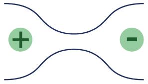
Induced Polarization

DISC

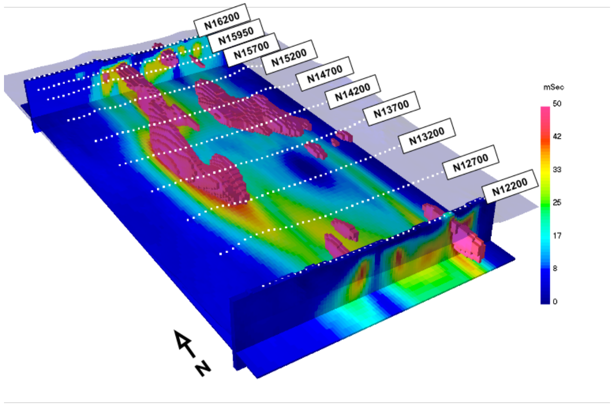
2017

Electromagnetics
Fundamentals and Applications

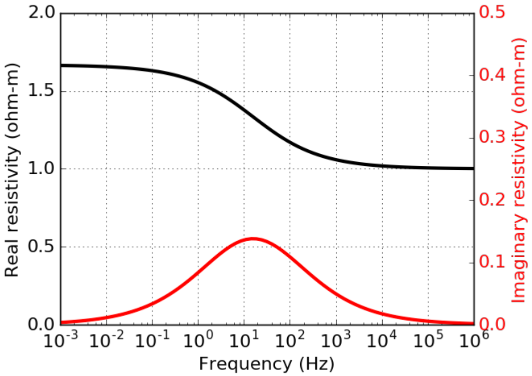


Motivation

Minerals

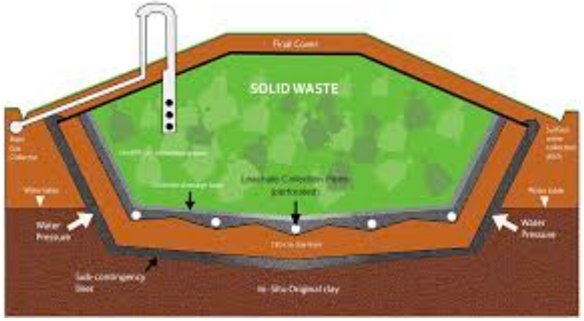


Complex resistivity

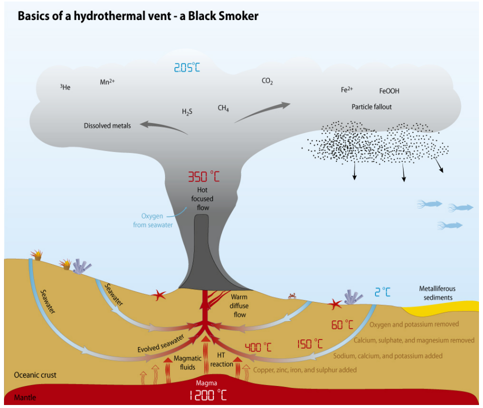


Permafrost

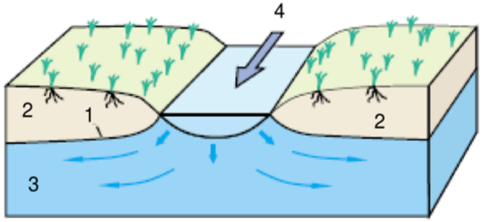
Geotechnical



Seafloor massive sulfide



Groundwater

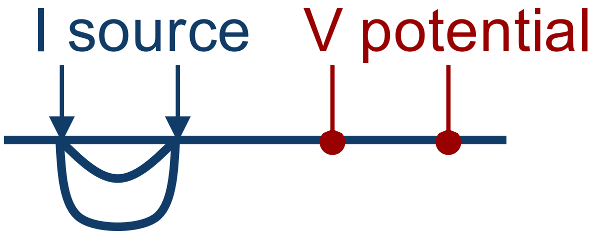


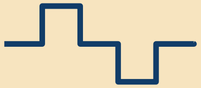
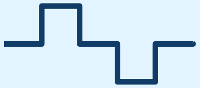
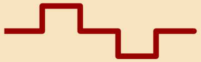
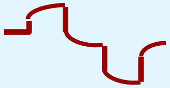
Outline

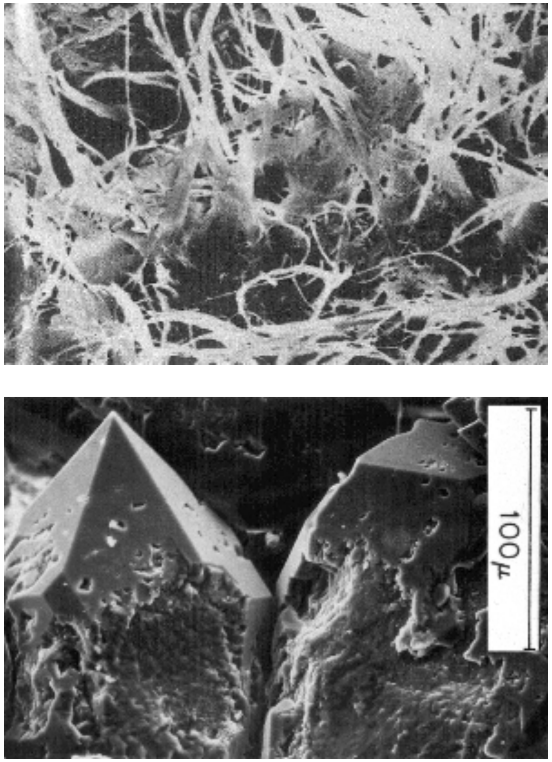
- Sources of IP
- Conceptual model of IP
- Chargeability
- IP data
- Pseudosections
- Two stage DC-IP inversion
- Case history: Mt. Isa
- IP over Landfills
- Case History: Denmark (Landfill)

Induced Polarization

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



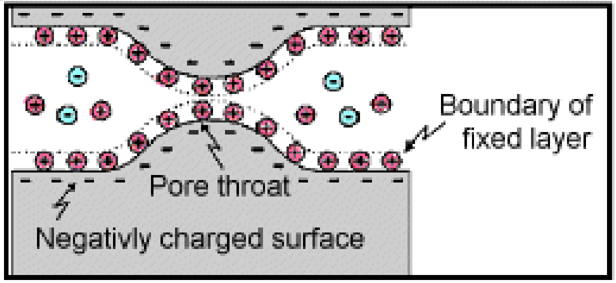
	Not chargeable	Chargeable
Source (Amps)		
Potential (Volts)		



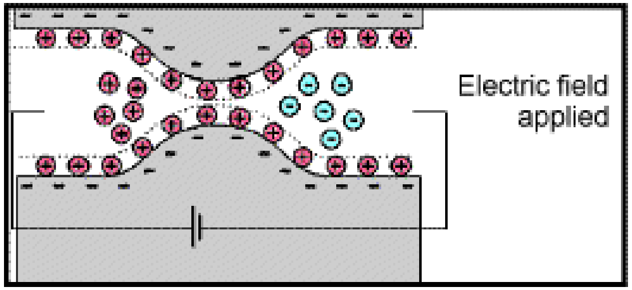
Conceptual Model of IP

Membrane polarization

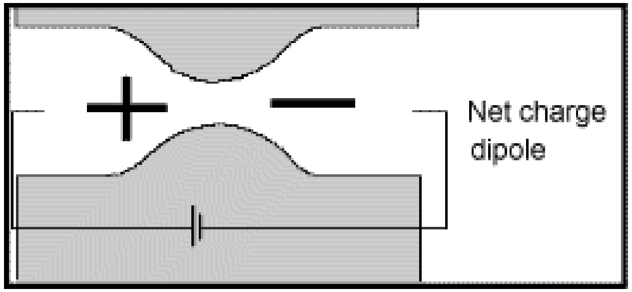
Initially - neutral



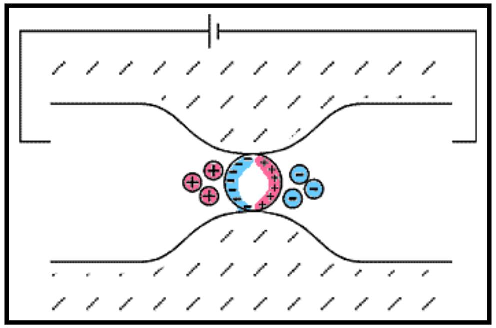
Apply electric field, build up charges

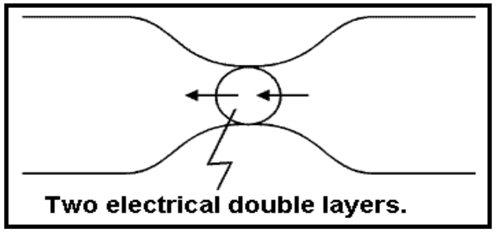


Charge polarization, Electric dipole

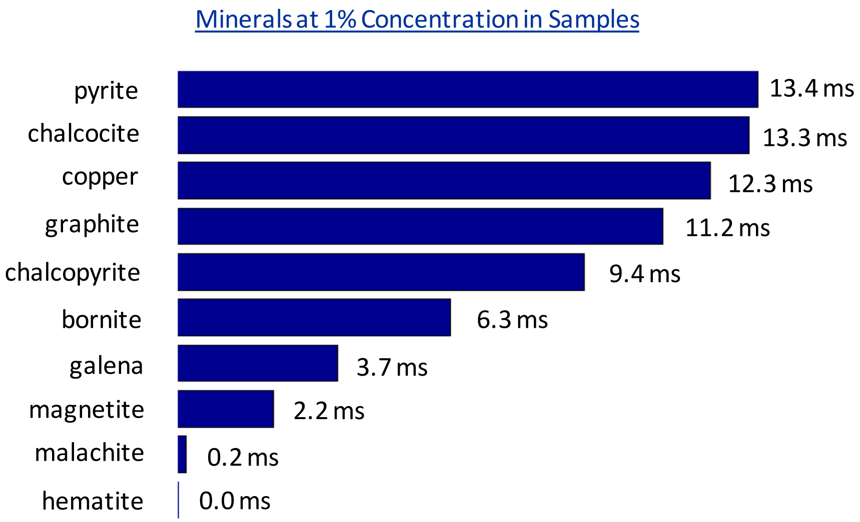


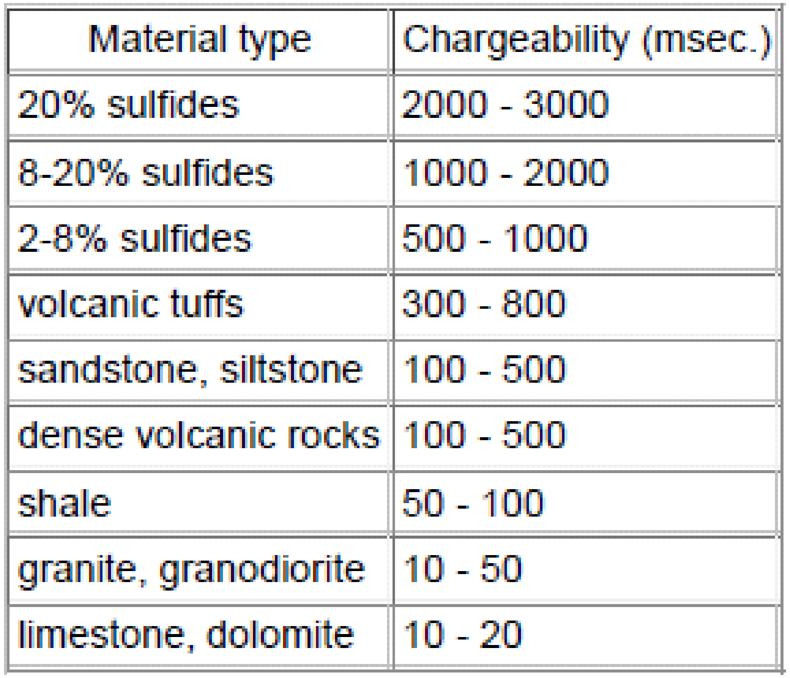
Electrode polarization



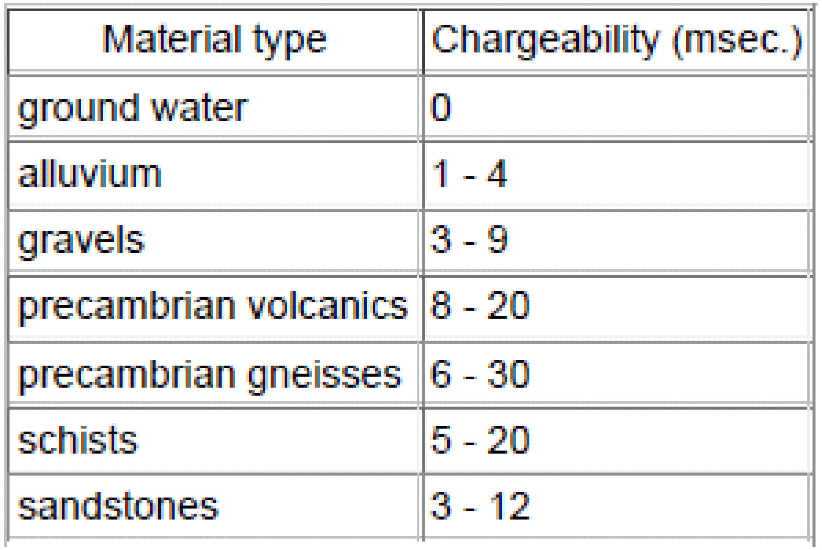


Chargeability


Minerals at 1% Concentration in Samples



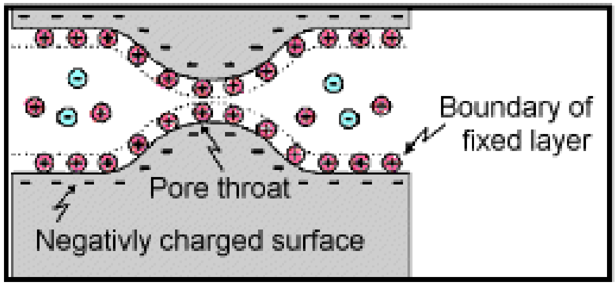
Material type	Chargeability (msec.)
20% sulfides	2000 - 3000
8-20% sulfides	1000 - 2000
2-8% sulfides	500 - 1000
volcanic tuffs	300 - 800
sandstone, siltstone	100 - 500
dense volcanic rocks	100 - 500
shale	50 - 100
granite, granodiorite	10 - 50
limestone, dolomite	10 - 20



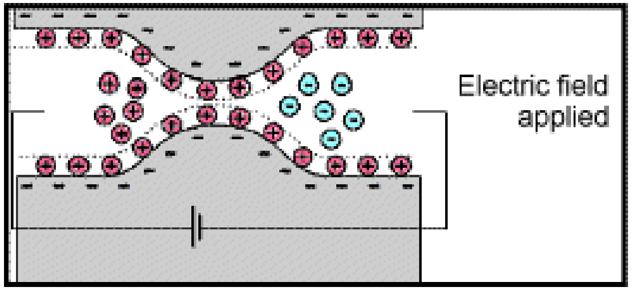
Material type	Chargeability (msec.)
ground water	0
alluvium	1 - 4
gravels	3 - 9
precambrian volcanics	8 - 20
precambrian gneisses	6 - 30
schists	5 - 20
sandstones	3 - 12

Chargeability

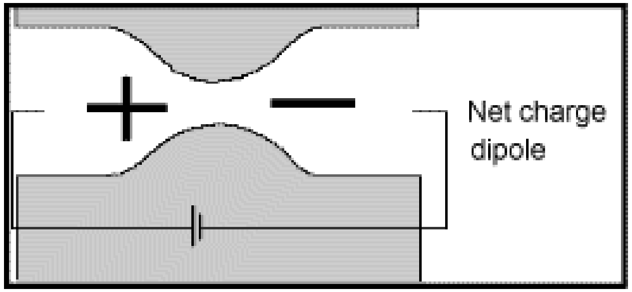
Initially - neutral



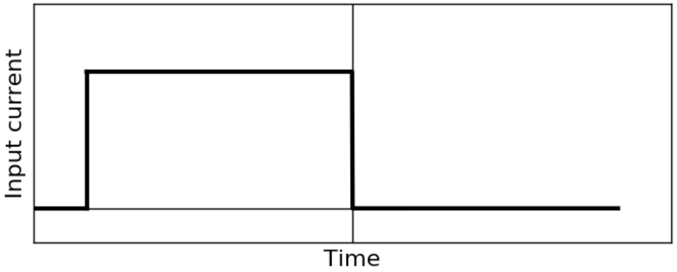
Apply electric field, build up charges



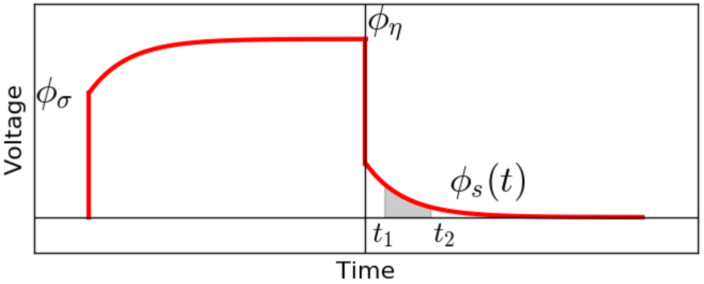
Charge polarization, Electric dipole



Input current



Measured voltage



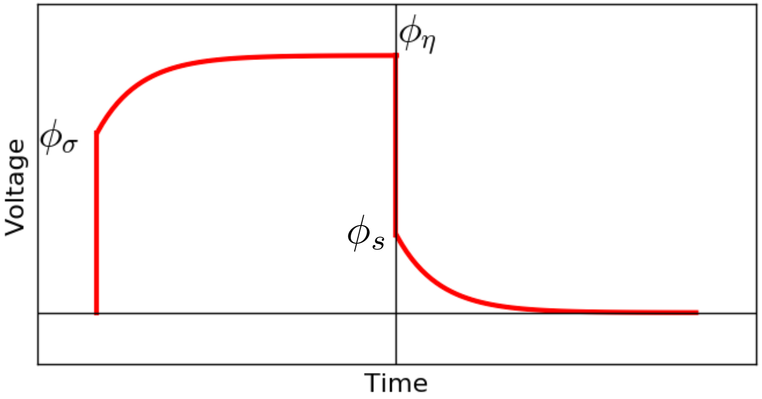
IP data

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

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

- Theoretical chargeability data

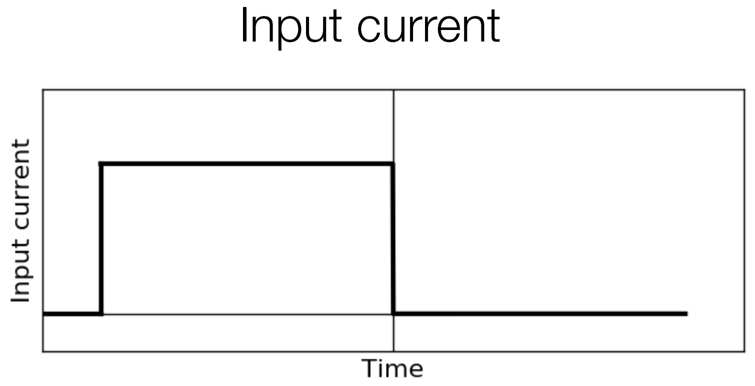
$$d^{IP} = \frac{\phi_s}{\phi_\eta} = \frac{\phi_\eta - \phi_\sigma}{\phi_\eta}$$

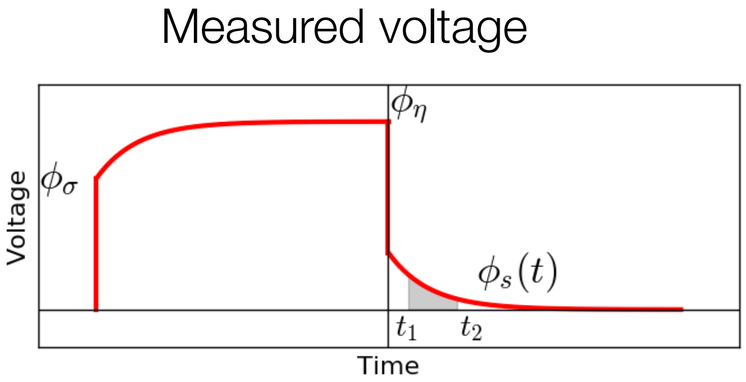


- Not directly measureable

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:

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

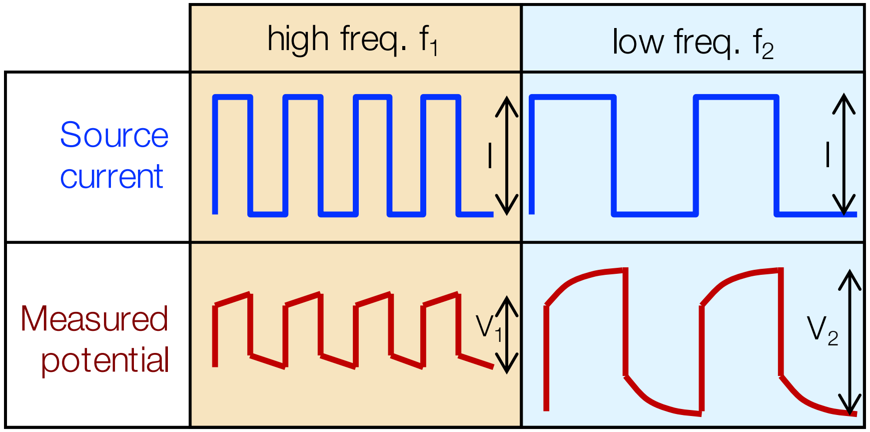
IP data: frequency domain

- Percent frequency effect:

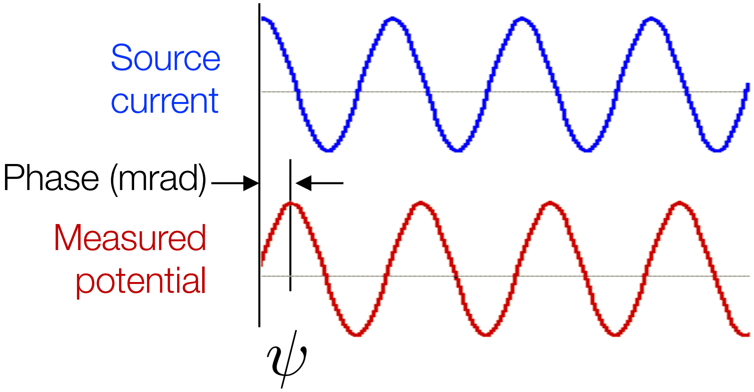
$$PFE = 100(\frac{\rho_{a2} - \rho_{a1}}{\rho_{a1}})$$

