GEOPHYSICS APPLICATIONS TO LUST SITES: CASE STUDIES AND ONLINE TOOLS

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NEIWPCC EPA ASTSWMO pennsylvania DEPARTMENT OF ENVIRONMENTAL PROTECTION
NTC 2022

OUTLINE

Why geophysics? Will it help?

1. Finding Underground Storage Tanks (USTs) and underground infrastructure
2. Mapping contaminant plumes from LUSTs
3. Monitoring active or passive remediation
4. Conceptual Site Model (CSM) Development

    Havasu Landing Resort, Chemehuevi Territory, Lake Havasu, CA

        Marine release site (CHEM001) & hardware store release site (CHEM04)

    Davis Chevrolet, Tuba City, AZ

5. Resources

    EPA's Environmental Geophysics web presence

    Free tools

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

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

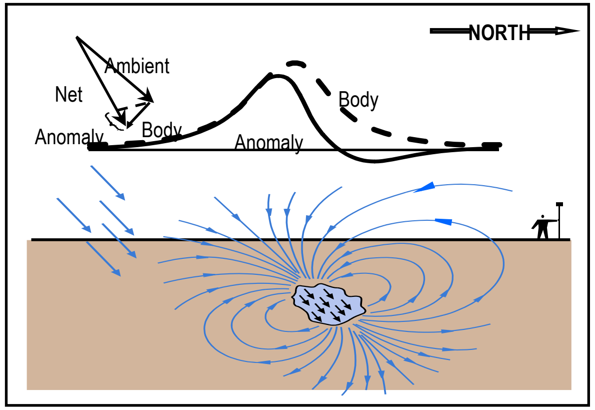
images credit: Lee Slater

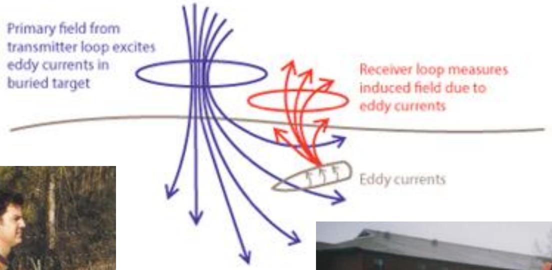
- Prior to expensive earth intrusive investigations (e.g., drilling, excavating, etc.) we can utilize geophysical imaging.
- Each geophysical method is used for specific purposes, for example:

Physical property measured	Geophysical Method
Electrical conductivity, resistivity, dielectric permittivity	Electrical resistivity (ER or ERT), ground penetrating radar (GPR), electromagnetic induction (EM or EMI)
Magnetic Susceptibility	Magnetic methods, EM
Seismic shear wave velocity, density, shear modulus	Active source seismic, passive seismic

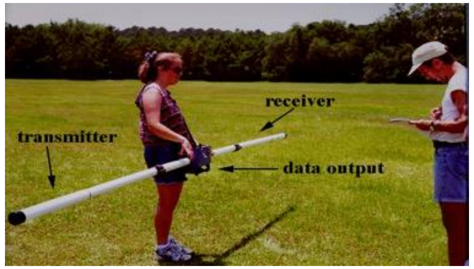
What is the physical property contrast?

1. Finding USTs & subsurface infrastructure





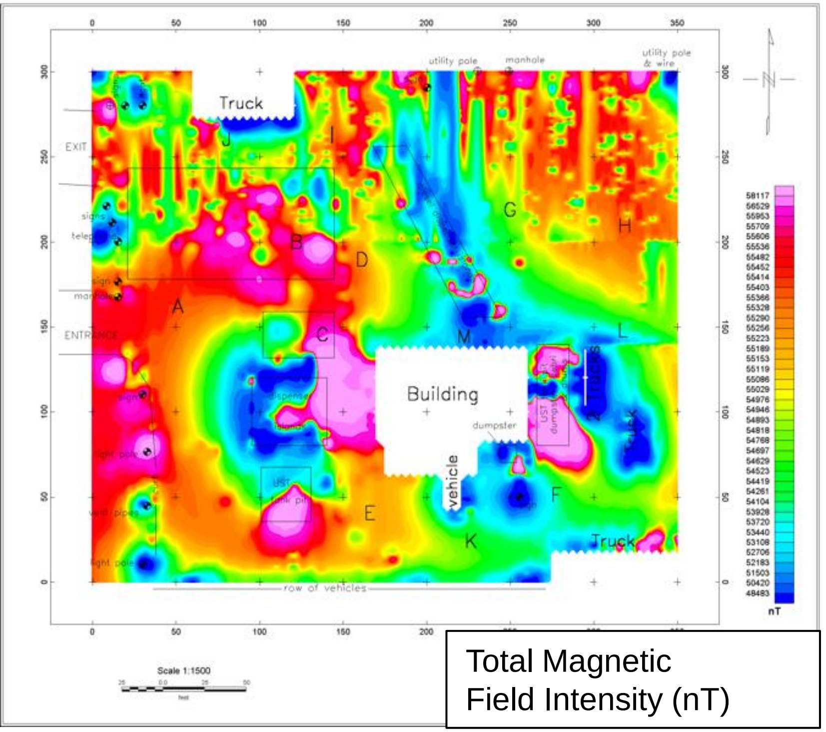
Geometrics G-858



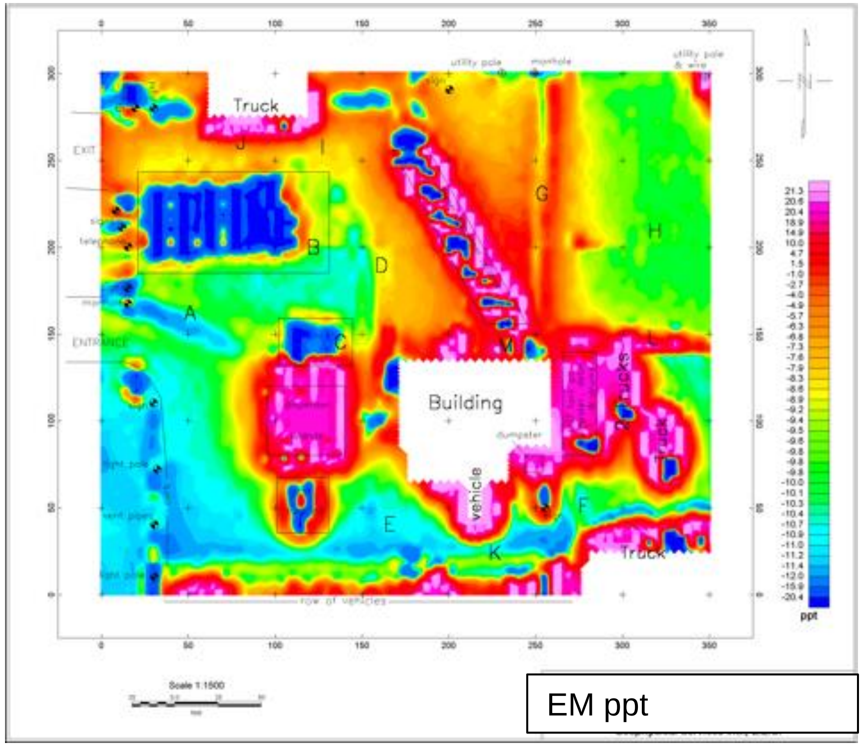
Geonics EM-31

GEM-2

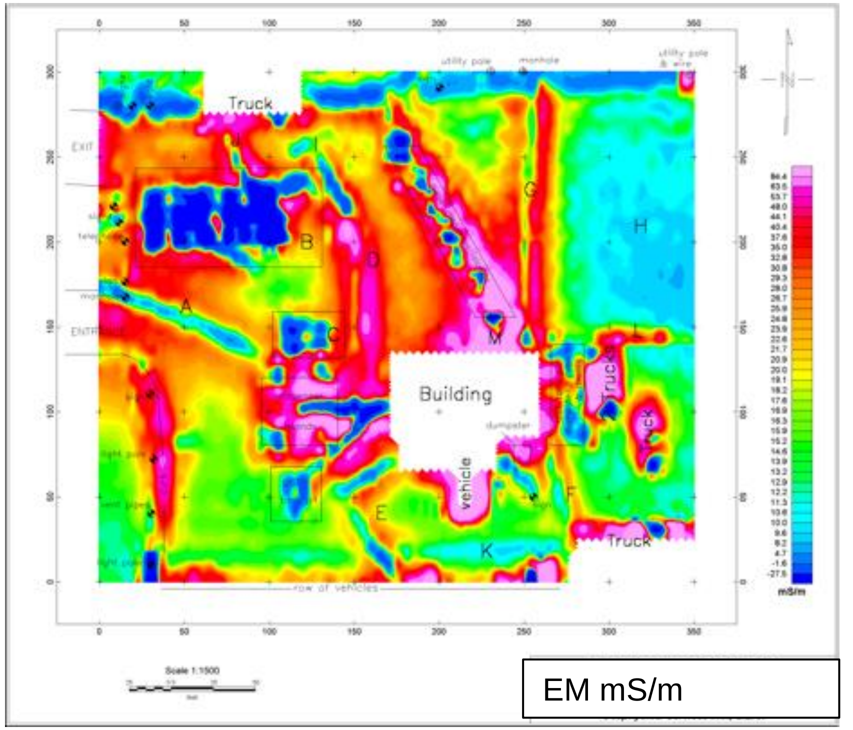
Geonics EM-61



Total Magnetic Field Intensity (nT)



EM ppt



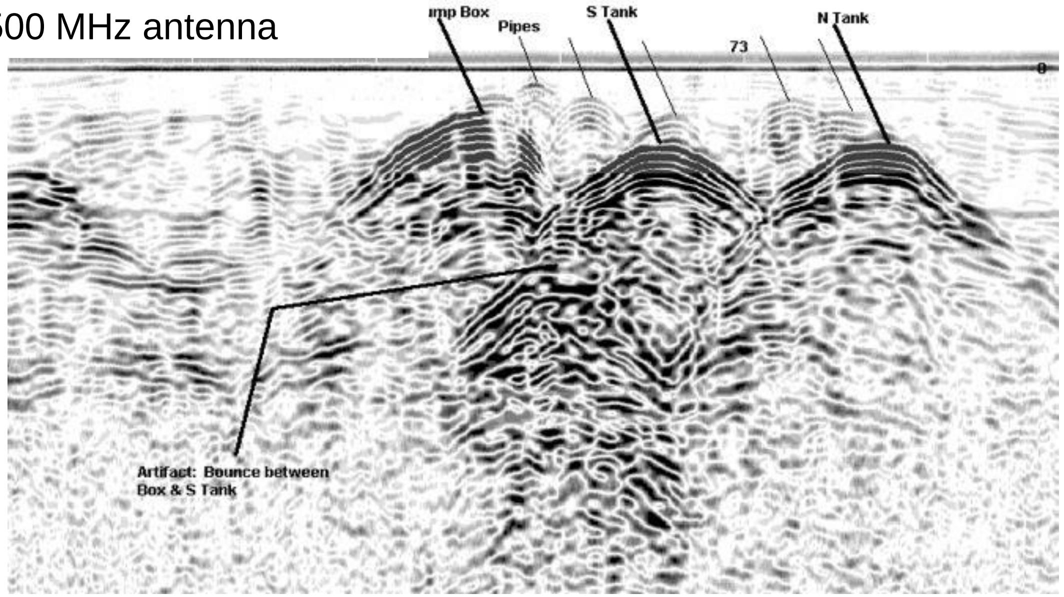
EM mS/m

Complimentary and converging lines of evidence

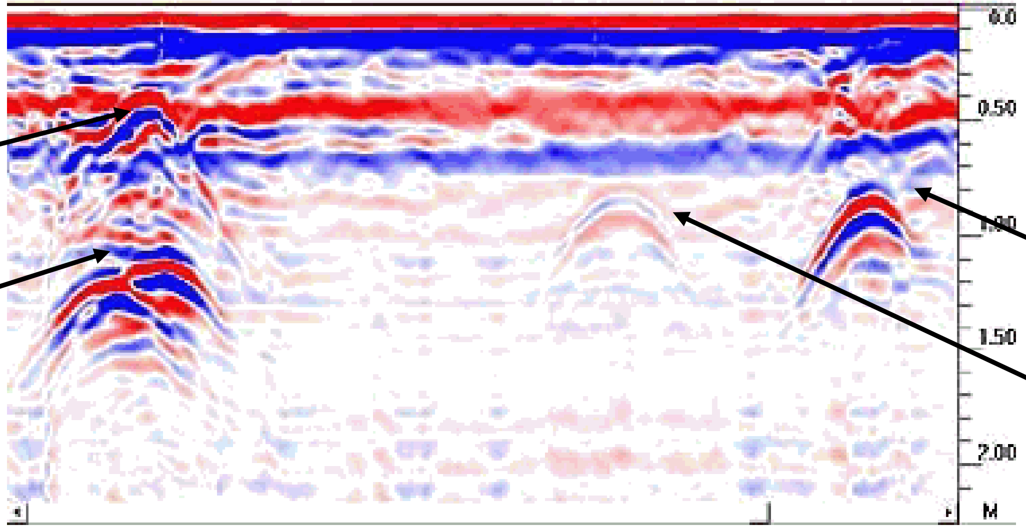
1. Finding USTs & subsurface infrastructure

Ground Penetration Radar (GPR) UST and utility examples

500 MHz antenna



400 MHz antenna



telephone cable

2 steel pipes

steel pipe

PVC pipe

- 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.

GSSI antenna

Mala GPR system

Note: <u>Hyperbolic</u> Reflections

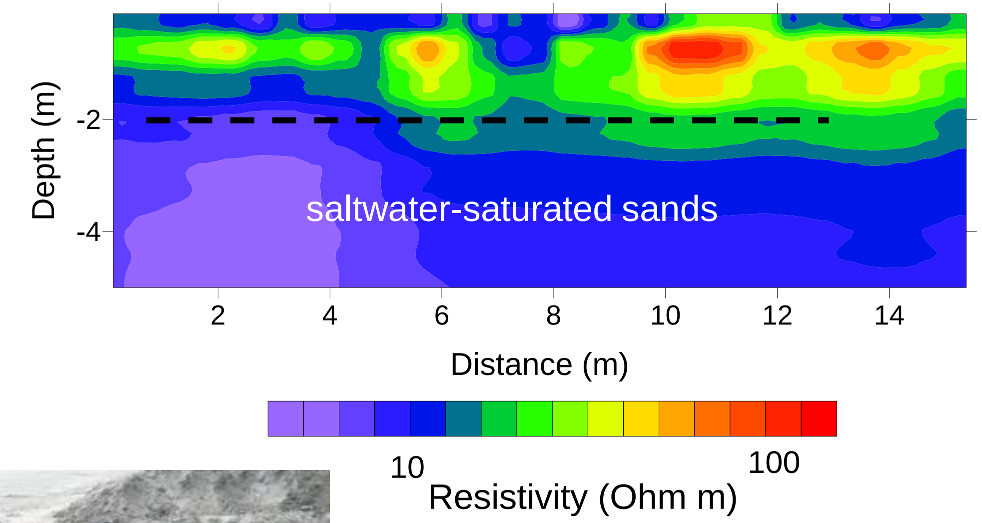
GPR sections from Bill Sauck, retired Western Michigan University

2. Mapping contaminant plumes

Deep Water Horizon Oil Spill Barrier Island Impact DC Resistivity Results

Zone of immature oil contamination imaged as resistive layer

NW ⟵ *Inland* *thinning of oil layer?* ⟵ *Offshore* ⟶ SE



Approximate location of ~0.3 m thick oil layer

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

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

Archie, 1942

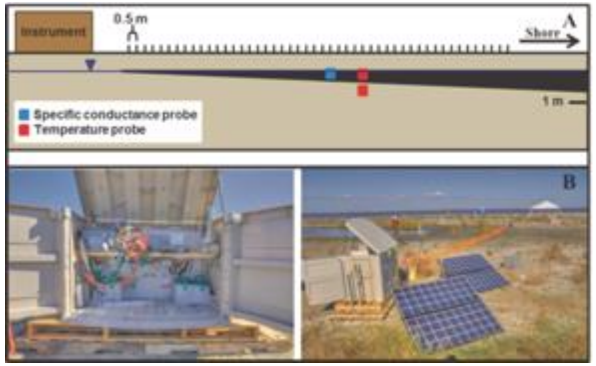
Oil layer

Oil impact thins away from the shoreline

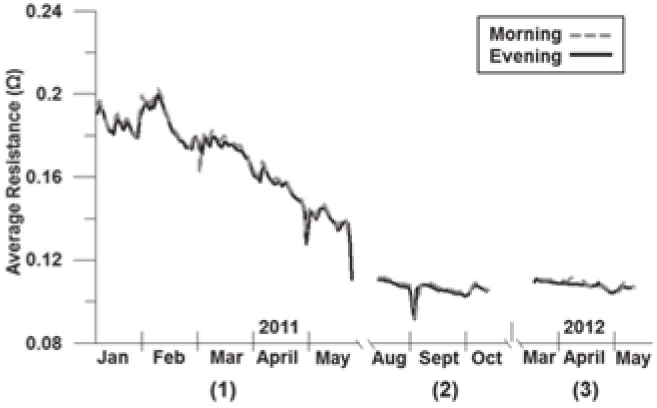
Heenan, J., Slater, L.D., Ntarlagiannis, D., Atekwana, E.A., Fathepure, B.Z., Dalvai, S., Ross, C., Werkema, D.D., and Atekwana, E.A., *Geophysics*, 2014

