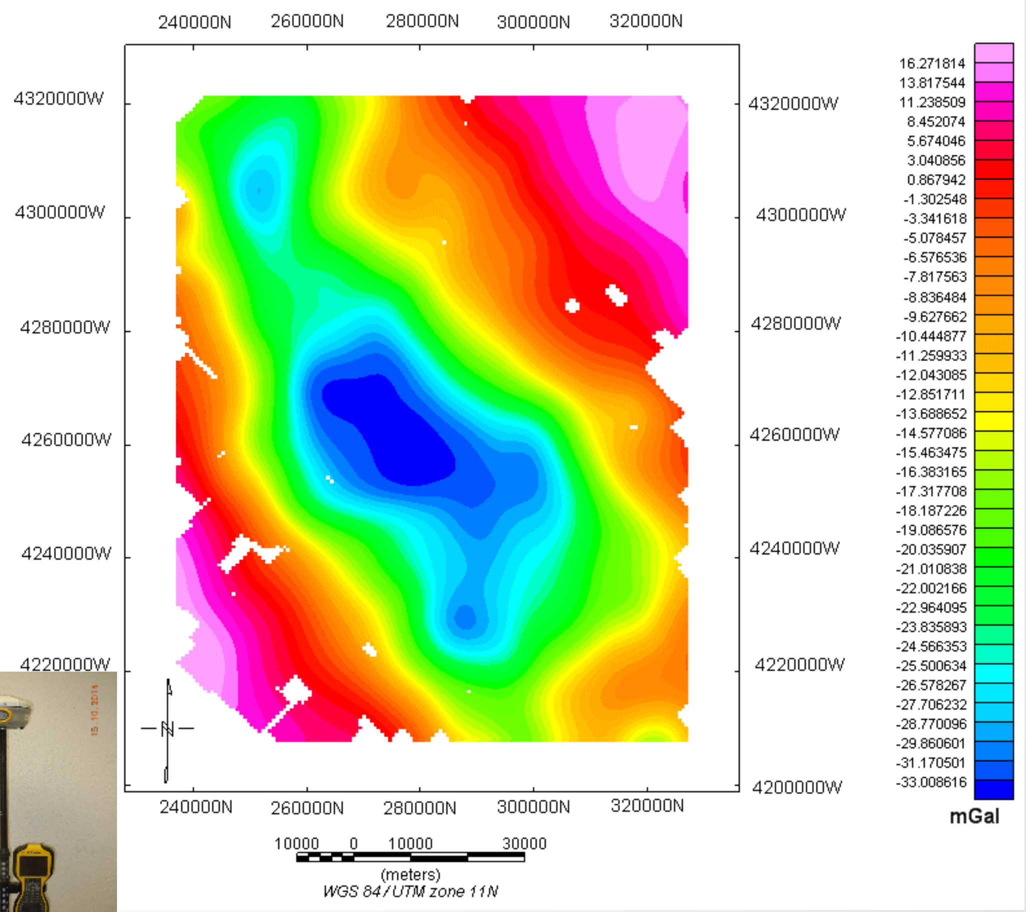
How are the physical properties of the mine tailings piles different from surrounding materials/geology?

Unconsolidated, Higher surface area, Less dense, Chemically available for weathering

Physical property measured	Geophysical Method
Density	Gravity
Magnetic susceptibility	Magnetic
Electrical conductivity	Electrical resistivity, ground penetrating radar
Chargeability/capacitance/surface area	Induced Polarization
Seismic velocity / density	Seismic

Surface Gravity Surveys for mapping subsurface density contrasts





Direct Current (DC) Resistivity Tomography (ERT)

Archie's Law
for Porous Media w/o clay

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

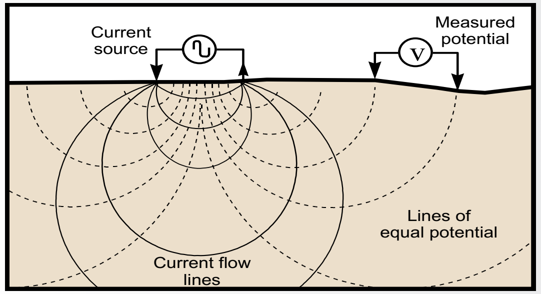
ρ_e = resistivity of the earth

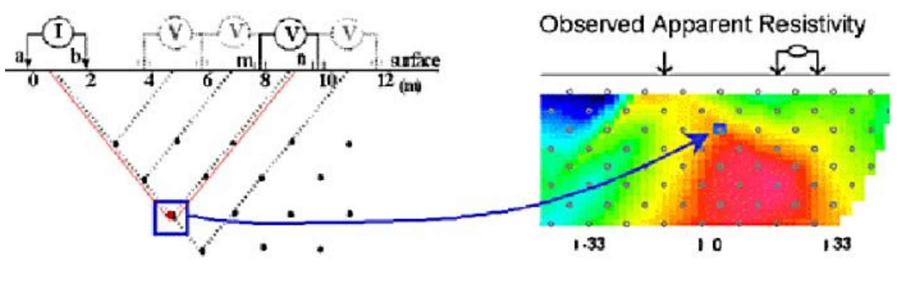
ϕ = fractional pore volume (porosity)

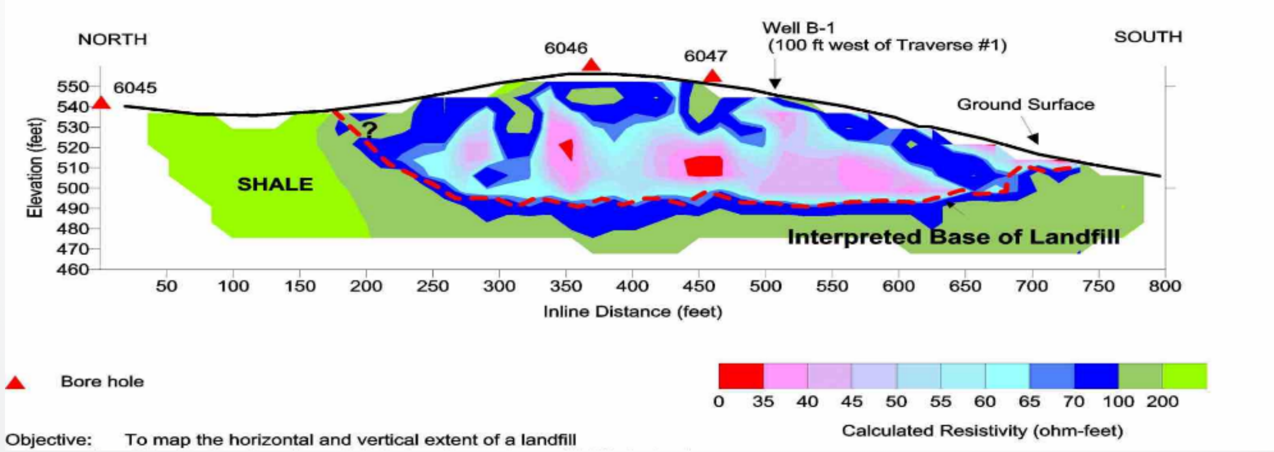
S = fraction of the pores containing fluid

ρ_w = the resistivity of the fluid

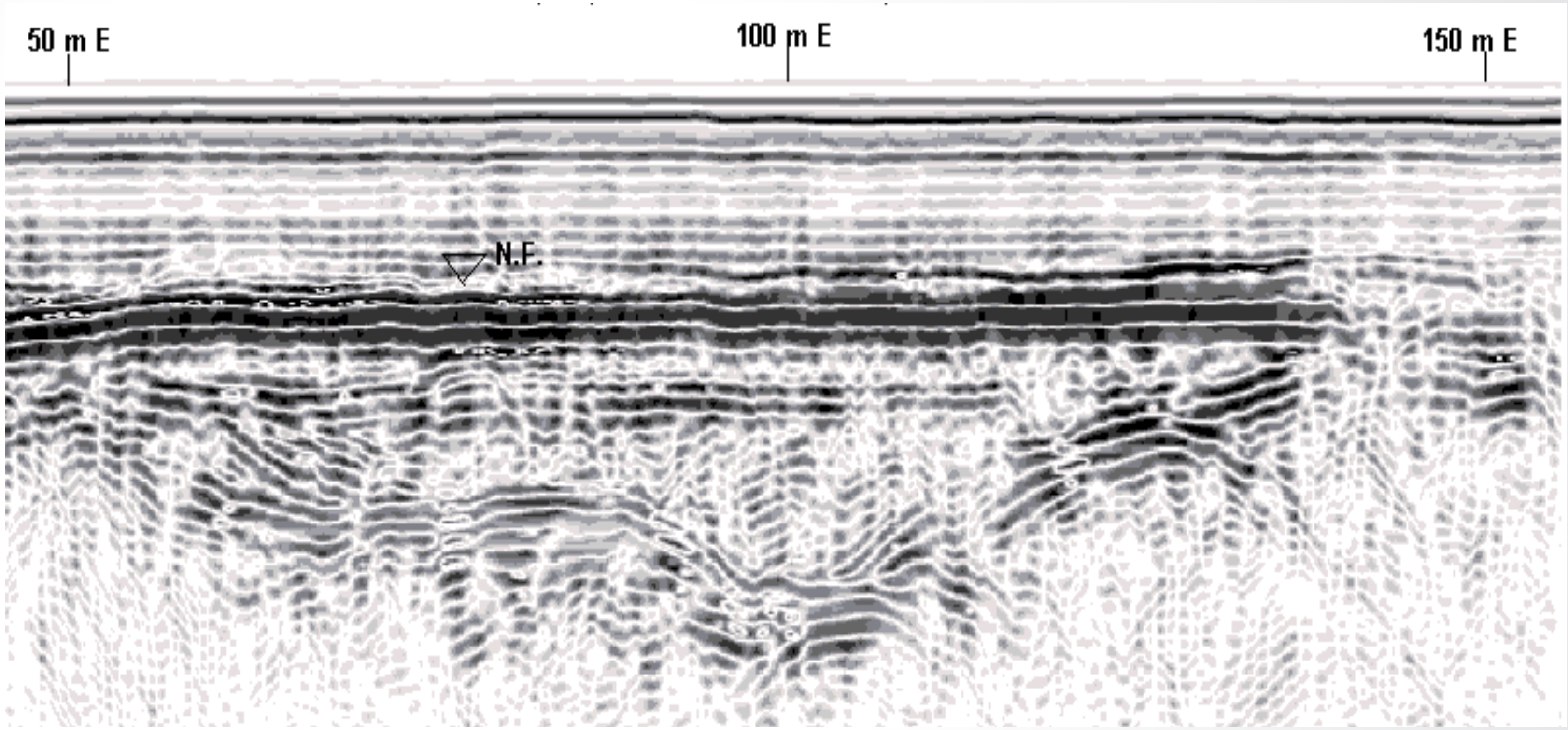
n, a and m are empirical constants







Ground Penetrating Radar (GPR)



GPR profile example of water table reflection and undulating, non-horizontal reflections below the water table showing geology structure and possible discrete objects.

