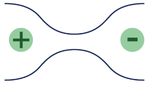
Induced Polarization

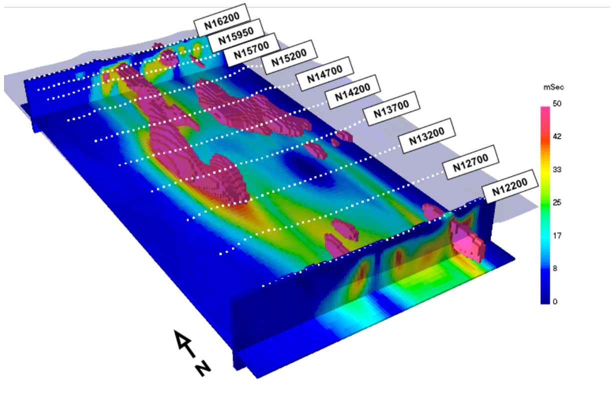
DISC 2017

Electromagnetics
Fundamentals and Applications

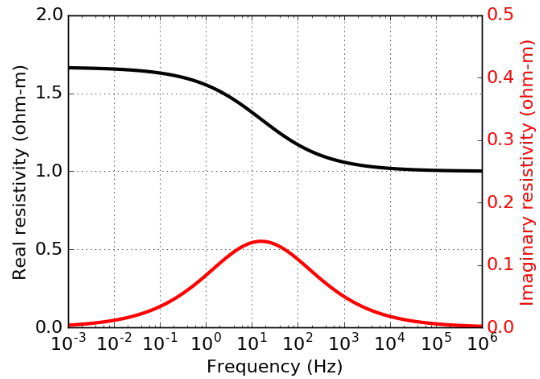


Motivation

Minerals

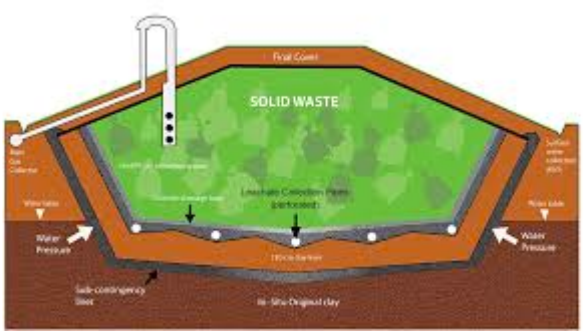


Complex resistivity

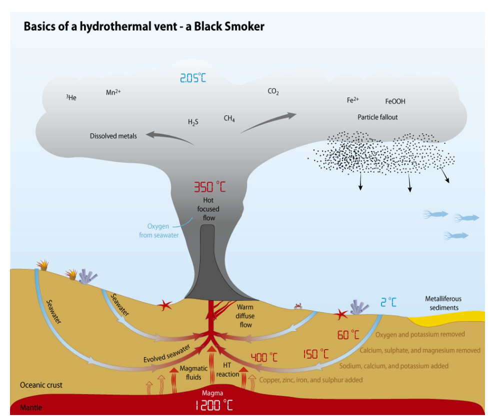


Permafrost

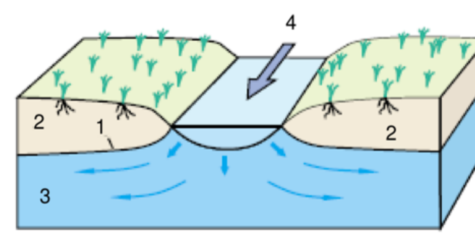
Geotechnical



Seafloor massive sulfide



Groundwater

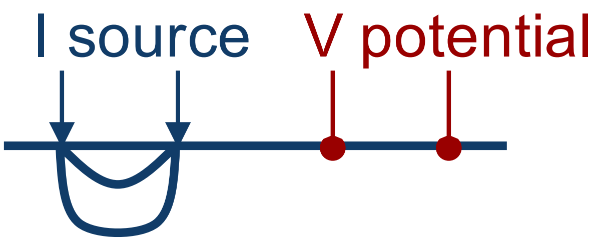


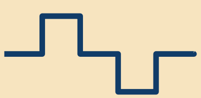
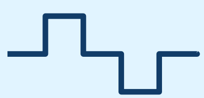
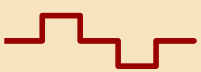
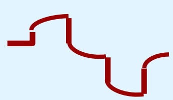
Outline

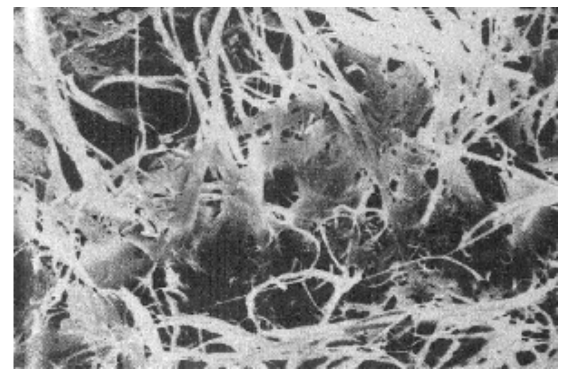
- Sources of IP
- Conceptual model of IP
- Chargeability
- IP data
- Pseudosections
- Two stage DC-IP inversion
- Case history: Mt. Isa
- Example: Landfills

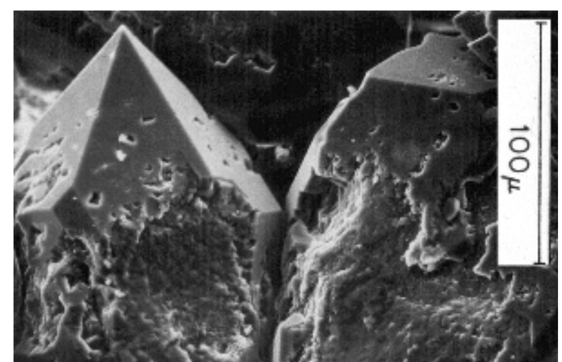
Induced Polarization

- Injected currents cause materials to become polarized
- Microscopic causes → macroscopic effect
- Phenomenon is called induced polarization



	Not chargeable	Chargeable
Source (Amps)		
Potential (Volts)		

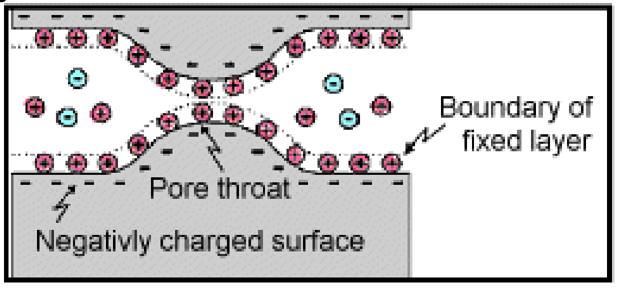




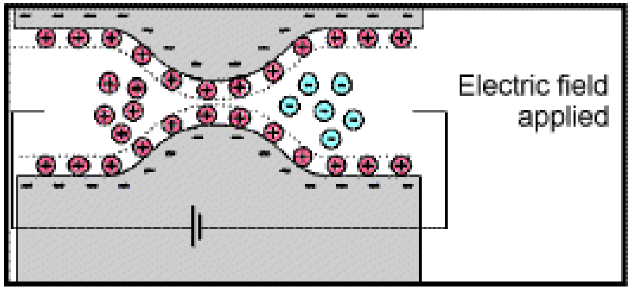
Conceptual Model of IP

Membrane polarization

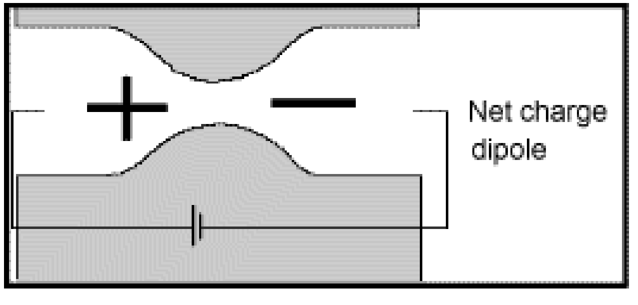
Initially - neutral



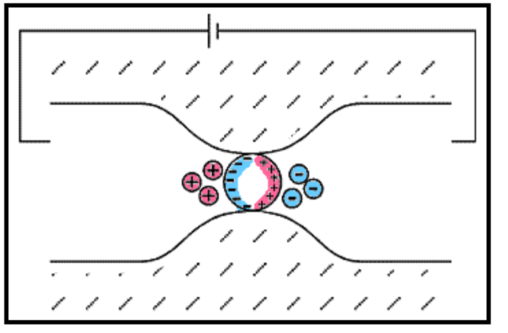
Apply electric field, build up charges

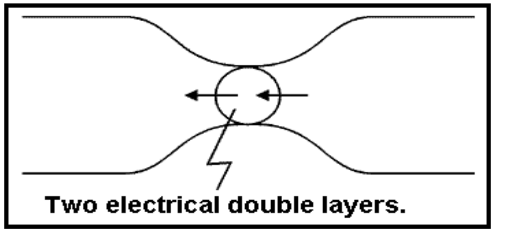


Charge polarization, Electric dipole



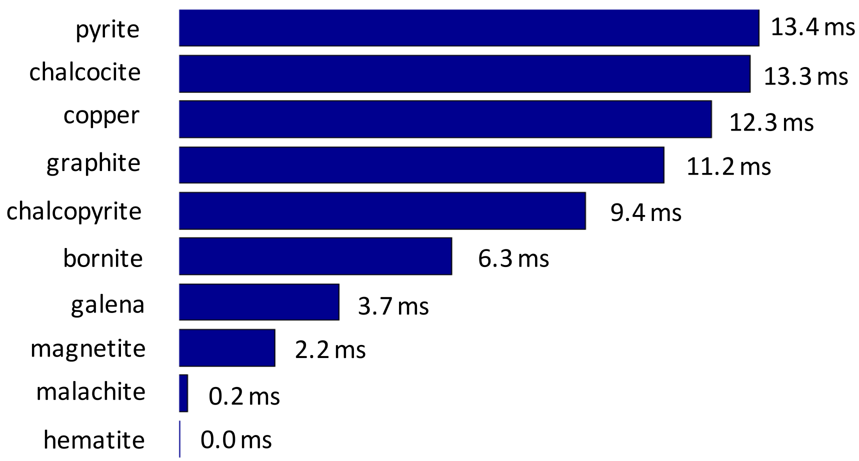
Electrode polarization





Chargeability

Minerals at 1% Concentration in Samples

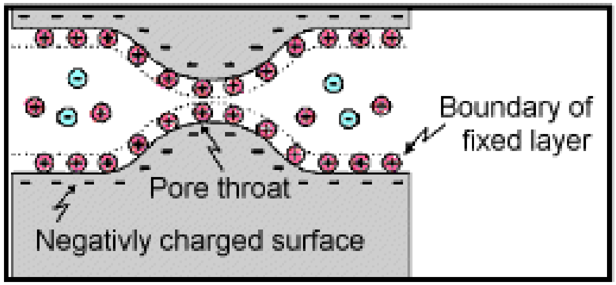


Material type	Chargeability (msec.)
20% sulfides	2000 - 3000
8-20% sulfides	1000 - 2000
2-8% sulfides	500 - 1000
volcanic tuffs	300 - 800
sandstone, siltstone	100 - 500
dense volcanic rocks	100 - 500
shale	50 - 100
granite, granodiorite	10 - 50
limestone, dolomite	10 - 20

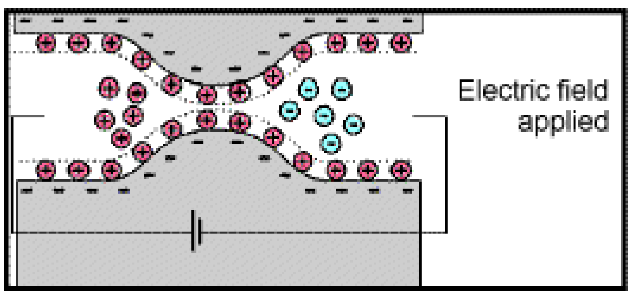
Material type	Chargeability (msec.)
ground water	0
alluvium	1 - 4
gravels	3 - 9
precambrian volcanics	8 - 20
precambrian gneisses	6 - 30
schists	5 - 20
sandstones	3 - 12

Chargeability

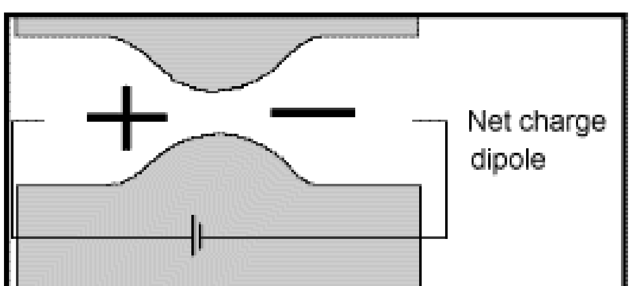
Initially - neutral



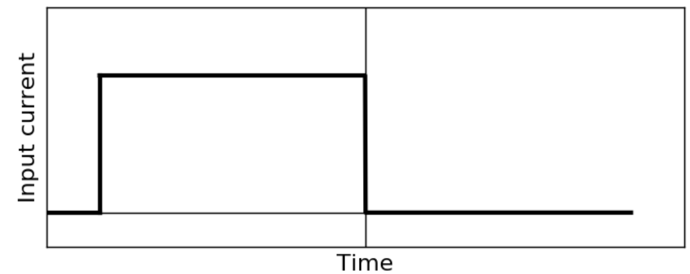
Apply electric field, build up charges



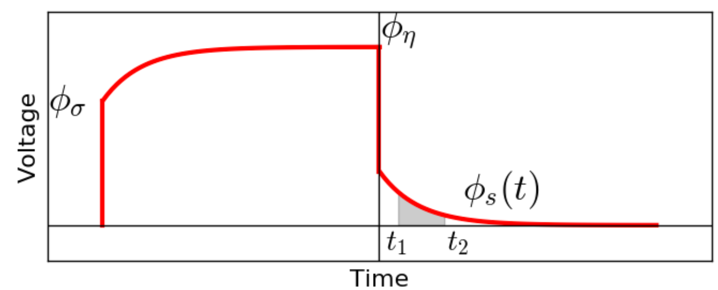
Charge polarization, Electric dipole



Input current



Measured voltage



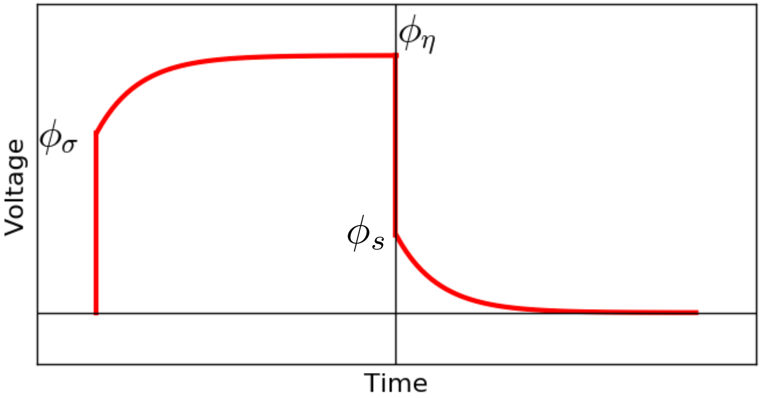
IP data

- Seigel (1959):
  - Introduced chargeability: η
  - Effect reduces conductivity

$$\sigma_\eta = \sigma(1 - \eta) \qquad \eta \in [0, 1)$$

- Theoretical chargeability data

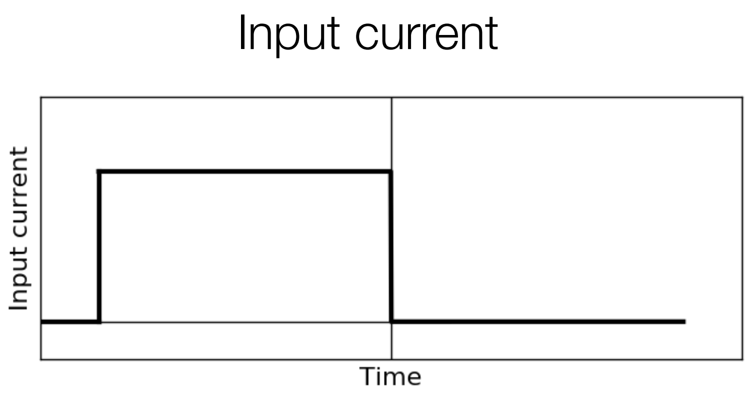
$$d^{IP} = \frac{\phi_s}{\phi_\eta} = \frac{\phi_\eta - \phi_\sigma}{\phi_\eta}$$

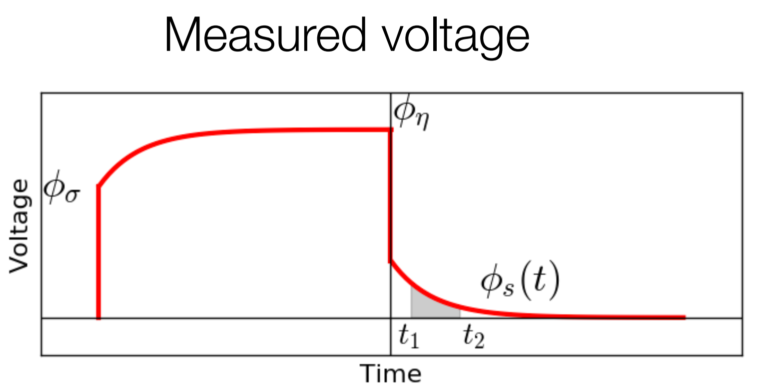


- Not directly measureable

IP data: time domain

- IP decay





- IP datum

Dimensionless: $\eta = \phi_s / \phi_\eta$

Value at individual time channel: $\phi_s(t)$

Area under decay curve: $M = \frac{1}{\phi_\eta} \int_{t_1}^{t_2} \phi_s(t) dt$

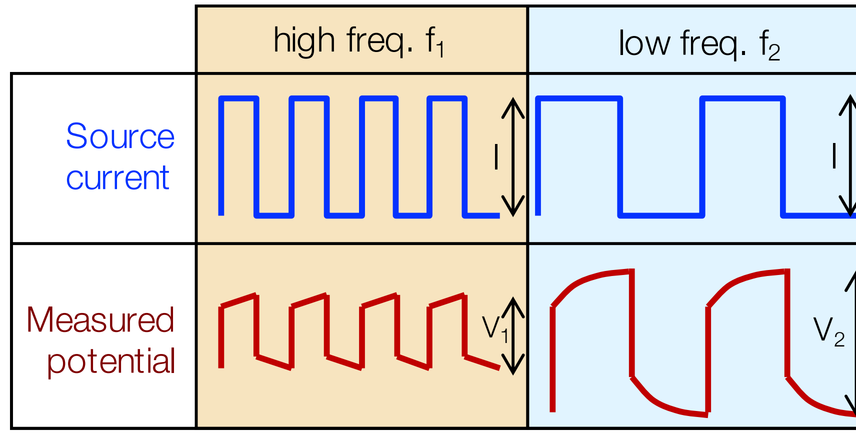
IP data: frequency domain

- Percent frequency effect:

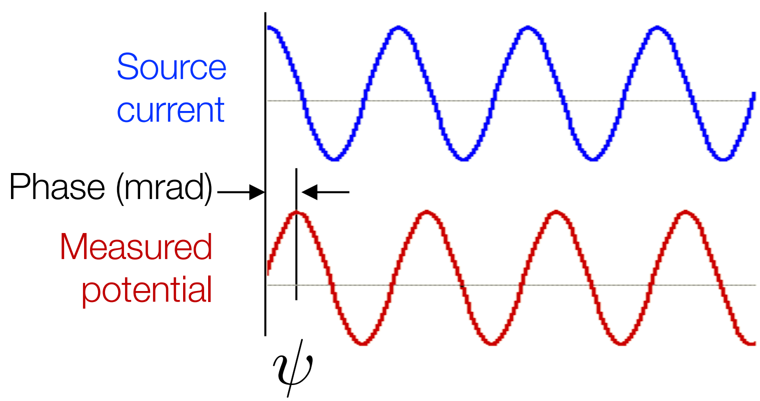
$$PFE = 100\left(\frac{\rho_{a2} - \rho_{a1}}{\rho_{a1}}\right)$$

ρ_{a1}: apparent resistivity at f_1

ρ_{a2}: apparent resistivity at f_2



- Phase ψ



IP data

- IP signals due to a perturbation (small change) in conductivity

$$\sigma_\eta = \sigma(1-\eta) \qquad\qquad \eta \in [0,1)$$

- An IP datum can be written as

$$d_i^{IP} = \sum_{j=1}^{M} J_{ij}\eta_j \qquad i = 1, \ldots, N$$

$$J_{ij} = \frac{\partial log \phi^i}{\partial log \sigma_j}$$

sensitivities for the DC resistivity problem

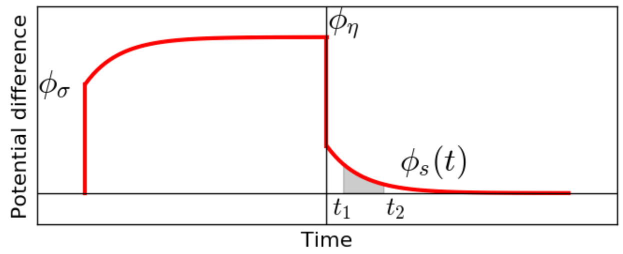
- In matrix form

$$\mathbf{d}^{IP} = \mathbf{J}\boldsymbol{\eta}$$

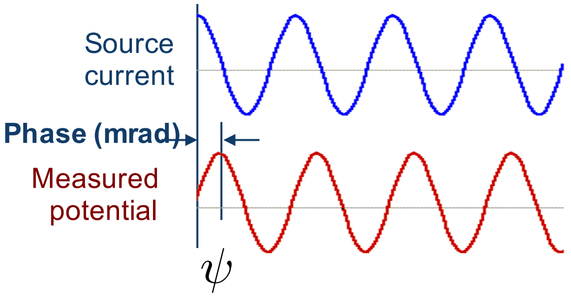
$\mathbf{J}$ is an N×M matrix

Summary of IP data

- Time domain:
  - Theoretical chargeability (dimensionless)
  - Integrated decay time (msec)