2. Mapping contaminant plumes

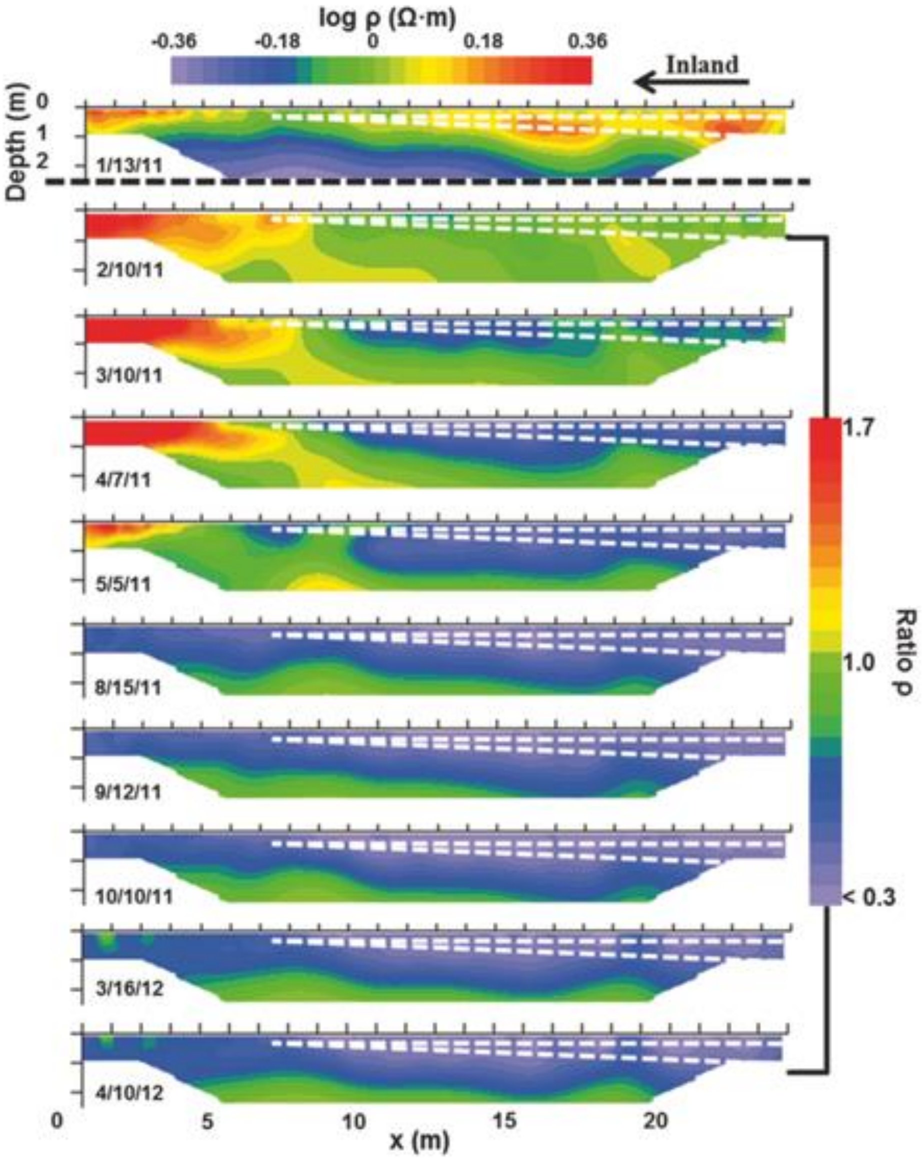
DWH Barrier Island Time-Lapse



Adaptation of field resistivity system to remote solar power acquisition



ave. resistance of anomaly vs. time

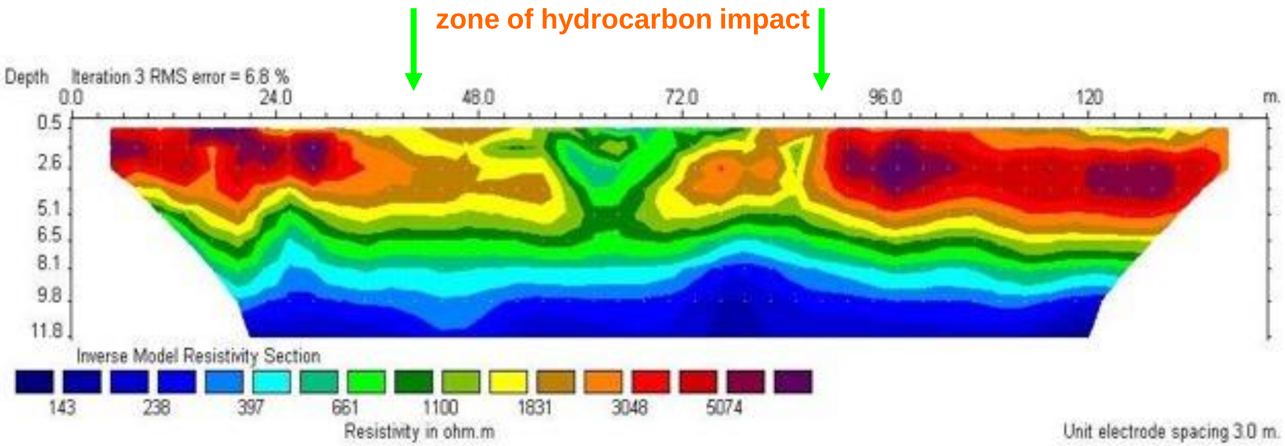


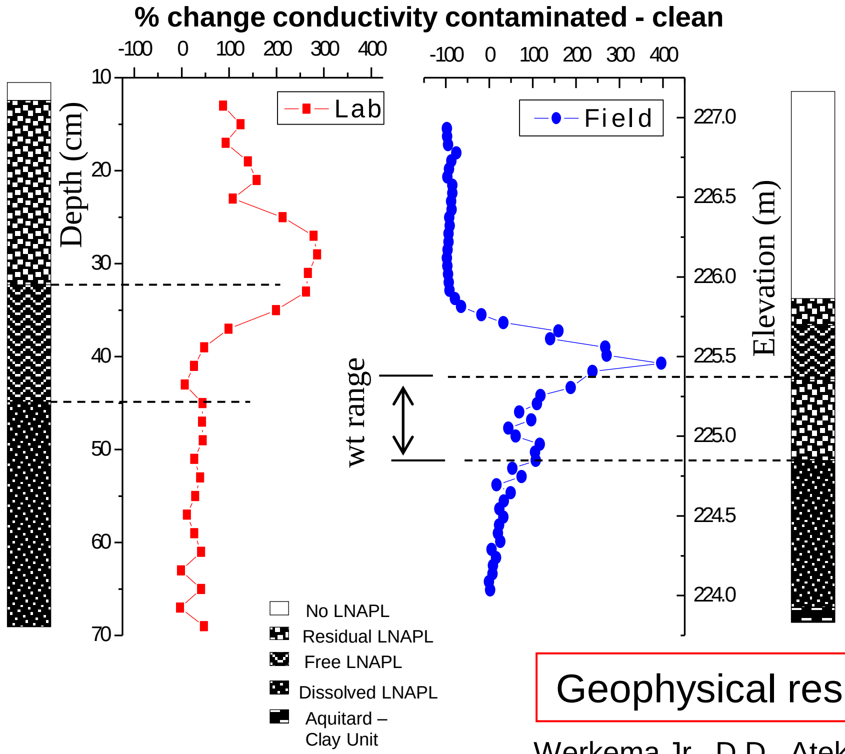
15 months resistivity

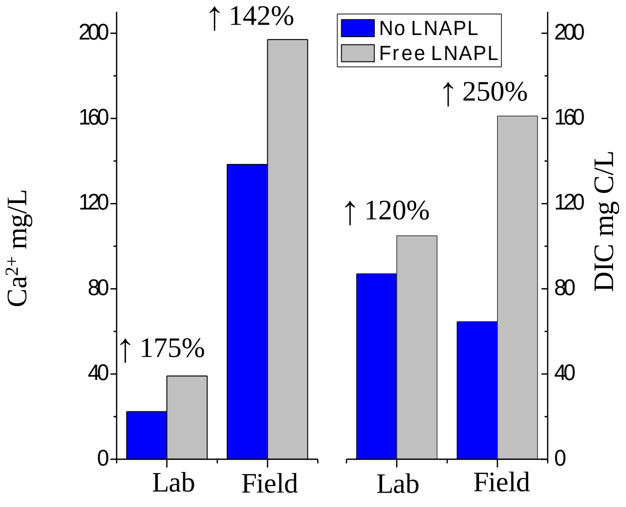
Heenan, J., Slater, L.D., Ntarlagiannis, D., Atekwana, E.A., Fathepure, B.Z., Dalvai, S., Ross, C., Werkema, D.D., and Atekwana, E.A., *Geophysics*, 2014

3. Remediation monitoring

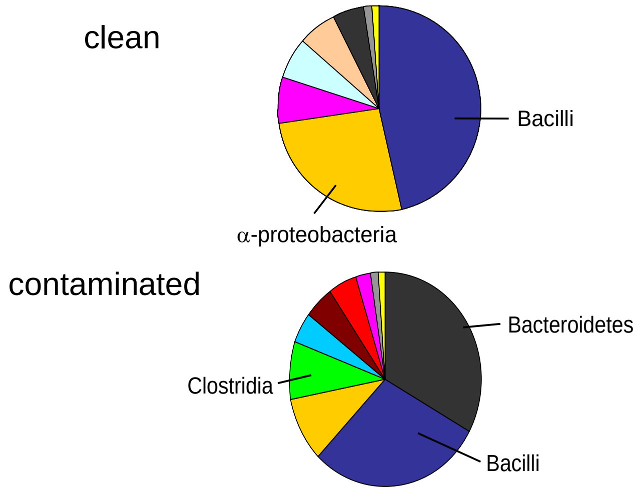
Direct Current Resistivity of mature LNAPL plume







% change of Ca^{2+} and DIC



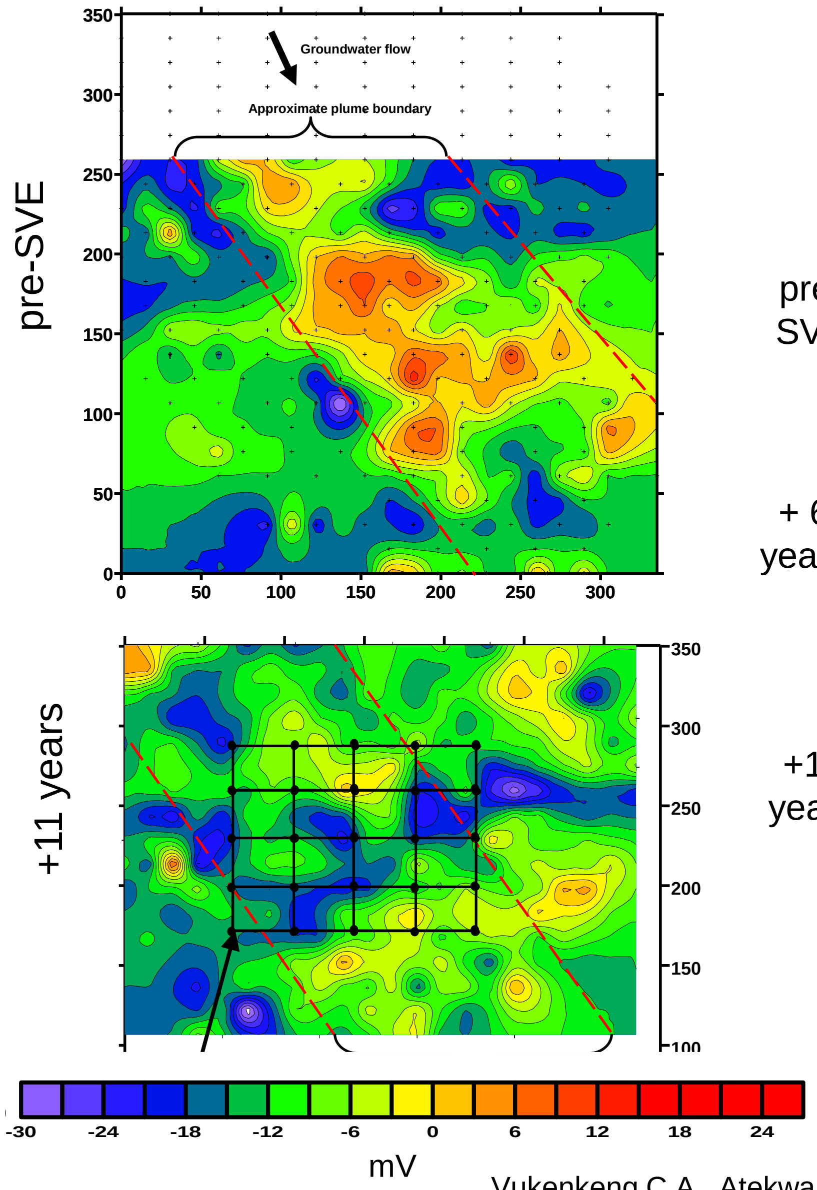
16S rRNA gene community composition

Geophysical response is coincident with microbiology and geochemical changes

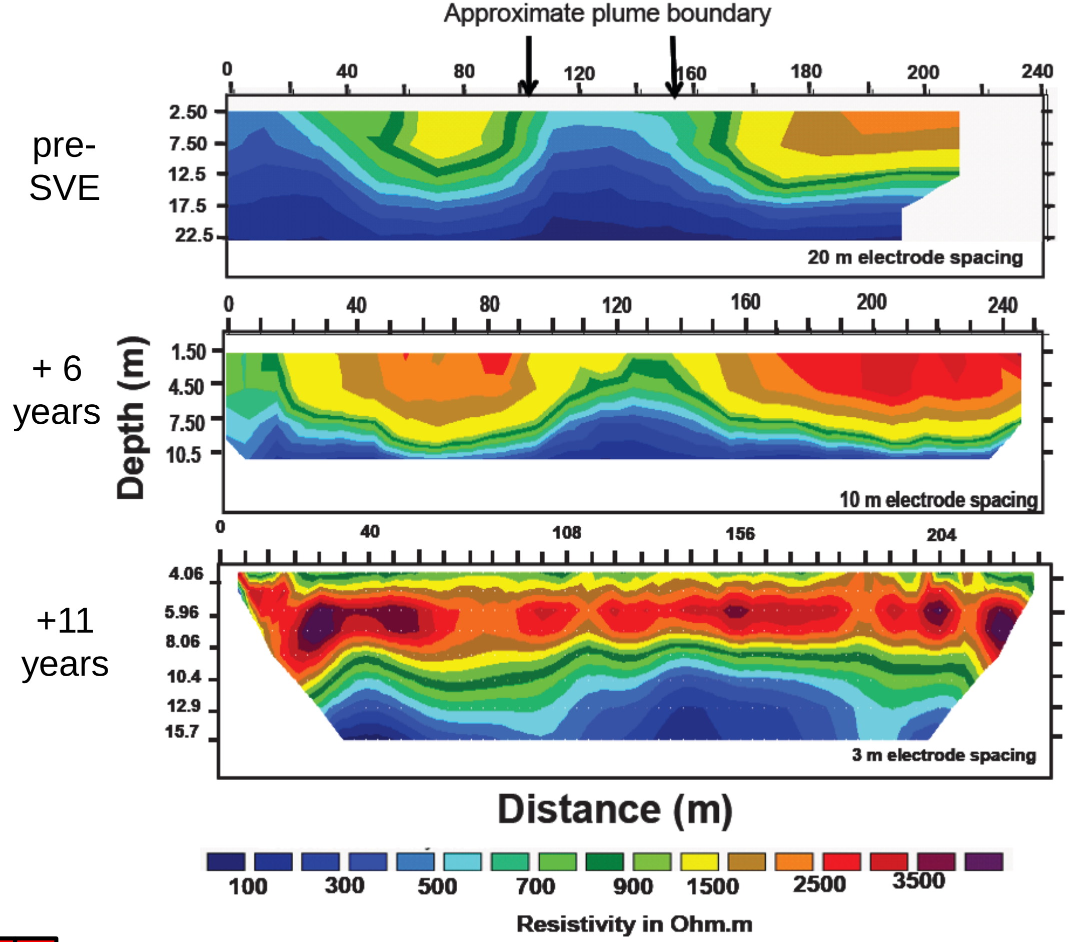
Werkema Jr., D.D., Atekwana. E.A., Endres, A., Sauck, W.A. and Cassidy. D.P., *Geophysical Research Letters*, 2003

3. Remediation monitoring of soil vapor extraction (SVE system)

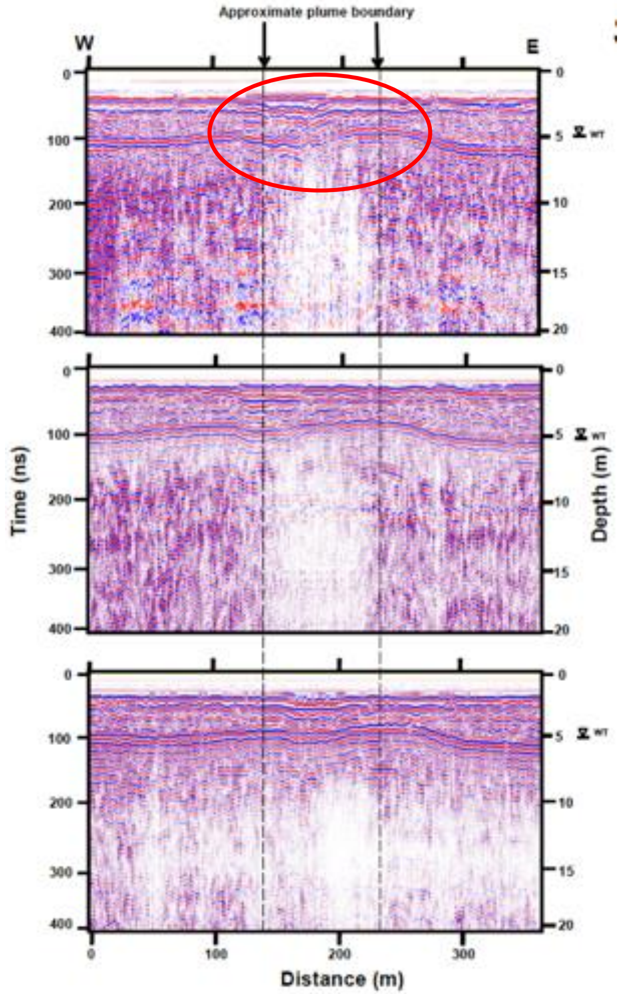
Self Potential (SP)