GPR velocity is a function of the speed of light and the relative permittivity (E_r) of the earth materials

$$v = c / (E_r)^{1/2}$$

2. Mapping acid mine drainage (AMD) – ground water plumes or the interactions with native materials

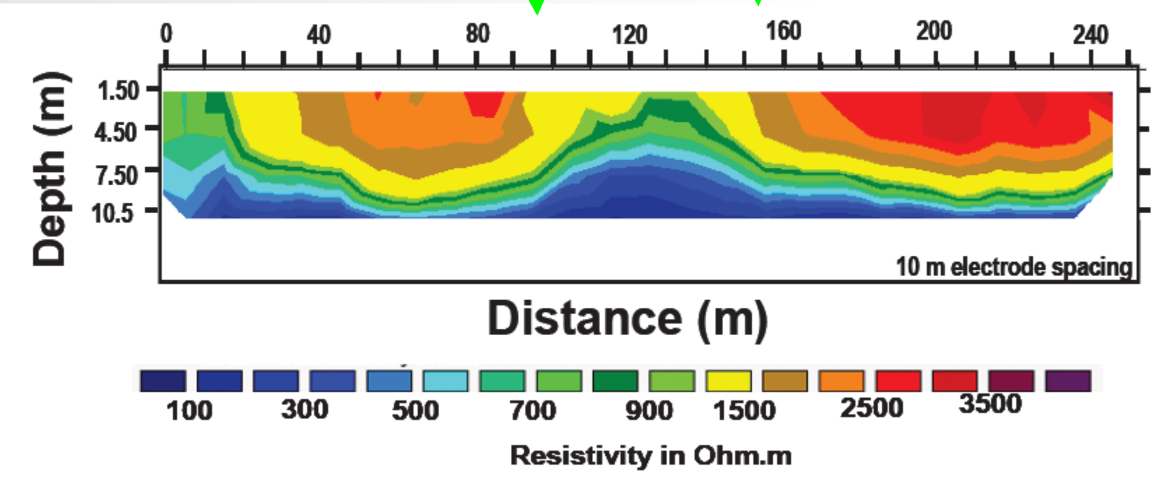
How are the physical properties of AMD and the interaction of AMD with the natural system different from the natural system, e.g., groundwater?

Lower pH, increased TDS, different chemical species, altered redox

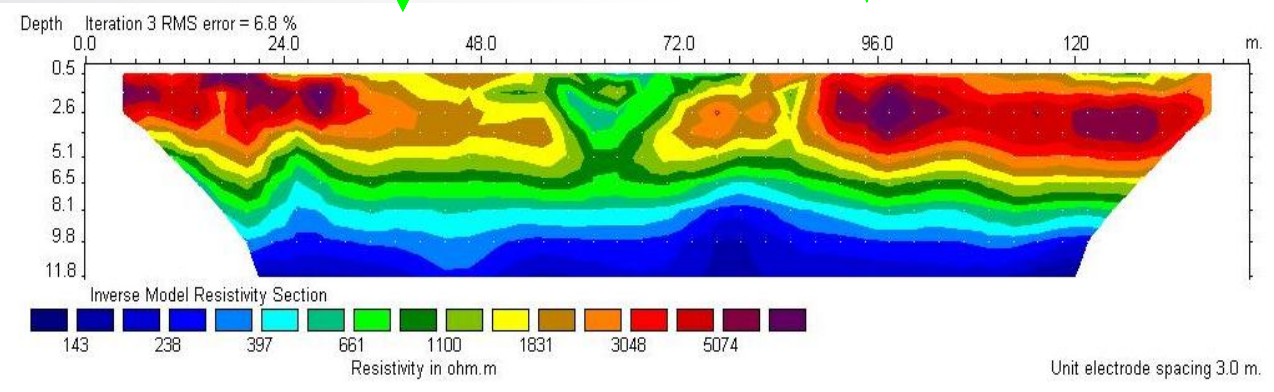
Physical property measured	Geophysical Method
Magnetic susceptibility	Magnetic
Electrical conductivity	Electrical resistivity, ground penetrating radar, electromagnetic induction
Chargeability/capacitance/surface area	Induced Polarization
Oxidation potential, ion concentrations	Self / Spontaneous - Potential