- Frequency domain:
  - PFE (dimensionless)
  - Phase (mrad)



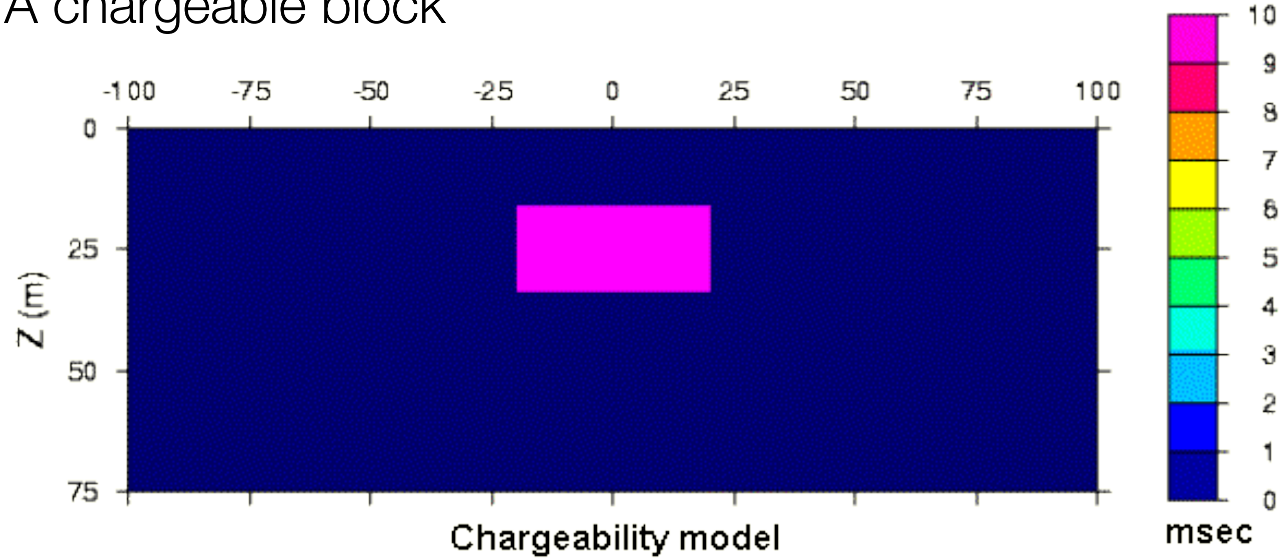
- For all data types: linear problem

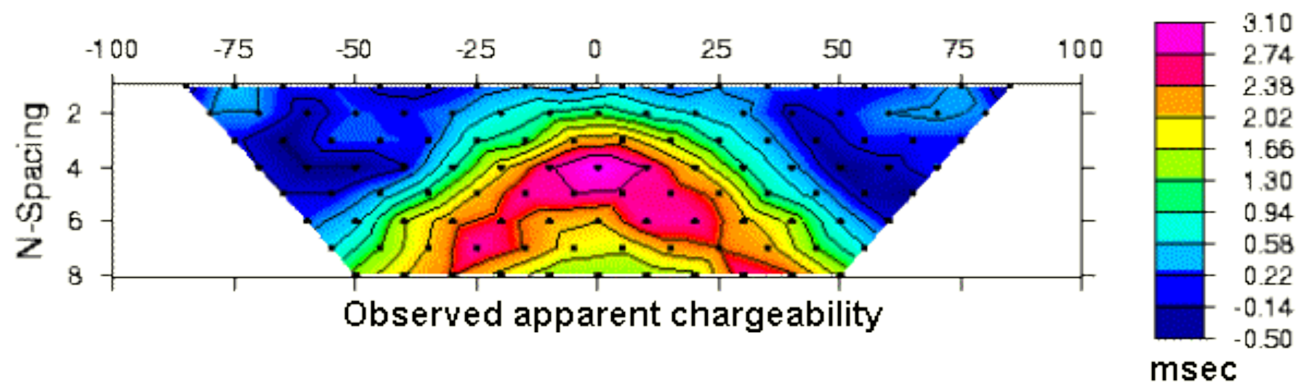
$$\mathbf{d}^{IP} = \mathbf{J}\boldsymbol{\eta}$$

$\mathbf{J}$ is an N×M matrix

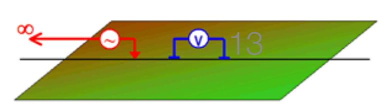
IP pseudosections

1) A chargeable block





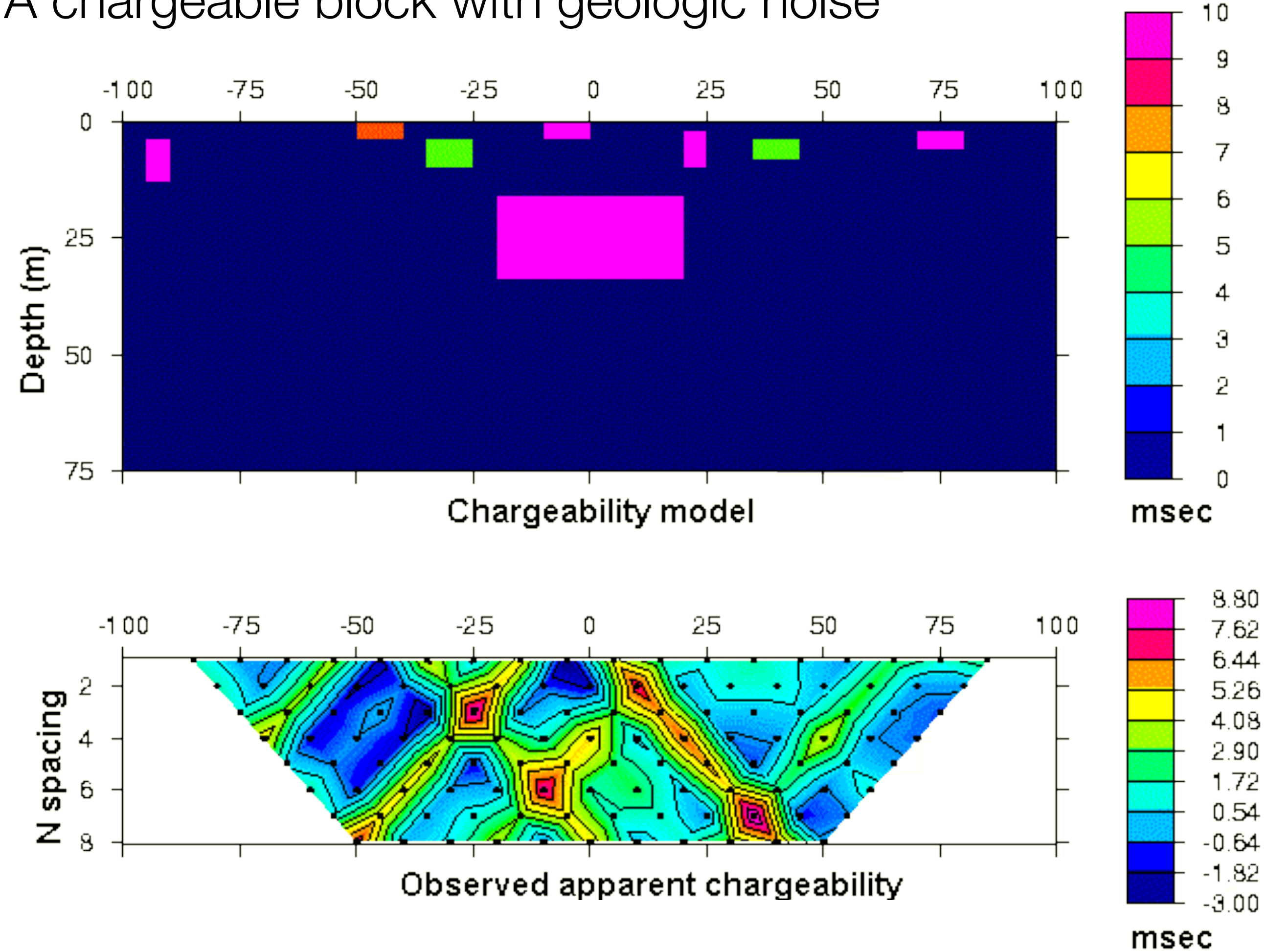
Pole-Dipole



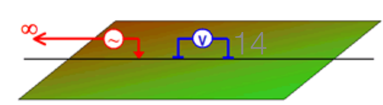
- Pole-dipole; n=1,8; a=10m; N=316

IP pseudosections

2) A chargeable block with geologic noise



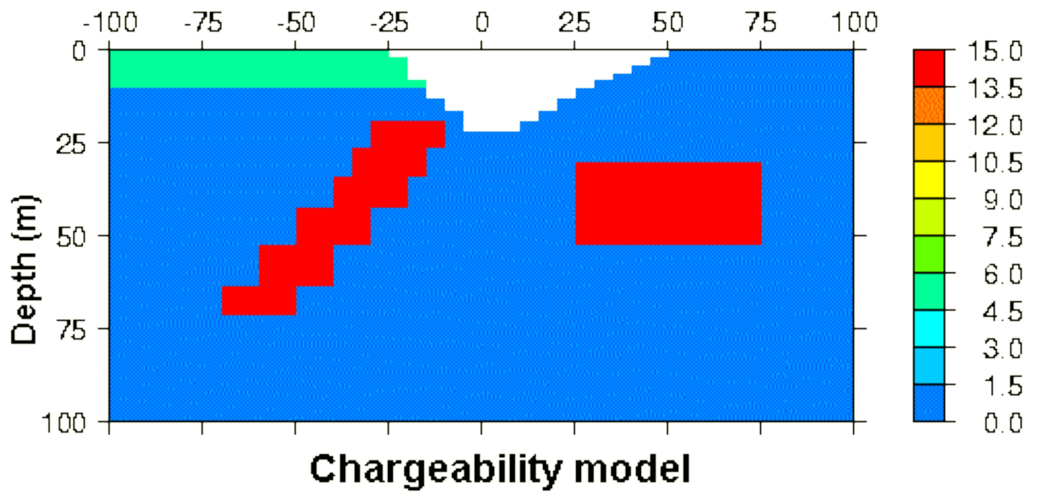
Pole-Dipole

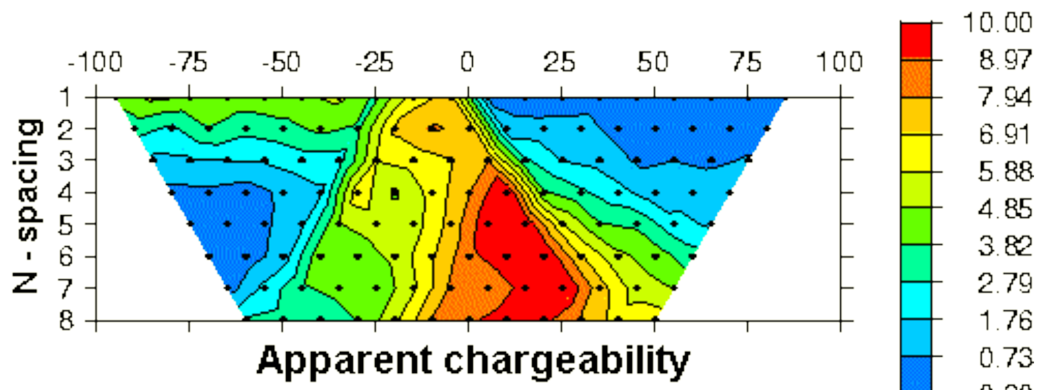


- Pole-dipole; n=1,8; a=10m; N=316

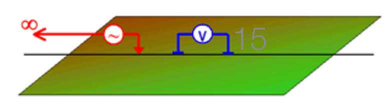
IP pseudosections

3) The "UBC-GIF model"

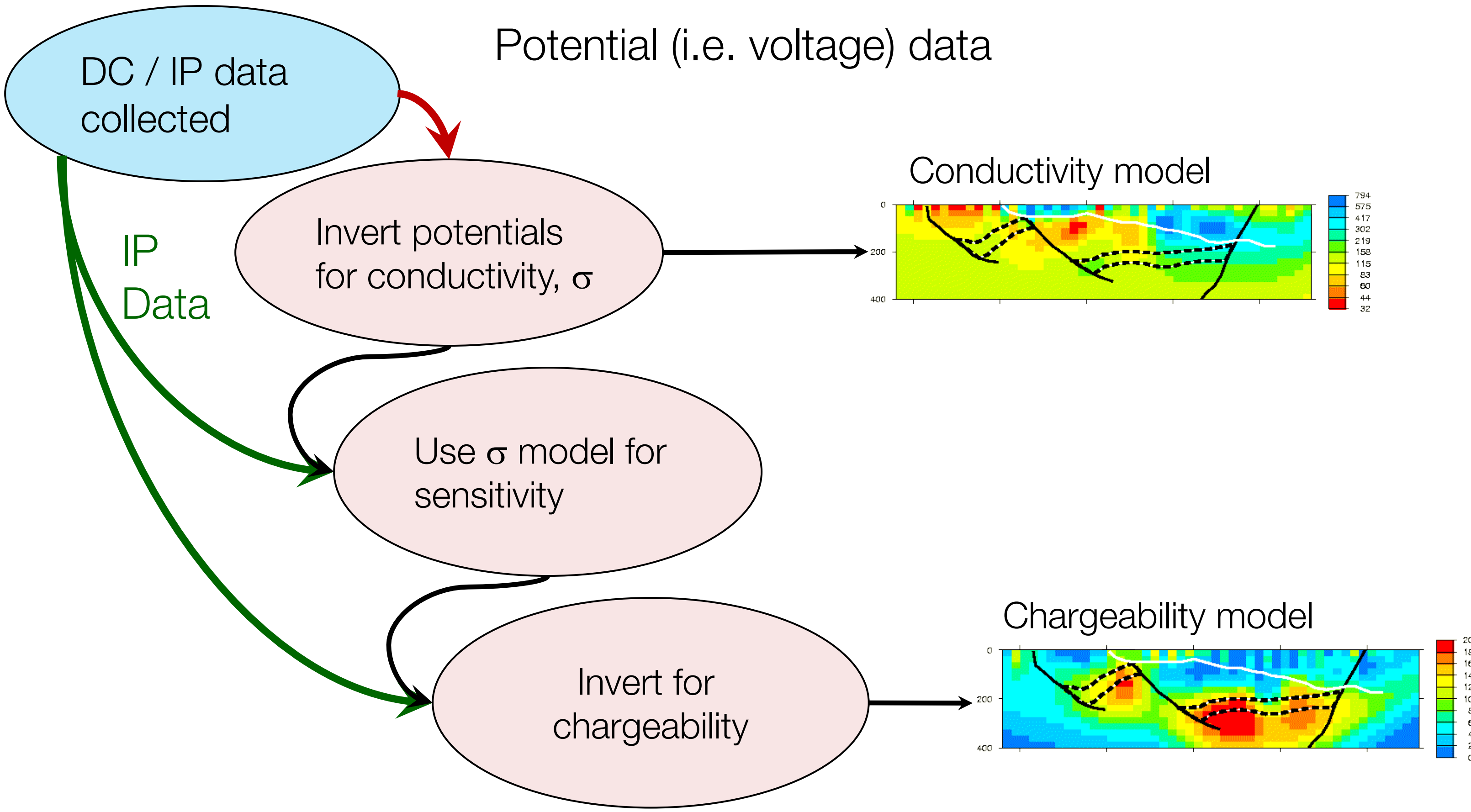




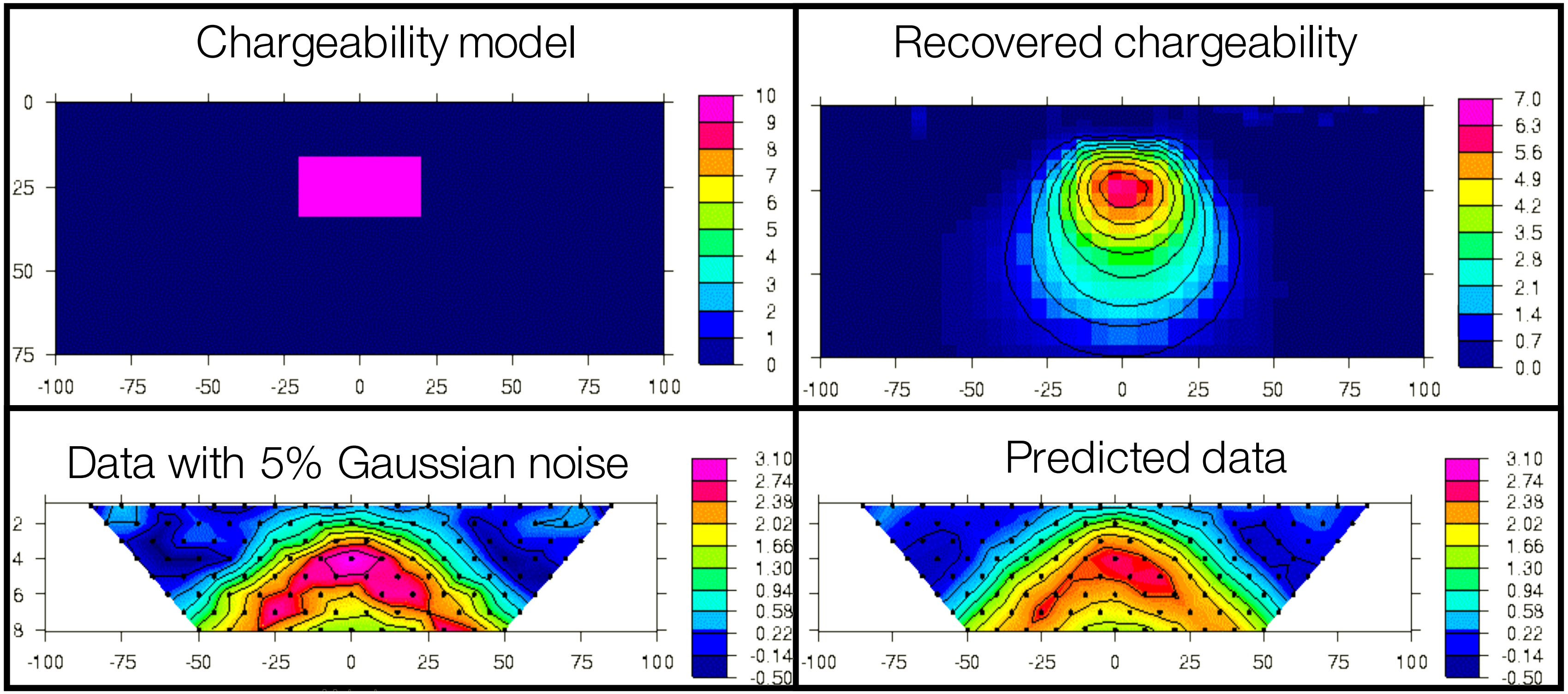
Pole-Dipole



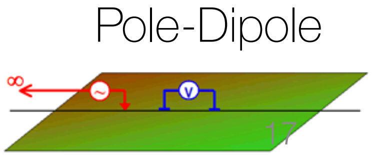
IP Inversion



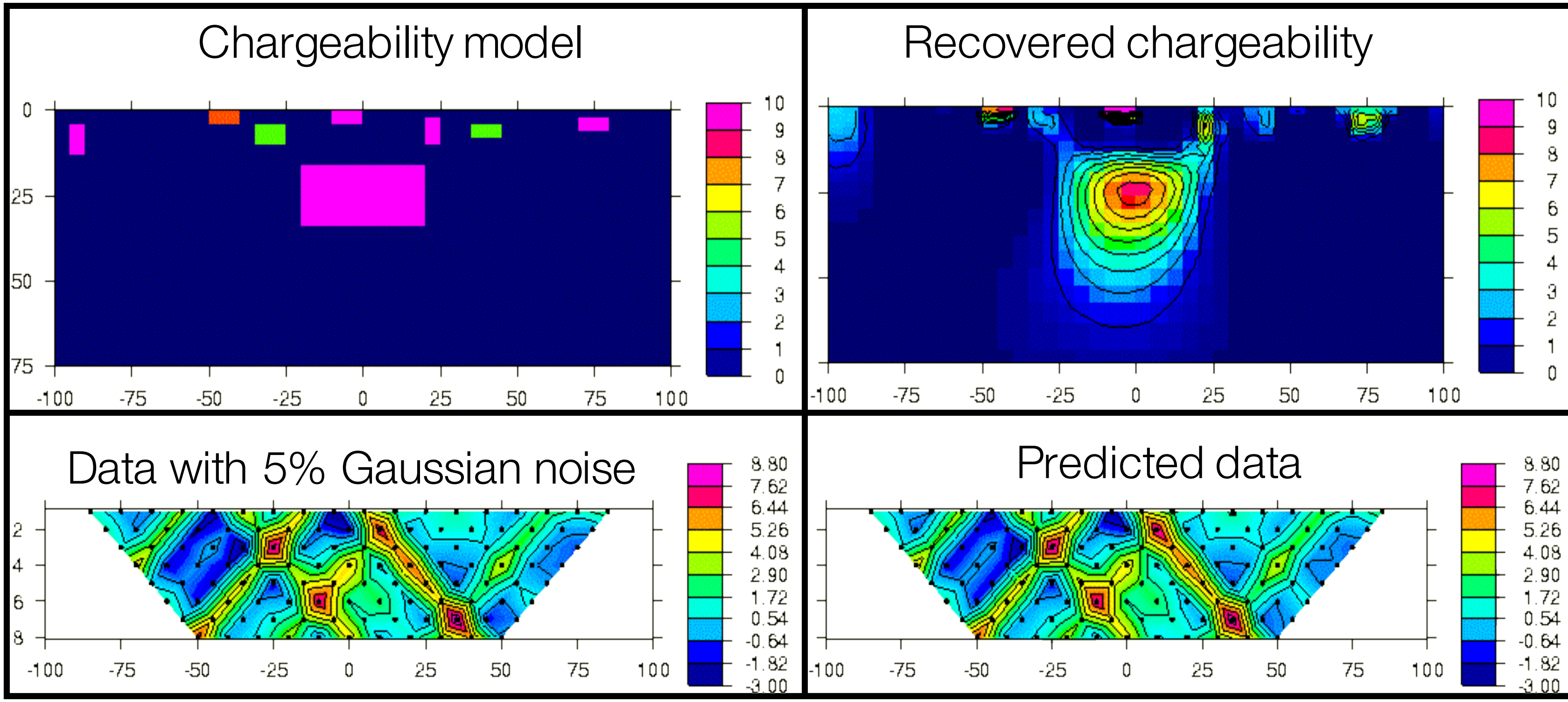
Example 1: buried prism



- Pole-dipole; n=1,8; a=10m; N=316; $(\alpha_s, \alpha_x, \alpha_z)$=(.001, 1.0, 1.0)