DC Resistivity response to SVE system



GPR Response to SVE System

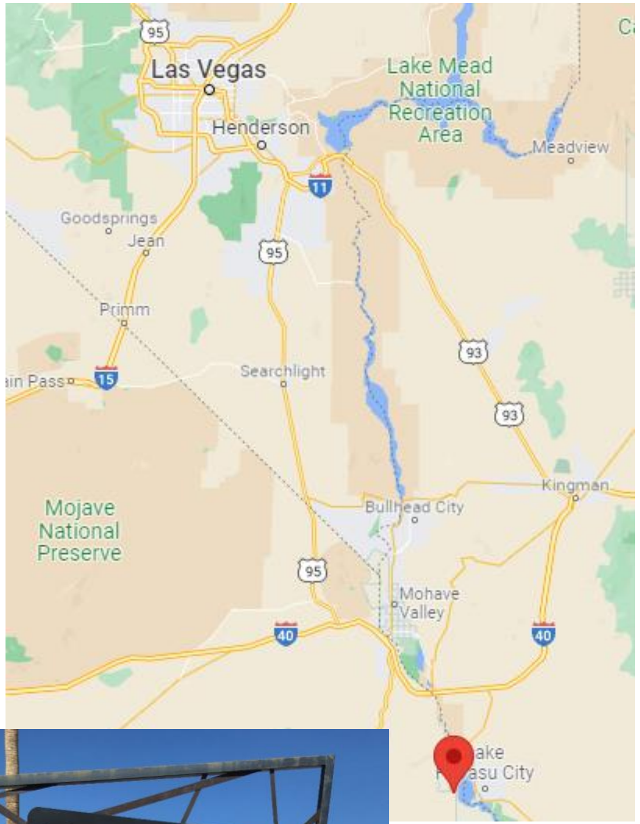


Vukenkeng C.A., Atekwana Estella.A., Atekwana, Eliot, A., Sauck, W.A., Werkema Jr., D.D., *Geophysics*, vol. 74, 2009

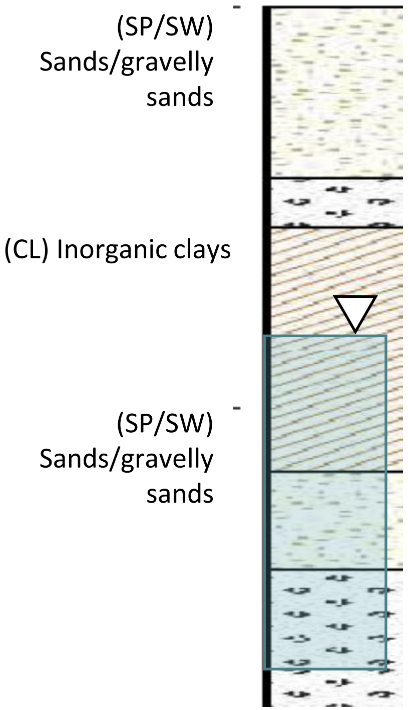
4. Conceptual Site Model (CSM) Development

Havasu Landing, CA; Chemehuevi Territory

Four leaking underground storage tanks (USTs) removed (1993)



HAVASU: HMW-6



Water table (<6 meters)

Predominant unconsolidated lithology

- Quaternary alluvial mixed unconsolidated sediments ranging from gravels to clays

Free product not reported in 2020 well sampling dataset, but was observed in wells during geophysical data collection in 2022

Max observed free product thickness (meters)

- 0.2
- 0.275
- 0.35
- 0.425
- 0.5

Geophysical Methods

4. Conceptual Site Model (CSM) Development

Surface geophysical methods

- Magnetic (dual sensor): ferrous objects, MS zones; CSM
- Electromagnetic Induction (FDEM & TDEM): bulk EC, MS; CSM
- Ground Penetrating Radar (several frequencies); structure, EC; CSM
- Electrical Resistivity (several electrode arrays); bulk EC, structure; CSM
- Passive seismic (HVSR); CSM, geologic contacts

G-858 Magnetometer

Borehole geophysical methods

- Natural gamma
- EM induction – bulk electrical conductivity
- Fluid specific conductivity
- Magnetic susceptibility

GEM-2

DualEM

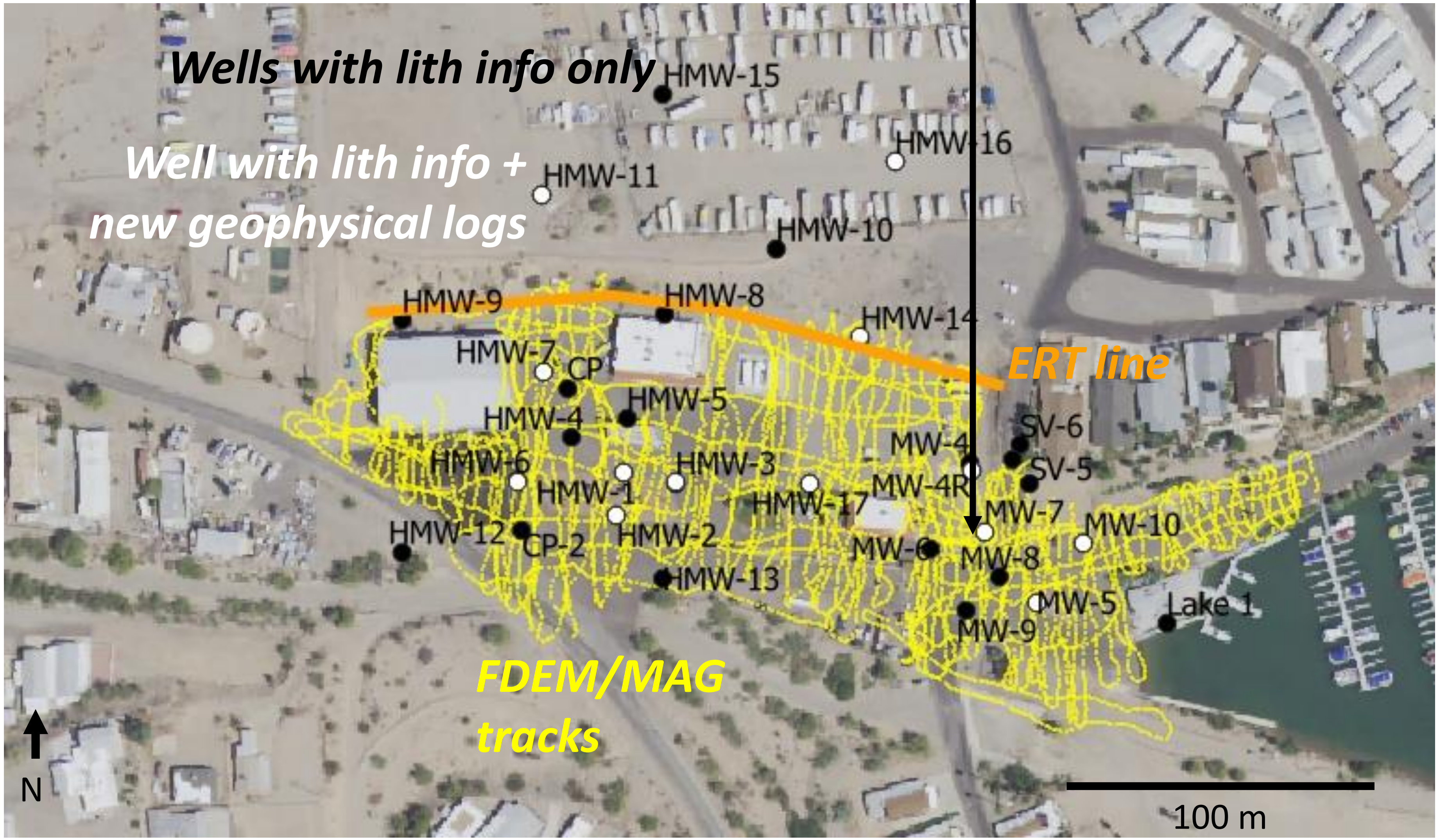
GPR

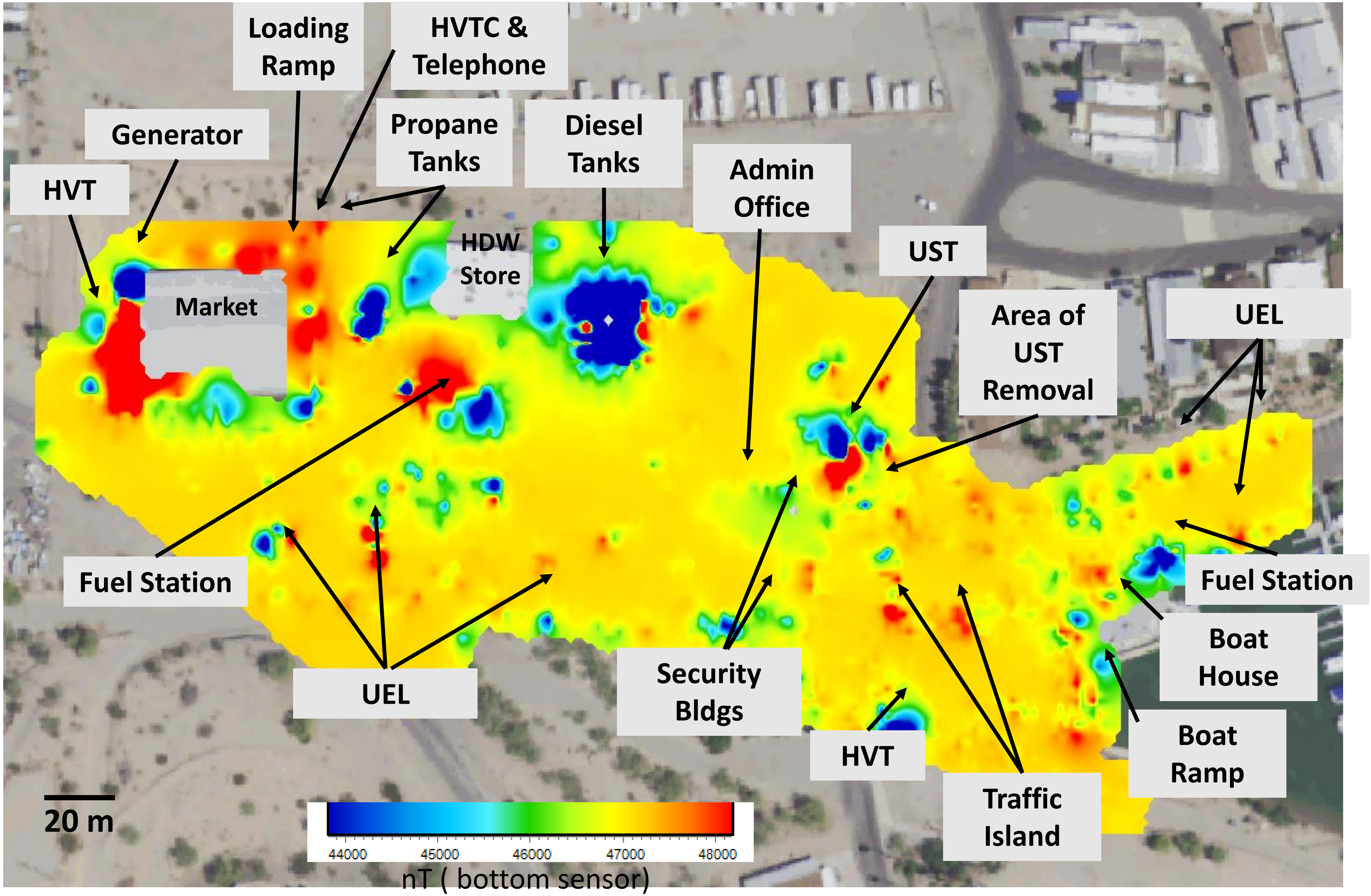
DC Resistivity Profile

Borehole logging

Data collection

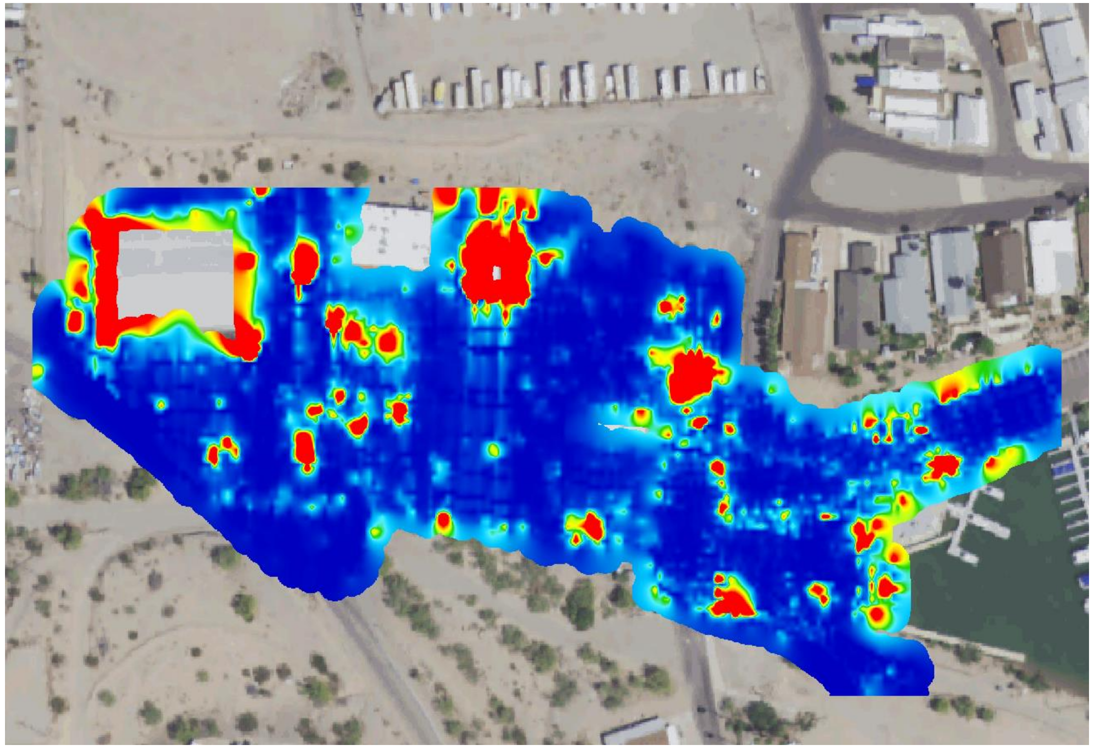
Area of UST removal

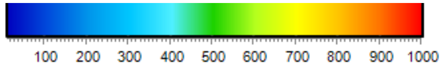




Loading Ramp
HVTC & Telephone
Generator
Propane Tanks
Diesel Tanks
Admin Office
HVT
HDW Store
Market
UST
Area of UST Removal
UEL
Fuel Station
UEL
Security Bldgs
HVT
Traffic Island
Boat House
Boat Ramp
Fuel Station
20 m
44000
45000
46000
47000
48000
nT (bottom sensor)