DC Resistivity response to elevated ground water electrical conductivity

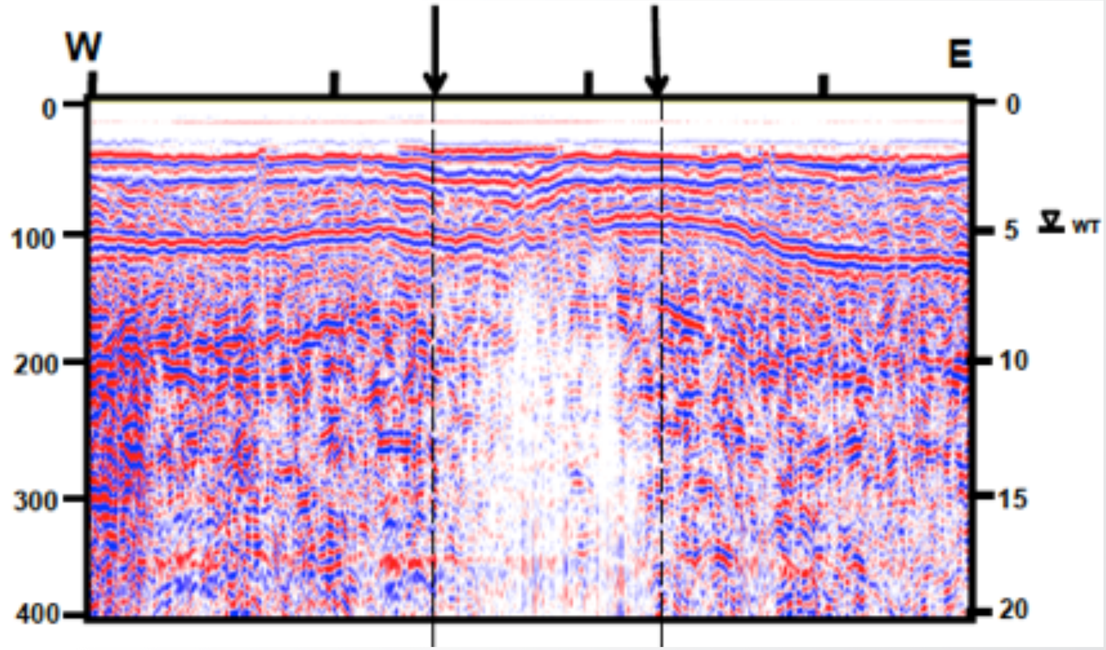
Conductive zone



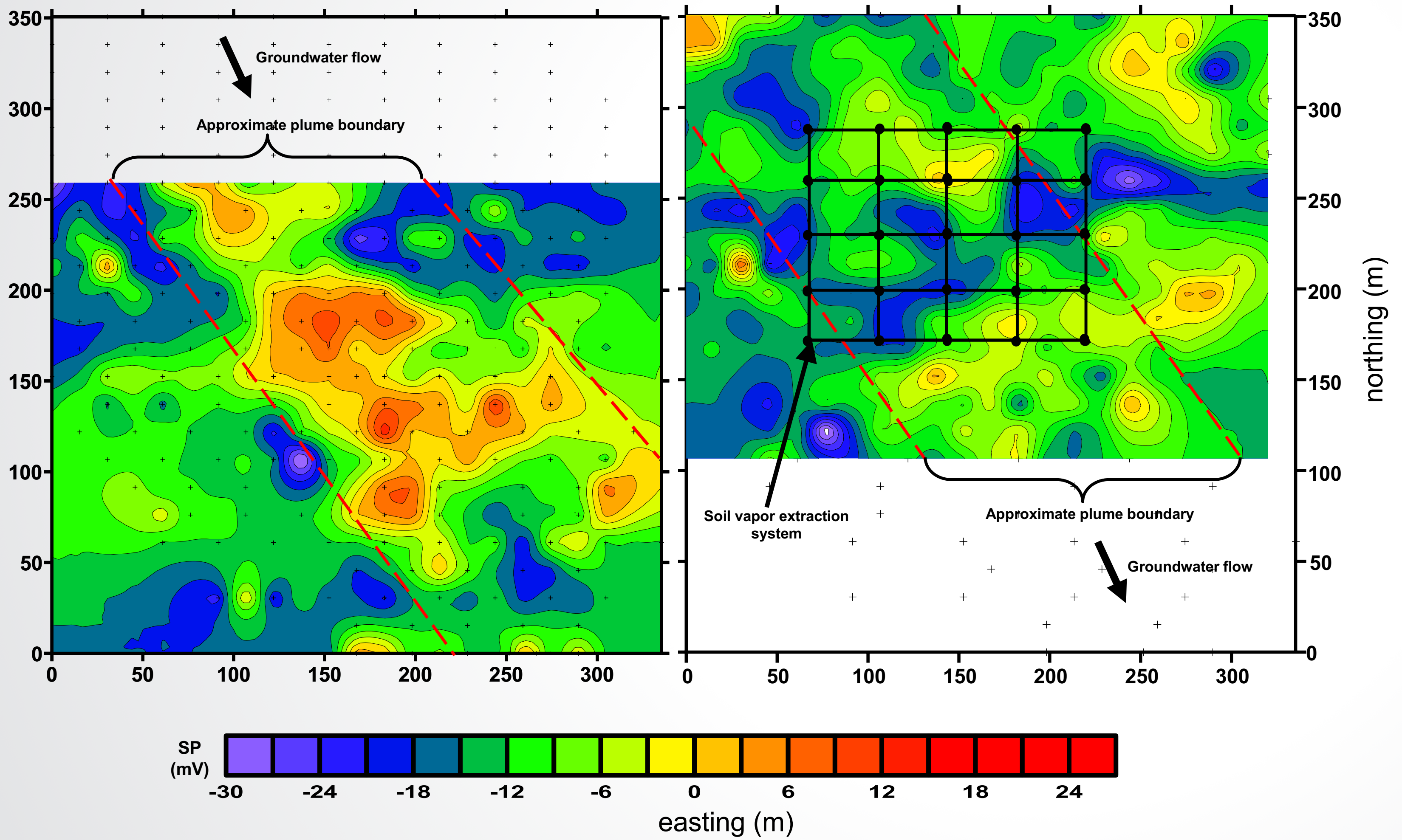
Conductive zone



GPR Response to increase electrical conductivity



Self-Potential (SP) response to elevated electrical conductivity



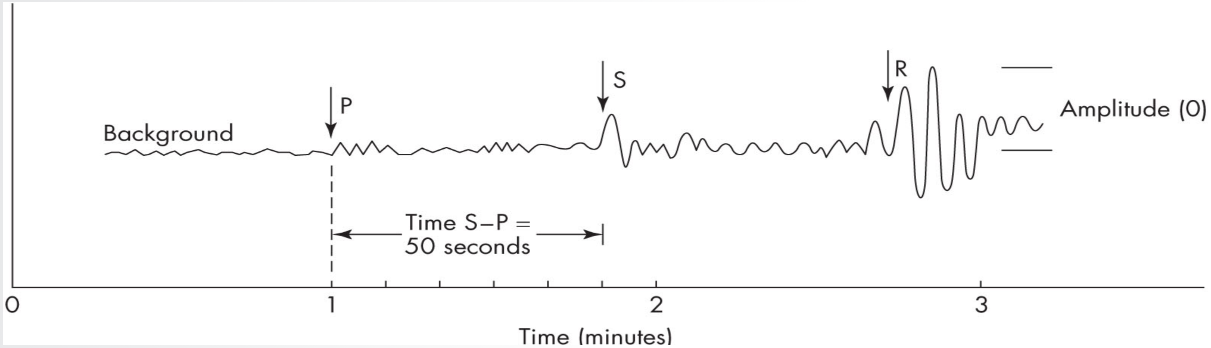
3. Mapping the geology – traditional geophysical exploration

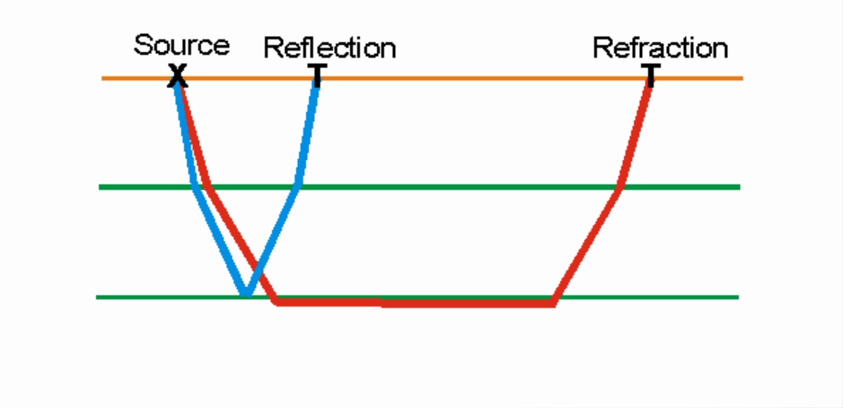
What is the fate and transport of the AMD groundwater?
What controls its movement?

- Geology governs flow
- Fractures
- Preferential flow paths for F&T

Physical property measured	Geophysical Method
Magnetic susceptibility – re-mineralized fractures	Magnetic
Electrical conductivity	Electrical resistivity, ground penetrating radar, electromagnetic induction
Seismic velocity / density	Seismic reflection, gravity

Seismic Methods





p-waves

- Compressional waves
- Wave propagation in direction of travel

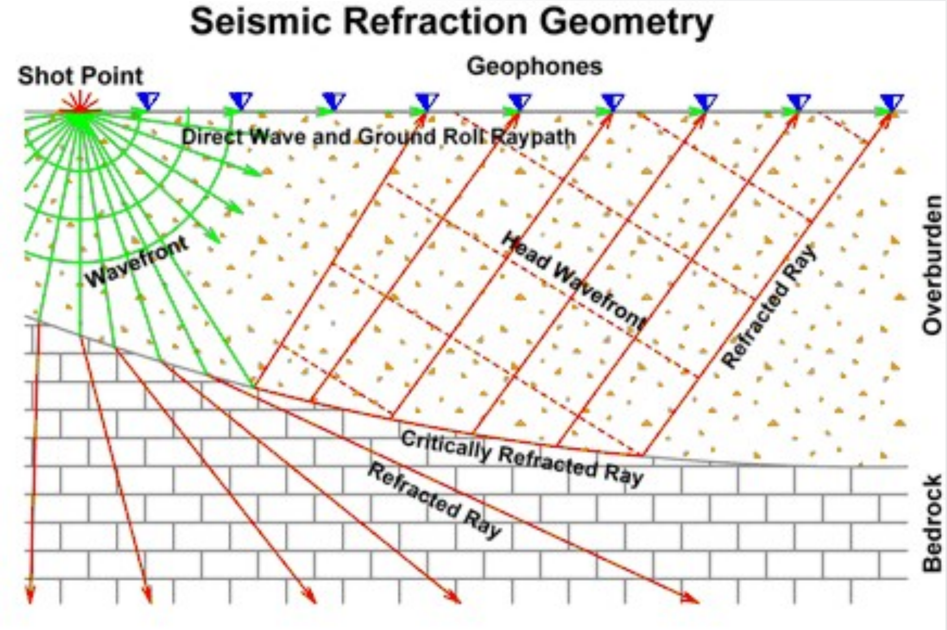
$$v_p = \sqrt{\frac{\kappa + \frac{4}{3}\mu}{\rho}}$$

S – waves

- transverse, secondary, or shear
- motion is at right angles to the direction of wave propagation
- pure shear strain

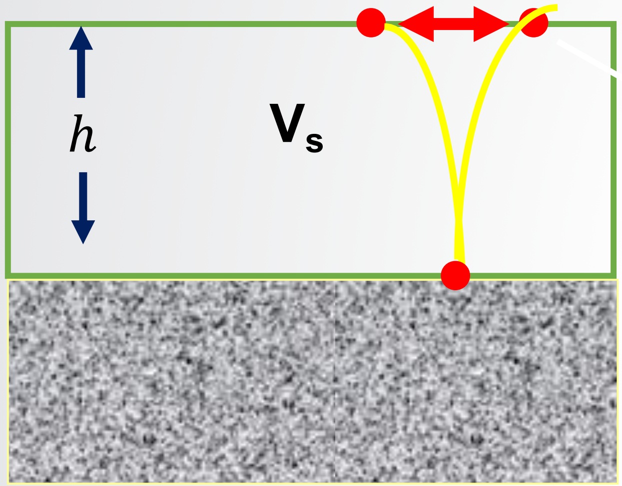
$$v_s = \sqrt{\frac{\mu}{\rho}}$$

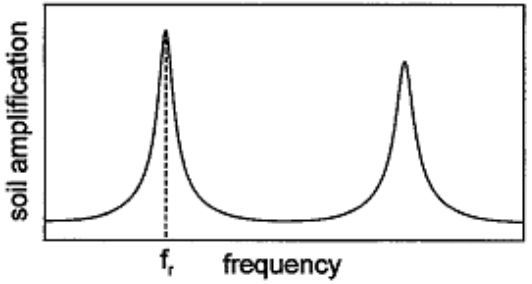
ρ = density
k = bulk modulus
μ = shear modulus



HVSR Seismic
(Horizontal / Vertical Seismic Ratio)