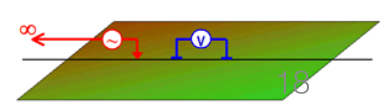


Example 2: prism with geologic noise

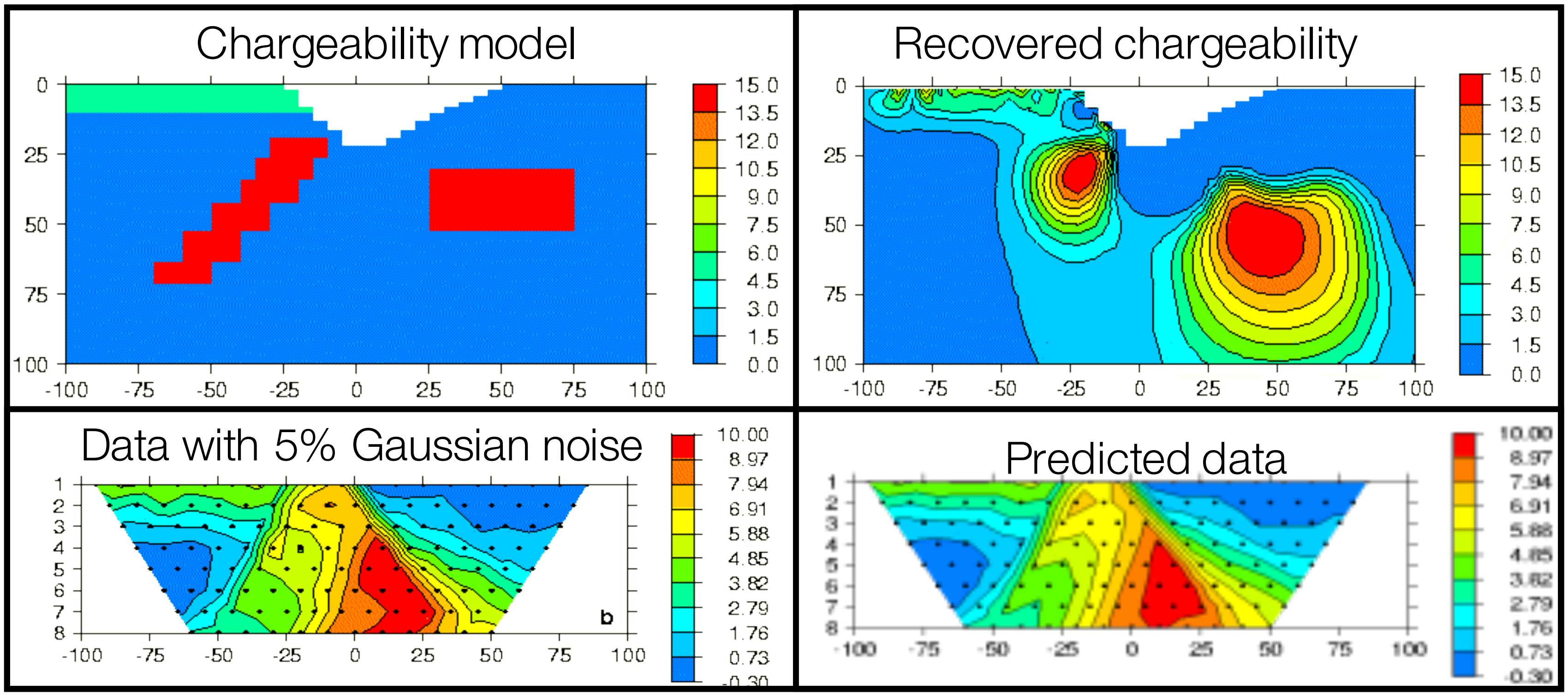


- Pole-dipole; n=1,8; a=10m; N=316; $(\alpha_s, \alpha_x, \alpha_z)$=(.001, 1.0, 1.0)

Pole-Dipole

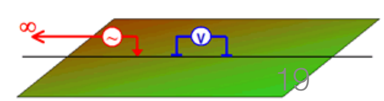


Example 3: UBC-GIF model



- Pole-dipole; n=1,8; a=10m

Pole-Dipole



Induced Polarization: Summary

- Sources of IP
- Conceptual model of IP
- Chargeability
- IP data
- Pseudosections
- Two stage DC-IP inversion

- Questions

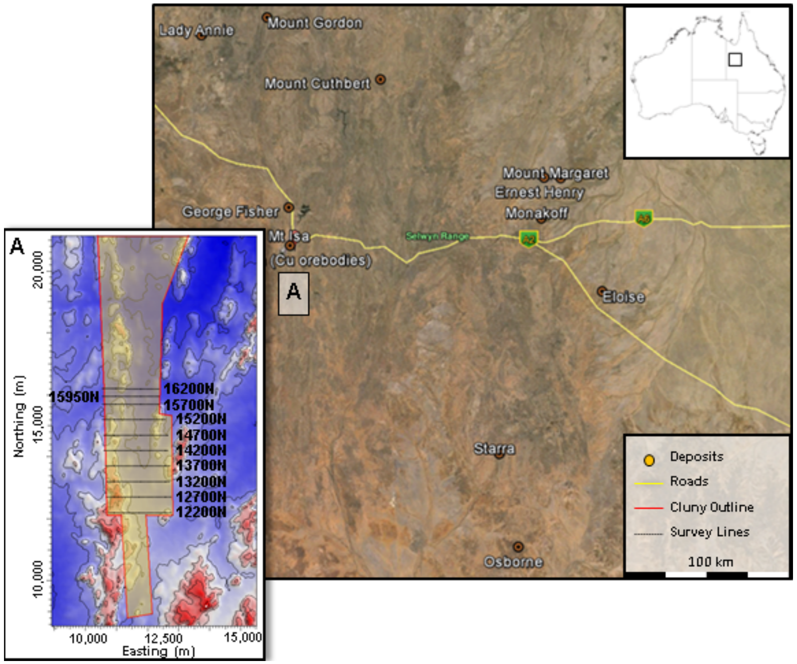
- Case history: Mt. Isa
- Example: Landfills

Case history: Mt. Isa

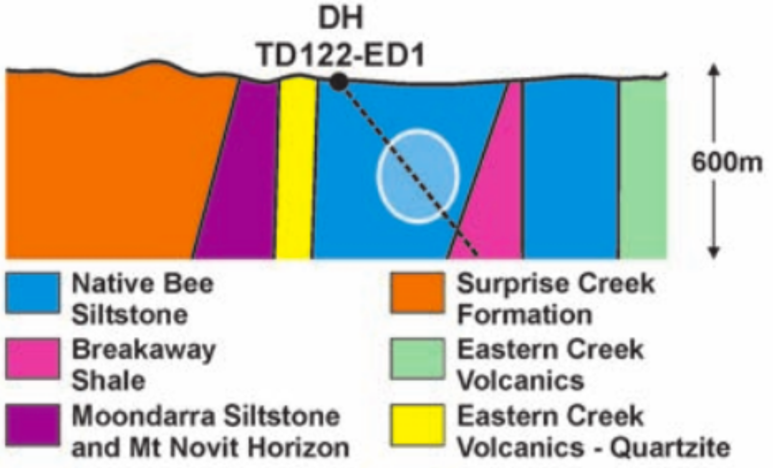
Rutley et al., 2001

Setup

- Mt. Isa (Cluny propect)



- Geologic model

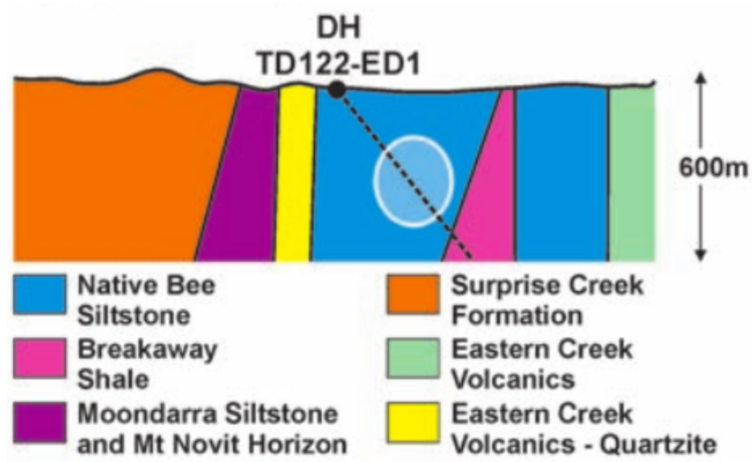


Question

- Can conductive, chargeable units, which would be potential targets within the siltstones, be identified with DC / IP data?

Properties

Geologic model



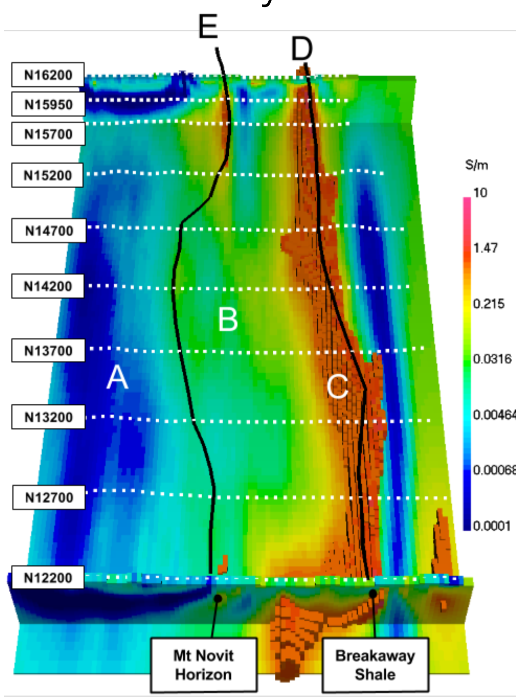
Resistivity and Chargeability

Rock Unit	Conductivity	Chargeability
Native Bee Siltstone	Moderate	Low
Moondarra Siltstone	Moderate	Low
Breakaway Shale	Very High	Low-None
Mt Novit Horizon	High	High
Surprise Creek Formation	Low	None
Eastern Creek Volcanics	Low	None

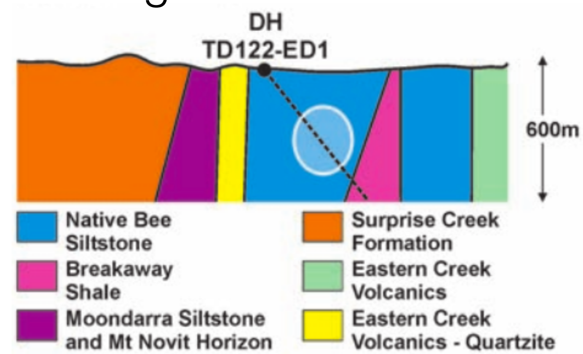
Recap: Synthesis from DC

- Identified a major conductor → black shale unit
- Some indication of a moderate conductor

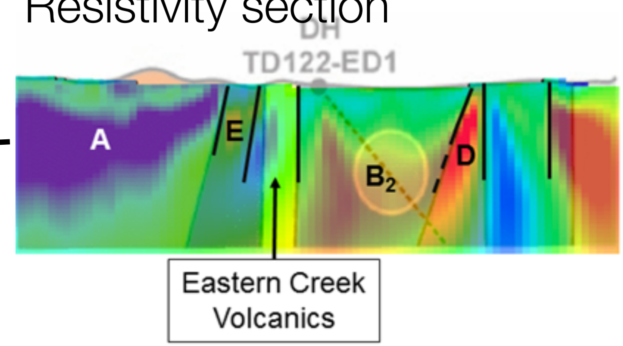
3D resistivity model



Geologic section



Resistivity section

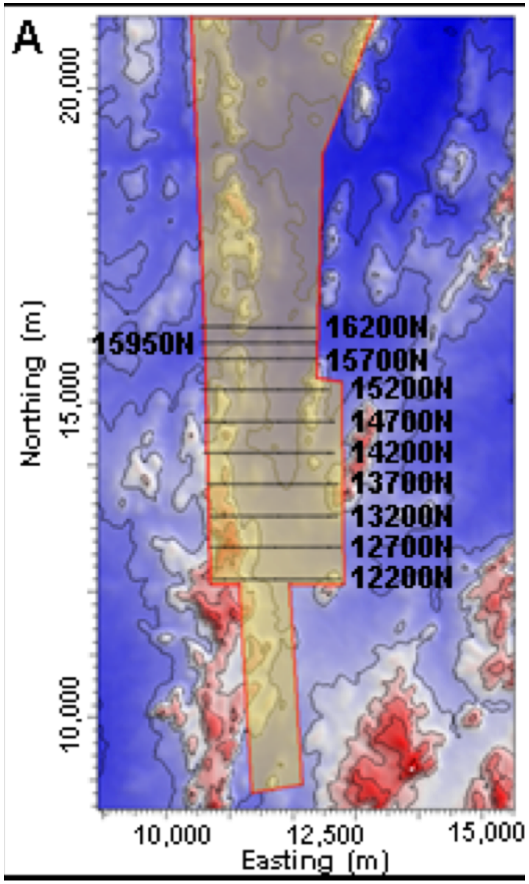


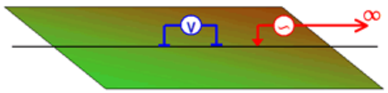
Can a **chargeable**, moderate conductor in the siltstones be identified?

Survey and data

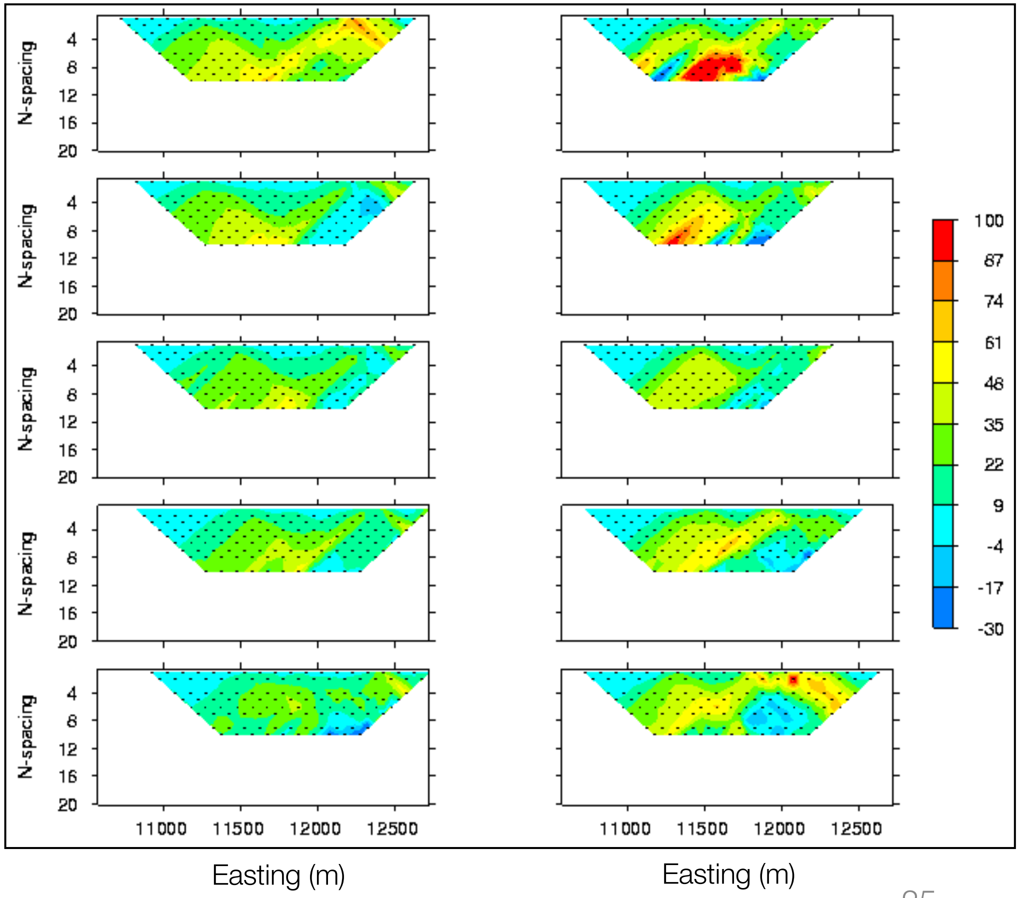
- Eight survey lines
- Two configurations

Surface topography



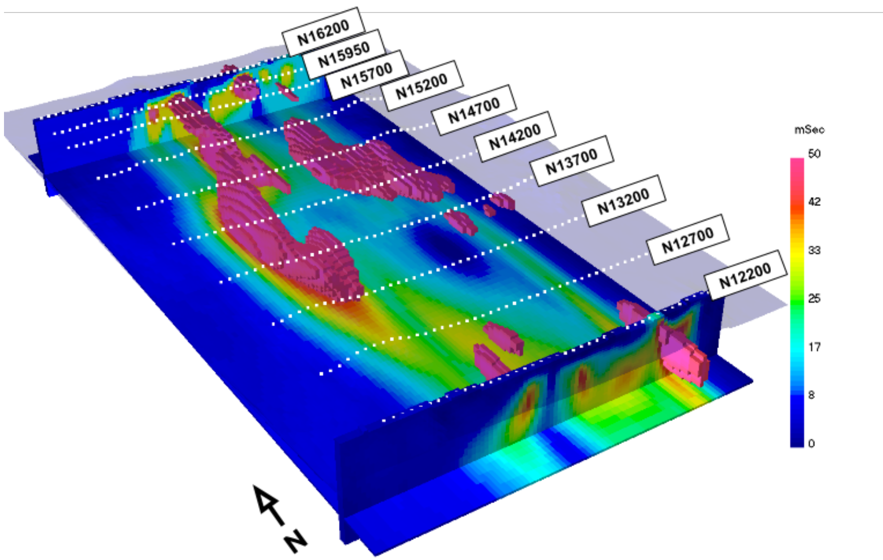


Apparent chargeability, dipole- pole.

