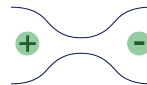
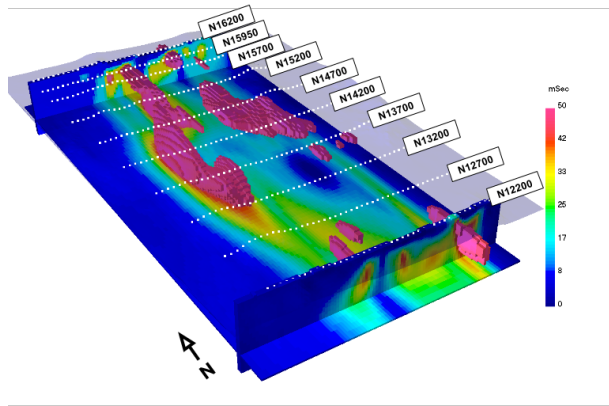


Induced Polarization

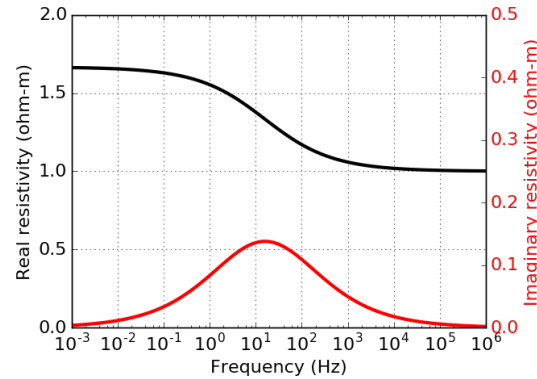


Motivation

Minerals



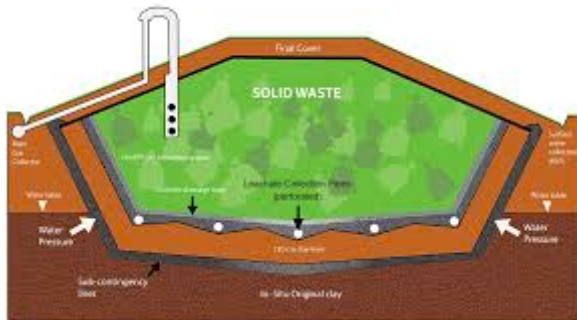
Complex resistivity



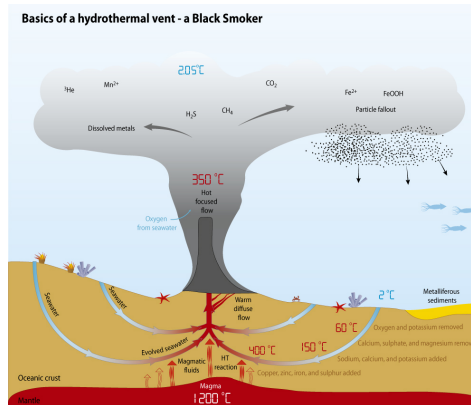
Permafrost



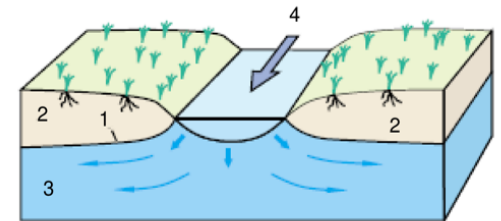
Geotechnical



Seafloor massive sulfide



Groundwater

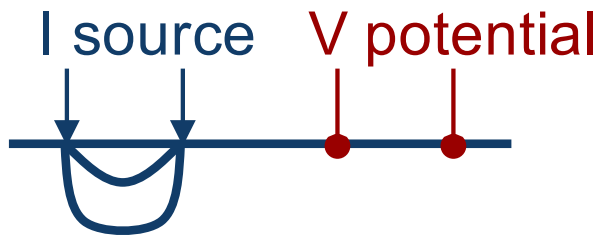


Outline

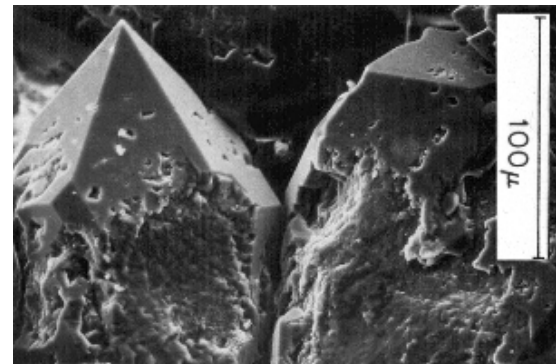
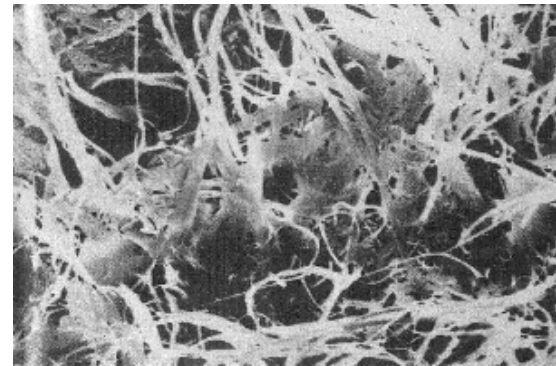
- Sources of IP
- Conceptual model of IP
- Chargeability
- IP data
- Pseudosections
- Two stage DC-IP inversion
- Case history: Mt. Isa
- EM Decoupling
- Case History: TKC (Airborne IP)

Induced Polarization

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



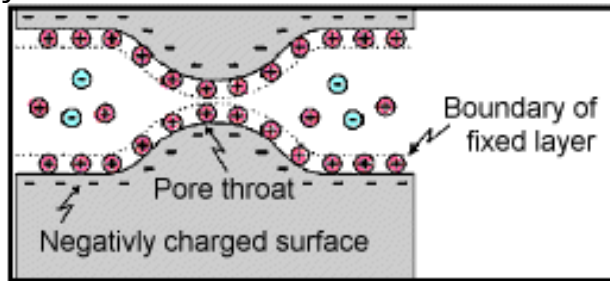
	Not chargeable	Chargeable
Source (Amps)		
Potential (Volts)		



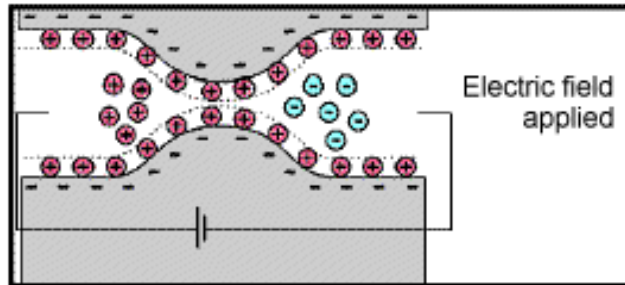
Conceptual Model of IP

Membrane polarization

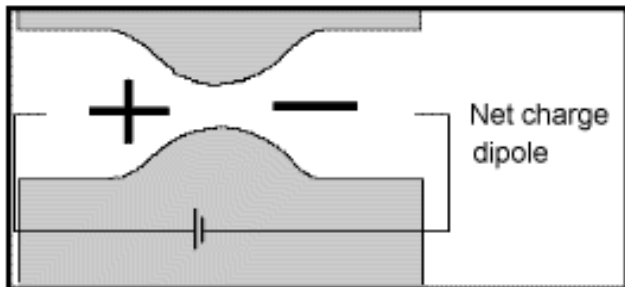
Initially - neutral



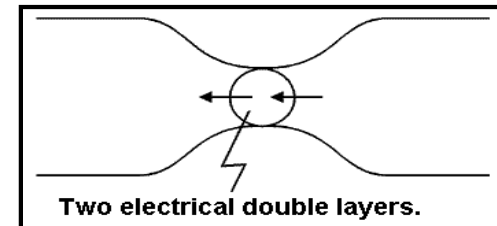
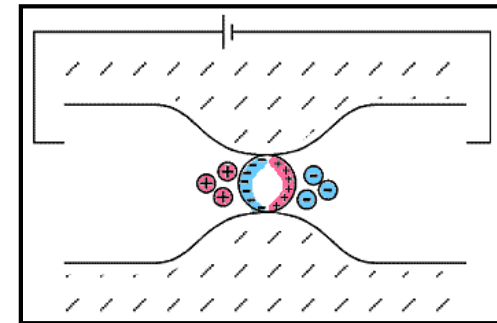
Apply electric field, build up charges



Charge polarization, Electric dipole

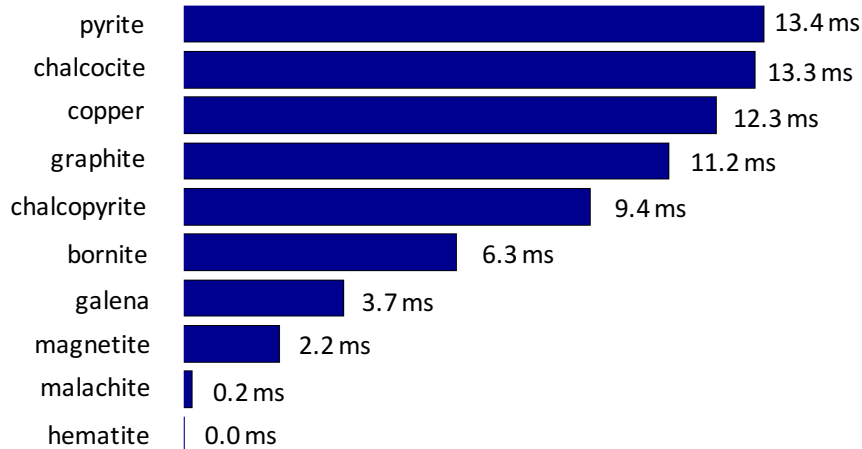


Electrode polarization



Chargeability

Minerals at 1% Concentration in Samples

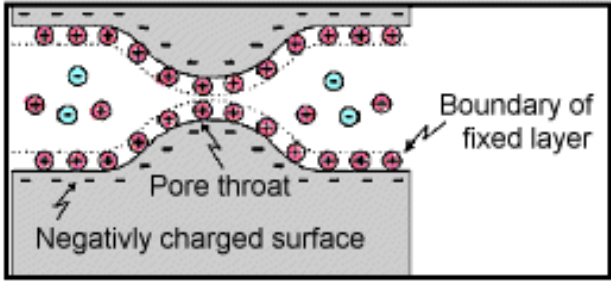


Material type	Chargeability (msec.)
20% sulfides	2000 - 3000
8-20% sulfides	1000 - 2000
2-8% sulfides	500 - 1000
volcanic tuffs	300 - 800
sandstone, siltstone	100 - 500
dense volcanic rocks	100 - 500
shale	50 - 100
granite, granodiorite	10 - 50
limestone, dolomite	10 - 20

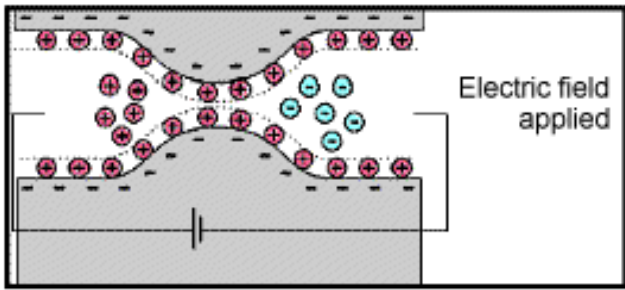
Material type	Chargeability (msec.)
ground water	0
alluvium	1 - 4
gravels	3 - 9
precambrian volcanics	8 - 20
precambrian gneisses	6 - 30
schists	5 - 20
sandstones	3 - 12

Chargeability

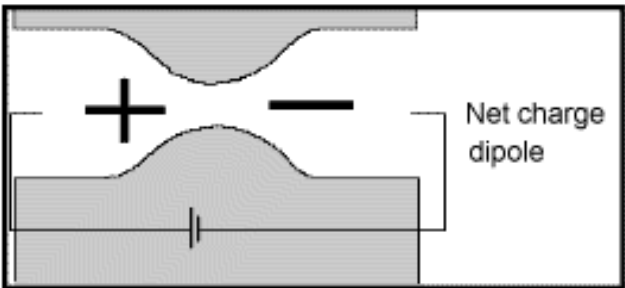
Initially - neutral



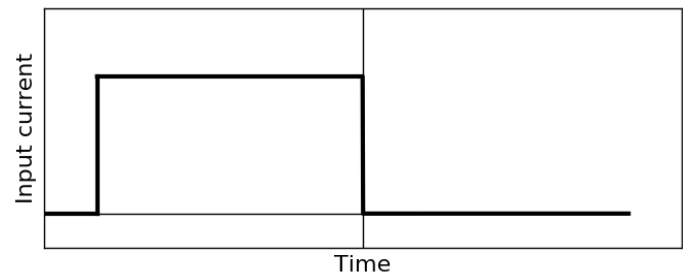
Apply electric field, build up charges



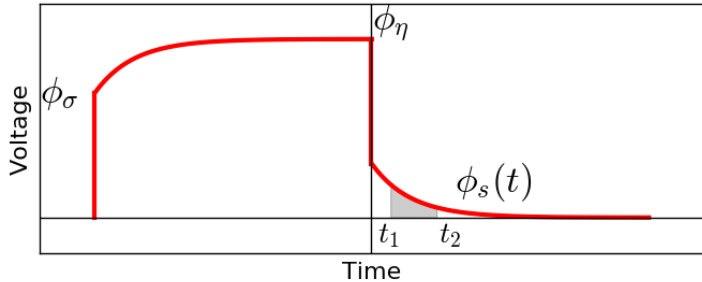
Charge polarization, Electric dipole



Input current



Measured voltage



IP data

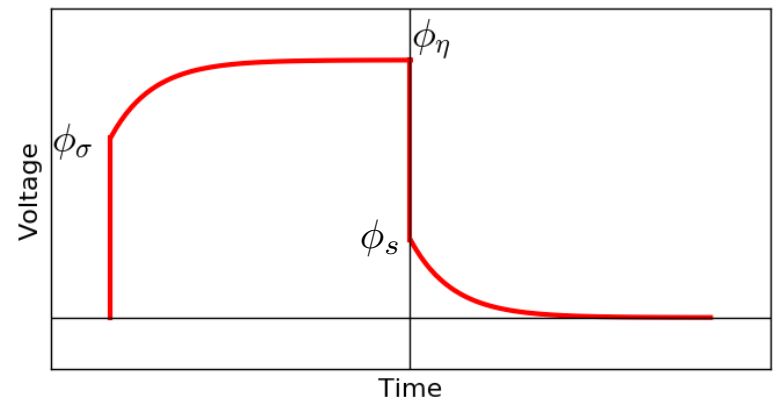
- Seigel (1959):
 - Introduced chargeability: η
 - Effect reduces conductivity

$$\sigma_{\eta} = \sigma(1 - \eta) \quad \eta \in [0, 1)$$

- Theoretical chargeability data

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

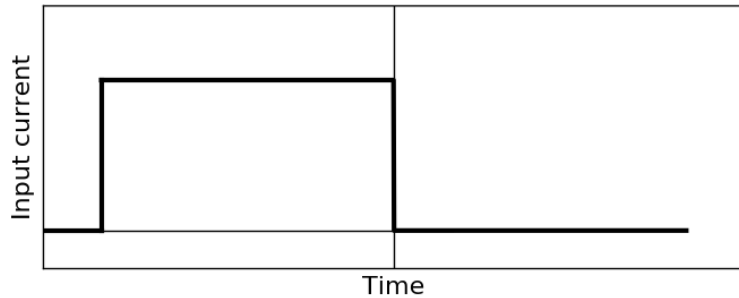
- Not directly measurable



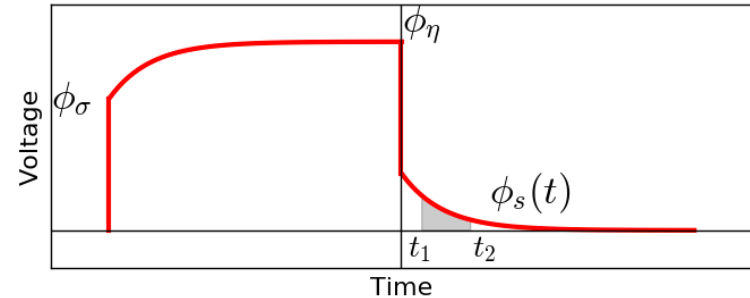
IP data: time domain

- IP decay

Input current



Measured voltage



- IP datum

Dimensionless:

$$\eta = \phi_s / \phi_\eta$$

Value at individual time channel:

$$\phi_s(t)$$

Area under decay curve:

$$M = \frac{1}{\phi_\eta} \int_{t_1}^{t_2} \phi_s(t) dt$$

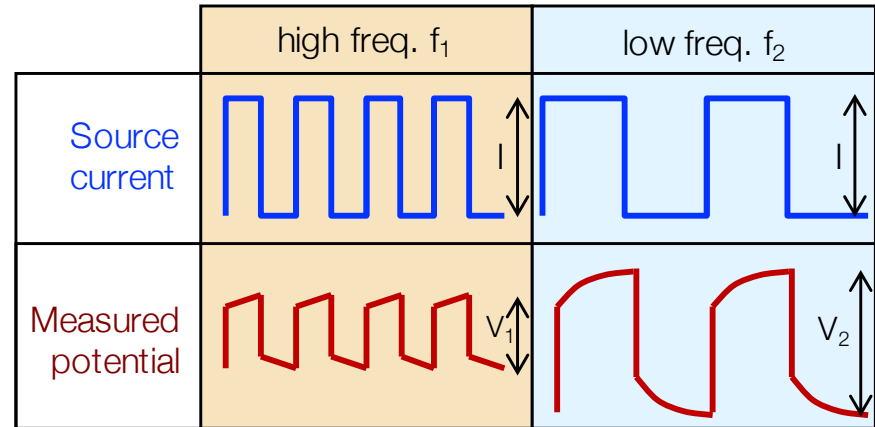
IP data: frequency domain

- Percent frequency effect:

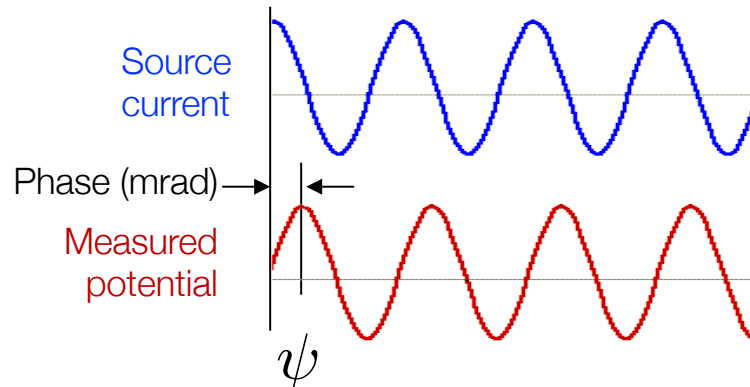
$$PFE = 100 \left(\frac{\rho_{a2} - \rho_{a1}}{\rho_{a1}} \right)$$

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

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

- An IP datum can be written as

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

$$J_{ij} = \frac{\partial \log \phi^i}{\partial \log \sigma_j} \quad \text{sensitivities for the DC resistivity problem}$$

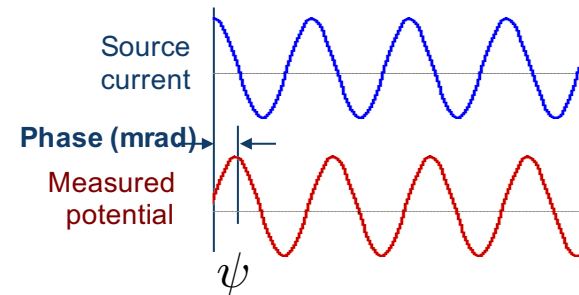
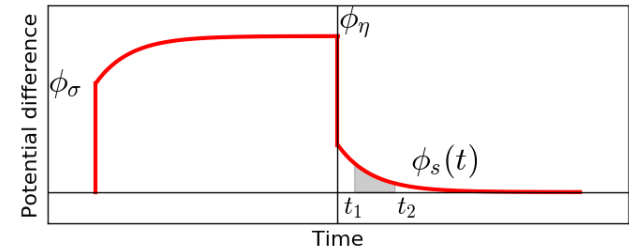
- In matrix form

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

\mathbf{J} is an $N \times M$ 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

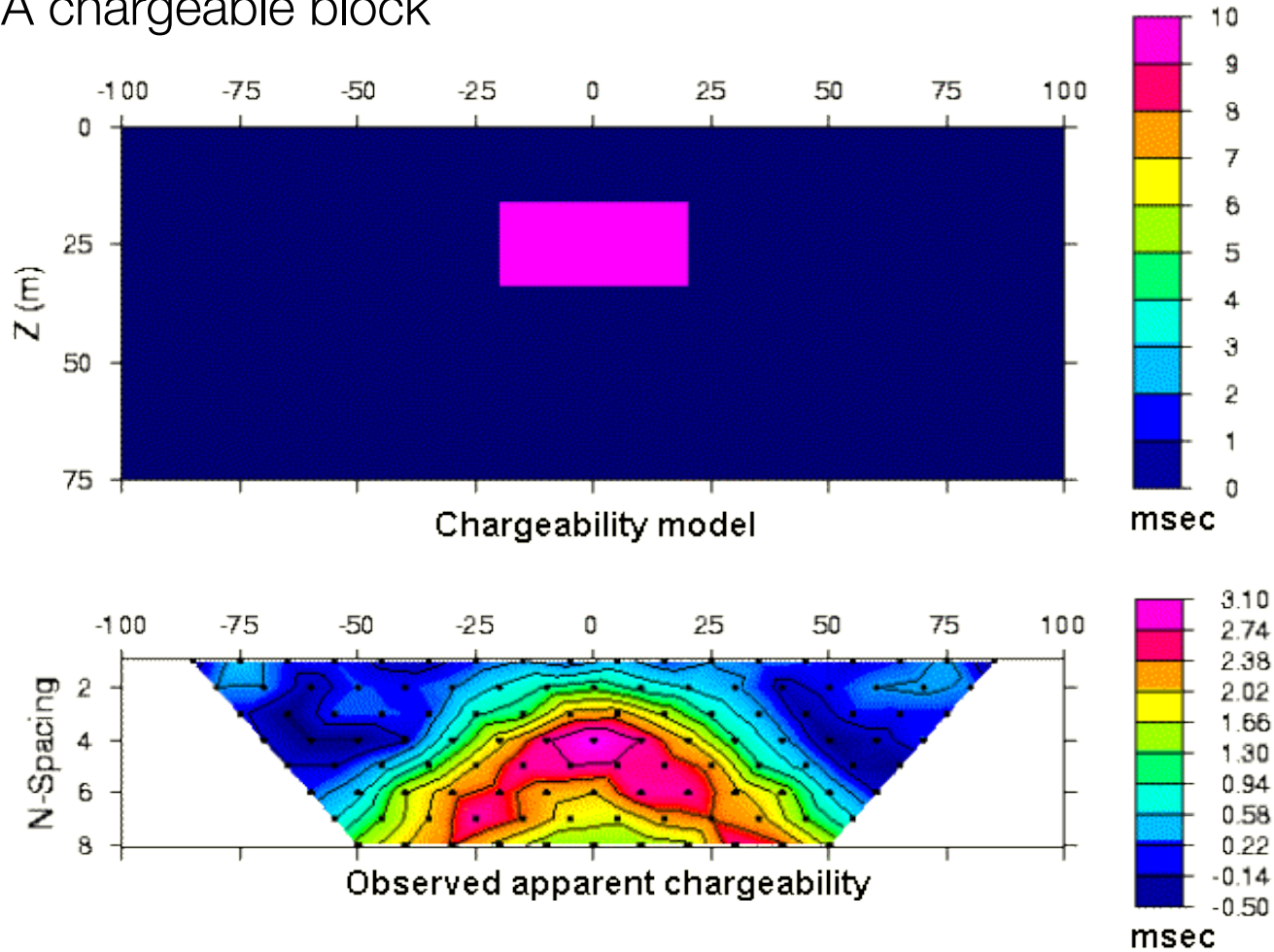


$$\mathbf{d}^{IP} = \mathbf{J}\boldsymbol{\eta}$$

J is an N×M matrix

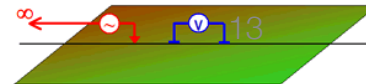
IP pseudosections

1) A chargeable block



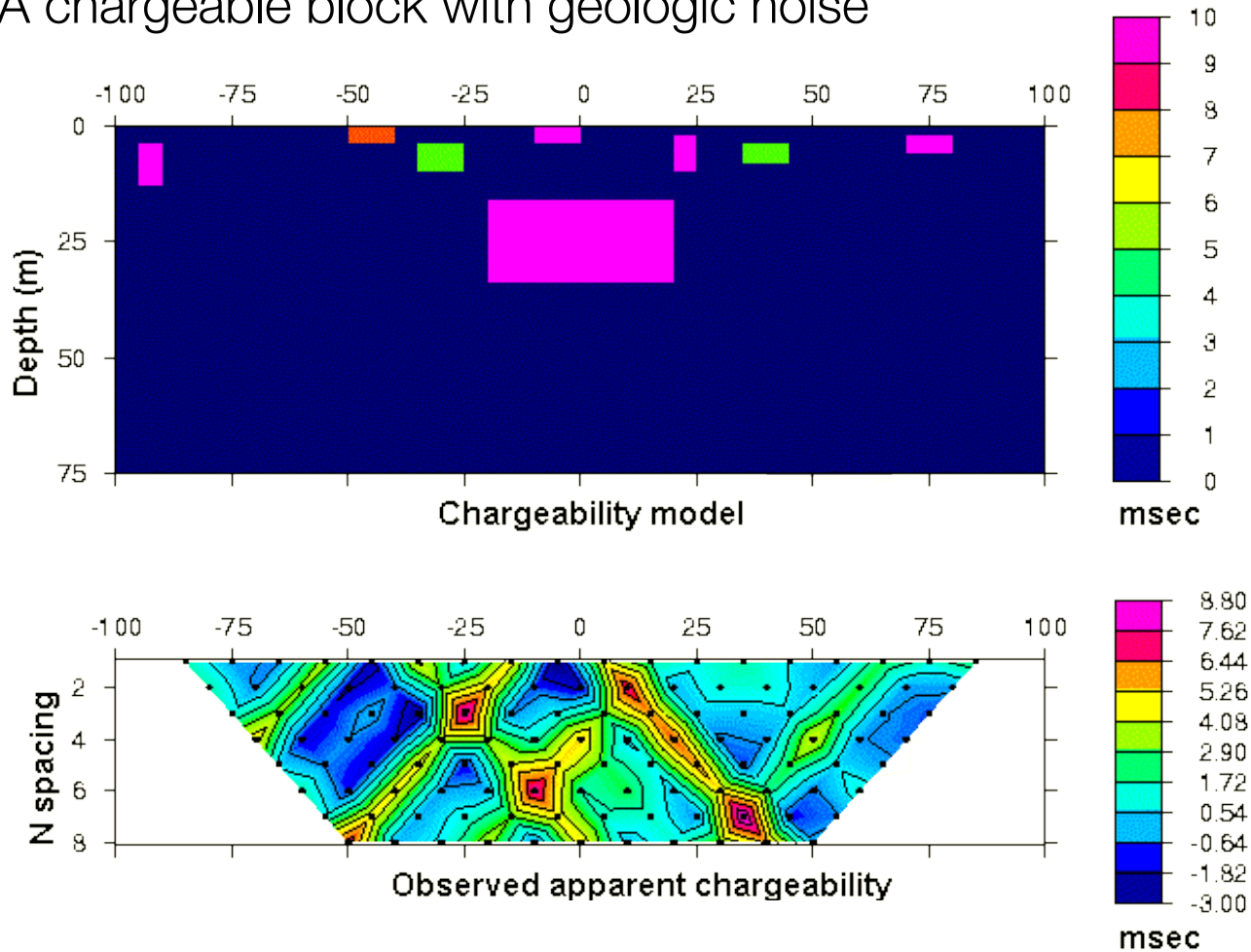
- Pole-dipole; $n=1,8$; $a=10\text{m}$; $N=316$

Pole-Dipole



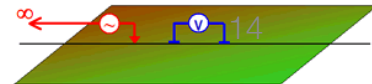
IP pseudosections

2) A chargeable block with geologic noise



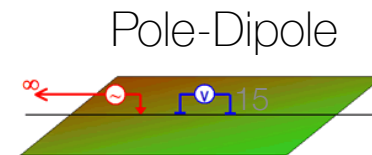
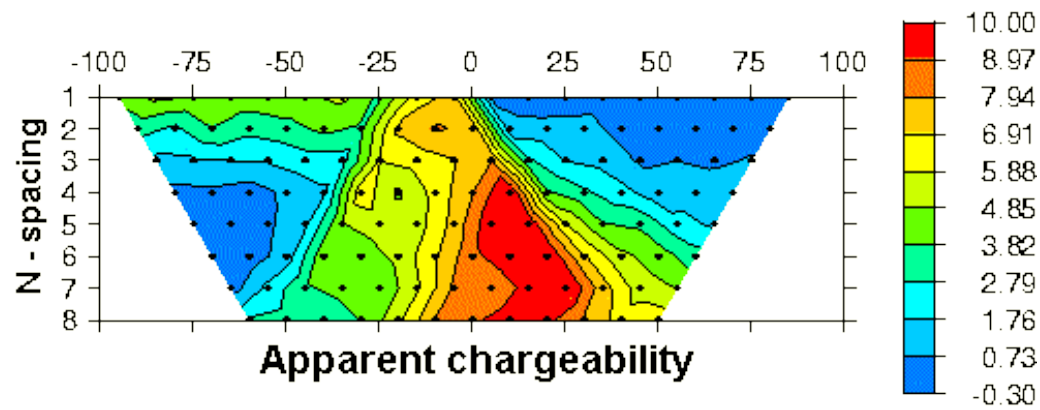
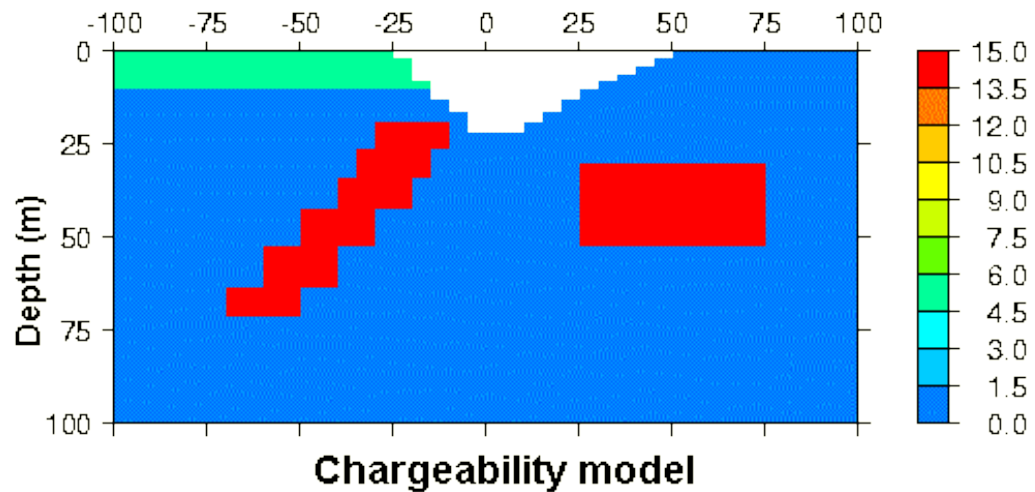
- Pole-dipole; $n=1,8$; $a=10\text{m}$; $N=316$