Unconsolidated Sediments over Bedrock resonance model





H/V

$$f_r = V_s/4h$$

Resonance Frequency Calculations

if thickness known

$$V_{s,\,avg} \approx 4hfr$$

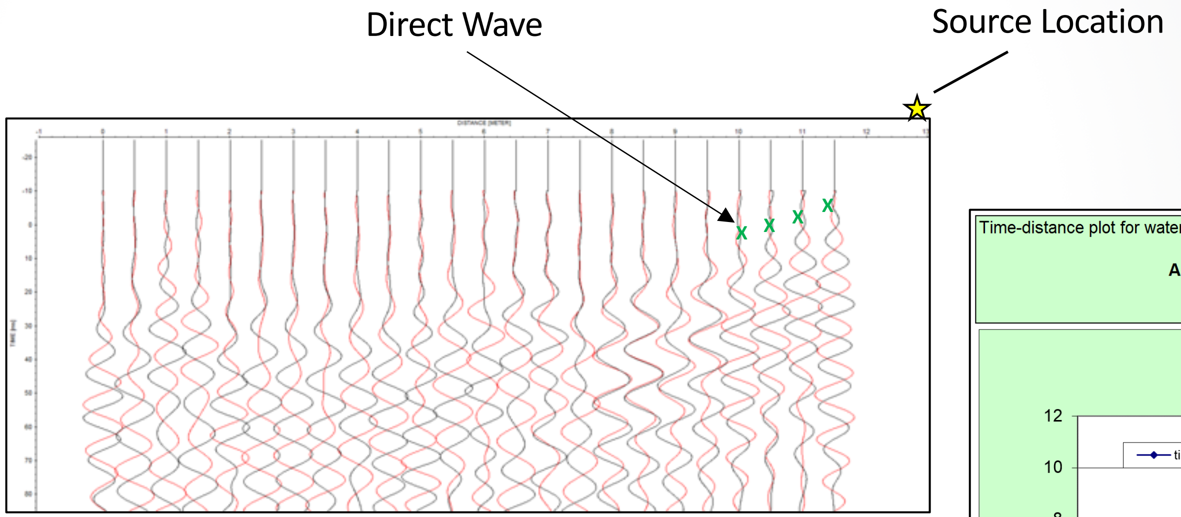
If surface Vs known

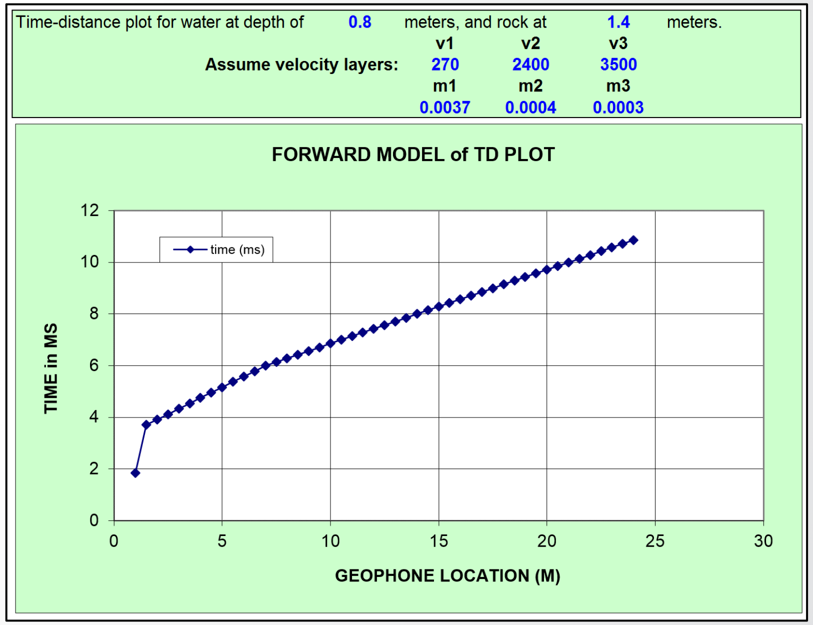
$$h_{min} \approx \frac{V_{s,\,surface}}{4fr}$$

Requirement: *Minimum* 2:1 Contrast in acoustic impedance at the boundary (> 3:1 is better)