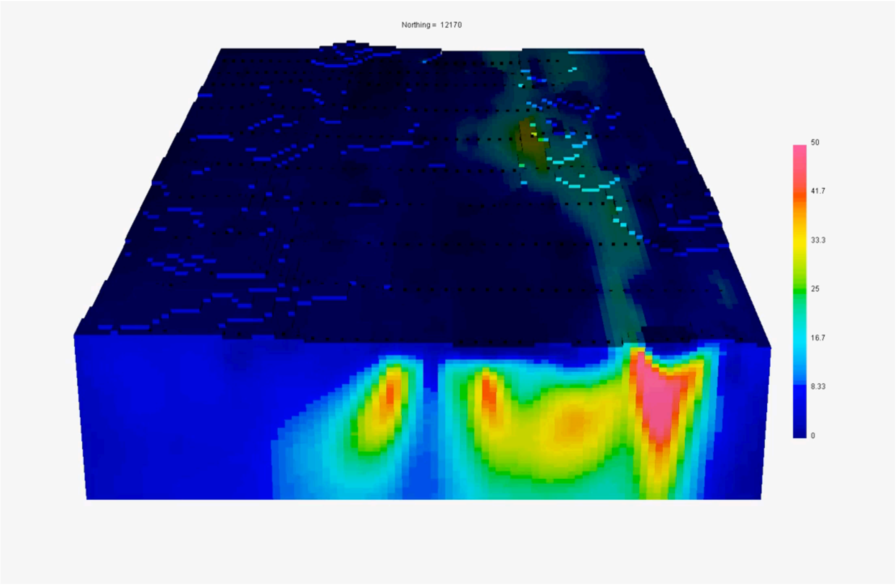


Processing

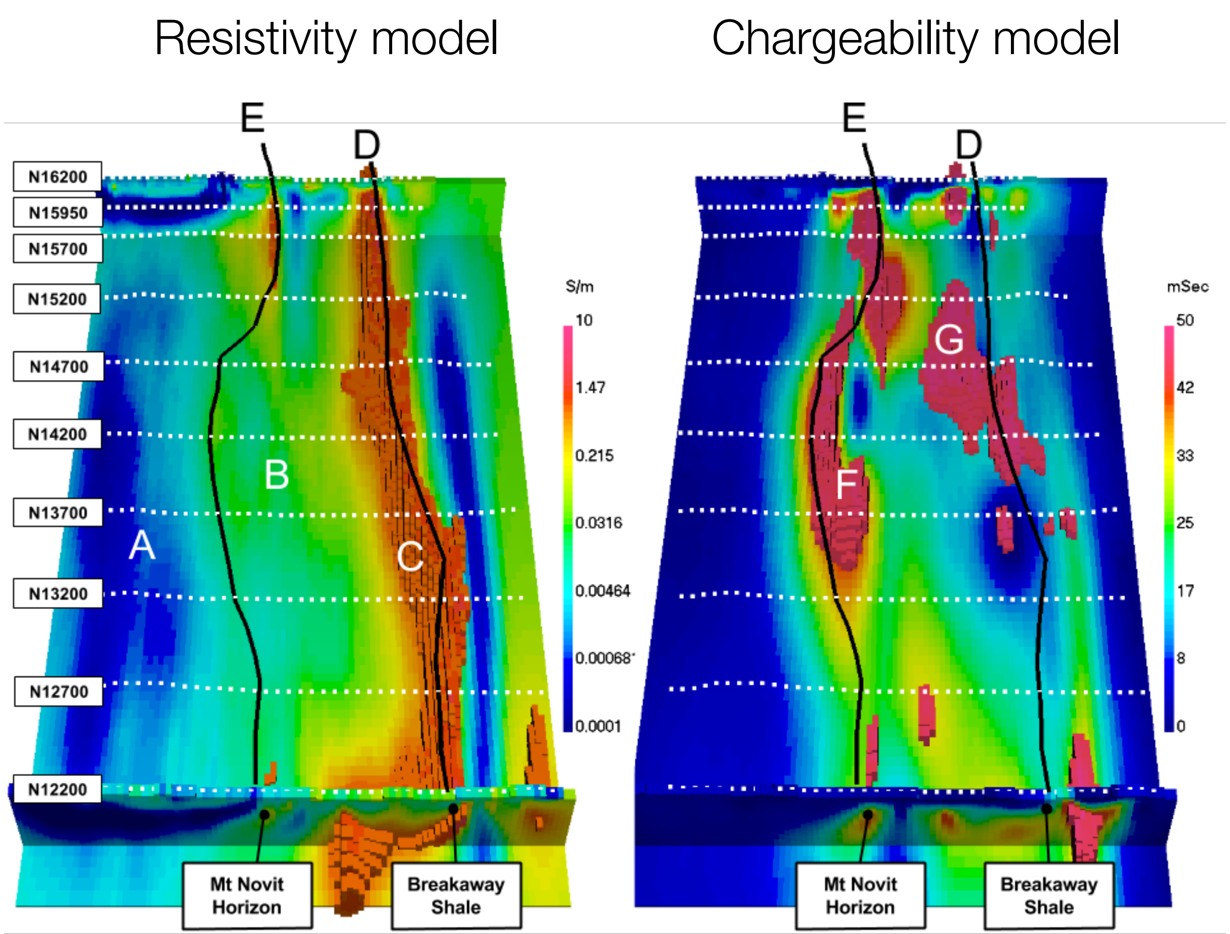
3D chargeability model



Animation



Interpretation



A: Resistive, Non-chargeable

B: Moderate conductivity; low chargeabilty

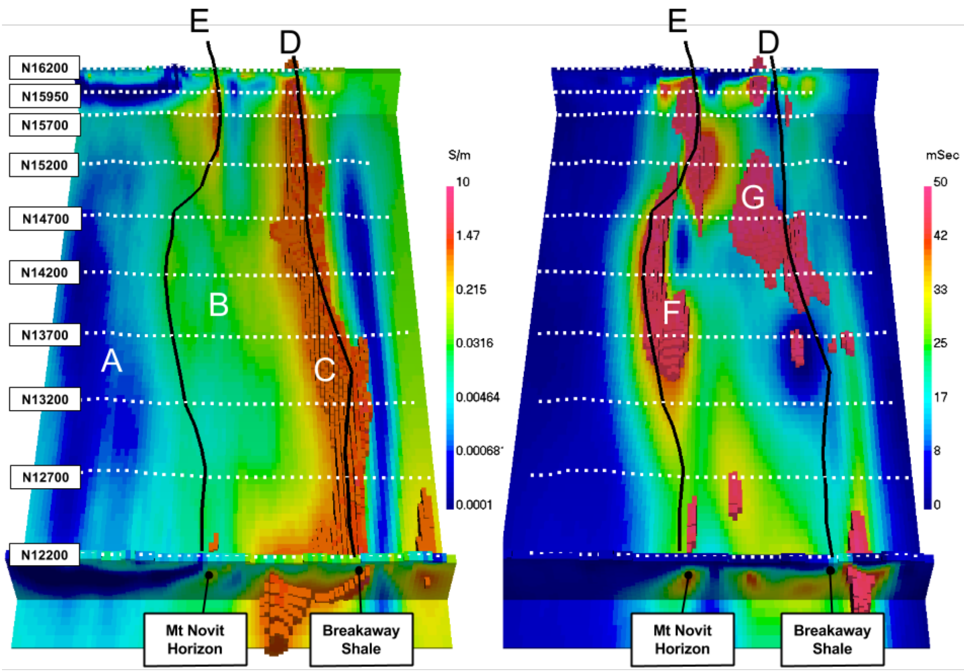
C: Very high conductivity (> 10 S/m)

E and F: High conductivity and high chargeability

G: Other chargeable regions

Synthesis

Resistivity model   Chargeability model



A: Surprise Creek Formation
- Resistive, non-chargeable

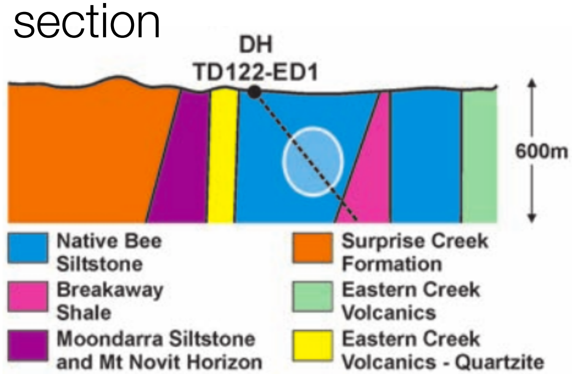
B: Moondarra and Native Bee siltstones

C: Breakaway Shales
- Very high conductivity

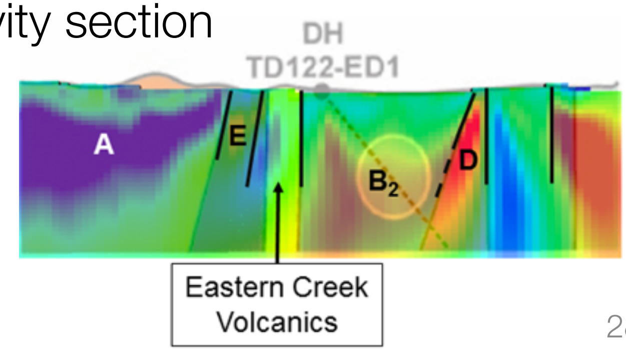
E and F: Mt Novit Horizon
- High conductivity and high chargeability

G: Other chargeable regions within siltstone complex

Geologic section



Resistivity section



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- Two stage DC-IP inversion
- Case history: Mt. Isa

- Questions

- Example: Landfills

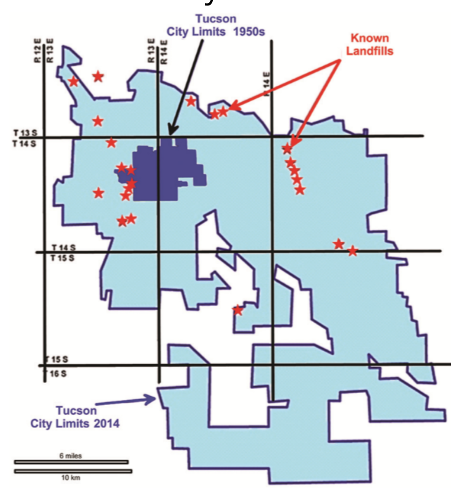
IP over Landfills

Landfills: Hazards and Goals

- Pollutants
  - Toxic leachates (mercury, arsenic, cadmium, lead, PVC, solvents)
- Concerns
  - Health
  - Water contamination
  - Construction hazard
  - Devalues property
- Goals
  - Locate abandoned landfills
  - Assess size
  - Characterize the waste
  - Monitor reclamation

Nearmont and Congress landfills, Tucson, Arizona

Tucson city limits and regional landfills



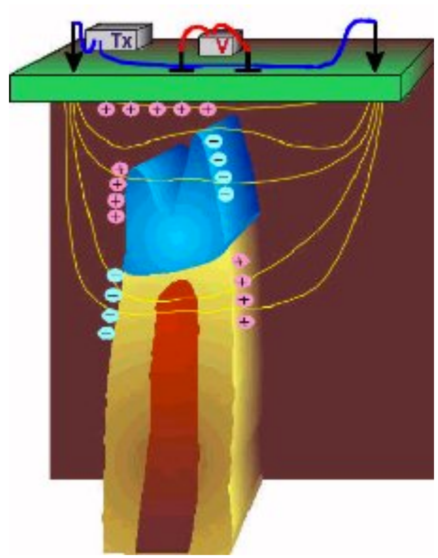
Physical Properties

Waste Type	Description	Resistivity	Susceptible	Chargeable
Electronic/ Technological	Metallic objects, heavy metals in solution	Low	Yes	Yes
Construction Debris	Wood, cement, iron rebar, wall board, asbestos, glass, plastics	High	Frequently	Weakly
Earth Materials	Clays, various fill	Low/Moderate	Occasionally	Yes
Green waste	trees, wood clippings etc	Variable	No	Weakly

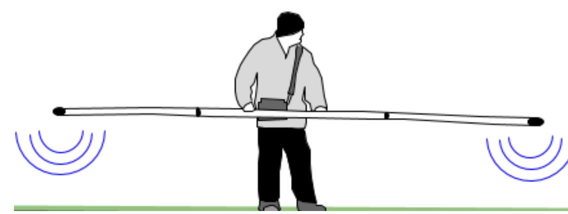
Traditional Landfill Surveys

Magnetic

DC Resistivity



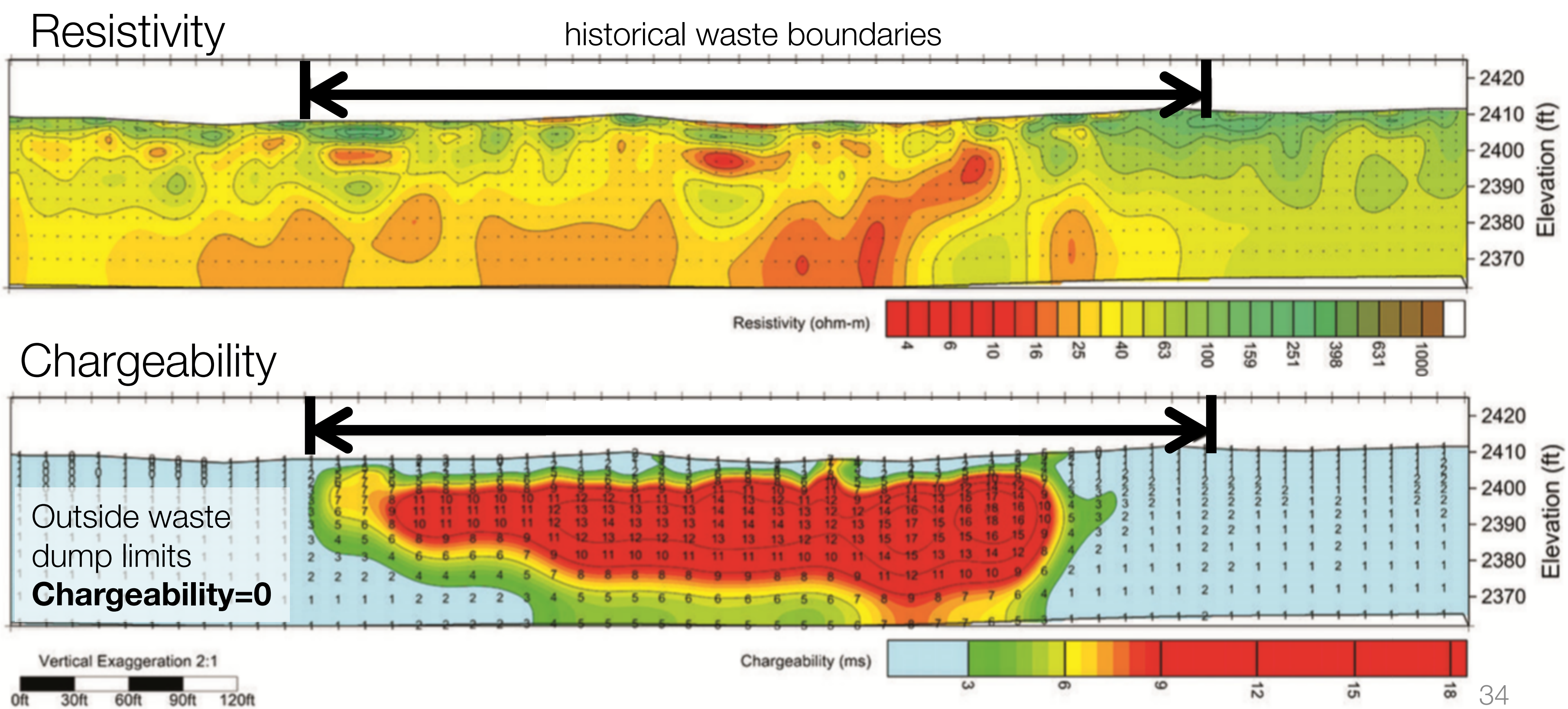
Near-Surface Electromagnetic



- Most popular surveys have limited success
- IP might be a better diagnostic
- Responsive to: metallic debris, green waste, organic matter, some construction materials

Ryan Airfield (Eastern Pit)

- Waste material: Mixed solid waste (MSW)
- Observations:
  - Resistivity not correlated with pit margins (non-diagnostic)
  - Chargeability (IP) correlates well with historical pit margins (diagnostic)

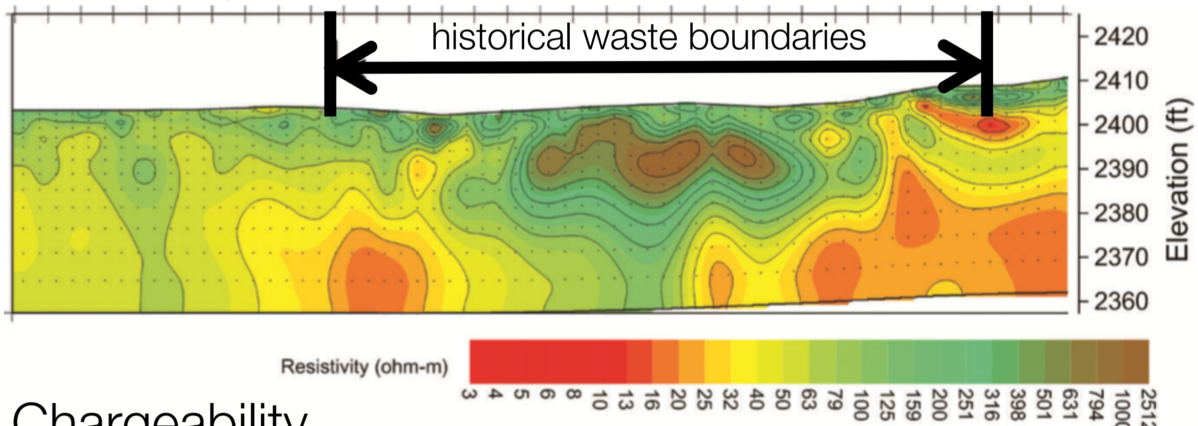


Dipole-dipole (a=7.5ft, n=0.5-6)

Ryan Airfield (Western Pit)

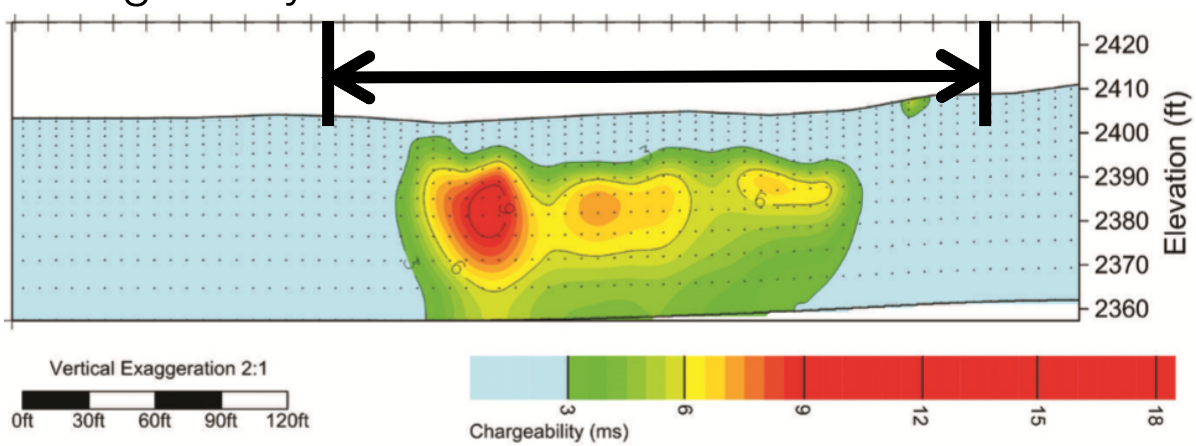
- Waste material: Construction / demolition
- Observations:
  - Waste correlates with region of high resistivity
  - Waste correlates with chargeable region (significant IP anomaly).

Resistivity



Resistive waste within landfill

Chargeability

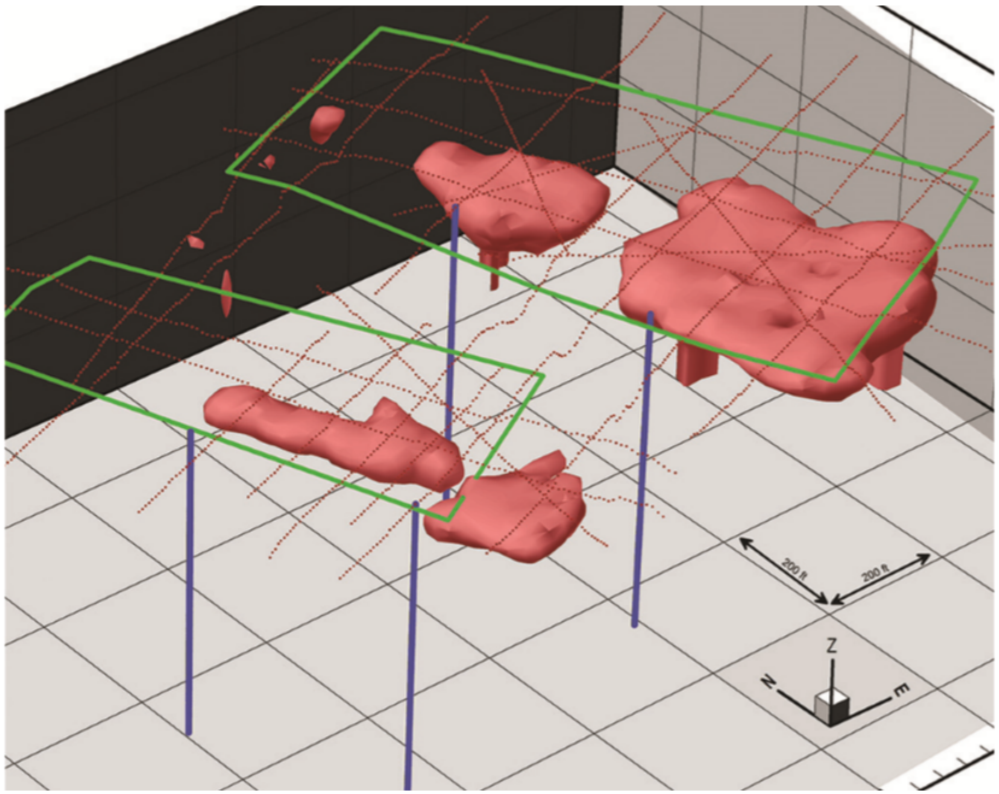


IP correlates with landfill

Dipole-dipole (a=7.5ft, n=0.5-6)

Ryan Airfield (Composite)