Pole-Dipole

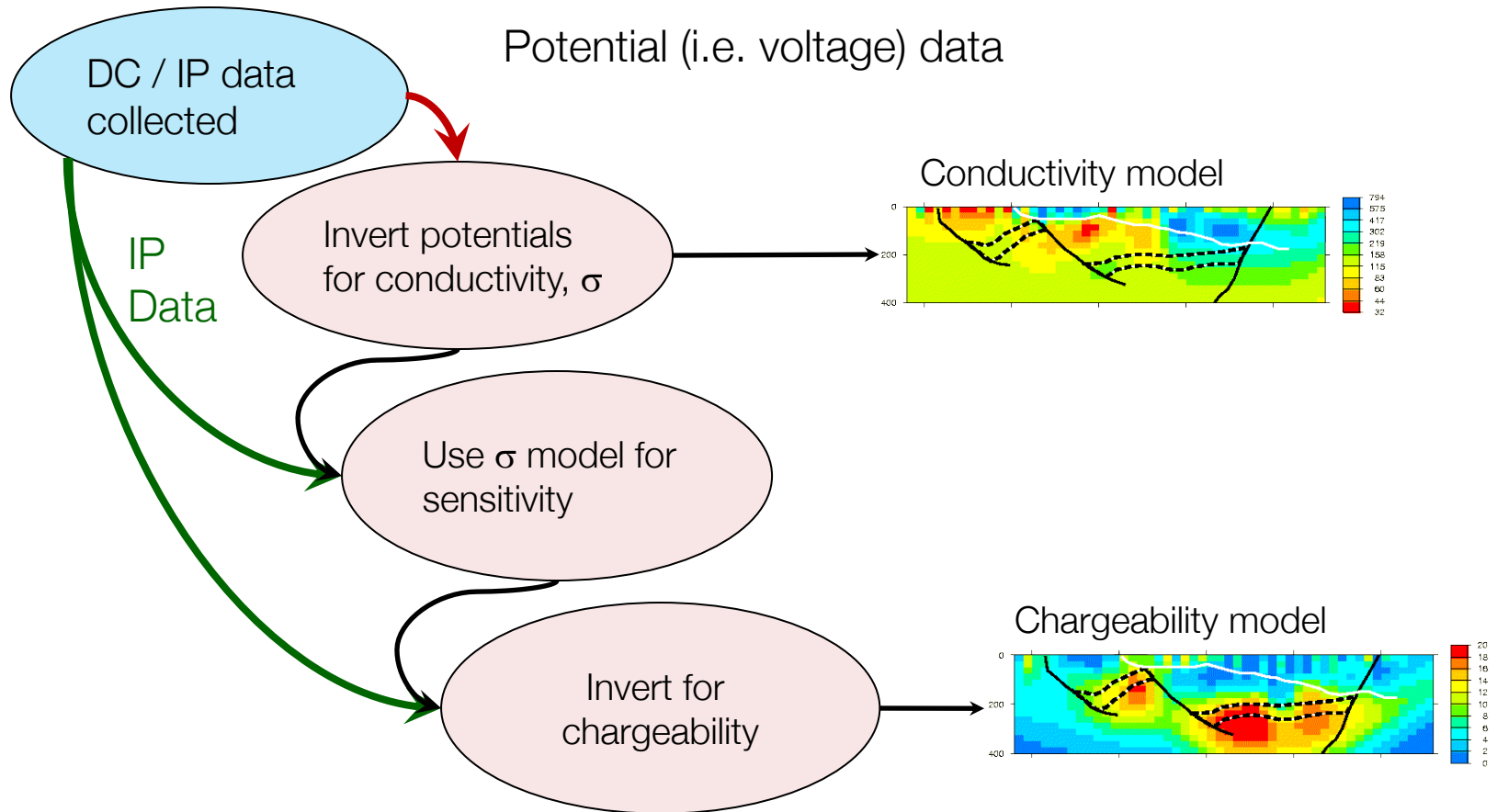


IP pseudosections

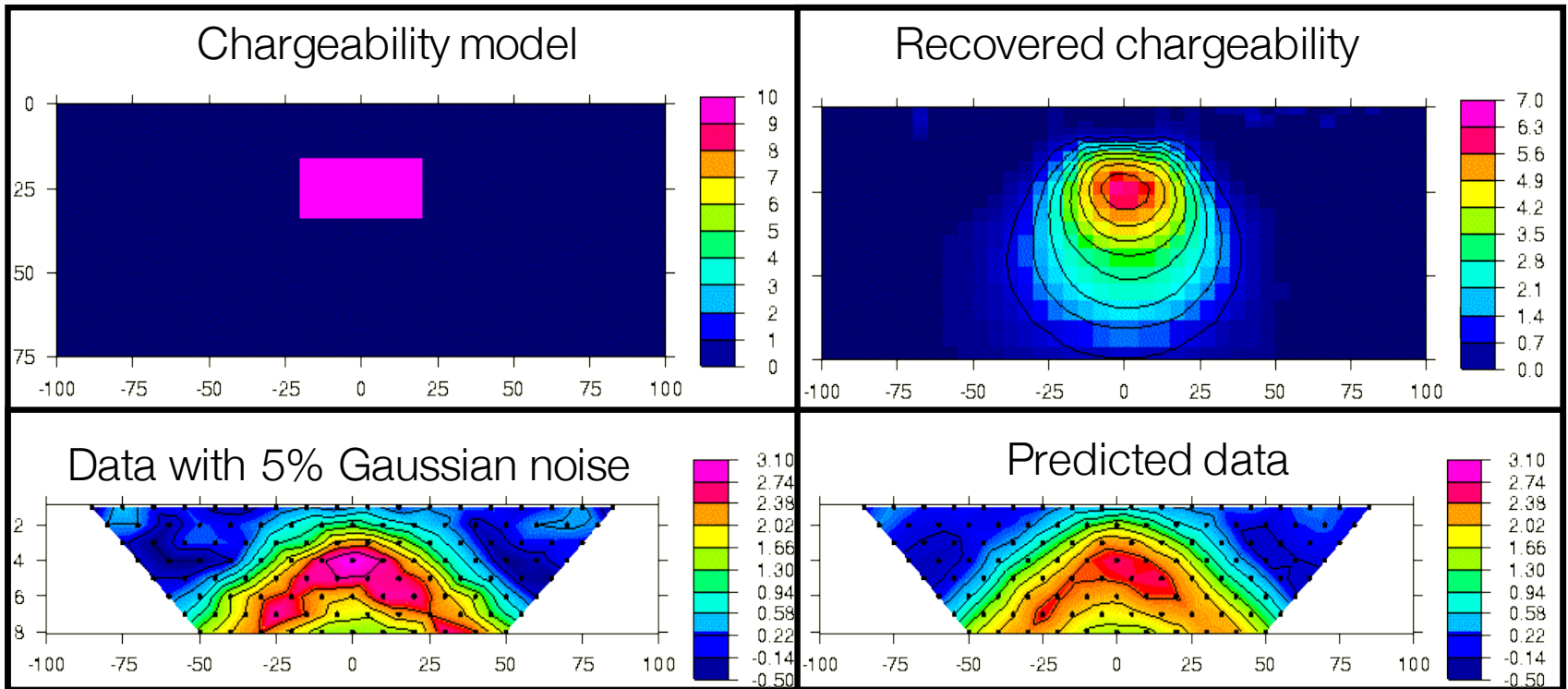
3) The “UBC-GIF model”



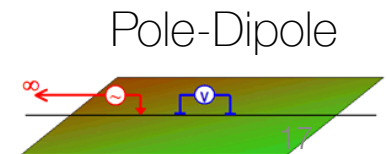
IP Inversion



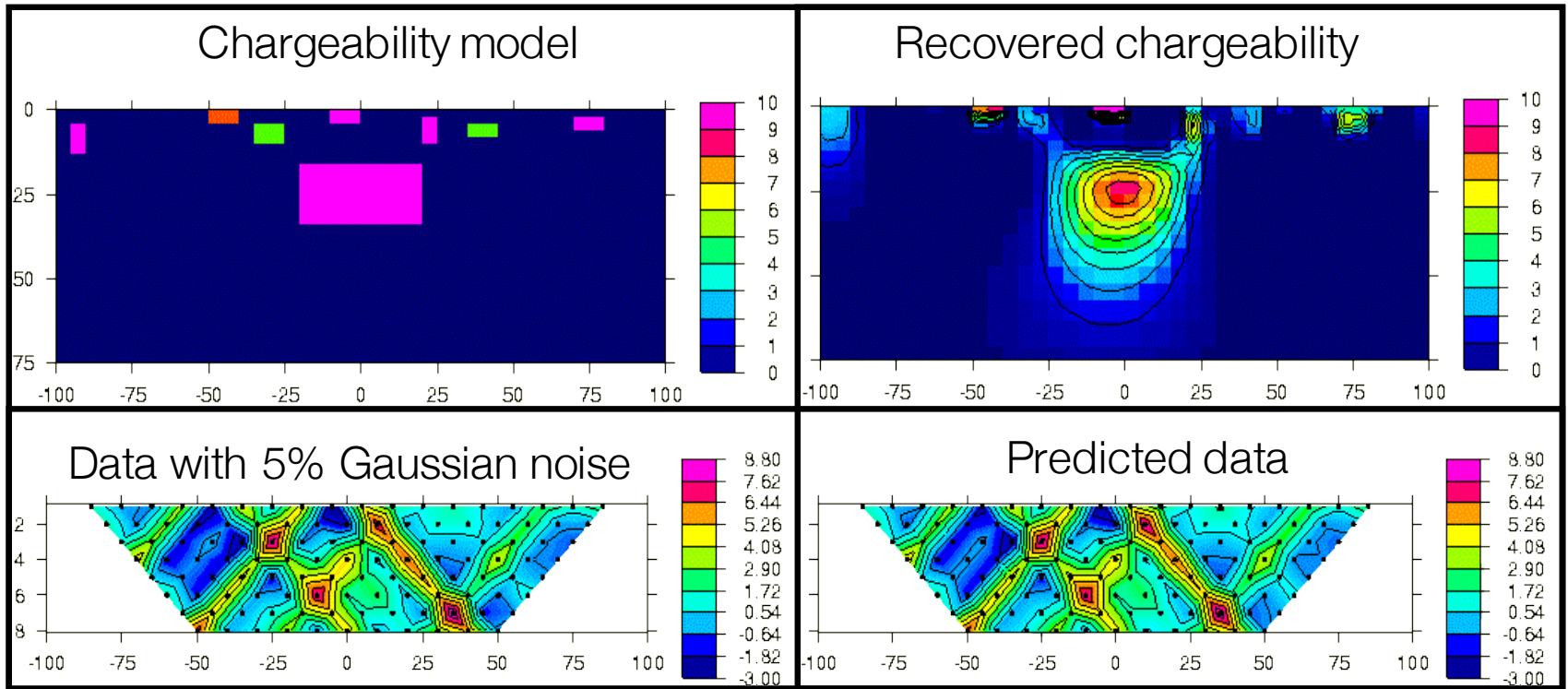
Example 1: buried prism



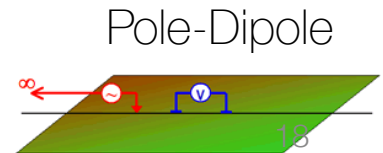
- Pole-dipole; $n=1,8$; $a=10\text{m}$; $N=316$; $(\alpha_s, \alpha_x, \alpha_z)=(.001, 1.0, 1.0)$



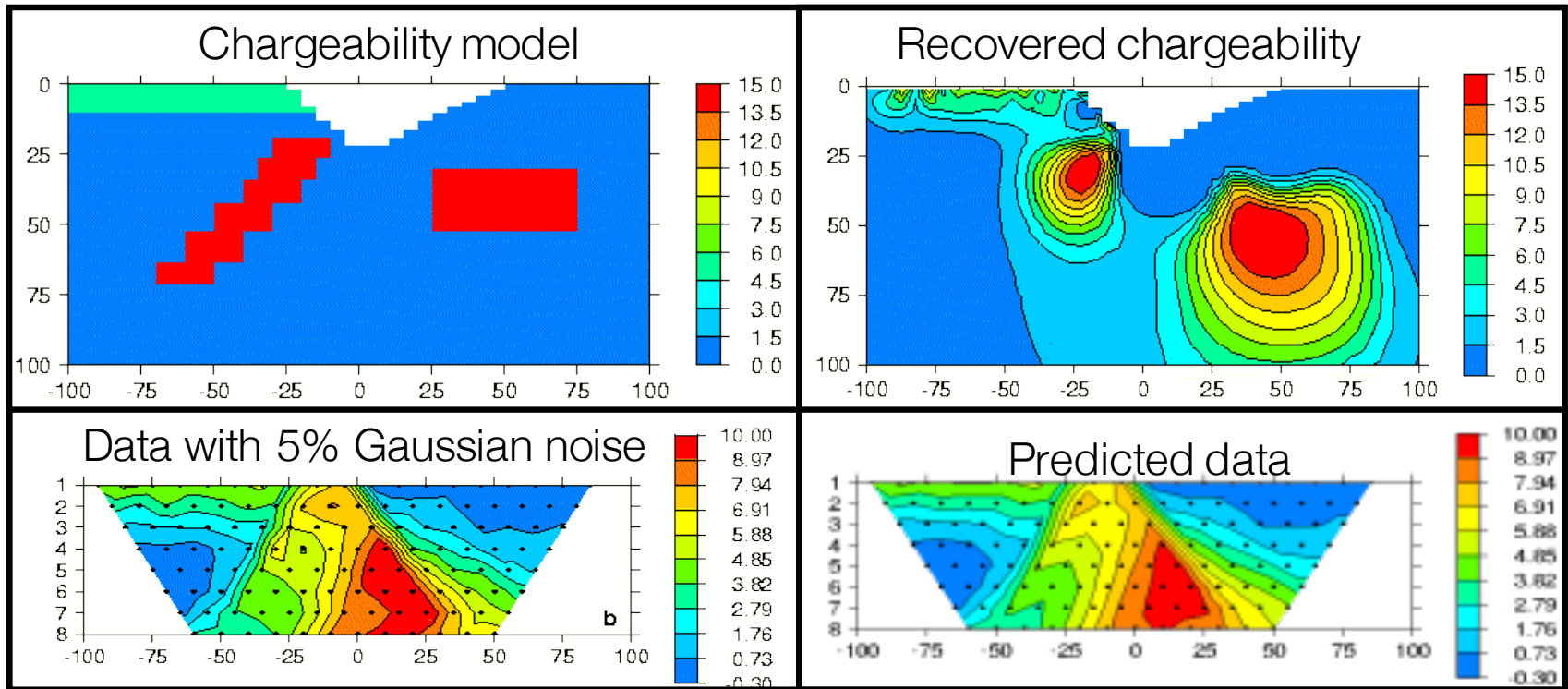
Example 2: prism with geologic noise



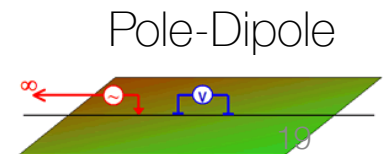
- Pole-dipole; $n=1,8$; $a=10\text{m}$; $N=316$; $(\alpha_s, \alpha_x, \alpha_z)=(.001, 1.0, 1.0)$



Example 3: UBC-GIF model



- Pole-dipole; $n=1,8$; $a=10\text{m}$



Induced Polarization: Summary

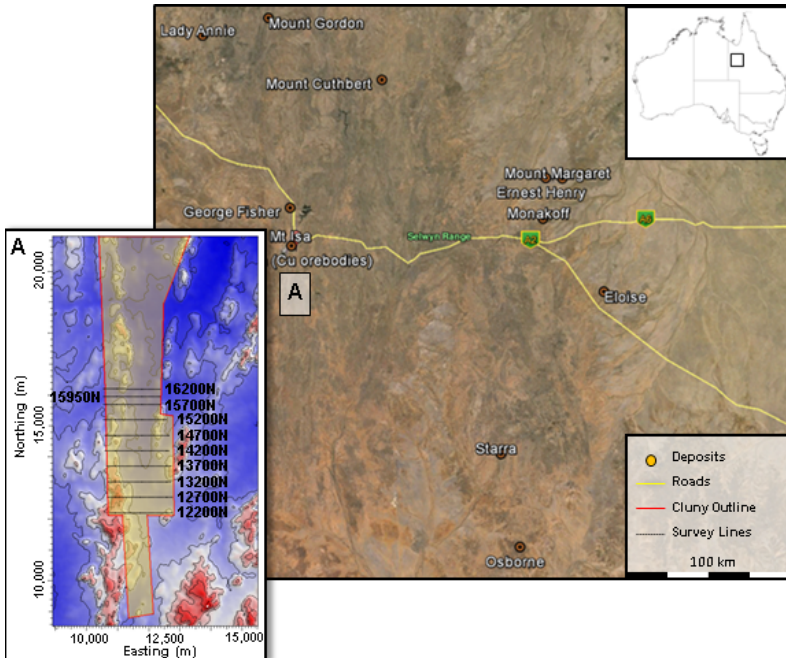
- Sources of IP
- Conceptual model of IP
- Chargeability
- IP data
- Pseudosections
- Two stage DC-IP inversion
- Case history: Mt. Isa
- EM Decoupling
- Case History: TKC (Airborne IP)

Case history: Mt. Isa

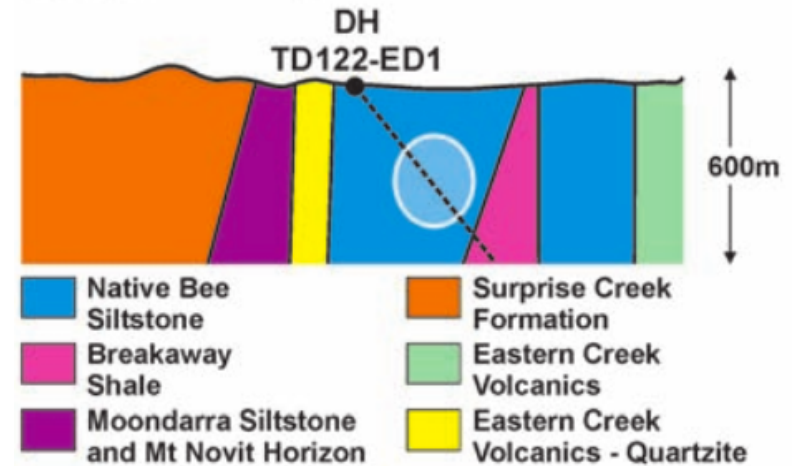
Rutley et al., 2001

Setup

- Mt. Isa (Cluny project)



- Geologic model

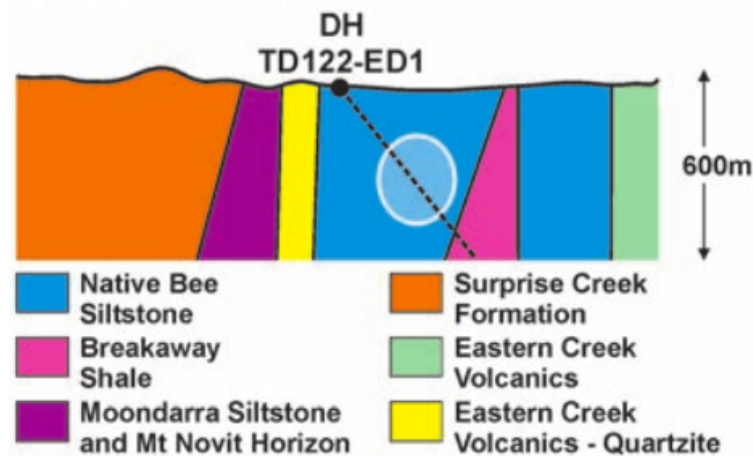


Question

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

Properties

Geologic model

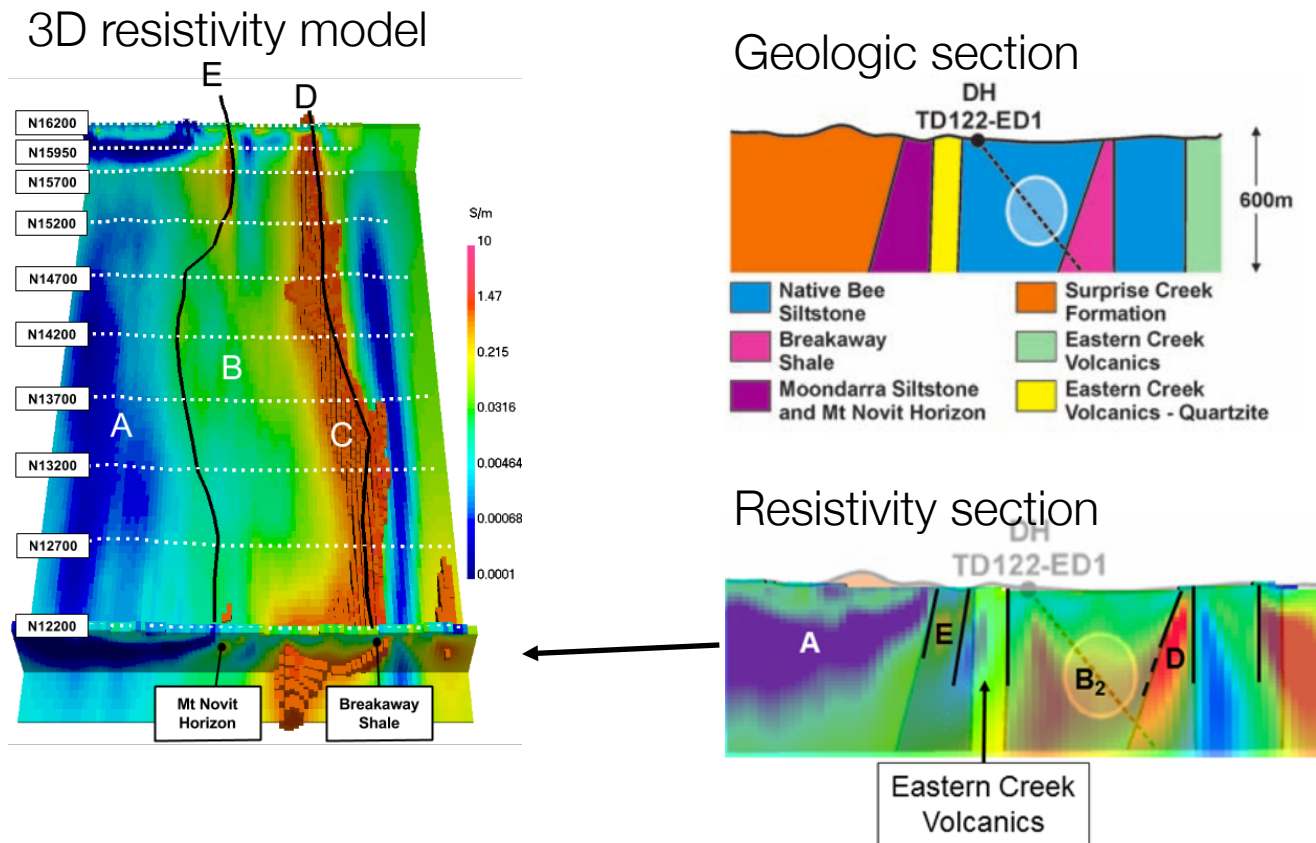


Resistivity and Chargeability

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

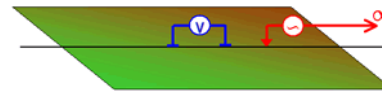
- Identified a major conductor → black shale unit
- Some indication of a moderate conductor



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

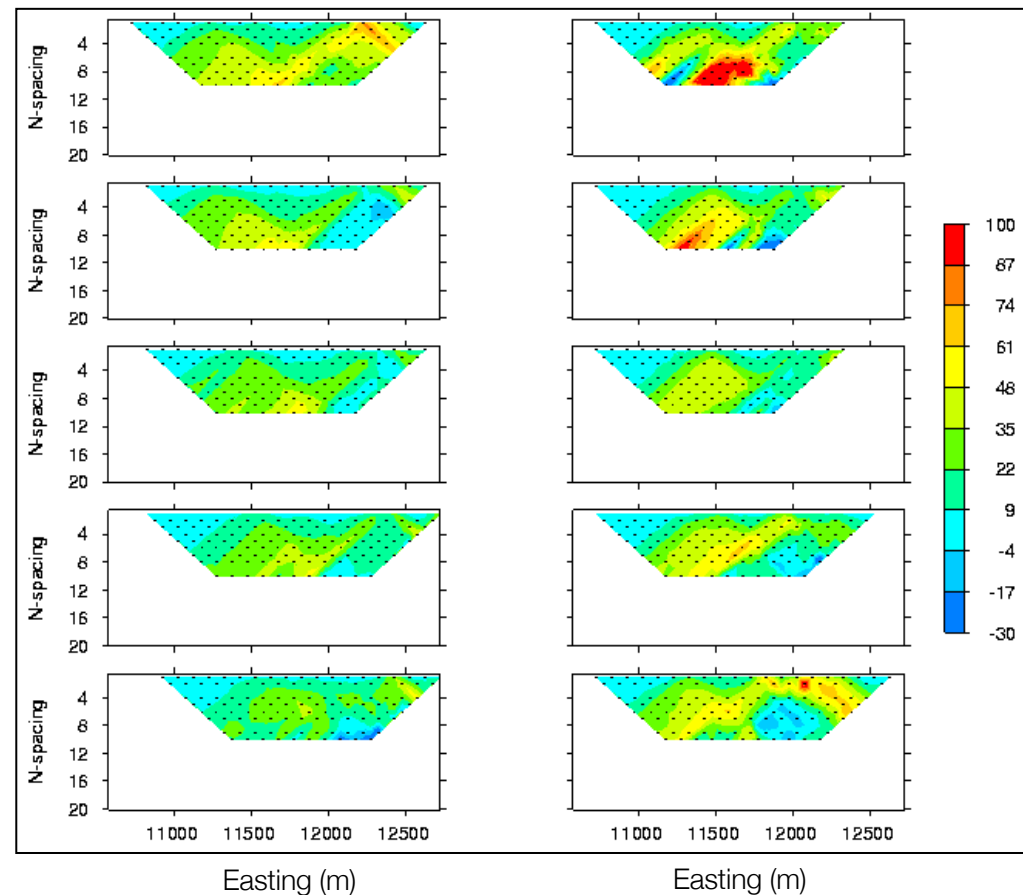
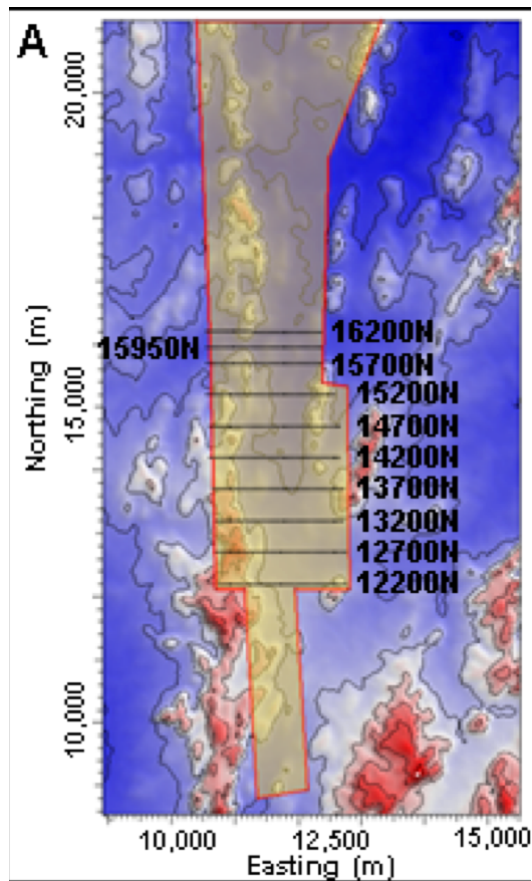
Survey and data

- Eight survey lines
- Two configurations



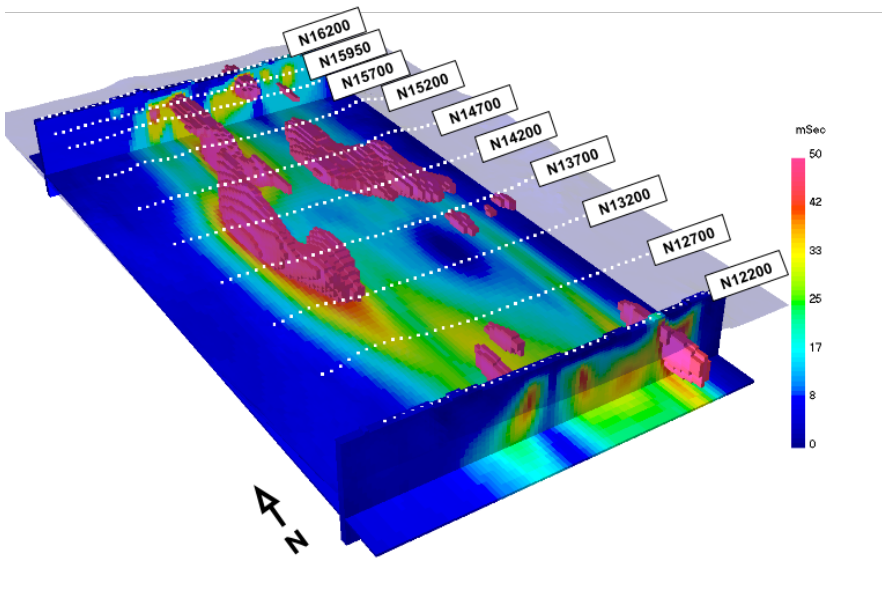
Apparent chargeability, dipole- pole.