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

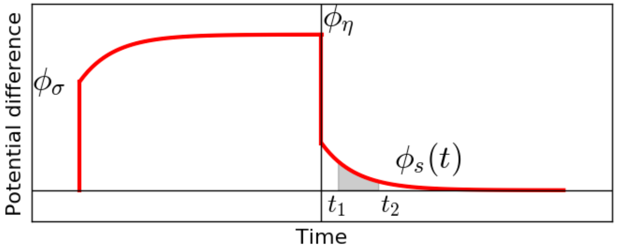
- In matrix form

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

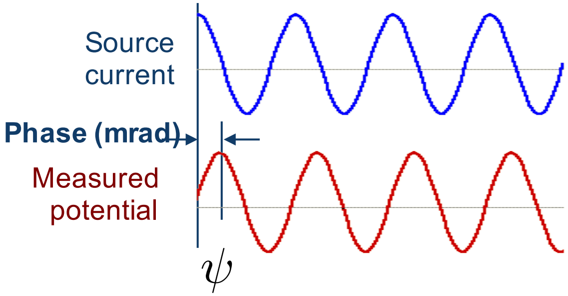
$\mathbf{J}$ is an N×M matrix

Summary of IP data

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



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



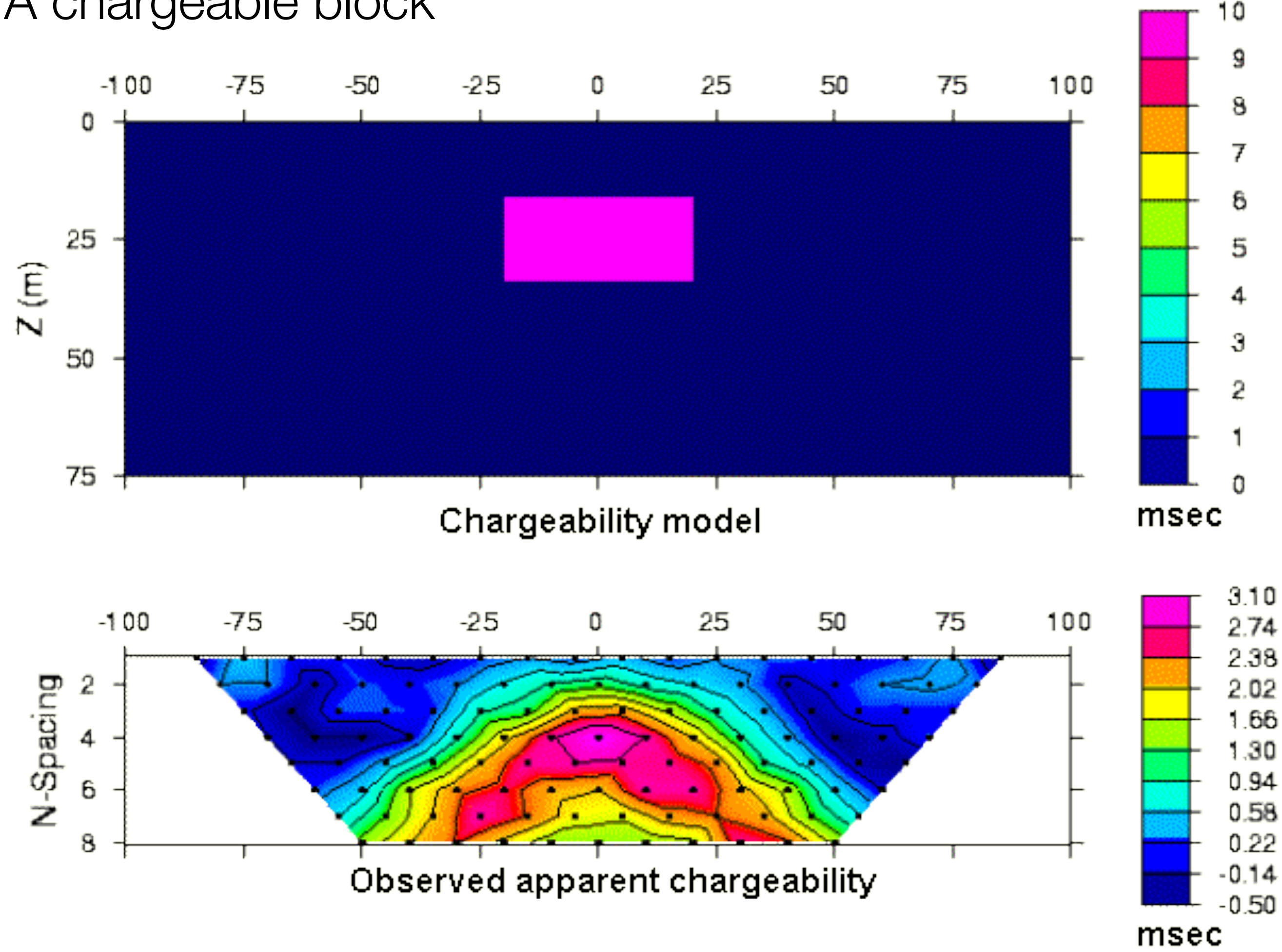
- For all data types: linear problem

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

$\mathbf{J}$ is an N×M matrix

IP pseudosections

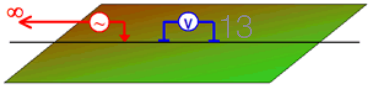
1) A chargeable block


Chargeability model

Observed apparent chargeability

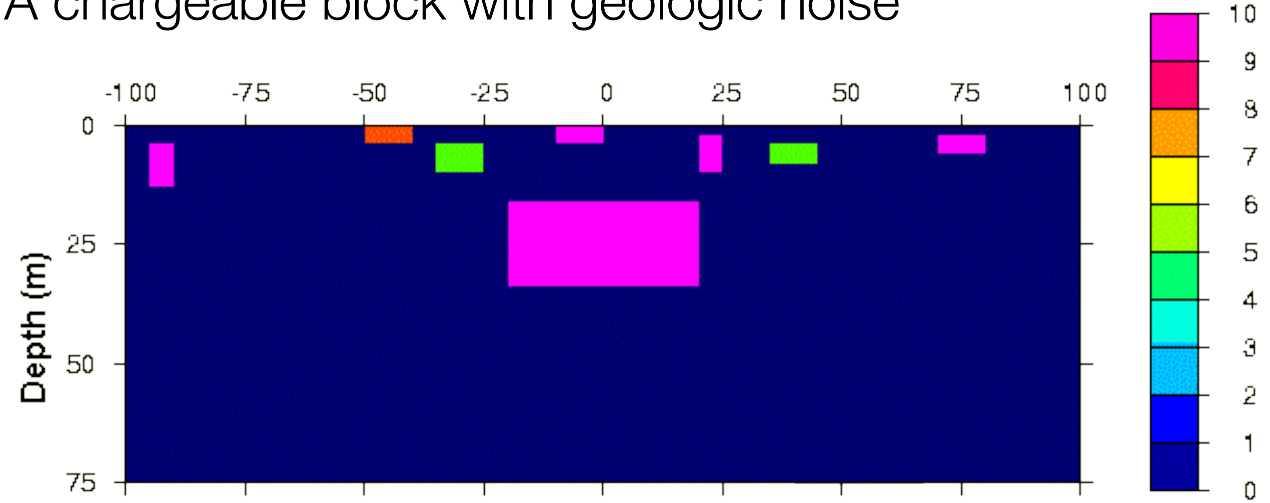
- Pole-dipole; n=1,8; a=10m; N=316

Pole-Dipole

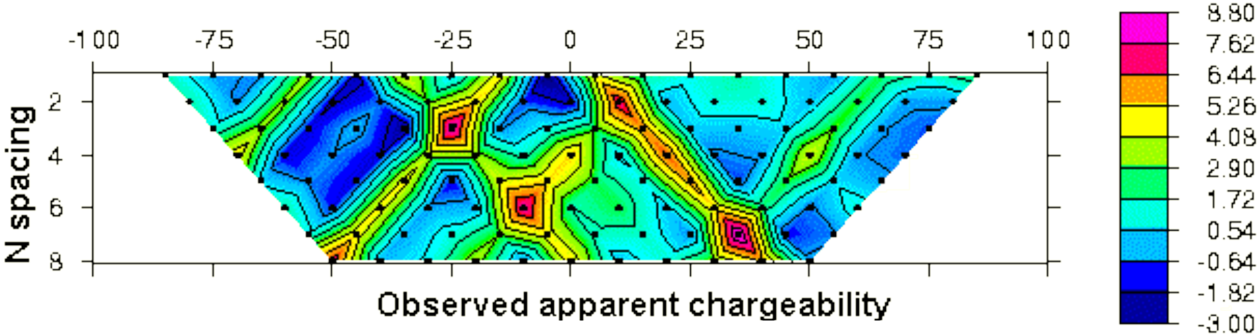


IP pseudosections

2) A chargeable block with geologic noise



Chargeability model



Observed apparent chargeability

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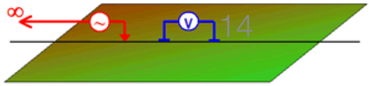
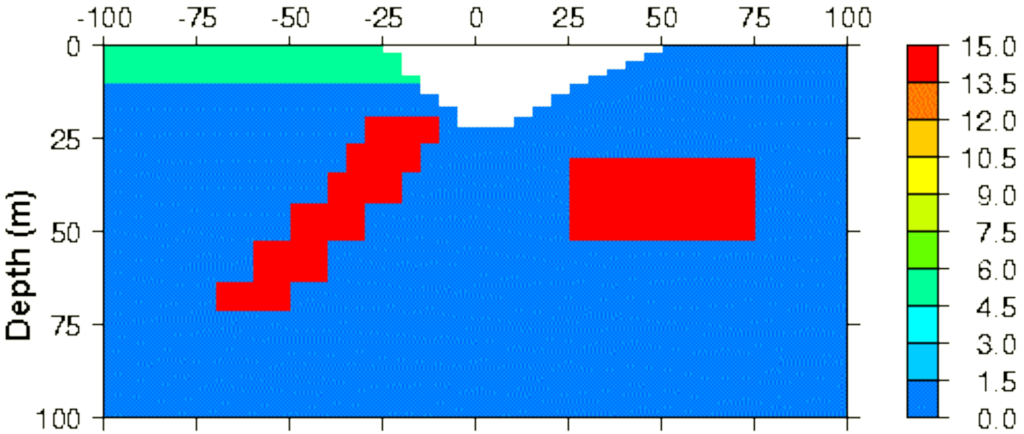
Pole-Dipole

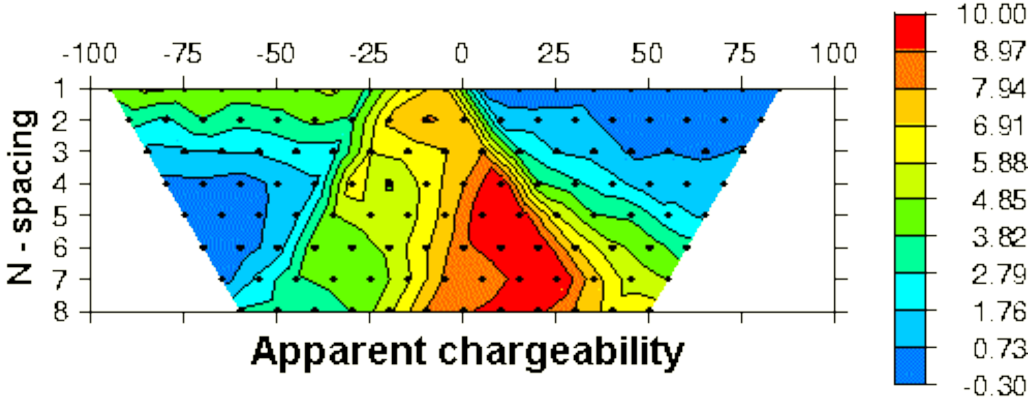


IP pseudosections

3) The “UBC-GIF model”

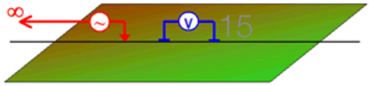


Chargeability model

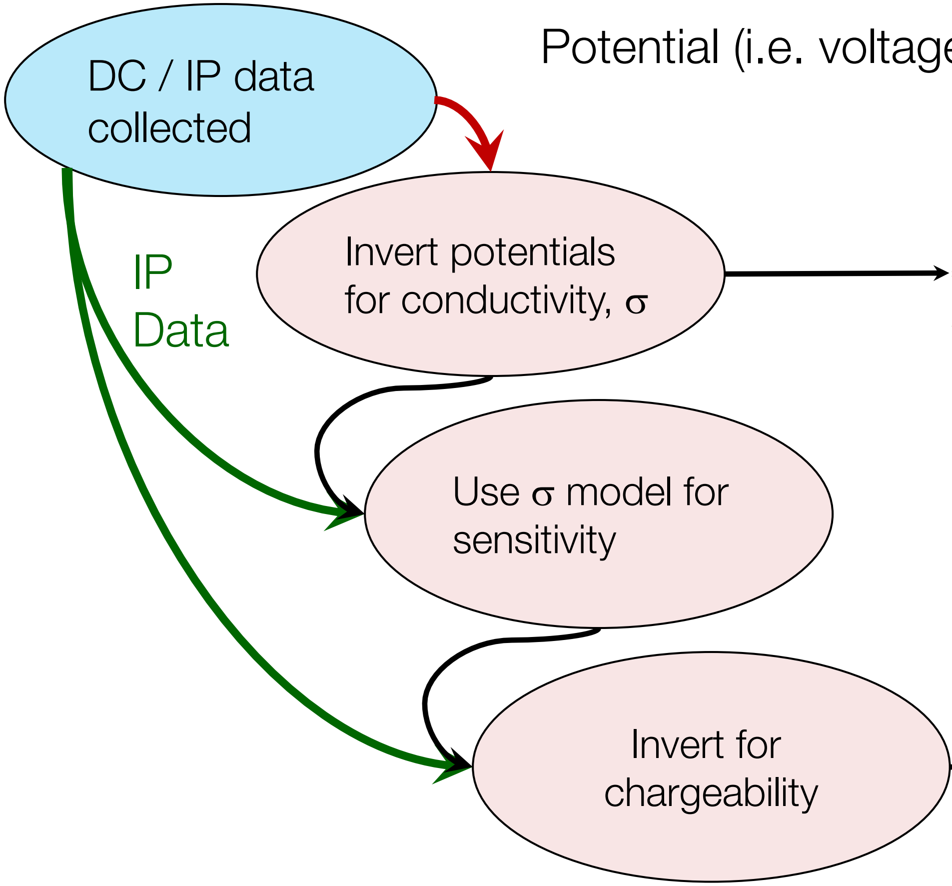


Apparent chargeability

Pole-Dipole



IP Inversion



Potential (i.e. voltage) data

DC / IP data collected

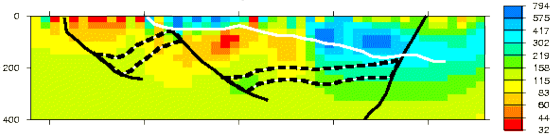
IP Data

Invert potentials for conductivity, σ

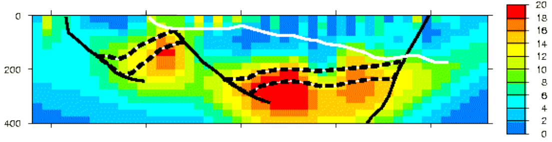
Use σ model for sensitivity

Invert for chargeability

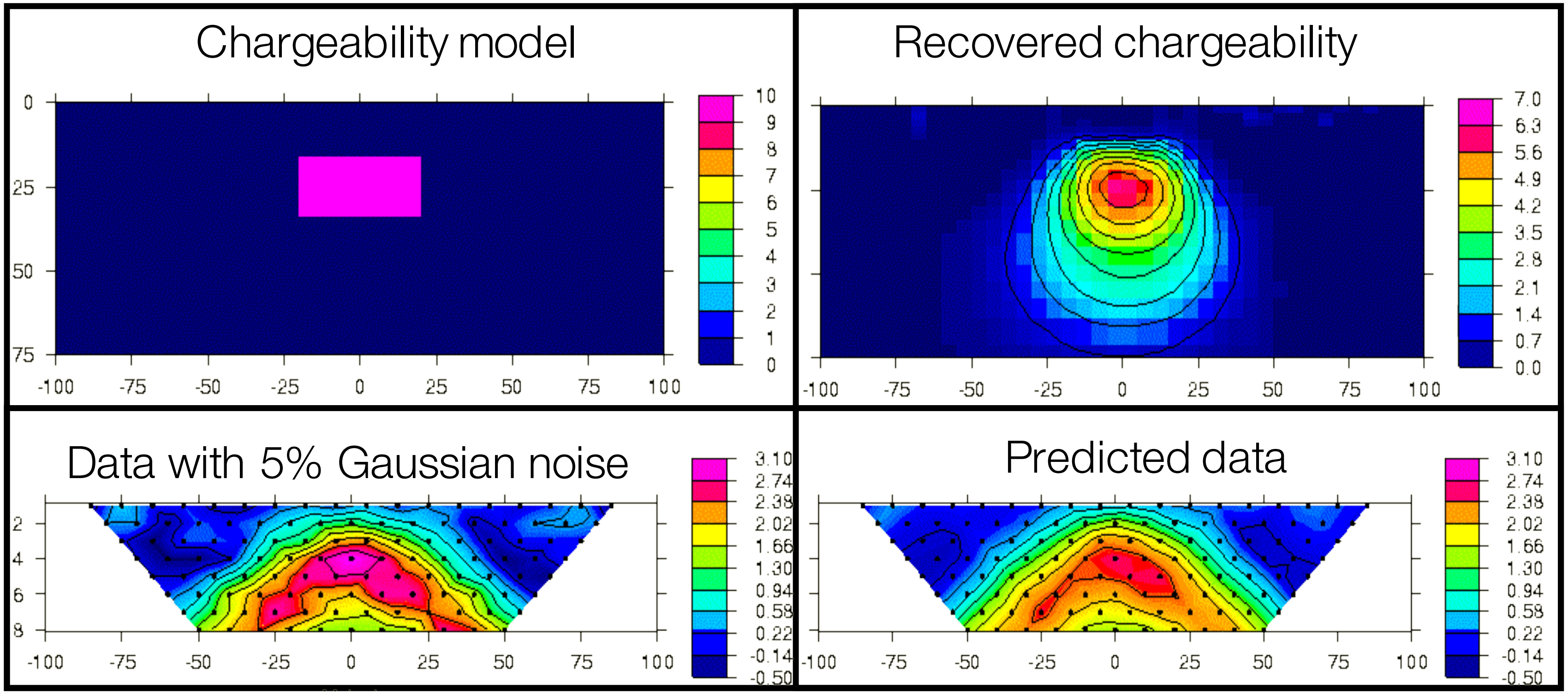
Conductivity model



Chargeability model



Example 1: buried prism


Chargeability model

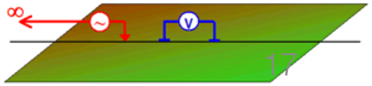
Recovered chargeability

Data with 5% Gaussian noise

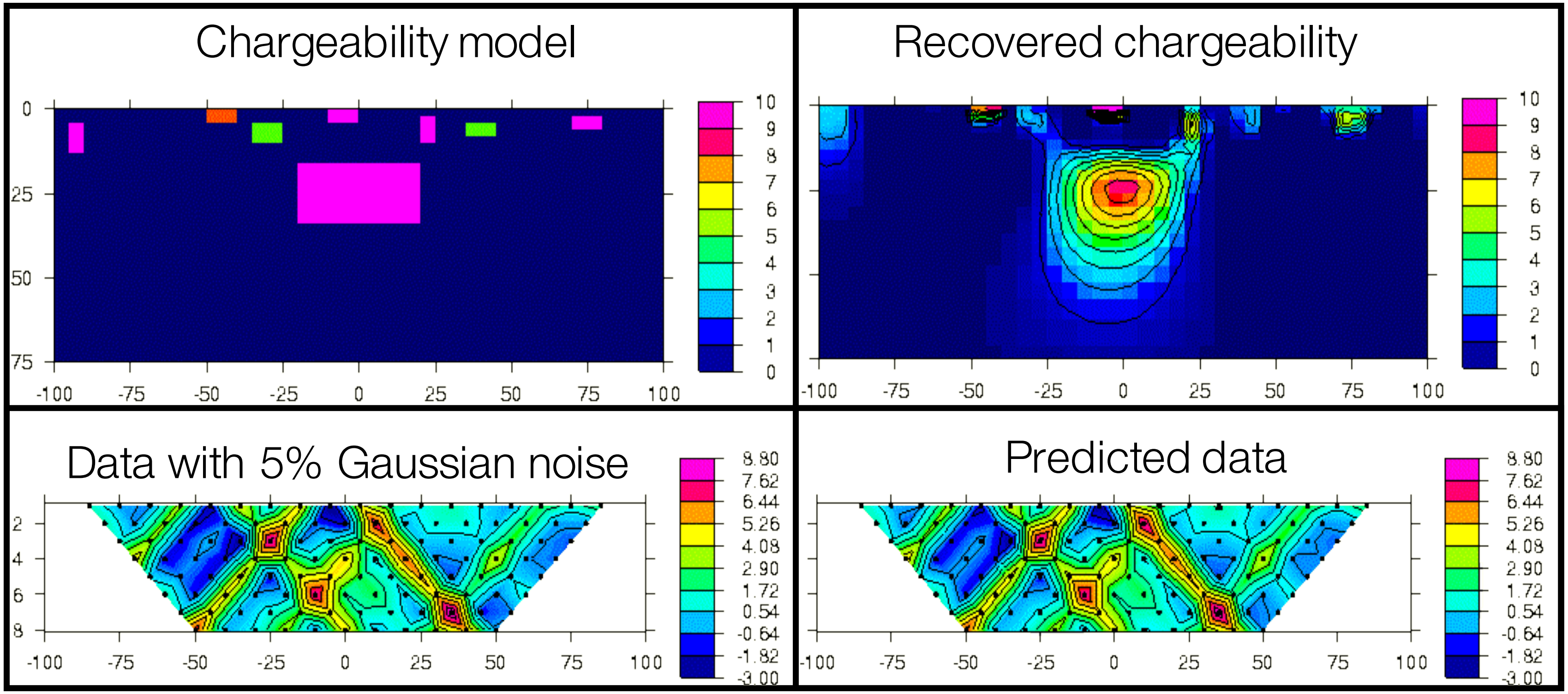
Predicted data

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

Pole-Dipole



Example 2: prism with geologic noise


Chargeability model

Recovered chargeability

Data with 5% Gaussian noise

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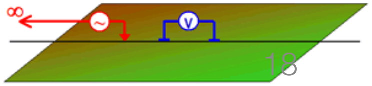
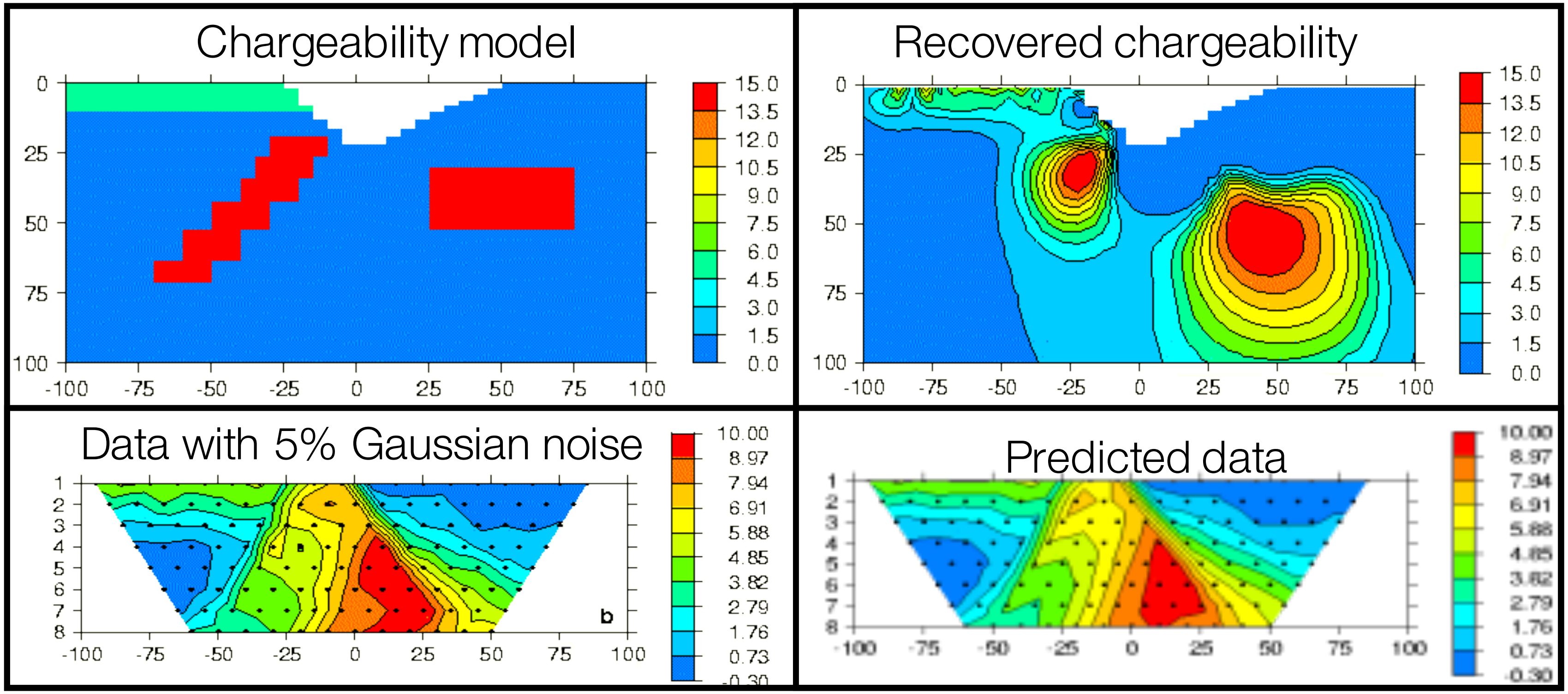
- Pole-dipole; n=1,8; a=10m; N=316; $(\alpha_s, \alpha_x, \alpha_z)$=(.001, 1.0, 1.0)