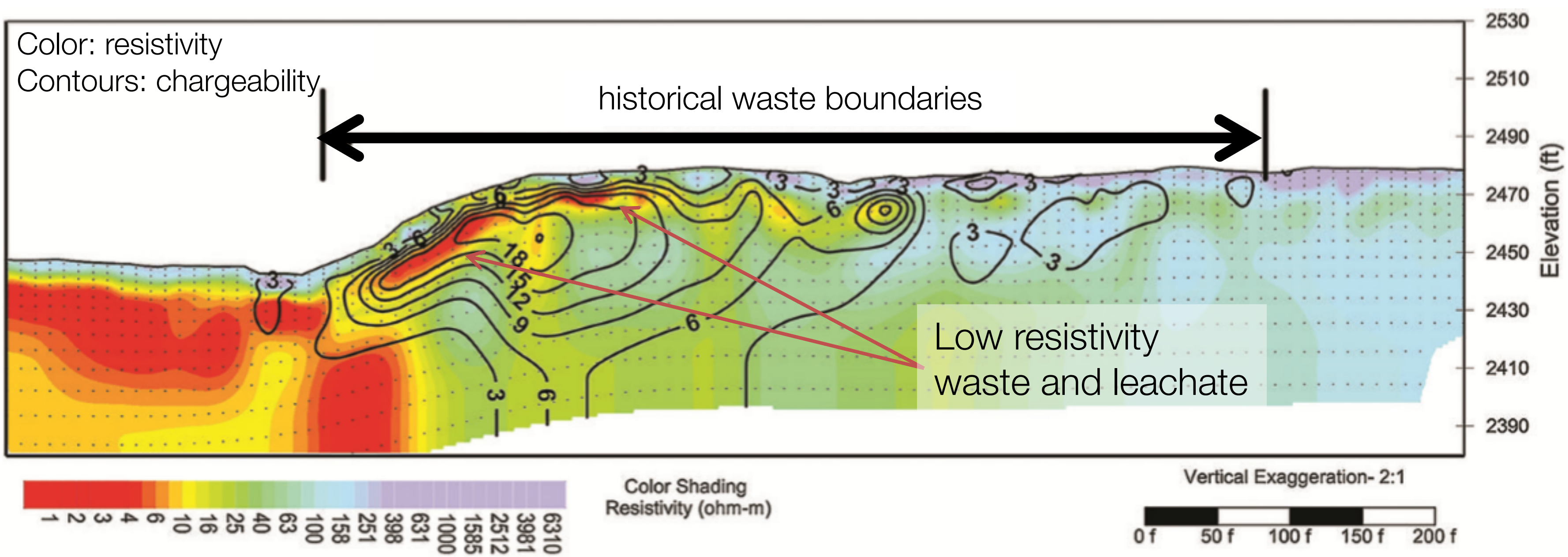
Chargeability isosurface



- Waste material:
  - MSW and construction / demolition
- Observations:
  - Well locations picked with aim of **not** intercepting waste
  - Verified by drilling

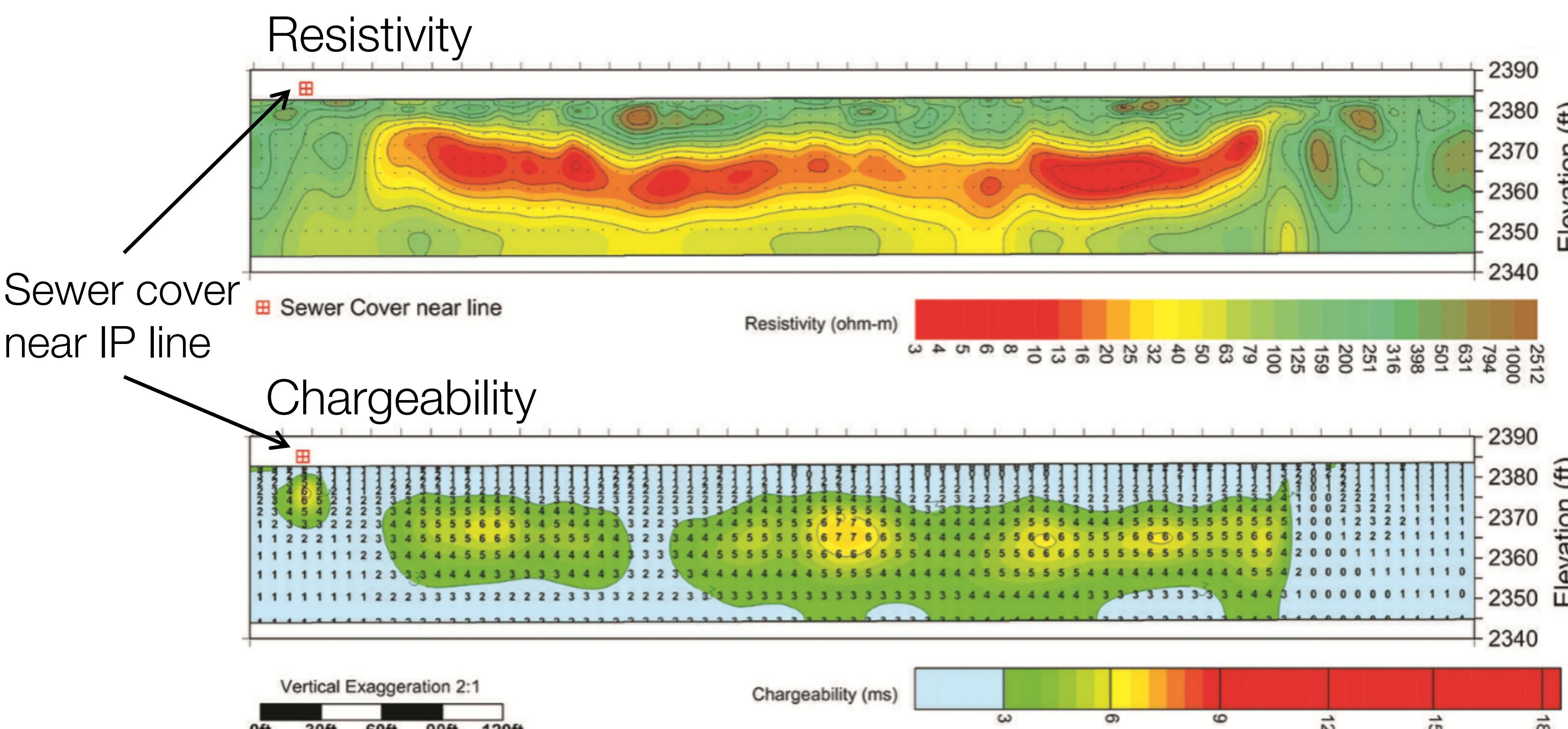
Tumamoc Landfill

- Waste material: Construction / demolition
- Observations:
  - Low resistivity down-gradient from waste → likely conductive leachate
  - Low resistivity and IP offset from one another
  - IP falls within historic landfill boundaries



Tucson region: Organic material

- Waste material: green-waste, trees, clippings
- Observations:
  - Resistivity low
  - Weak but elevated IP signature

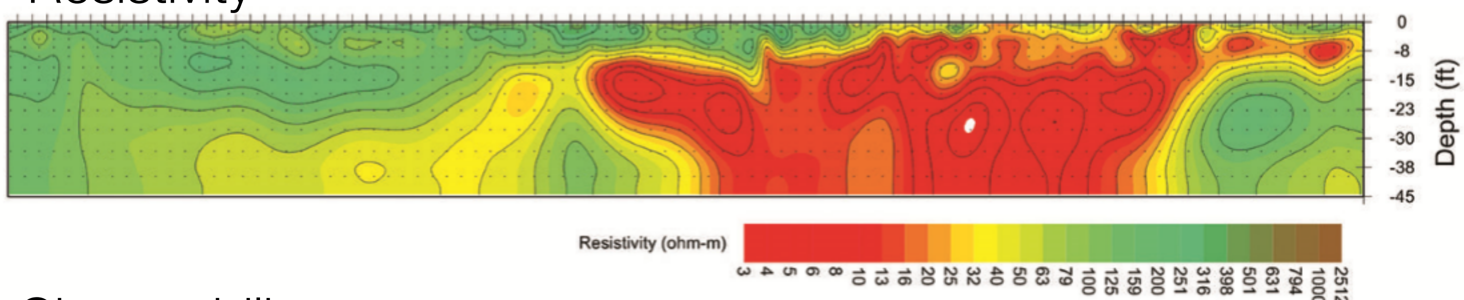


Dipole-dipole (a=7.5ft, n=0.5-6)

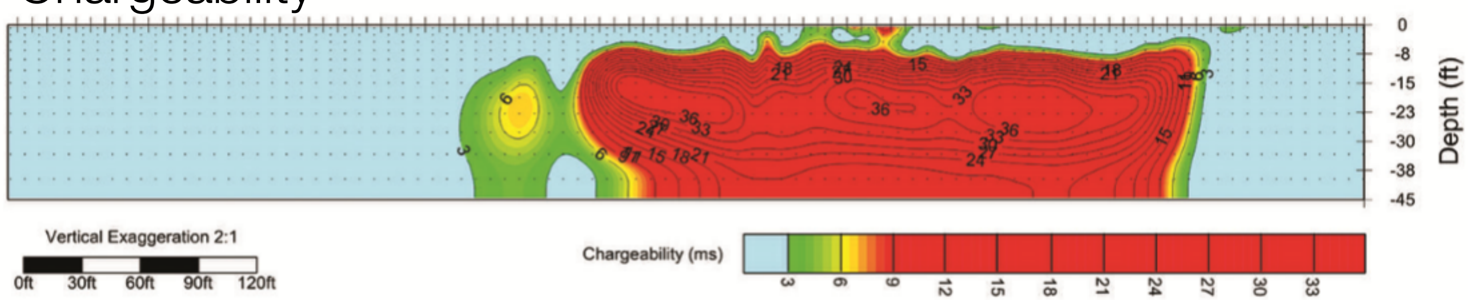
Nearmont Landfill

- Waste material: Municipal solid waste (MSW)
- Observations:
  - low resistivity + high IP (ideal “fingerprint”)
  - MSW waste confirmed with drilling

Resistivity



Chargeability



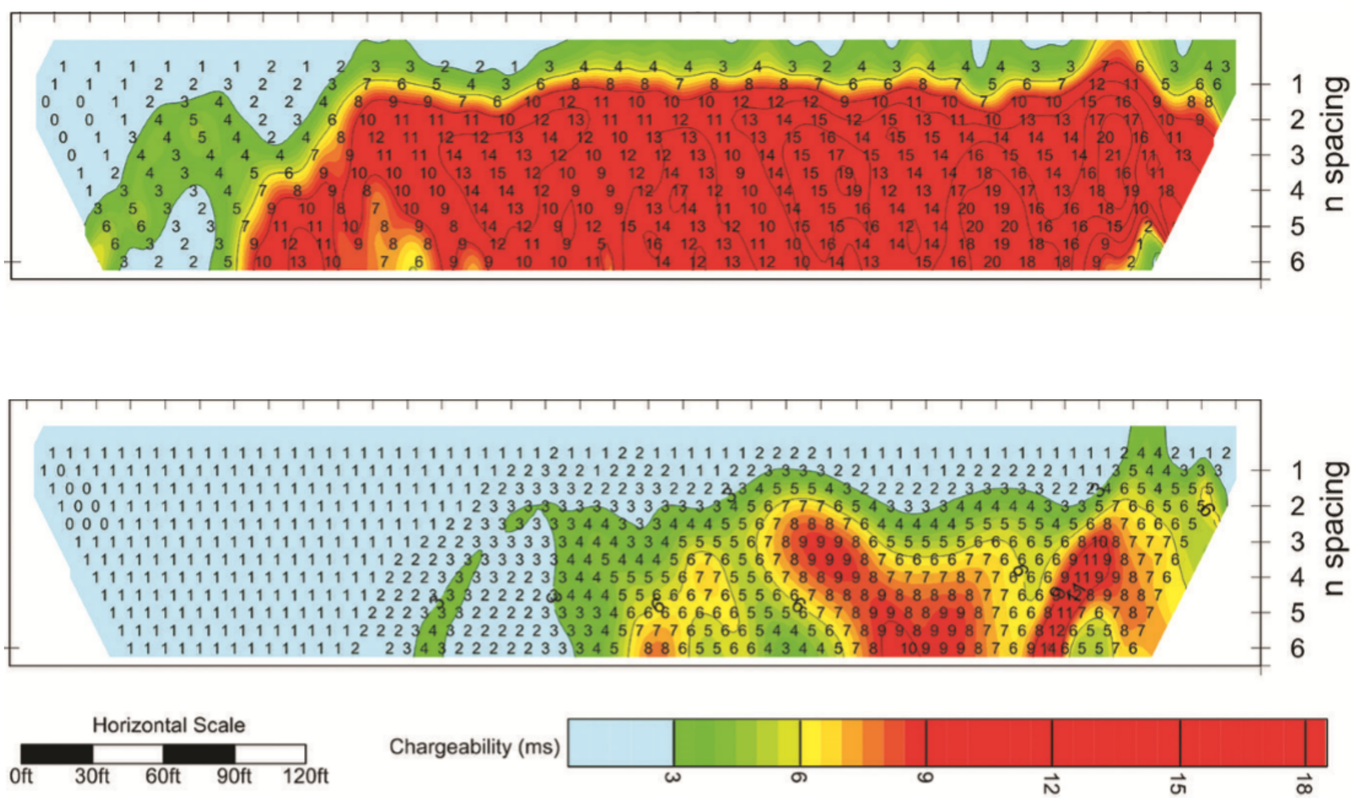
Dipole-dipole (a=7.5ft, n=0.5-6)

Example: Landfill Monitoring

- Waste material: municipal solid waste (MSW)
- Surveys:
  - 2003: IP survey
  - 2003-2007: 4 year biodegrediation program
  - 2009: Repeat IP survey
- Observations:
  - Reduction in IP anomaly indicates the effectiveness of biodegredation