Surface topography

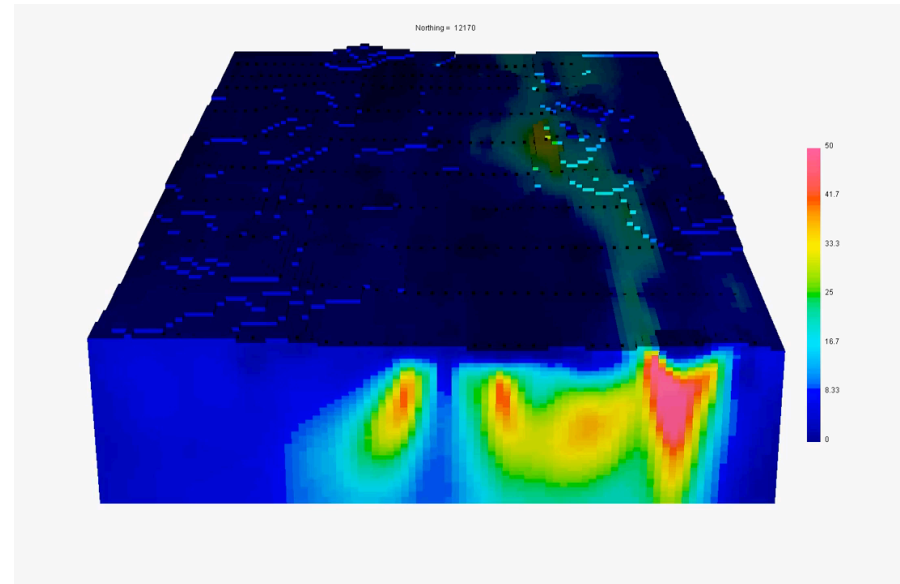


Processing

3D chargeability model



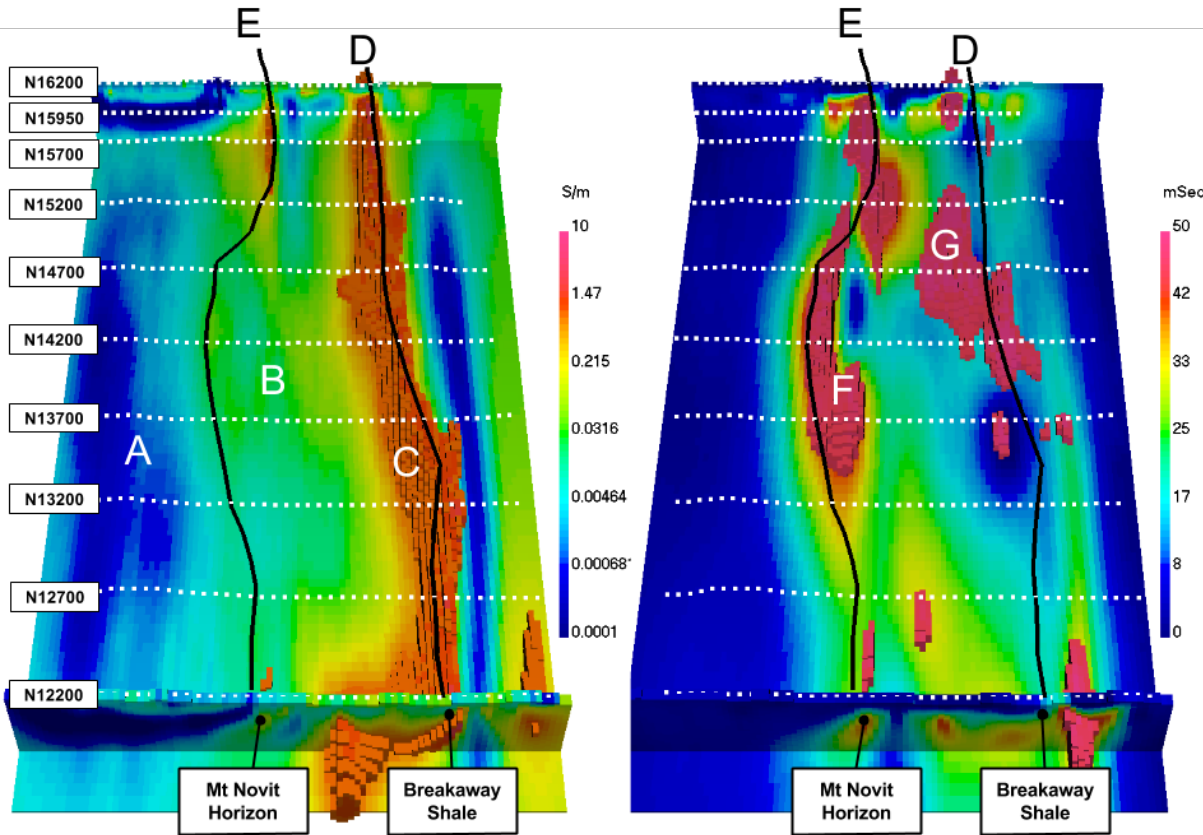
Animation



Interpretation

Resistivity model

Chargeability model



A: Resistive, Non-chargeable

B: Moderate conductivity; low chargeability

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

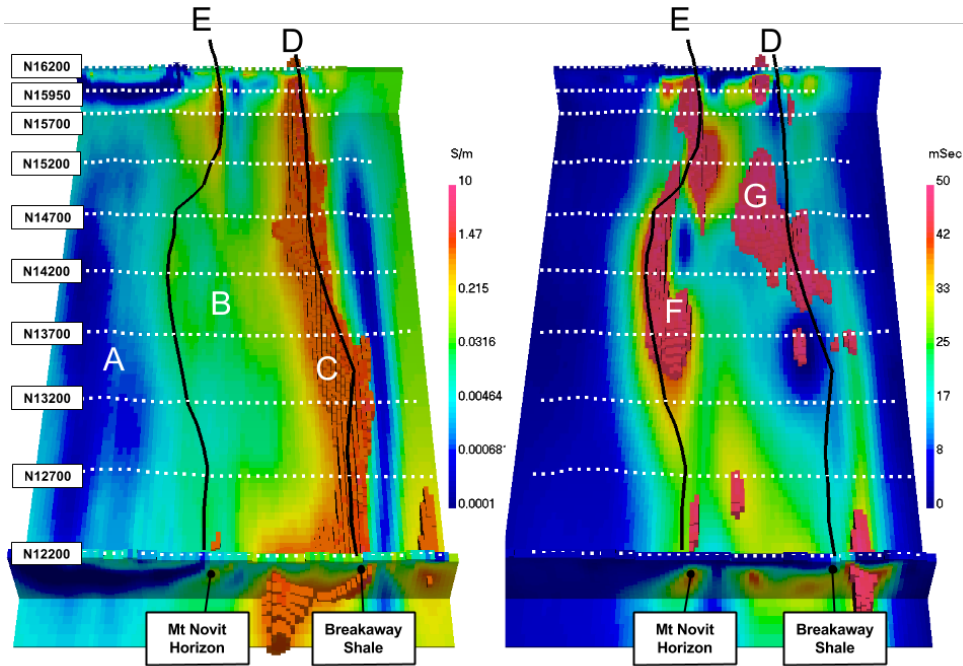
E and F: High conductivity and high chargeability

G: Other chargeable regions

Synthesis

Resistivity model

Chargeability model



A: Surprise Creek Formation
 – Resistive, non-chargeable

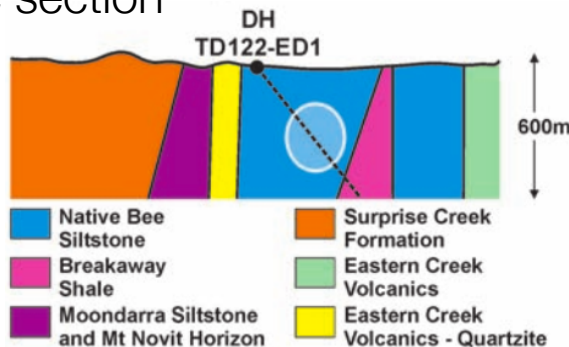
B: Moondarra and Native Bee siltstones

C: Breakaway Shales
 – Very high conductivity

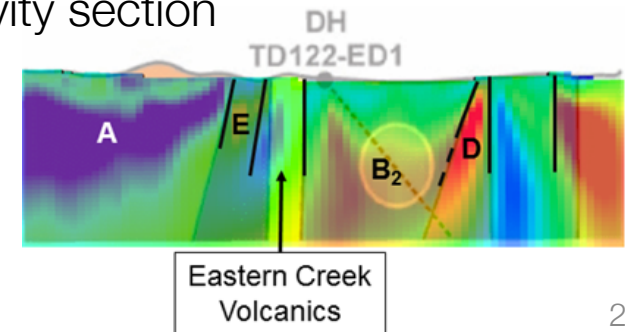
E and F: Mt Novit Horizon
 – High conductivity and high chargeability

G: Other chargeable regions within siltstone complex

Geologic section



Resistivity section



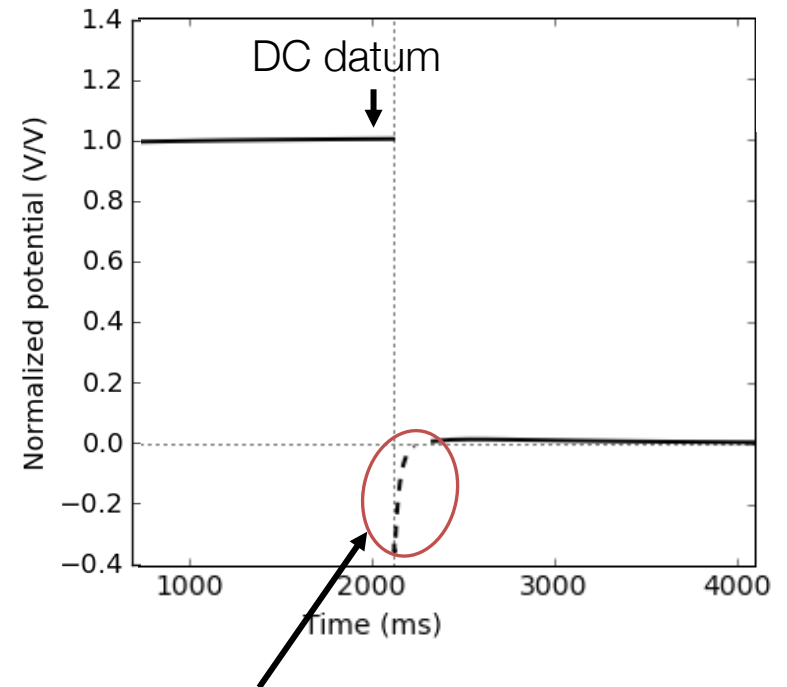
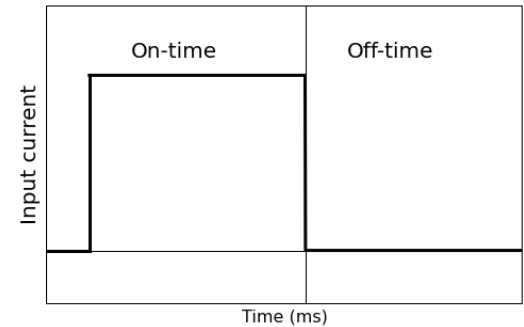
Induced Polarization: Summary

- Sources of IP
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- IP data
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- Two stage DC-IP inversion
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- EM Decoupling
- Case History: TKC (Airborne IP)

EM-IP Inversion

EM-IP Inversion: Goals

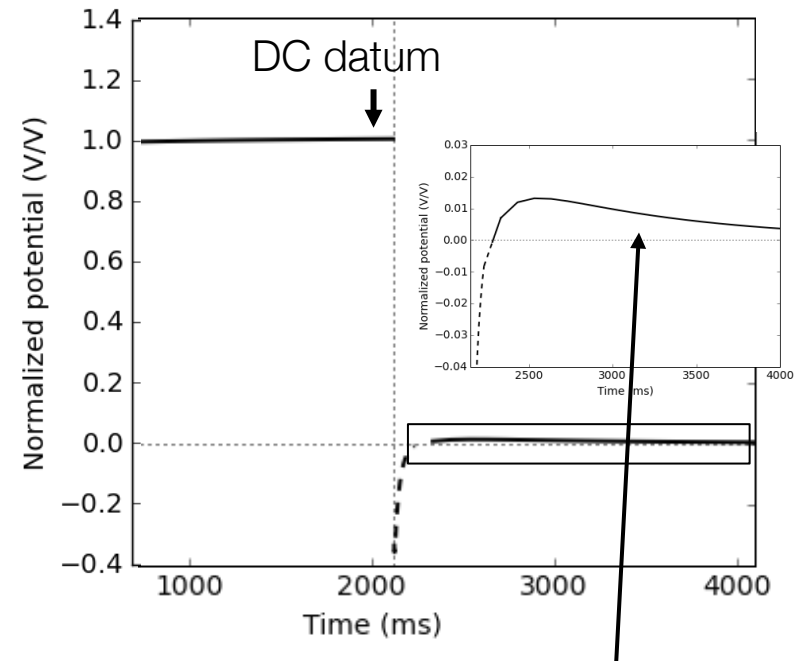
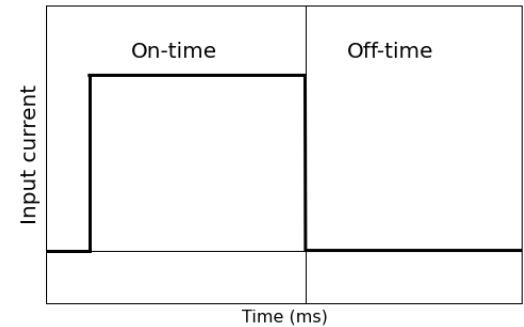
- Standard time domain DC-IP
- Conductivity inversion
 - DC data
 - EM data
- Illustrate the value of data which is often discarded



EM portion
Generally considered noise

EM-IP Inversion: Goals

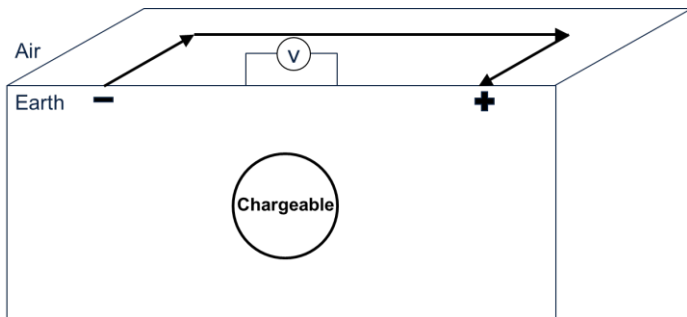
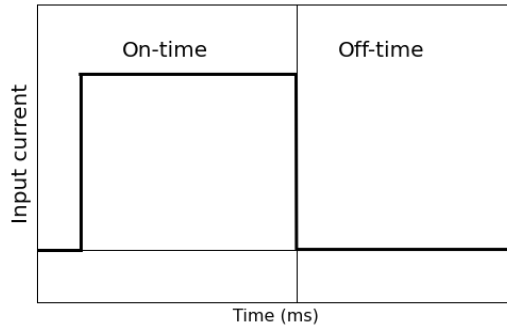
- Standard time domain DC-IP
- Conductivity inversion
 - DC data
 - EM data
- Illustrate the value of data which is often discarded
- Use EM conductivity to obtain clean IP data:
 - $IP = Observation - EM$
- Numerical example from a gradient array



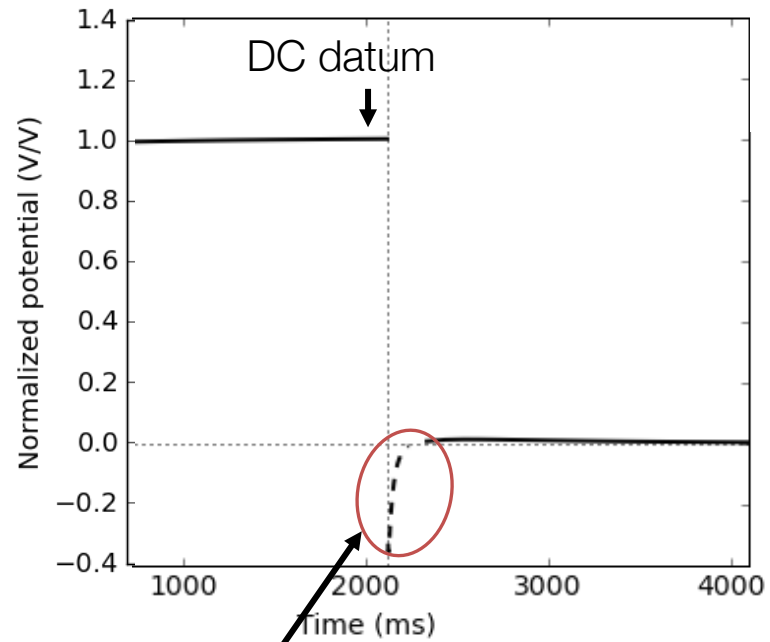
IP portion
Assumed no EM-coupling

Survey and Data

Transmitter



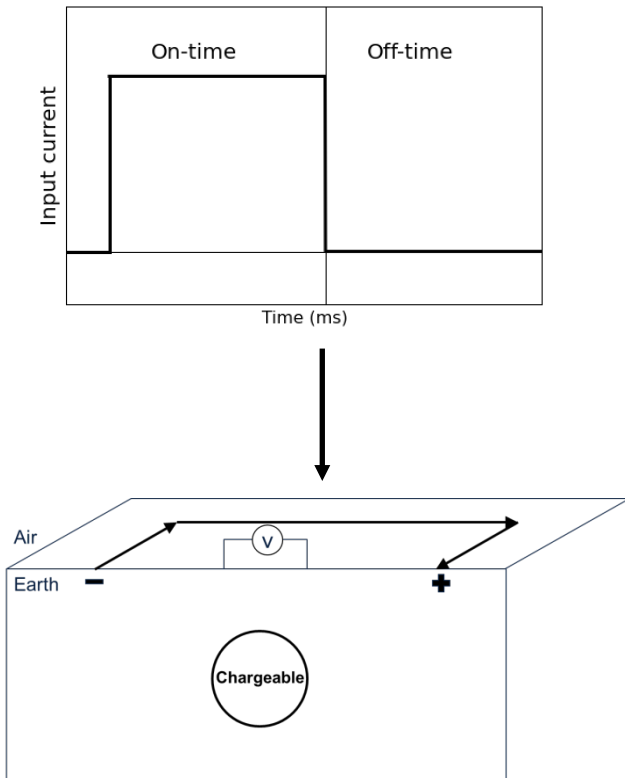
Measured Voltage



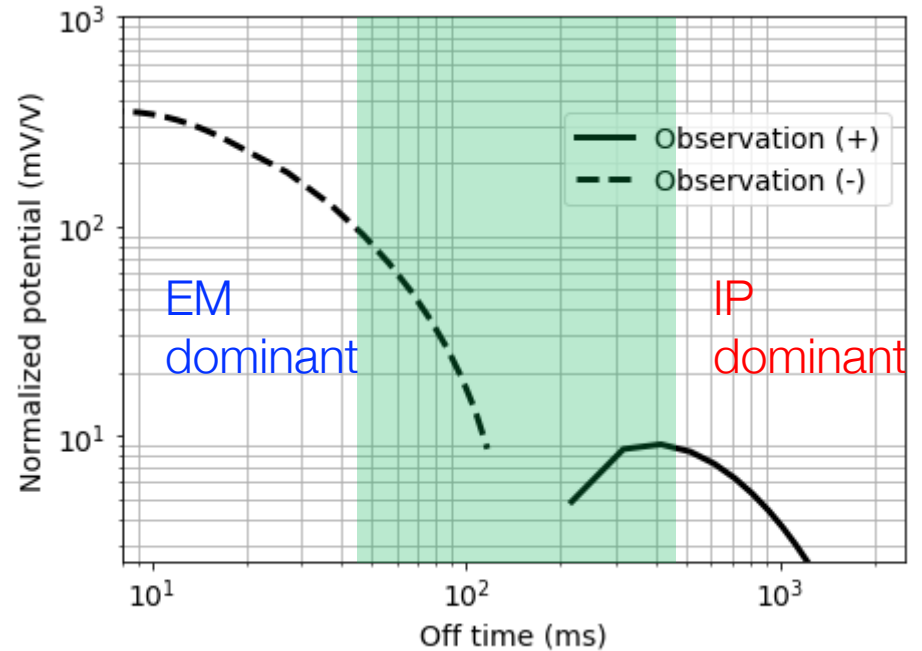
EM portion
Generally considered noise

Survey and Data

Transmitter



Measured Voltage (off-time)



$$\text{Observation} = \text{EM} + \text{IP}$$

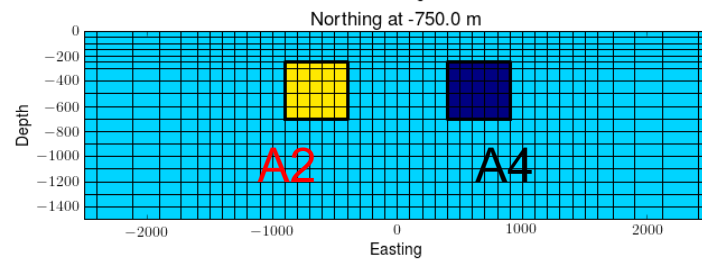
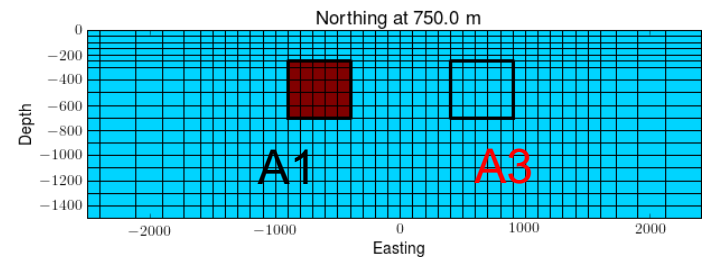
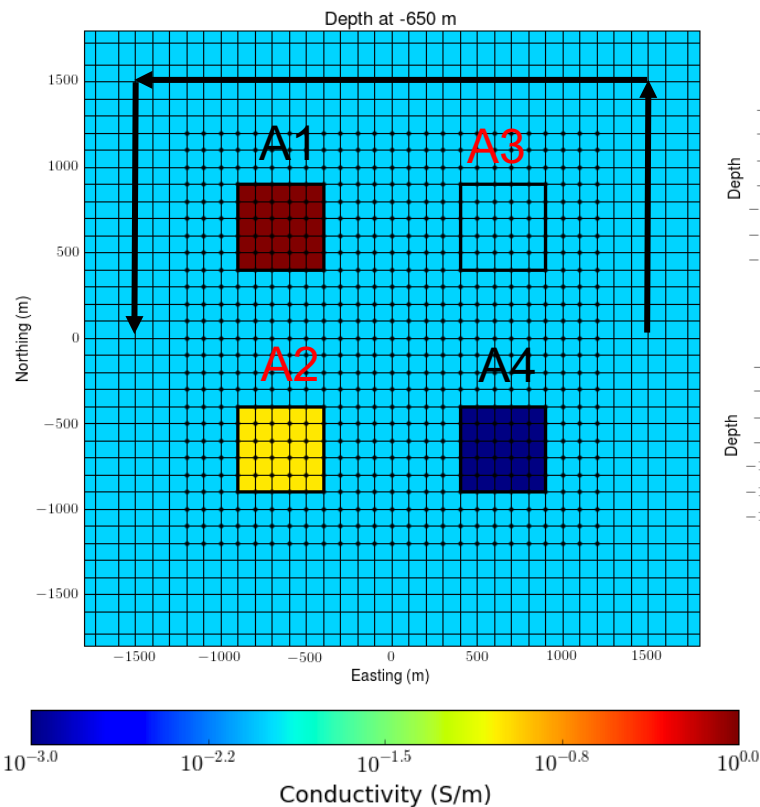
Gradient array

- Model

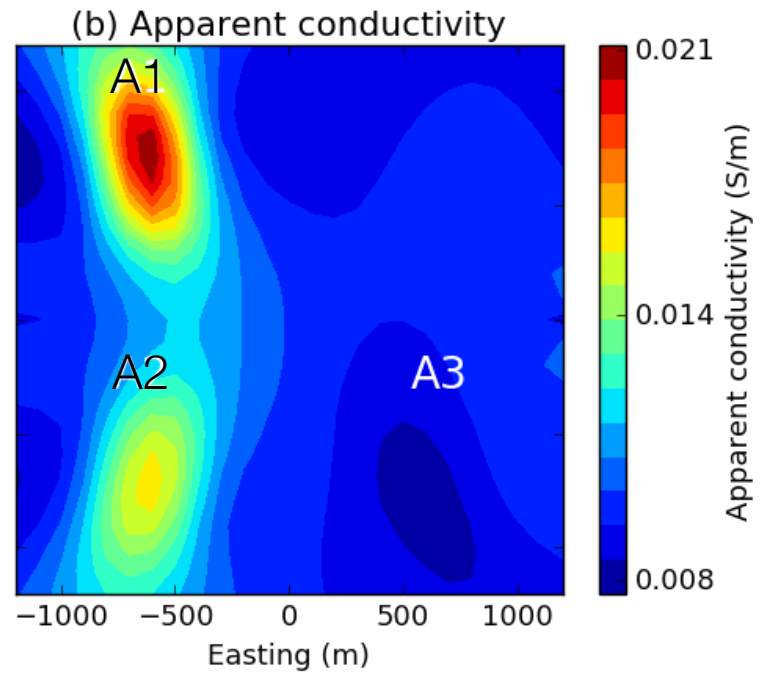
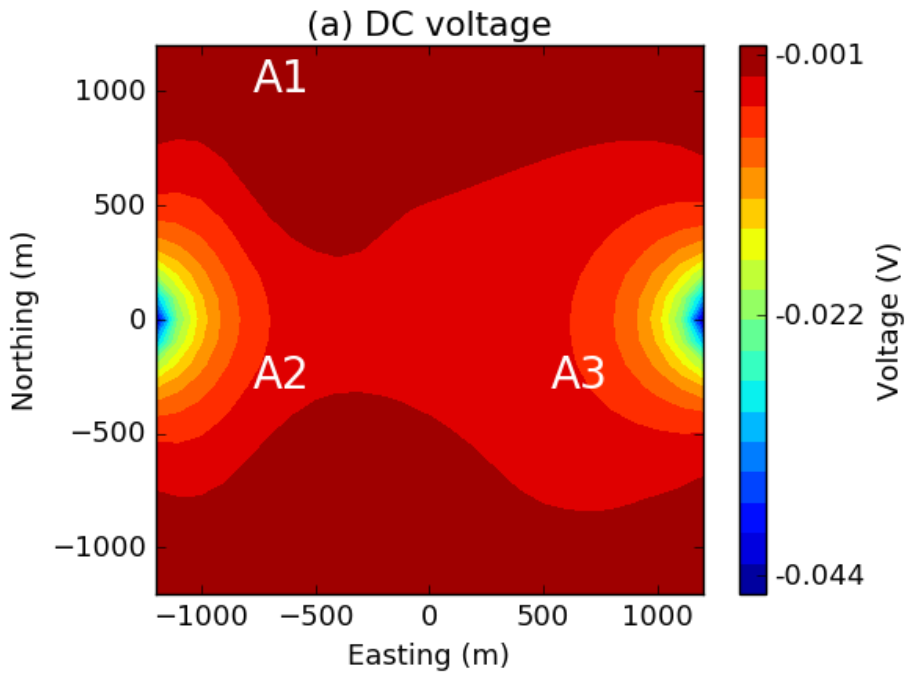
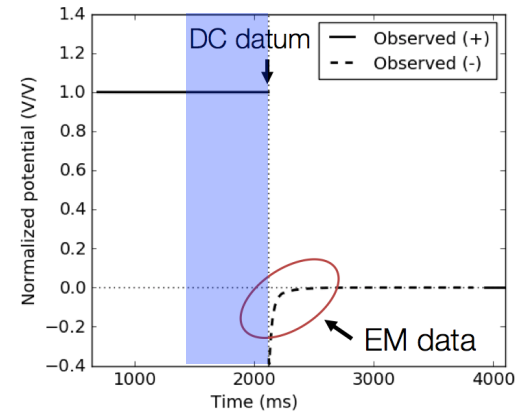
	σ (S/m)	η	τ (s)
A1	1	0	
A2	0.1	0.1	0.5
A3	0.01	0.1	
A4	0.001	0	0.5

- Survey

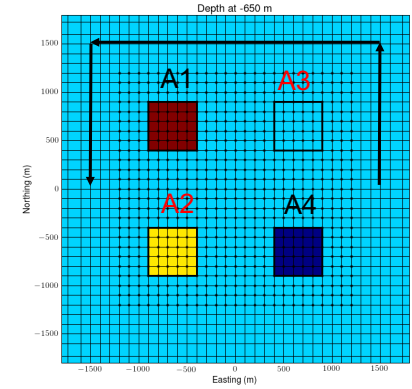
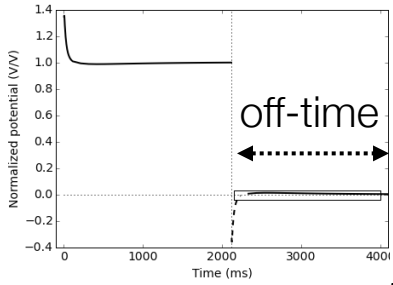
- 200m bi-pole (625 data)
- times: 1-600ms



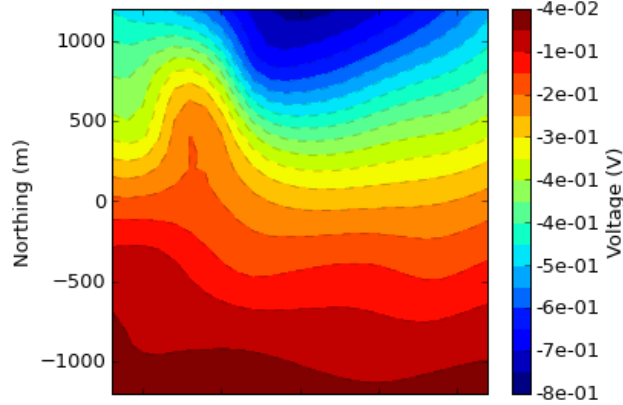
DC data



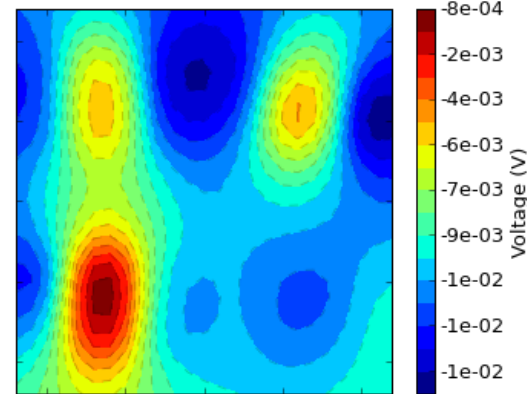
Off-time data



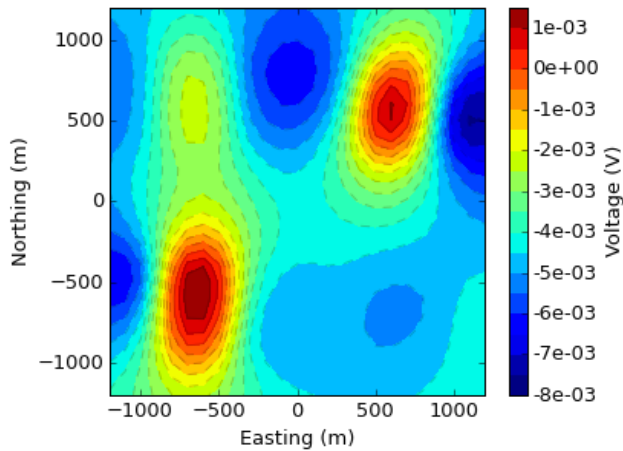
5 ms



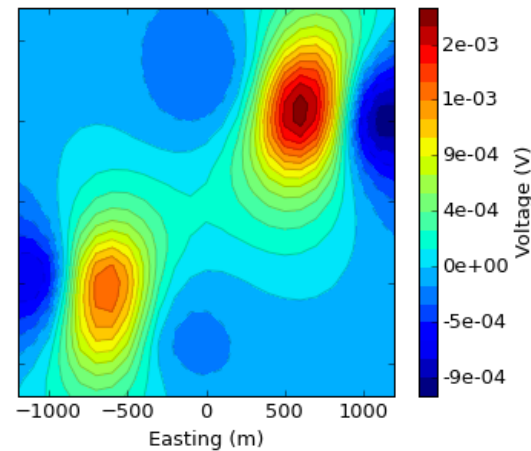
80 ms



130 ms

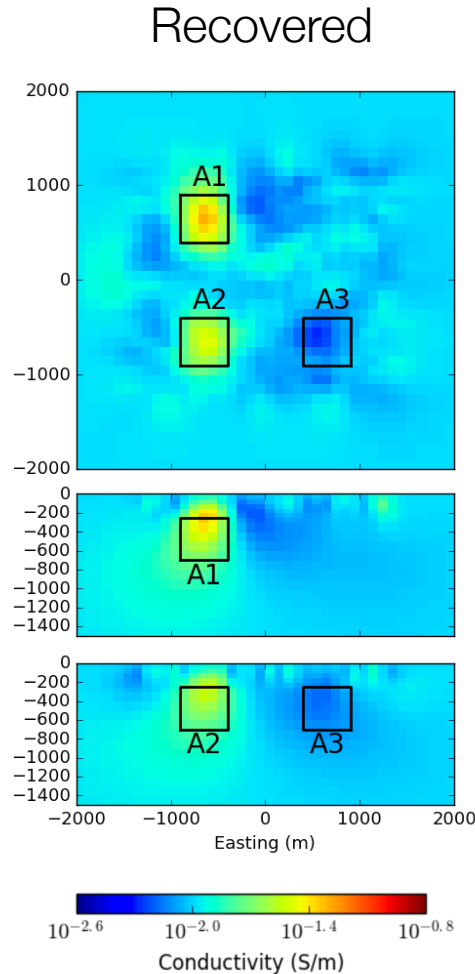
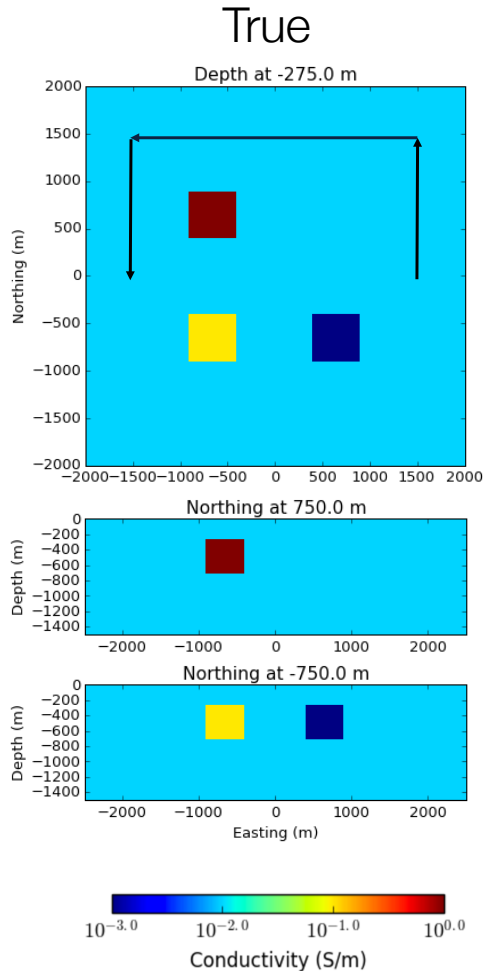