Pole-Dipole

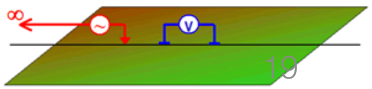


Example 3: UBC-GIF model



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

Pole-Dipole



Induced Polarization: Summary

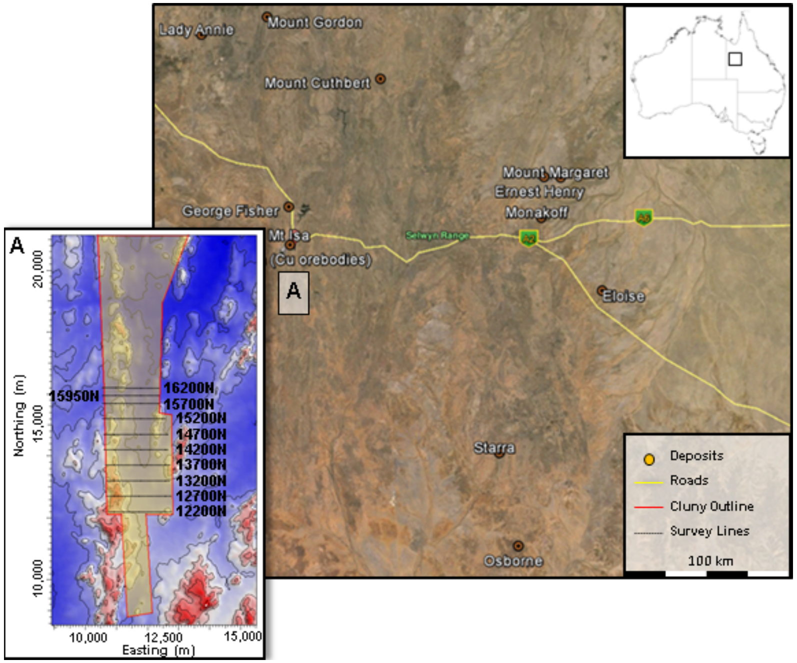
- Sources of IP
- Conceptual model of IP
- Chargeability
- IP data
- Pseudosections
- Two stage DC-IP inversion
- Case history: Mt. Isa
- EM-IP Inversion (EM decoupling)
- Case history: TKC

Case history: Mt. Isa

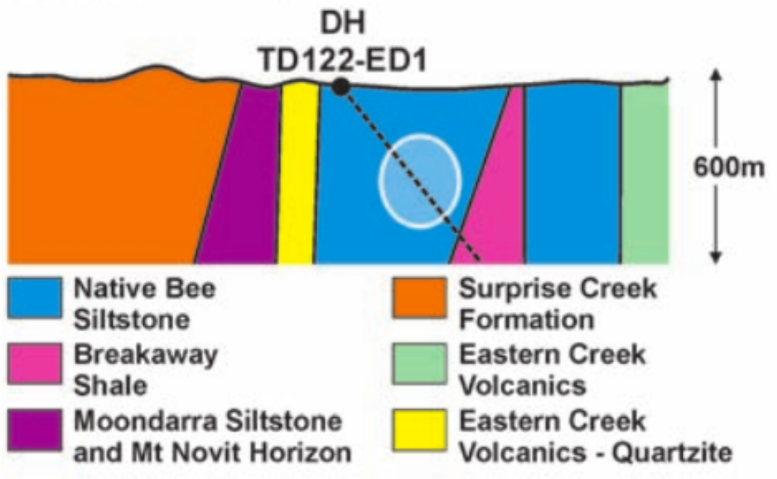
Rutley et al., 2001

Setup

- Mt. Isa (Cluny propect)



- Geologic model

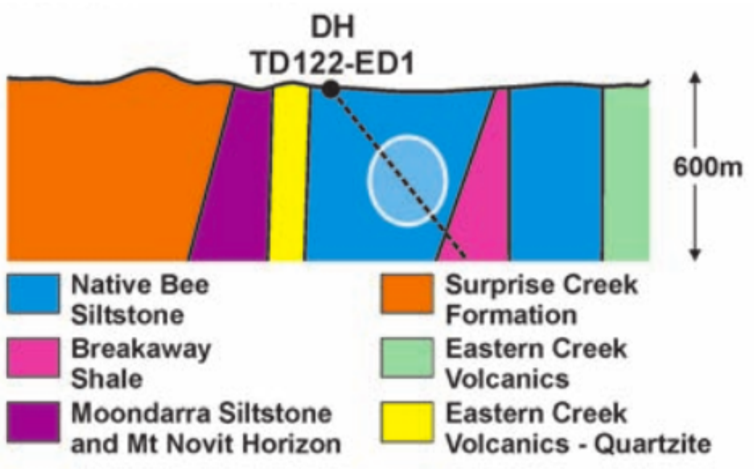


Question

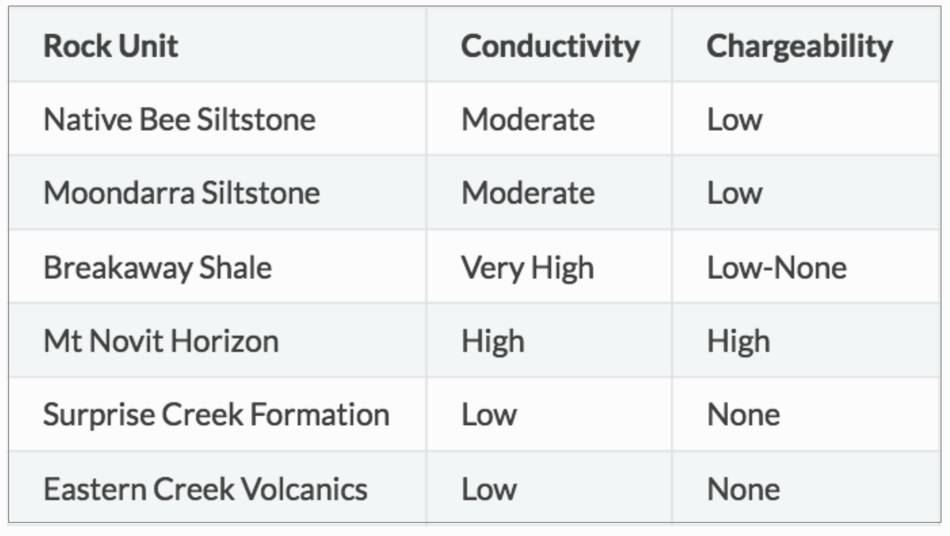
- Can conductive, chargeable units, which would be potential targets within the siltstones, be identified with DC / IP data?

Properties

Geologic model



Resistivity and Chargeability

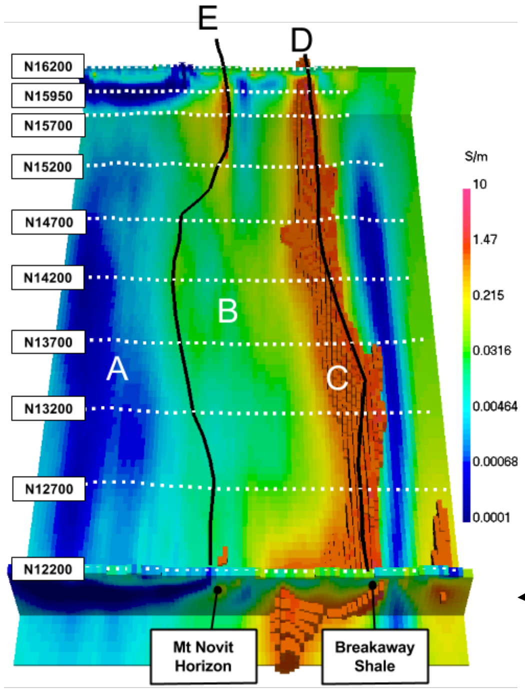


Rock Unit	Conductivity	Chargeability
Native Bee Siltstone	Moderate	Low
Moondarra Siltstone	Moderate	Low
Breakaway Shale	Very High	Low-None
Mt Novit Horizon	High	High
Surprise Creek Formation	Low	None
Eastern Creek Volcanics	Low	None

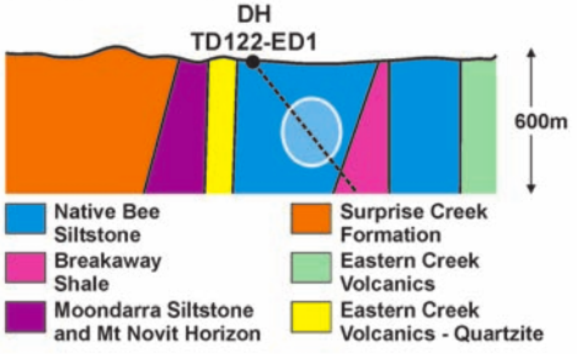
Recap: Synthesis from DC

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

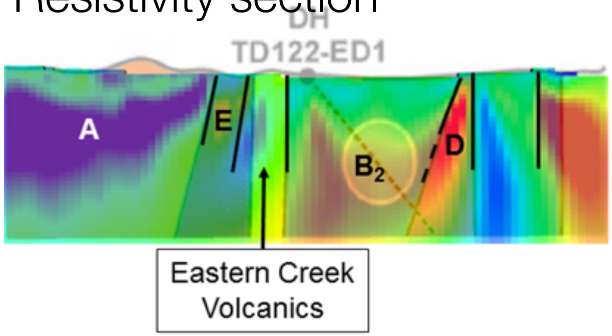
3D resistivity model



Geologic section



Resistivity section

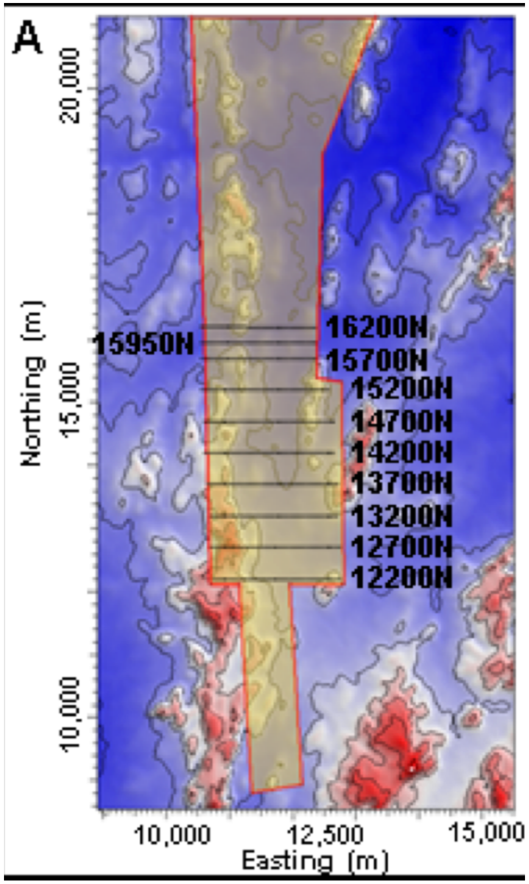


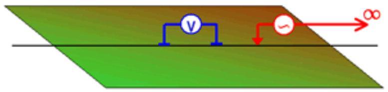
Can a **chargeable**, moderate conductor in the siltstones be identified?

Survey and data

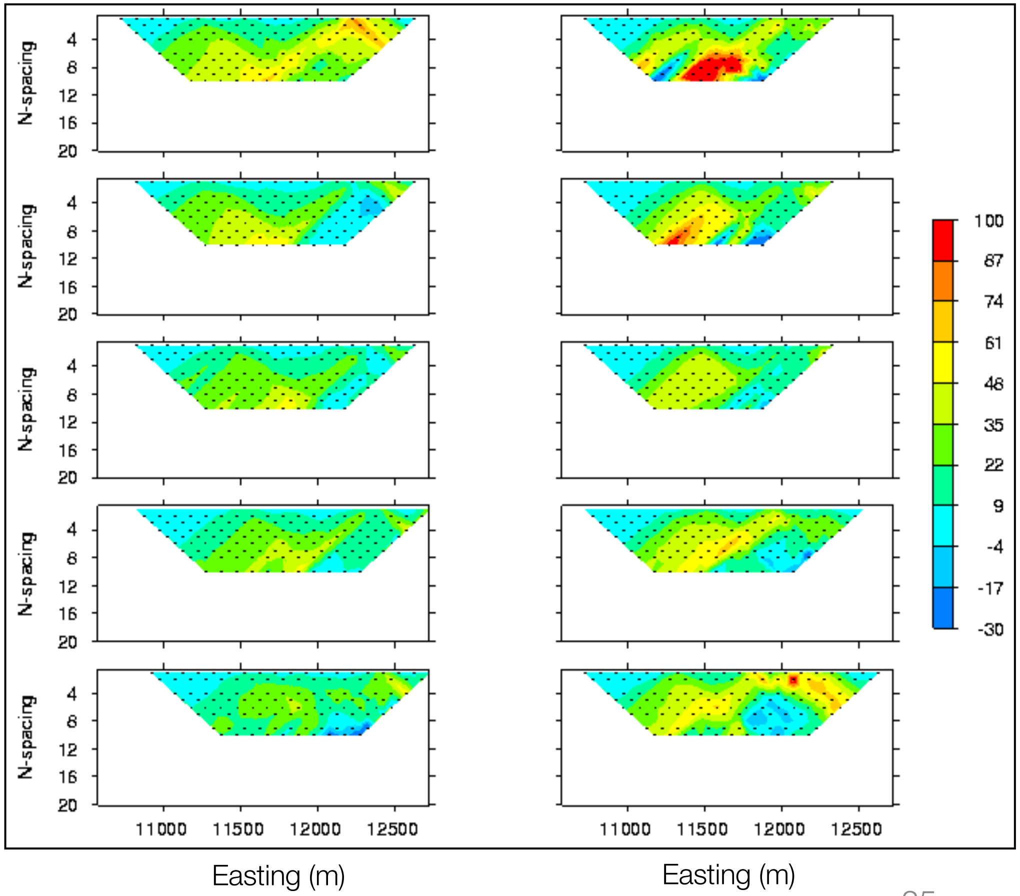
- Eight survey lines
- Two configurations

Surface topography



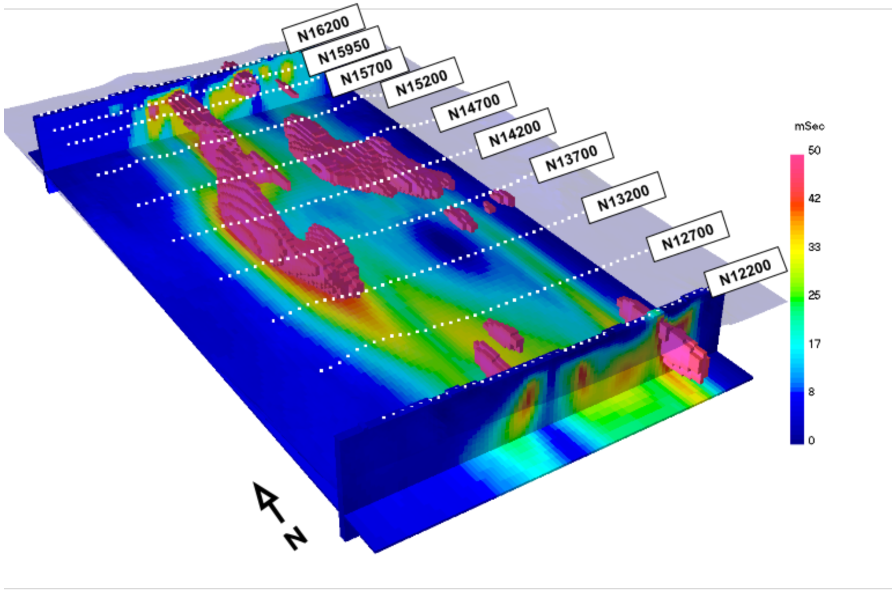


Apparent chargeability, dipole- pole.

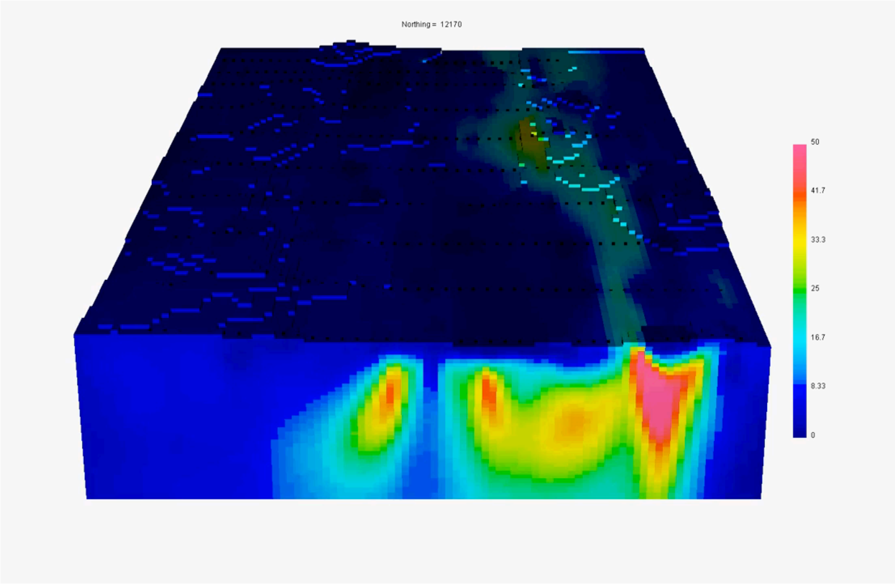


Processing

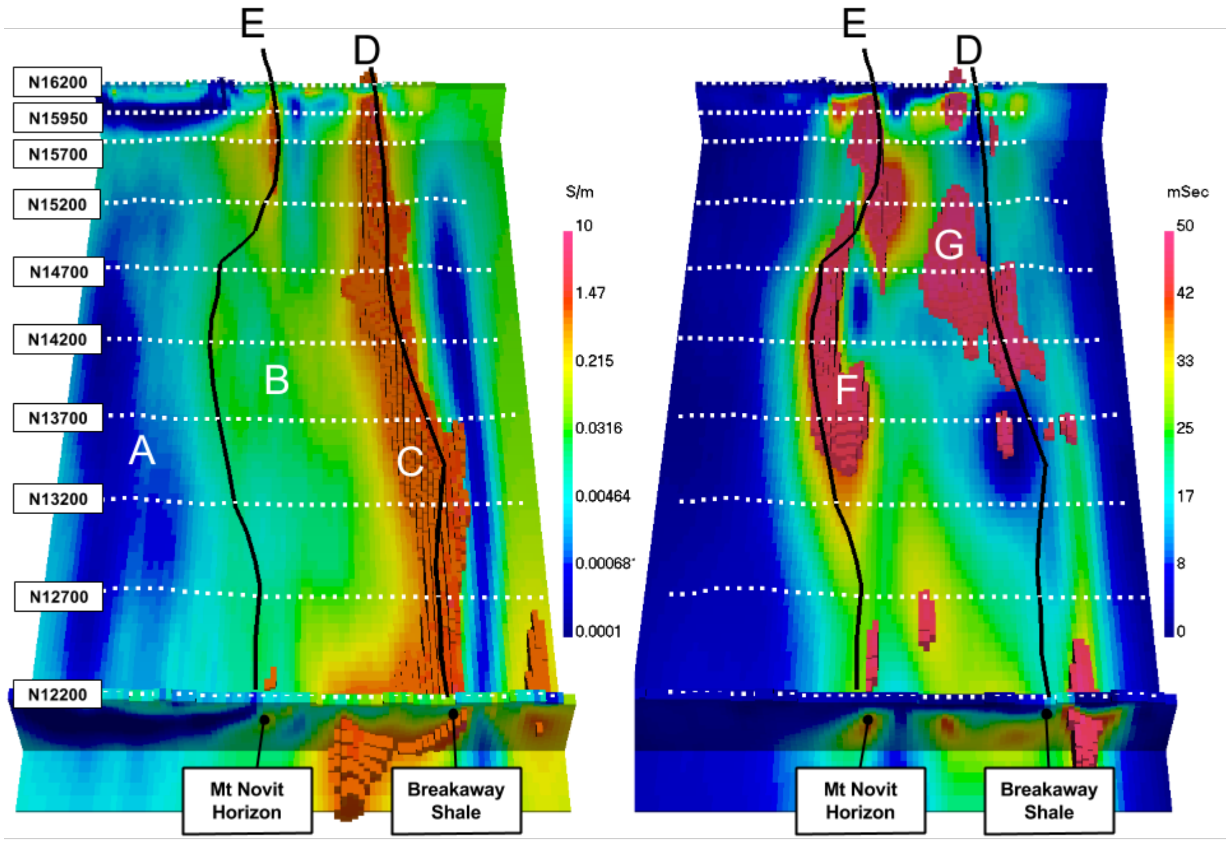
3D chargeability model



Animation



Interpretation



Resistivity model

Chargeability model

A: Resistive, Non-chargeable

B: Moderate conductivity; low chargeabilty

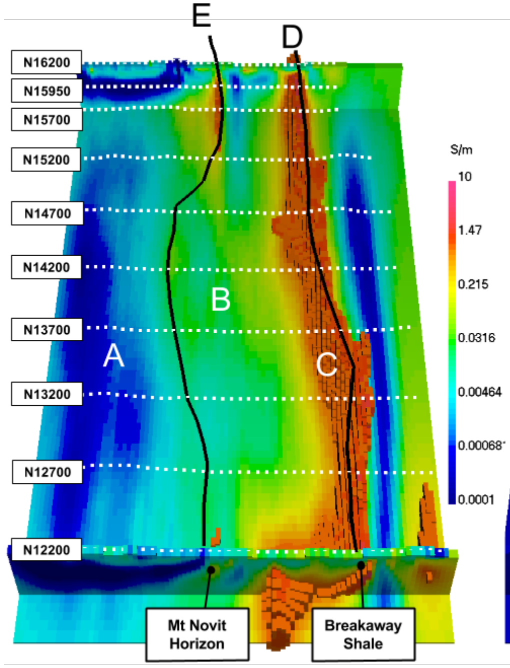
C: Very high conductivity (> 10 S/m)