Seismic – Shear-Wave (Vs) Survey for HVSR calculation

- Vs is used to get an average Vs for computing depth to rock for HVSR

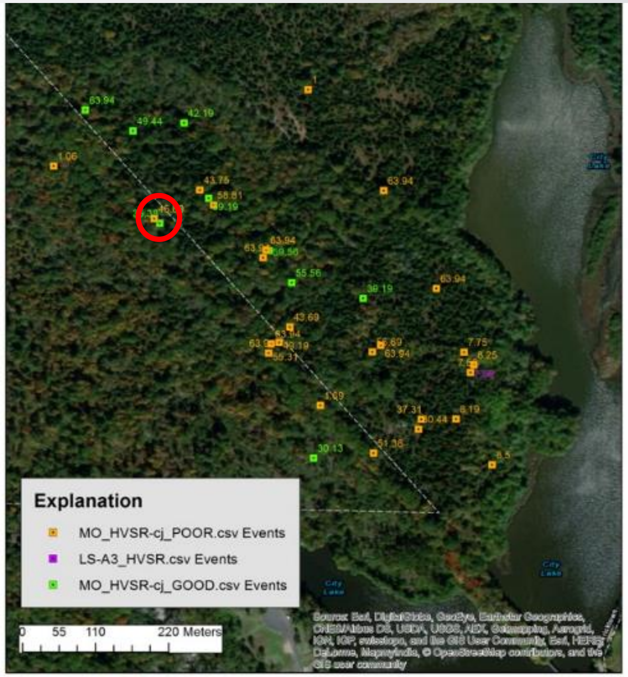




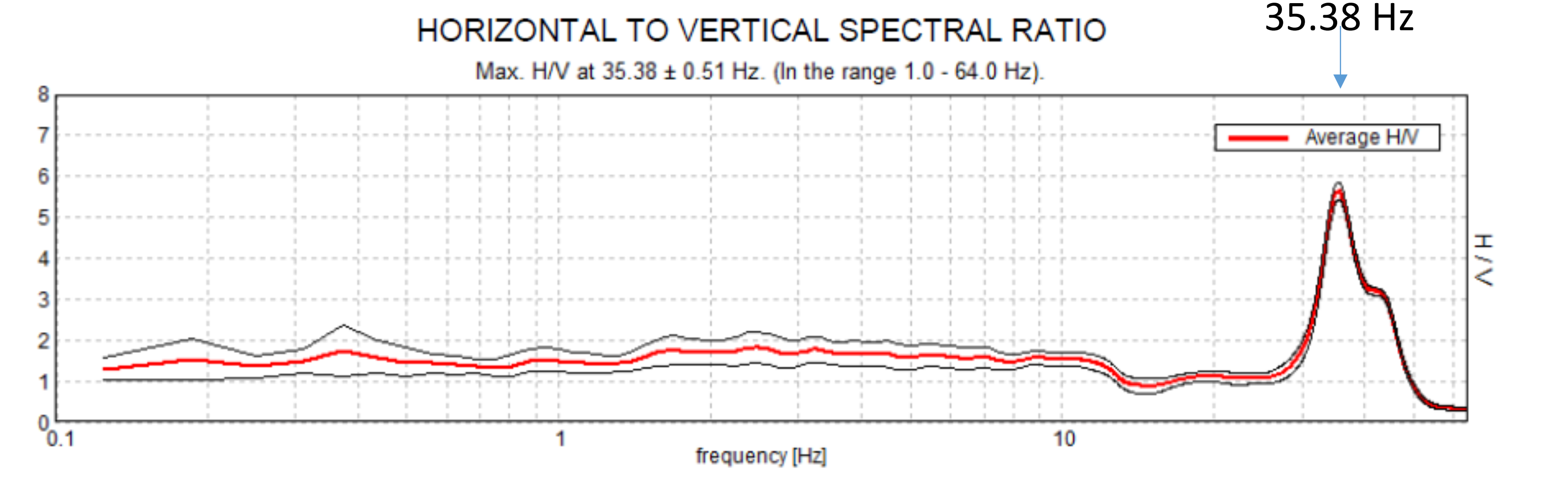
V_s Layer 1 = 270 m/s

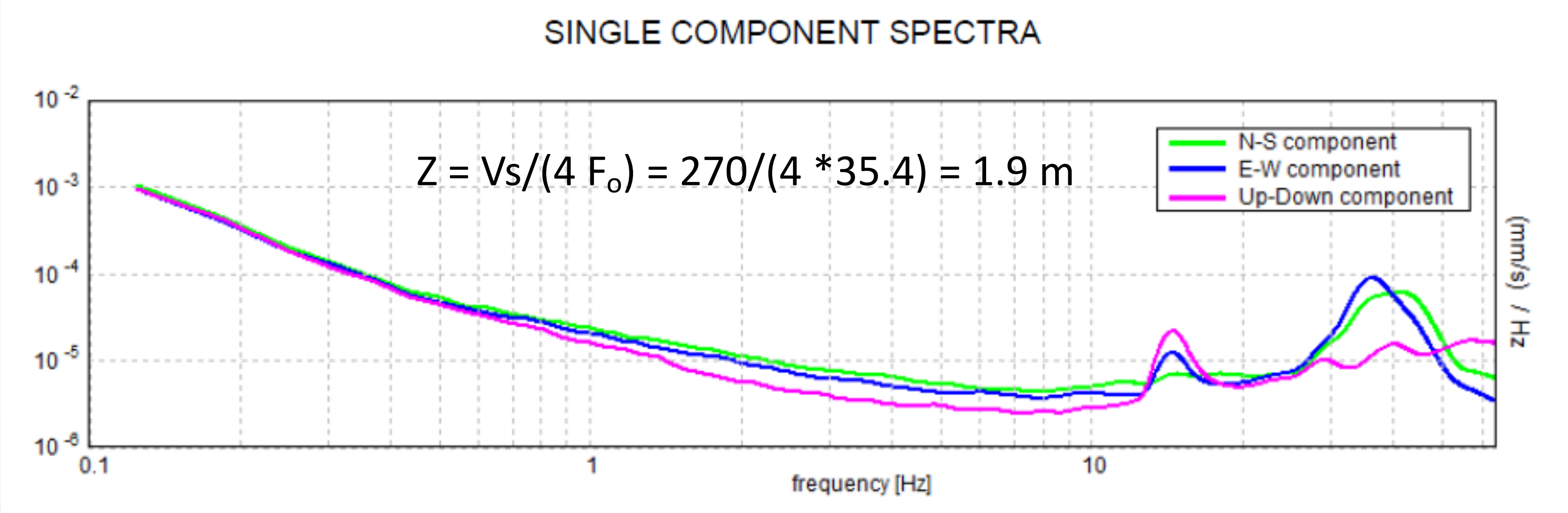
Mavko et al, , 1988

Resonance Frequency



35.38 Hz





$Z = V_s/(4\ F_o) = 270/(4 * 35.4) = 1.9$ m

1.9 m =
Depth to rock
Interface between Unconsolidated and competent rock

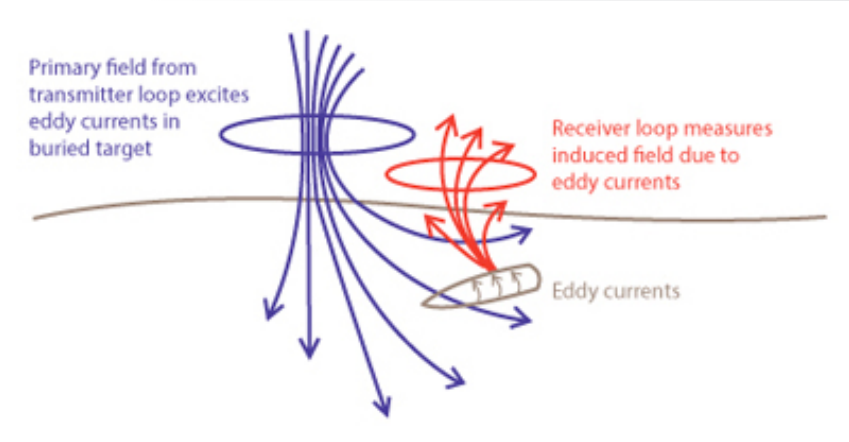
4. Locating and monitoring groundwater – surface water interactions

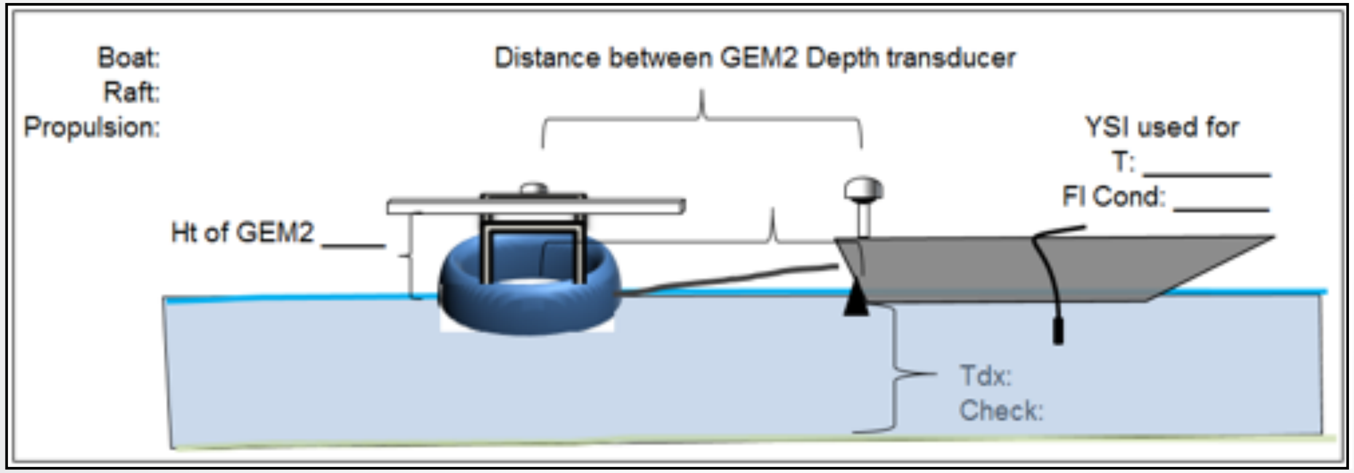
Where is the AMD in groundwater entering a surface water body (e.g. creek, stream)?
What physical properties are likely to be different in the groundwater vs. surface water?

- **pH**
- **Electrical conductivity**
- **Temperature**

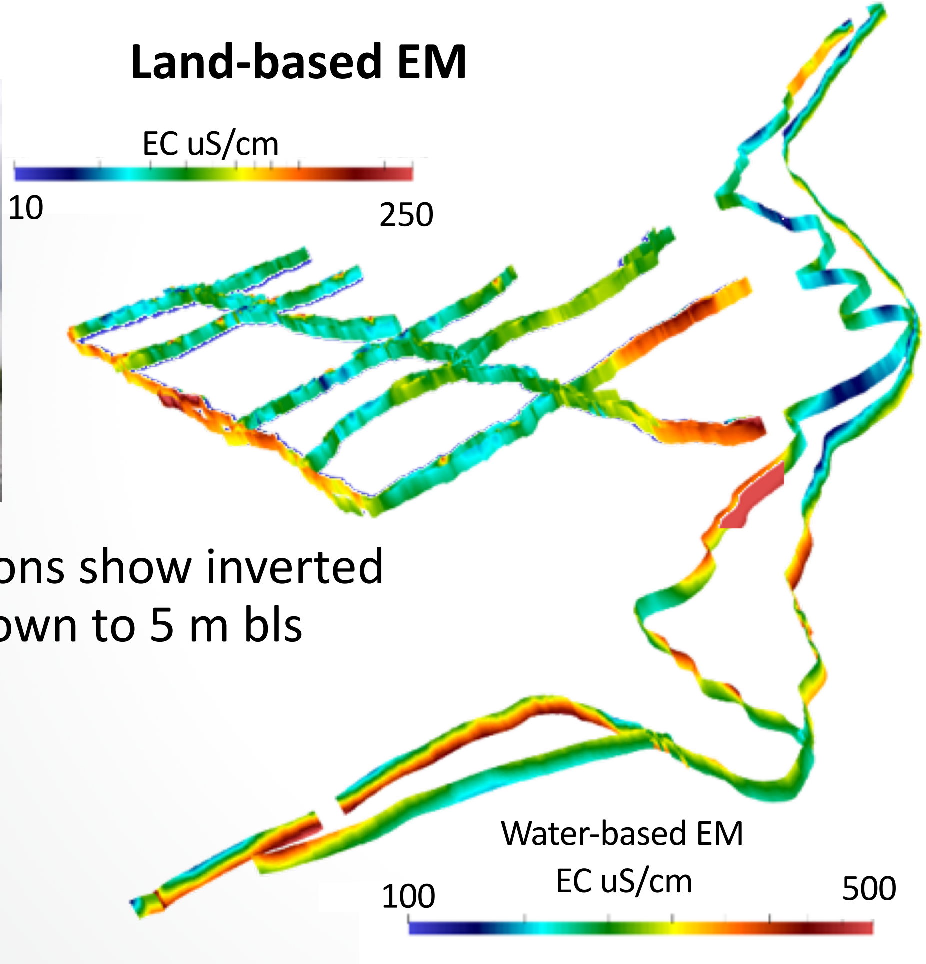
Physical property measured	Geophysical Method
Electrical conductivity	Electrical resistivity, ground penetrating radar, electromagnetic induction
Temperature / Thermal conductivity	Thermal Infrared, Heat flow

Electromagnetic Induction (EM or EMI)