650 ms

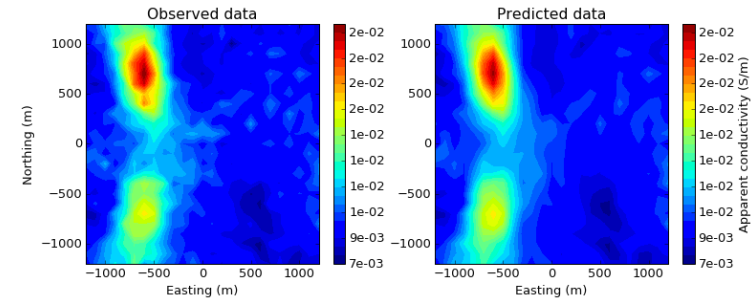


DC inversion

- Recovered 3D conductivity



Apparent conductivity

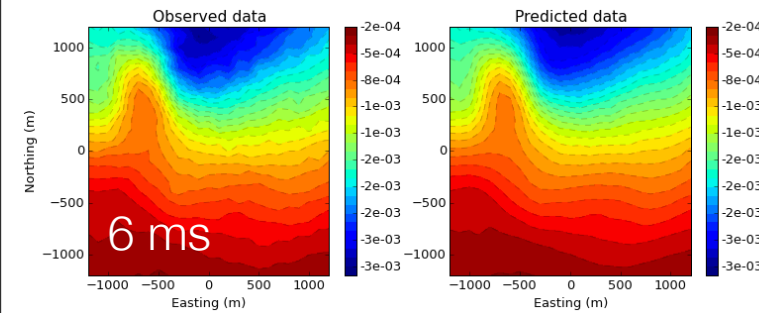
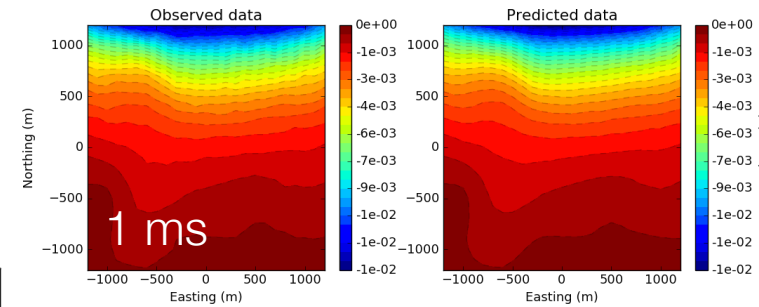
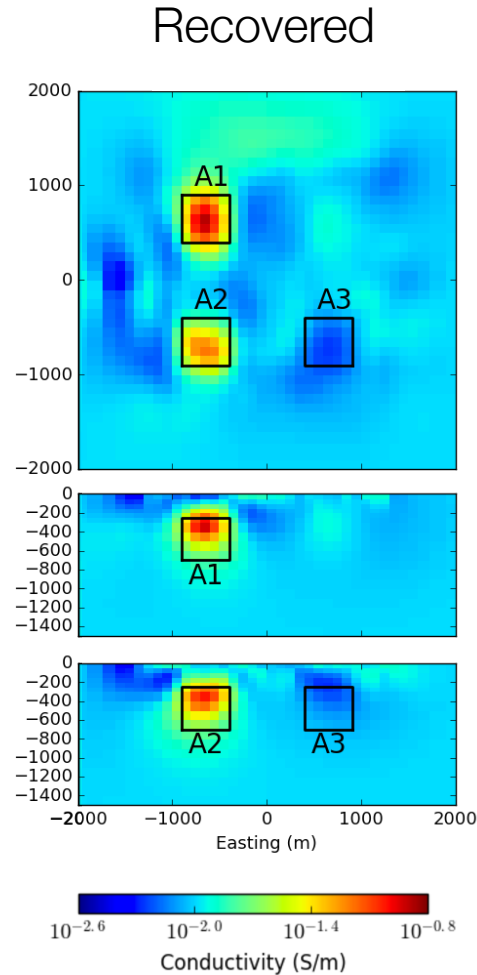
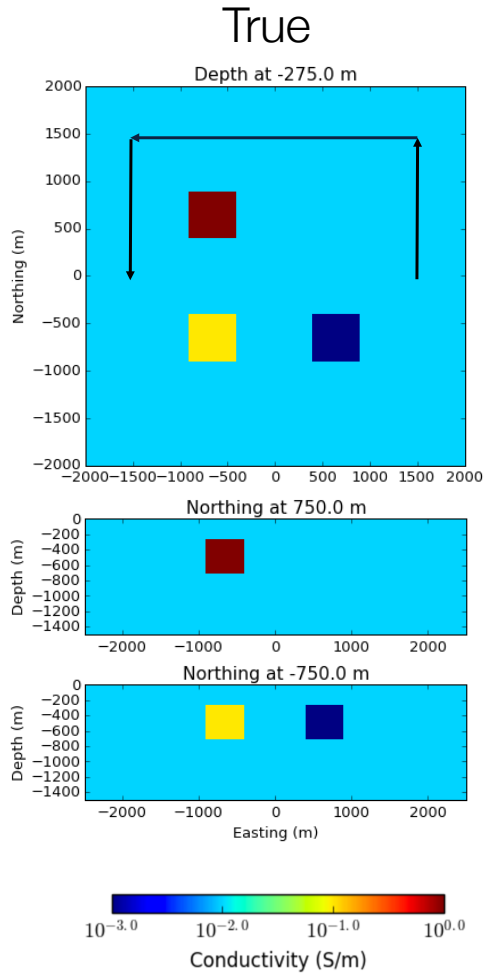


- Depth weighting
 - Compensate for high sensitivity near surface (similar to mag.)

$$\frac{1}{(z - z_0)^3}$$

EM inversion

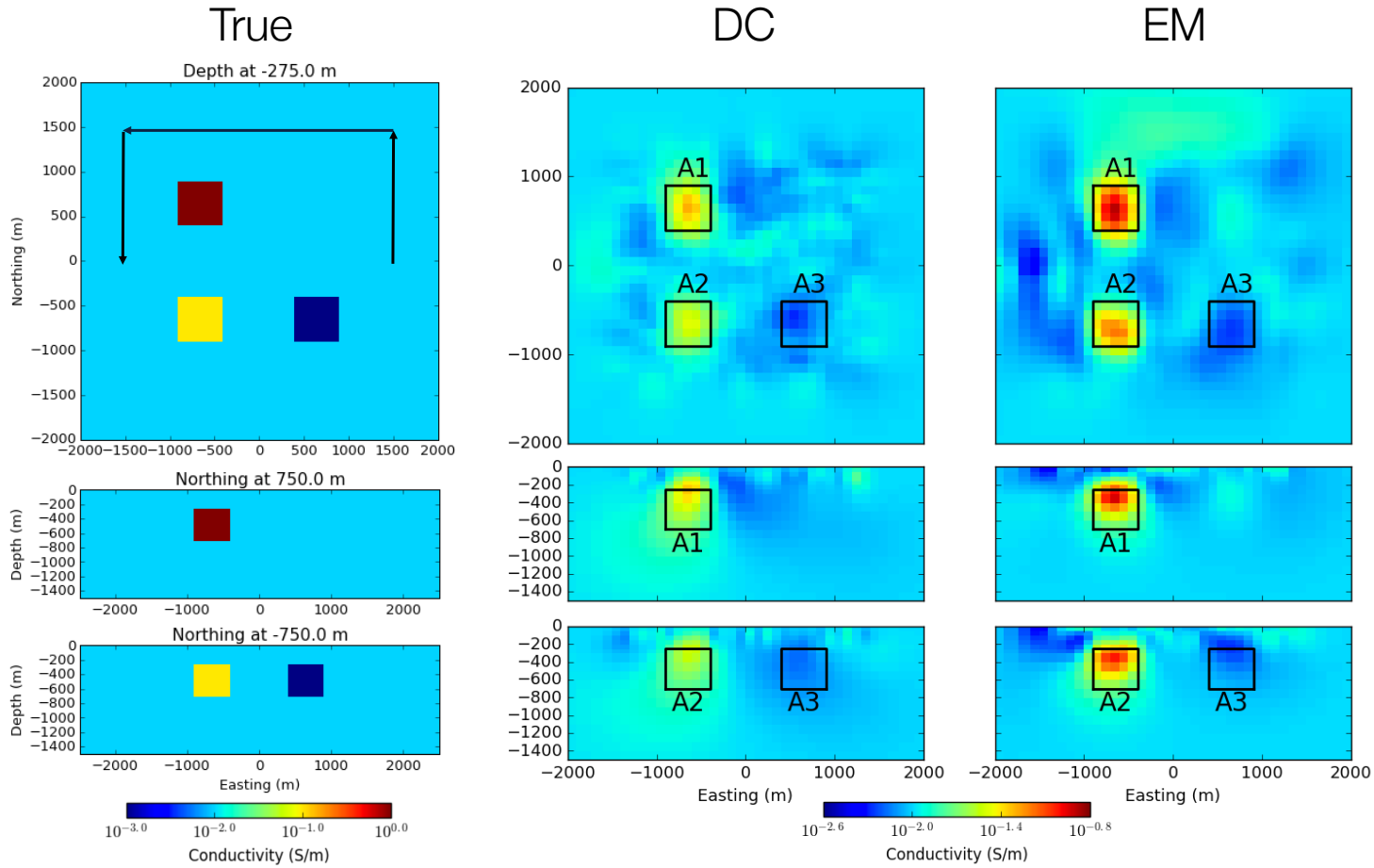
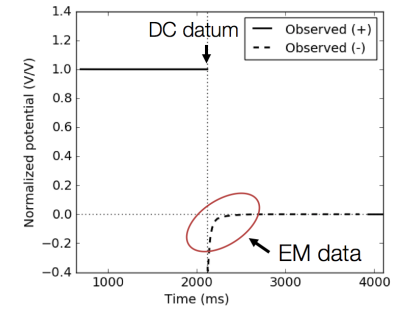
- Recovered 3D conductivity



- No depth weighting

Conductivity models

- True, DC, and EM conductivities



EM data contain signal

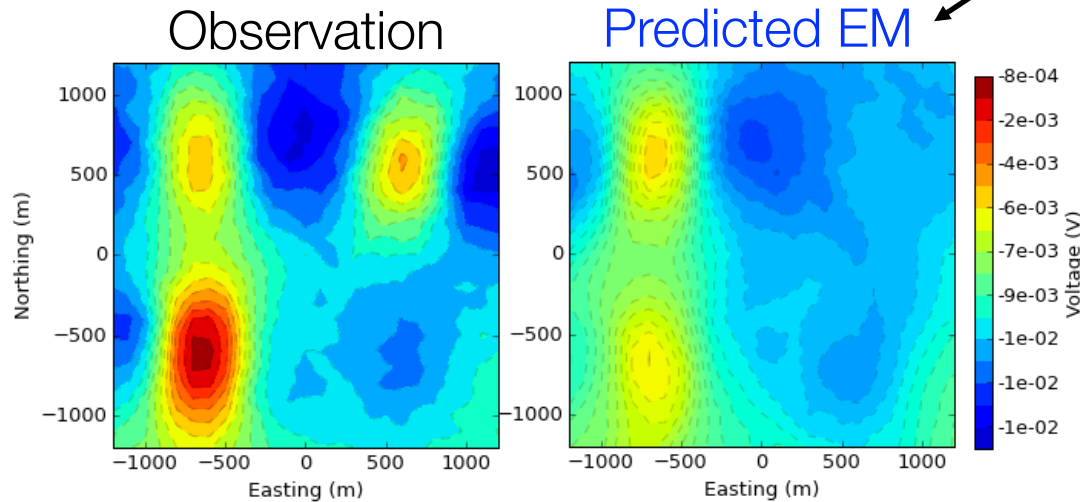
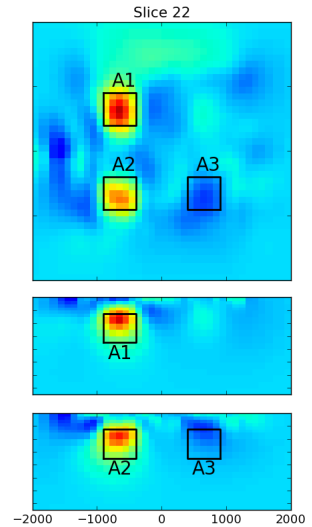
EM decoupling

- Off-time at 80 ms

$$IP = \text{Observation} - EM$$

TDEM simulation

EM conductivity



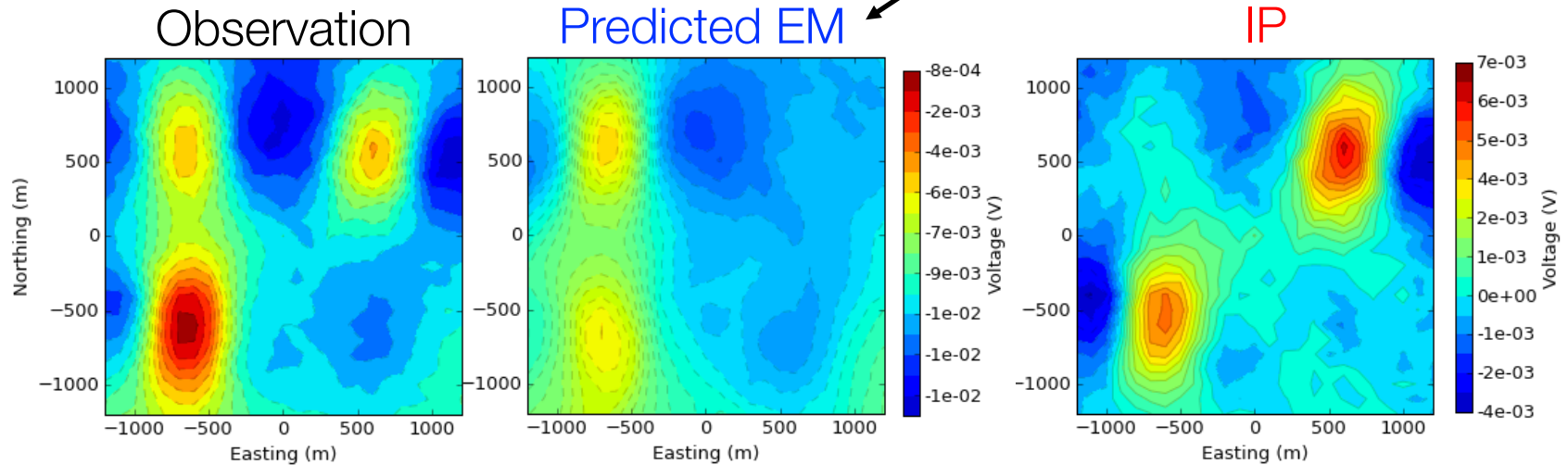
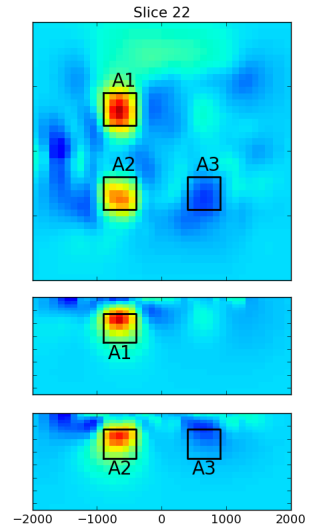
EM decoupling

- Off-time at 80 ms

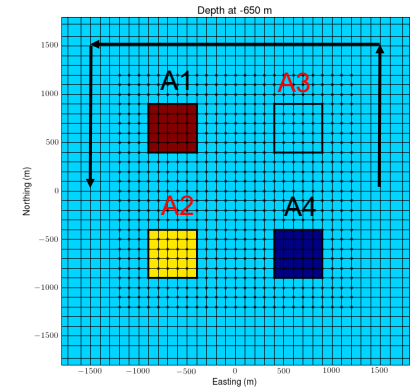
$$IP = \text{Observation} - EM$$

TDEM simulation

EM conductivity



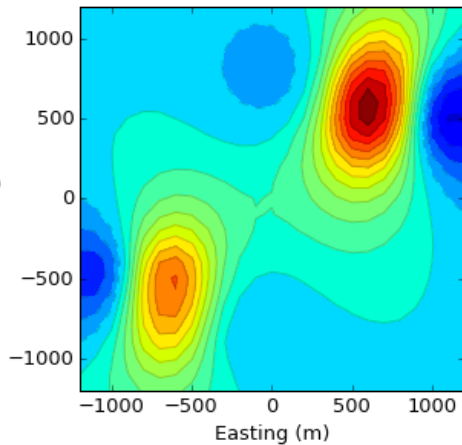
EM decoupling



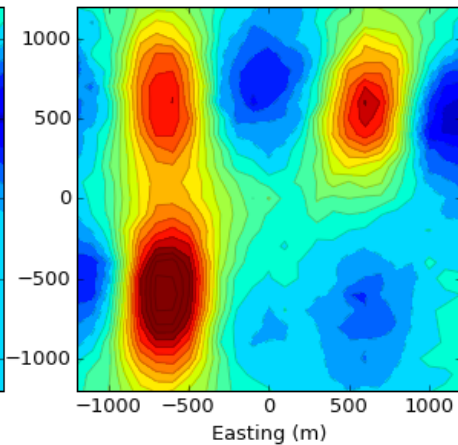
$$IP = \text{Observation} - EM$$

IP data at 80 ms

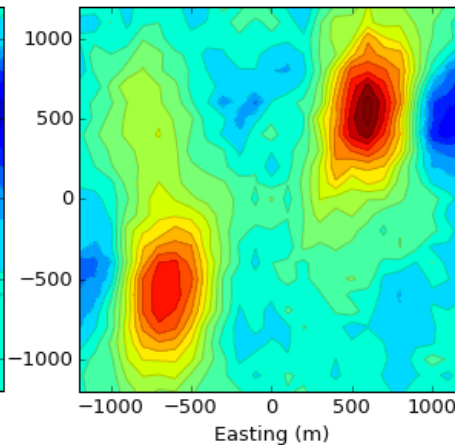
True IP



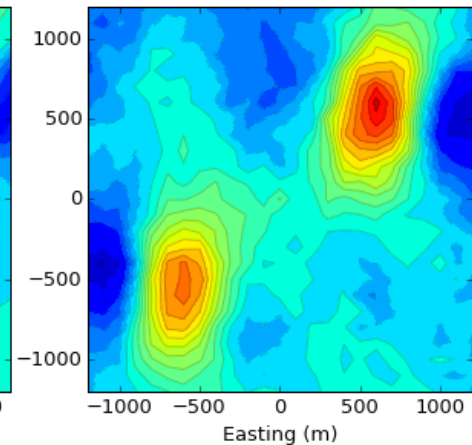
Half-space



DC



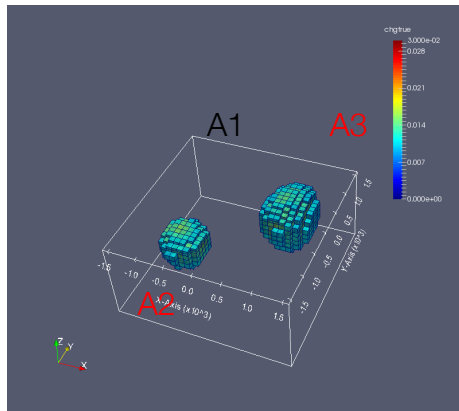
EM



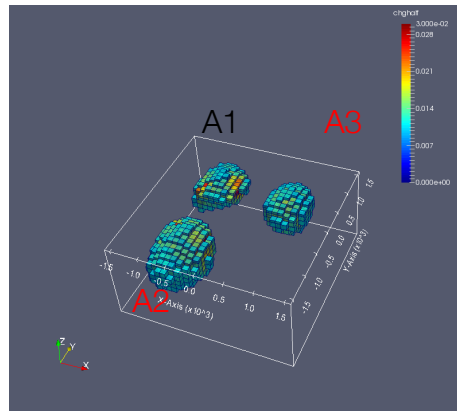
IP inversion

Chargeability > 0.015

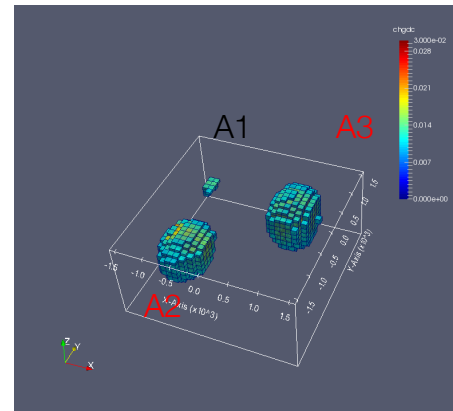
True IP



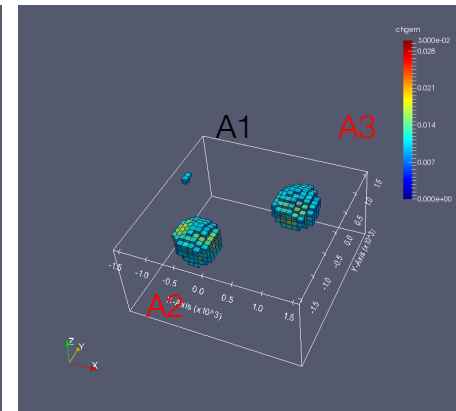
Half-space



DC



EM

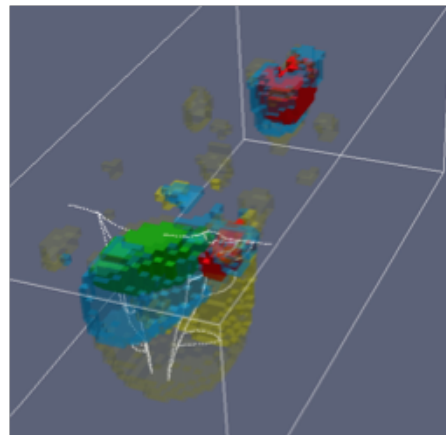


Case History:

Inversion of airborne geophysical data over the Tli Kwi Cho kimberlite complex

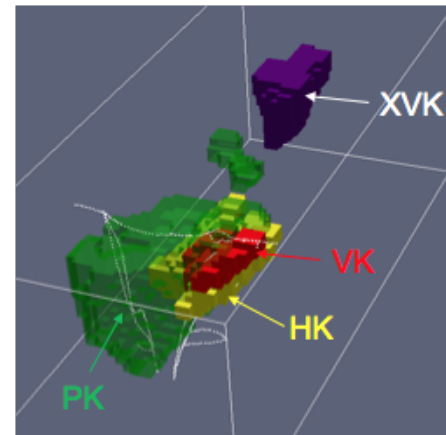
[Devriese et al, 2017](#); [Fournier et al, 2017](#); [Kang et al, 2017](#)

Rock Model from Geophysics



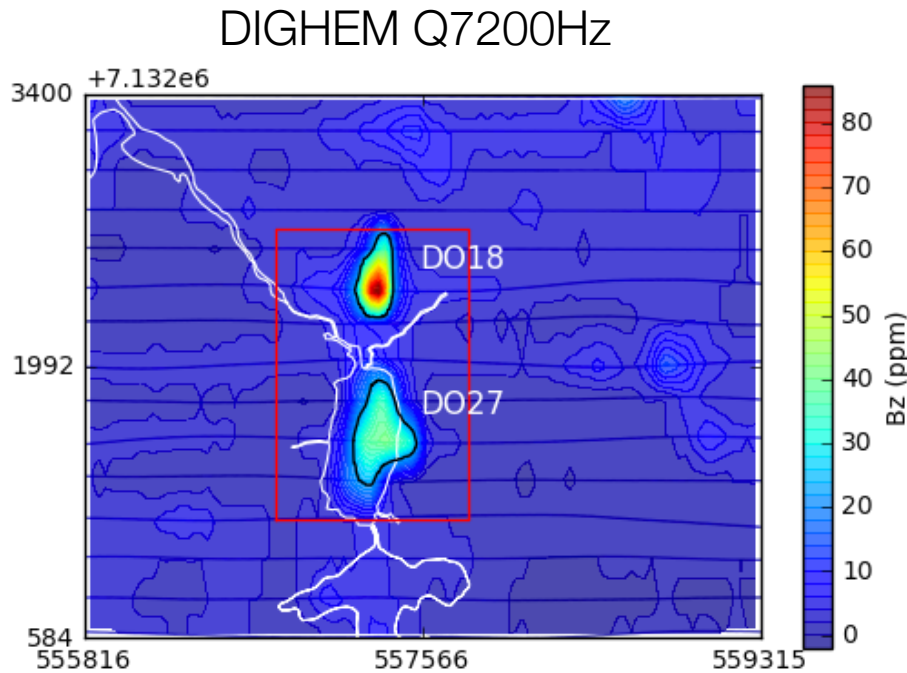
R0 R1 R2 R3 R4 R5
Rock units

Rock Model from Drilling

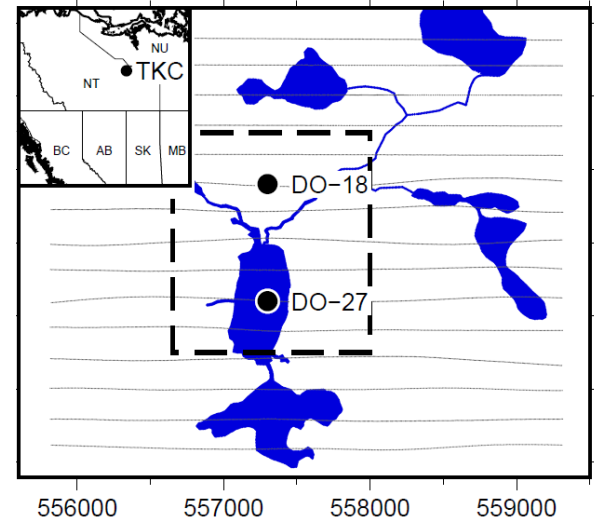


Host Till HK XVK VK PK
Rock units

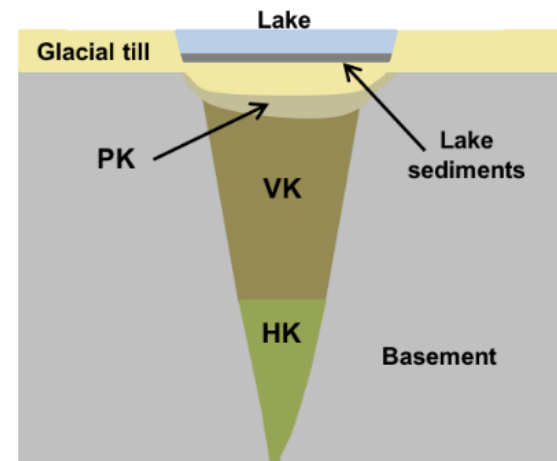
Discovery of Tli Kwi Cho (TKC)



Location of TKC, NWT



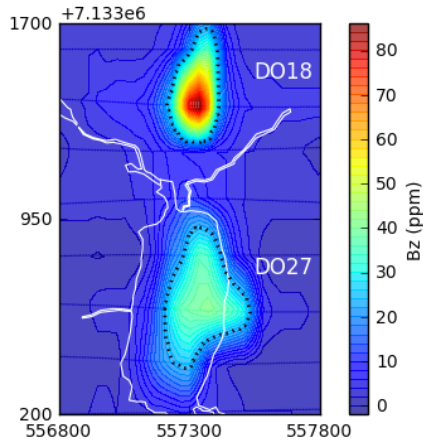
Kimberlite pipe structure



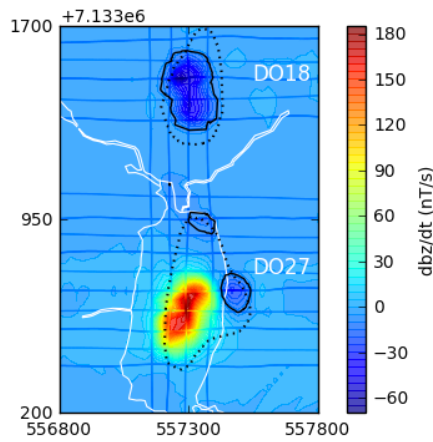
Devriese et al. (2016)

Time domain EM data

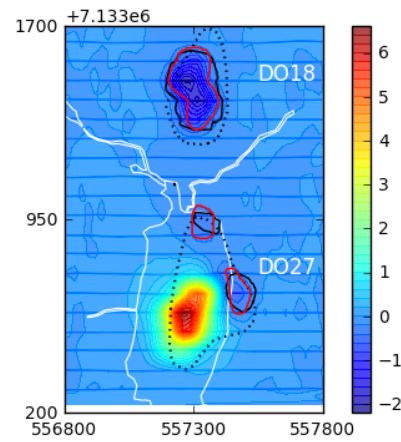
DIGHEM
(1992)



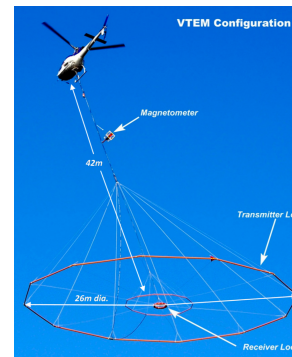
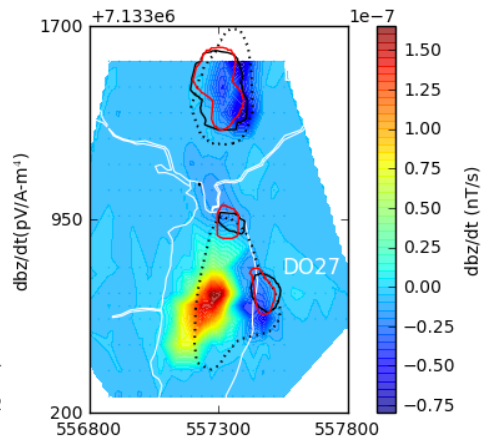
AeroTEMII
(2003)



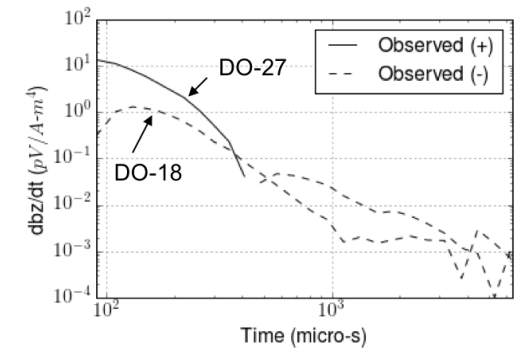
VTEM
(2004)



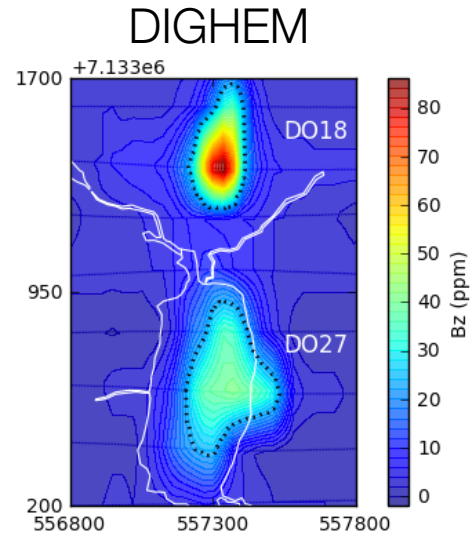
NanoTEM
(1993)