E and F: High conductivity and high chargeability

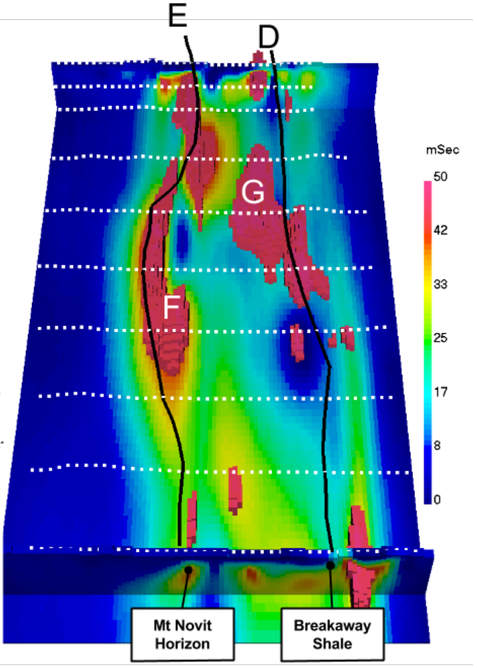
G: Other chargeable regions

Synthesis

Resistivity model



Chargeability model



A: Surprise Creek Formation

- Resistive, non-chargeable

B: Moondarra and Native Bee siltstones

C: Breakaway Shales

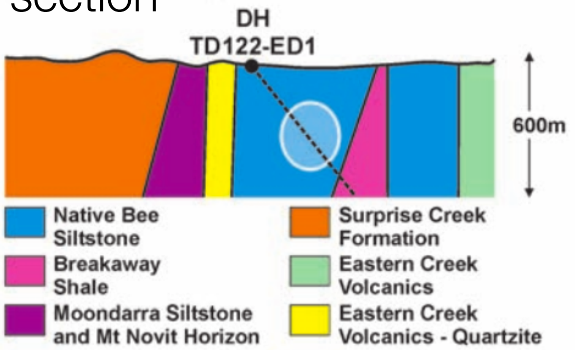
- Very high conductivity

E and F: Mt Novit Horizon

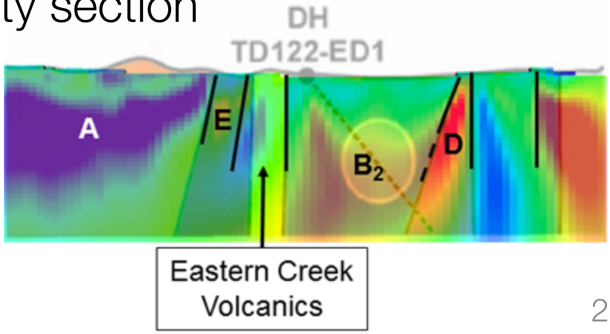
- High conductivity and high chargeability

G: Other chargeable regions within siltstone complex

Geologic section



Resistivity section



Induced Polarization: Summary

- Sources of IP
- Conceptual model of IP
- Chargeability
- IP data
- Pseudosections
- Two stage DC-IP inversion
- Case history: Mt. Isa
- IP over Landfills
- Case History: Denmark (Landfill)

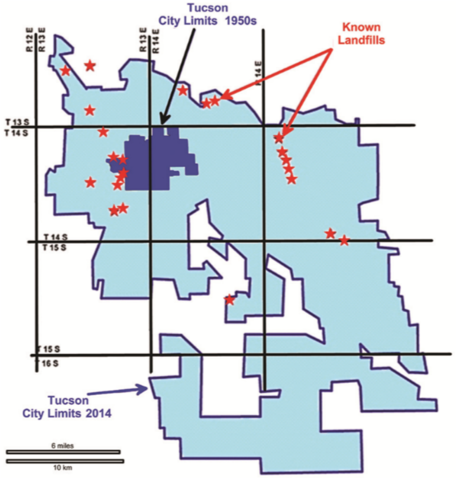
IP over Landfills

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



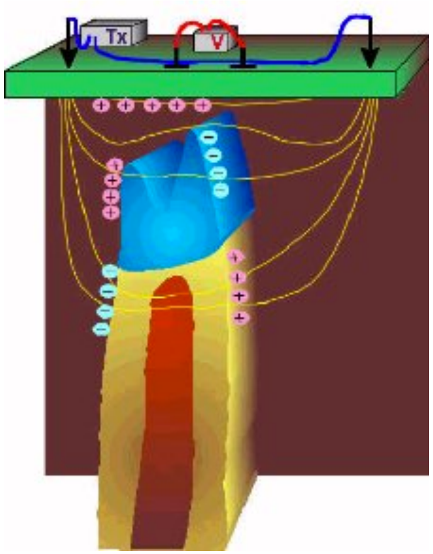
Physical Properties

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

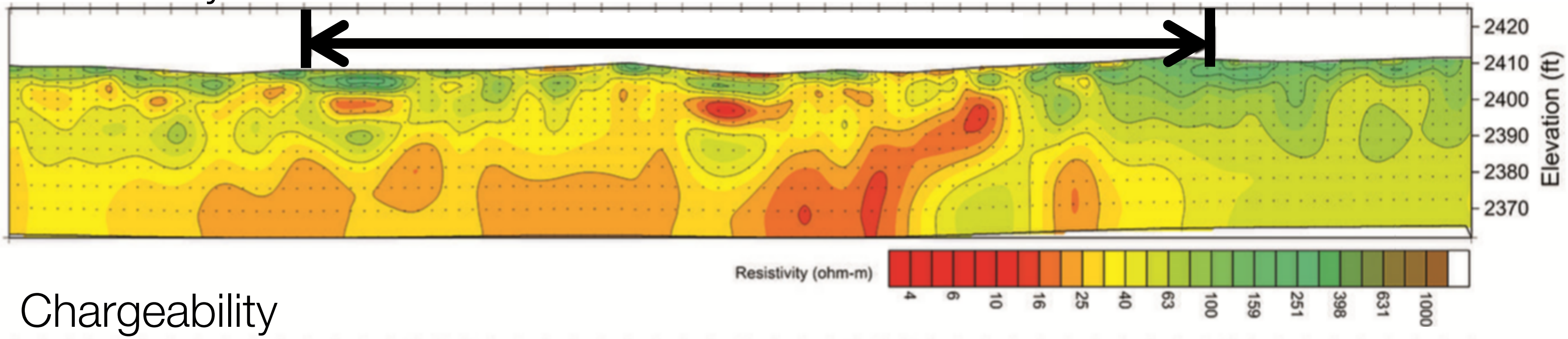
- Most popular surveys have limited success
- IP might be a better diagnostic
- Responsive to: metallic debris, green waste, organic matter, some construction materials

Ryan Airfield (Eastern Pit)

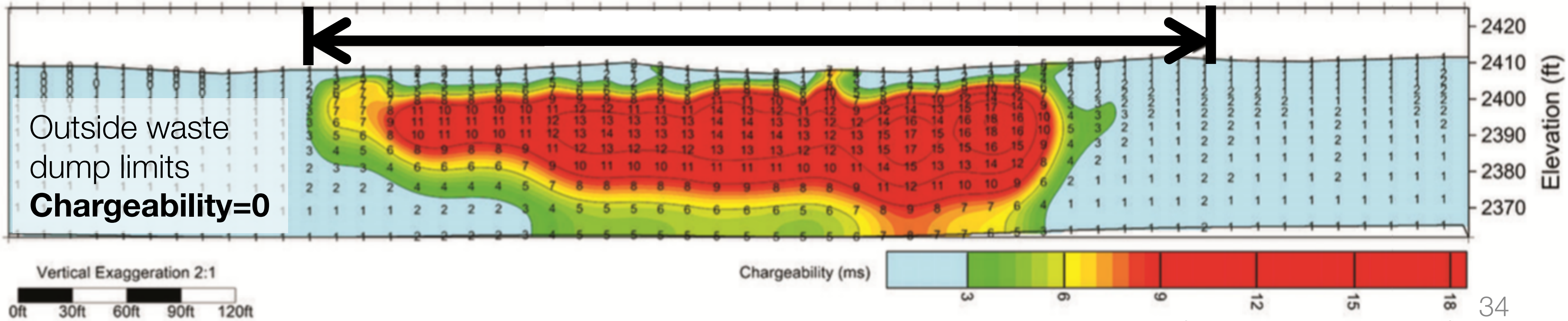
- Waste material: Mixed solid waste (MSW)
- Observations:
  - Resistivity not correlated with pit margins (non-diagnostic)
  - Chargeability (IP) correlates well with historical pit margins (diagnostic)

Resistivity

historical waste boundaries



Chargeability

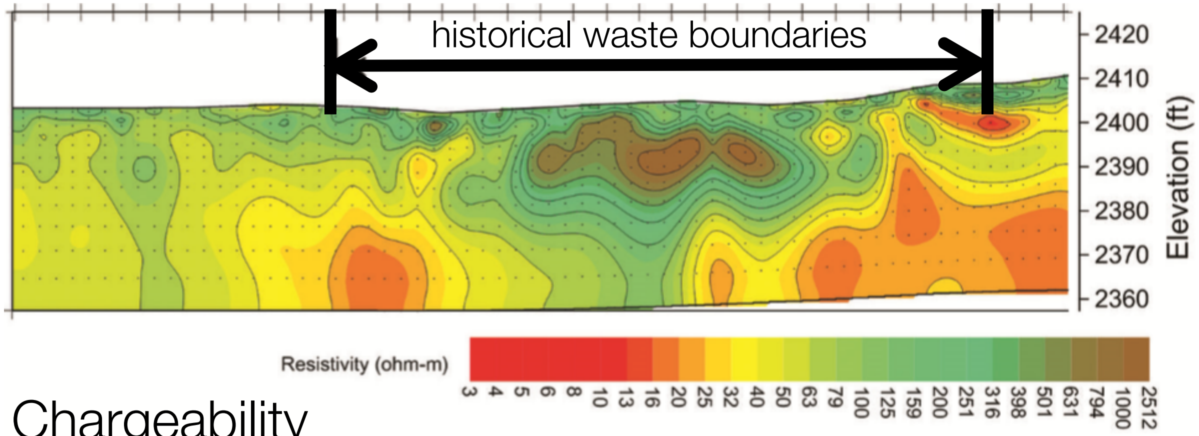

Outside waste dump limits
Chargeability=0

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

Ryan Airfield (Western Pit)

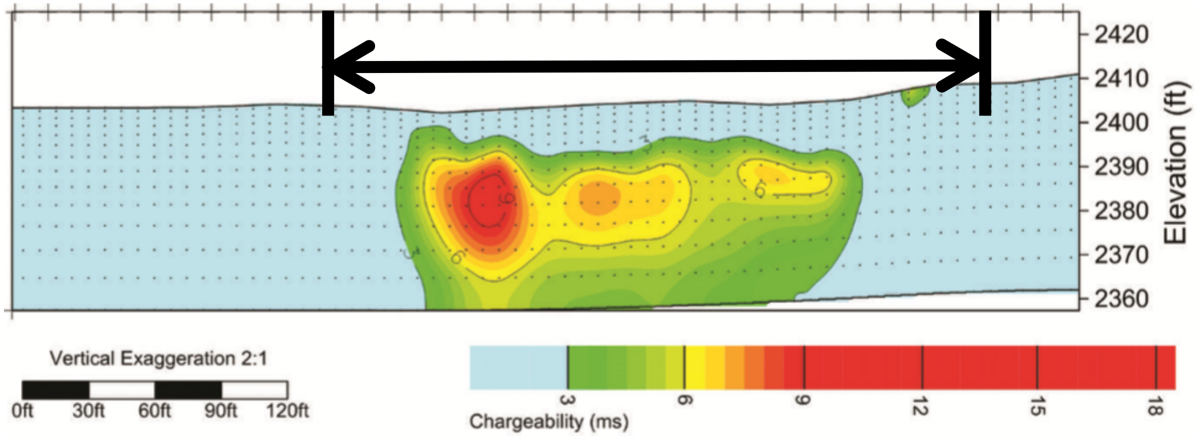
- Waste material: Construction / demolition
- Observations:
  - Waste correlates with region of high resistivity
  - Waste correlates with chargeable region (significant IP anomaly).

Resistivity



Resistive waste within landfill

Chargeability

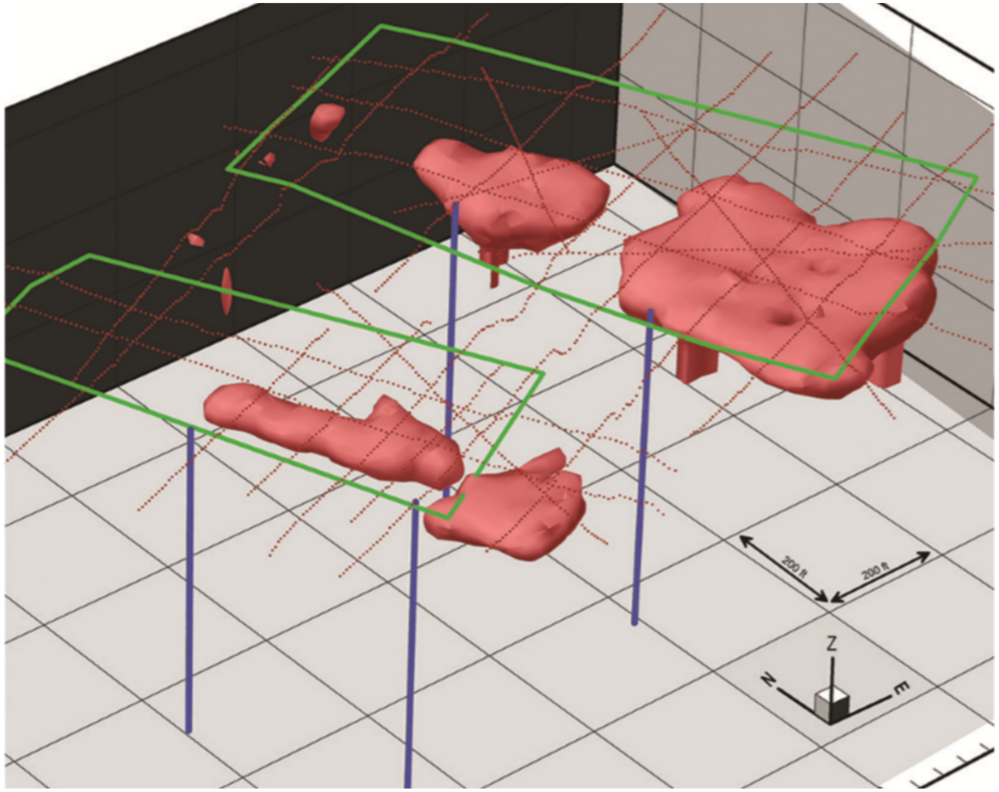


IP correlates with landfill

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

Ryan Airfield (Composite)

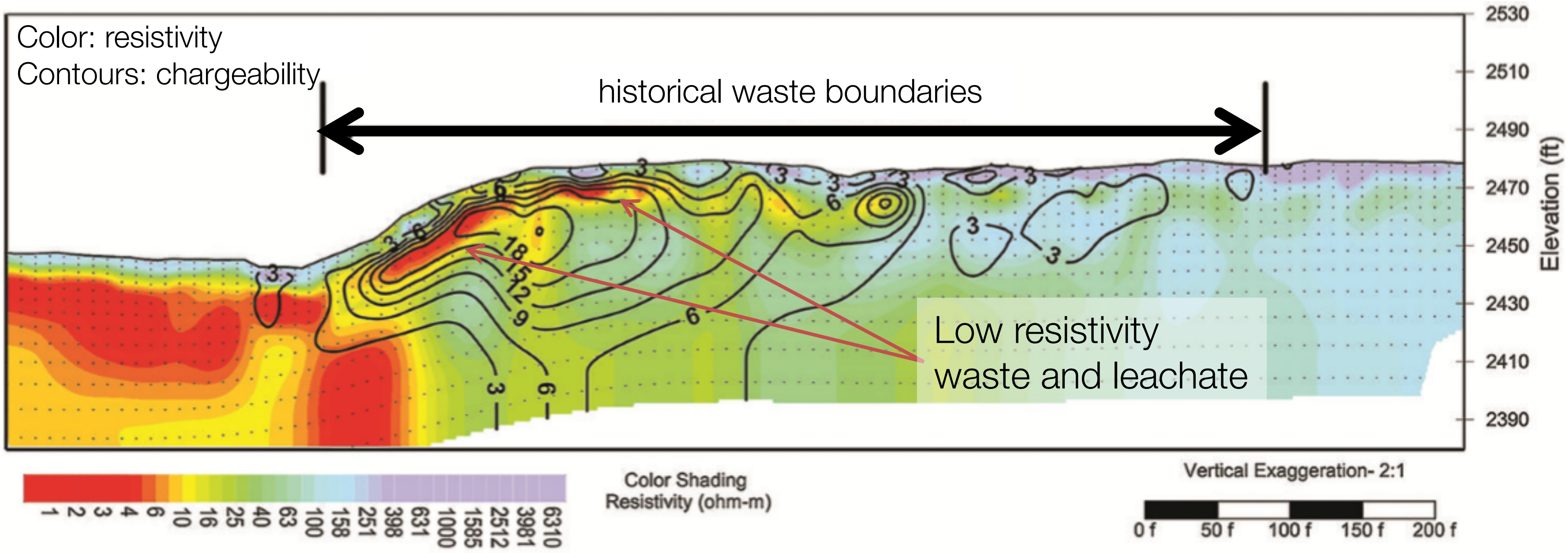
Chargeability isosurface



- 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

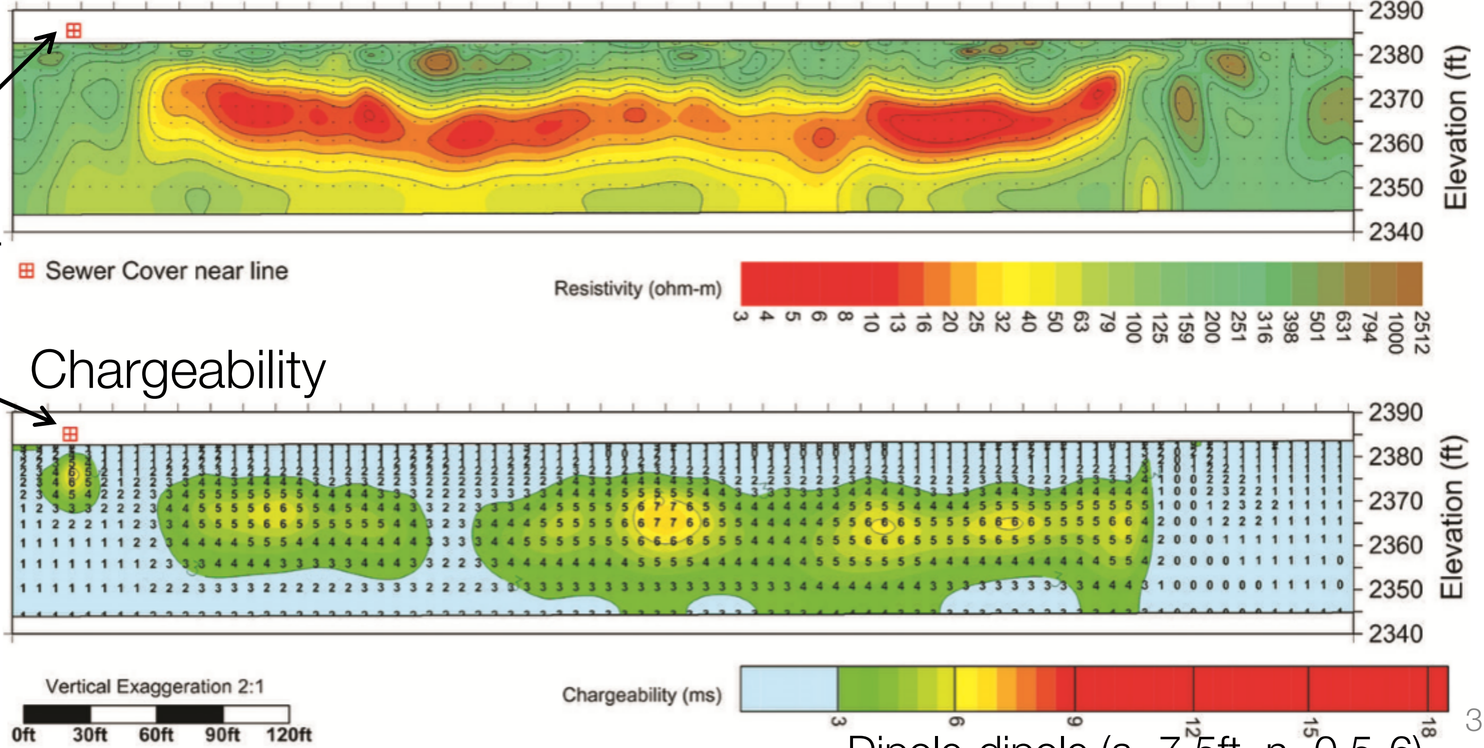

Color: resistivity
Contours: chargeability

historical waste boundaries

Low resistivity waste and leachate

Tucson region: Organic material

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

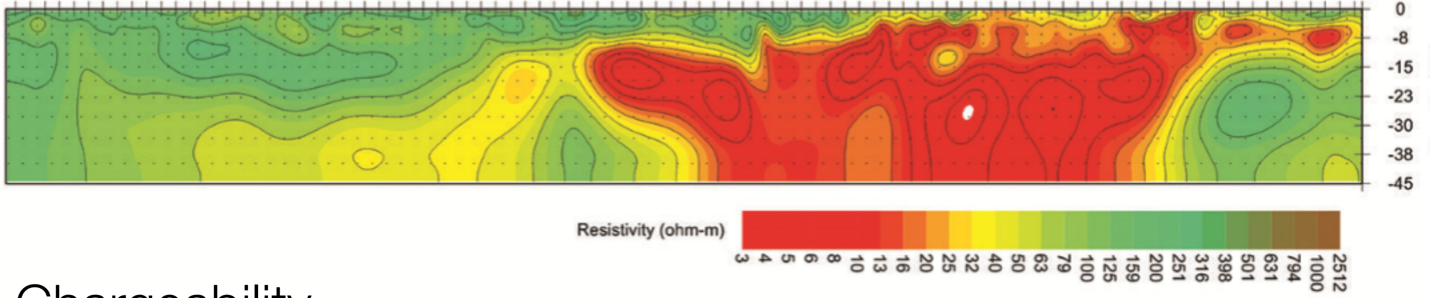


Dipole-dipole (a=7.5ft, n=0.5-6)

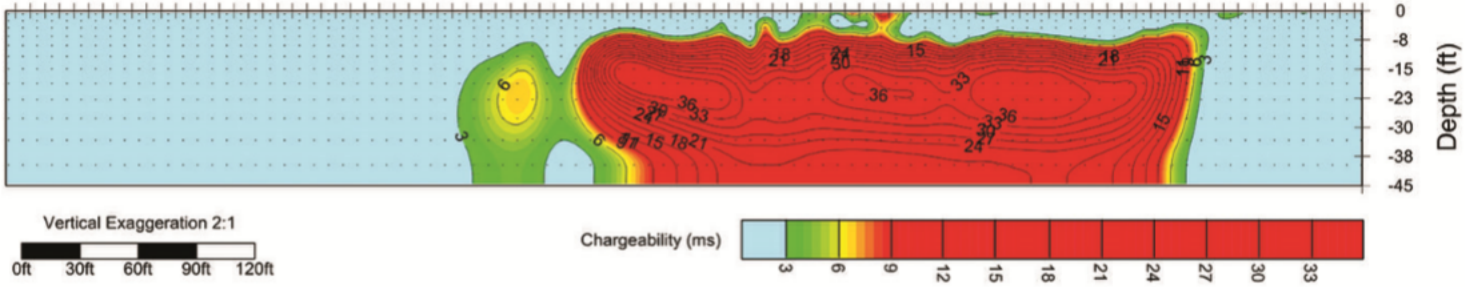
Nearmont Landfill

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

Resistivity



Chargeability

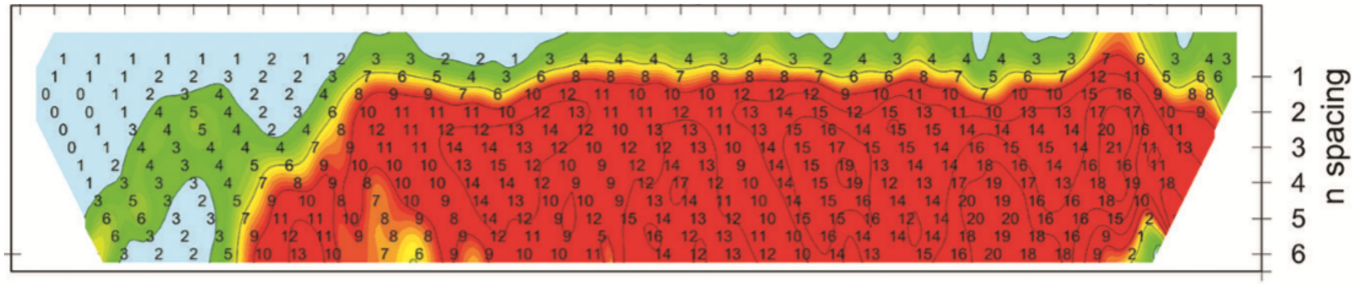


Dipole-dipole (a=7.5ft, n=0.5-6)