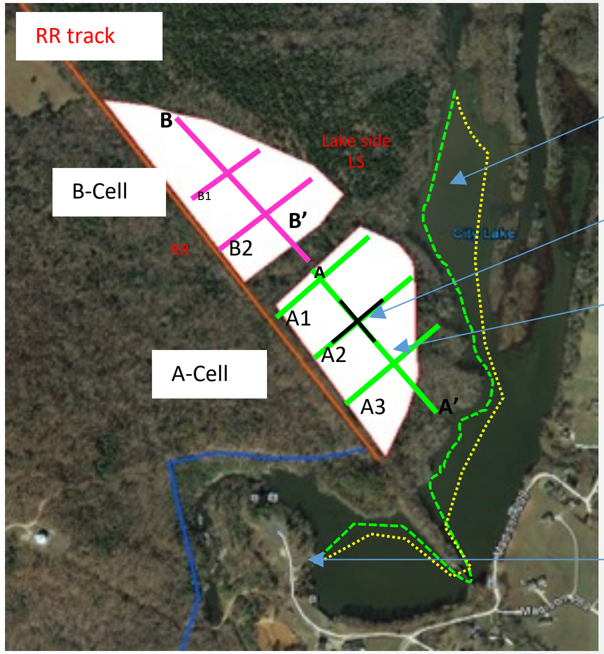




Electrical Conductivity Color Scales Optimized for both Land and Water

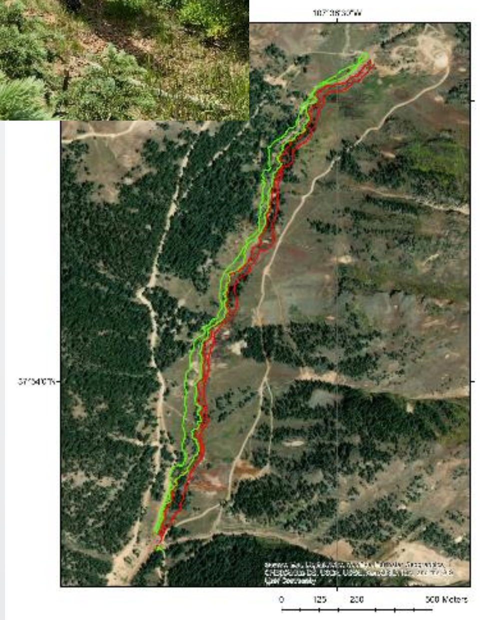


Ribbons show inverted EC down to 5 m bls



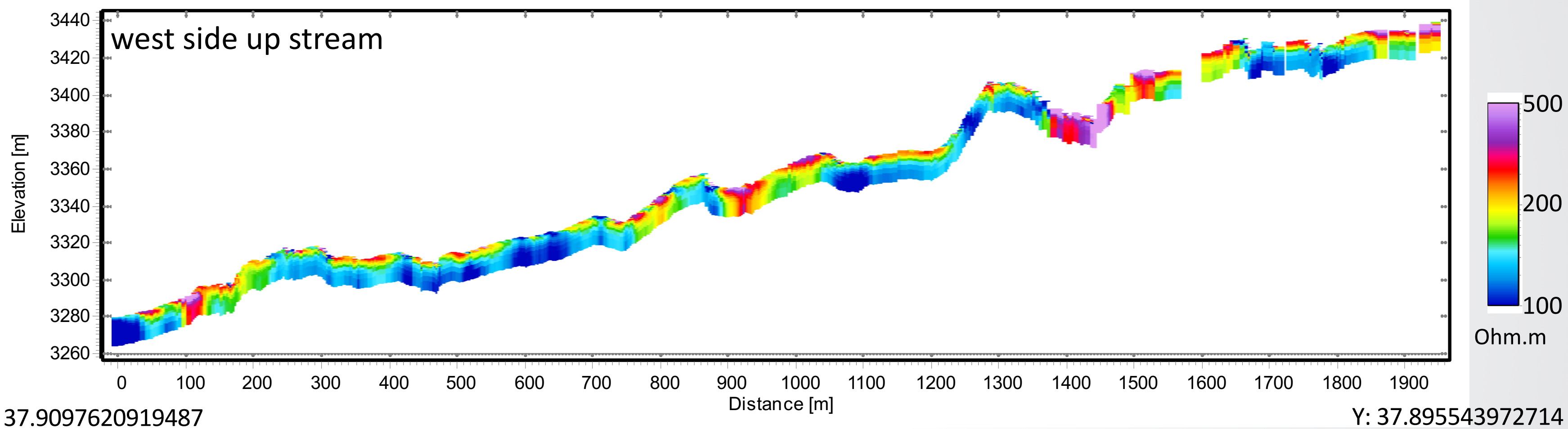
Variation in water-borne EM inverse results – some high EC zones observed in subsurface

EMI results from high alpine mine influenced streams



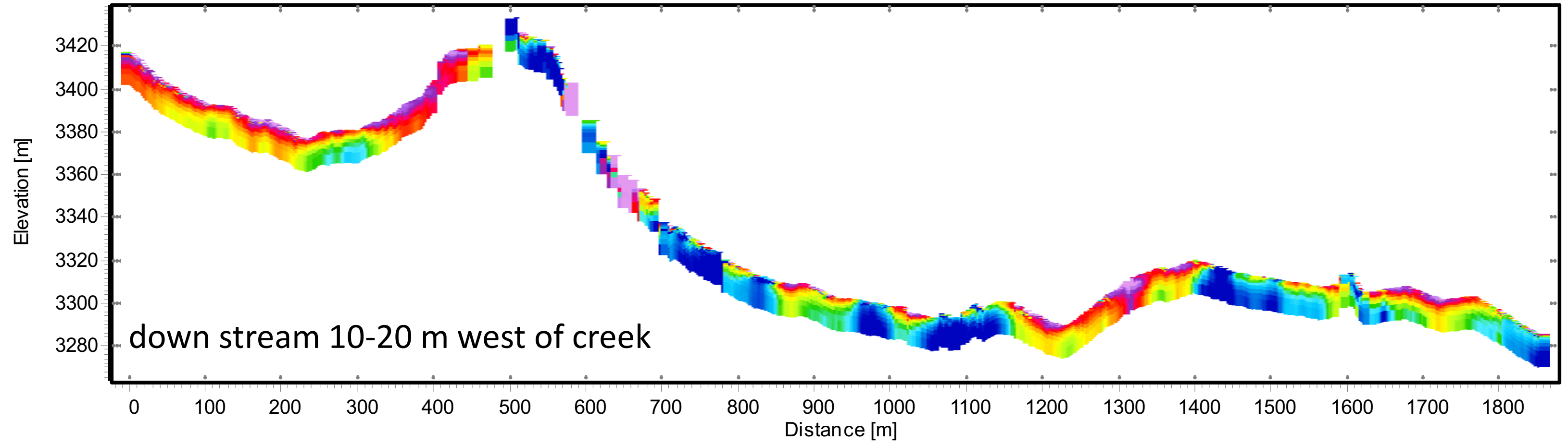
Y: 37.8954947186526
X: -95.6470311696618

Y: 37.9097215562722
X: -95.6407566426773

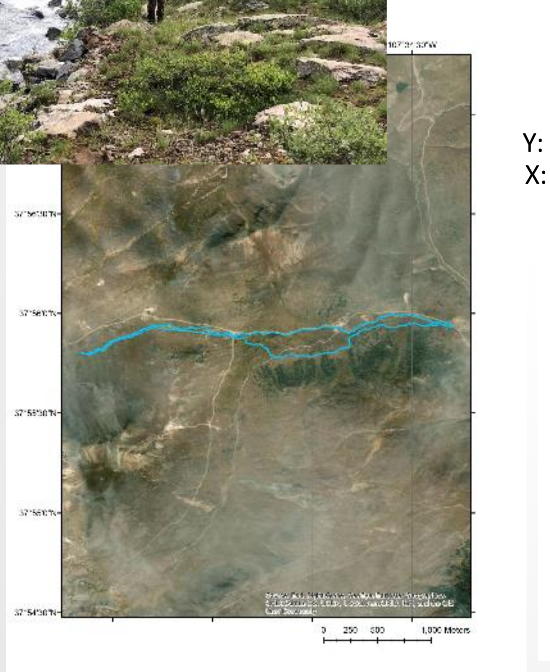


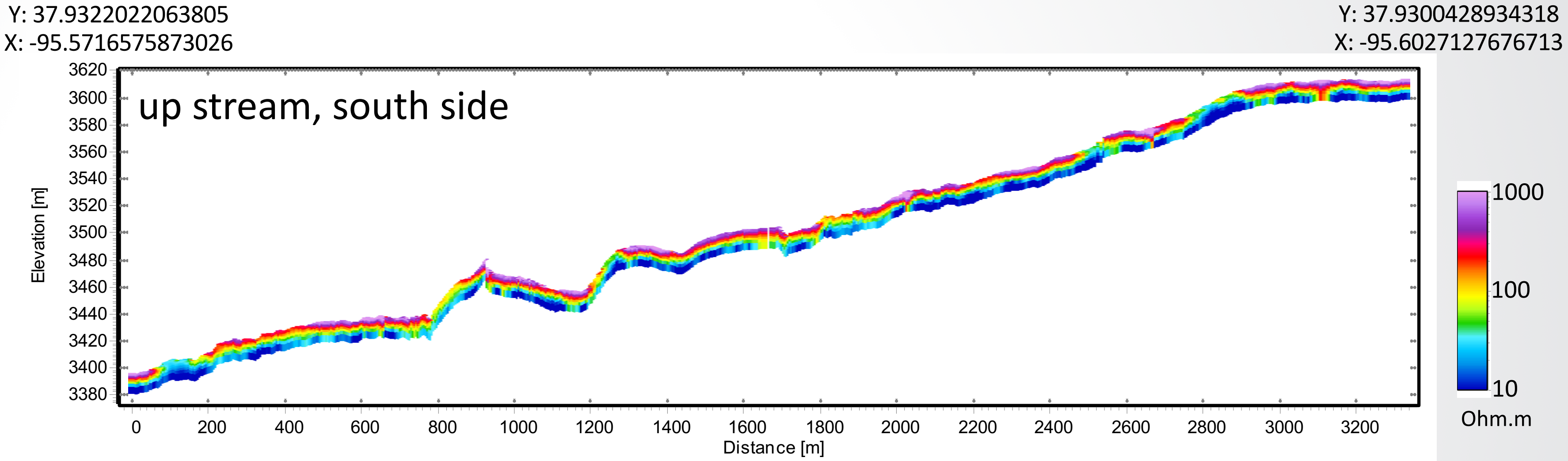
Y: 37.9097620919487
X: -95.6408251667218