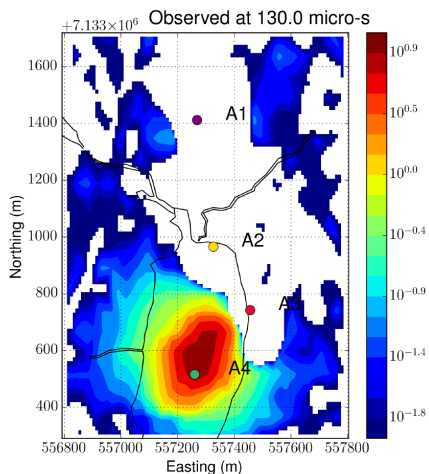
Decay curve



Step 1: Conductivity inversion

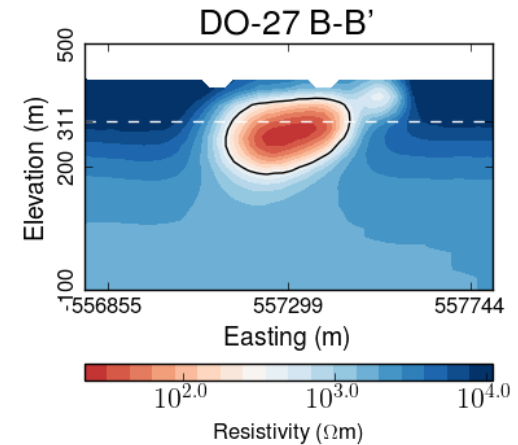
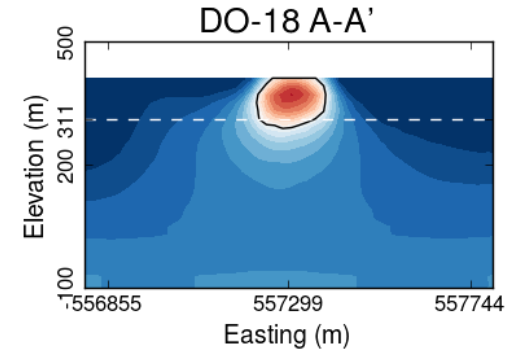
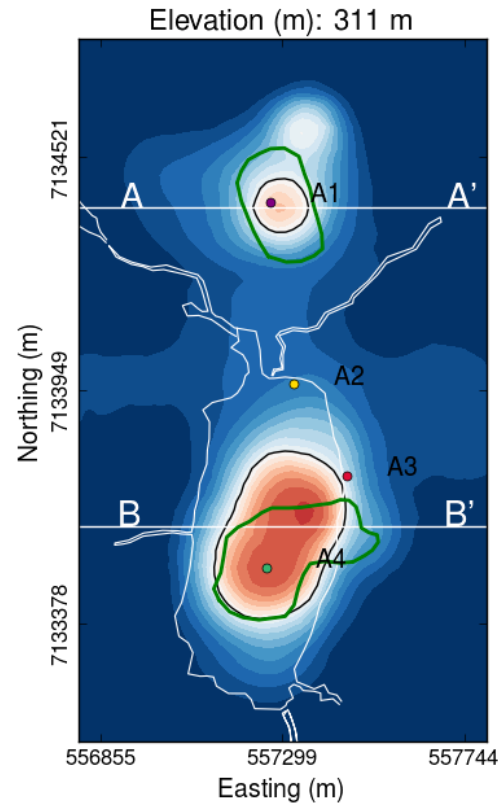


Positive VTEM
(EM-dominant)



Cooperative
Inversion

Recovered 3D conductivity



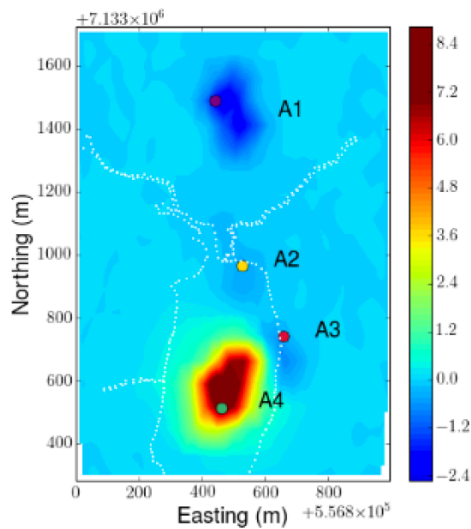
Outline of two pipes

Step 2: EM-decoupling

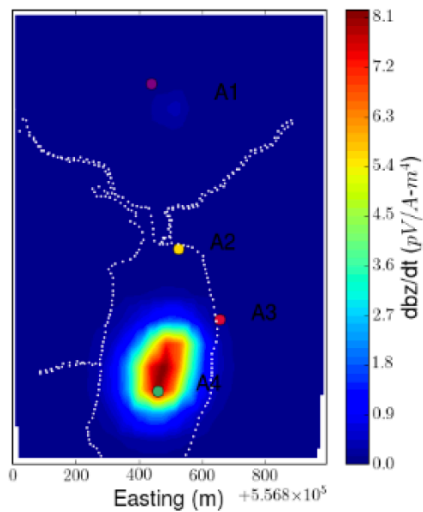
$$IP = \text{Observation} - EM$$

130 micro-s

Observed



Predicted EM

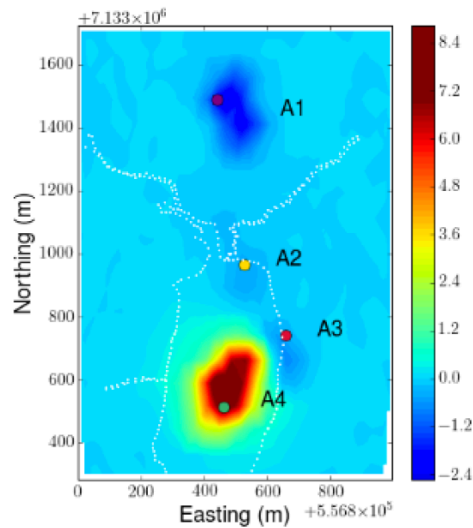


Step 2: EM-decoupling

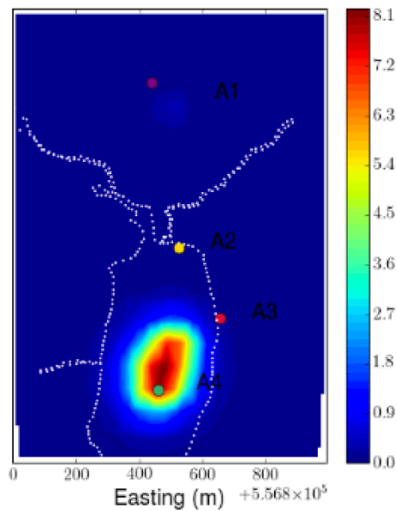
$$IP = \text{Observation} - EM$$

130 micro-s

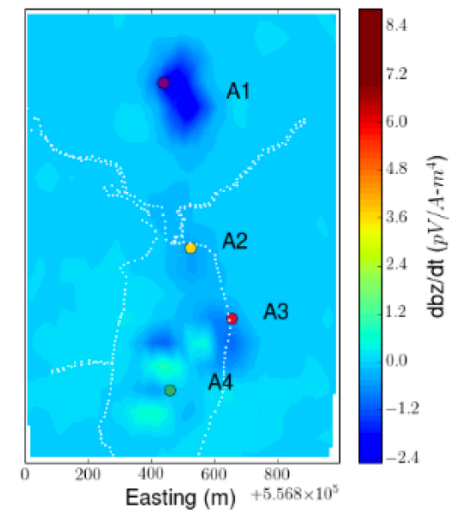
Observed



Predicted EM



IP

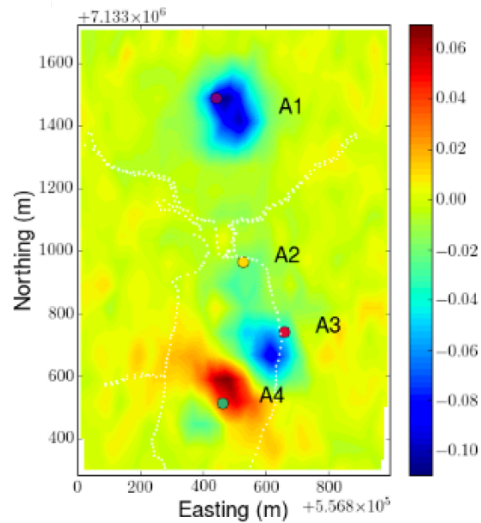


Step 2: EM-decoupling

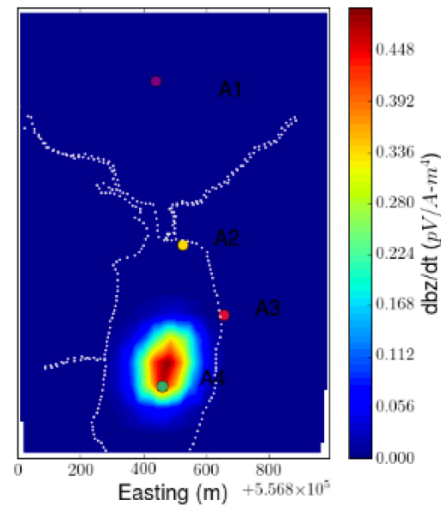
$$IP = \text{Observation} - EM$$

410 micro-s

Observed



Predicted EM

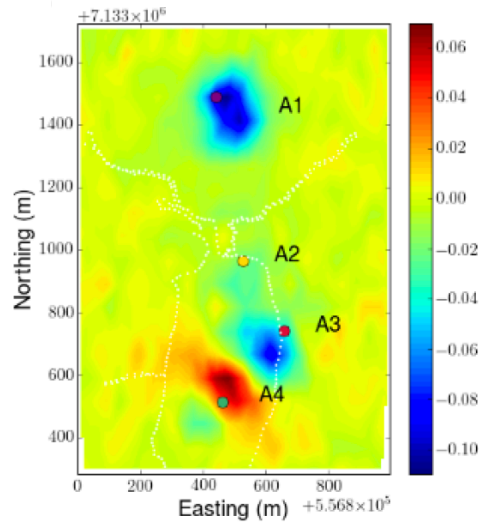


Step 2: EM-decoupling

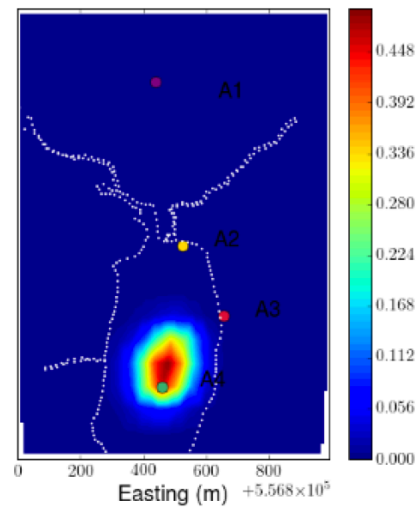
$$IP = \text{Observation} - EM$$

410 micro-s

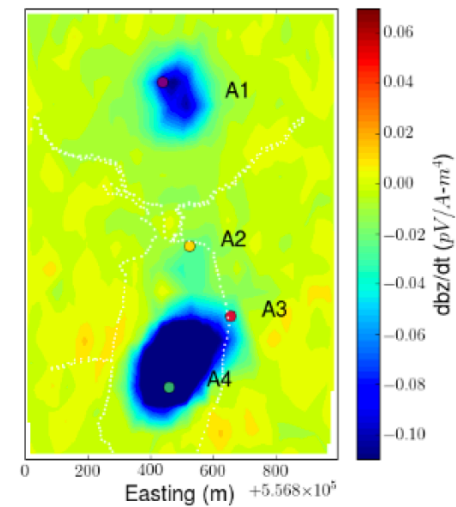
Observed



Predicted EM



IP

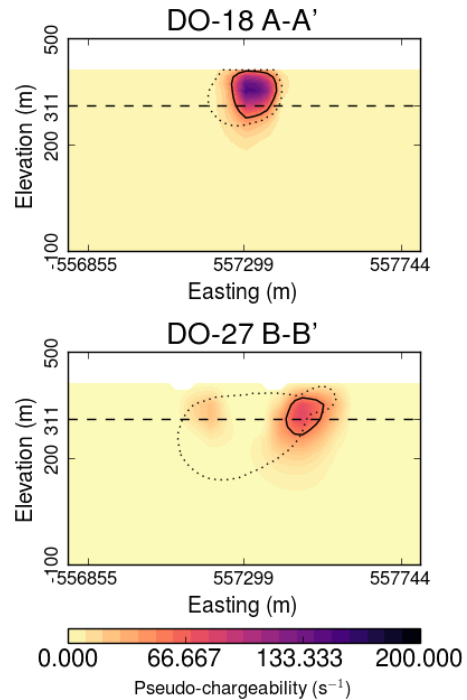
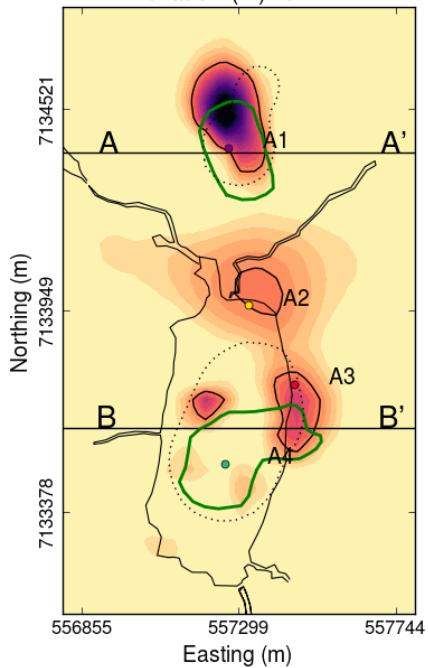


Step 3: 3D IP inversion

Recovered 3D pseudo-chargeability

130 micro-s

Elevation (m): 311 m



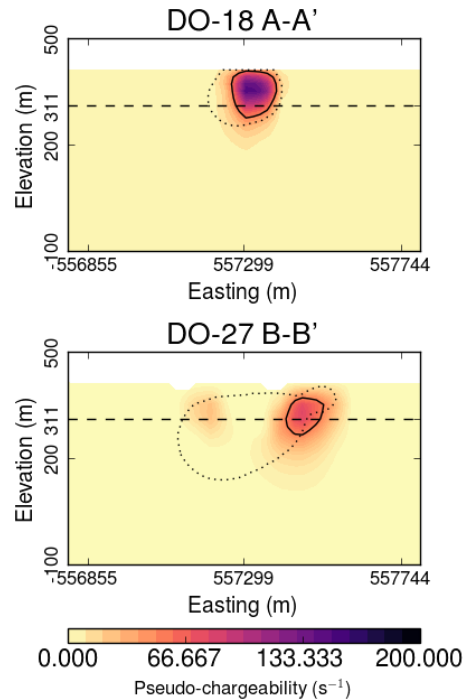
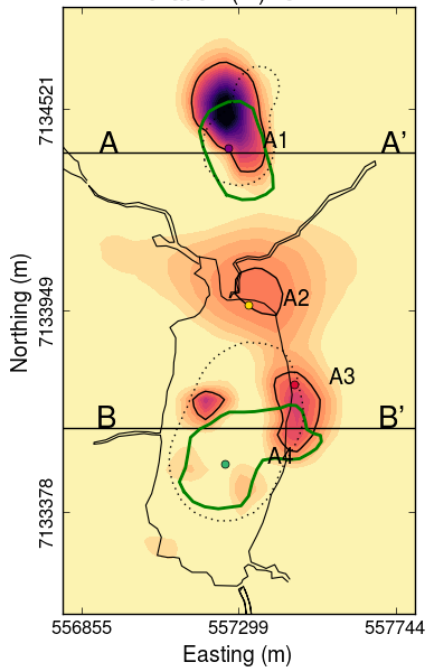
- Outline of two pipes
- Conductivity contour

Step 3: 3D IP inversion

Recovered 3D pseudo-chargeability

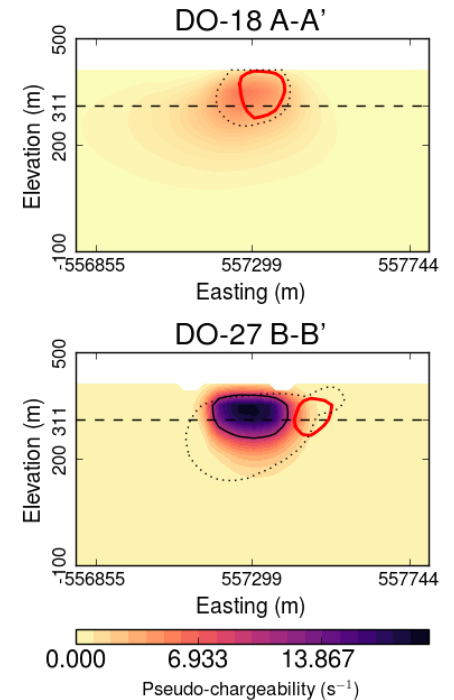
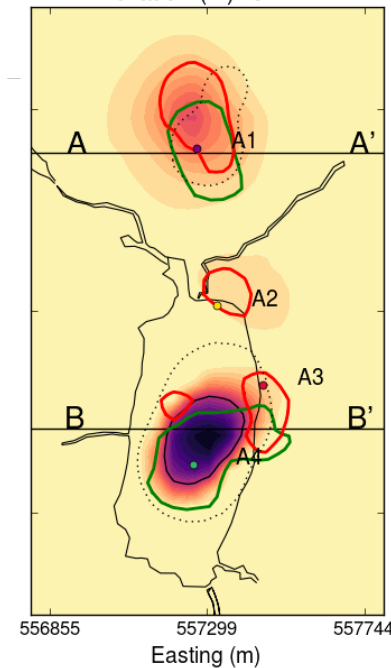
130 micro-s

Elevation (m): 311 m



410 micro-s

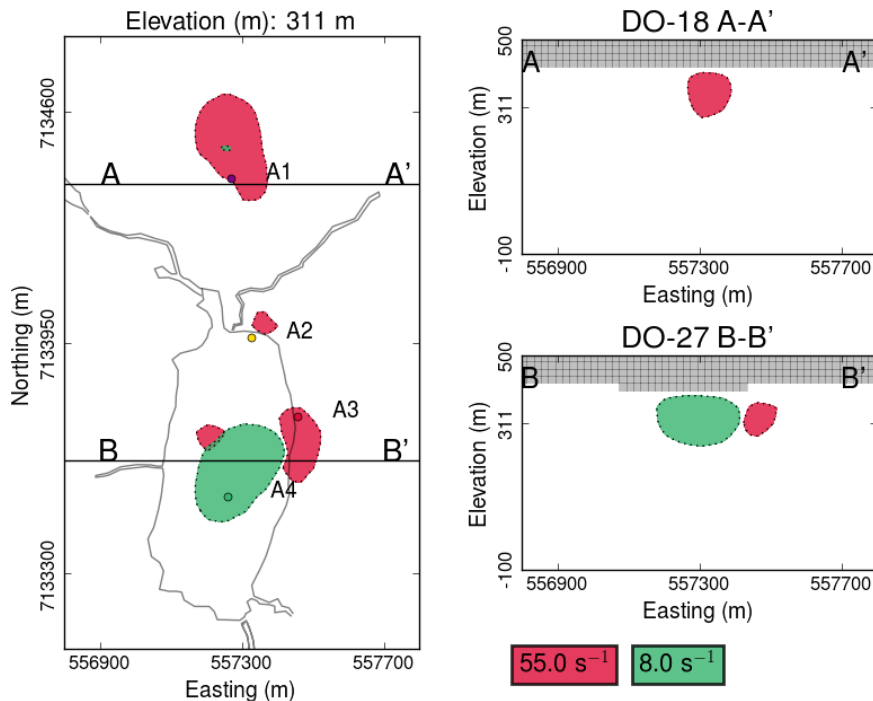
Elevation (m): 311 m



- Outline of two pipes
- Conductivity contour

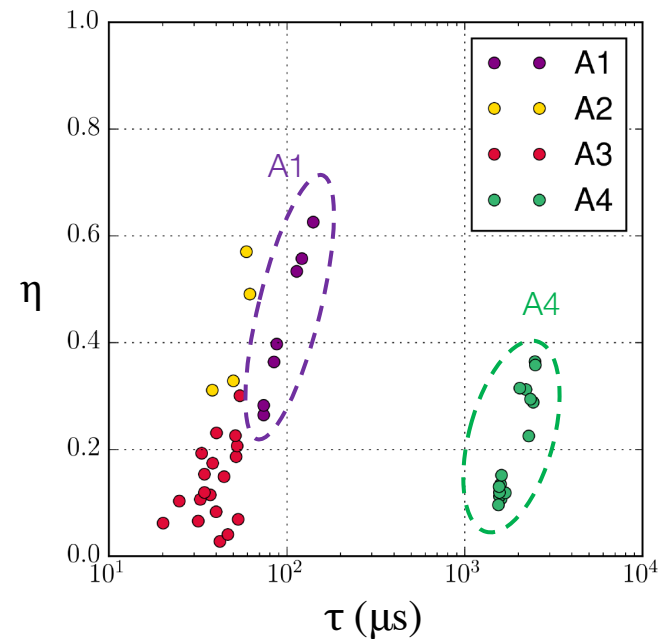
Step 4: Estimate η and τ

Anomaly contours



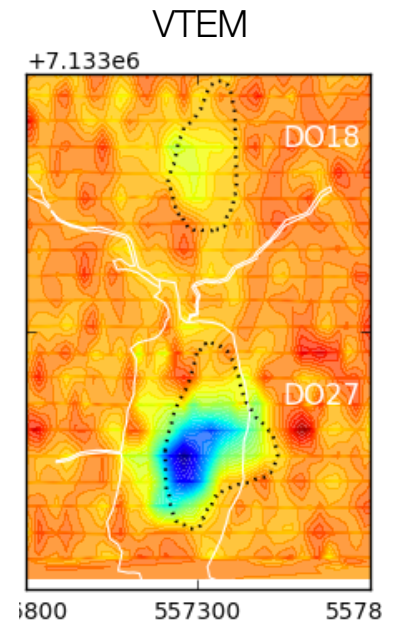
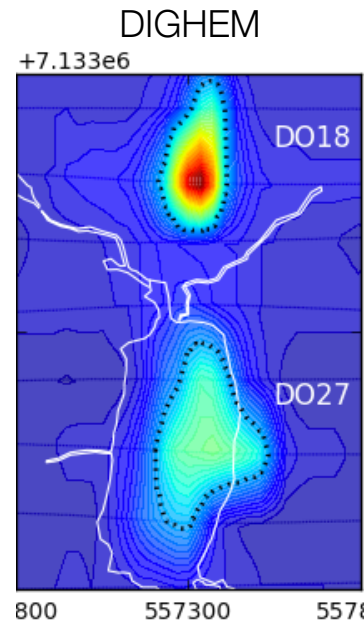
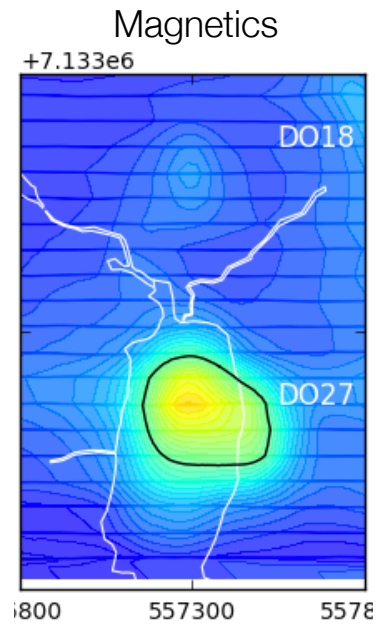
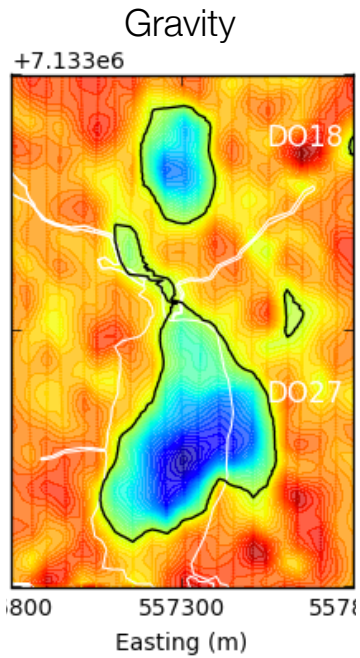
Cole-Cole model

$$\sigma(\omega) = \sigma_{\infty} + \sigma_{\infty} \frac{\eta}{1 + (1 - \eta)(\omega\tau)^c}$$

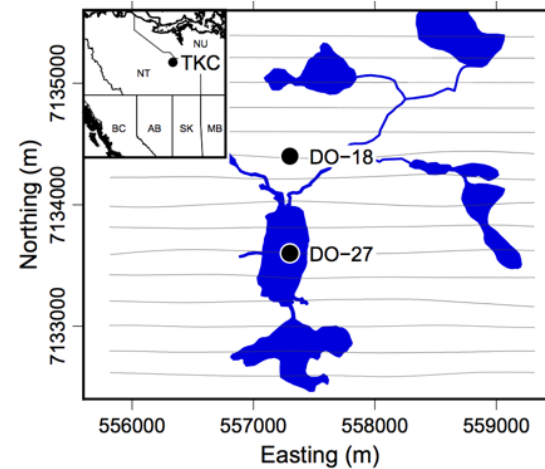
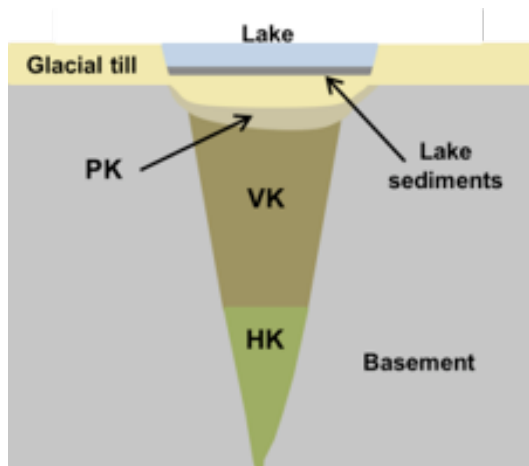


- A1-A3 has small time constant
- A4 has greater time constant

Data Integration

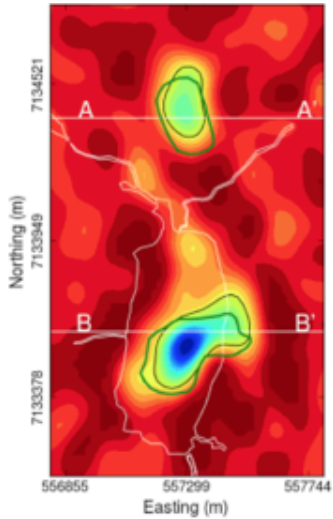


Kimberlite Model

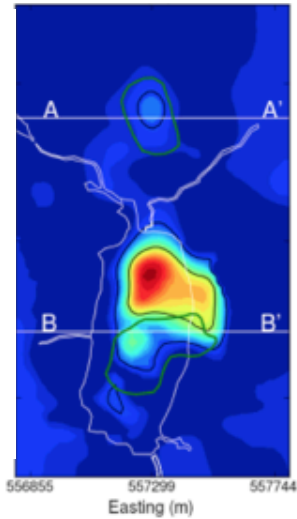


Data Integration: 5 physical property models

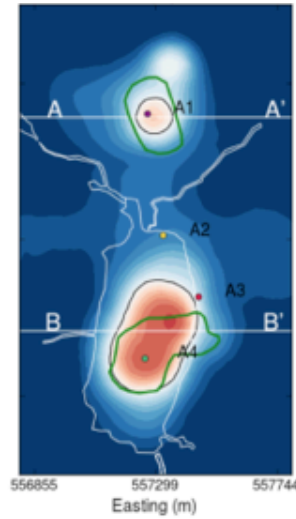
Density



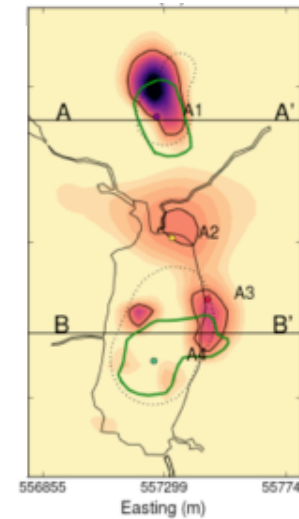
Susceptibility



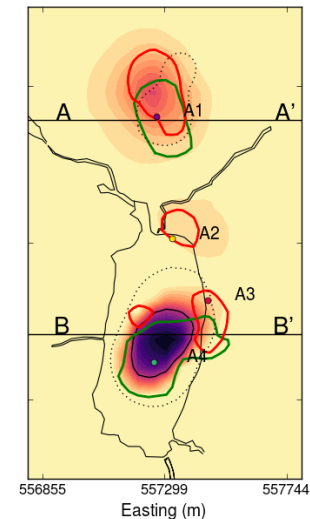
Conductivity



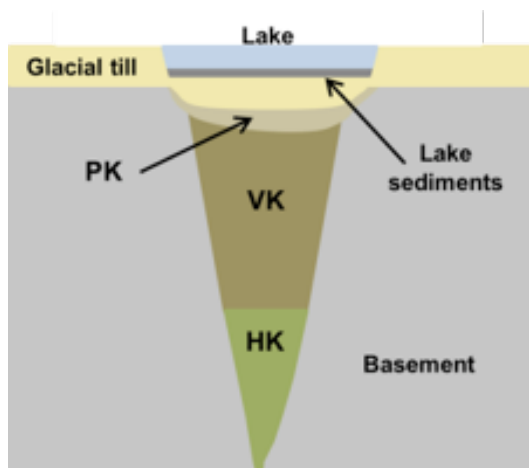
Early chargeability



Late chargeability



Kimberlite Model



Data Integration: 5 physical property models

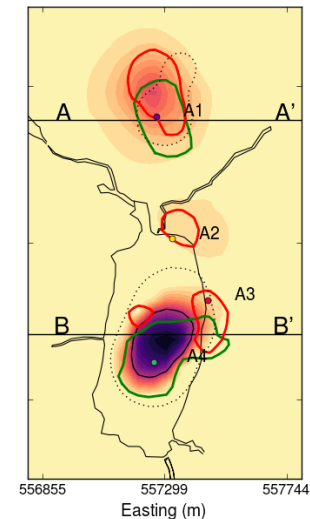
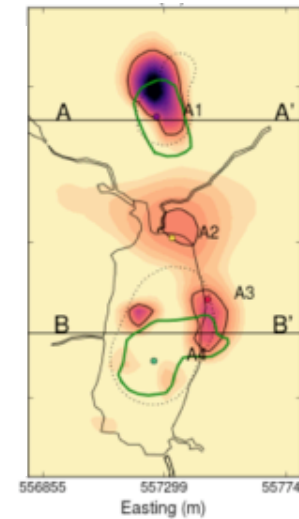
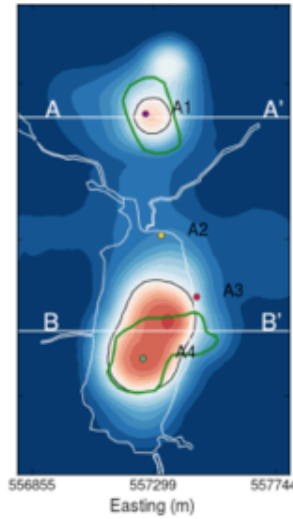
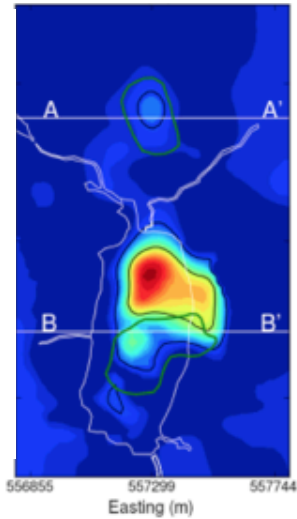
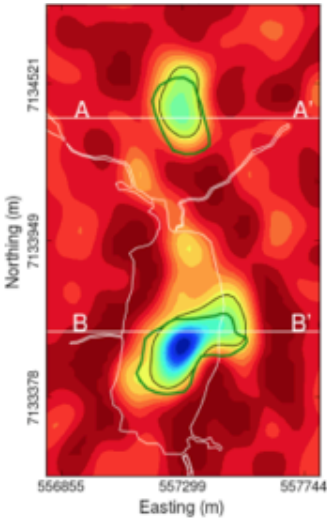
Density