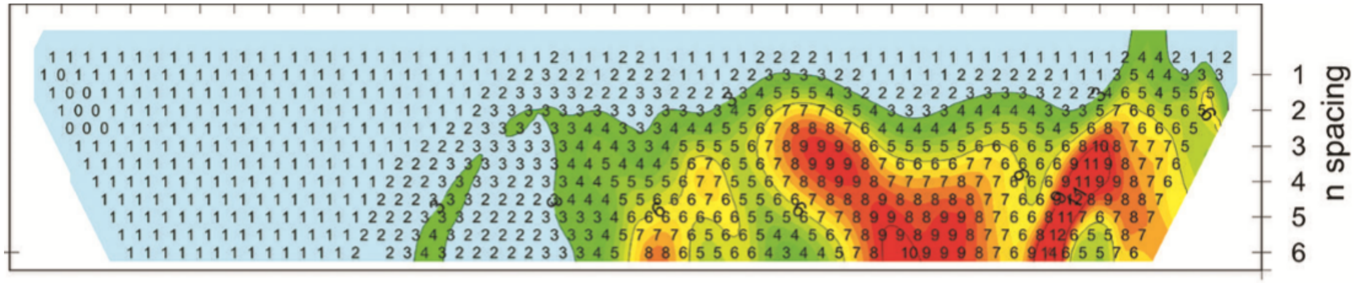
Example: Landfill Monitoring

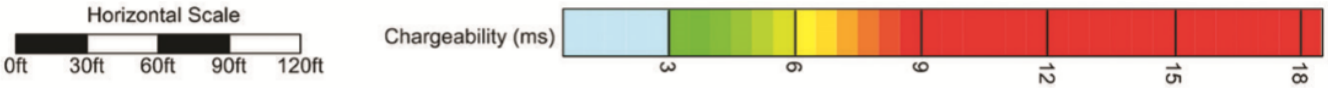
- Waste material: municipal solid waste (MSW)
- Surveys:
  - 2003: IP survey
  - 2003-2007: 4 year biodegrediation program
  - 2009: Repeat IP survey
- Observations:
  - Reduction in IP anomaly indicates the effectiveness of biodegredation

Before



After

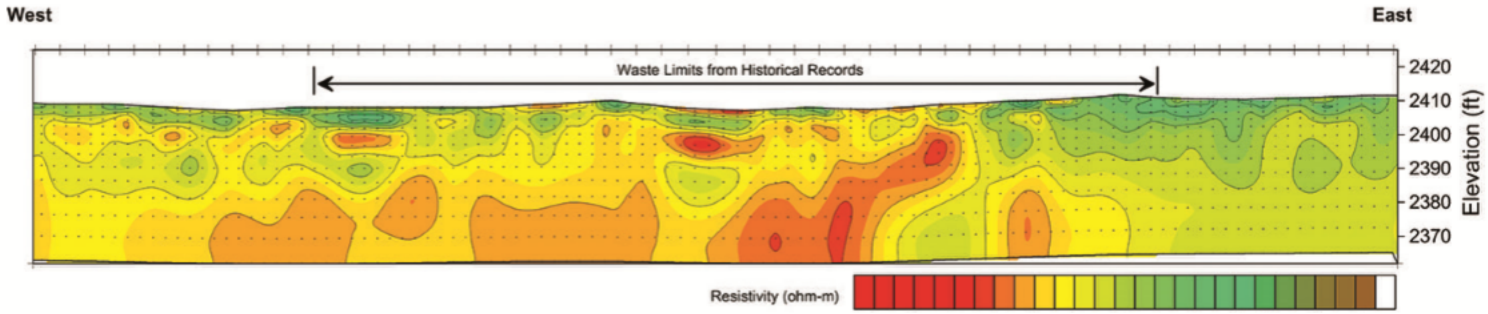




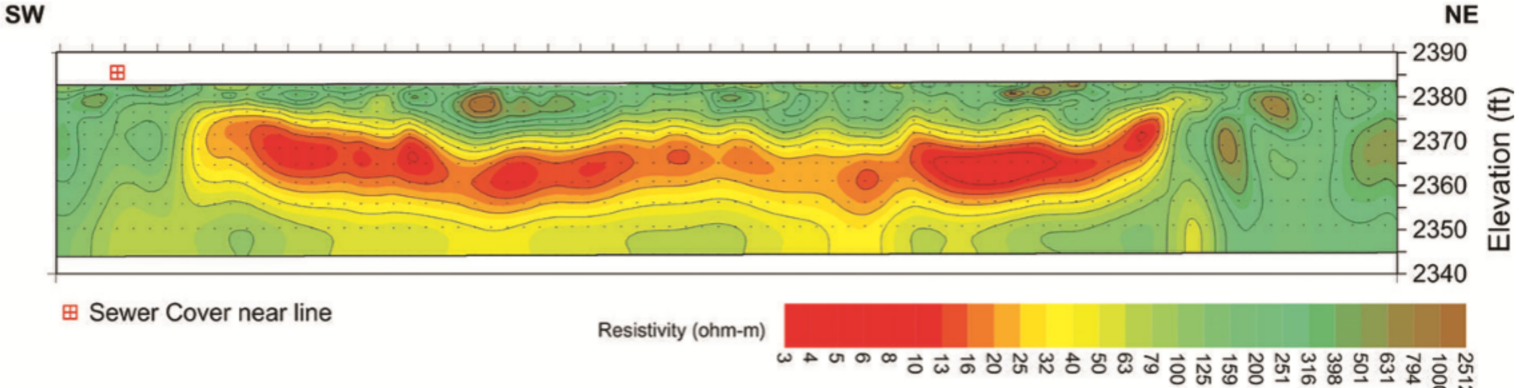
Summary

- Resistivity may not be a good indicator of waste

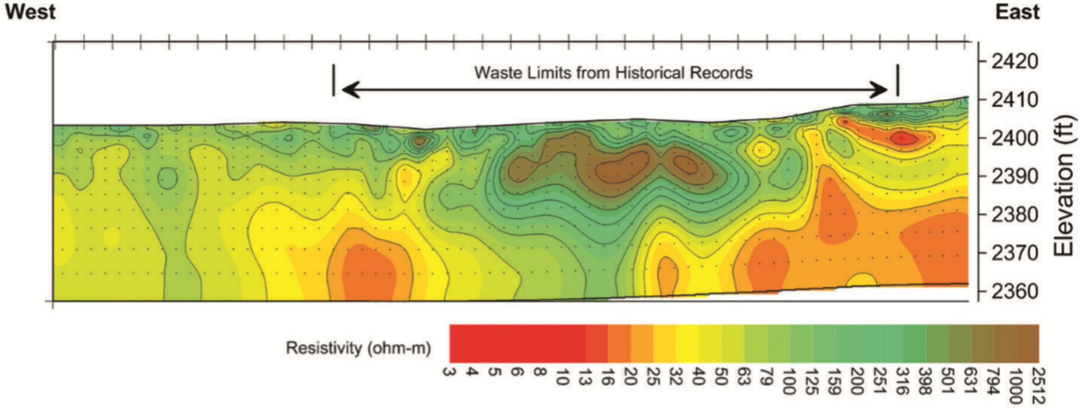
Mixed Waste



Green Waste



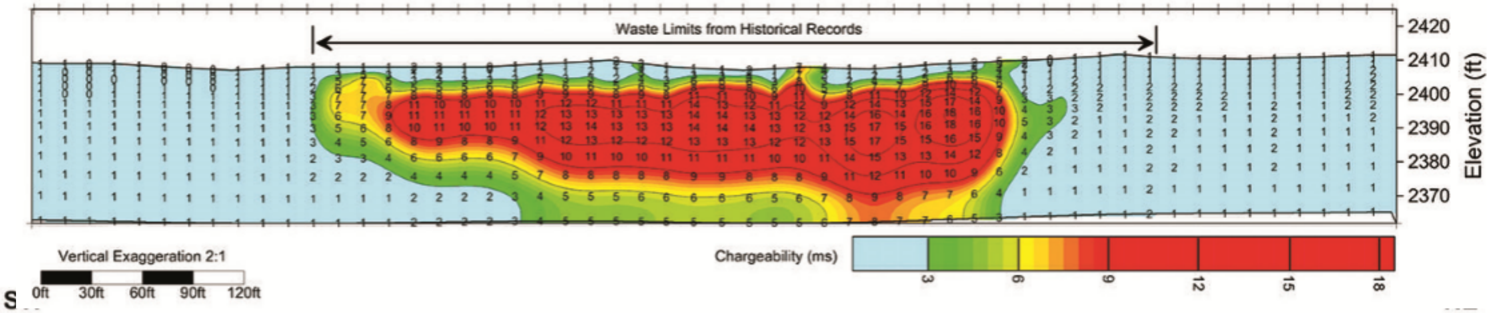
Construction/
Demolition
Waste



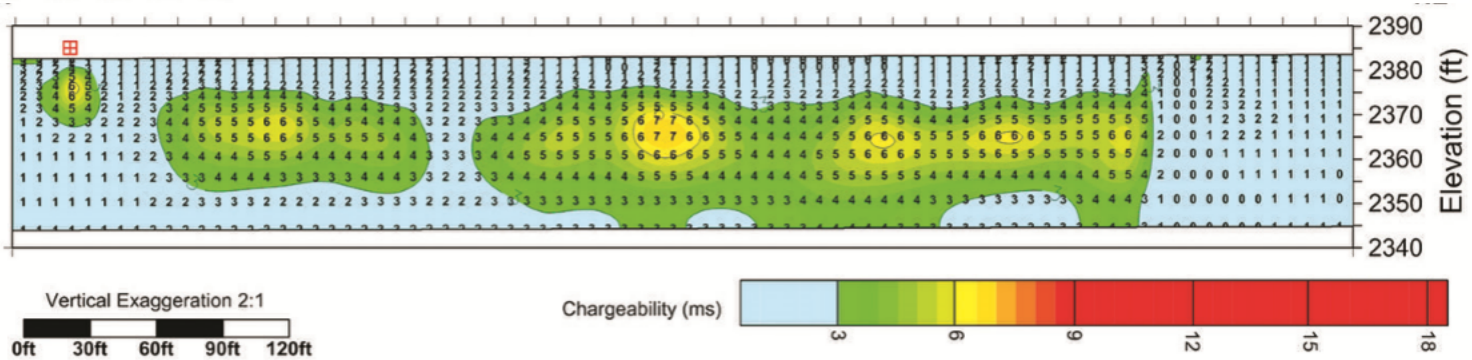
Summary

- Chargeability may be a more consistent indicator of waste

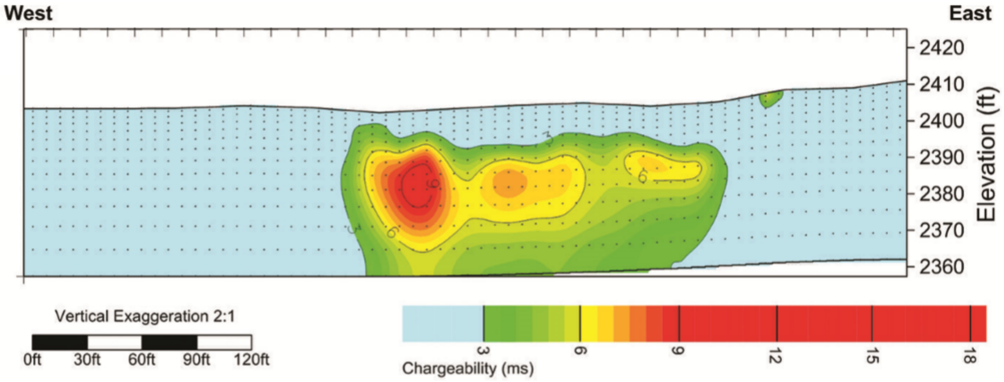
Mixed Waste



Green Waste

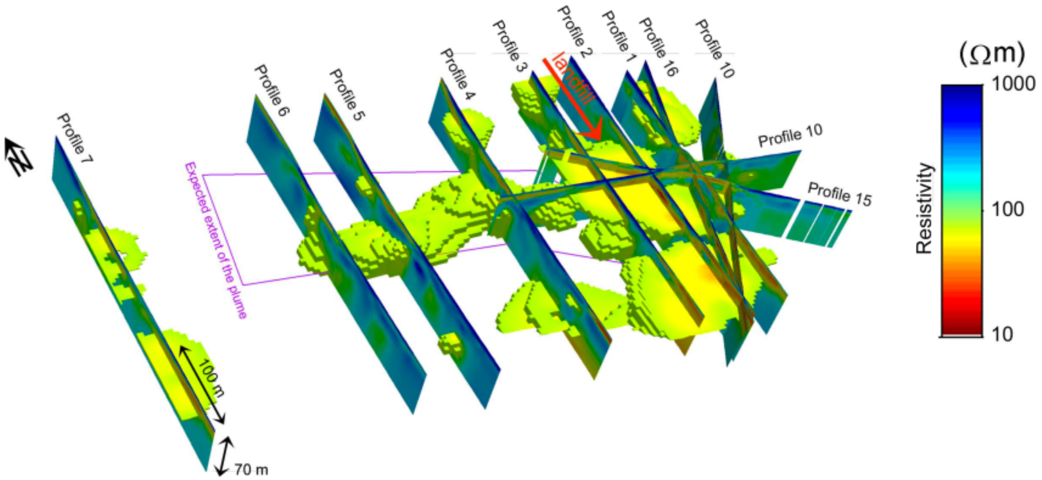


Construction/
Demolition
Waste



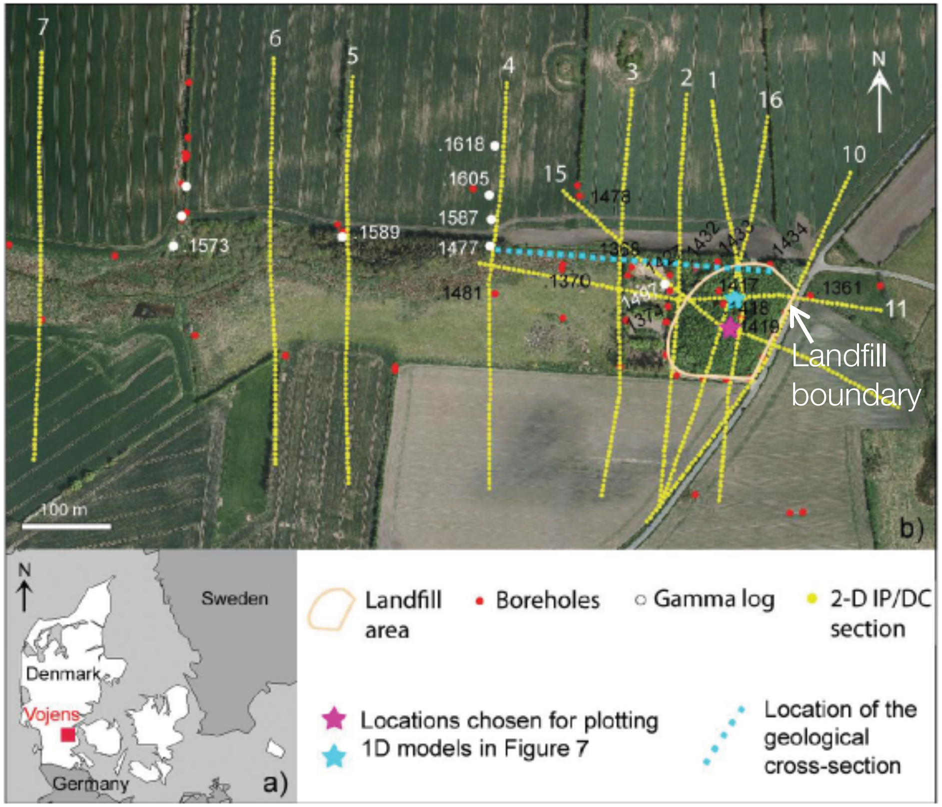
Case History:
Mapping a landfill, Denmark

Gazoty et al., 2012



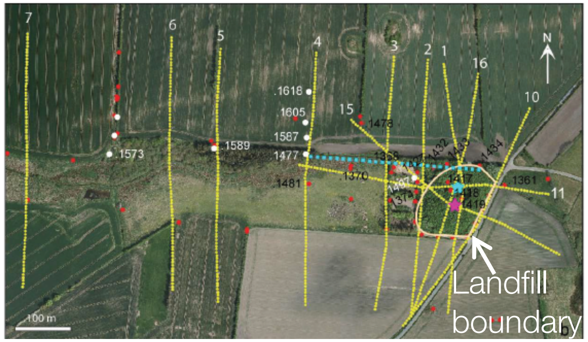
Setup

Horlokke area, Denmark

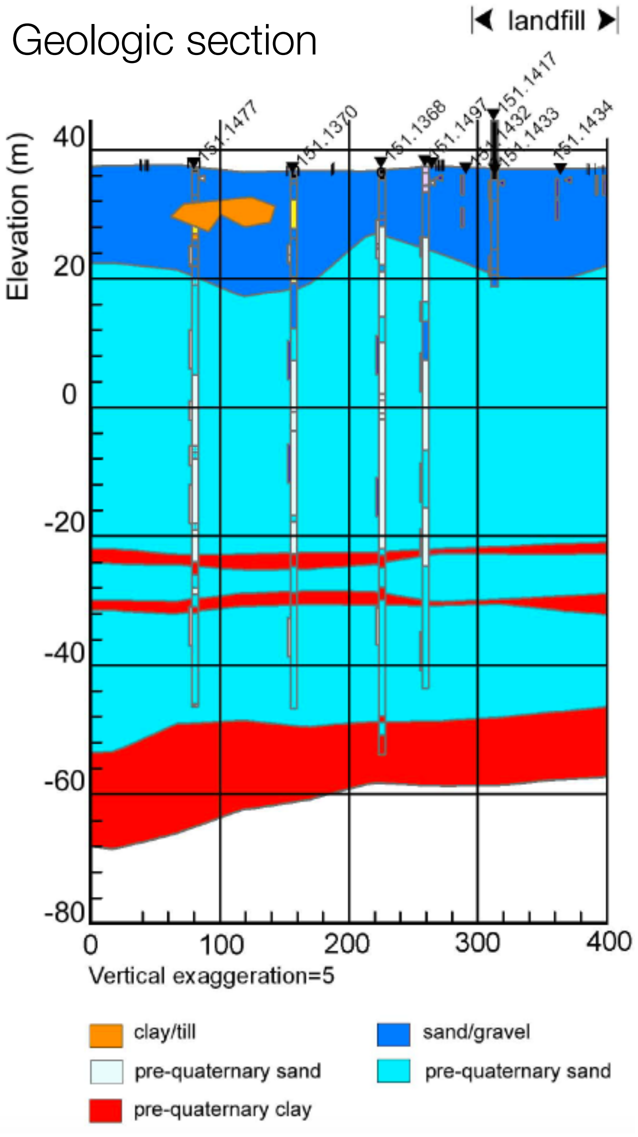


- Landfill
  - Years: 1968-1978
  - 100m x 100m
  - Sludge from waste treatment plant
  - Estimated volume: 65,000m^3
- Containment
  - No membrane
  - No leachate capture
  - No isolation system
- Current state
  - Landfill: hydrocarbons, iron, inorganics
  - Contaminant plume
    - 500m to west; depth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

Setup

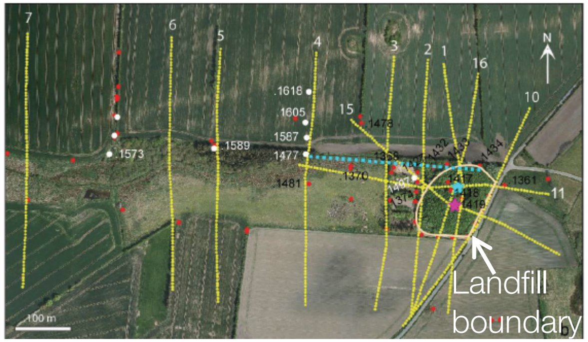


Geologic section

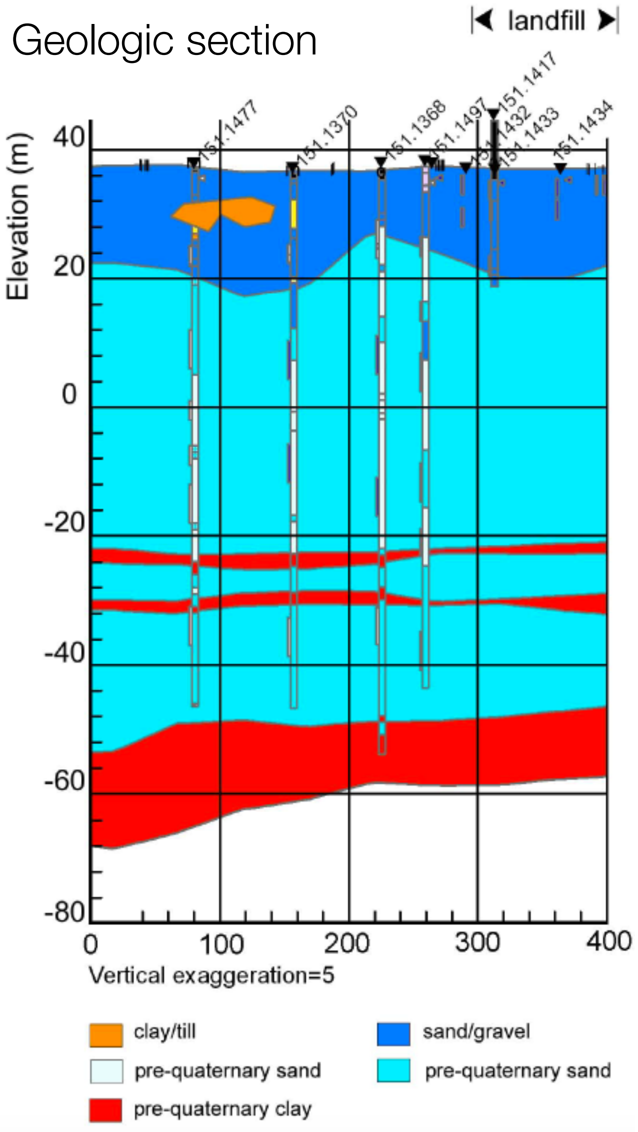


- Horlokke landfill
  - Located on an outwash plane (low topography)
  - Clay layer: top 2-3m
  - Waste layer: 6-8m thick
- General geology
  - Gravel and sand with interbedded clay
  - Water level: 2-3m depth
  - Sand layers below landfill host regional aquifer
- Aquifer is used for drinking water
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