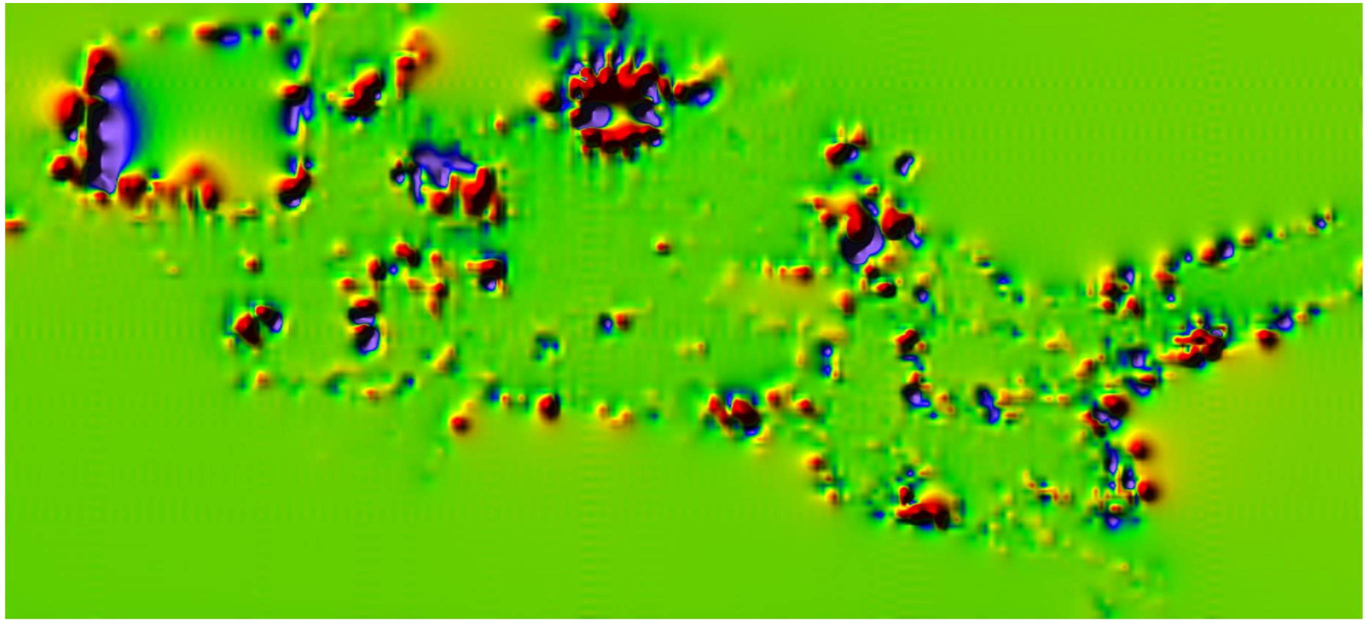
Magnetometer processing and analysis

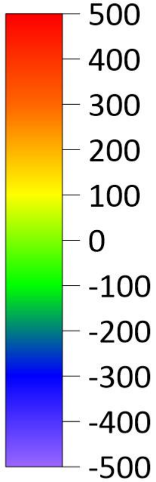




Vertical Gradient, in nT

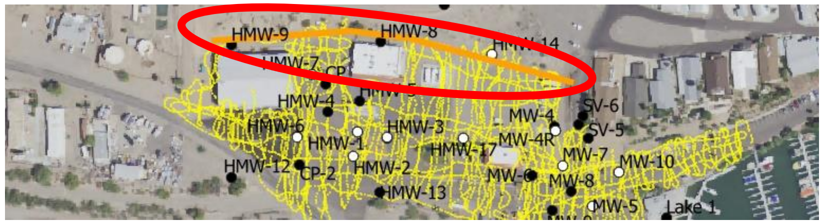
Downward Continuation

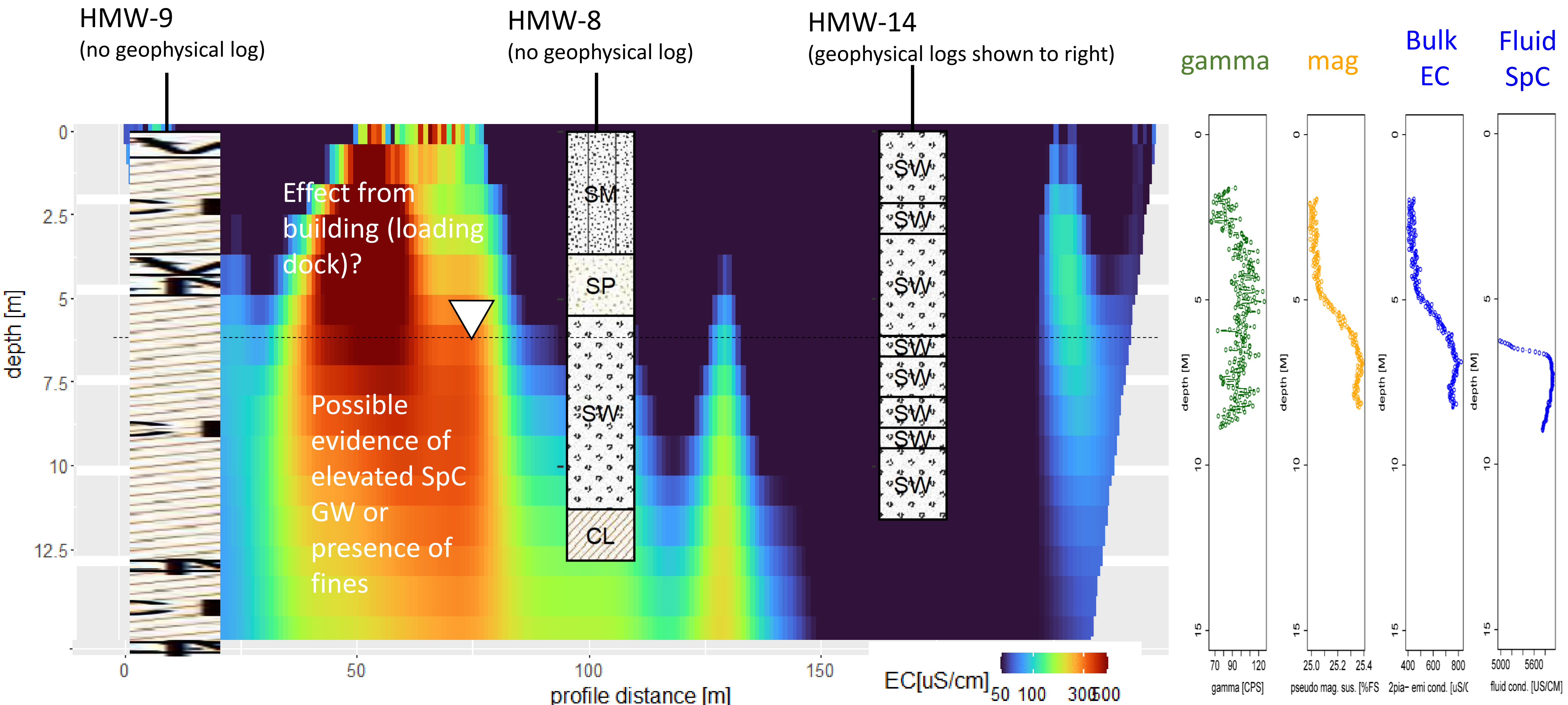




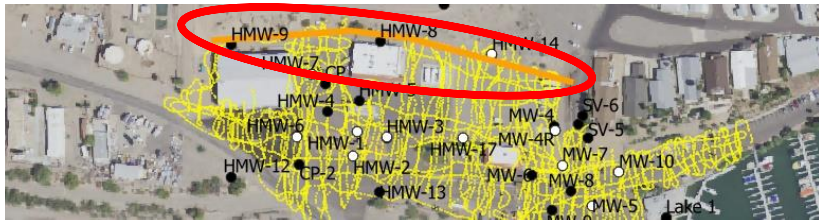
nT

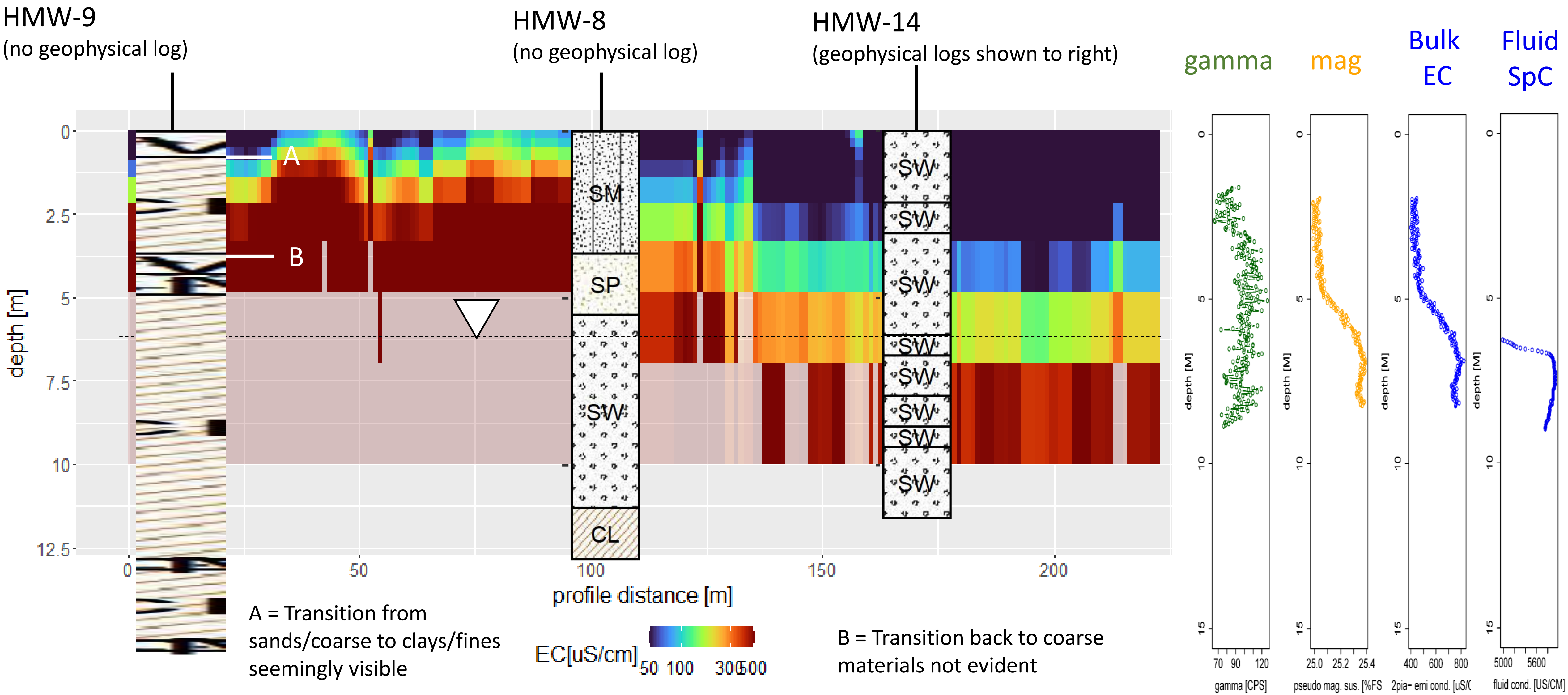
ERT inversion





DualEM inversion result along ERT line

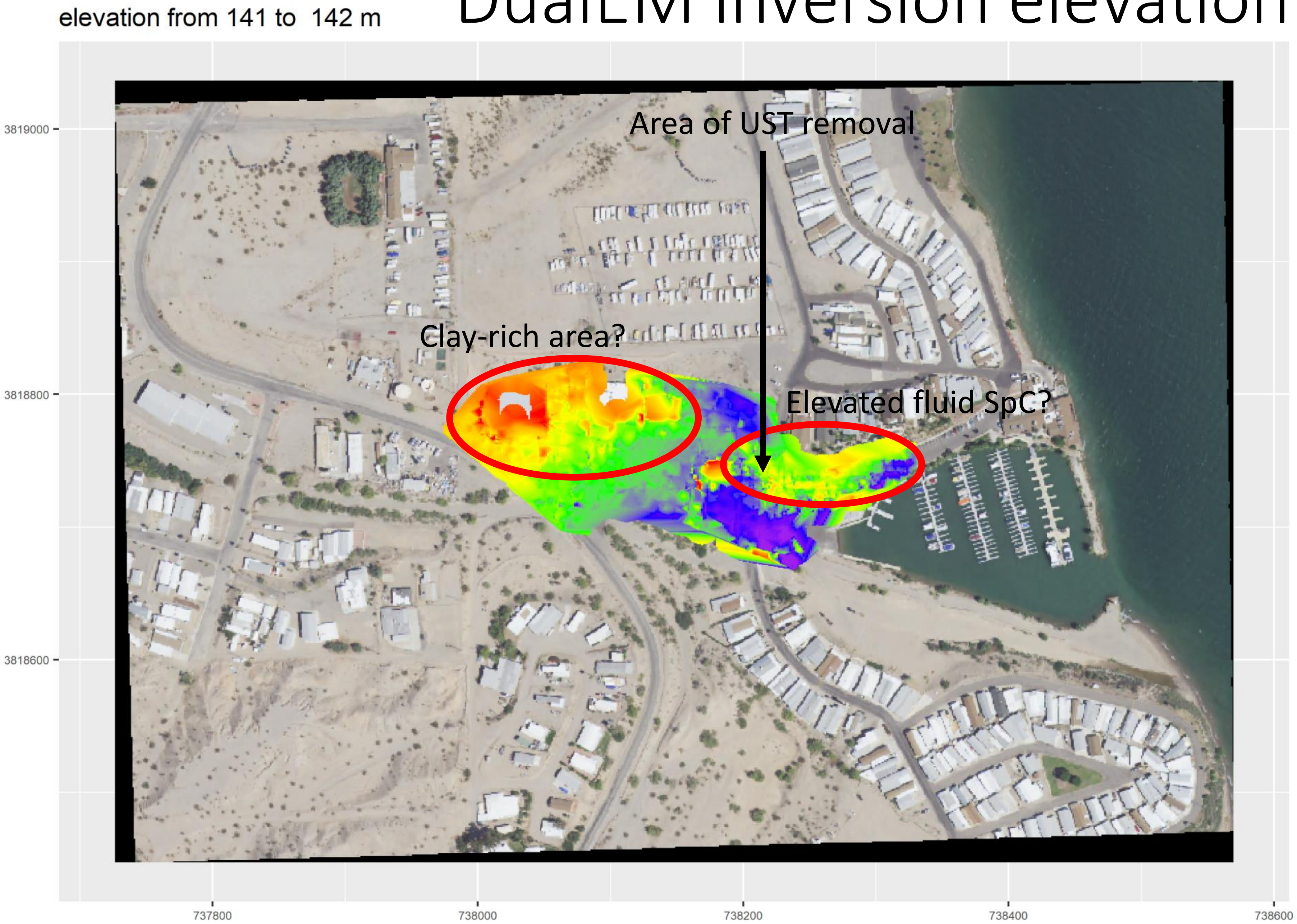


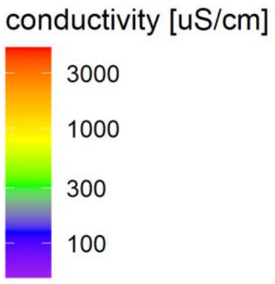


A = Transition from sands/coarse to clays/fines seemingly visible

B = Transition back to coarse materials not evident

DualEM inversion elevation slice





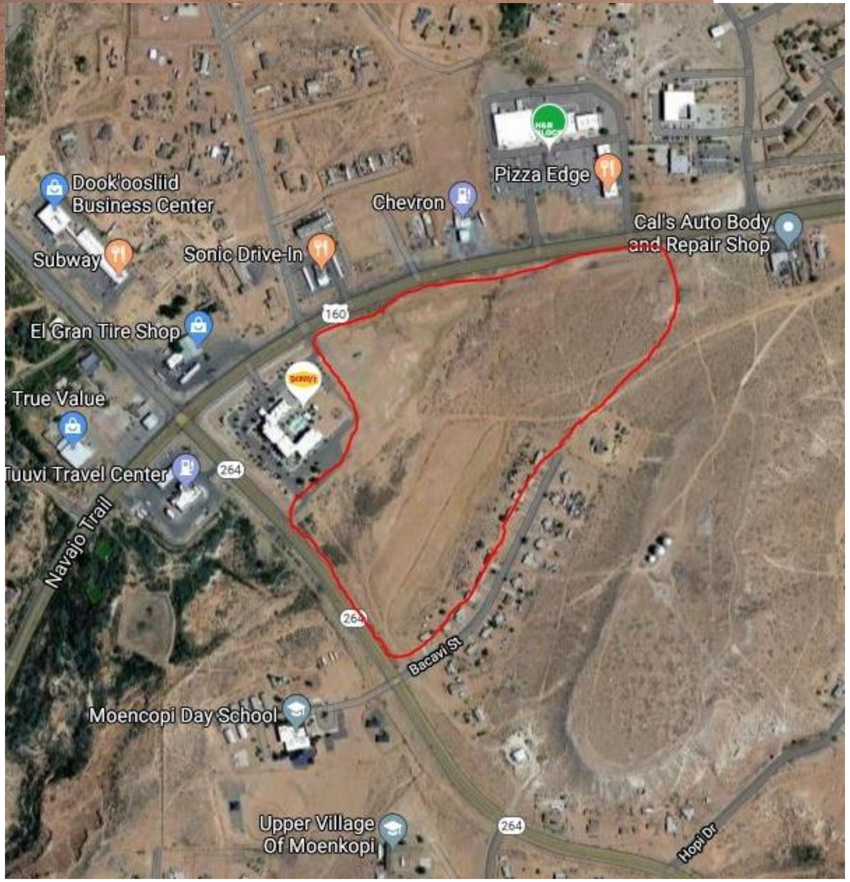
Fines observed on downhole tool at MW-11

***142 m approximate water table elevation at time of survey**

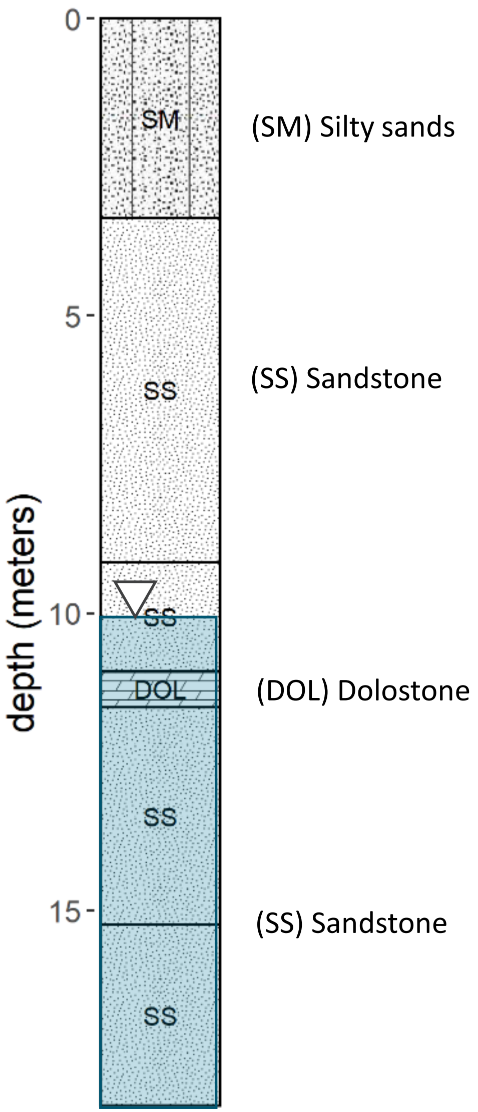
4. CSM DEVELOPMENT

TUBA CITY AZ; HOPI TERRITORY

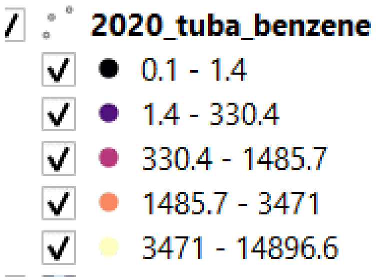
Three LUSTs (pre-2006)