Susceptibility

Conductivity

Early chargeability

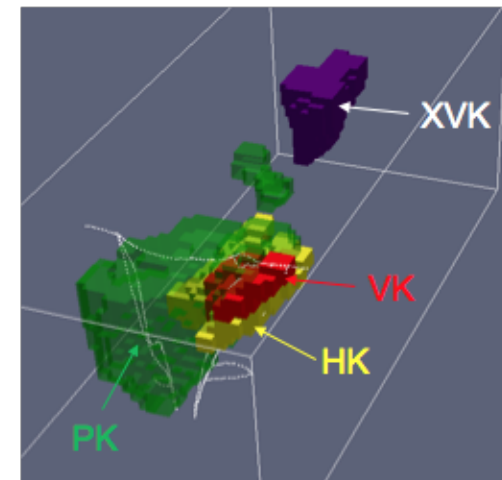
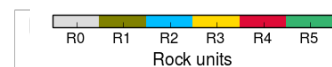
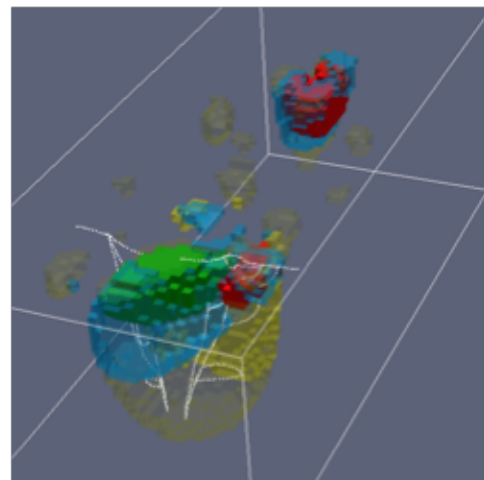
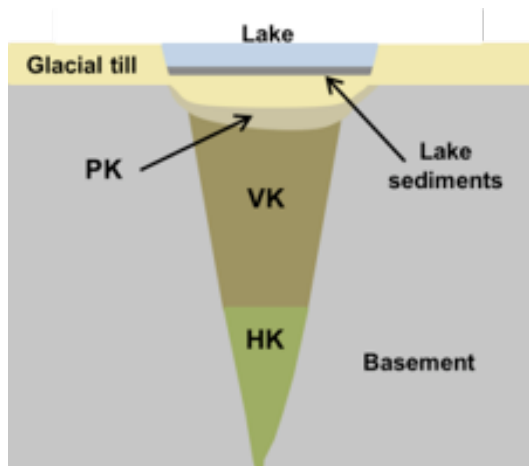
Late chargeability



Rock Model from Geophysics

Rock Model from Drilling

Kimberlite Model



Additional Material

- IP over Landfills
- Case History: Landfill in Denmark

IP over Landfills

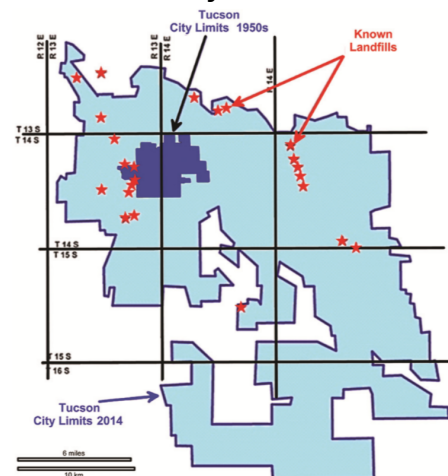
Landfills: Hazards and Goals

- 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



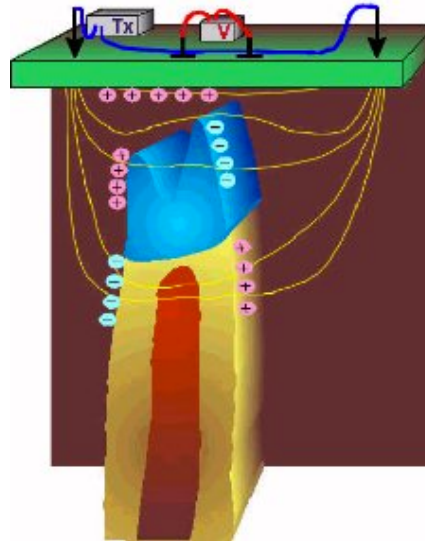
Waste Type	Description	Resistivity	Susceptible	Chargeable
Electronic/ Technological	Metallic objects, heavy metals in solution	Low	Yes	Yes
Construction Debris	Wood, cement, iron rebar, wall board, asbestos, glass, plastics	High	Frequently	Weakly
Earth Materials	Clays, various fill	Low/Moderate	Occasionally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

Traditional Landfill Surveys

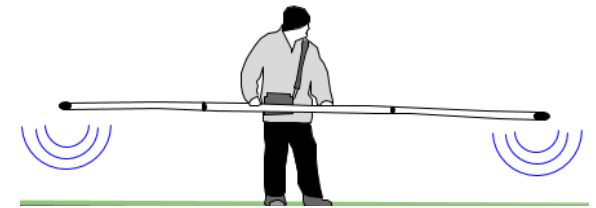
Magnetic



DC Resistivity



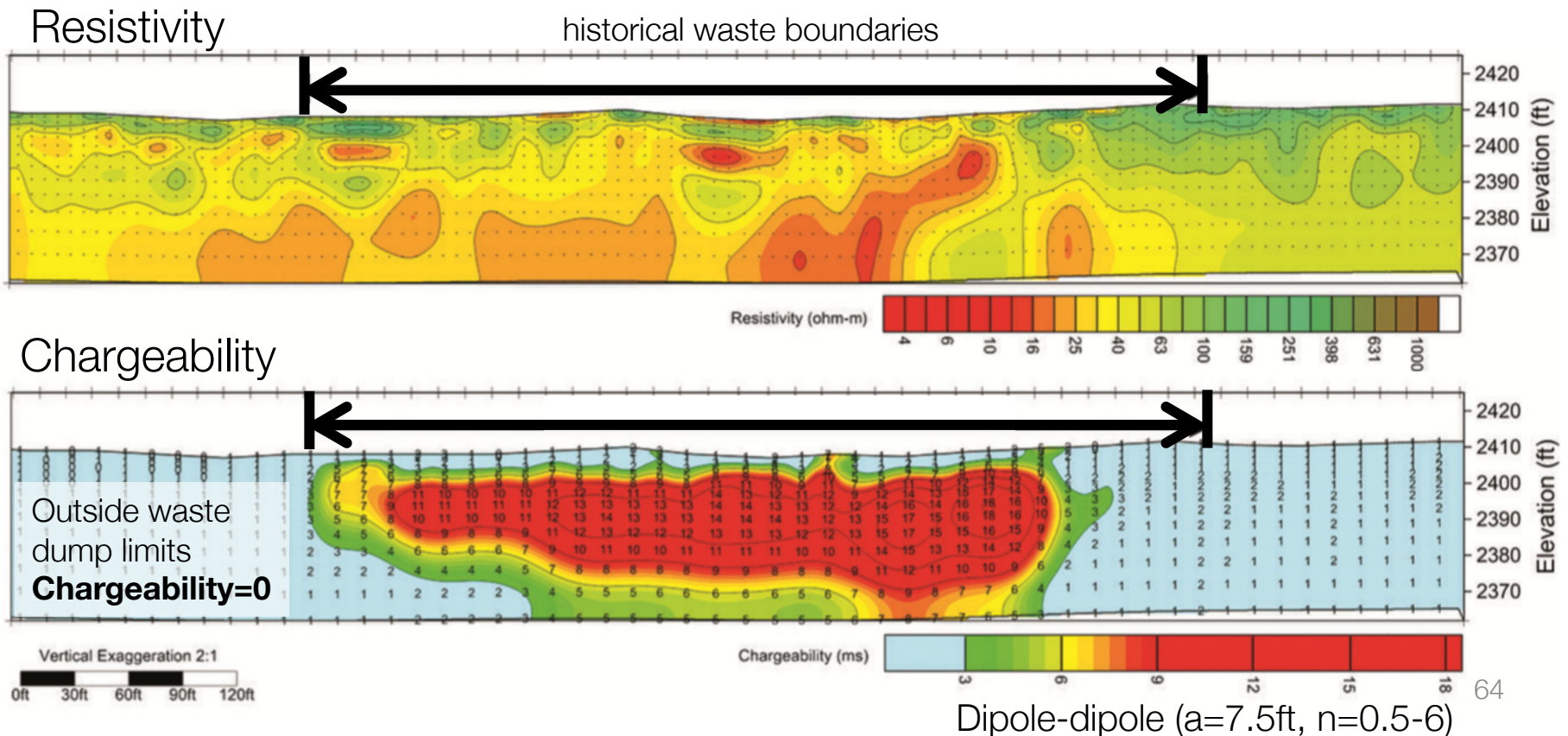
Near-Surface Electromagnetic



- 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)

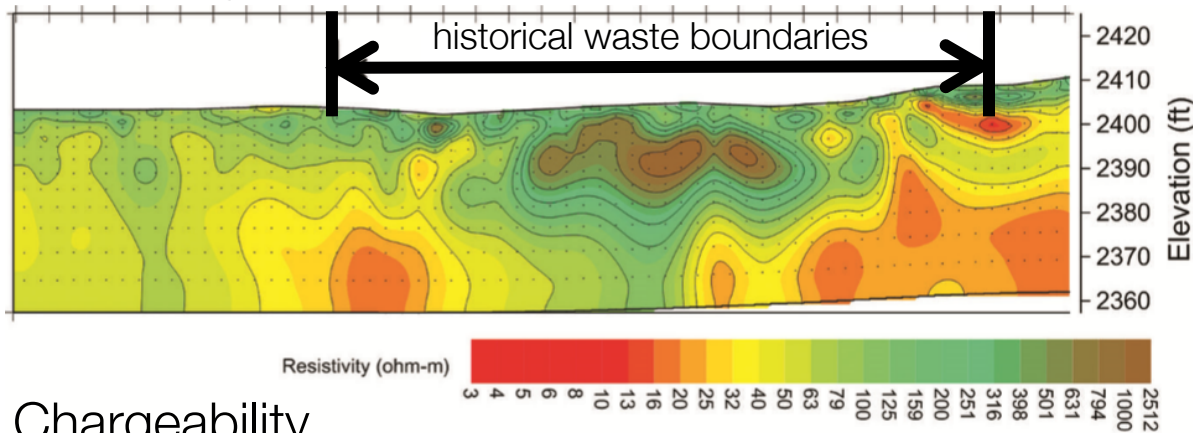
- Waste material: Mixed solid waste (MSW)
- Observations:
 - Resistivity not correlated with pit margins (non-diagnostic)
 - Chargeability (IP) correlates well with historical pit margins (diagnostic)



Ryan Airfield (Western Pit)

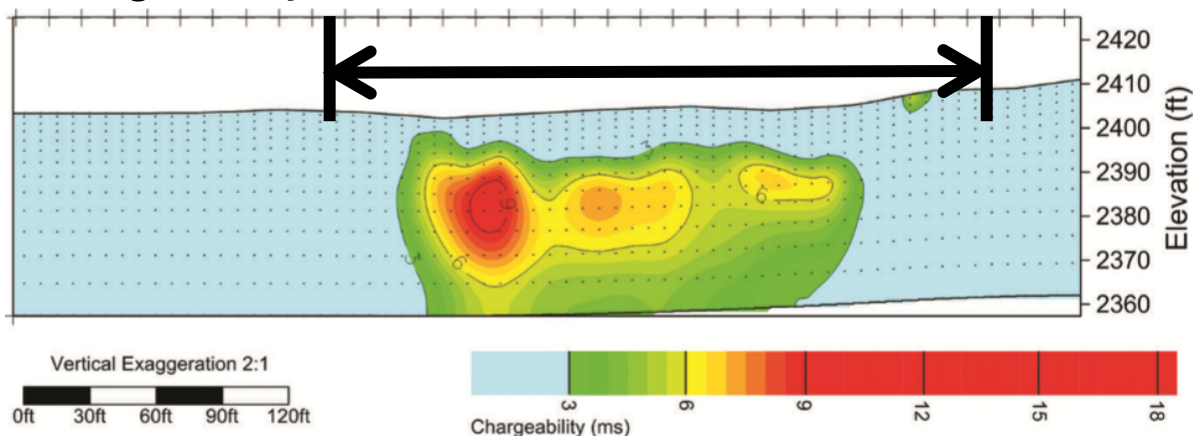
- Waste material: Construction / demolition
- Observations:
 - Waste correlates with region of high resistivity
 - Waste correlates with chargeable region (significant IP anomaly).

Resistivity



Resistive waste
within landfill

Chargeability

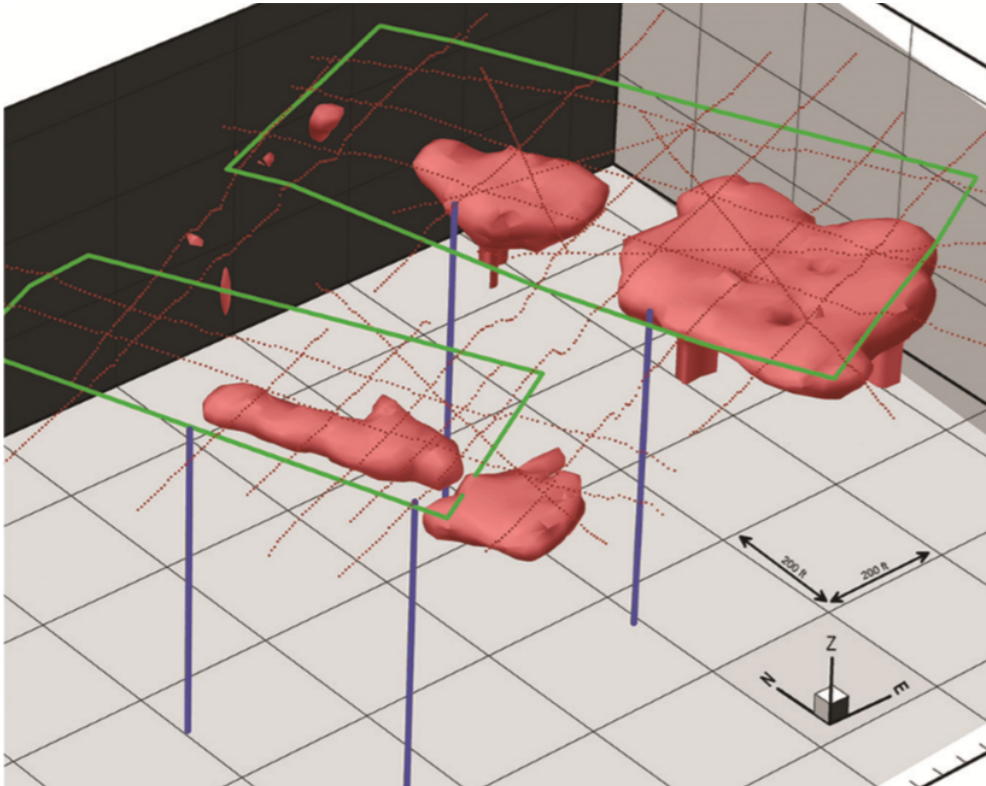


IP correlates with
landfill

Dipole-dipole ($a=7.5\text{ft}$, $n=0.5-6$)

Ryan Airfield (Composite)

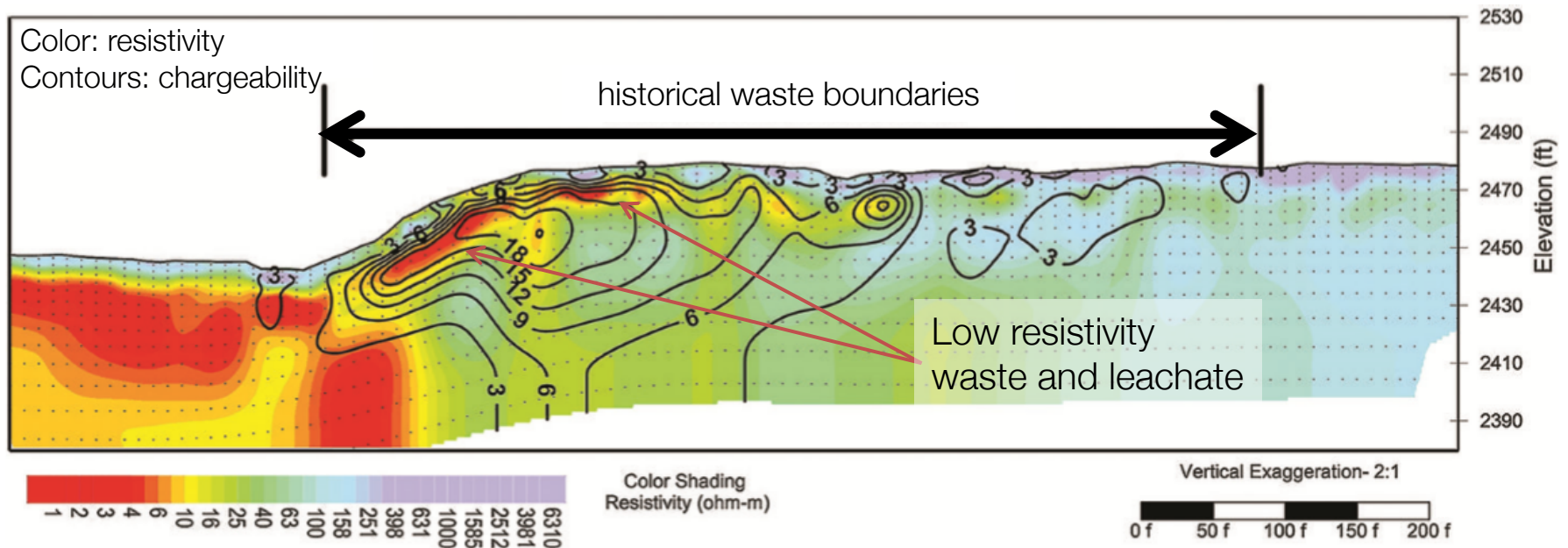
Chargeability isosurface



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

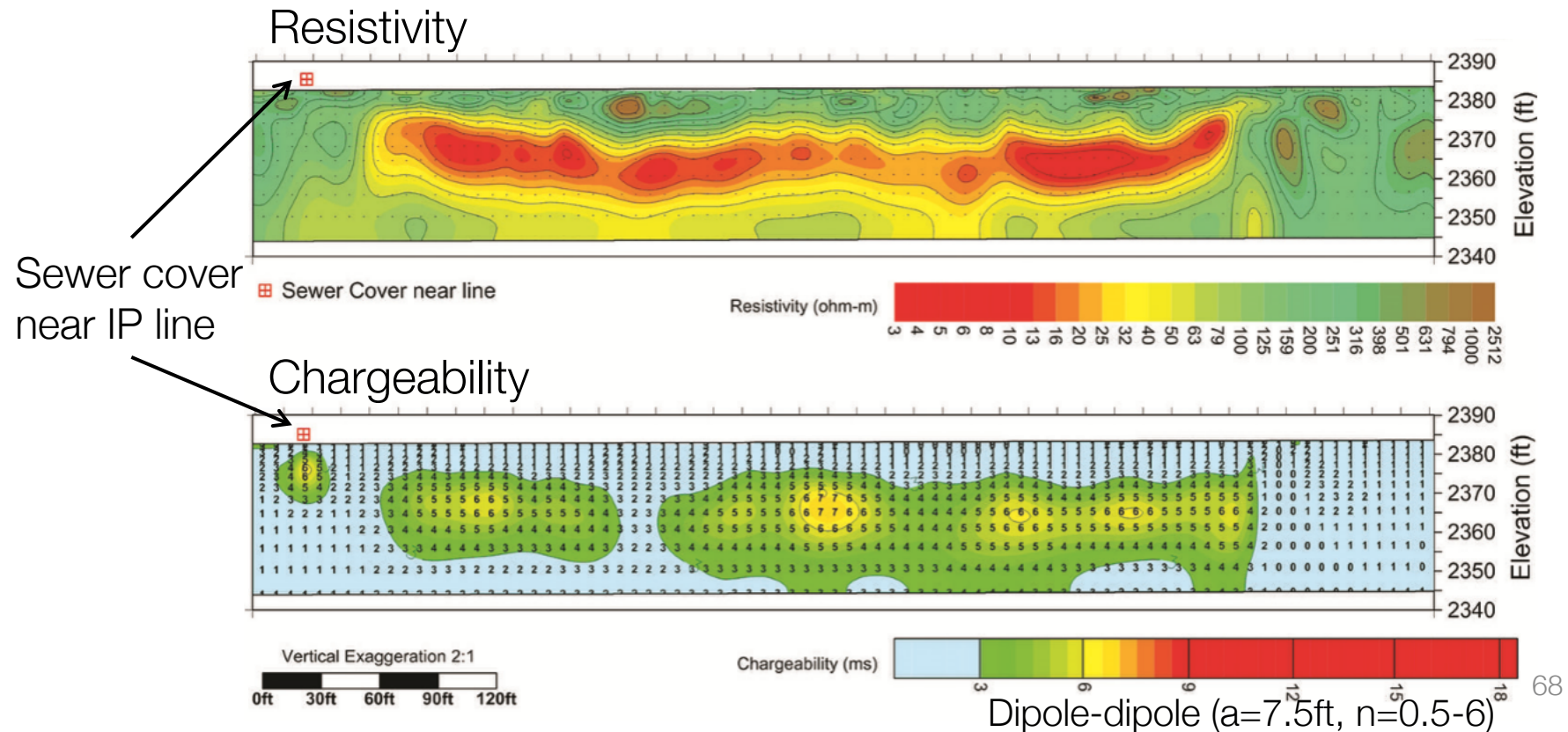
Tumamoc Landfill

- 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

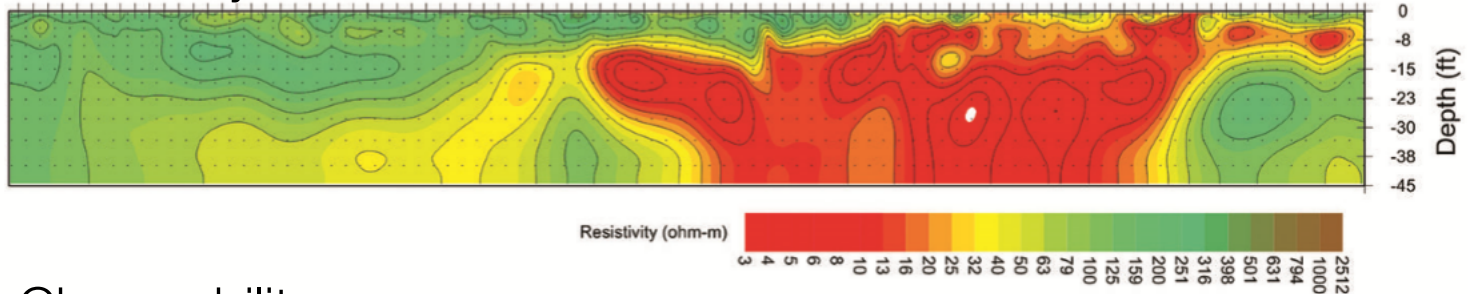
- Waste material: green-waste, trees, clippings
- Observations:
 - Resistivity low
 - Weak but elevated IP signature



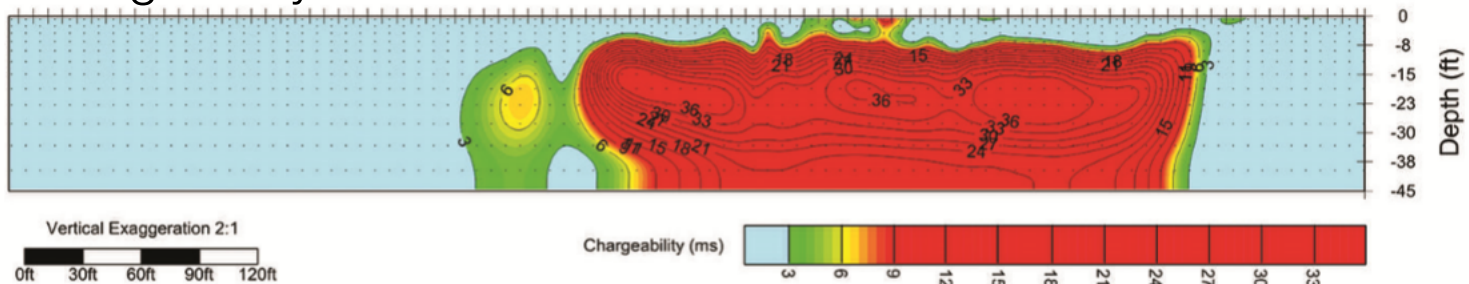
Nearmont Landfill

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

Resistivity



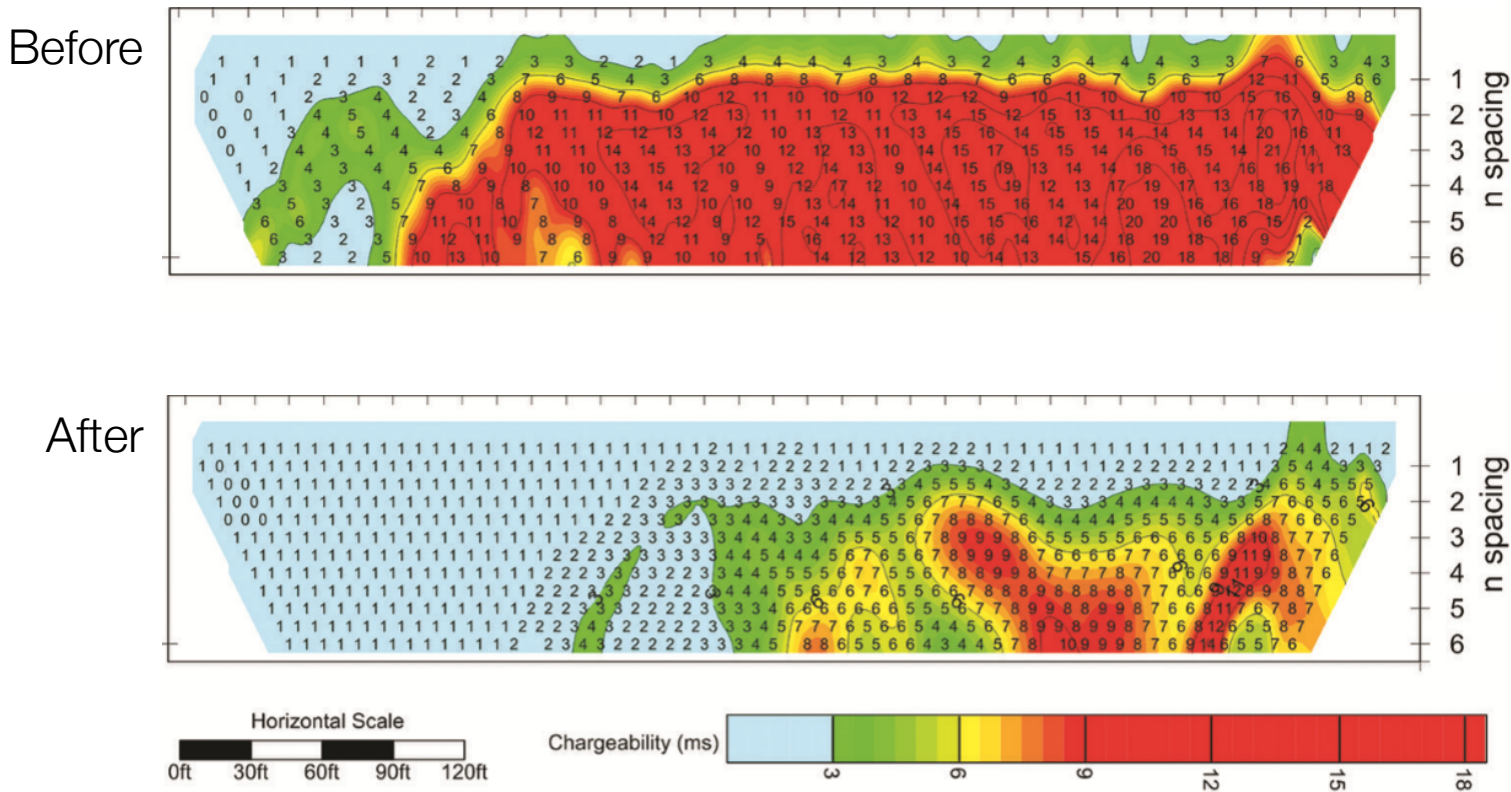
Chargeability



Dipole-dipole ($a=7.5\text{ft}$, $n=0.5-6$)