Objectives



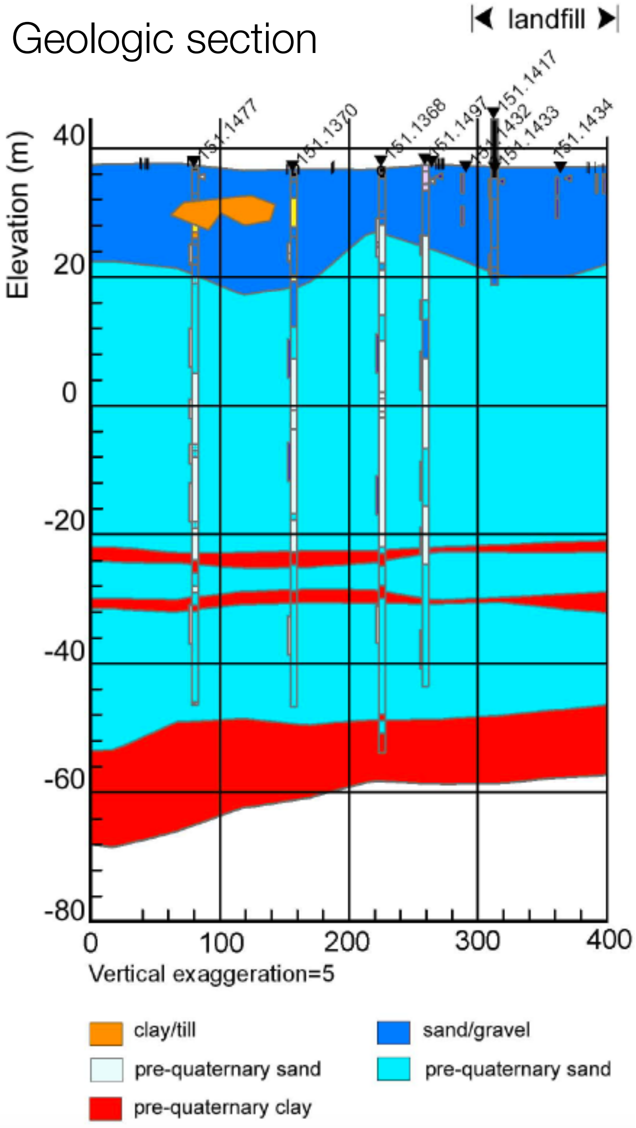
Geologic section



- 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

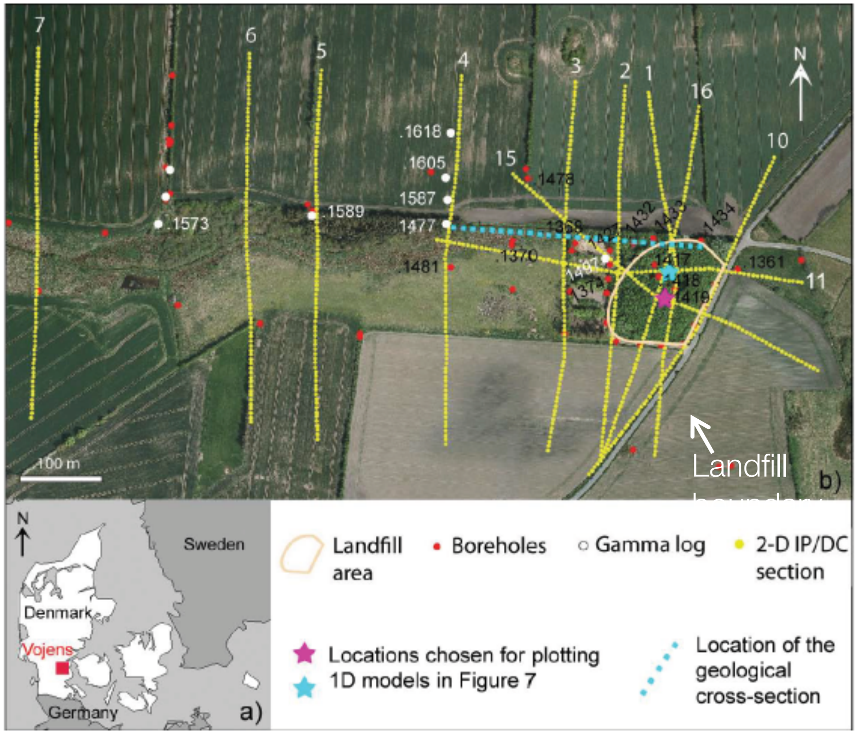


Physical properties

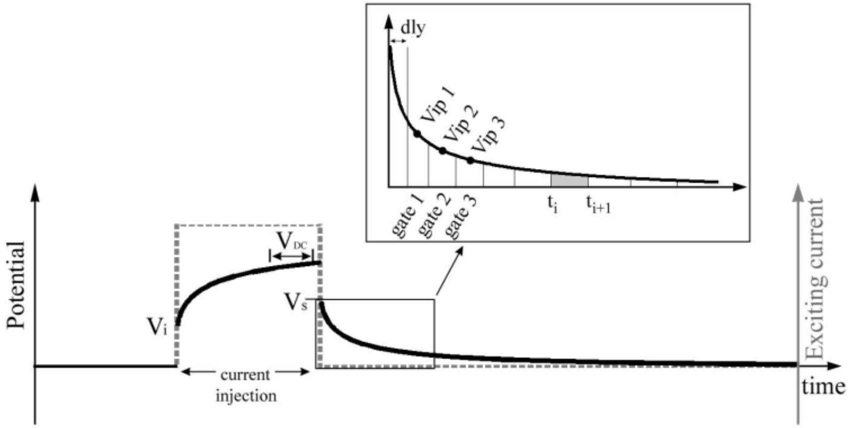
	Resistivity	**Chargeability**	**Gamma**
sand/gravel	High	Low	Low
clay/till	Low	High	High
sand	High	Low	Low
landfill	High (?)	High	(?)

Survey

Study area



Time domain IP (TDIP)



Data (chargeability):

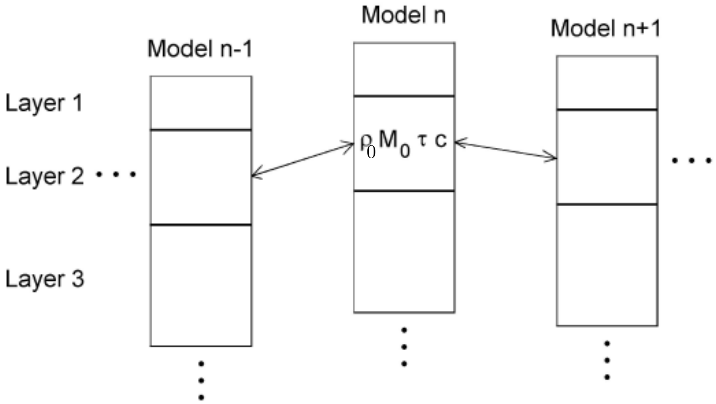
$$M_i = \frac{1}{V_{DC} \cdot \left[t_{i+1} - t_i\right]} \int_{t_i}^{t_{i+1}} V_{ip}\, dt$$

- 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)

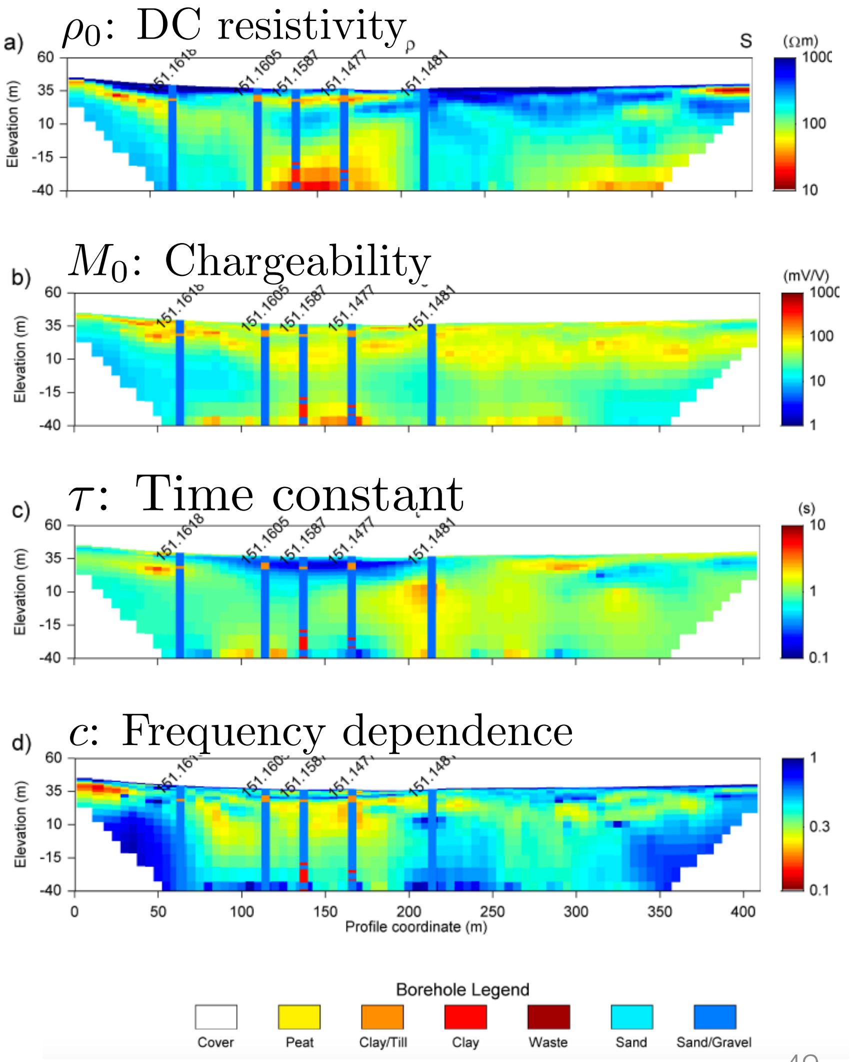
Processing / Inversion

- 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:


ρ_0: DC resistivity

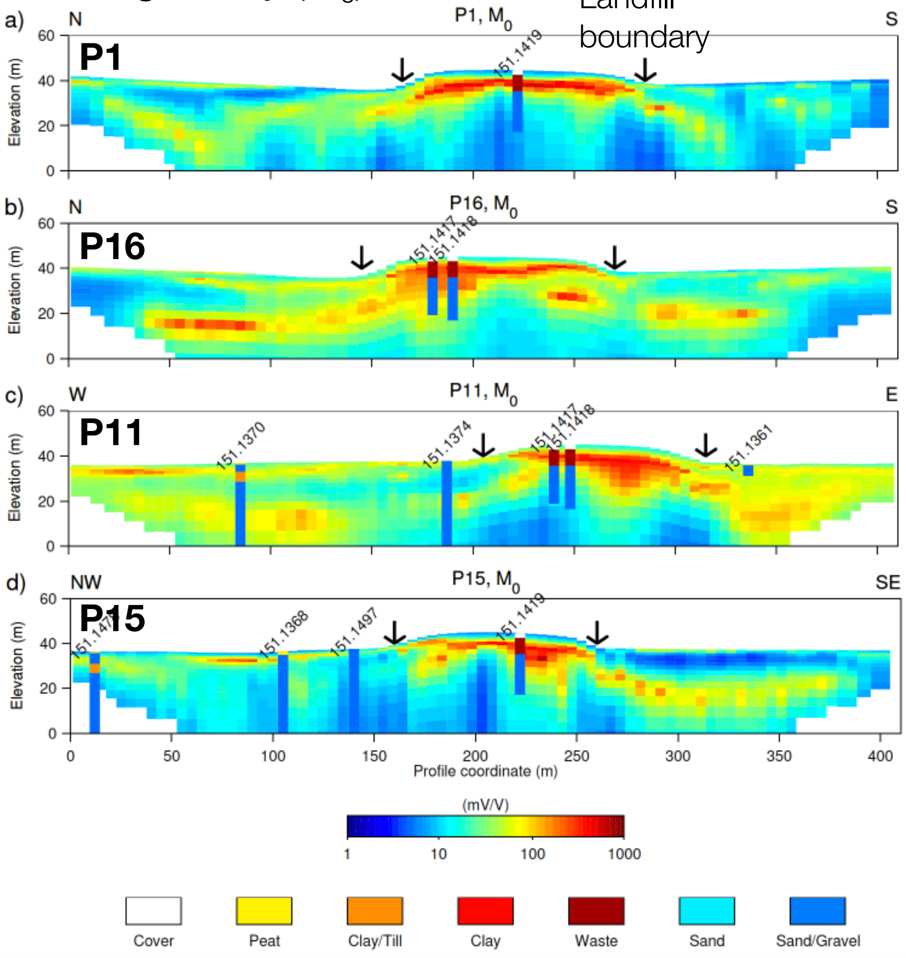
M_0: Chargeability

τ: Time constant

c: Frequency dependence

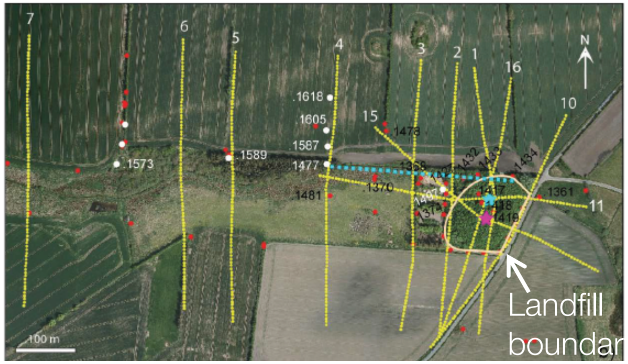
Interpretation: Delineating the landfill

Chargeability (M_0) sections

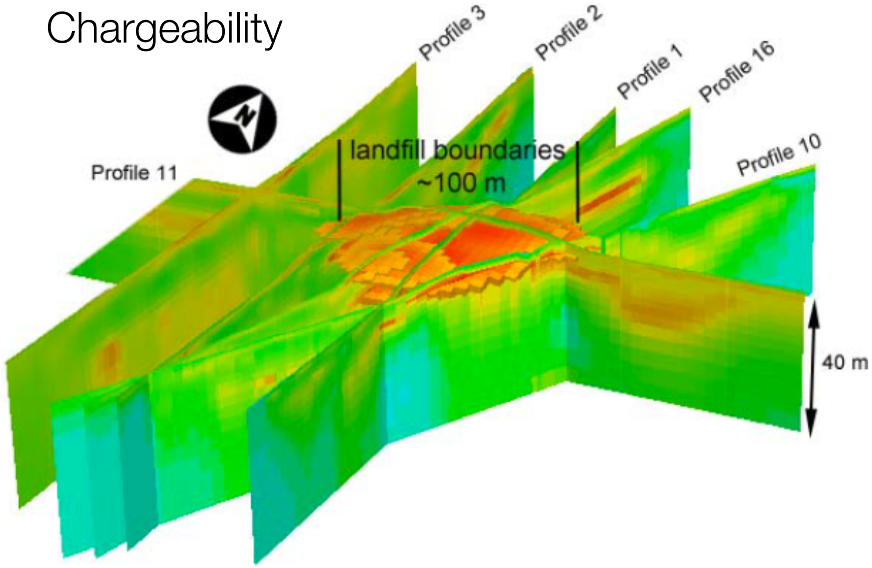


Landfill boundary

Location map



Chargeability

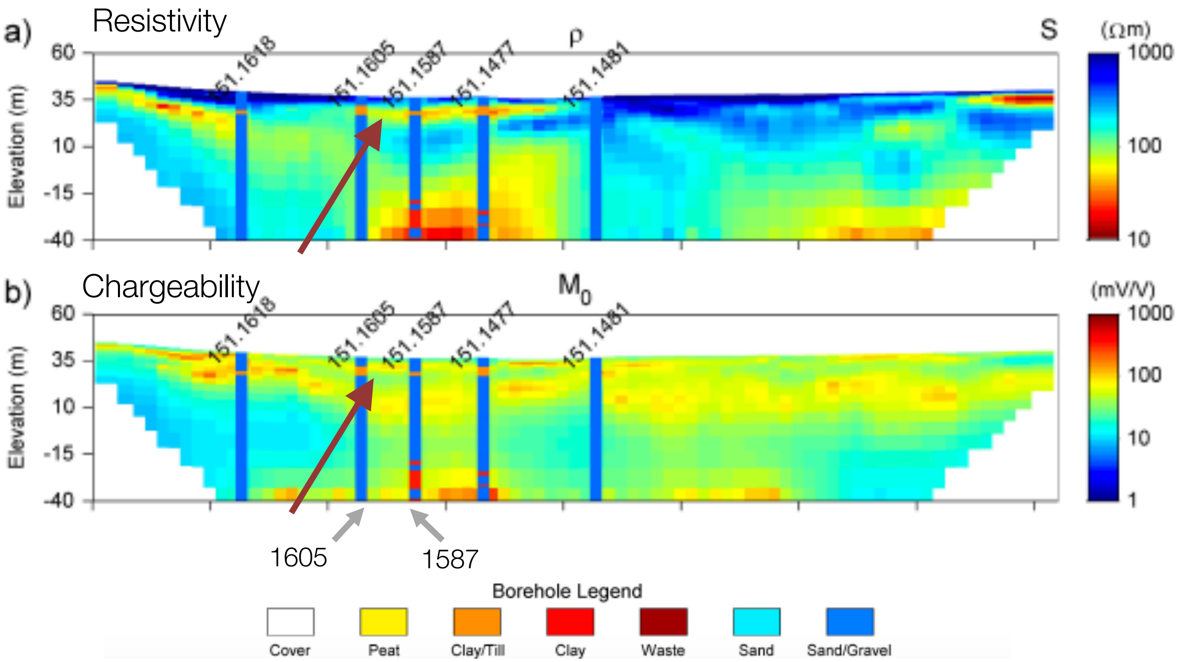


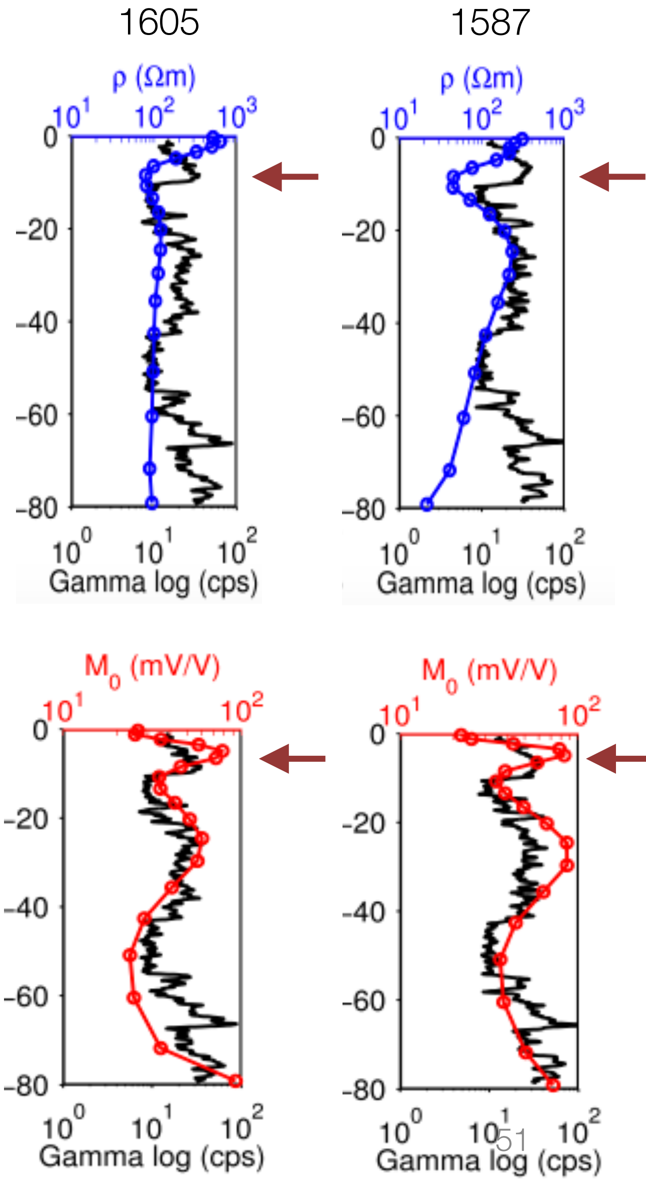
Estimated volume

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

Interpretation: Clay layer (Aquitard)

Resistivity and chargeability sections





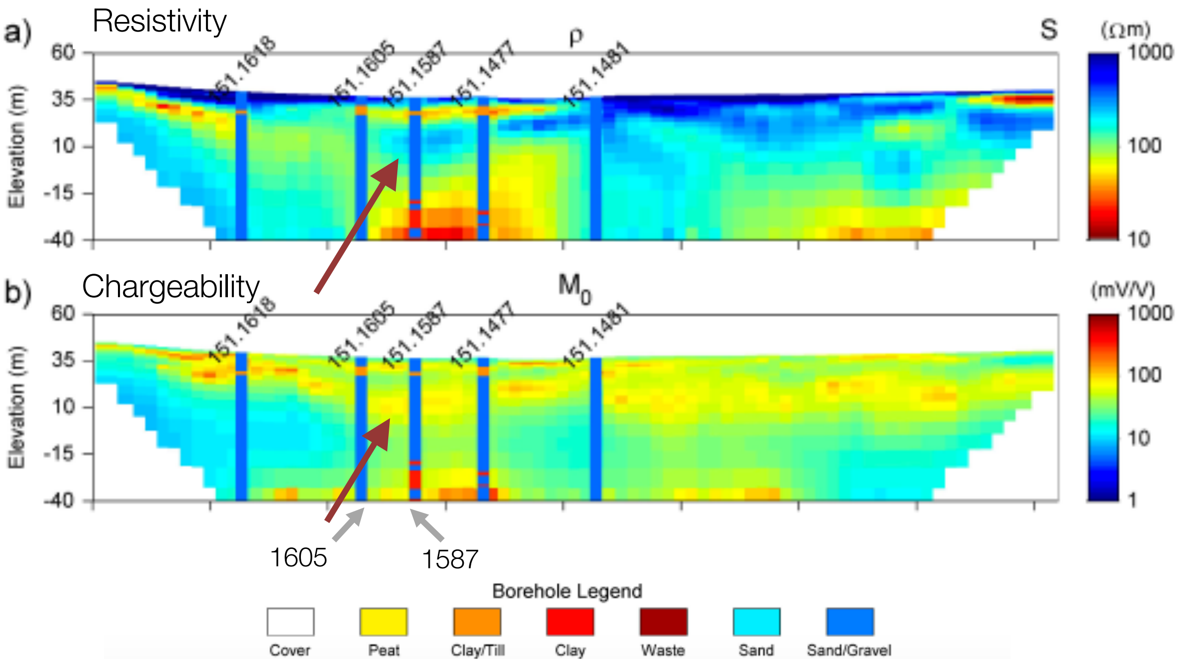
Formation	Resistivity	Chargeability	Gamma
Clay	Low (60 ohm m)	High	High