Before

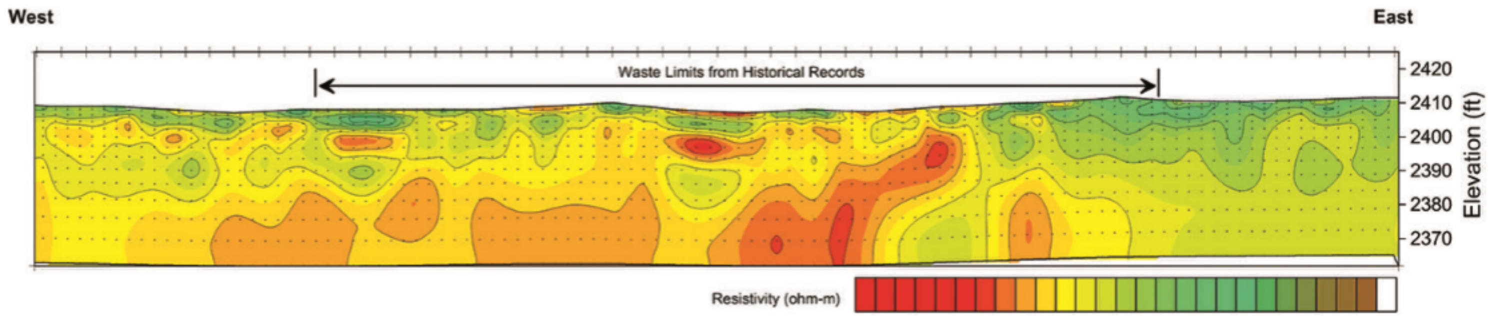
After



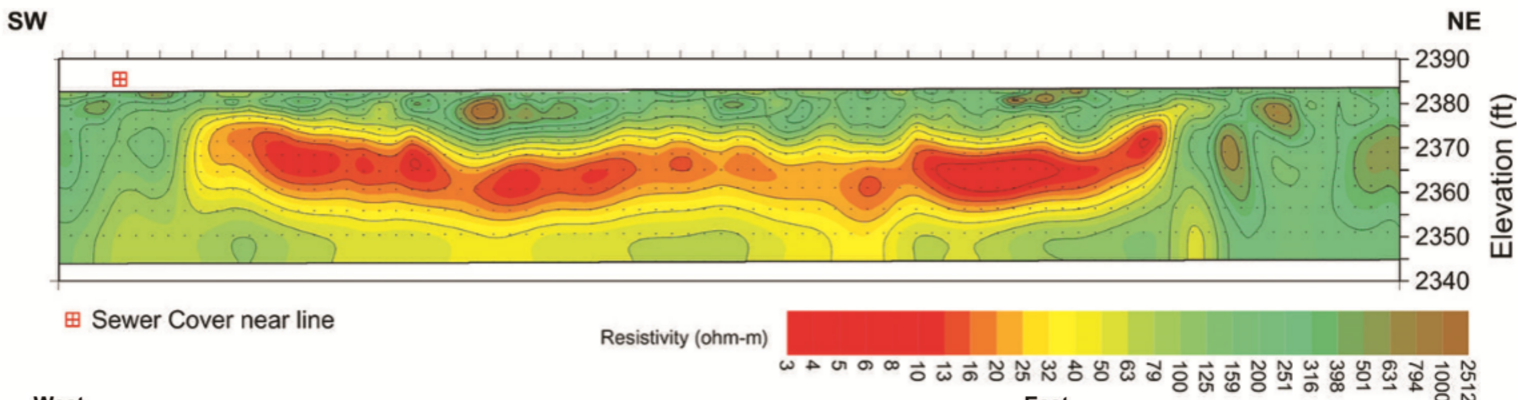
Summary

- Resistivity may not be a good indicator of waste

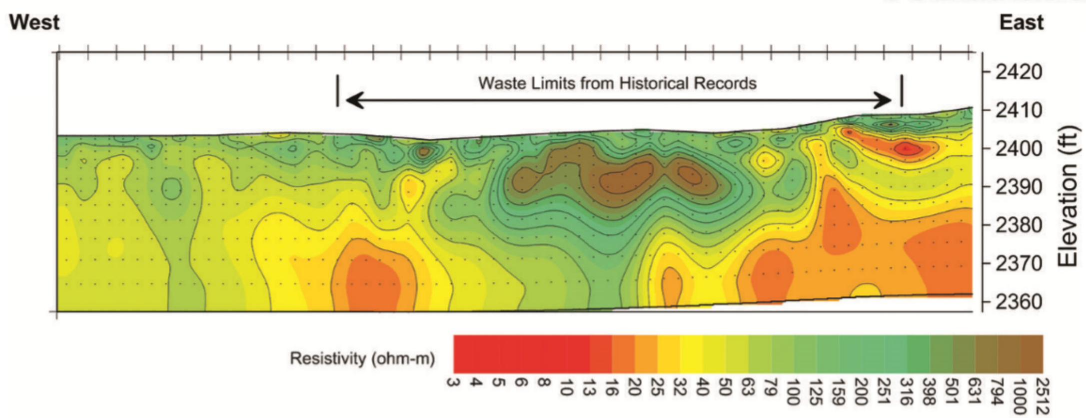
Mixed Waste



Green Waste



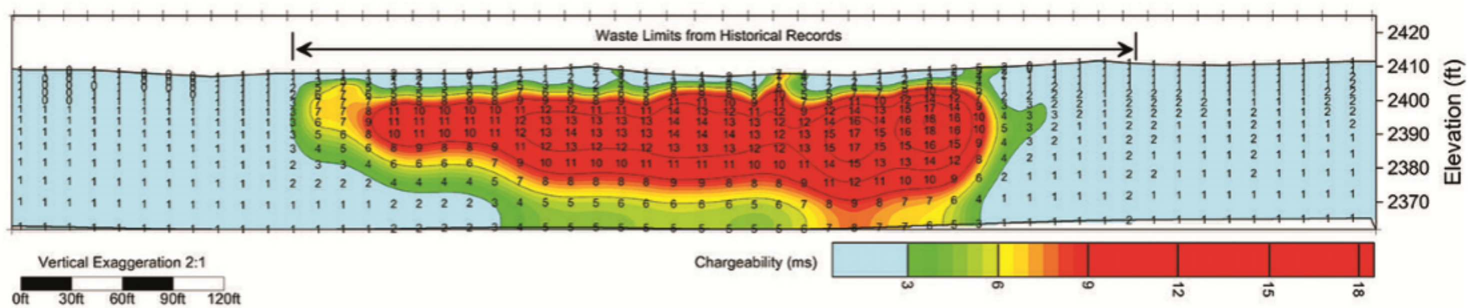
Construction/
Demolition
Waste



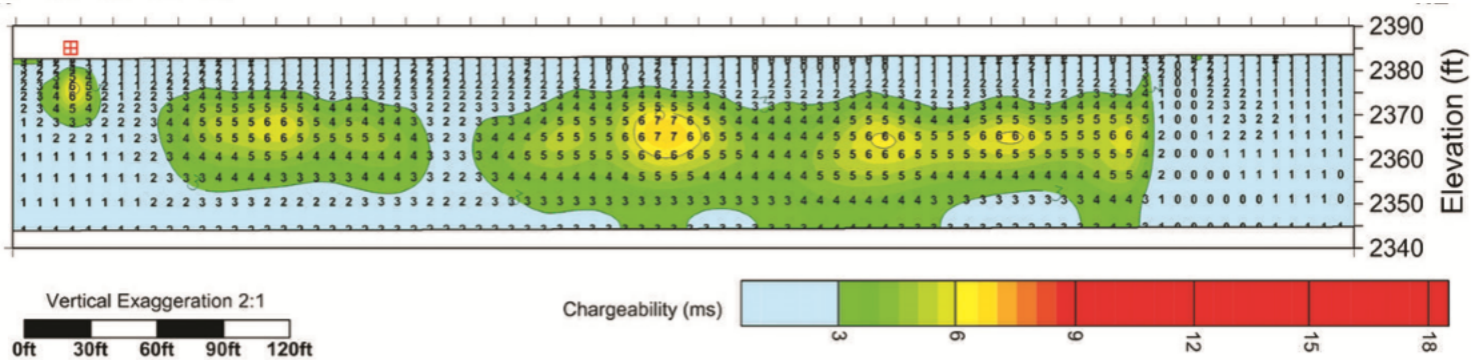
Summary

- Chargeability may be a more consistent indicator of waste

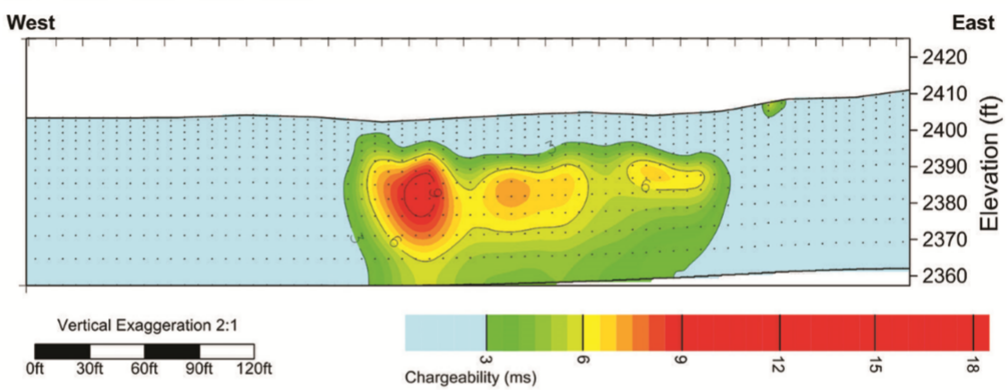
Mixed Waste



Green Waste

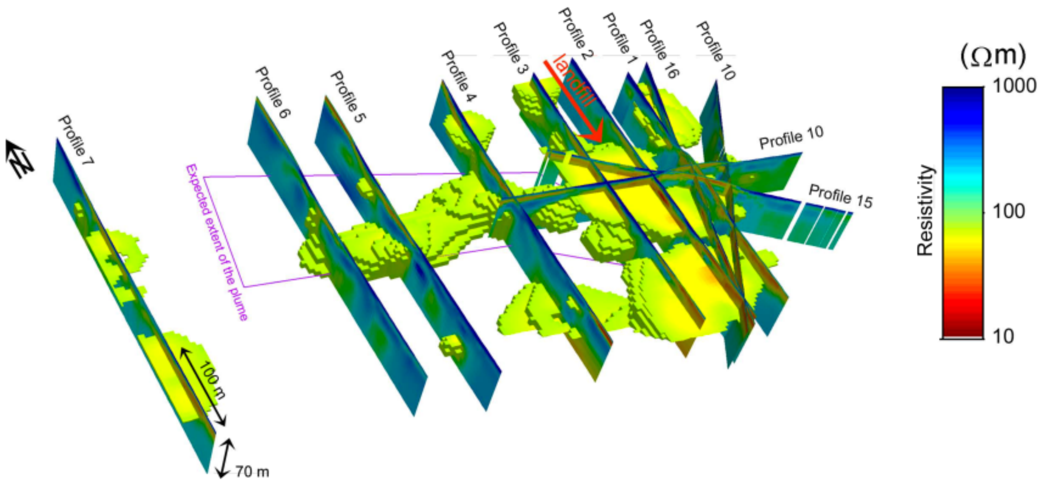


Construction/ Demolition Waste



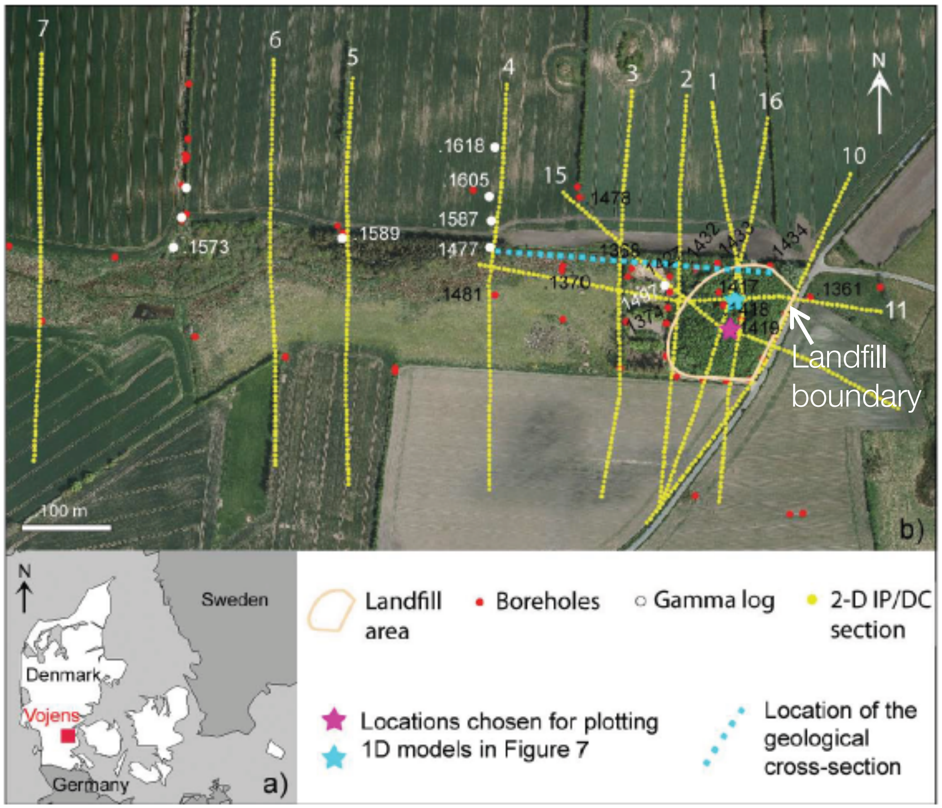
Case History:
Mapping a landfill, Demark

Gazoty et al., 2012



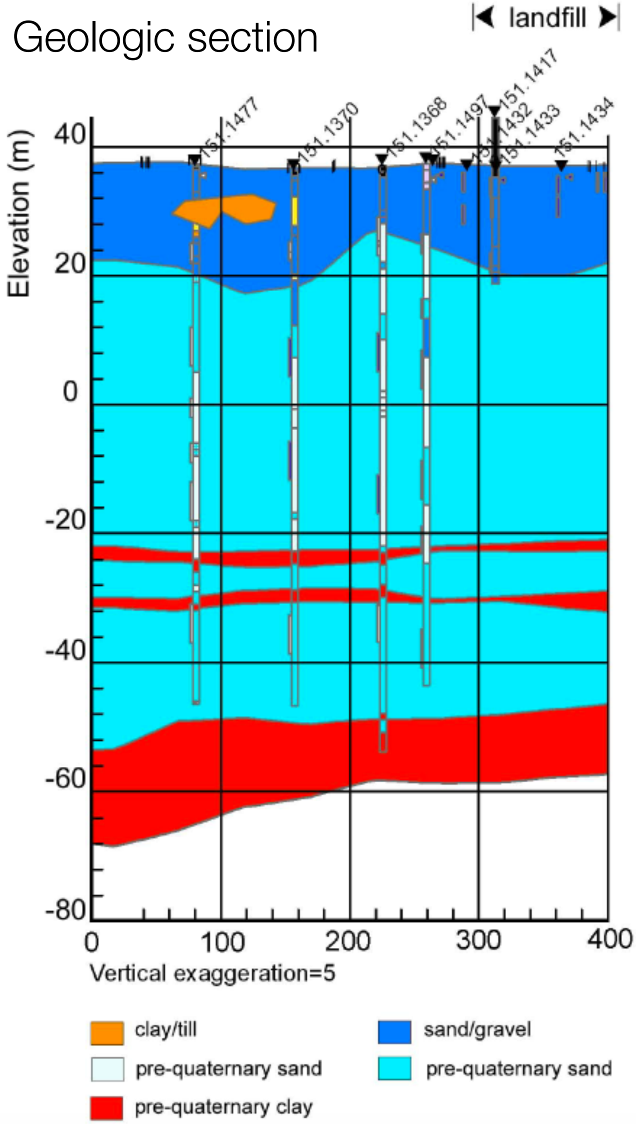
Setup

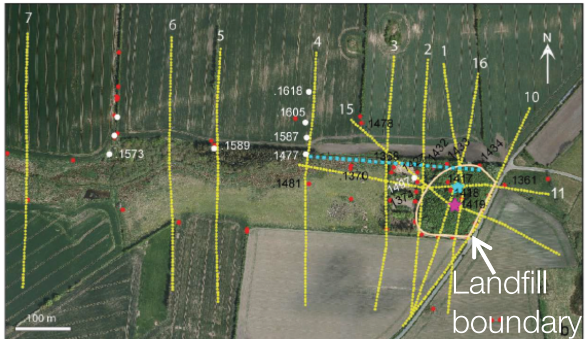
Horlokke area, Denmark



- Landfill
  - Years: 1968-1978
  - 100m x 100m
  - Sludge from waste treatment plant
  - Estimated volume: 65,000m^3
- Containment
  - No membrane
  - No leachate capture
  - No isolation system
- Current state
  - Landfill: hydrocarbons, iron, inorganics
  - Contaminant plume
    - 500m to west; depth (50-60 m)
    - Chlorinated compounds

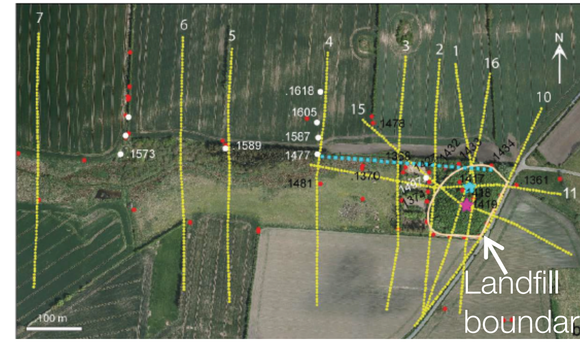
Setup



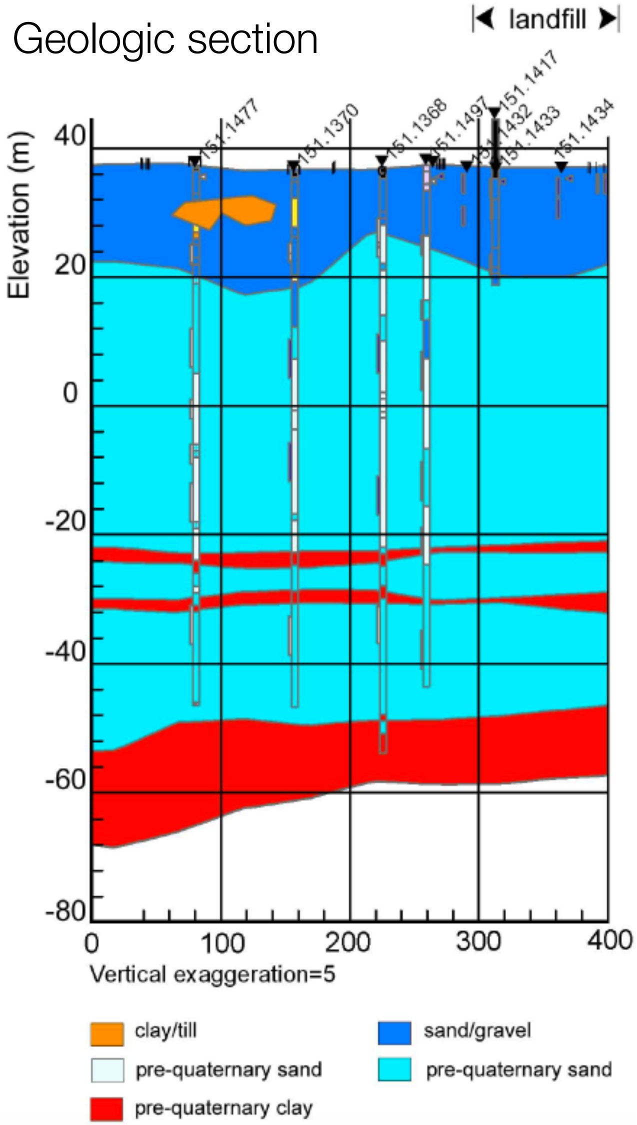


- Horlokke landfill
  - Located on an outwash plane (low topography)
  - Clay layer: top 2-3m
  - Waste layer: 6-8m thick
- General geology
  - Gravel and sand with interbedded clay
  - Water level: 2-3m depth
  - Sand layers below landfill host regional aquifer
- Aquifer is used for drinking water
  - Watershed is west of the site
  - No risk currently
  - Concern if watershed shifts east due to climate change

Objectives



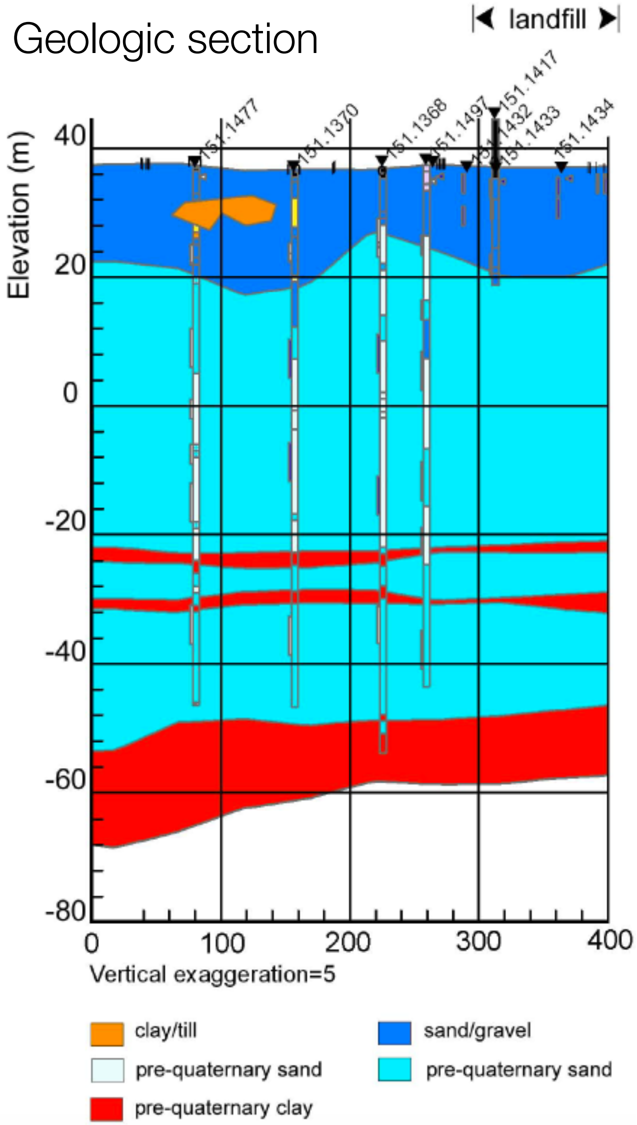
Geologic section



- Delineate the boundaries and depth of the current landfill
- Locate the leachate plume
- Identify lithologies
  - Aquitards
  - Clay-rich sandy layers
  - Deep silt/clay lens

Properties

Geologic section

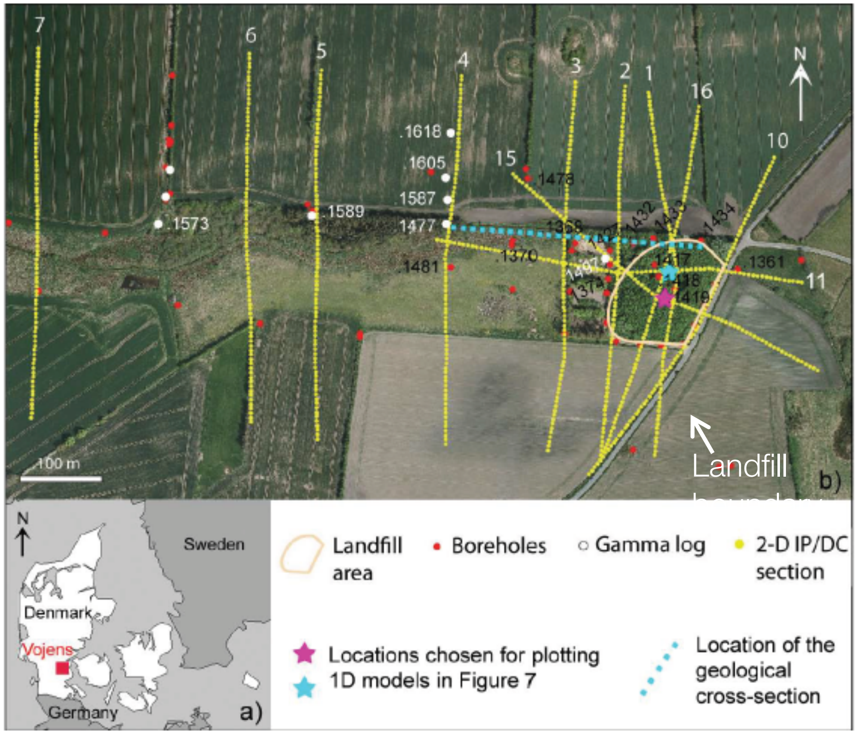


Physical properties

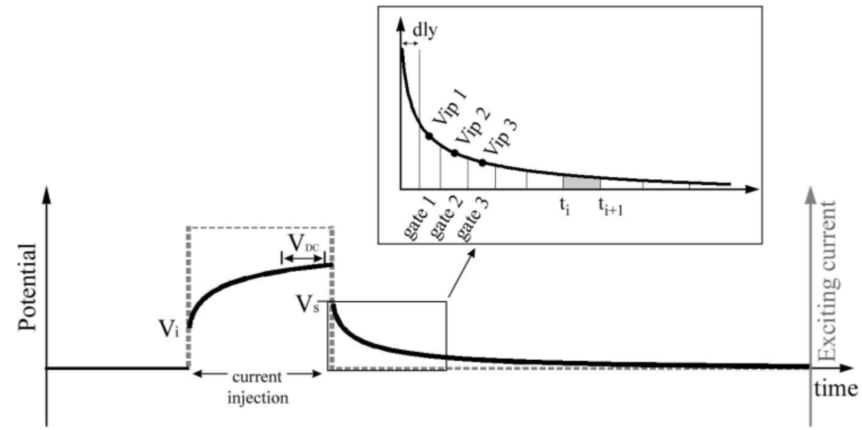
	Resistivity	Chargeability	Gamma
sand/gravel	High	Low	Low
clay/till	Low	High	High
sand	High	Low	Low
landfill	High (?)	High	(?)

Survey

Study area



Time domain IP (TDIP)



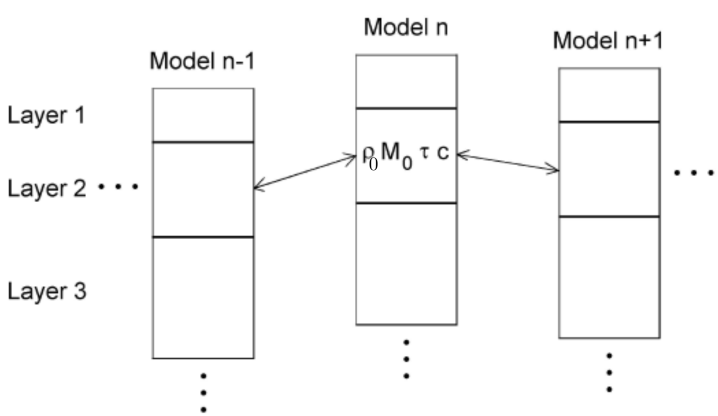
Data (chargeability):

$$M_i = \frac{1}{V_{DC} \cdot [t_{i+1} - t_i]} \int_{t_i}^{t_{i+1}} V_{ip} \, dt$$

- Well logs:
  - 25 boreholes, ~85 m depth
  - Gamma logs (white dots)
  - Induction and resistivity logs
- DC-IP survey:
  - 11 lines (each ~410 m)
  - Gradient array
  - Input current: 4sec on and 4sec off
  - 20 time gates (8 per decade)

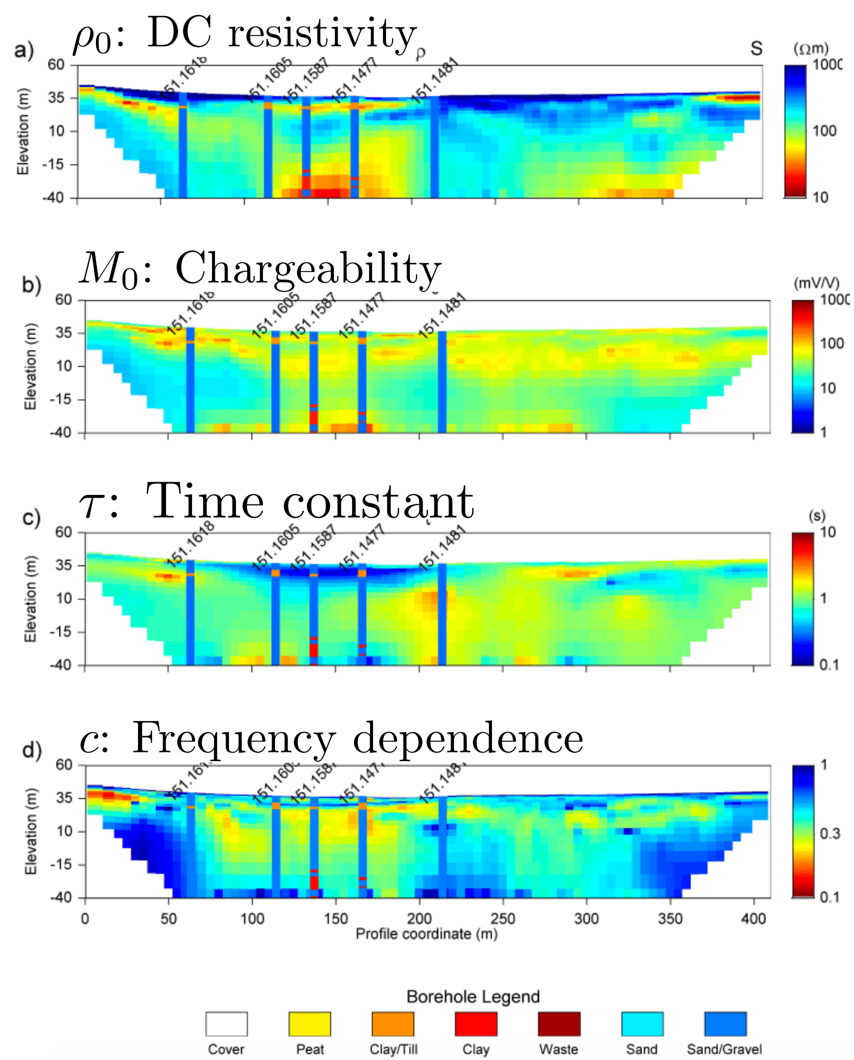
Processing / Inversion

- Cole-Cole inversion:
  - Laterally constrained inversion (LCI)
  - Invert for Cole-Cole parameters