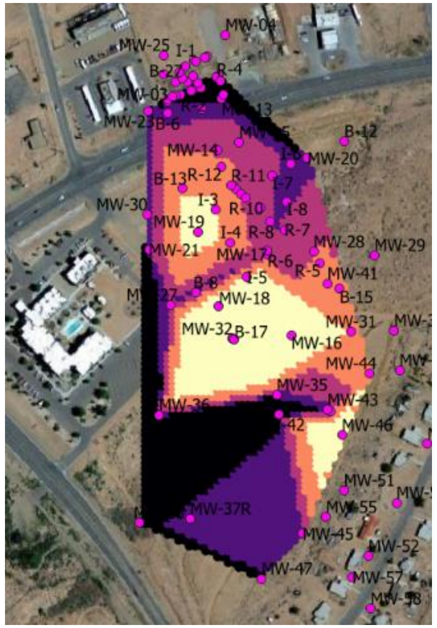


TUBA: MW-47



BENZENE MONITORING



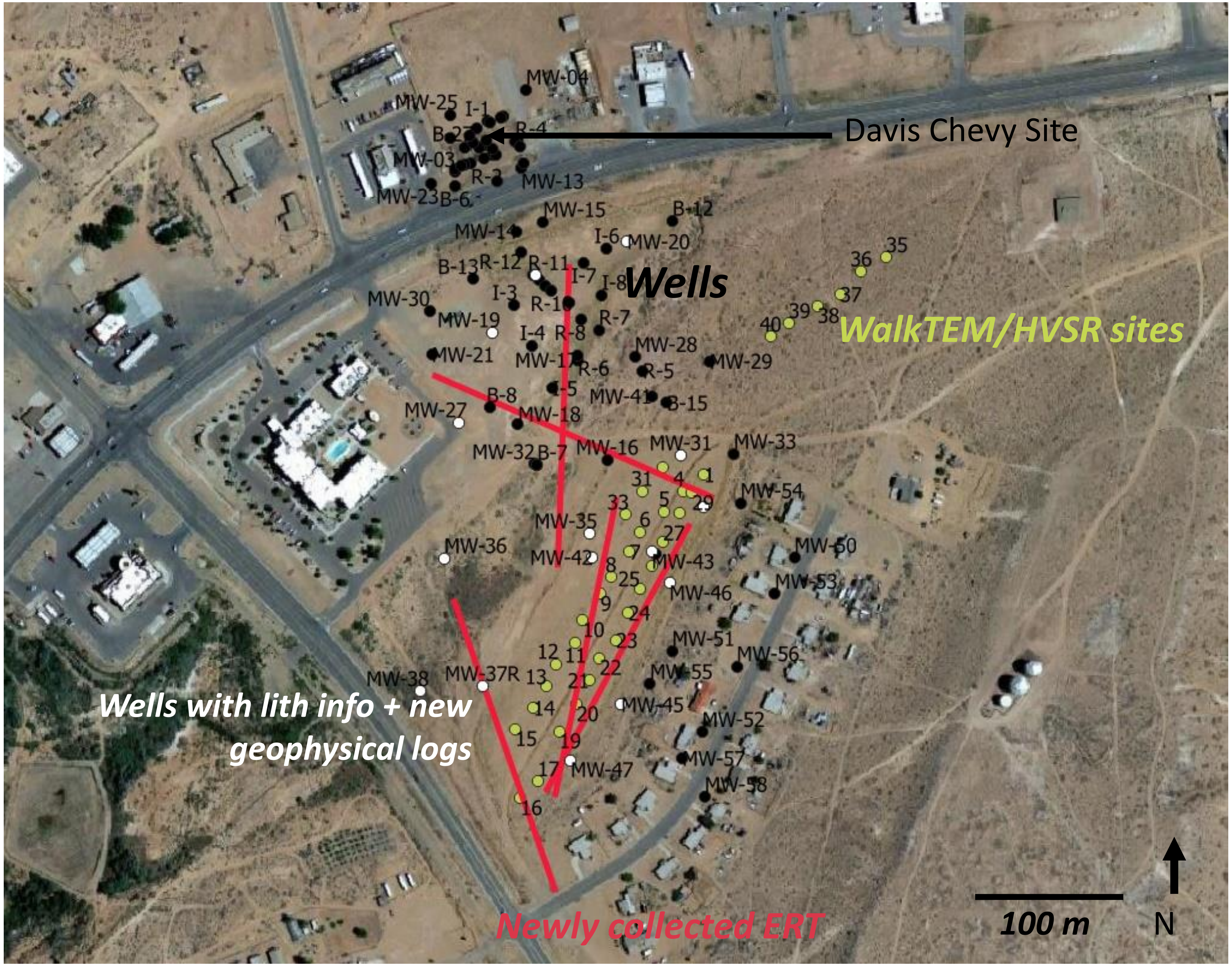


Plume migrating south

- Water table >10 meters
- Predominant lithology:
  - Sedimentary bedrock
  - Thin cap of weathered sediments, sandstone bedrock with interbedded dolostone

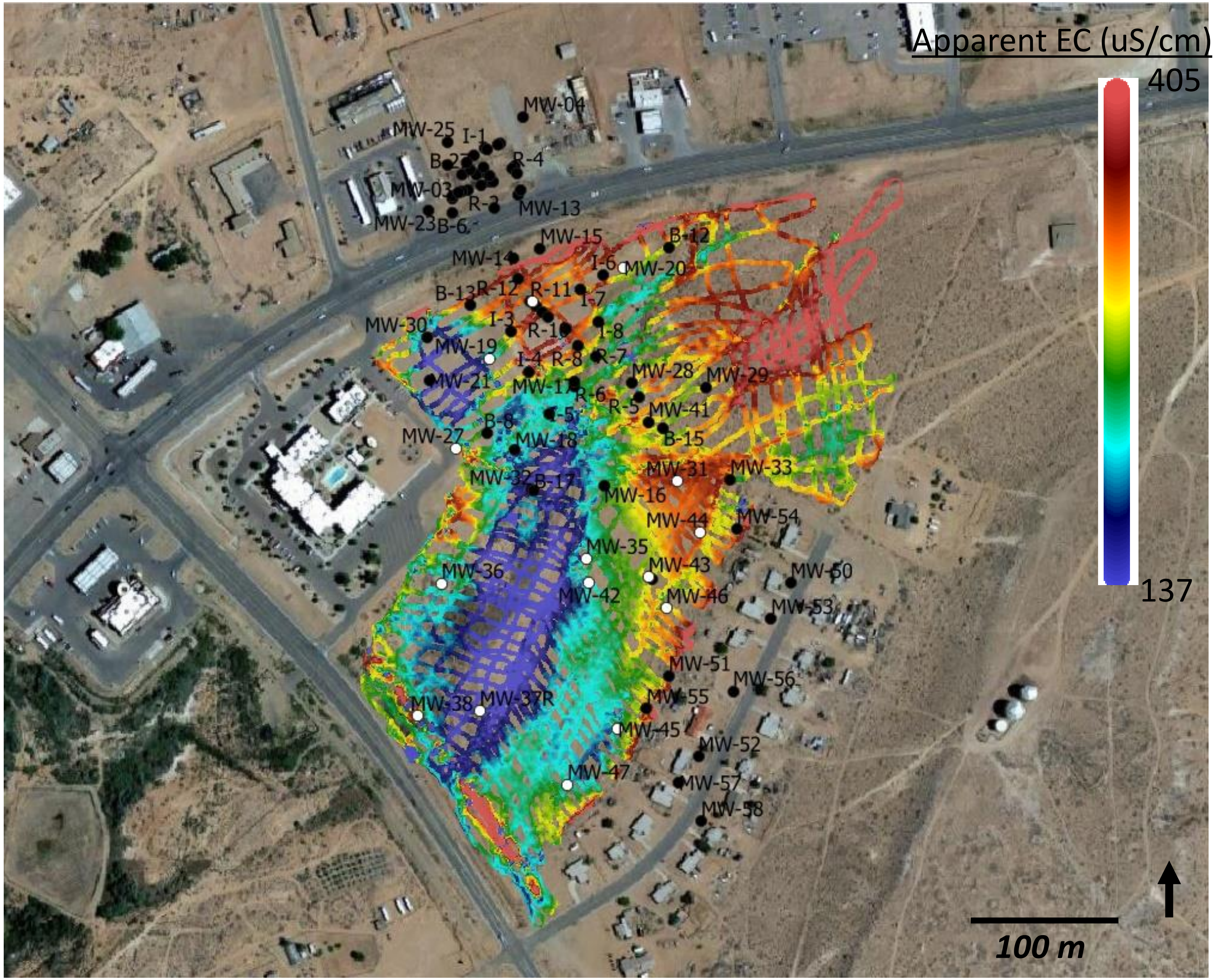
Tuba City 2022 data collection

Magnetic: G-858
FDEM: GEM-2 and DualEM
TDEM: WalkTEM
DC Resistivity: AGI Sting
GPR: Mala
HVSR: Tromino
Borehole: gamma, EMI, MS, Fluid SpC