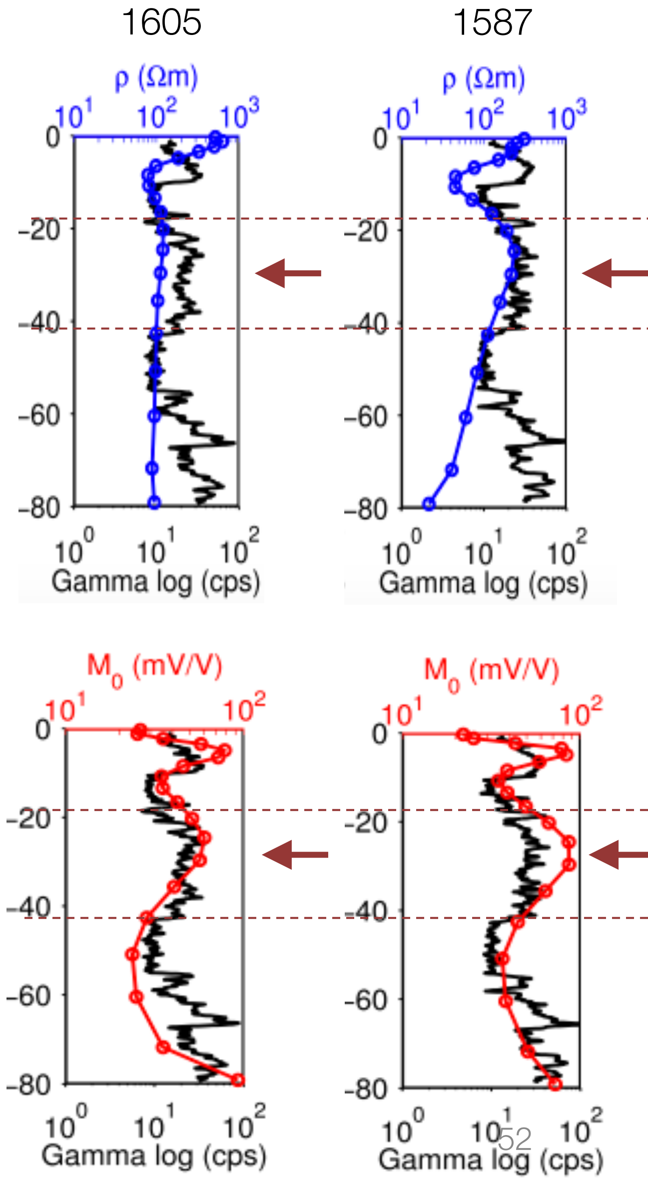
Interpretation

- Creek overlays the clay layer (acts as aquitard)

Interpretation: Clay-rich sandy layer

Resistivity and chargeability sections

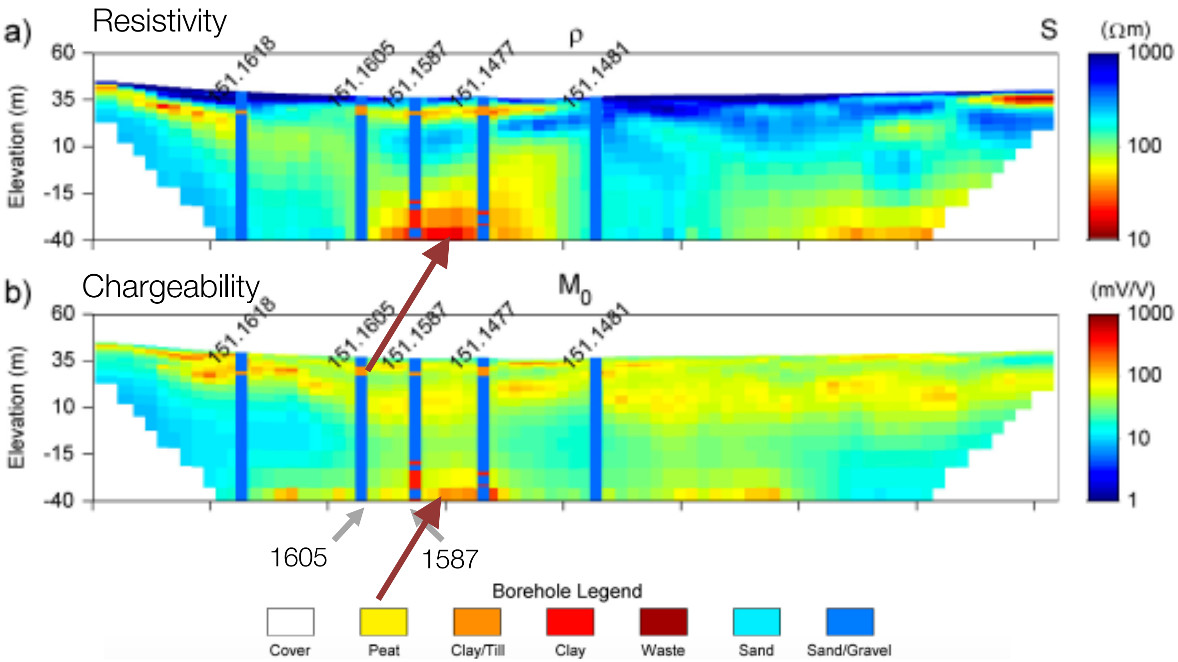


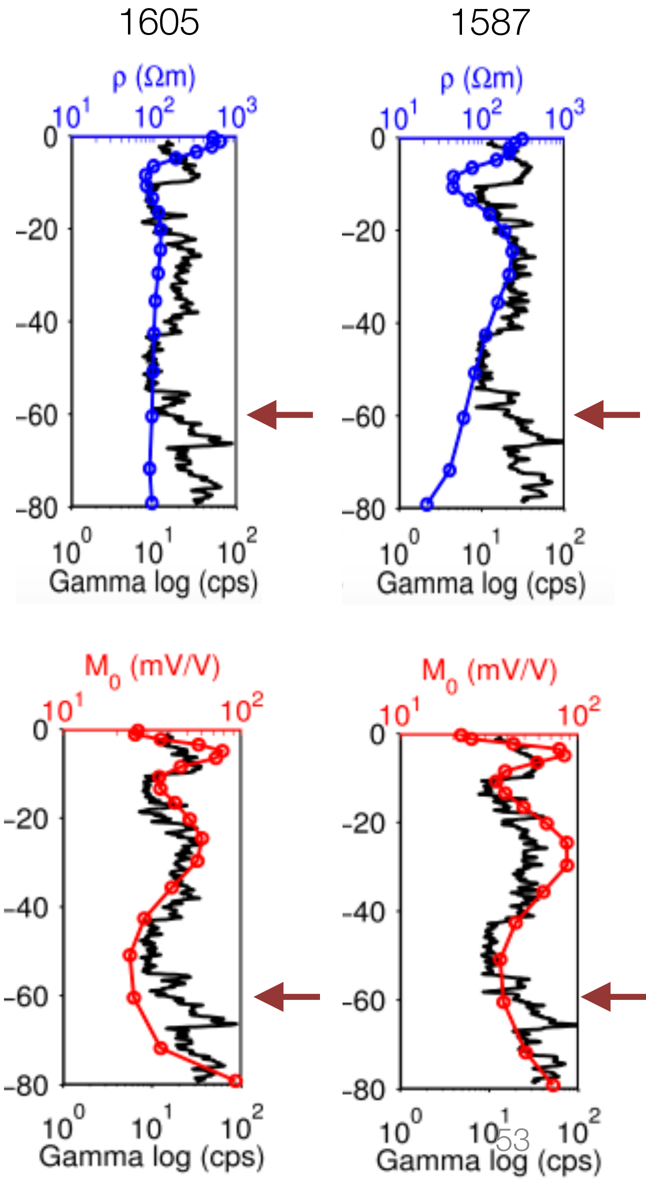


Formation	Resistivity	Chargeability	Gamma
Clay	Low	High	High
Clay-rich sandy layer	High	Moderate (50-100 mV/V)	High

Interpretation: Silt/clay lens

Resistivity and chargeability sections

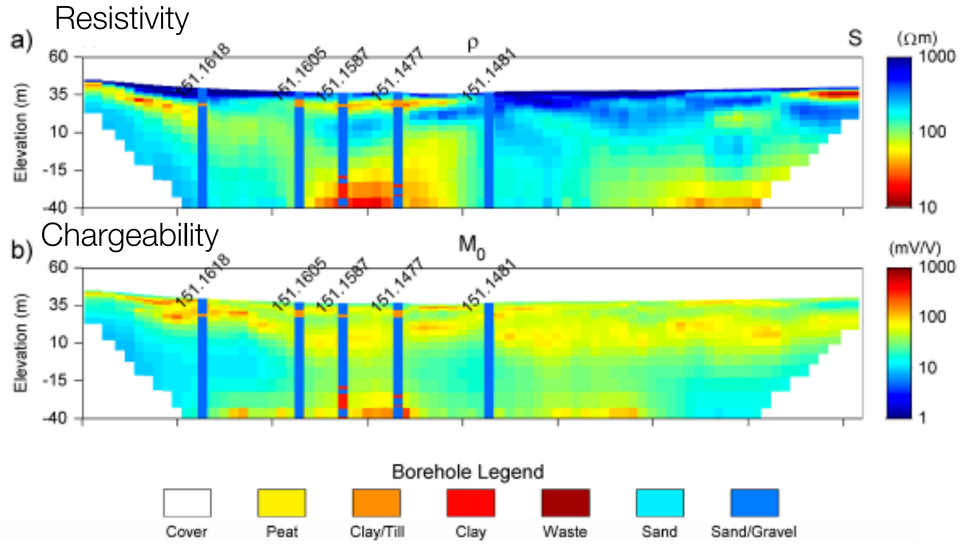




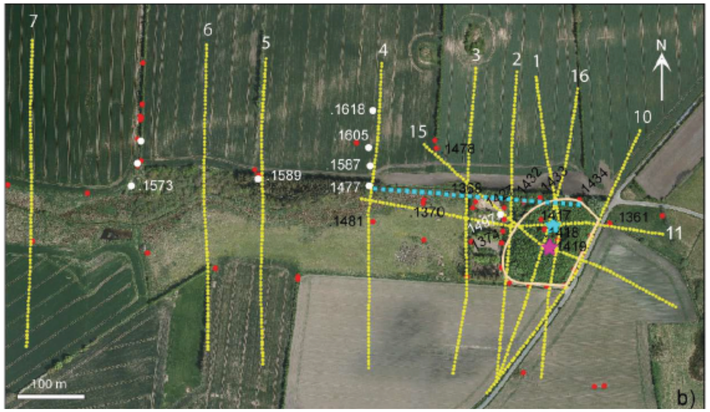
Formation	Resistivity	Chargeability	Gamma
Clay	Low	High	High
Clay rich sandy layer	High	Moderate (50-100 mV/V)	High
Silt/clay lens	Low	High	High

Interpretation: Lithology

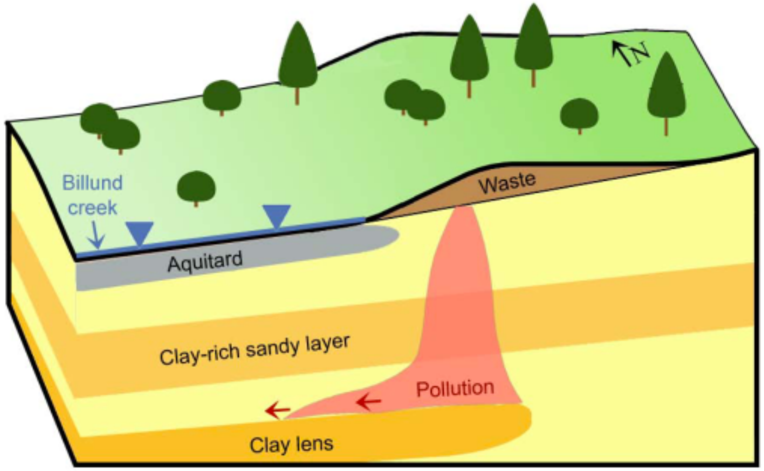
Resistivity and chargeability sections



Location map

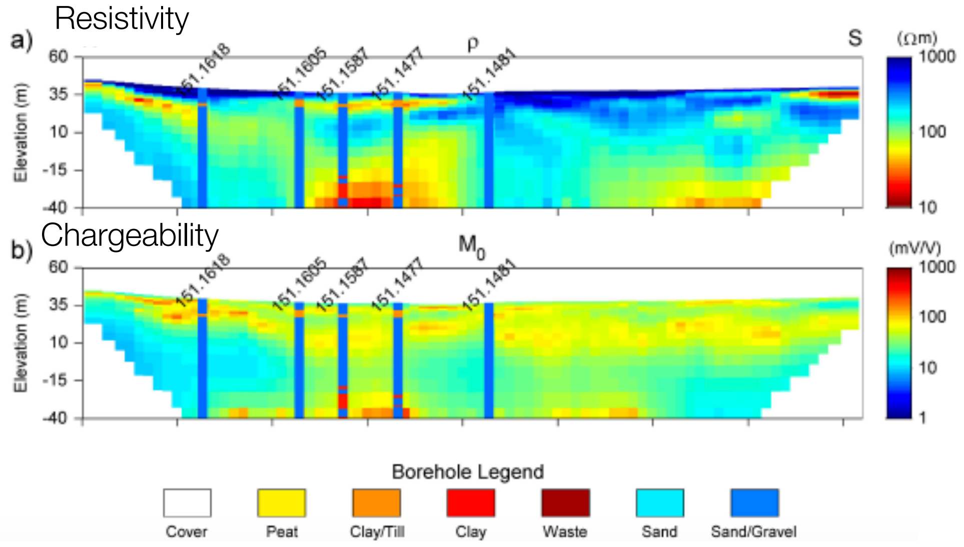


Geologic interpretation

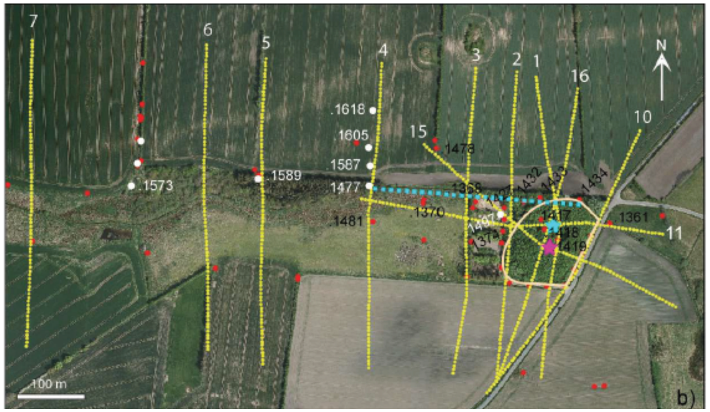


Interpretation: Lithology

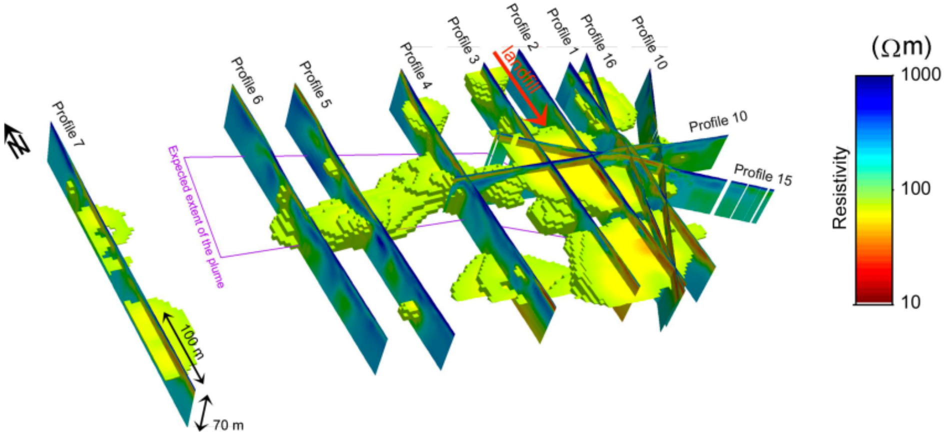
Resistivity and chargeability sections



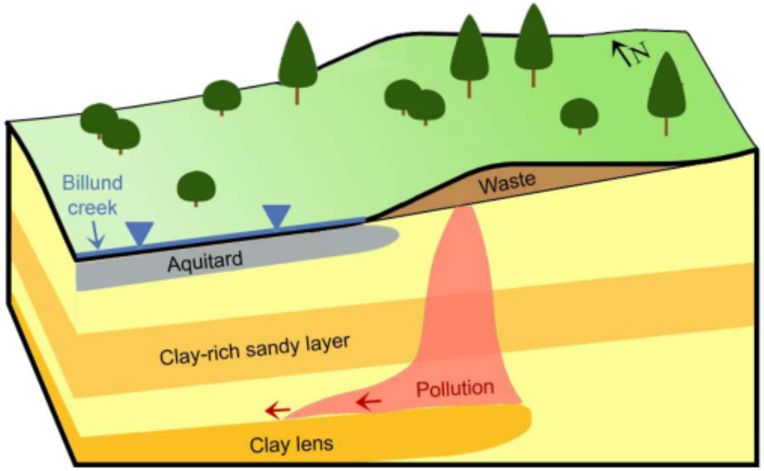
Location map



Resistivity cut-off volume (<100 Ωm)

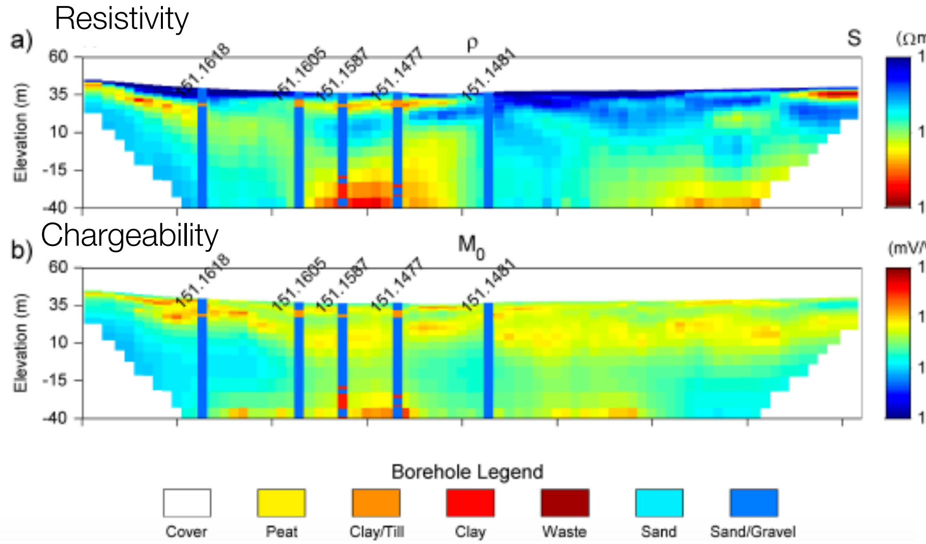


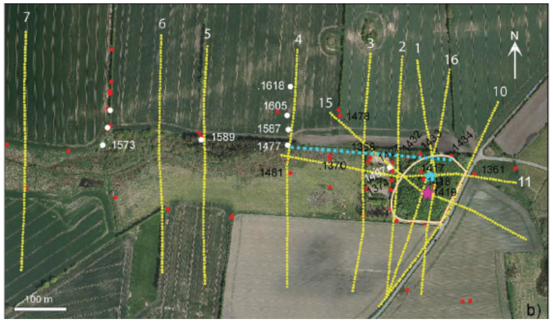
Geologic interpretation



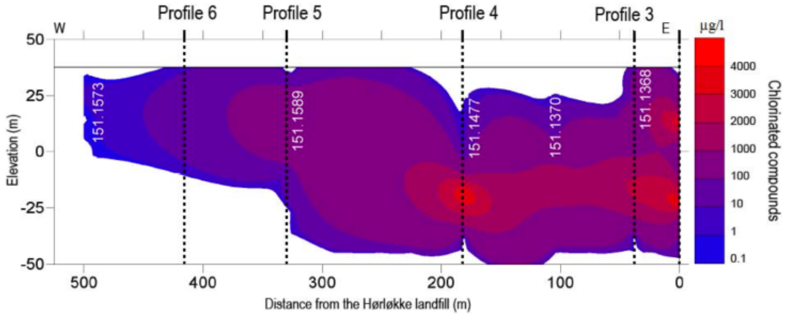
Synthesis: delineating the leachate

Resistivity and chargeability sections

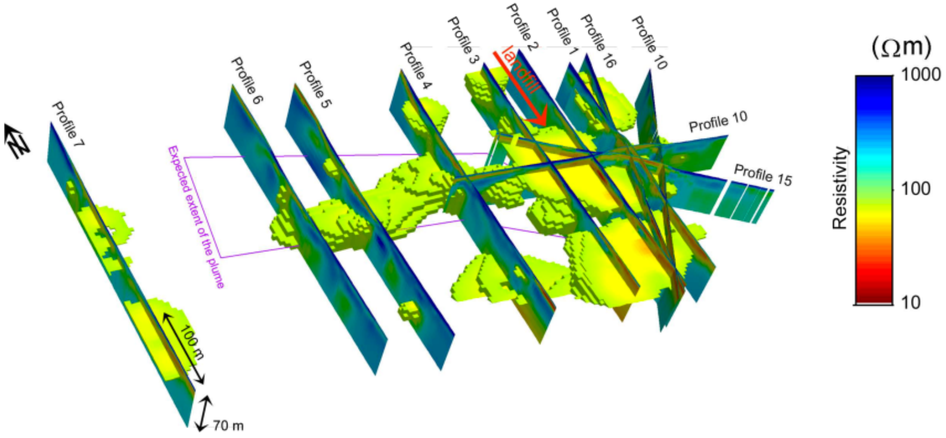




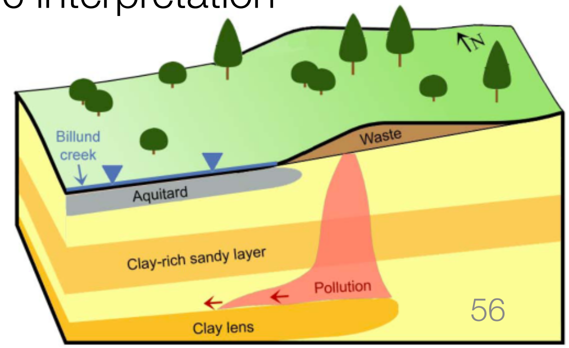
Contaminated plume section



Resistivity cut-off volume (<100 Ωm)