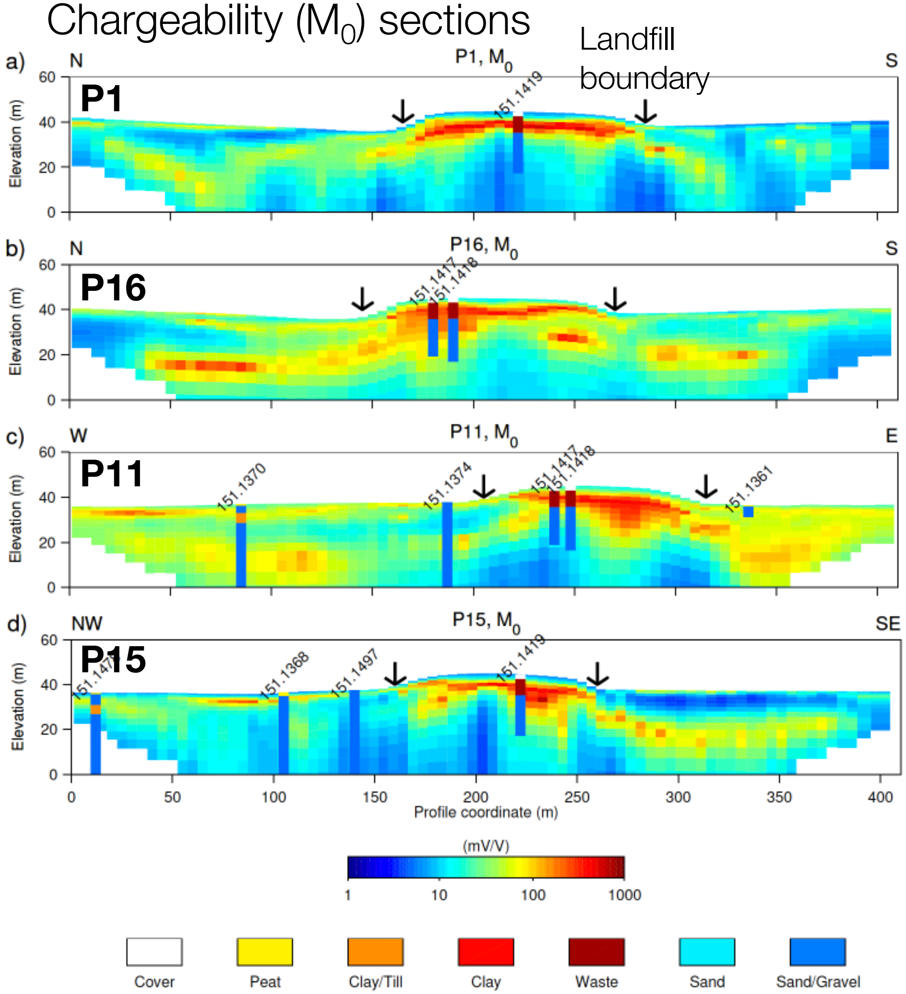
$$\rho(\omega) = \rho_0 \left[1 + M_0 \left(1 - \frac{1}{1 + (i\omega\tau)^c} \right) \right]$$

Recovered Cole-Cole sections:

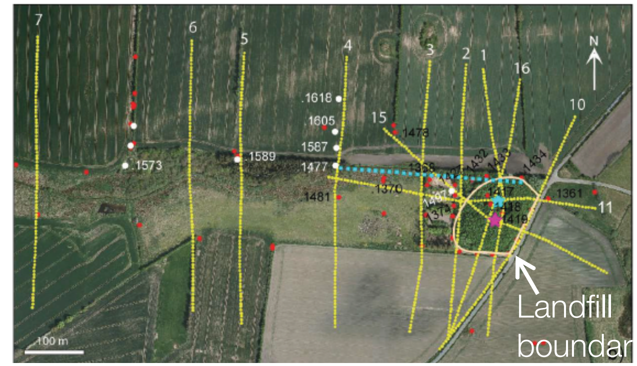


Interpretation: Delineating the landfill

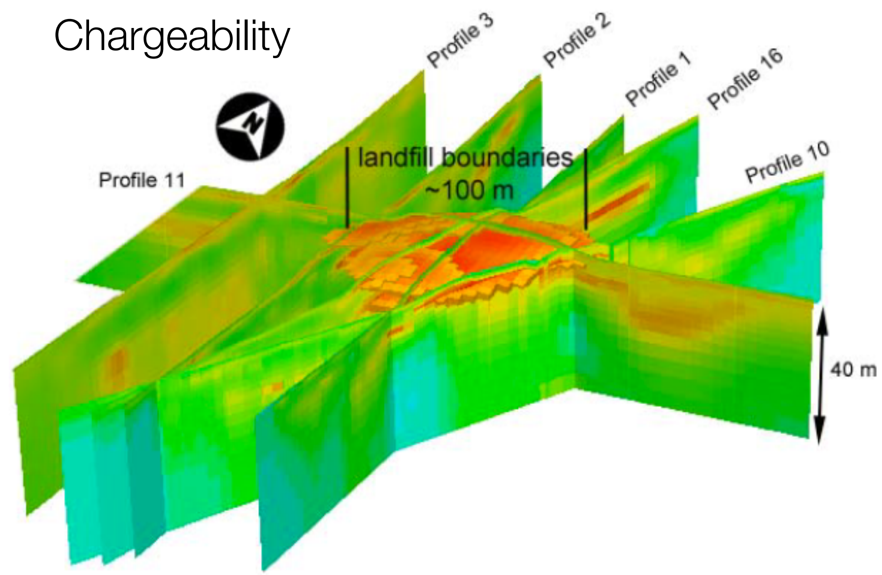
Chargeability (M_0) sections



Location map



Chargeability

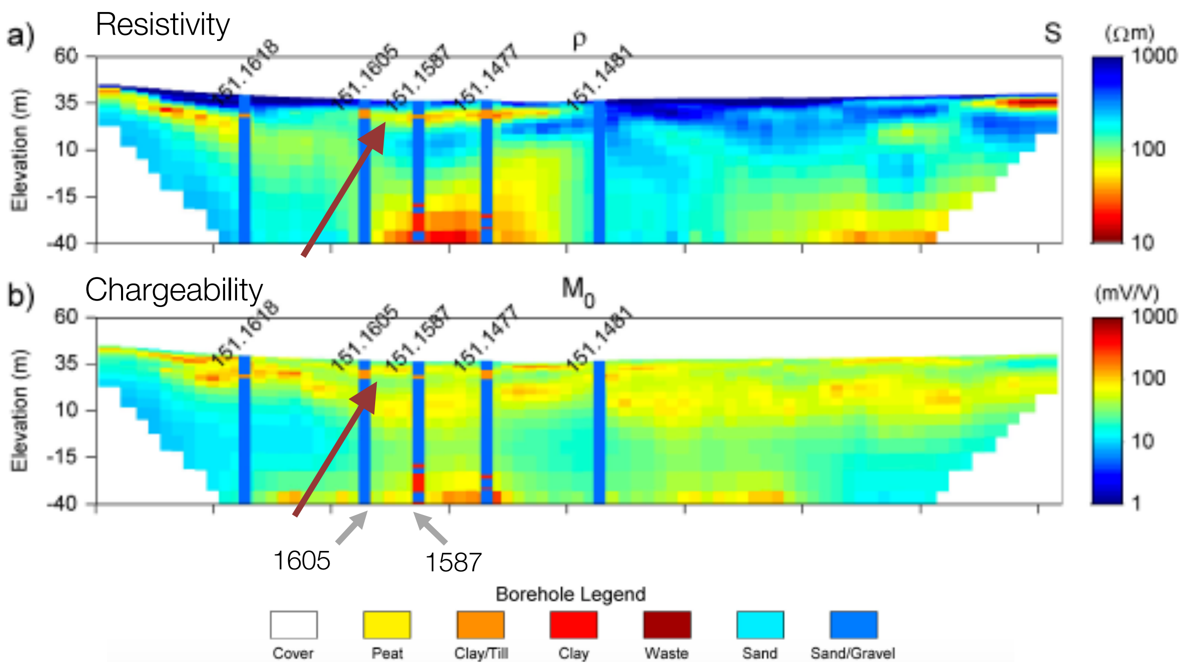


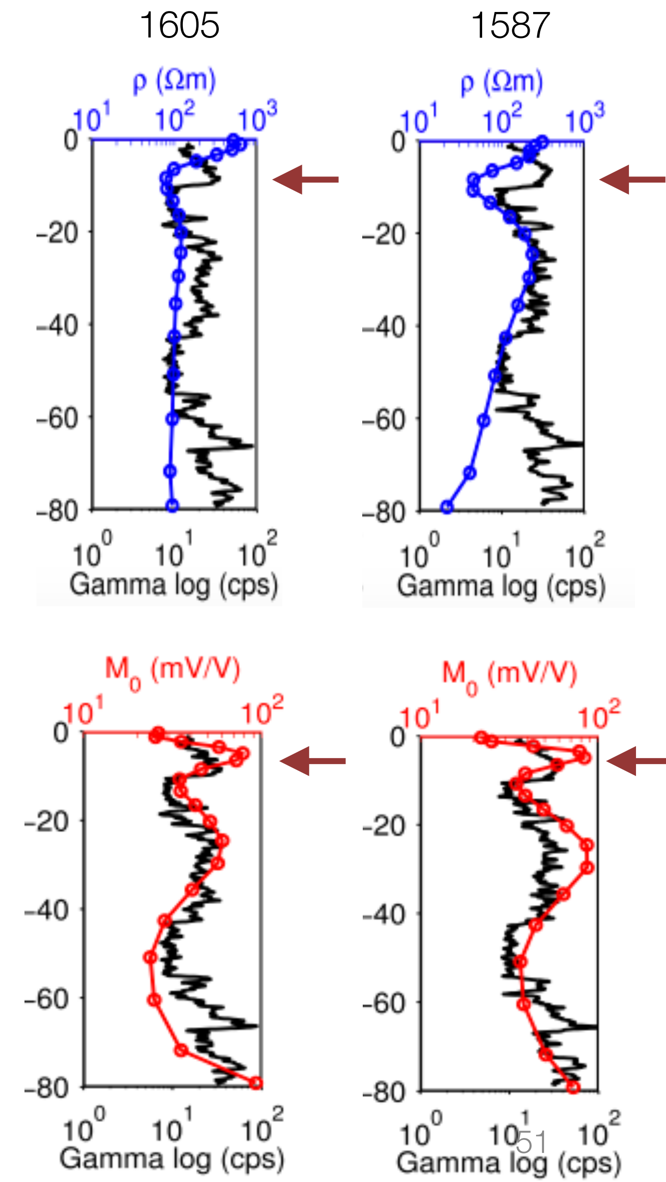
Estimated volume

Using 100 mV/V cutoff: 50,000m^3
From historic record: 65,000m^3

Interpretation: Clay layer (Aquitard)

Resistivity and chargeability sections





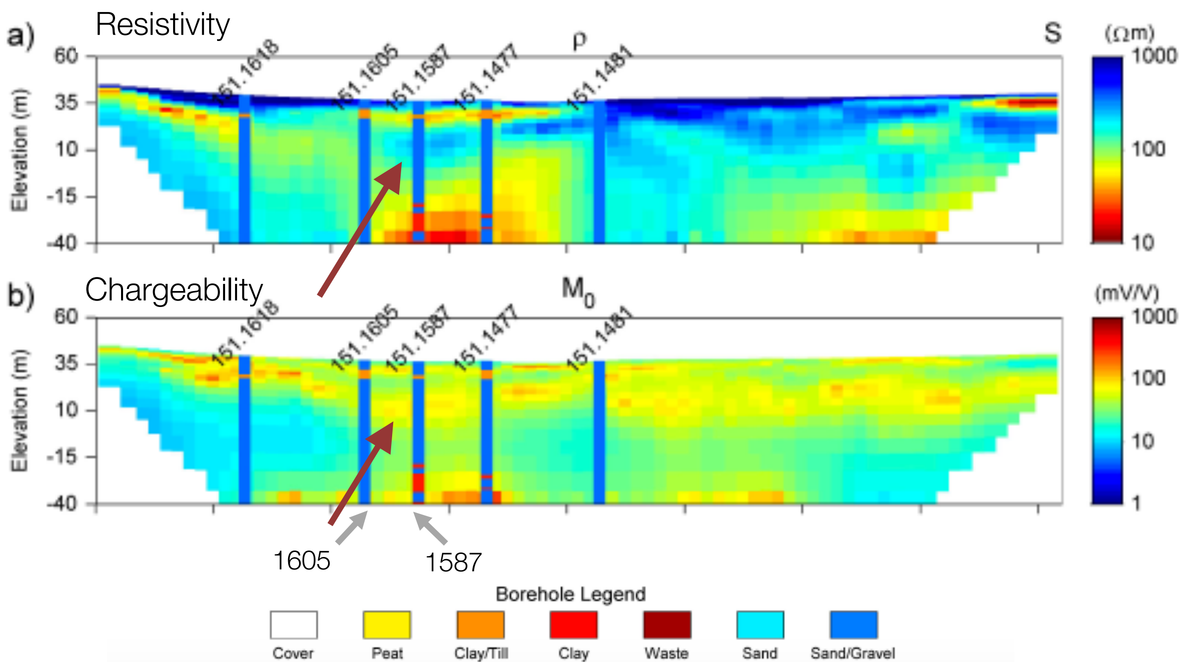
Formation	Resistivity	Chargeability	Gamma
Clay	Low (60 ohm m)	High	High

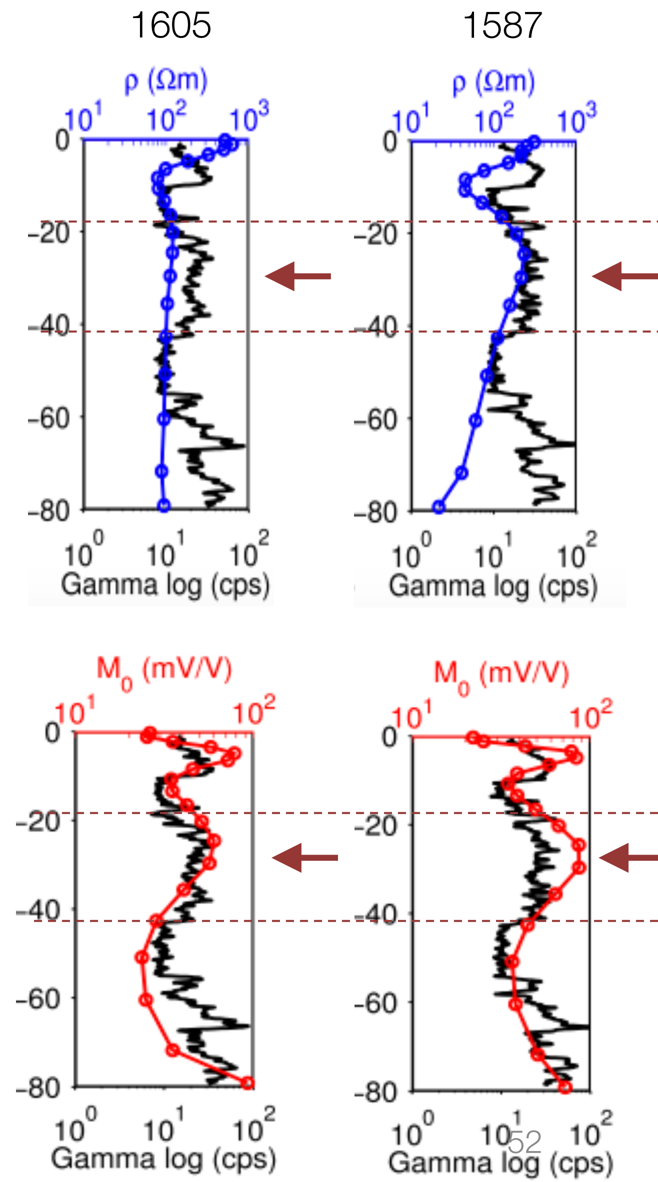
Interpretation

- Creek overlays the clay layer (acts as aquitard)

Interpretation: Clay-rich sandy layer

Resistivity and chargeability sections

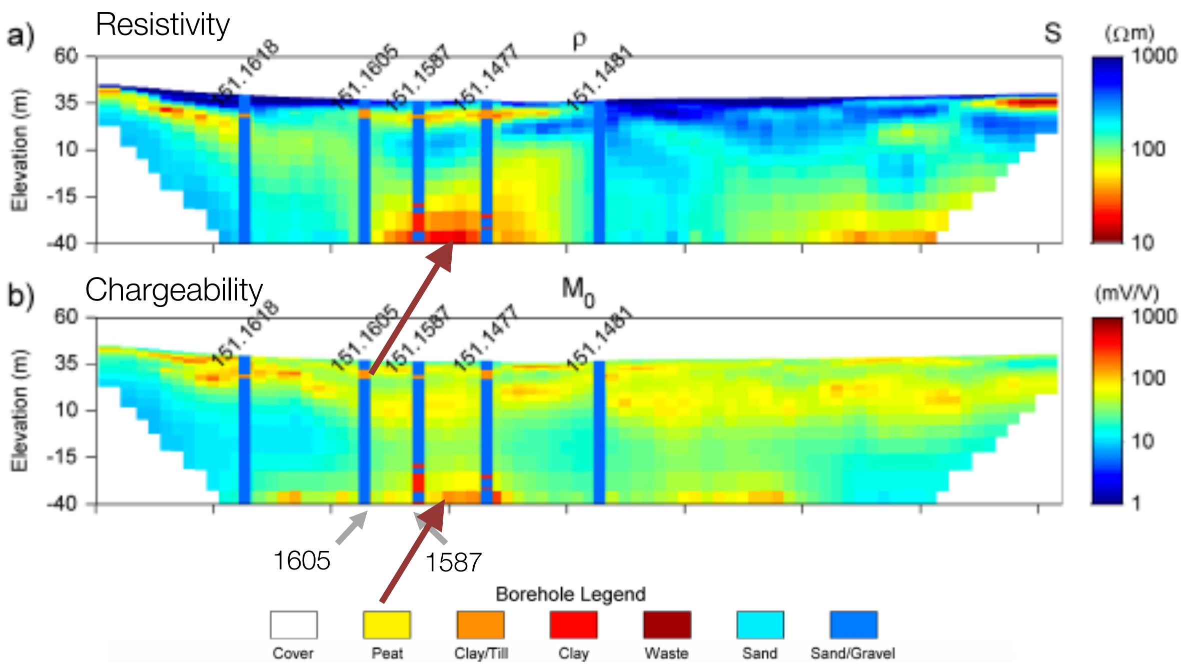


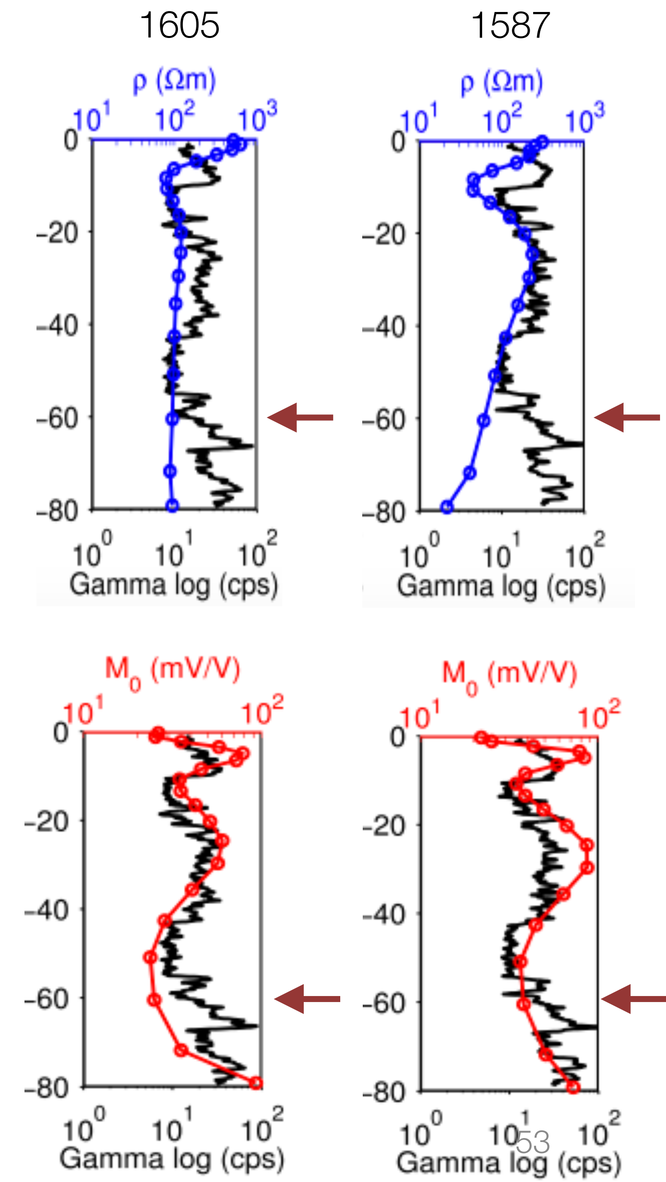


Formation	Resistivity	Chargeability	Gamma
Clay	Low	High	High
Clay-rich sandy layer	High	Moderate (50-100 mV/V)	High