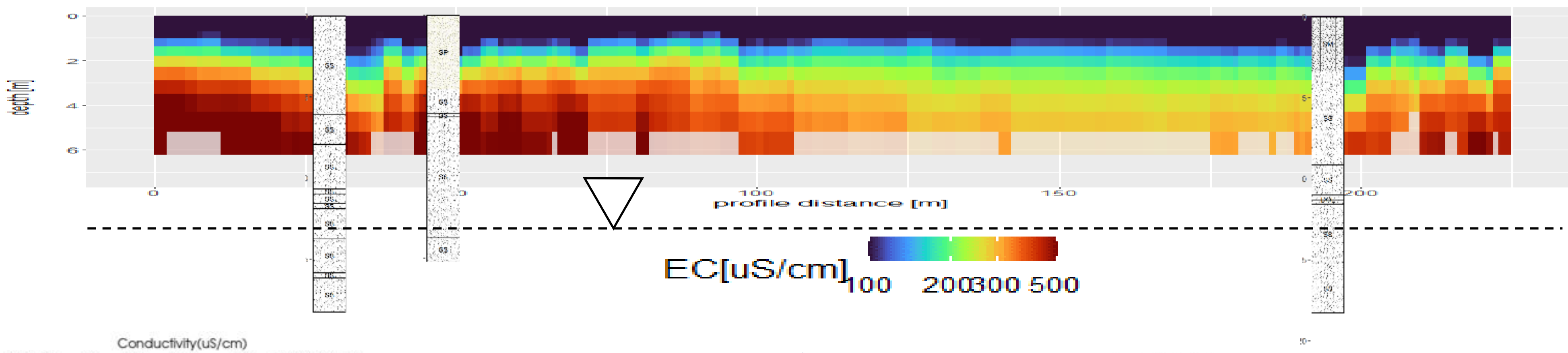
Tuba City 2022 data collection

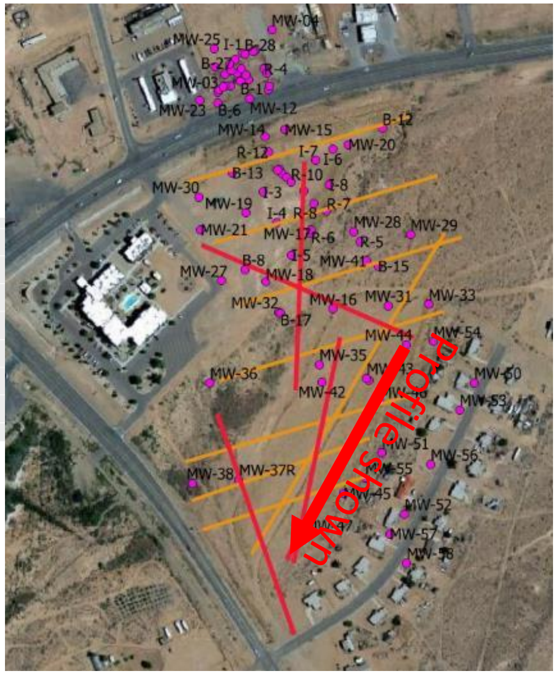
Raw DualEM apparent conductivity

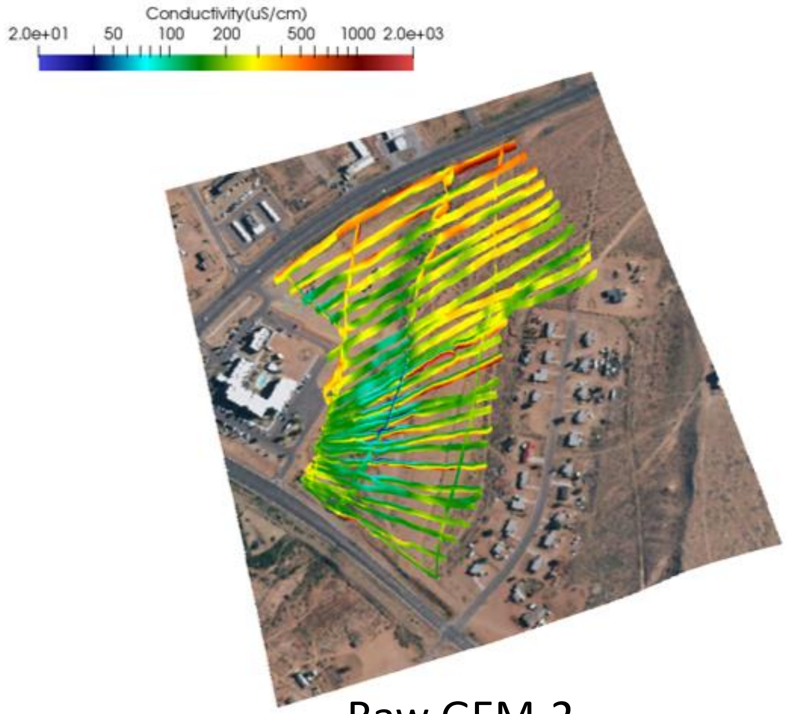


DualEM inversion result along ERT Line 1

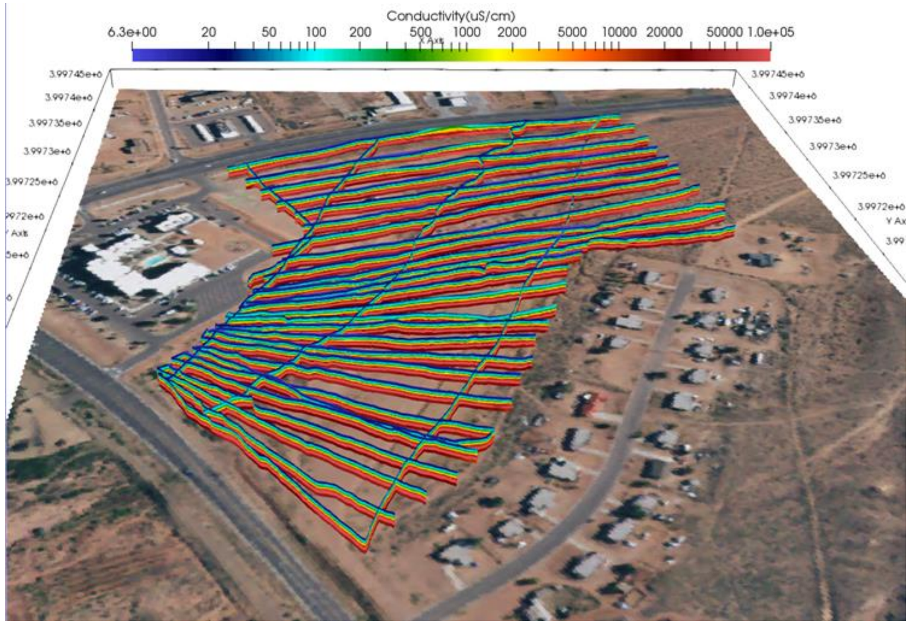
MW-43 MW-46 MW-47







Raw GEM-2

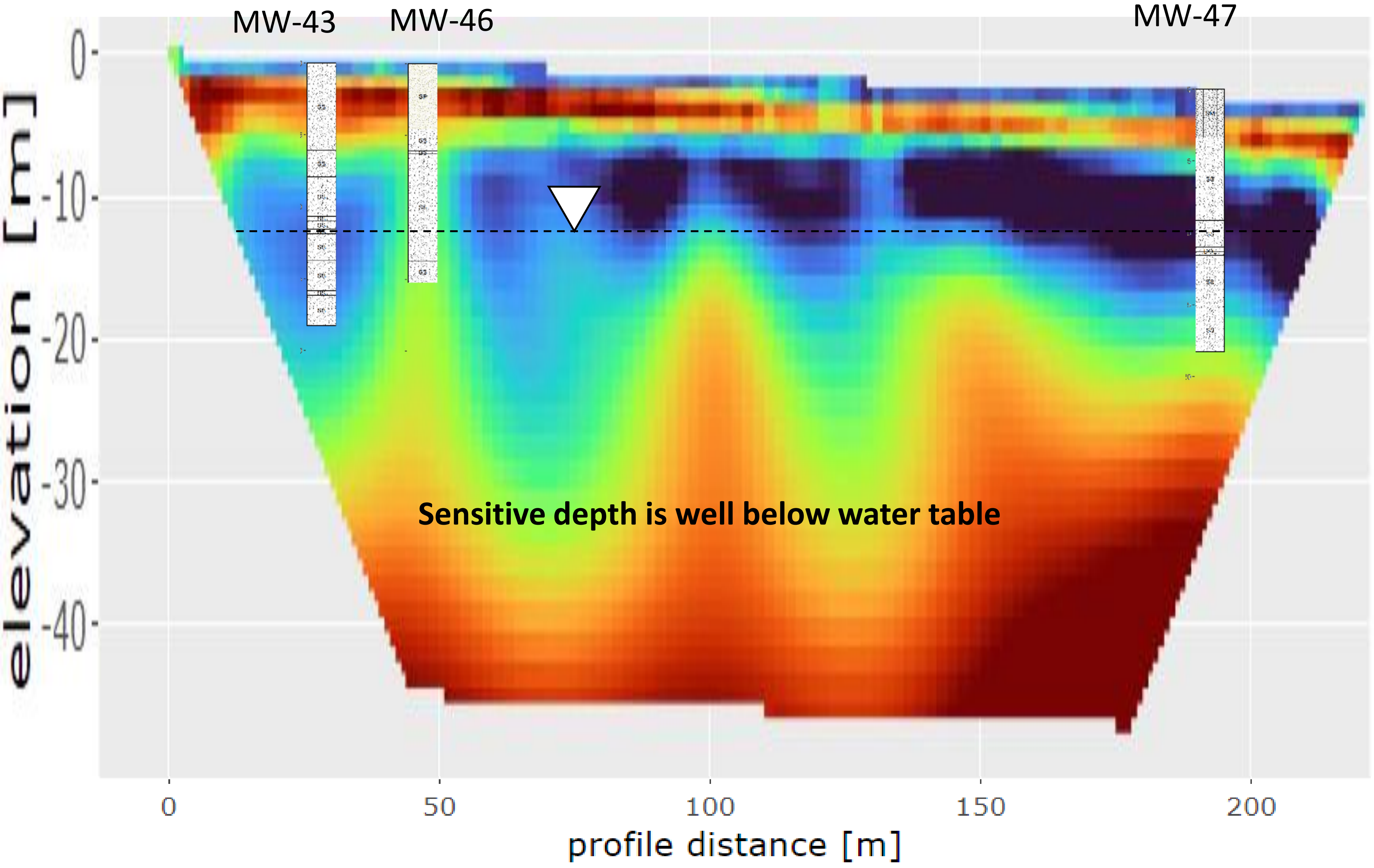


GEM-2 Inversion result

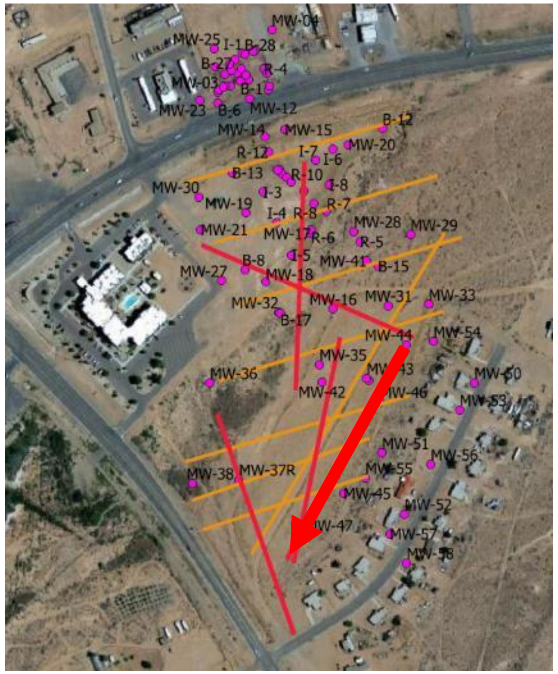
GEM-2 results

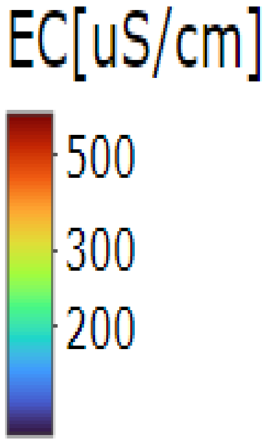
No info below the water table

ERT line 1



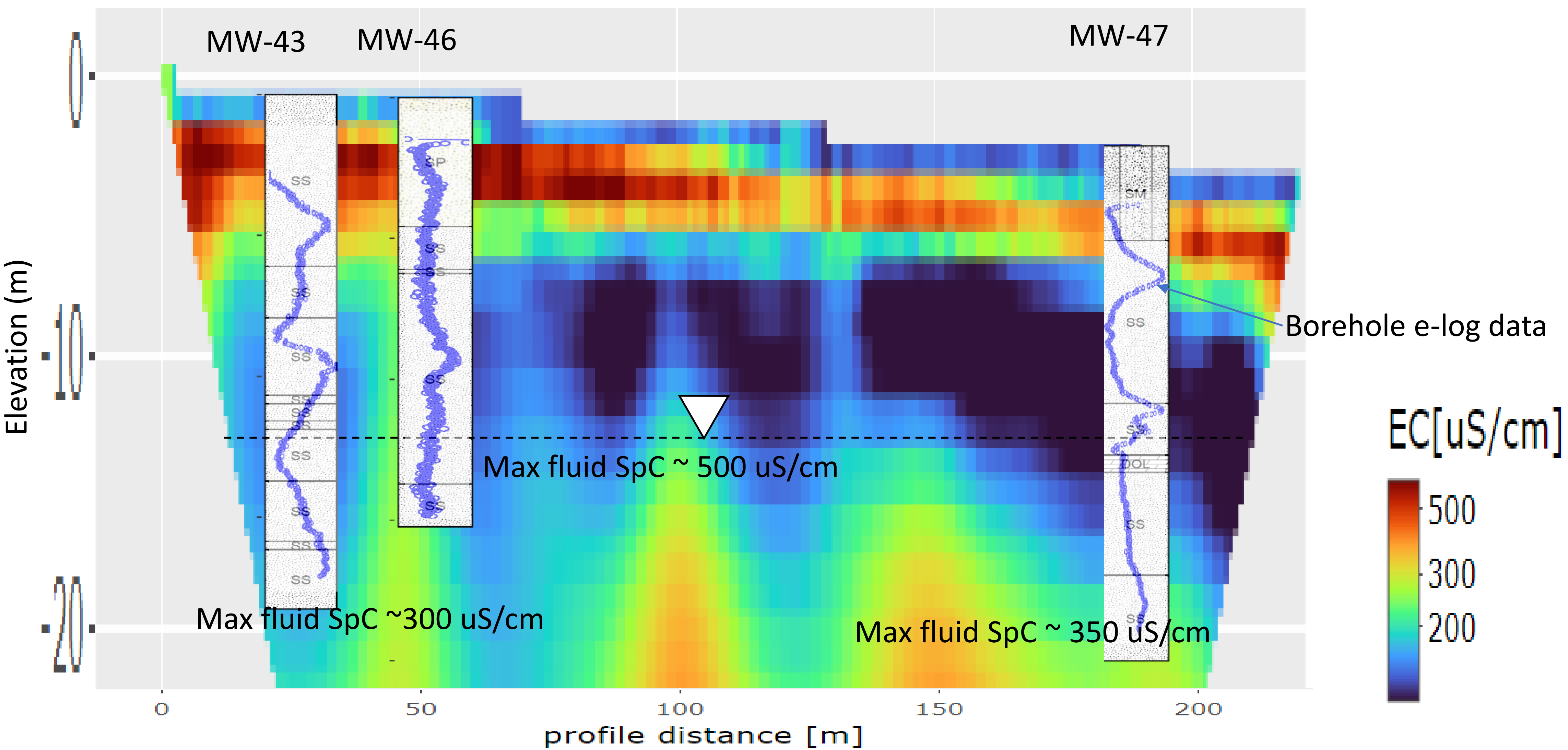
MW-43
MW-46
MW-47
Sensitive depth is well below water table
elevation [m]
0
-10
-20
-30
-40
profile distance [m]
0
50
100
150
200



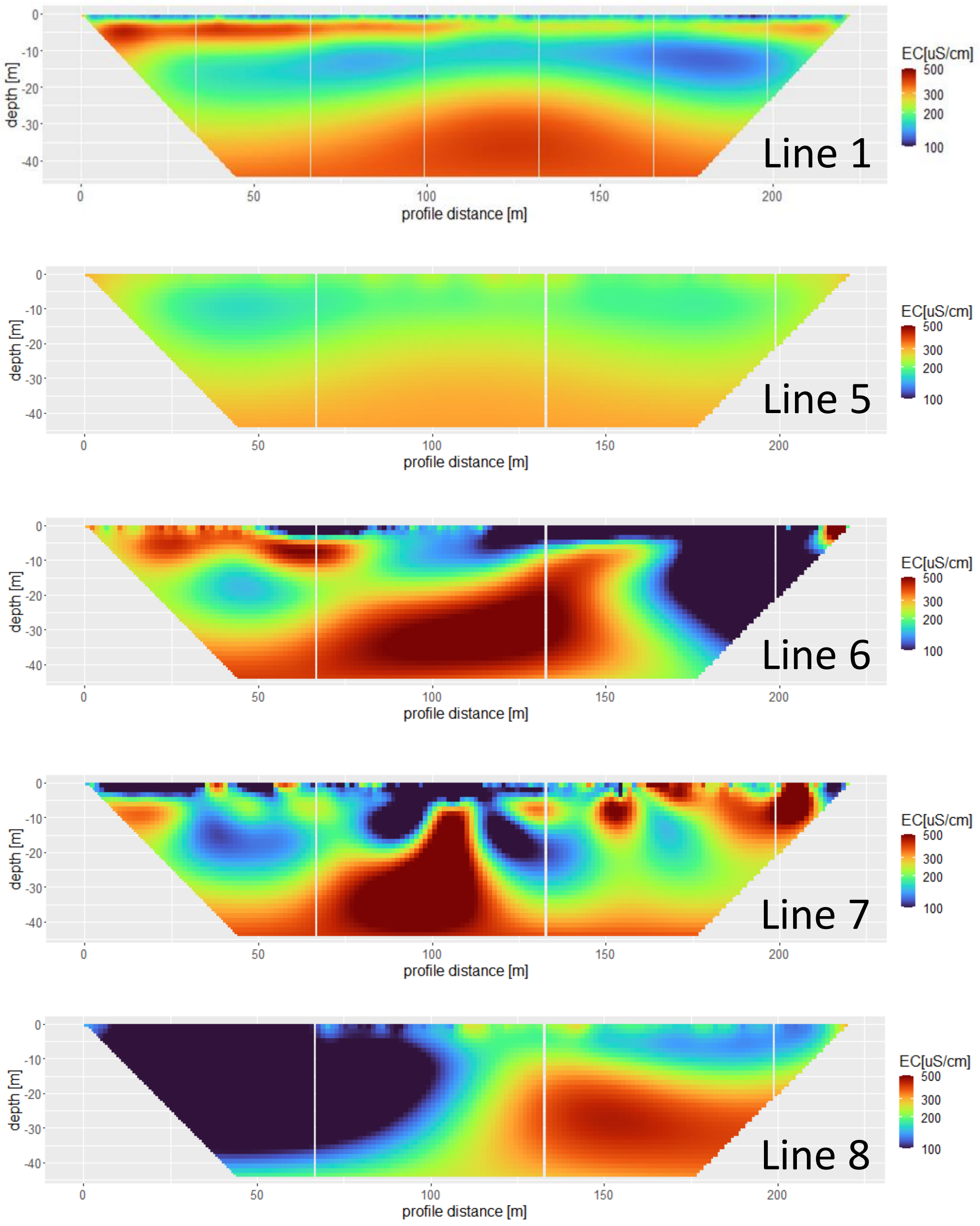


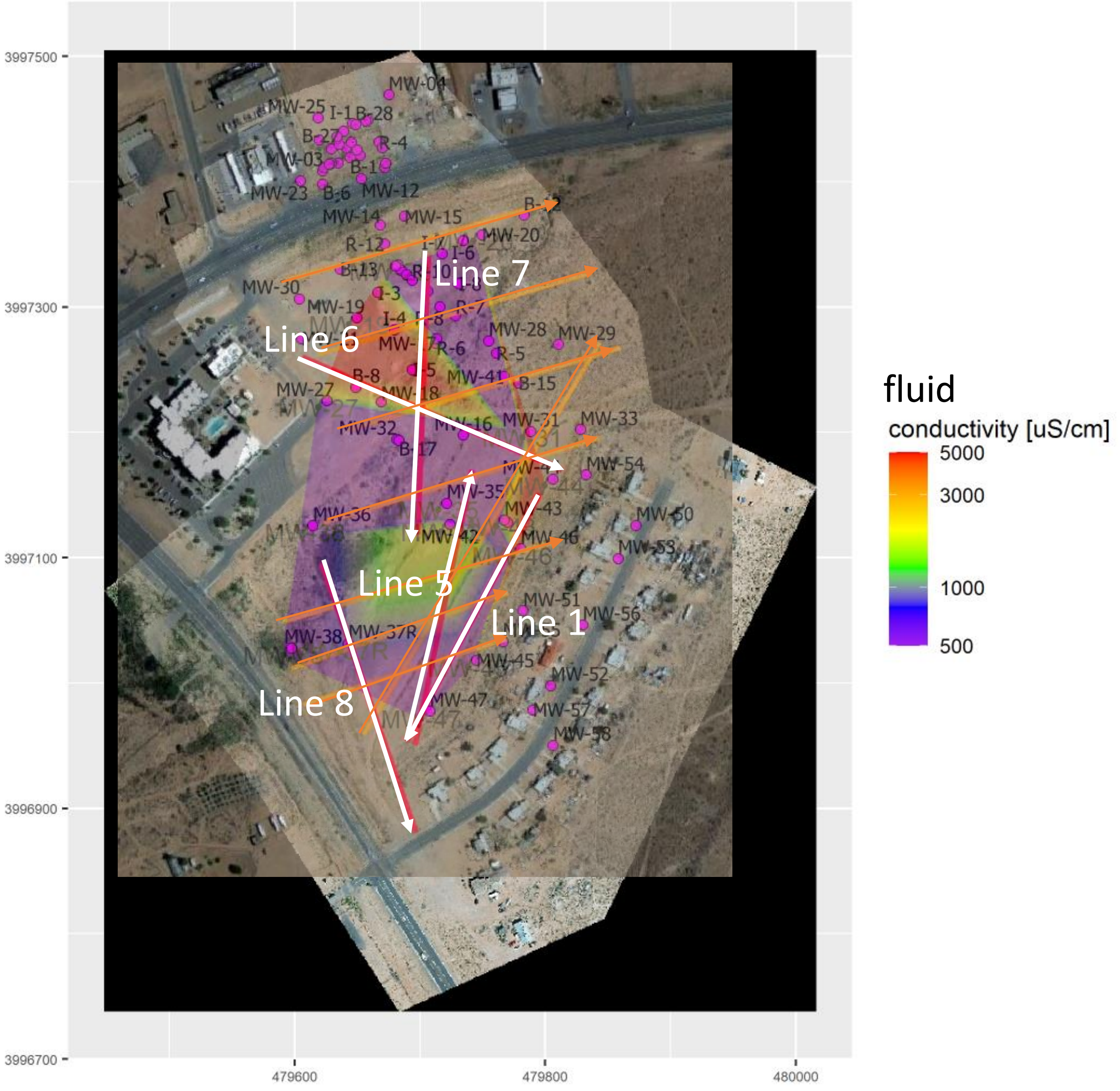
EC[uS/cm]
500
300
200

ERT line 1 (zoom)