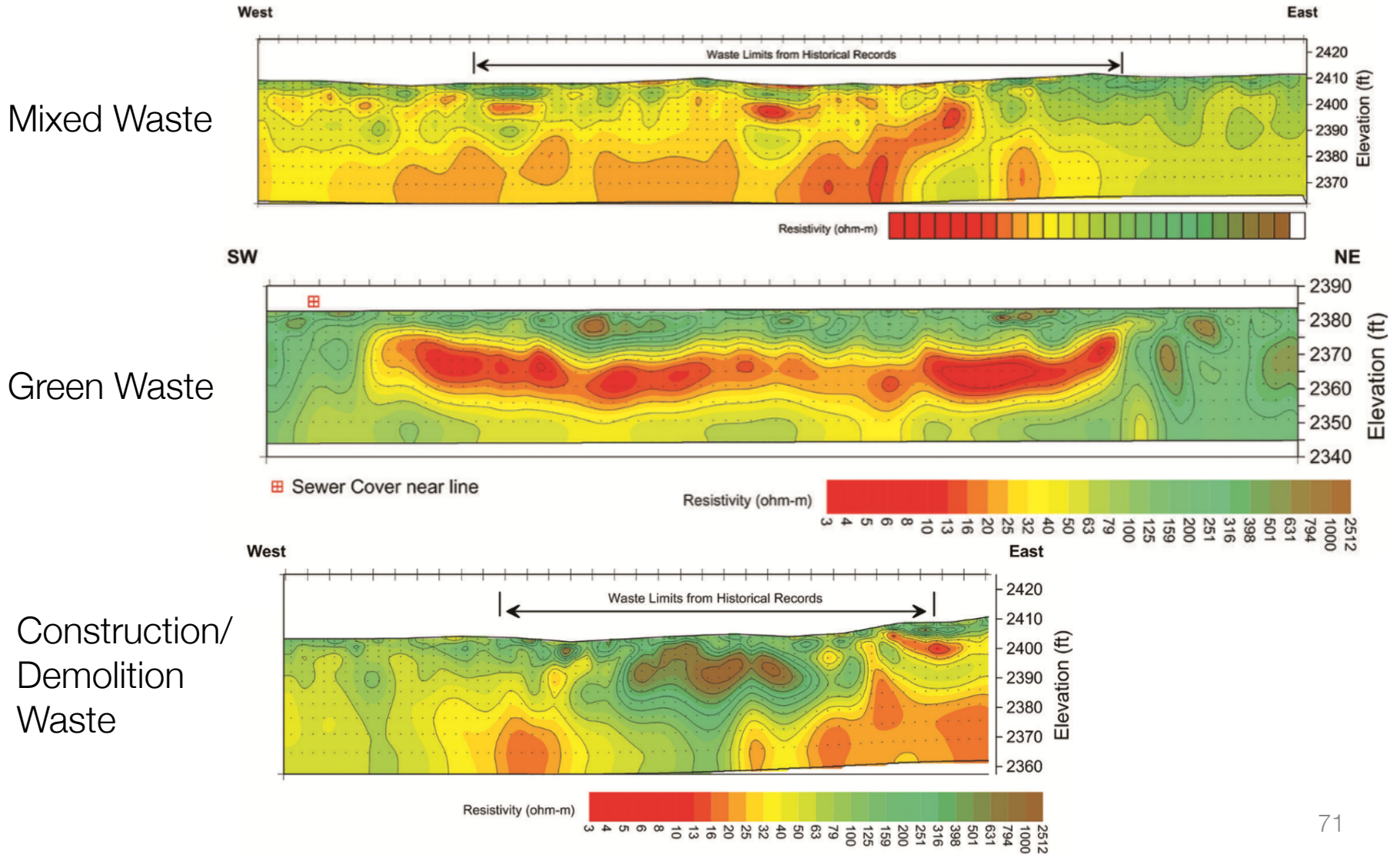
Example: Landfill Monitoring

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



Summary

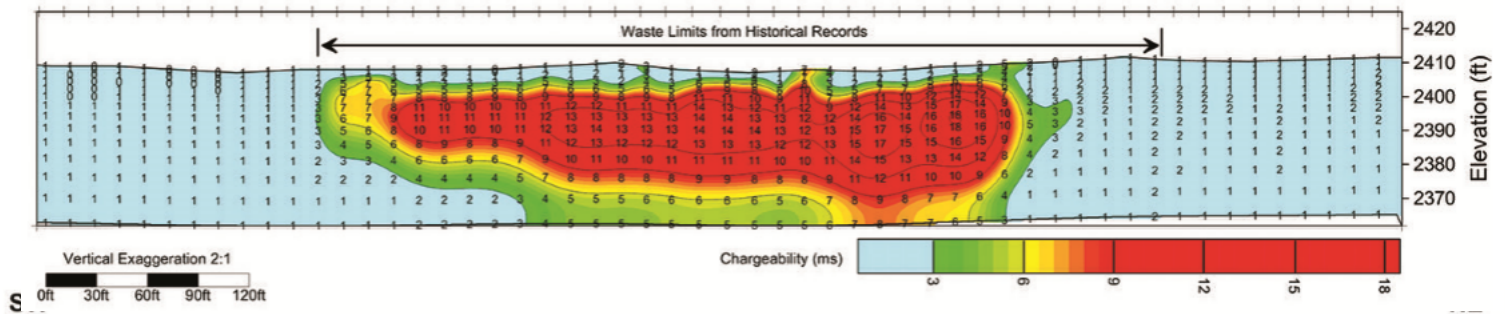
- Resistivity may not be a good indicator of waste



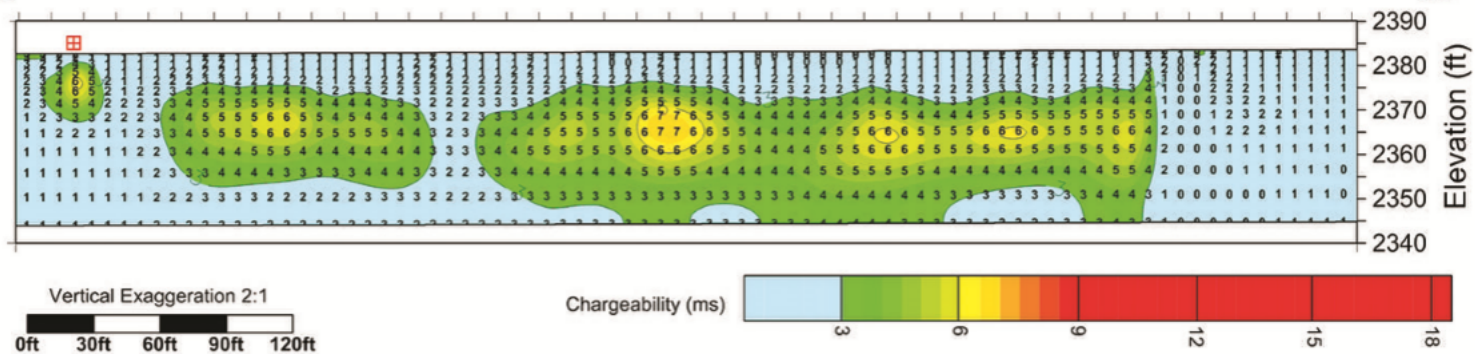
Summary

- Chargeability may be a more consistent indicator of waste

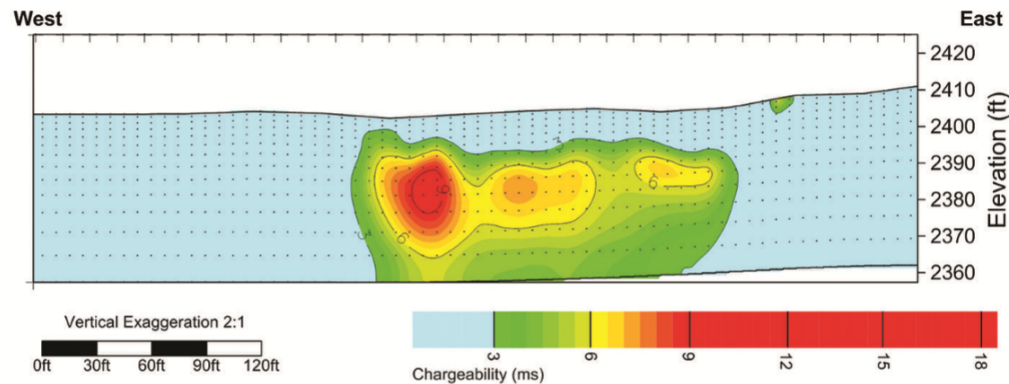
Mixed Waste



Green Waste

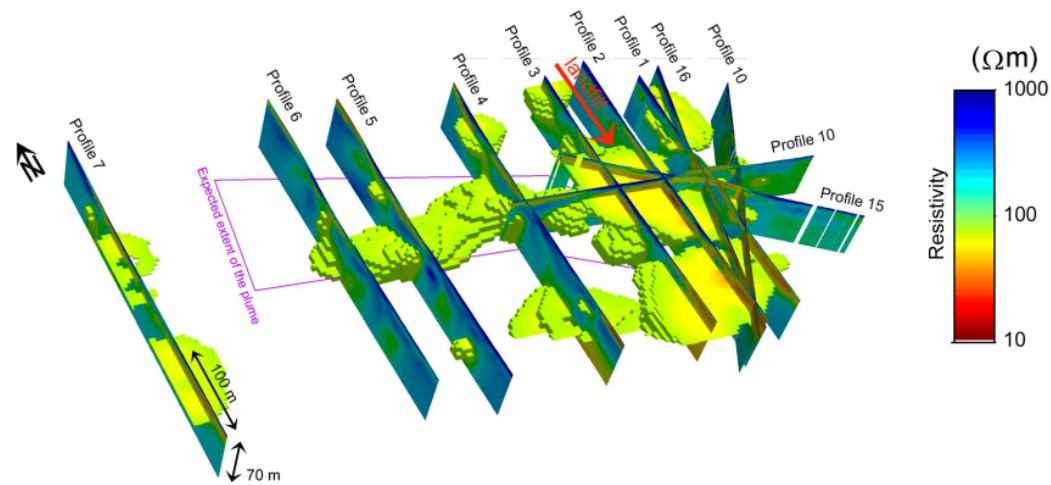


Construction/
Demolition
Waste



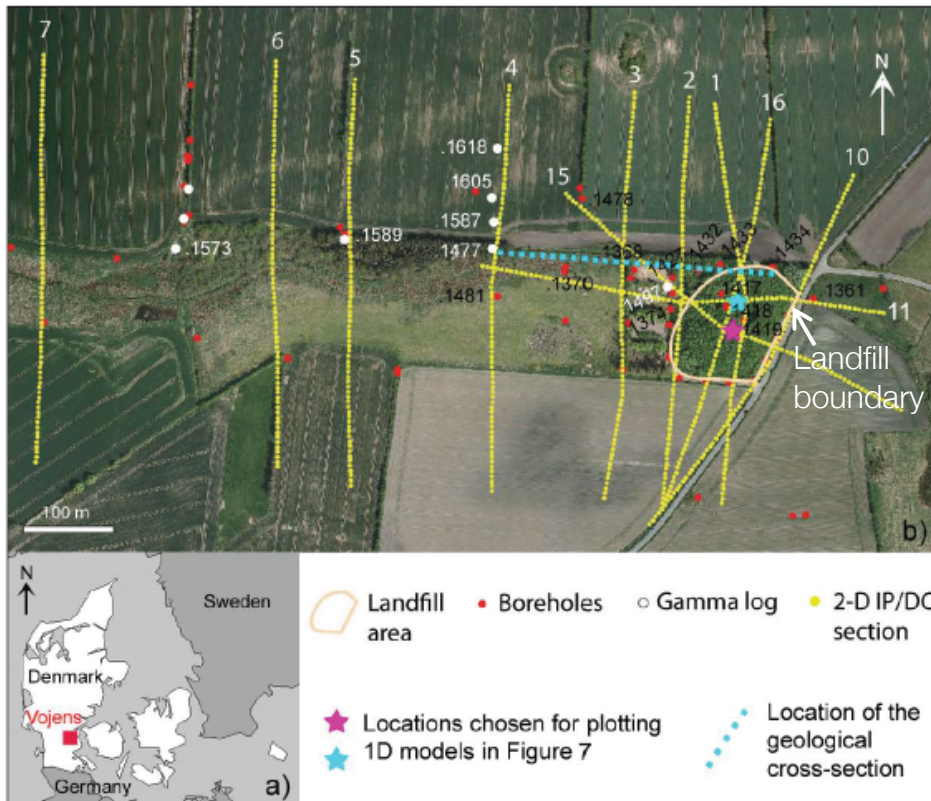
Case History: Mapping a landfill, Denmark

Gazoty et al., 2012



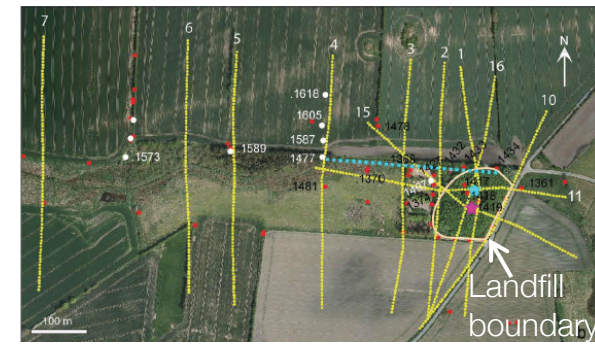
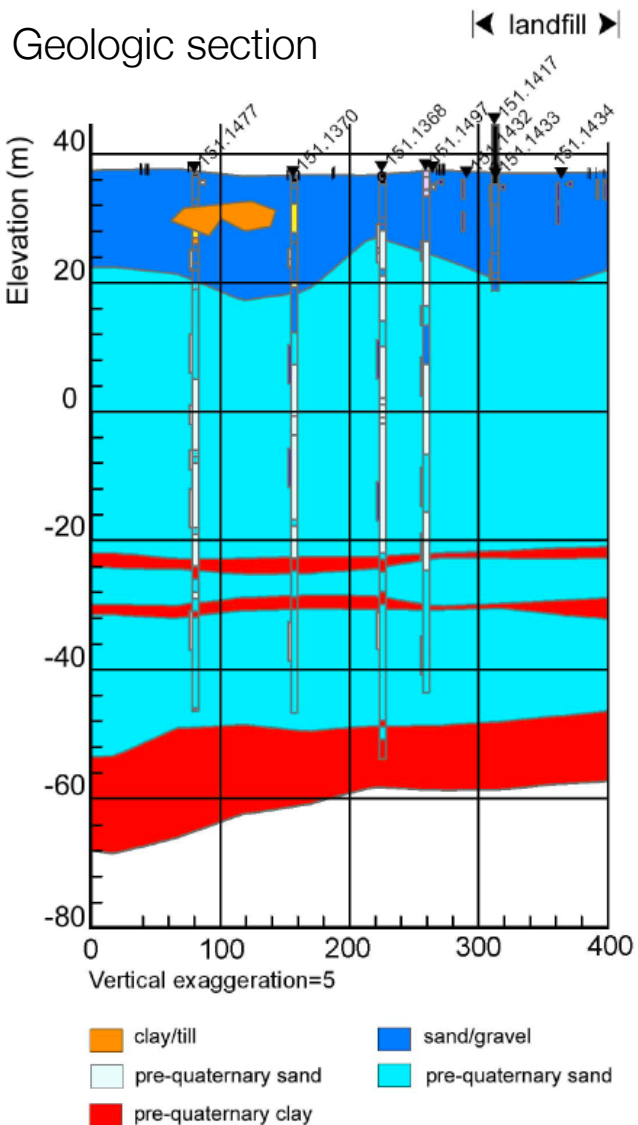
Setup

Horlokke area, Denmark



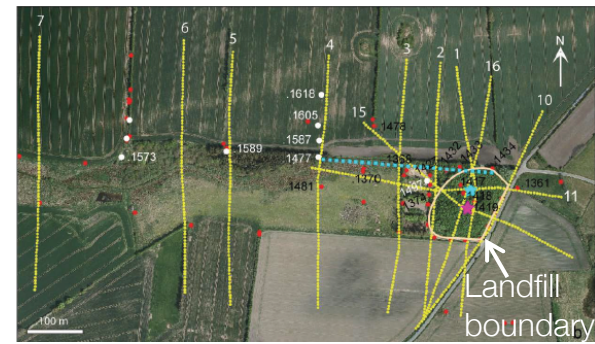
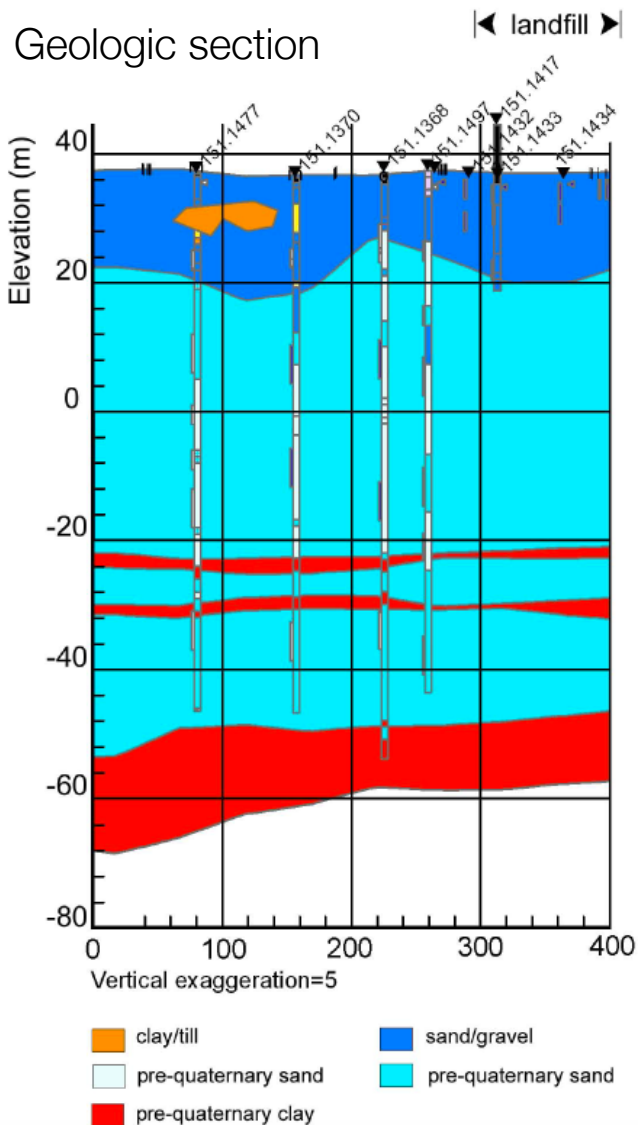
- Landfill
 - Years: 1968-1978
 - 100m x 100m
 - Sludge from waste treatment plant
 - Estimated volume: 65,000m³
- Containment
 - No membrane
 - No leachate capture
 - No isolation system
- Current state
 - Landfill: hydrocarbons, iron, inorganics
 - Contaminant plume
 - 500m to west; depth (50-60 m)
 - Chlorinated compounds

Setup



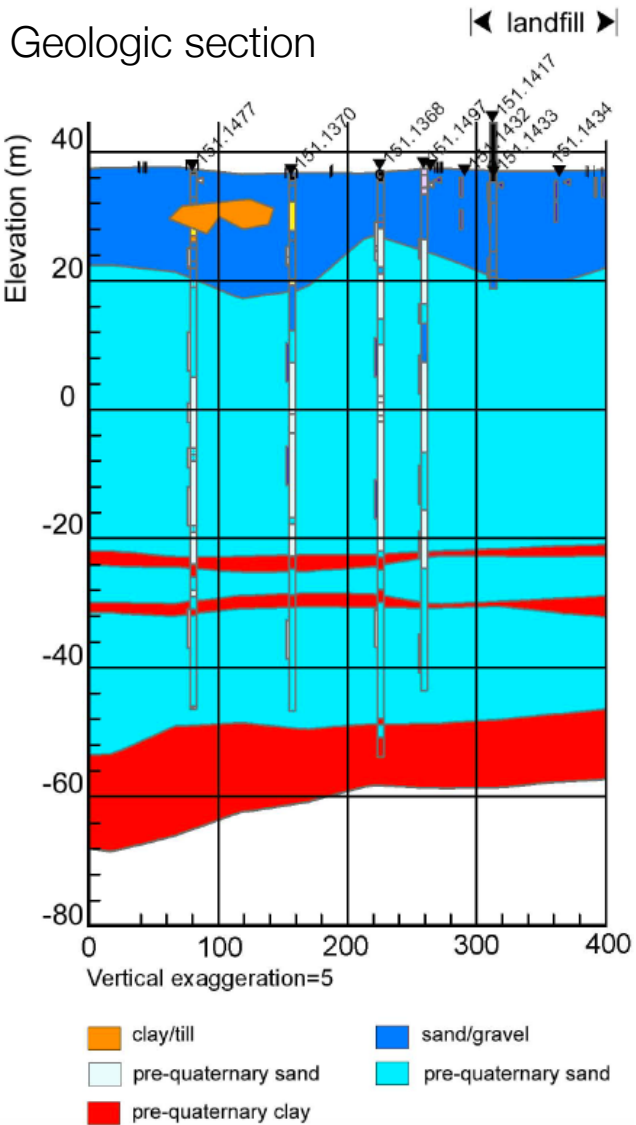
- Horlokke landfill
 - Located on an outwash plane (low topography)
 - Clay layer: top 2-3m
 - Waste layer: 6-8m thick
- General geology
 - Gravel and sand with interbedded clay
 - Water level: 2-3m depth
 - Sand layers below landfill host regional aquifer
- Aquifer is used for drinking water
 - Watershed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

Objectives



- 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

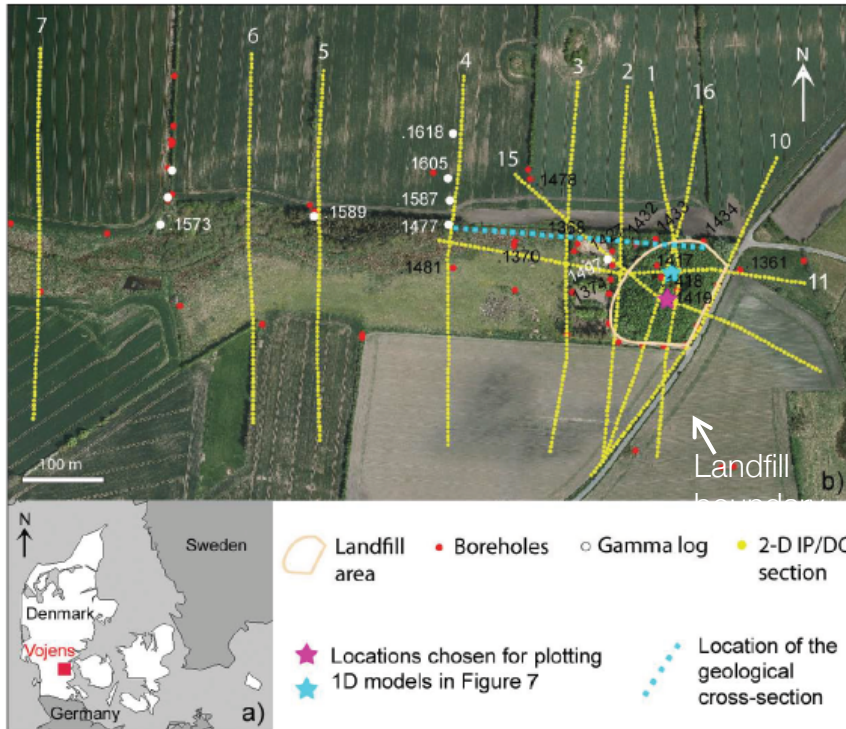


Physical properties

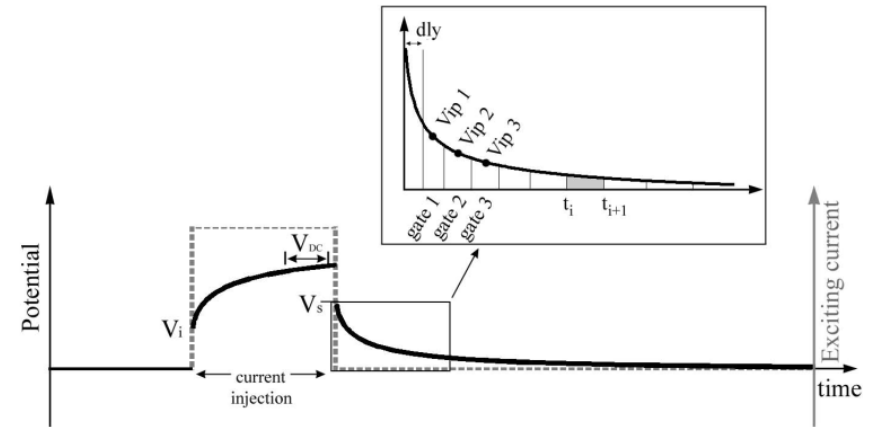
	Resistivity	Chargeability	Gamma
sand/gravel	High	Low	Low
clay/till	Low	High	High
sand	High	Low	Low
landfill	High (?)	High	(?)

Survey

Study area



Time domain IP (TDIP)



Data (chargeability):

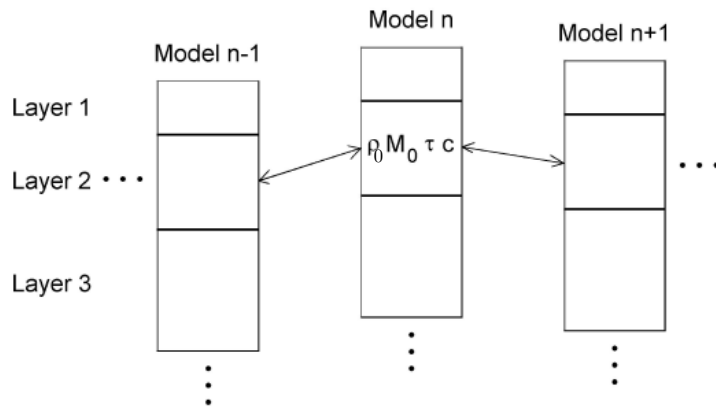
$$M_i = \frac{1}{V_{DC} \cdot [t_{i+1} - t_i]} \int_{t_i}^{t_{i+1}} V_{ip} dt$$

- 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)

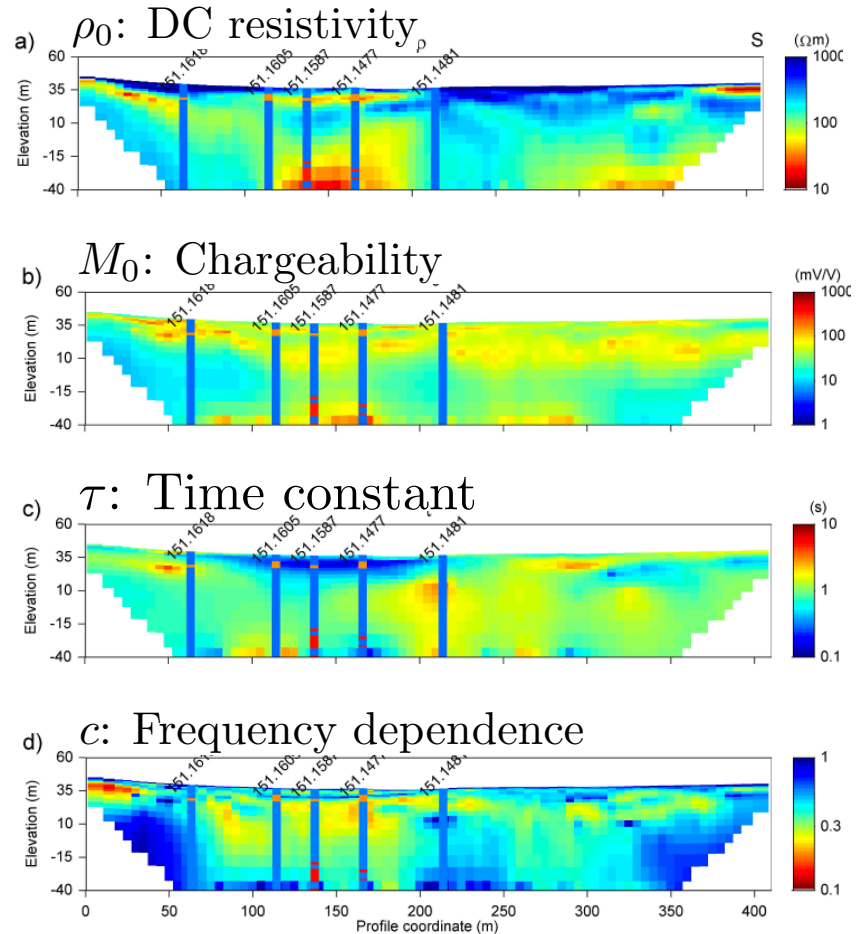
Processing / Inversion

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



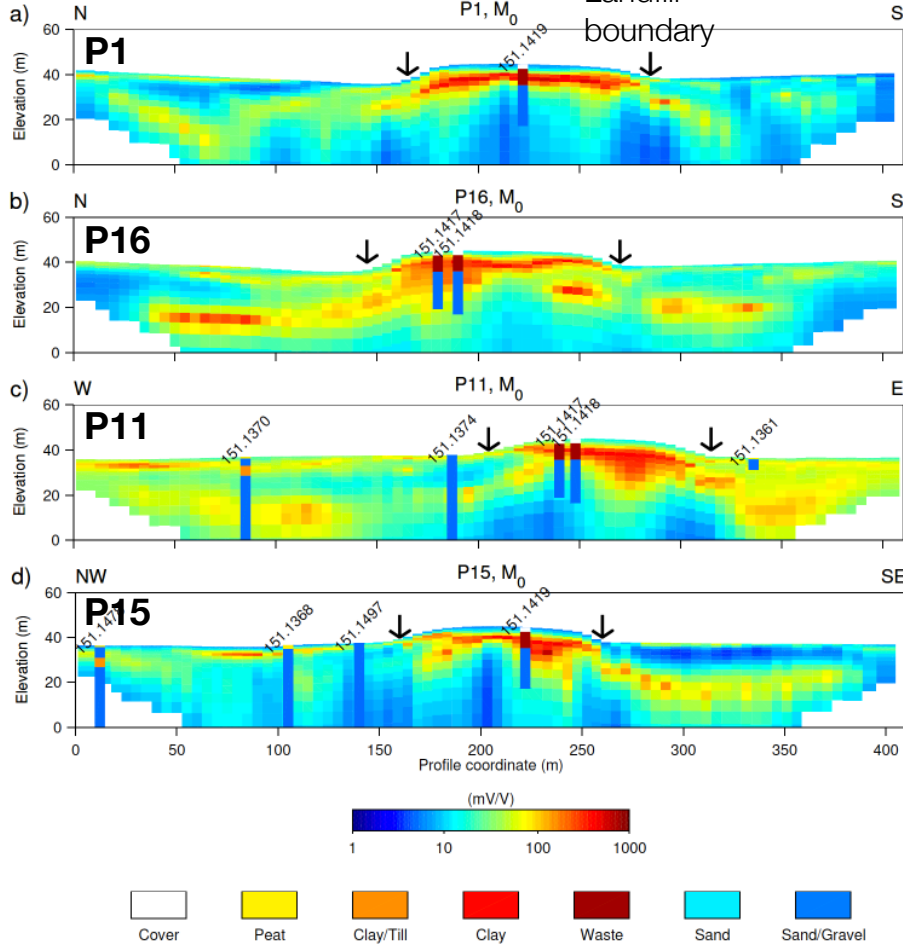
$$\rho(\omega) = \rho_0 \left[1 + M_0 \left(1 - \frac{1}{1 + (i\omega\tau)^c} \right) \right]$$

Recovered Cole-Cole sections:



Interpretation: Delineating the landfill

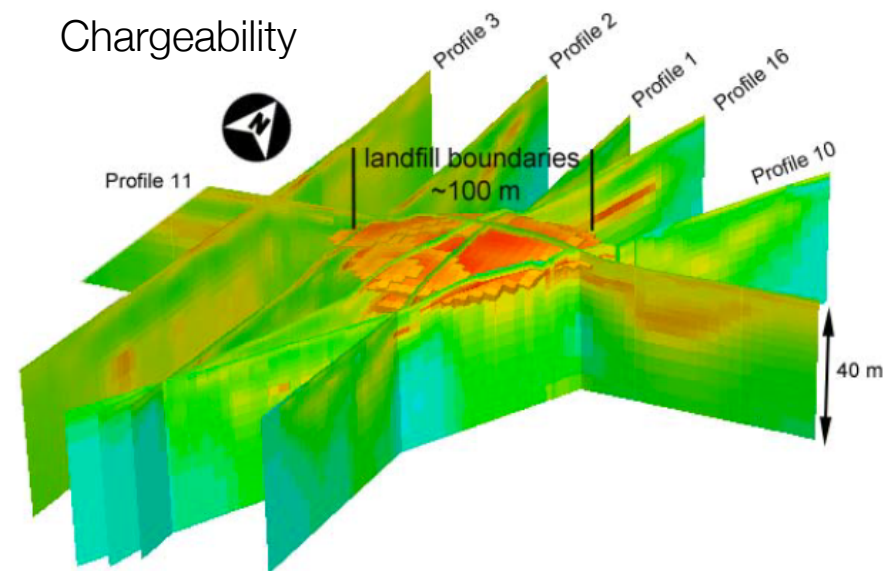
Chargeability (M_0) sections



Location map



Chargeability

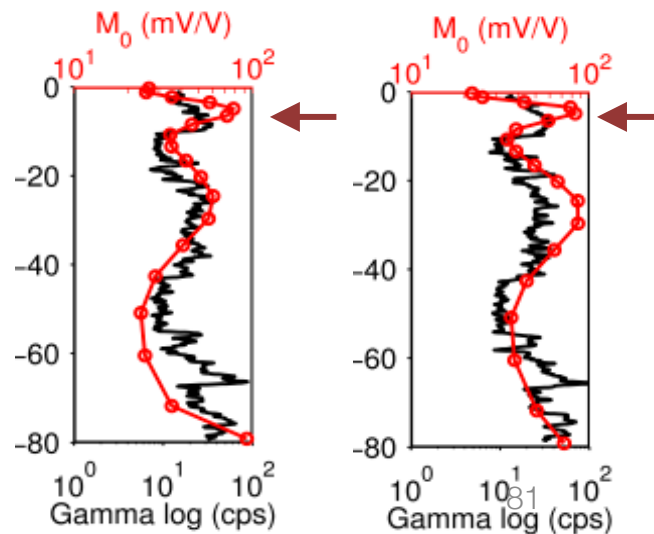
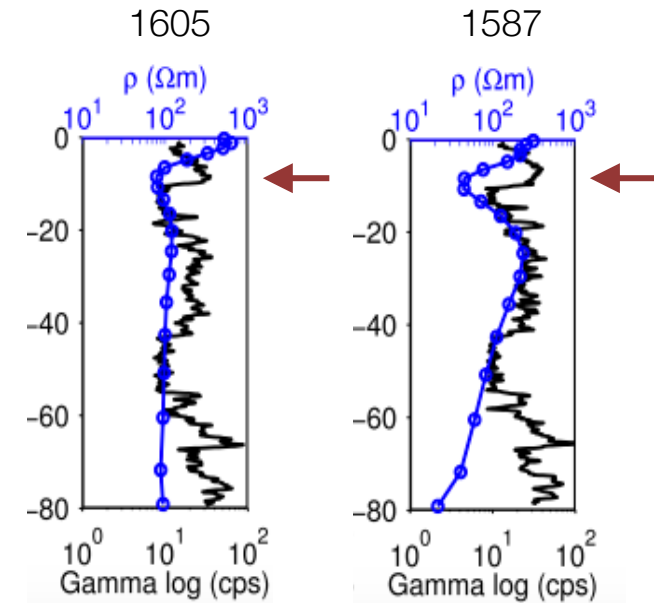
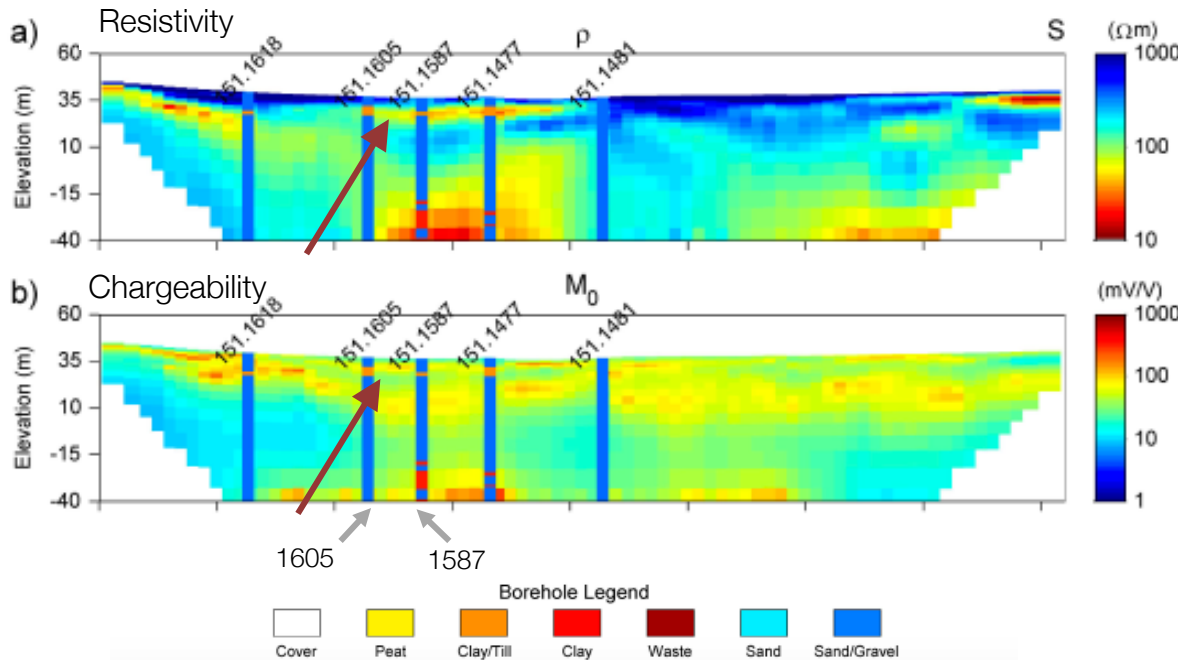


Estimated volume

Using 100 mV/V cutoff: 50,000m³
 From historic record: 65,000m³

Interpretation: Clay layer (Aquitard)

Resistivity and chargeability sections



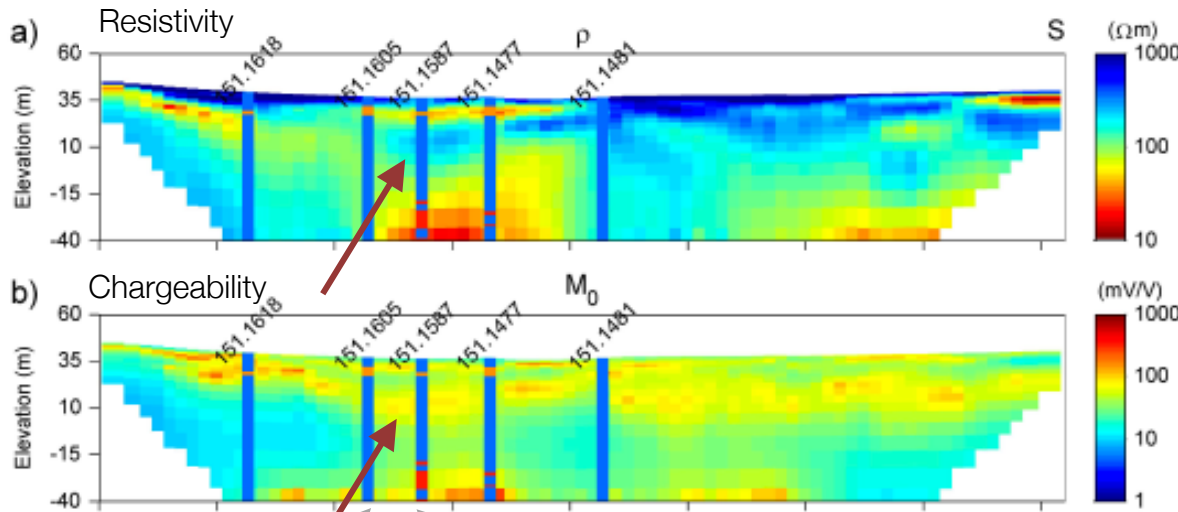
Formation	Resistivity	Chargeability	Gamma
Clay	Low (60 ohm m)	High	High

Interpretation

- Creek overlays the clay layer (acts as aquitard)

Interpretation: Clay-rich sandy layer

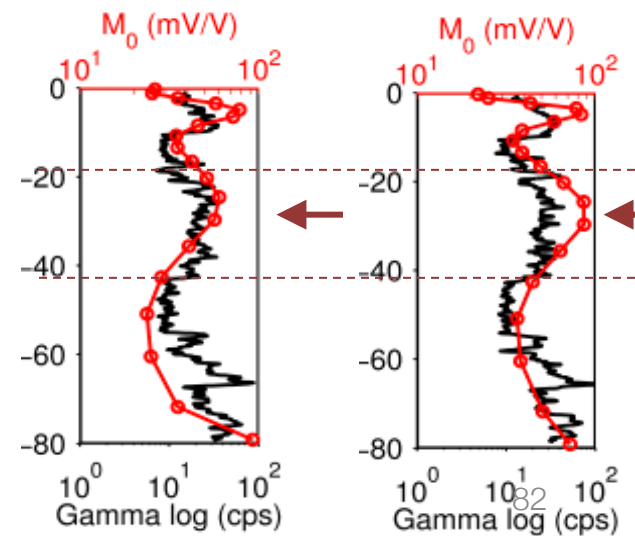
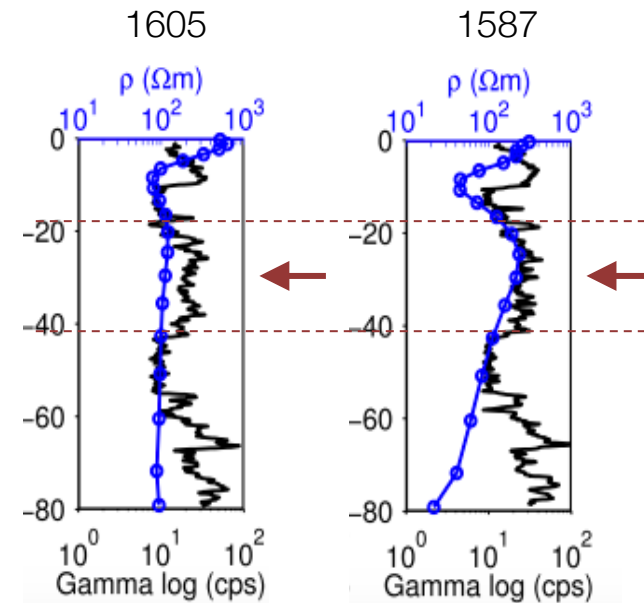
Resistivity and chargeability sections



1605 1587

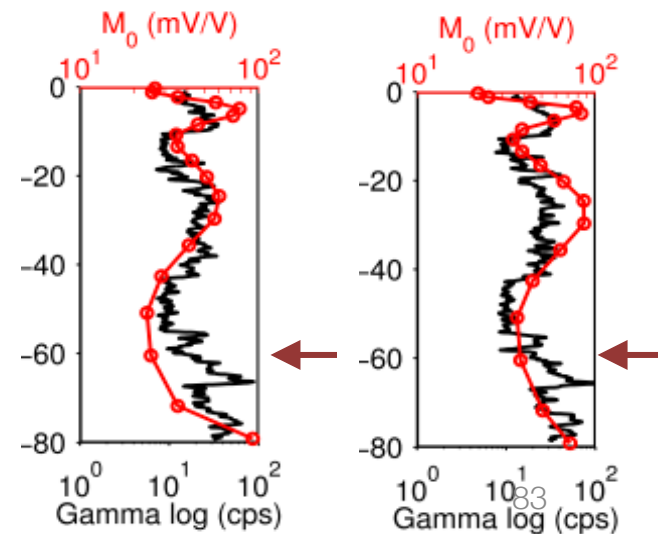
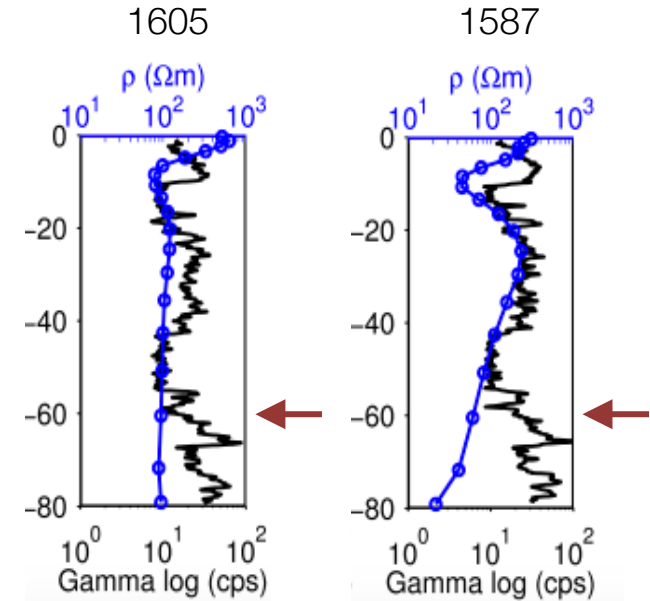
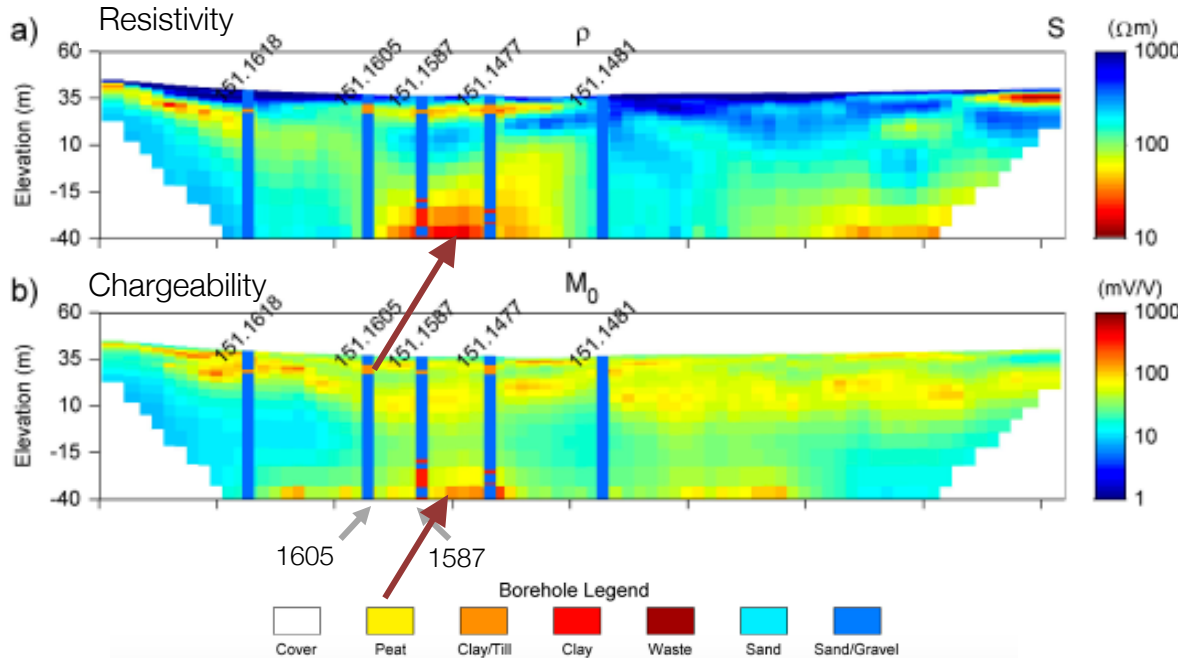


Formation	Resistivity	Chargeability	Gamma
Clay	Low	High	High
Clay-rich sandy layer	High	Moderate (50-100 mV/V)	High



Interpretation: Silt/clay lens

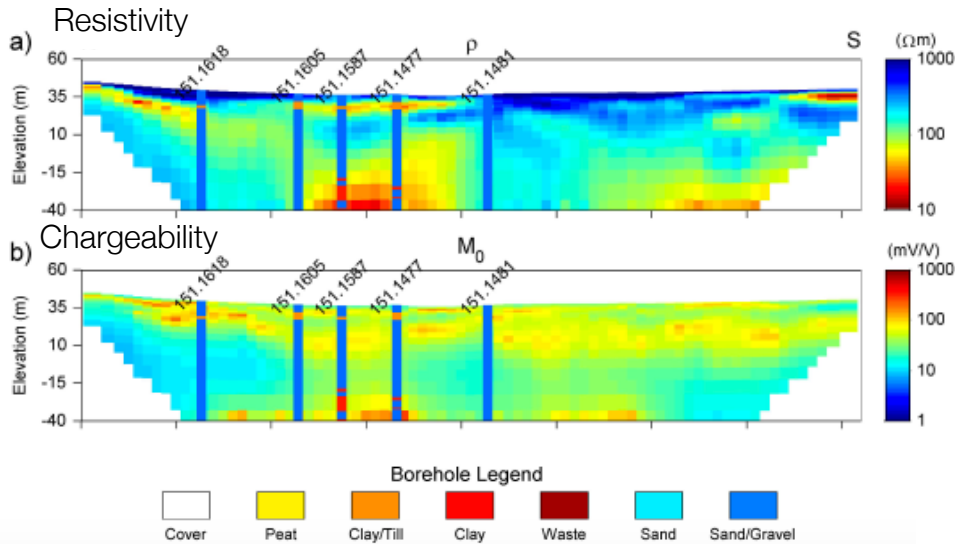
Resistivity and chargeability sections



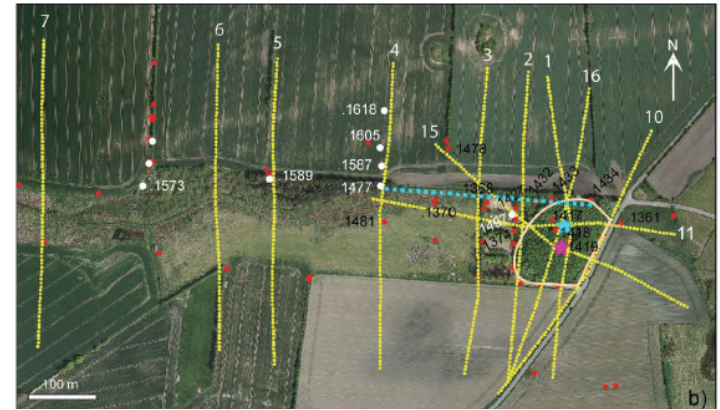
Formation	Resistivity	Chargeability	Gamma
Clay	Low	High	High
Clay rich sandy layer	High	Moderate (50-100 mV/V)	High
Silt/clay lens	Low	High	High

Interpretation: Lithology

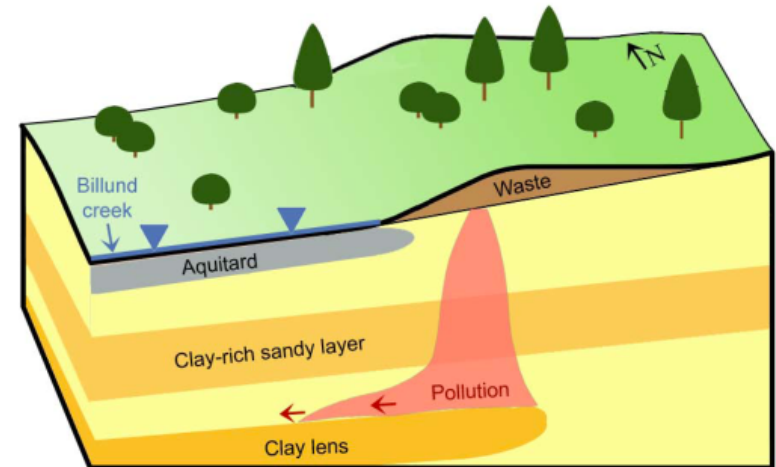
Resistivity and chargeability sections



Location map

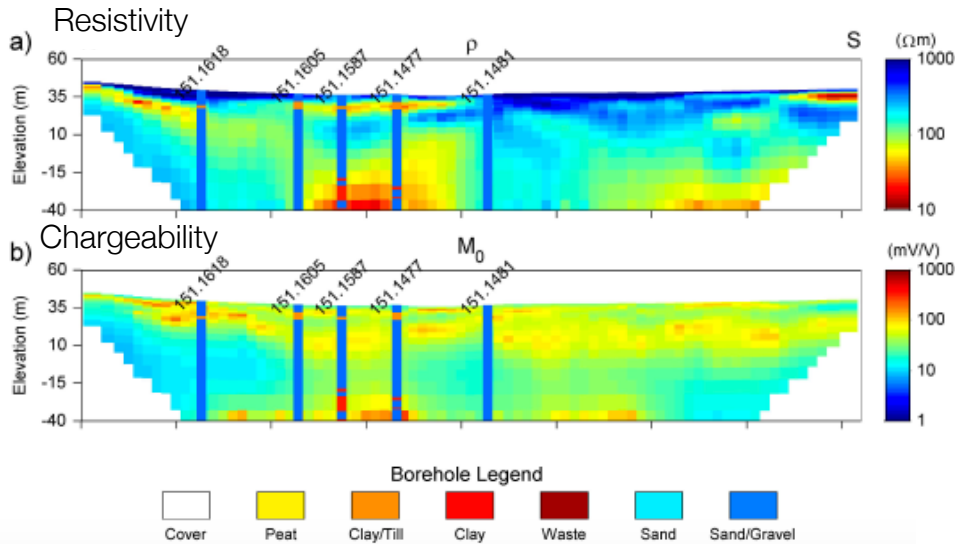


Geologic interpretation

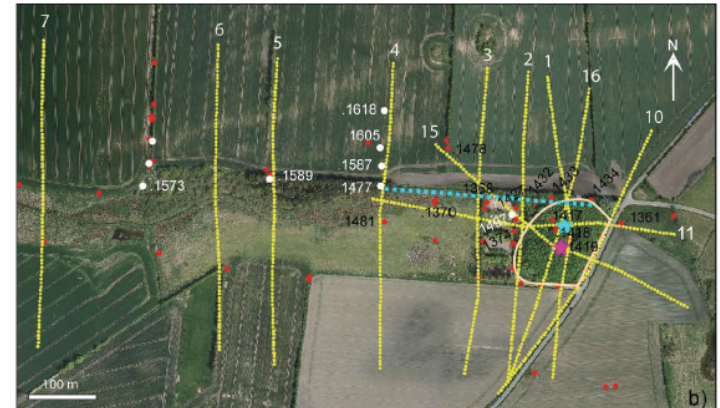


Interpretation: Lithology

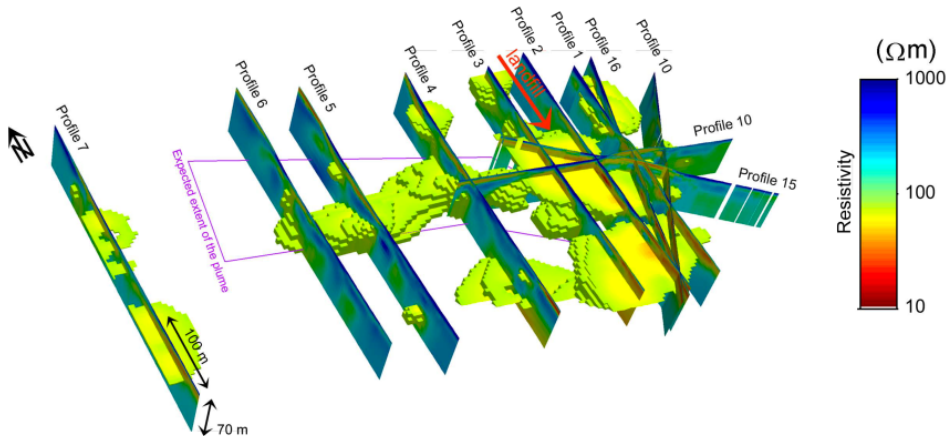
Resistivity and chargeability sections



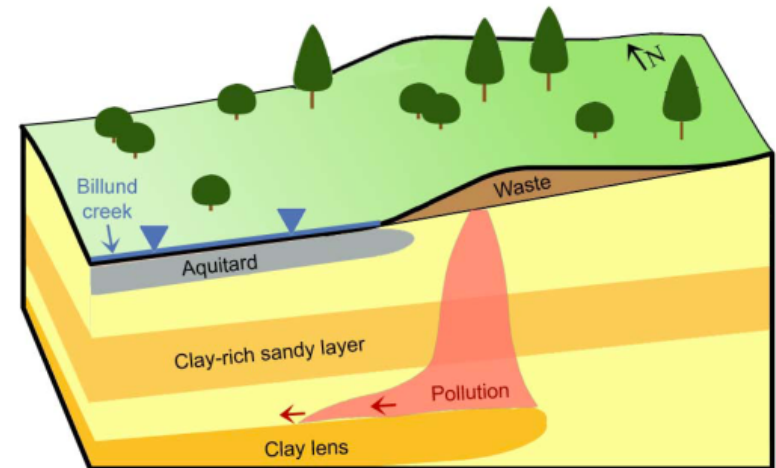
Location map



Resistivity cut-off volume ($<100 \Omega\text{m}$)

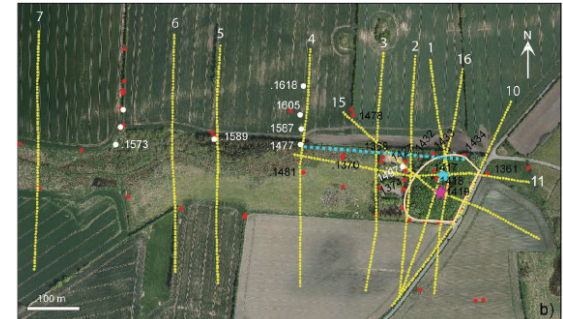
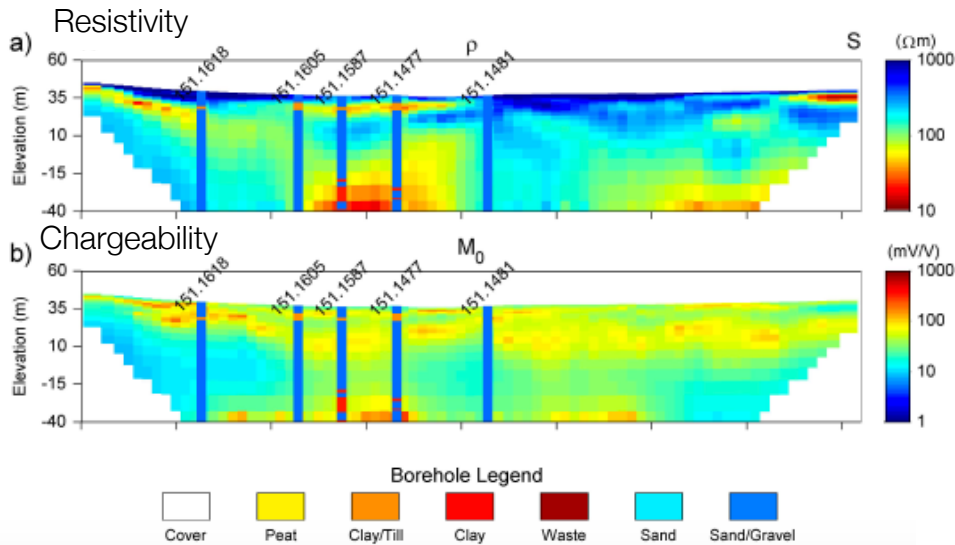


Geologic interpretation

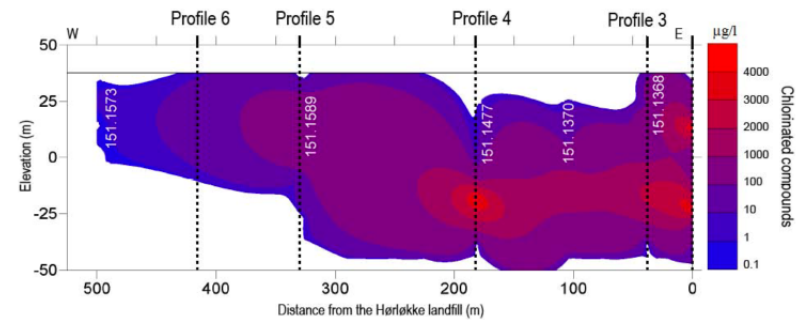


Synthesis: delineating the leachate

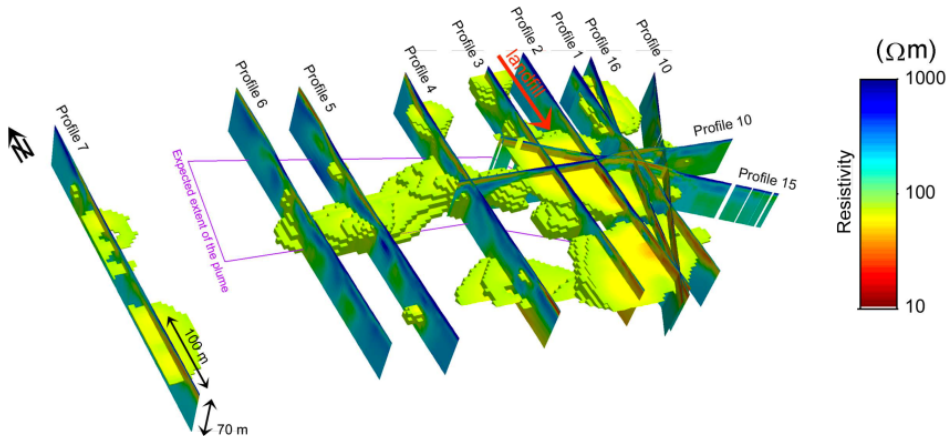
Resistivity and chargeability sections



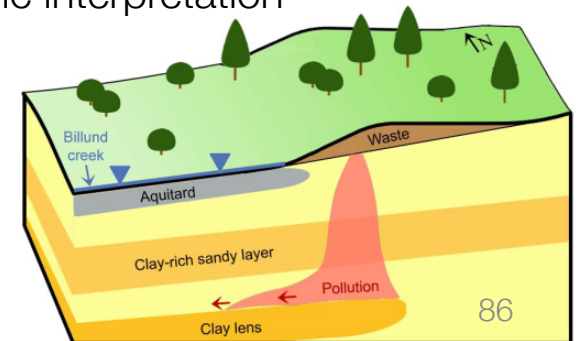
Contaminated plume section



Resistivity cut-off volume ($<100 \Omega\text{m}$)

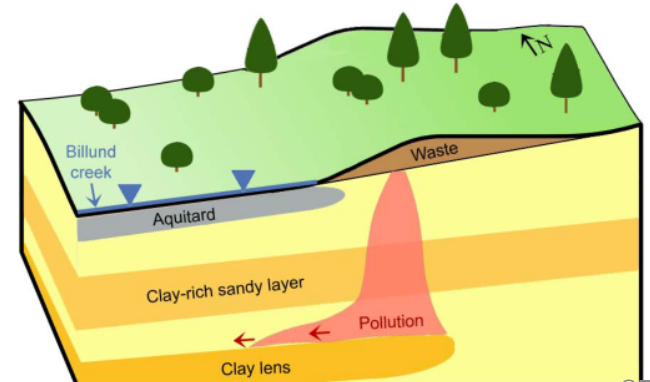
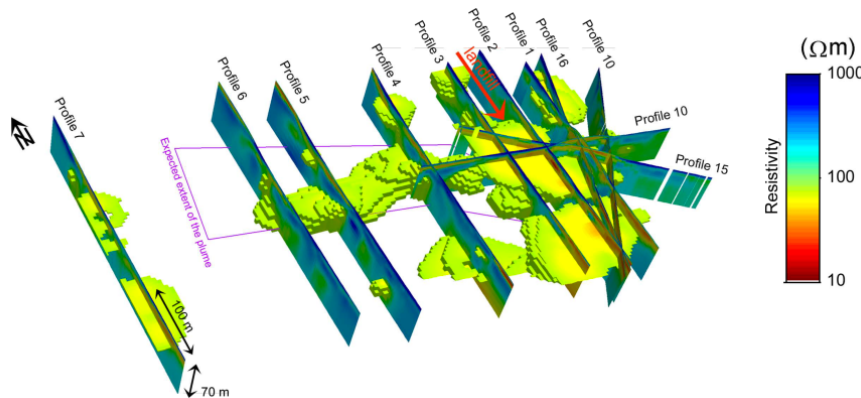
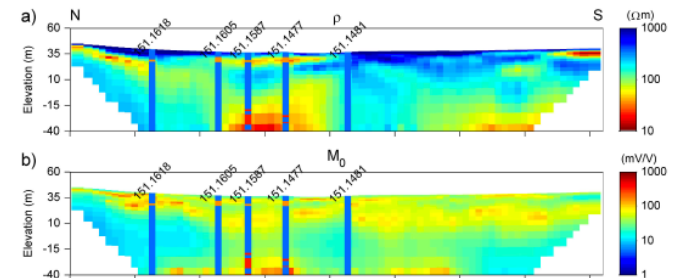
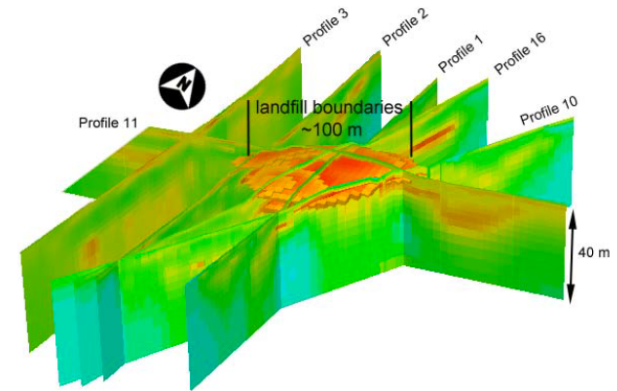


Geologic interpretation



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