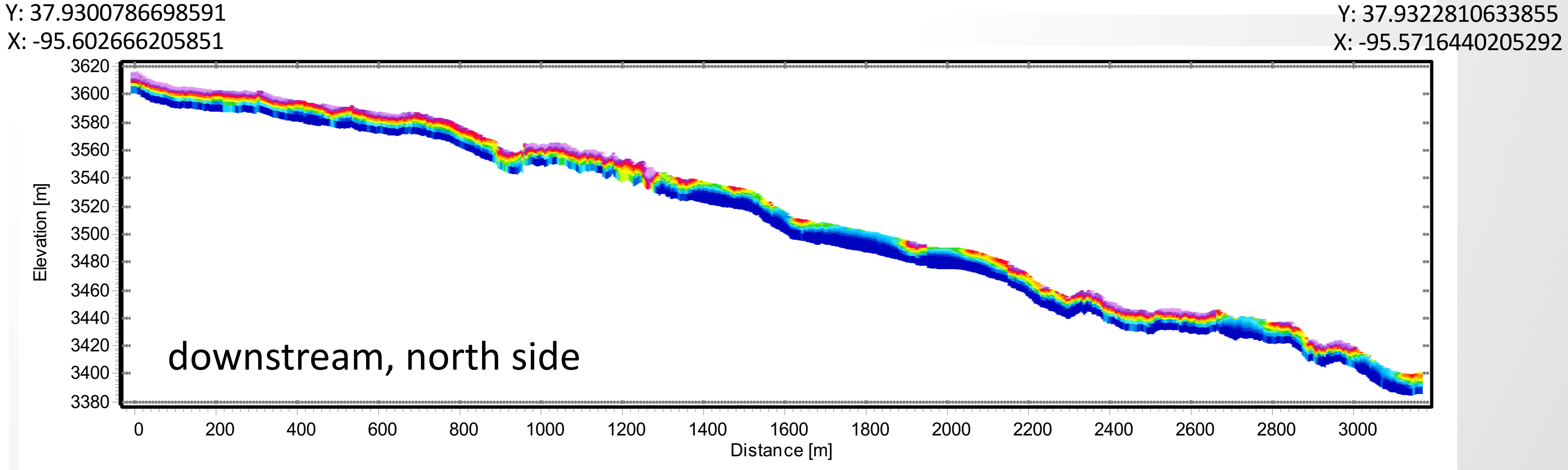
Y: 37.895543972714
X: -95.6471076421364



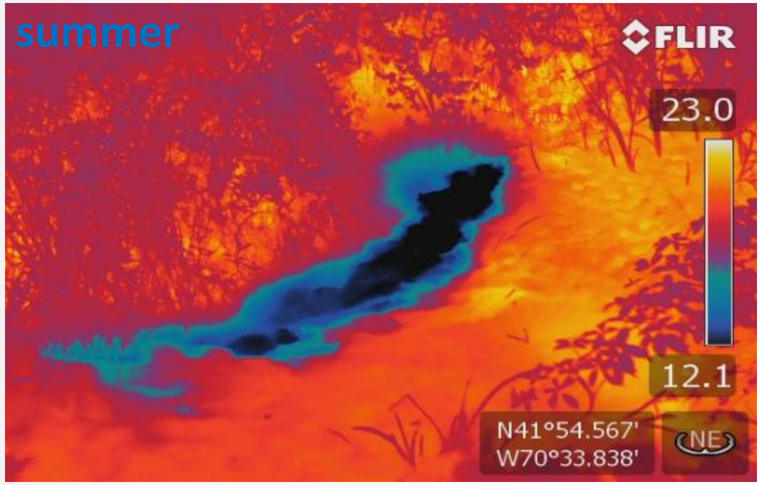
EMI results from high alpine mine influenced streams





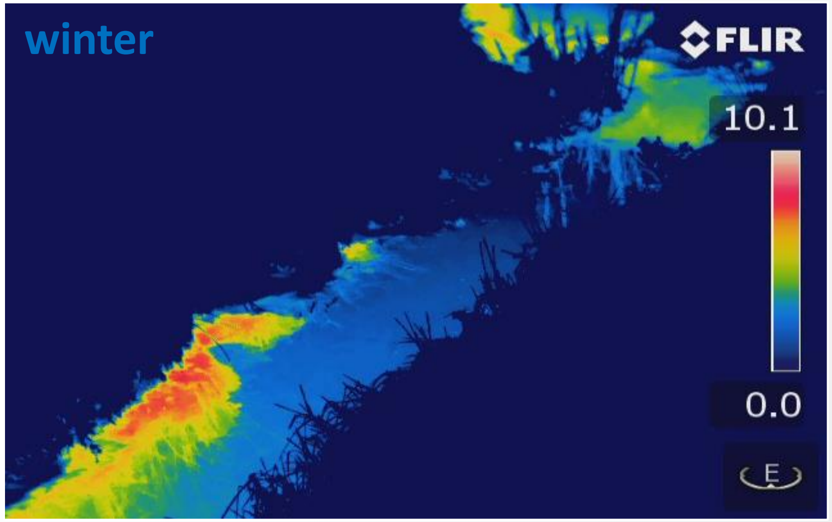


Heat tracing for the geolocation of groundwater seepage – thermal infrared imaging



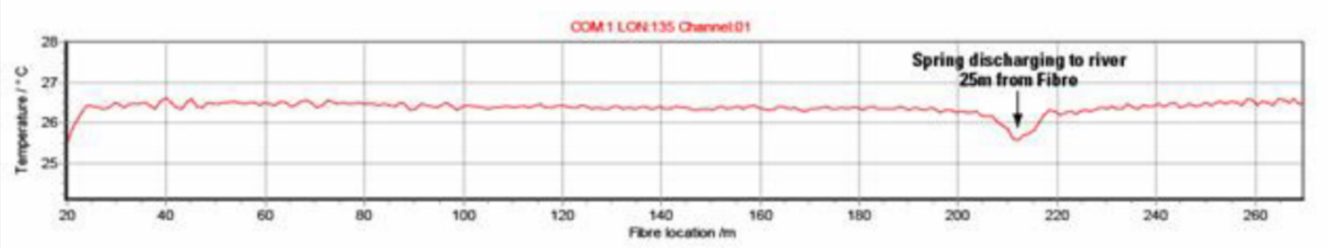
Groundwater temperature is relatively constant throughout the year compared to surface water, and therefore acts as a natural tracer which may be relatively cold and dense in summer…

…and relatively warm and buoyant in the winter, compared to surface water. Groundwater inflows can be identified quickly throughout aquatic systems based on thermal anomalies and zones of buffered temperature change.



Slide credit: Marty Briggs, USGS

Fiber Optic Distributed Temperature System (FODTS)

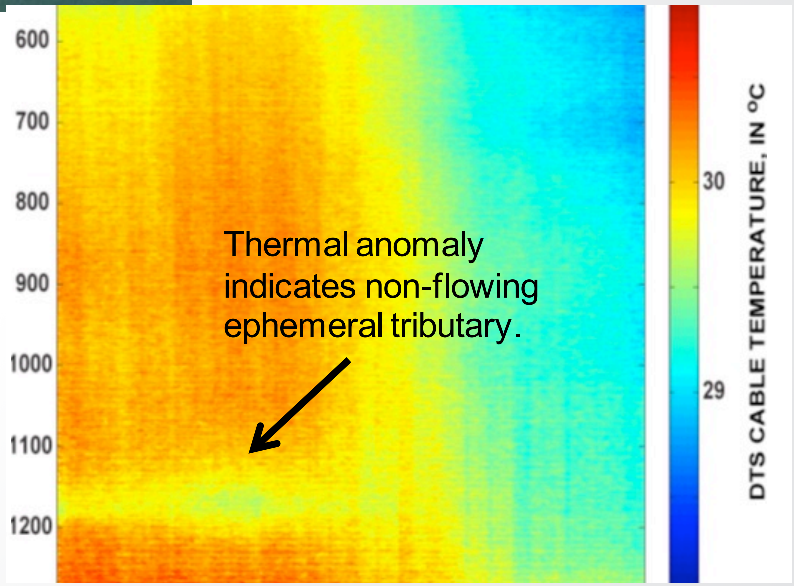


STRENGTHS:

- Direct temperature measurement of streambed (not possible with thermal infrared)
- High spatial resolution (~0.25 to 1 m linear)
- High precision (0.01 °C) potential
- Large scale (10 km possible, <5 km common)
- Continuous measurement (in time and space)
- Continuous data download (no retrieval/disturbance)

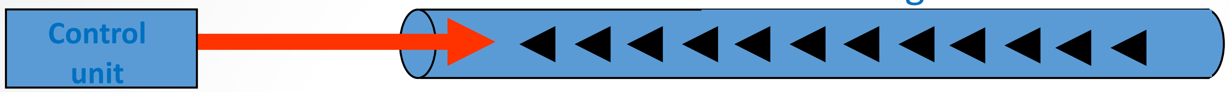
LIMITATIONS:

- Fiber is glass – can be damaged
- Deployment can be labor-intensive
- DTS systems are costly ($25-50K)
- Require calibration and field verification with conventional measurements; georeferencing



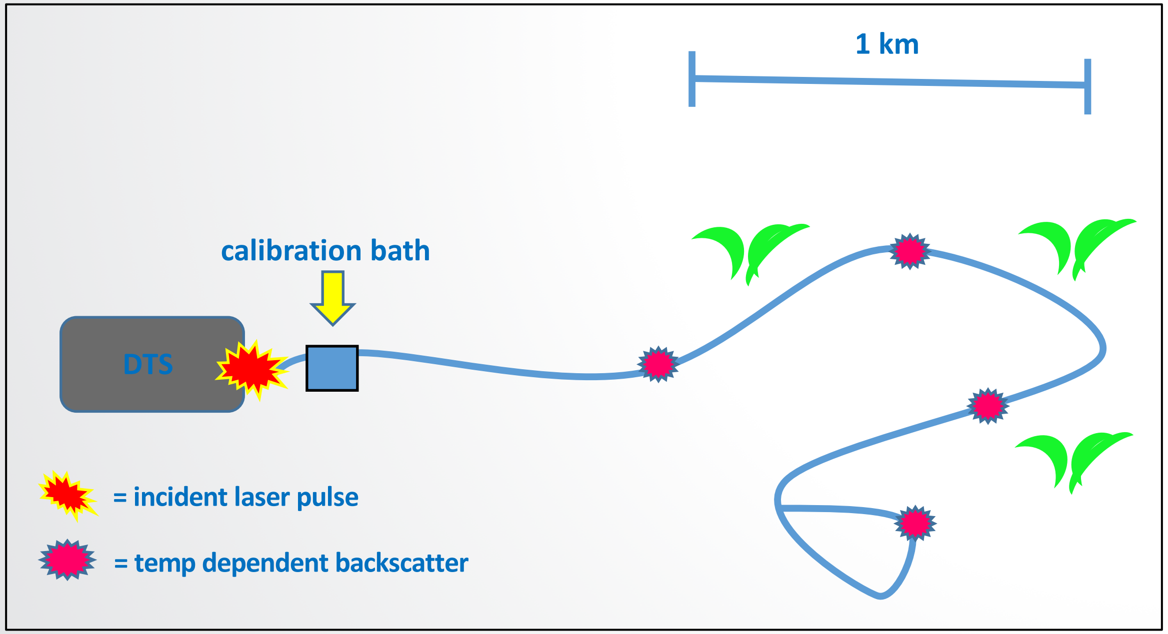
Voytek, E.B., Drenkelfuss, A., Day-Lewis, F.D., Healy, R., Lane, Jr., J.W. and Werkema, D., 2013