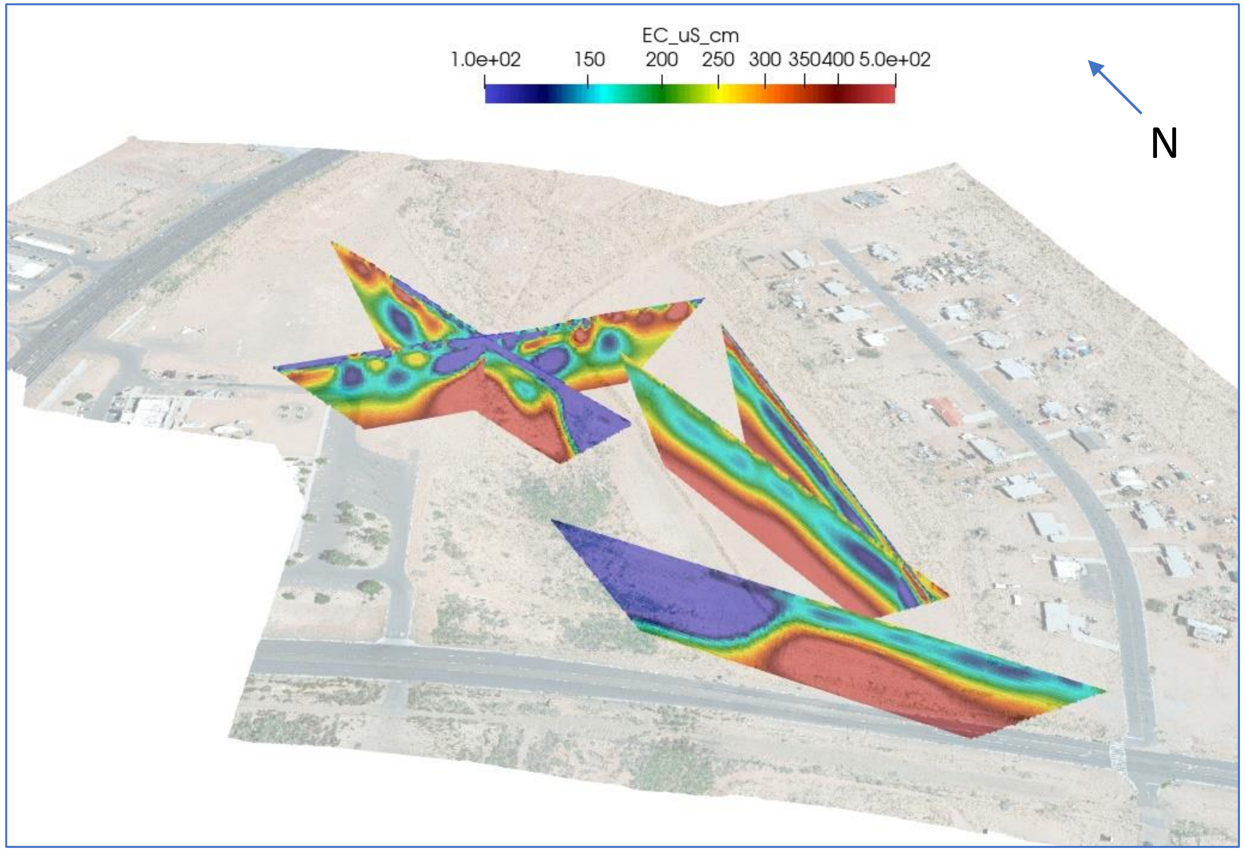


2022 ERT inversions

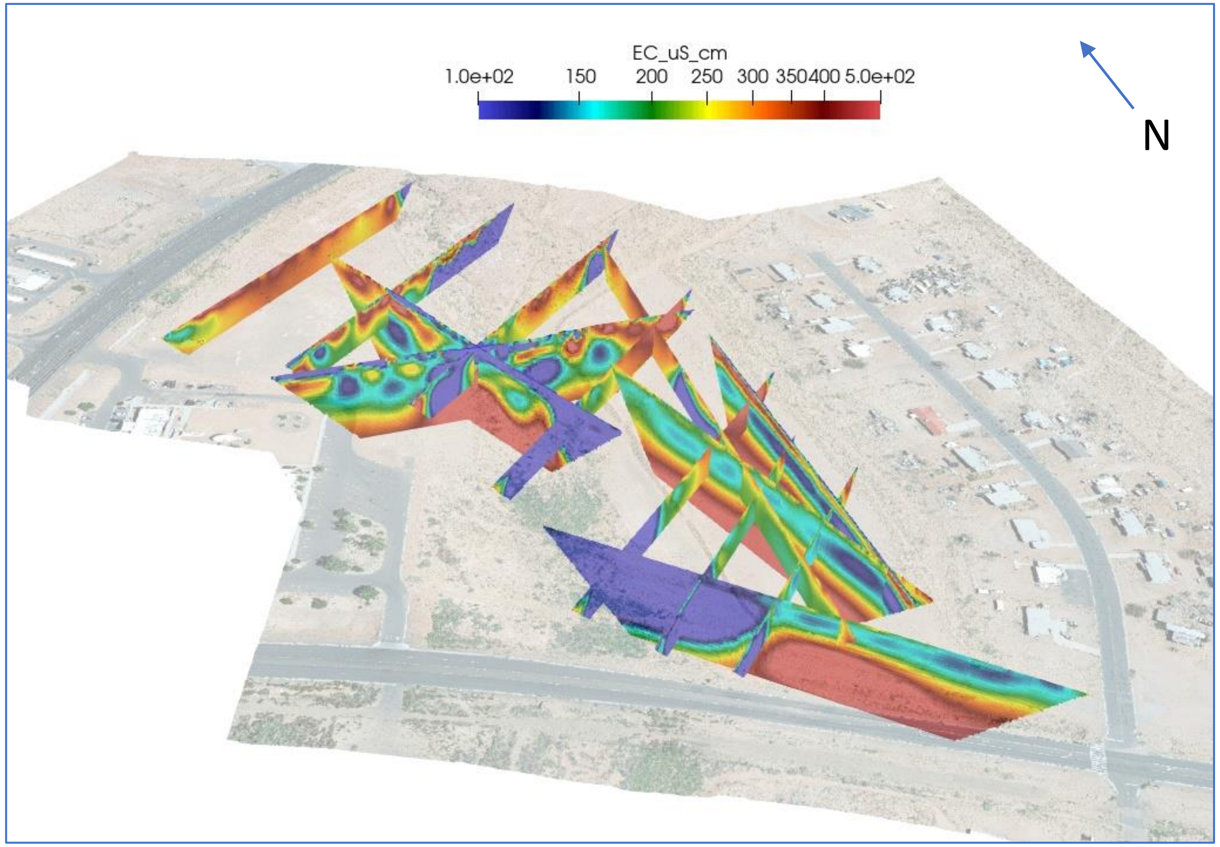




ERT all 2022 inversions

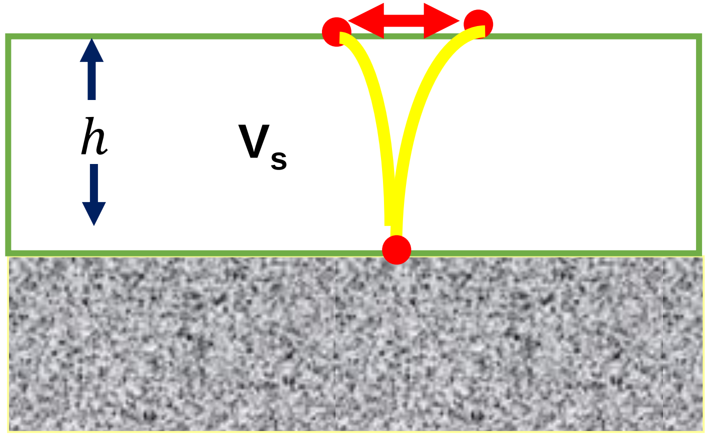


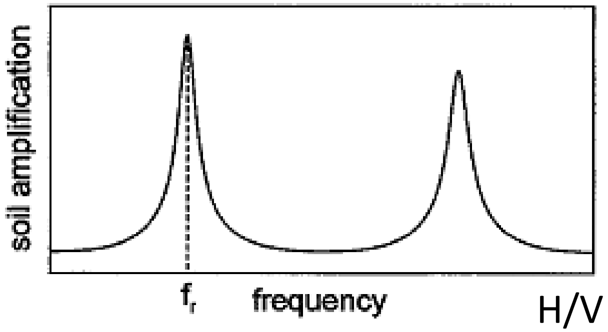
ERT 2022 inversions with previous ERT lines shown



Using the horizontal to vertical seismic ratio (HVSR) to map bedrock

Unconsolidated Sediments over Bedrock resonance model





$$f_r = V_s/4h$$

$$V_{s,avg} \approx 4hfr$$ **if thickness known**

Resonance Frequency Calculations

$$h_{min} \approx \frac{V_{s,surface}}{4fr}$$ **if surface Vs known**

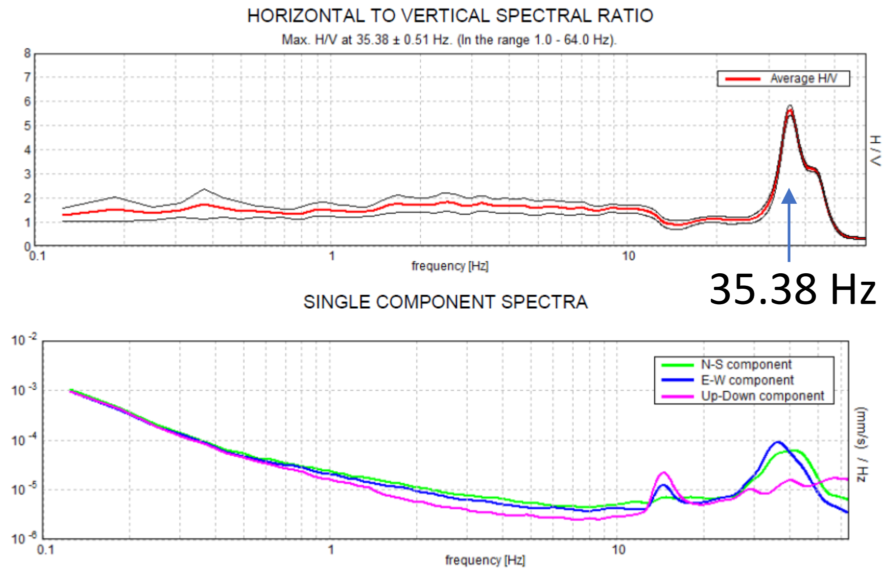
$$v_s = \sqrt{\frac{\mu}{\rho}}$$

ρ = density
μ = shear modulus

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

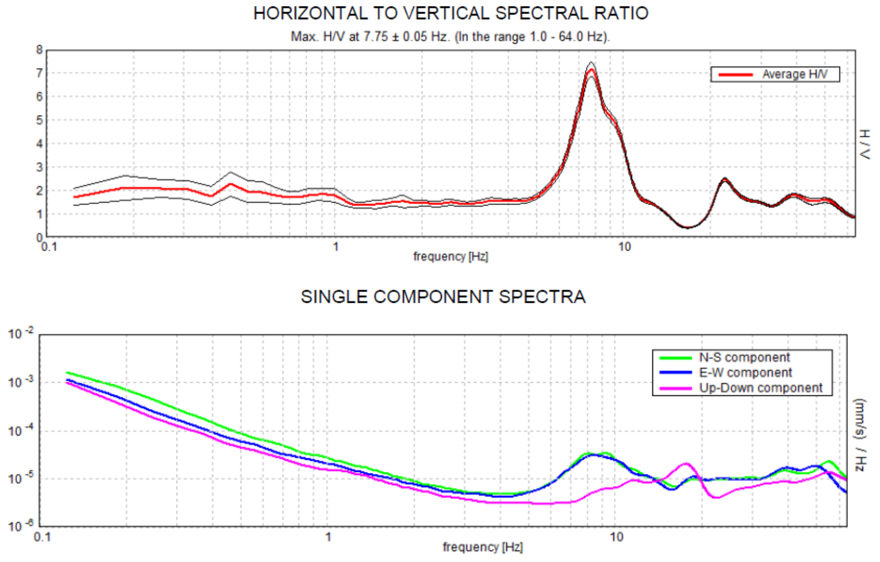
Koller, M.G., Chatelain, J-L., Guillier, B., Duval, A-M., Atakan, K., Lacave, C., Bard, P-Y., 2004, Practical user guidelines and software implementation of the H/V ratio technique: measuring conditions, processing method and results interpretation, *in* 13th World Conference on Earthquake Engineering, Vancouver.

Location A



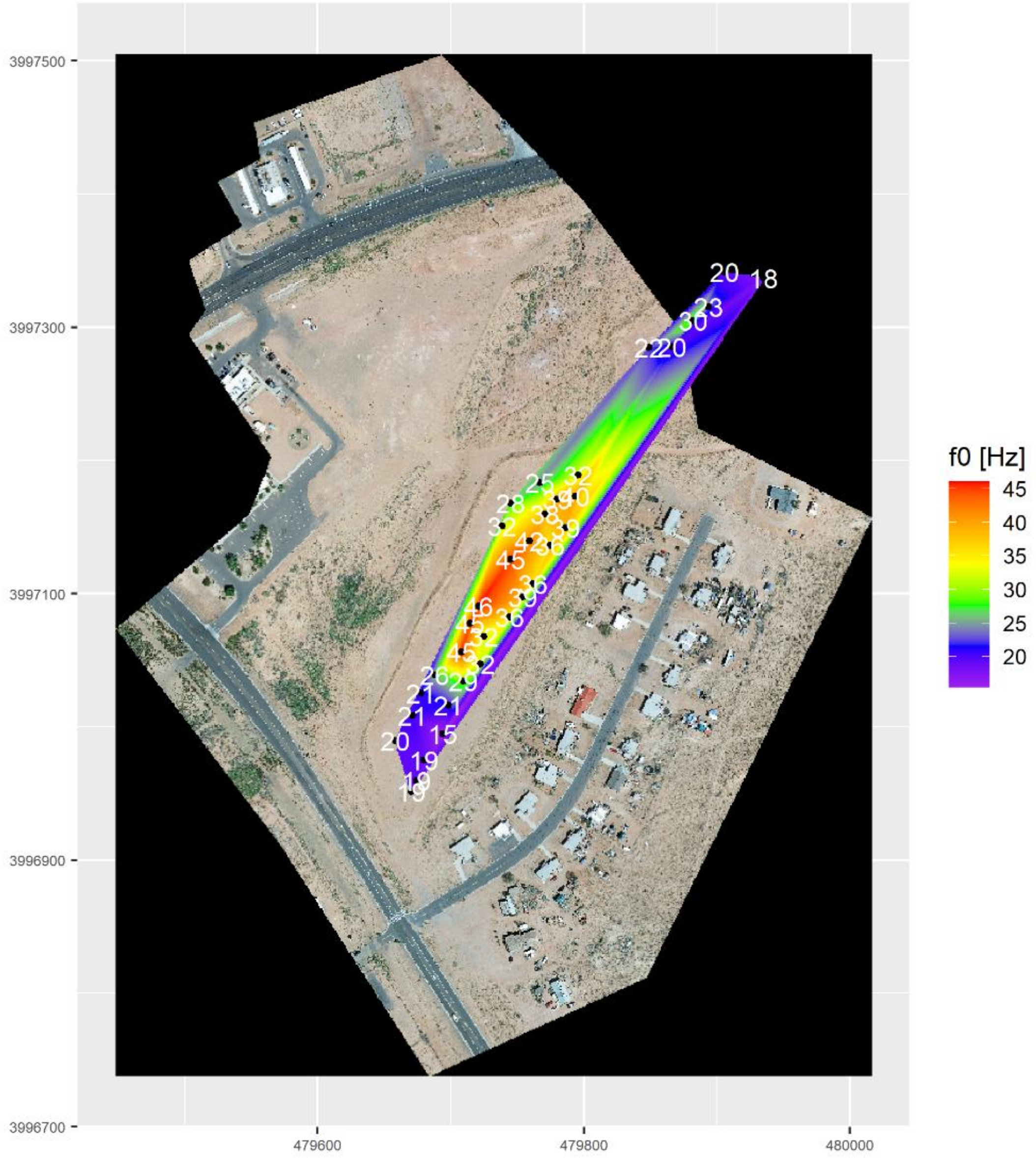
$Z = Vs/(4\ F_o) = 270/(4\ *35.4) = 1.9$ m

Location B



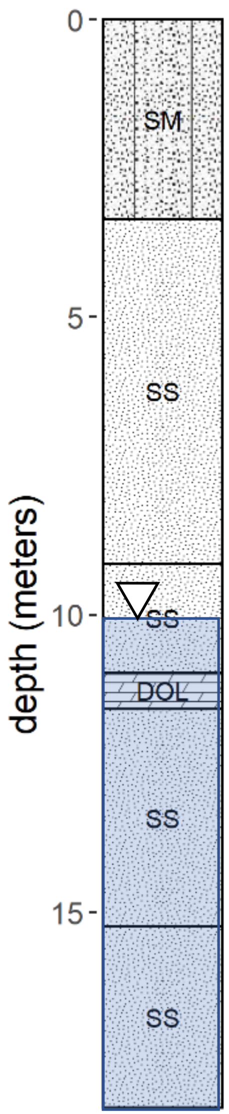
$Z = Vs/(4\ F_o) = 270/(4\ *7.75) = 8.7$ m

Interpolated HVSR



Interpolated HVSR with ERT profiles

TUBA: MW-47



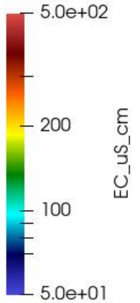
(SM) Silty sands

*

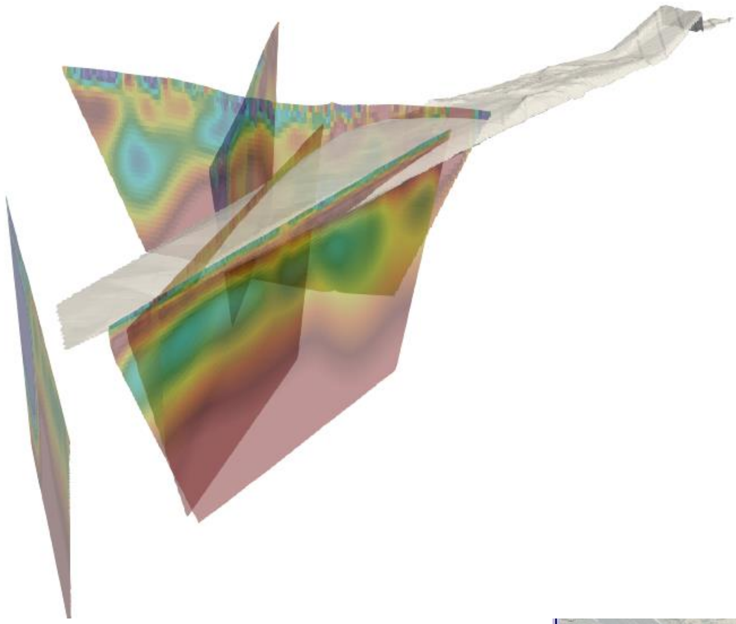
(SS) Sandstone

(DOL) Dolostone

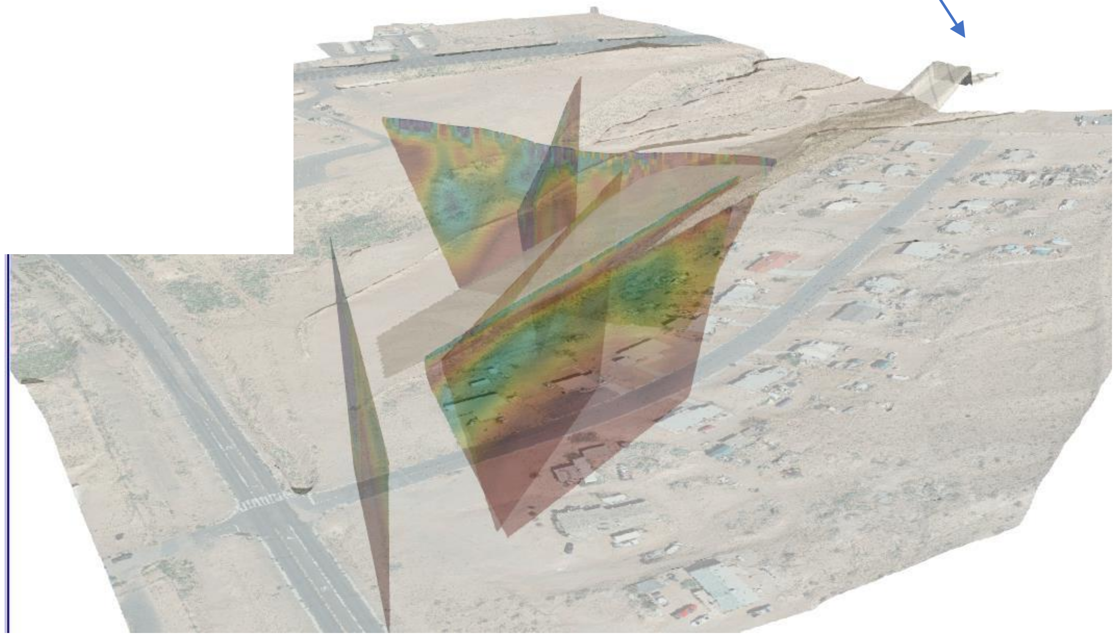
(SS) Sandstone



N



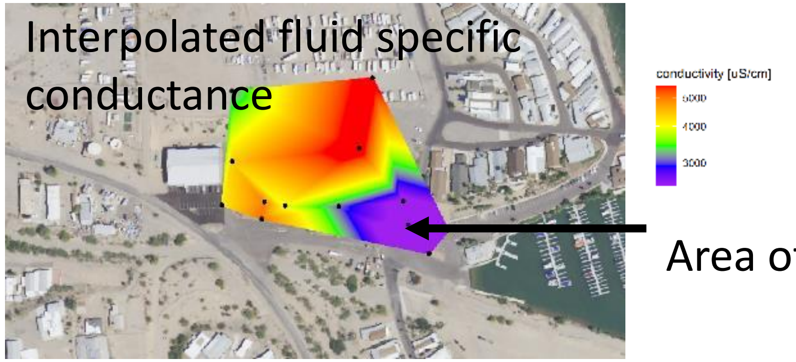
HVSR surface assuming 300 m/ns shear wave velocity