Interpretation: Silt/clay lens

Resistivity and chargeability sections

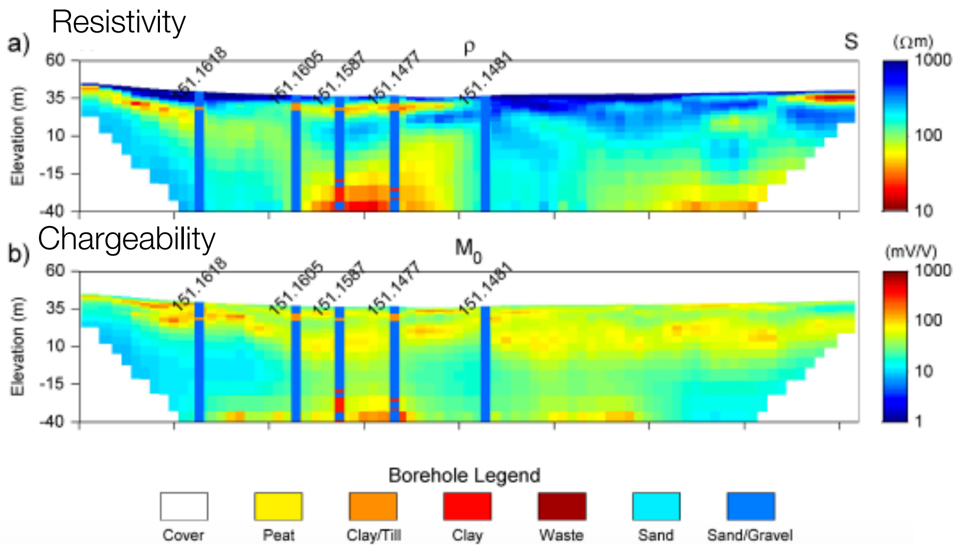




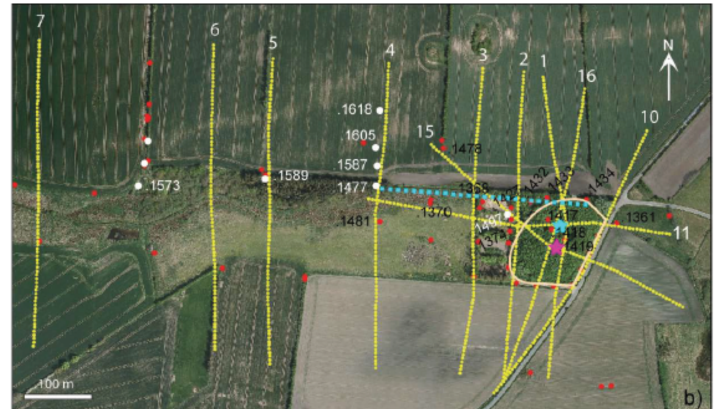
Formation	Resistivity	Chargeability	Gamma
Clay	Low	High	High
Clay rich sandy layer	High	Moderate (50-100 mV/V)	High
Silt/clay lens	Low	High	High

Interpretation: Lithology

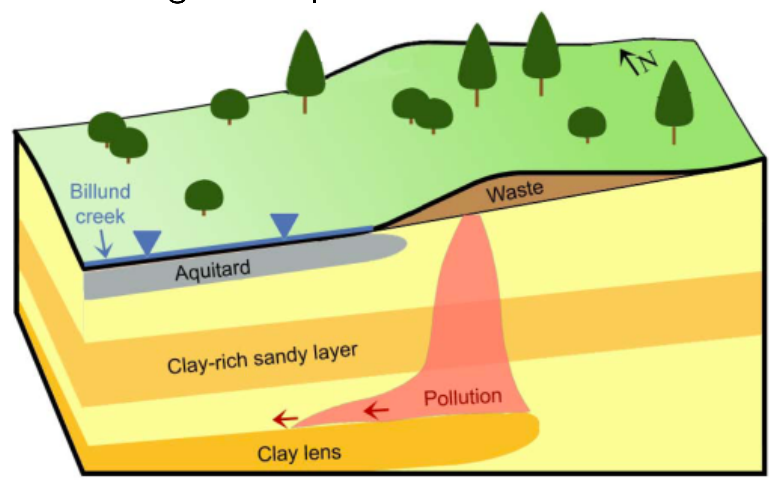
Resistivity and chargeability sections



Location map

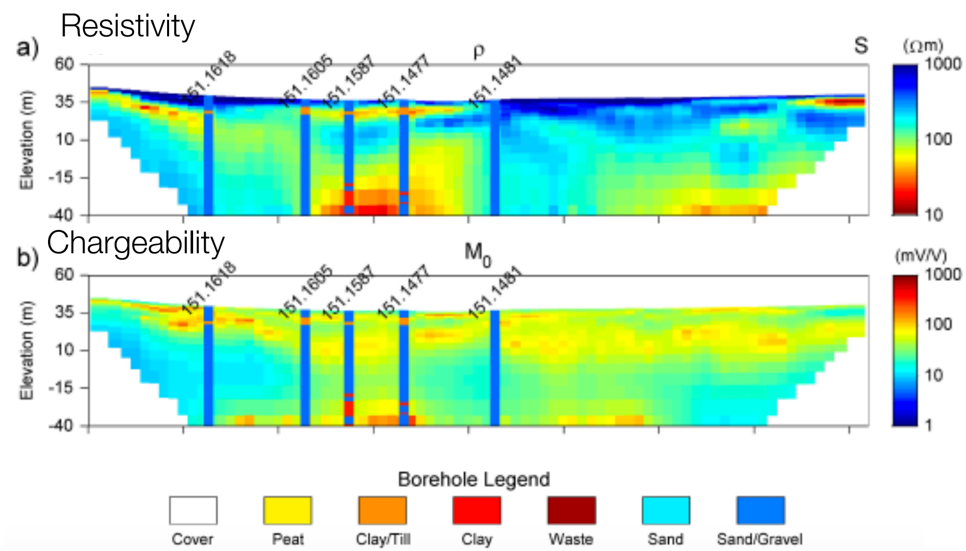


Geologic interpretation

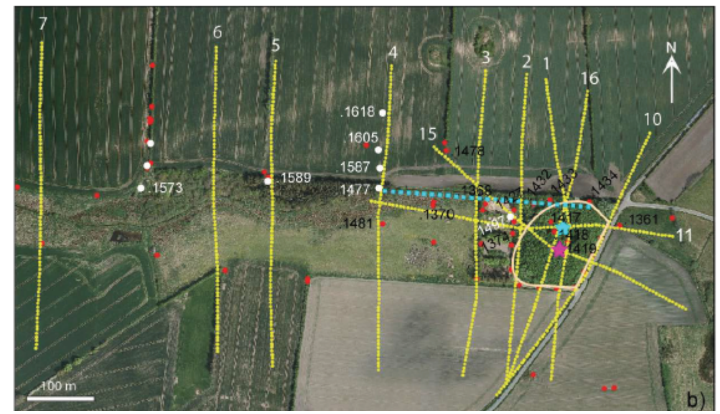


Interpretation: Lithology

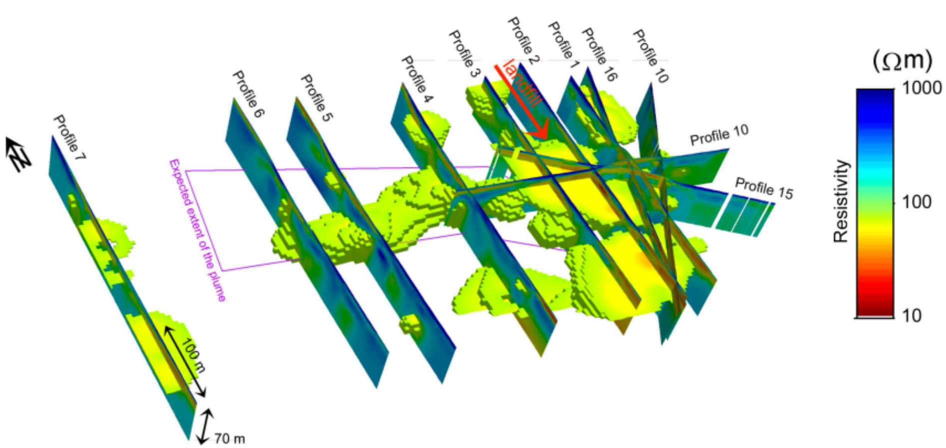
Resistivity and chargeability sections



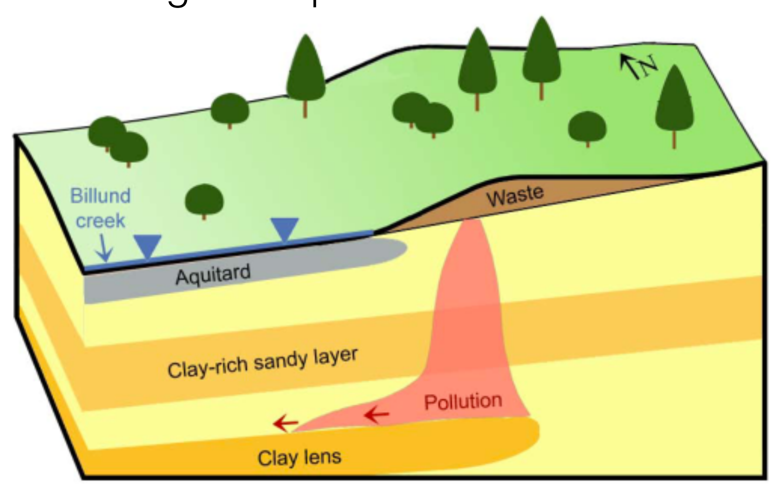
Location map



Resistivity cut-off volume (<100 Ωm)

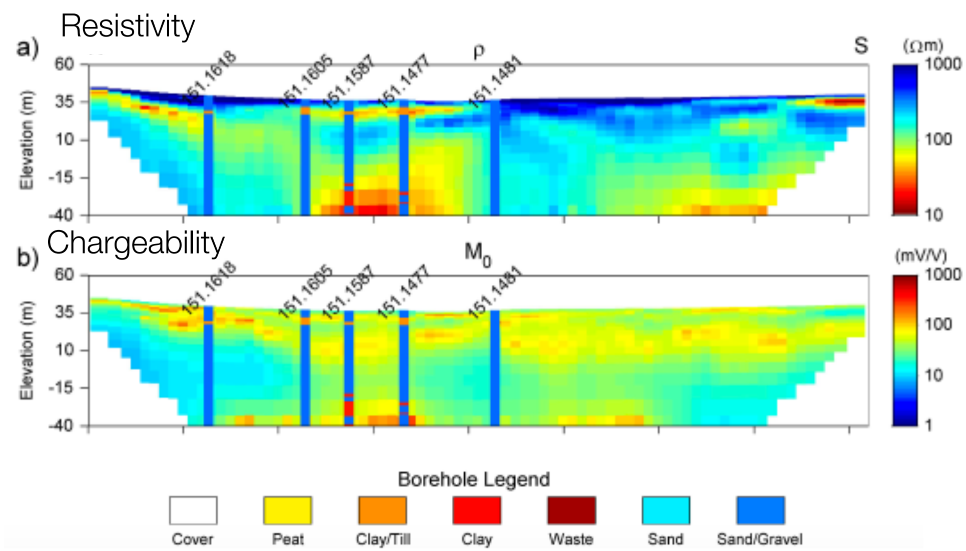


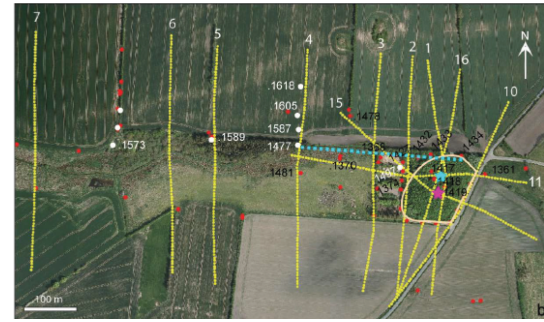
Geologic interpretation



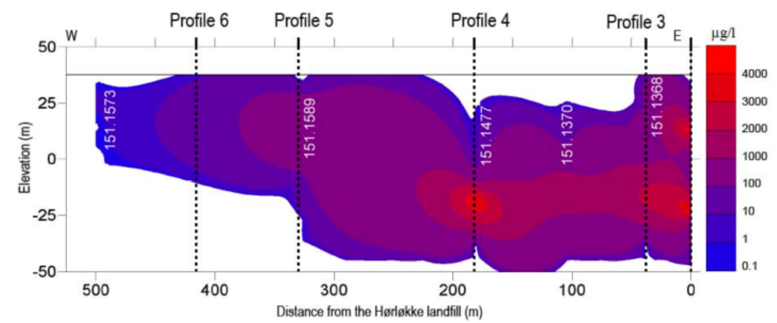
Synthesis: delineating the leachate

Resistivity and chargeability sections

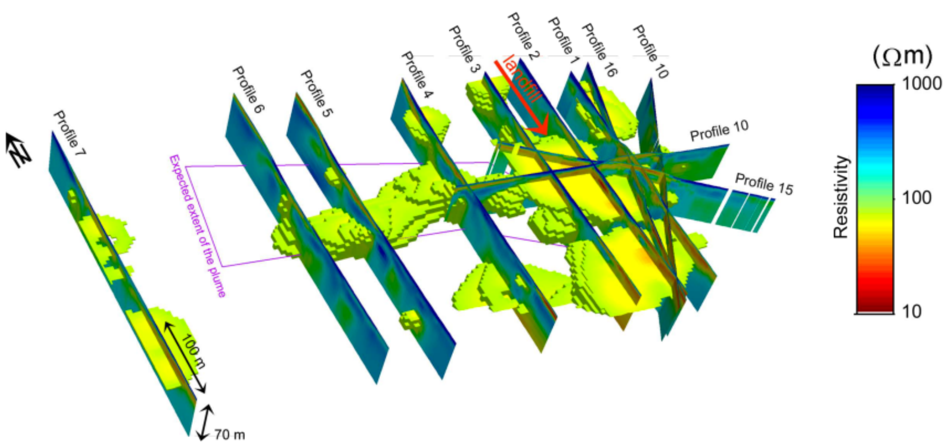




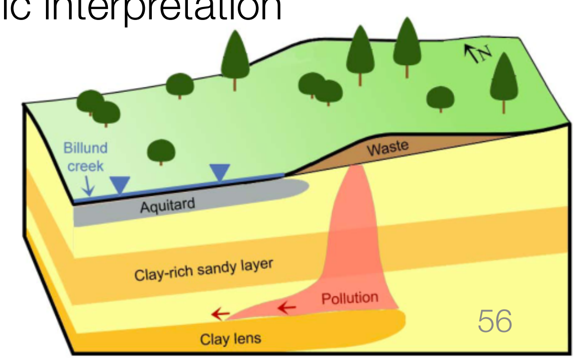
Contaminated plume section



Resistivity cut-off volume (<100 Ωm)

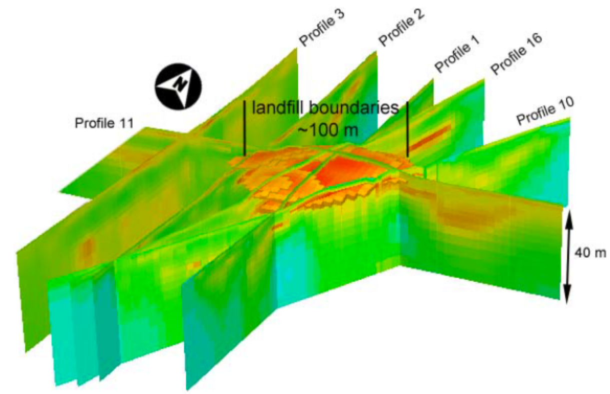


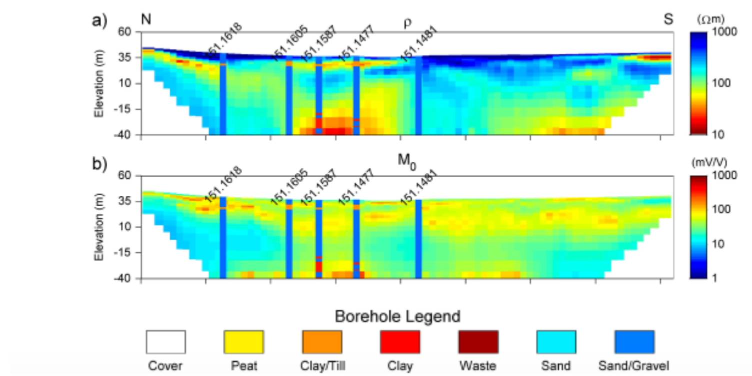
Geologic interpretation

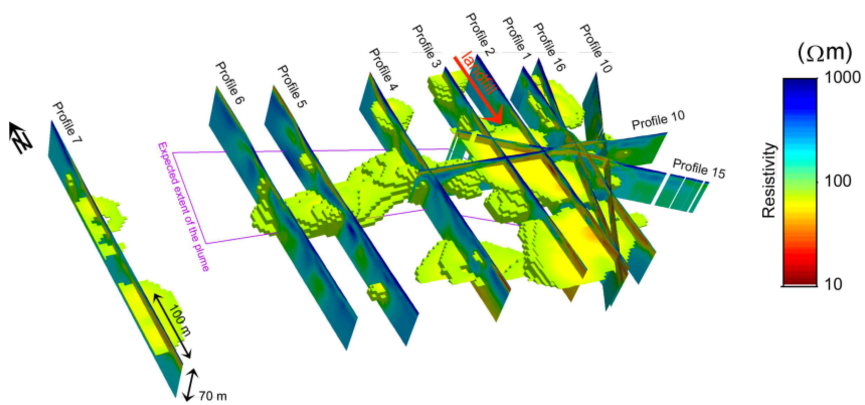


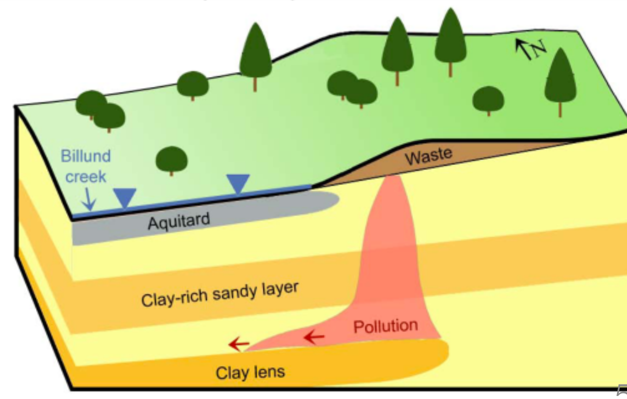
Summary

- Found boundaries for the waste
- Estimated volume for the waste
- Delineated the leachate plume
- Lithology of the background
  - Aquitard
  - Clay-rich sandy layer
  - Clay lens

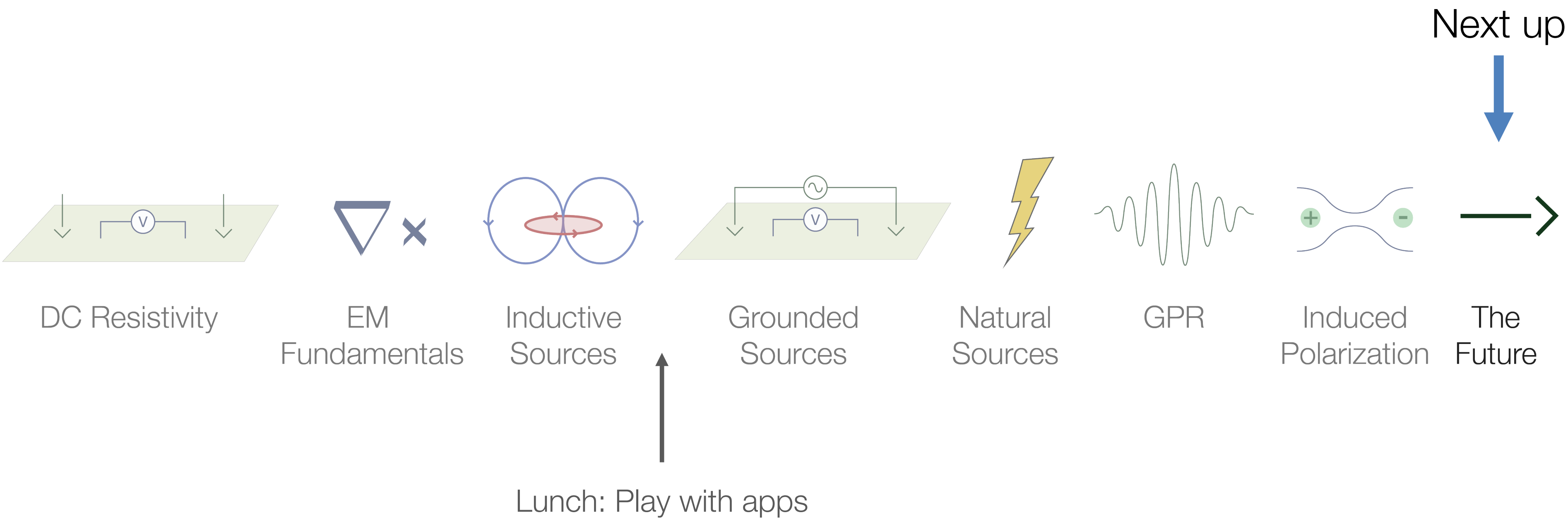








End of IP


Next up
DC Resistivity
EM Fundamentals
Inductive Sources
Grounded Sources
Natural Sources
GPR
Induced Polarization
The Future
Lunch: Play with apps