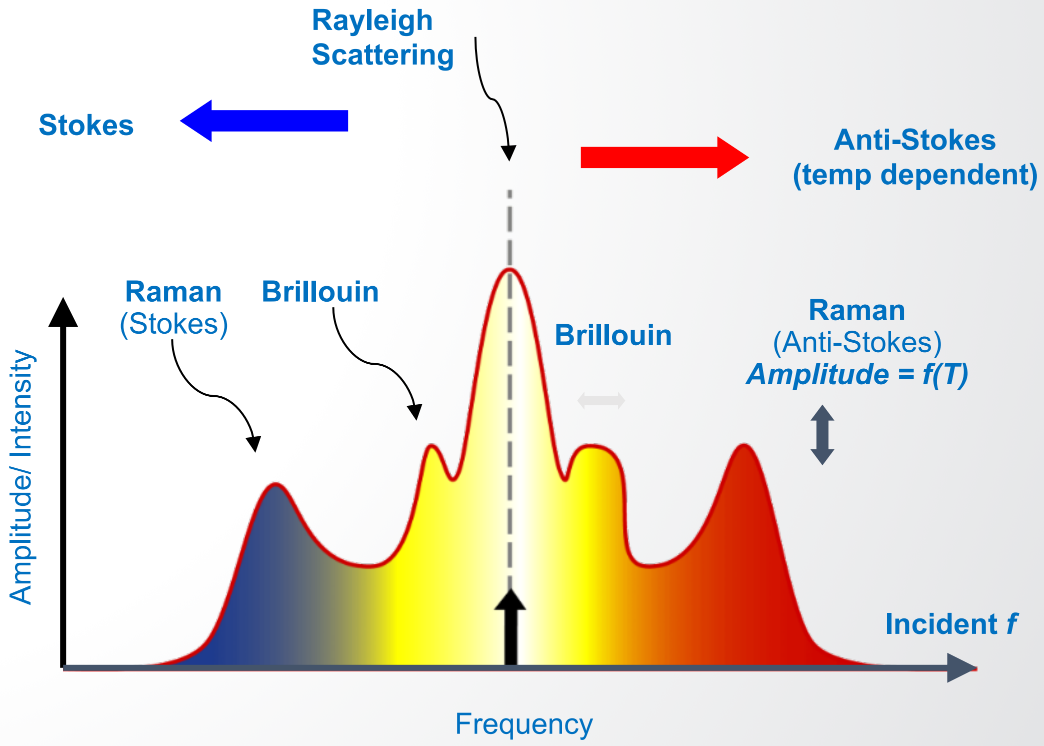
FODTS Measurement physics



- Optical fiber in cable acts as a “light pipe” for transmitted laser light from control unit
- Light scatters back to the control unit by several mechanisms (Rayleigh, Brillouin, Raman)

Raman backscatter is analyzed to estimate temperature and location along the cable



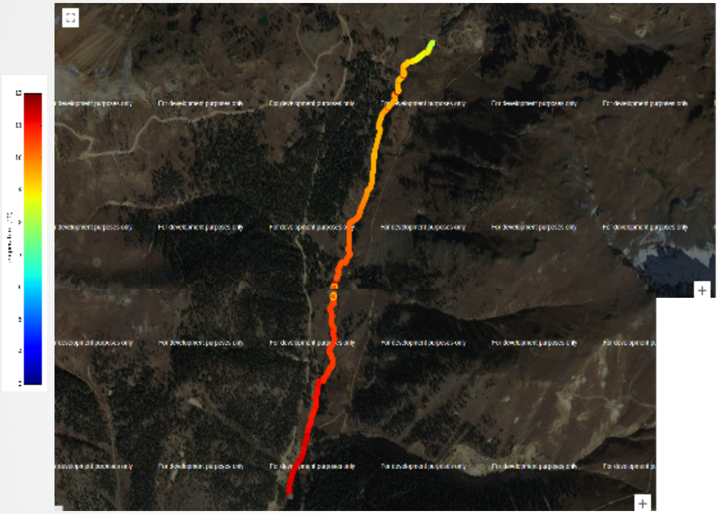


Modified from S.Tyler DTS presentation

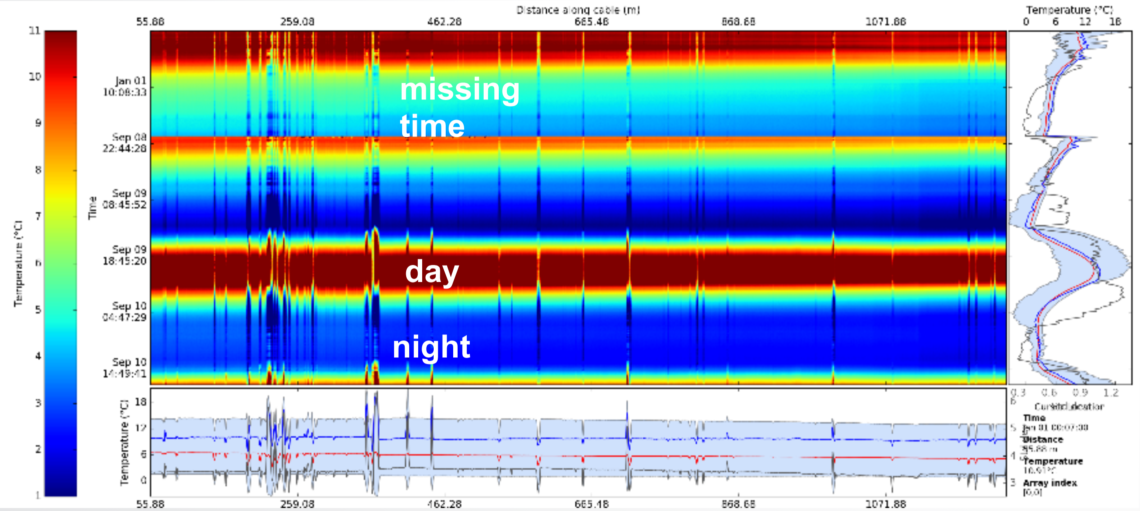
Slide credit: Marty Briggs, USGS

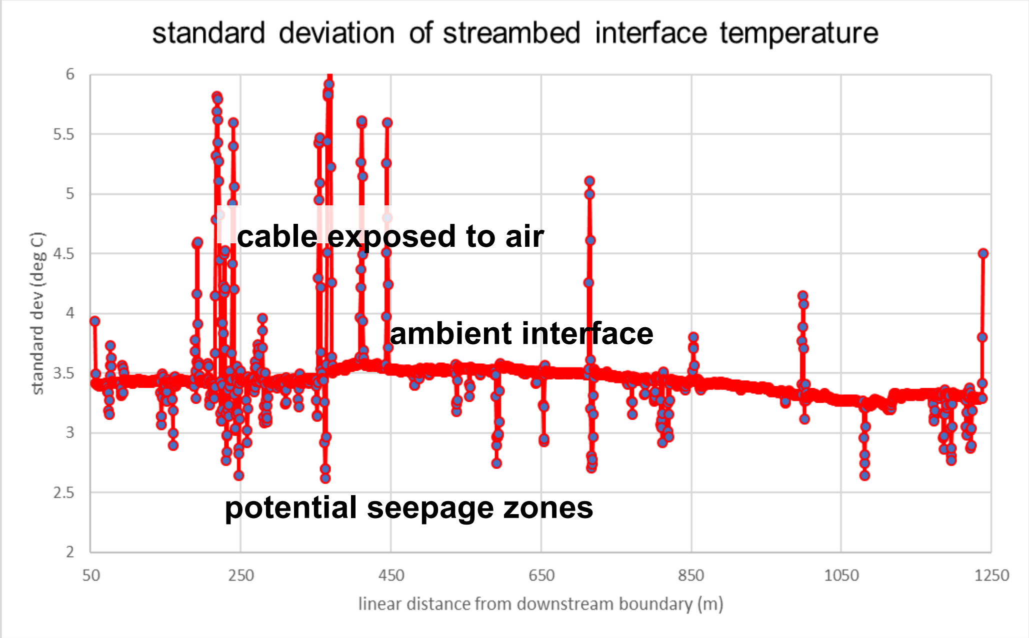
Preliminary DTS data (not reviewed/approved)

day



night





Slide credit: Marty Briggs, USGS

Summary

- Match the geophysical method with the objectives and the scale of investigation

- Use more than one geophysical method – converging lines of evidence

- Is there a physical property contrast, or is there an expected/anticipated contrast – forward modeling the geophysical response

The geophysical response is a function of the geology, hydrogeology, biology, and chemistry of the subsurface. <u><- and the interactions</u>

Acknowledgements

- Thank you clui-in.org and the Mine Waste study organizers for this opportunity.

- USGS, Storrs, CT personnel: Marty Briggs, Carole Johnson, Eric White, Neil Terry, Fred Day-Lewis, and John Lane for their help in many of these field investigations, data processing, and interpretations.

- Bruce Smith (USGS –retired) for some slide content

- Beth Rutila (ORISE), Steve Dyment (EPA), Rob Runkel (USGS), Rory Cowie and Nate Rock (Mountain Studies Institute)