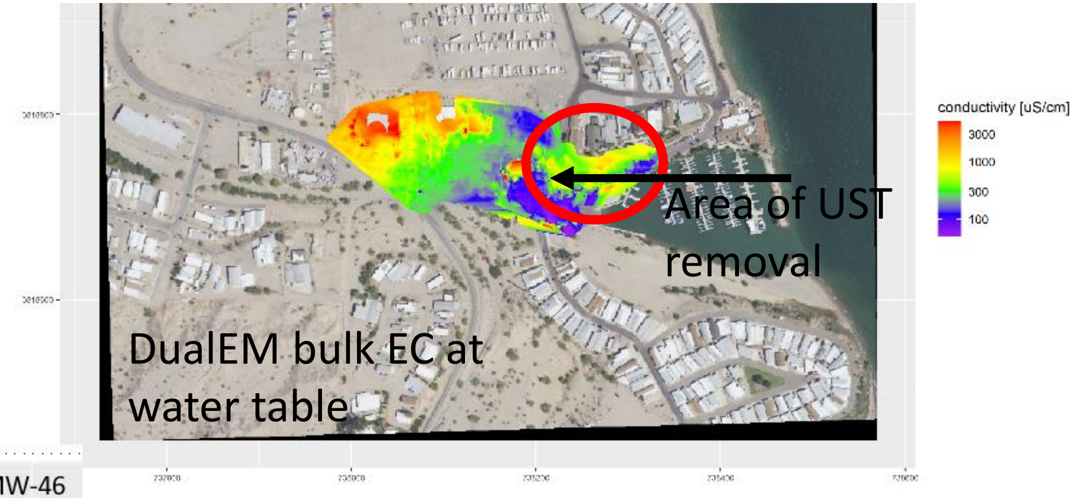


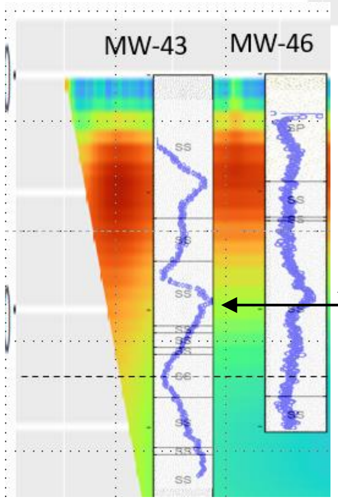
* Likely responding to the acoustic impedance between SM and SS

CSM Summary

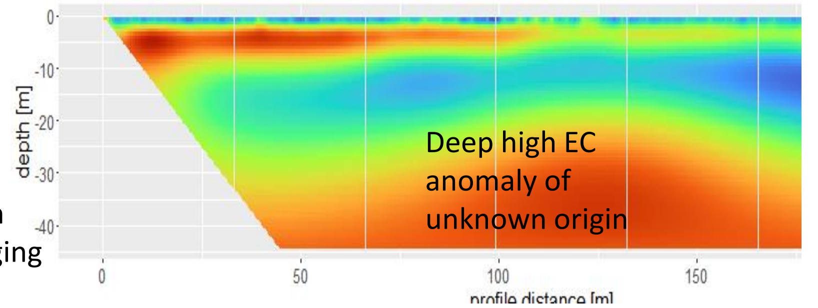
- Havasu Landing
  - FDEM seemingly shows sensitivity to both fine-grained materials and elevated groundwater SpC
  - Original spill site suggests relatively low groundwater SpC, yet high EC anomaly downgradient?
- Tuba City
  - Hand-carried FDEM has insufficient DOI
  - ERT performed well, with low contact resistances
    - Does not capture subtle dynamics suggested from borehole logs
    - Does see deeper high EC zone







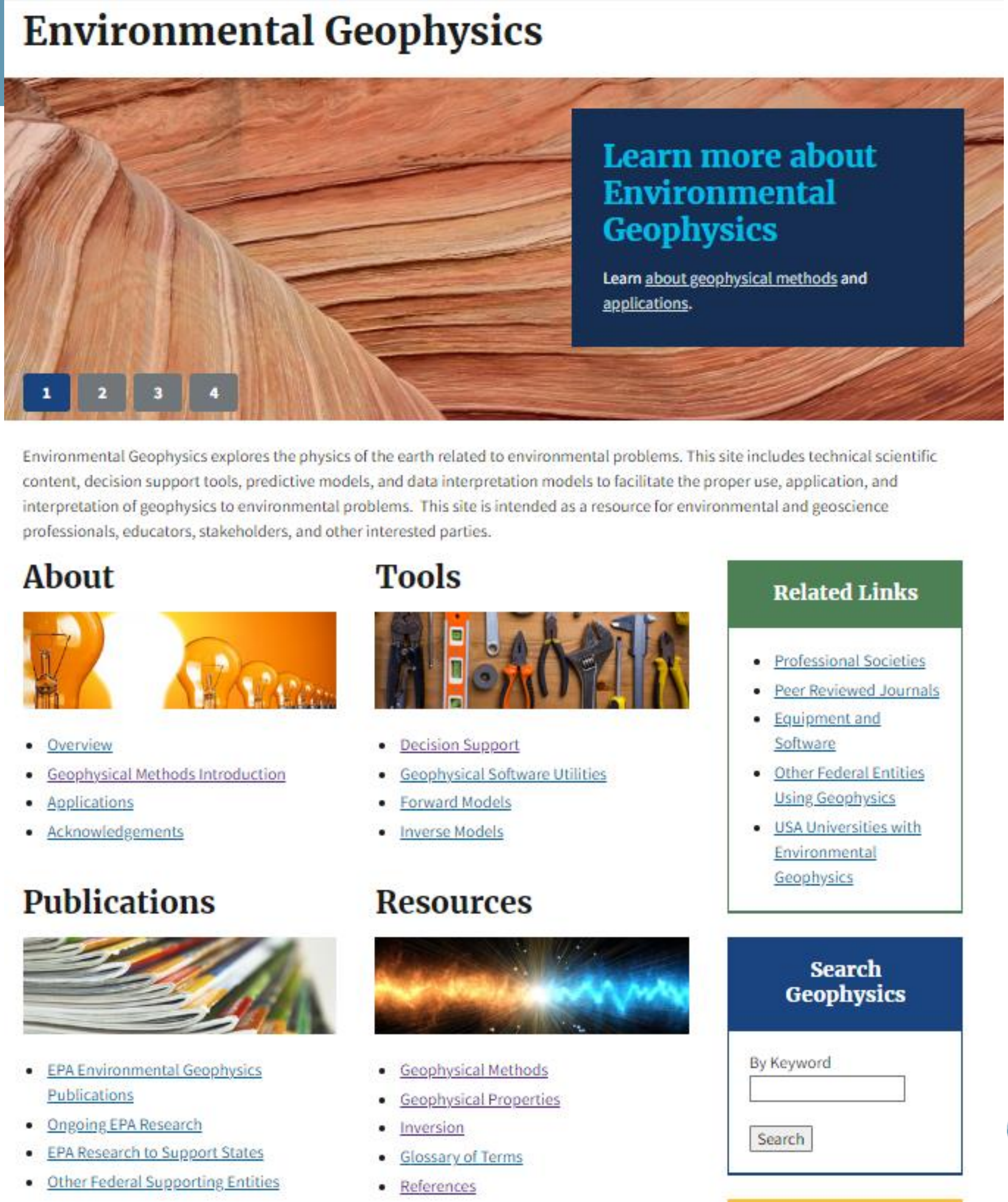
Subtle EC increases detected with borehole logging not seen in surface ERT



5. MODELS & DECISION SUPPORT

ONLINE RESOURCES

WEB SITE*



https://www.epa.gov/environmental-geophysics

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Environmental Geophysics

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Geophysical Methods

Geophysics is the study of earth through the collection and analysis of physical property measurements that are recorded at or near the ground surface. Thus, geophysical methods include a vast array of techniques that apply various principles of physics to investigate the physical properties of the subsurface.

Geophysical methods can be broadly categorized by the environment in which they are applied: on the earth surface, within a borehole/well, or on a surface waterbody. Each environmentally dependent category (i.e., surface-, borehole-, and waterborne- geophysics) can be further subdivided according to the underlying physics employed within the methodology.

The discussions linked below introduce the general theories and applications of the method type and provide a list of commonly employed geophysical methods. Each individual method that is listed is also linked to information, examples, and references for further review.

- Surface Geophysical Methods
- Borehole Geophysical Methods
- Waterborne Geophysical Methods

The remaining portion of this online textbook covers topics that are useful in developing a more comprehensive awareness for the use of these methods. Such topics include: the inversion approaches used to process and analyze the data, geophysical properties involved in the methodology, a glossary of terms, and a list of environmental geophysics references.

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References

Last Updated: 5-11-2022

The following searchable table includes mostly applied environmental geophysics papers, reports, and other relevant publicly available documents. This table is not all inclusive, but a potential starting point or additional source of information. The table is sortable by column heading and searchable. For instance, typing DNAPL, mine waste, or mapping, will cull items with that term in the title, keyword, abstract, or publication information. Search results are exportable in the formats shown. Clicking the green plus button by the title expands the abstract, if available.

Save current page | Excel | CSV | PDF | Show 10 entries

Search:

Title	Author	Year
Time-lapse electrical resistivity tomography (ERT) monitoring of used engine oil contamination in laboratory setting	Mohammed Nazifi, Hafiz et. al.	2022
Performance of geophysical methods in determining fault zone at Darakeh Area (Tehran Province; Iran)	Jahanbin, Mohsen et. al.	2022
Magnetic response of urban topsoil to land use type in Shanghai and its relationship with city gross domestic product	Wang, Guan et. al.	2022
Simultaneous inversion of spectral IP data with frequency constraints	Kim, Bitnarae et. al.	2022
4D inversion of resistivity monitoring data with adaptive time domain regularization	Cho and Jeong	2022
Pedoenvironmental variations assessment using magnetic susceptibility in Lut Watershed, Central Iran	Rasooli, Najmeh et. al.	2022
An integrated model to optimize irrigation amount and time in shallow groundwater area under drought conditions	Zhang, Xiaoxing et. al.	2022
Refrapy: A Python program for seismic refraction data analysis	Guedes, Victor José Cavalcanti Bezerra et. al.	2022
Detecting the ground-dependent structural damages in a historic mosque by employing GPR	Işık, Nursen et. al.	2022
Rapid 3D geophysical imaging of aquifers in diverse hydrogeological settings	Chandra and Tiwari	2022

Showing 1 to 10 of 807 entries

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5. Models & Decision Support

ONLINE RESOURCES

Environmental Geophysics CONTACT US

- Environmental Geophysics Home
- About Environmental Geophysics
- Decision Support
- Geophysical Software Utilities
- Forward Models
- Inverse Models
- Geophysical Methods
  - Surface Geophysical Methods
  - Borehole Geophysical Methods
  - Waterborne Geophysical Methods
- Geophysical Properties
  - Density
  - Porosity
- Inversion
- References

Decision Support

The following resources are available to support decisions on the application of geophysical methods to environmental investigations.

- Fractured Rock Geophysical Toolbox Method Selection Tool (FRGT-MST EXIT) is an Excel-based tool, developed in collaboration with the USGS, that is used for the identification of geophysical methods most likely applicable for investigations in fractured rock settings.
- Groundwater – Surface Water Method Selection Tool (GWSW-MST EXIT) is an Excel-based tool, developed in collaboration with the USGS, that is used to determine which field methods and approaches are best suited for groundwater – surface water investigations.

For more information:

- FRGT-MST EXIT
- GWSW-MST EXIT

Environmental Geophysics CONTACT US

- Environmental Geophysics Home
- About Environmental Geophysics
- Decision Support
- Geophysical Software Utilities
- Forward Models
- Inverse Models
- Geophysical Methods
  - Surface Geophysical Methods
  - Borehole Geophysical Methods

Geophysics Software Utilities

Several free and downloadable Utilities are listed below.

Electromagnetic Induction (EMI) Skin Depth and Depth of Investigation (DOI) calculator EM Skin Depth and DOI Estimator (xlsx) . This application enables the calculation of the DOI below the ground surface when performing electromagnetic induction surveys. The DOI calculator allows the input of parameters to approximate the depth of signal penetration to determine how deep an EMI investigation will image subsurface electromagnetic properties.

Archie's Law calculator Archies Law Estimator (xlsx) . The Archie's Law calculator enables the user to estimate Archie parameters (e.g., fluid conductivity, formation factor, and porosity) when performing an electrical resistivity survey.

DTSGUI EXIT is a public-domain software tool to import, manage, parse/cull, georefence, analyze, and visualize fiber-optic distributed temperature sensor (FO-DTS) data.

These Utilities are for instructional and demonstrational purposes only. EPA does not endorse their use or validate results generated from these calculators. Use at your own risk.

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- Geophysics
- mental
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- ethods
- hysical

Forward Models

Forward models are predictive models that can help answer the question: what if? For instance, forward models can predict the geophysical response given some known or assumed information about a site, such as its geology, hydrogeology, and/or contaminant distribution.

Forward models can also be used to virtually experiment with field acquisition parameters to not only simulate the geophysical response but to also simulate what acquisition parameters will achieve the objectives on the investigation.

Forward models are specific for each geophysical method (or t

- Scenario Evaluator for Electrical Resistivity (SEER) EXIT

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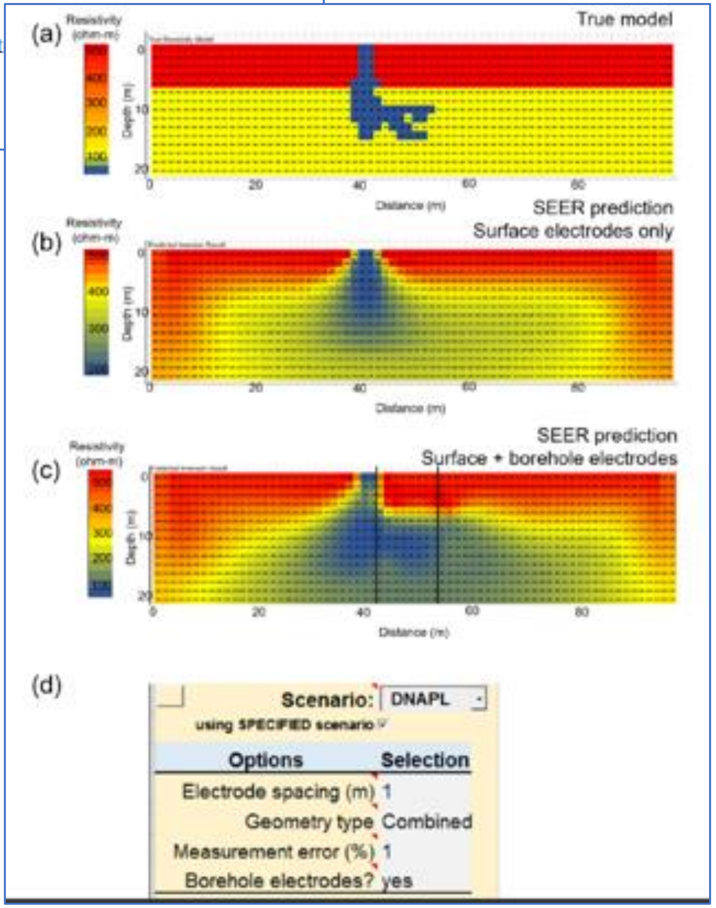
- Environmental Geophysics Home
- About Environmental Geophysics
- Decision Support
- Geophysical Software Utilities
- Forward Models
- **Inverse Models**

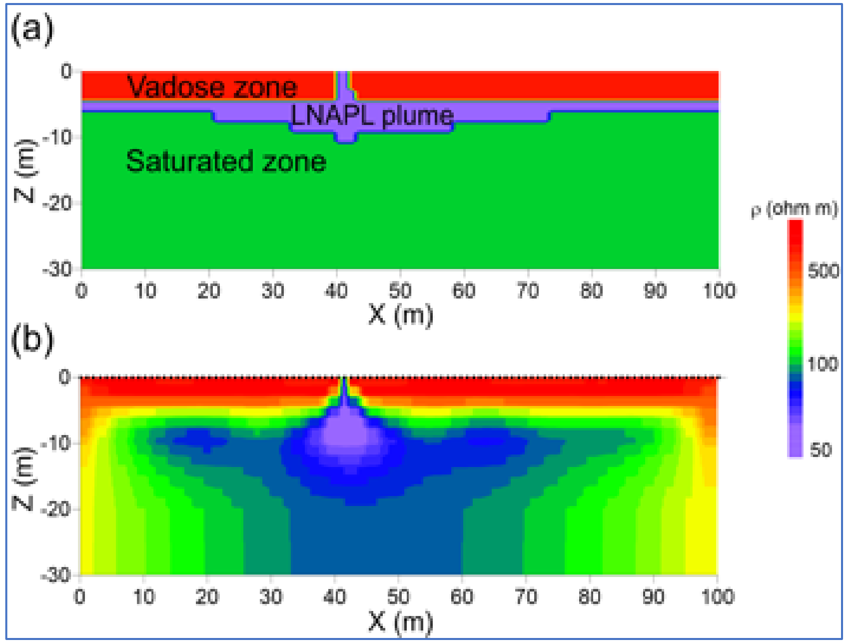
Inverse Models

Inverse models convert geophysical data to physical properties. The following were developed in collaboration with the USGS.

- MoistureEC EXIT: R-based Graphical User Interface (GUI) to combine electrical conductivity data with point moisture measurements.
- 1DTempPro EXIT: A program for analysis of vertical one-dimensional (1D) temperature profiles.

SEER – Scenario Evaluator for Electrical Resistivity





(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

* web site pending agency approval

Concluding Thoughts

Geophysical methods are part of the site investigator’s toolbox.

1. Find Underground Storage Tanks
2. Direct detection of some contaminants
3. Passive and active remediation
4. CSM development
5. 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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    - *UNLV:* Meghan Magill, Nihad Rajabdeen
    - *Rutgers*: Jeff Heenan, Yves Robert-Personna,
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