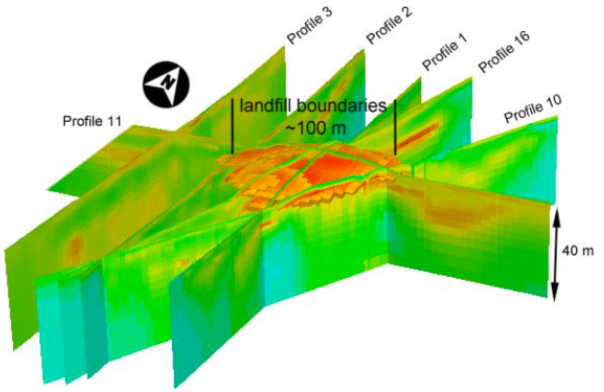


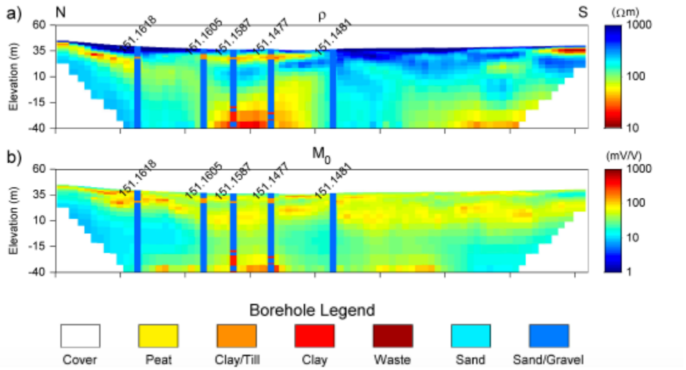
Geologic interpretation

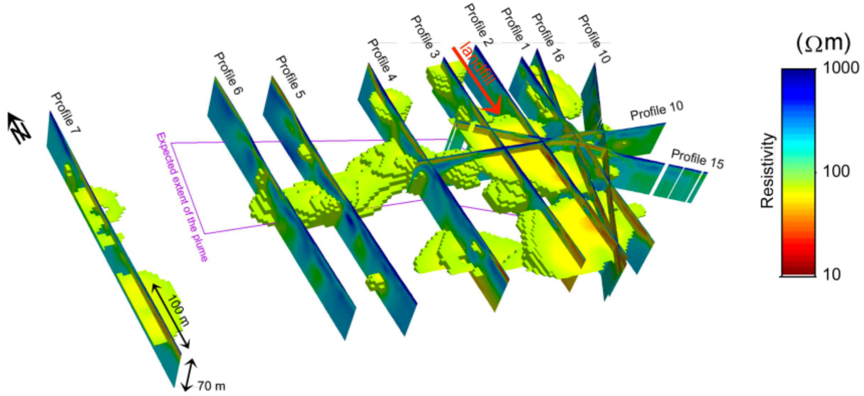


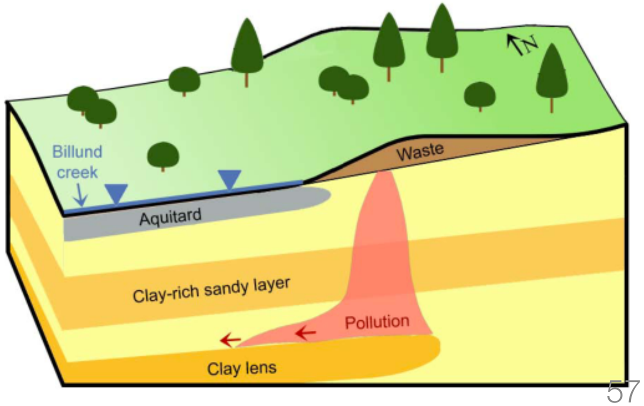
Summary

- 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



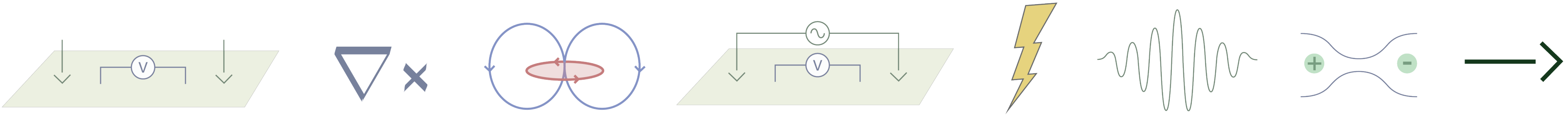






End of IP

Next up



DC Resistivity

EM Fundamentals

Inductive Sources

Grounded Sources

Natural Sources

GPR

Induced Polarization

The Future

Lunch: Play with apps

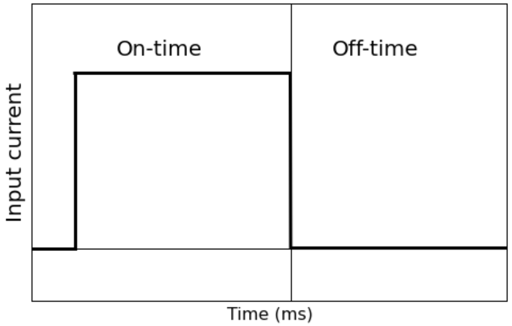
Additional Material

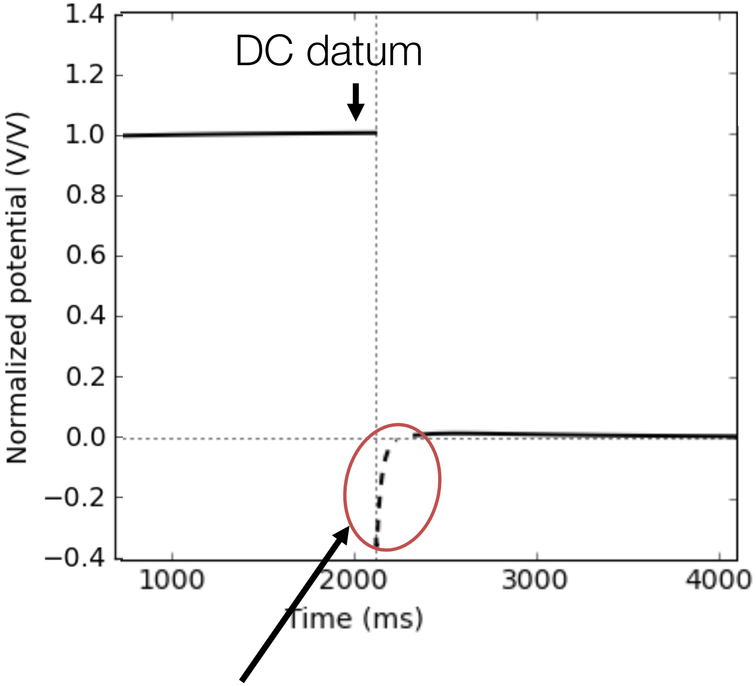
- EM Decoupling
- Case History: TKC (Minerals)

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

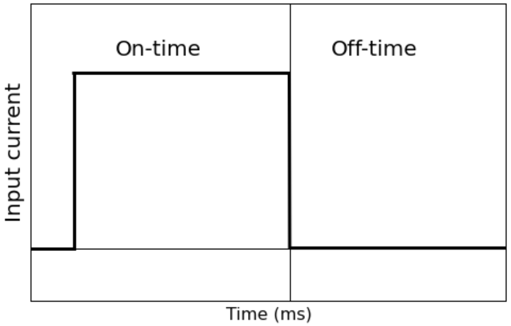


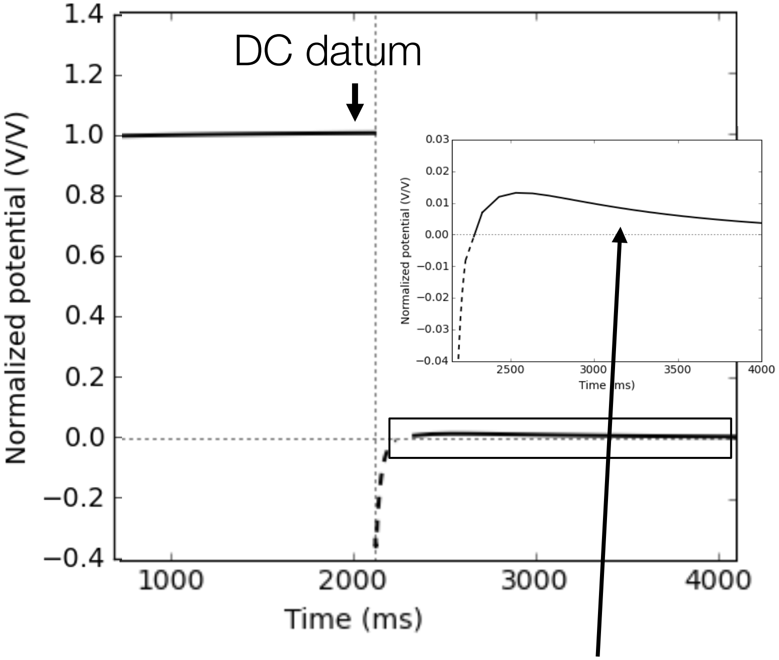


EM portion
Generally considered noise

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

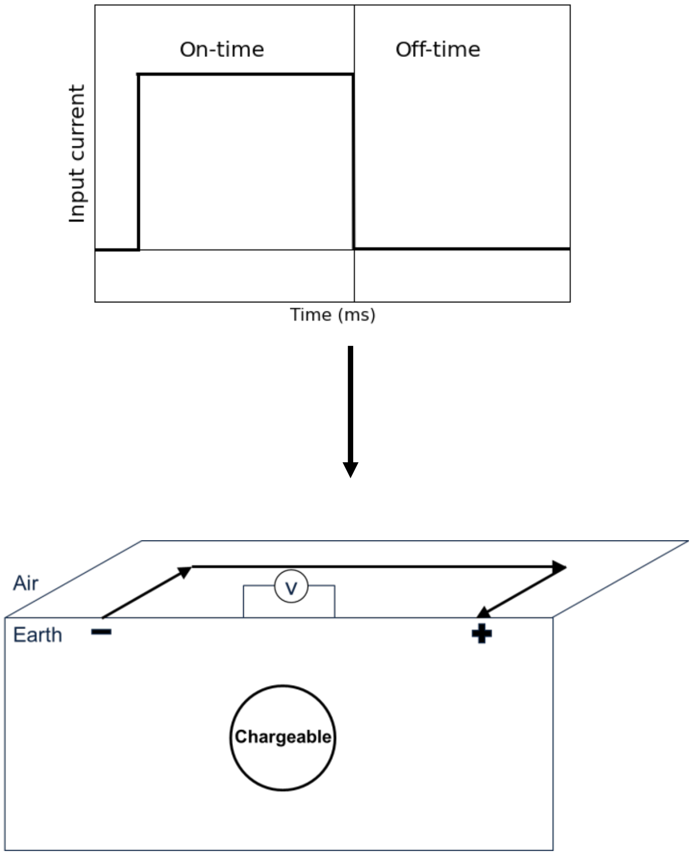




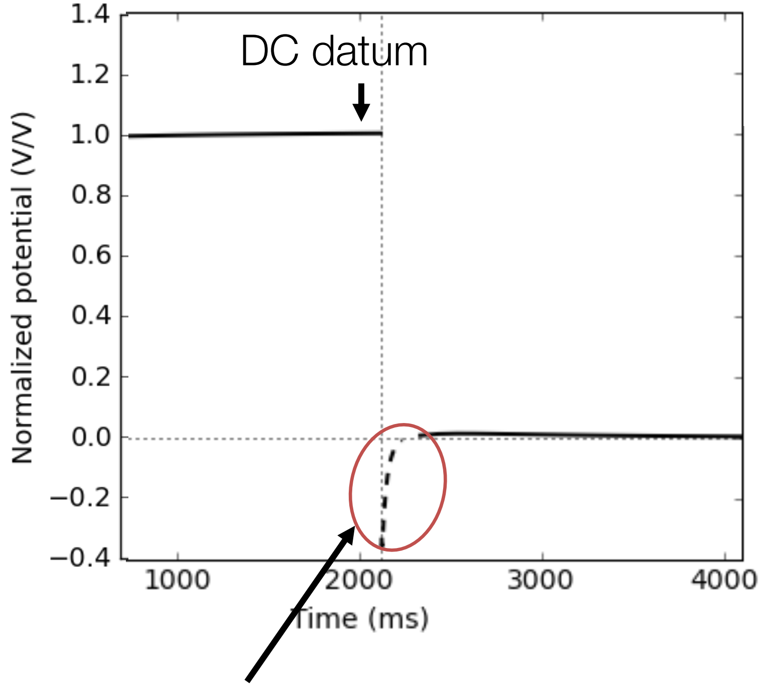
IP portion
Assumed no EM-coupling

Survey and Data

Transmitter



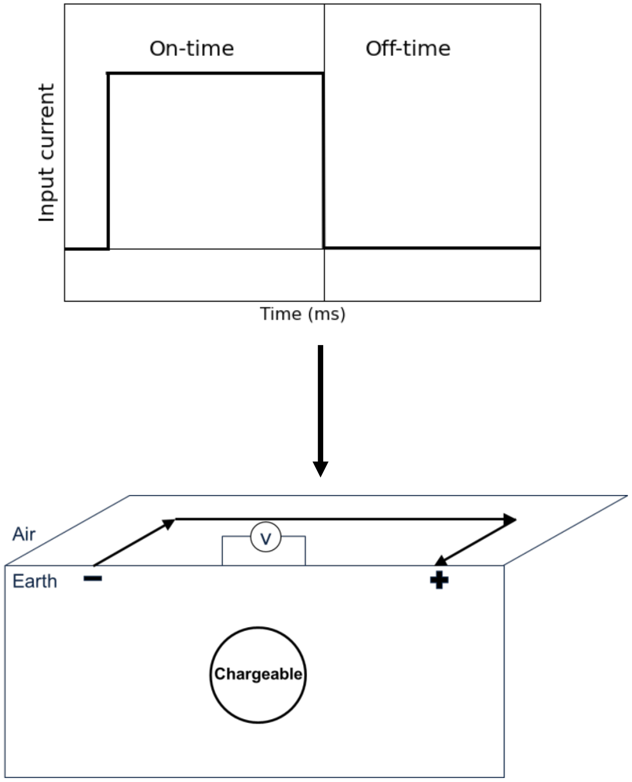
Measured Voltage



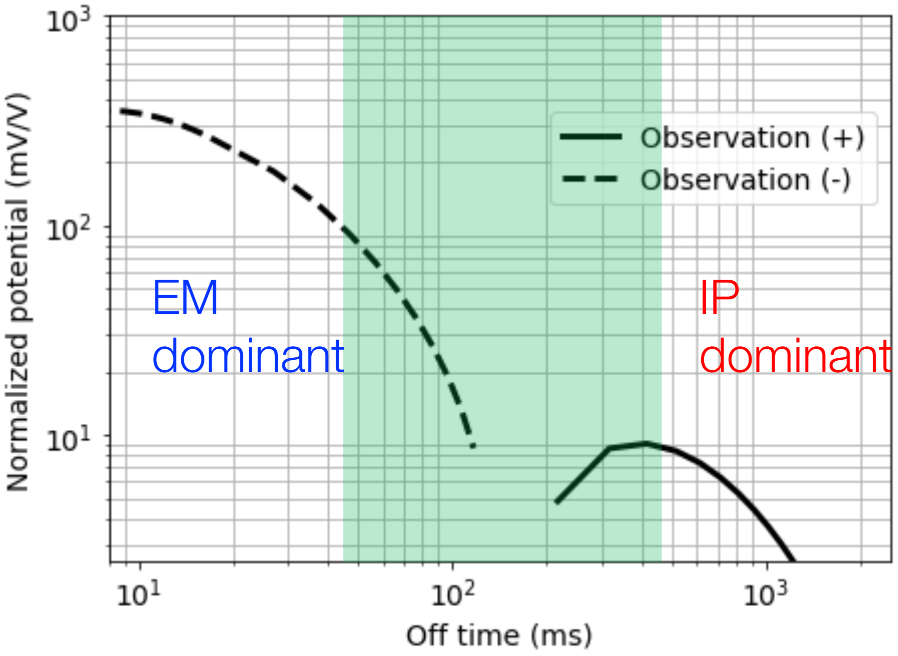
EM portion
Generally considered noise

Survey and Data

Transmitter



Measured Voltage (off-time)



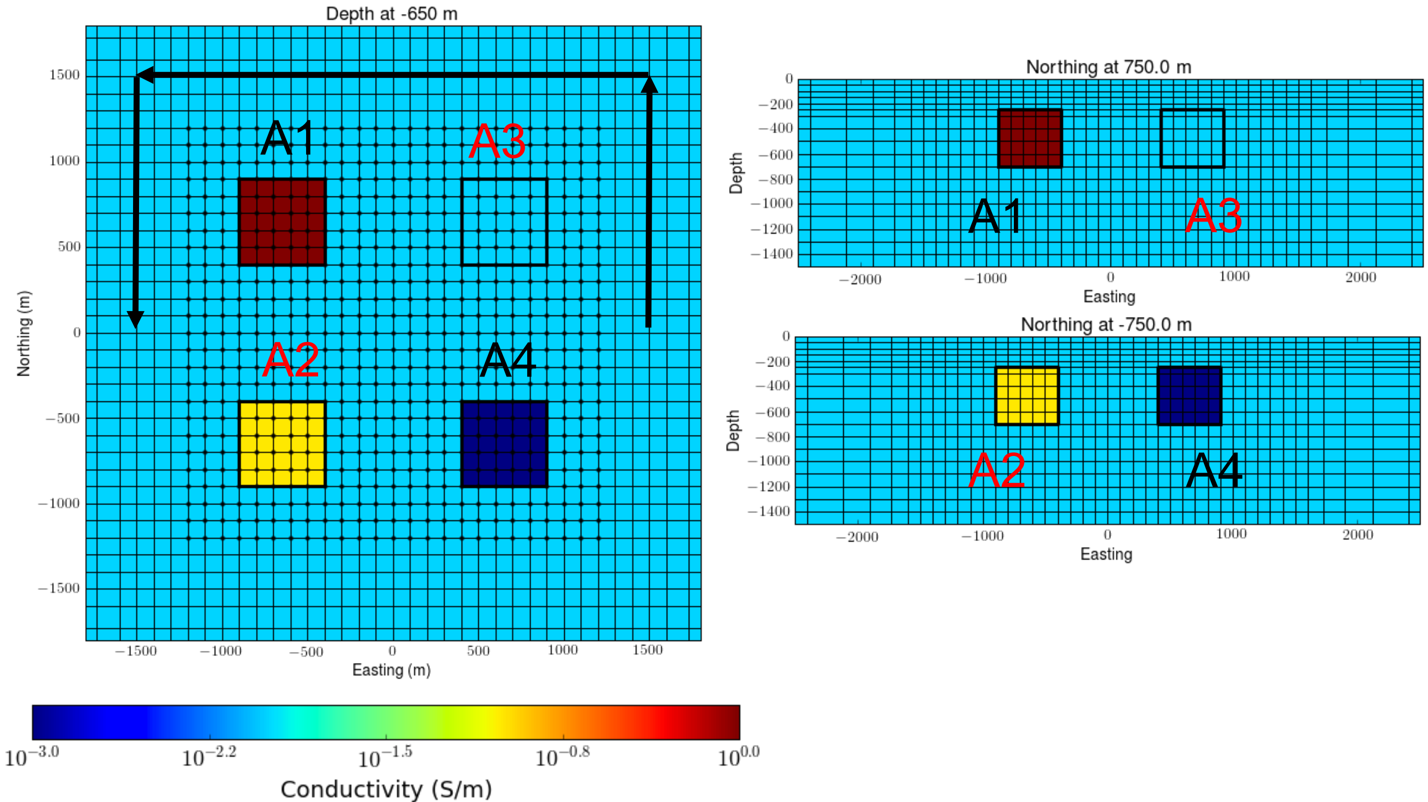
Observation = EM + IP

Gradient array

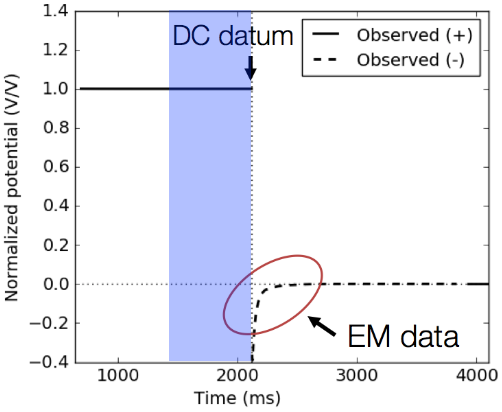
- Model

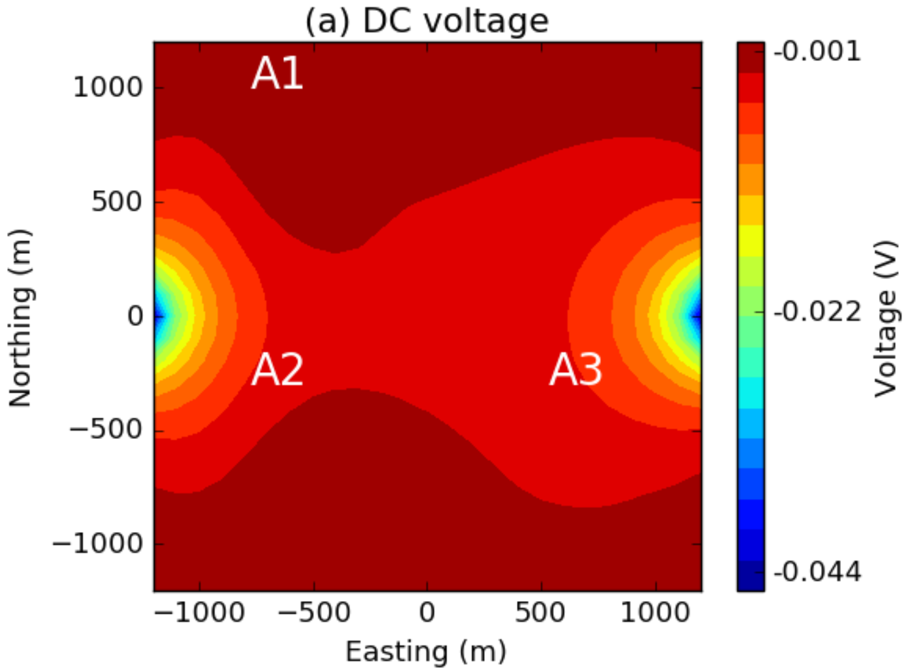
	σ (S/m)	**η**	**τ** (s)
A1	1	0	
A2	0.1	0.1	0.5
A3	0.01	0.1	
A4	0.001	0	0.5

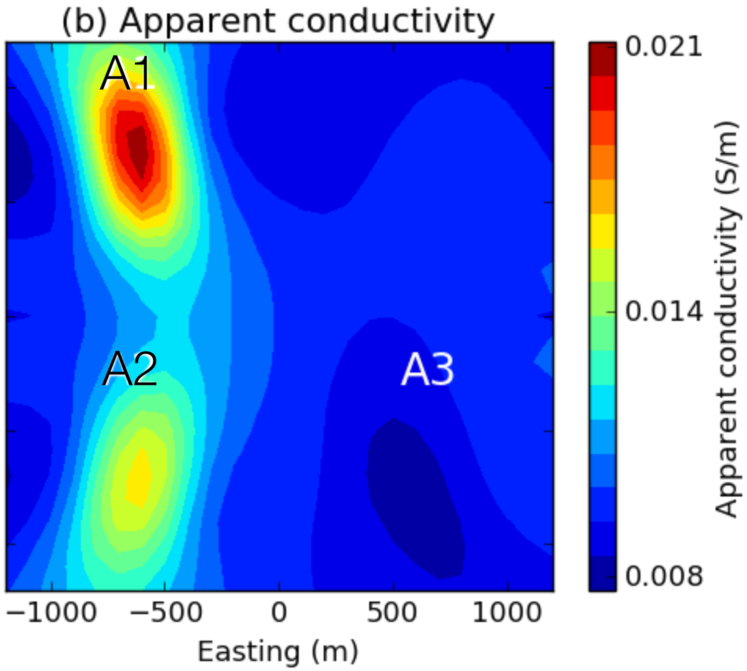
- Survey
  - 200m bi-pole (625 data)
  - times: 1-600ms



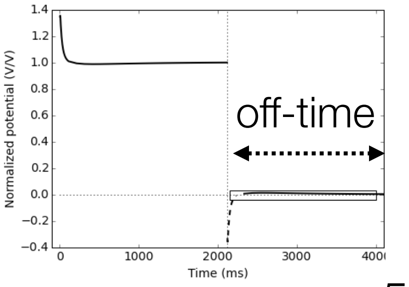
DC data

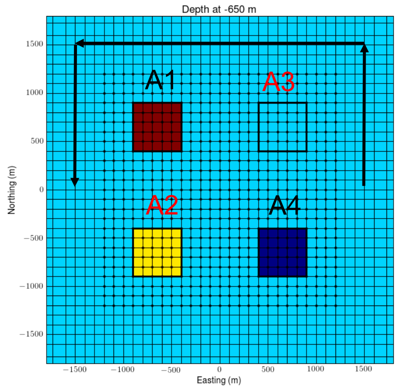

DC datum
Observed (+)
Observed (-)
EM data
Normalized potential (V/V)
Time (ms)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
1000
2000
3000
4000


(a) DC voltage
A1
A2
A3
Northing (m)
Easting (m)
Voltage (V)
-0.001
-0.022
-0.044
1000
500
0
−500
−1000
−1000
−500
0
500
1000

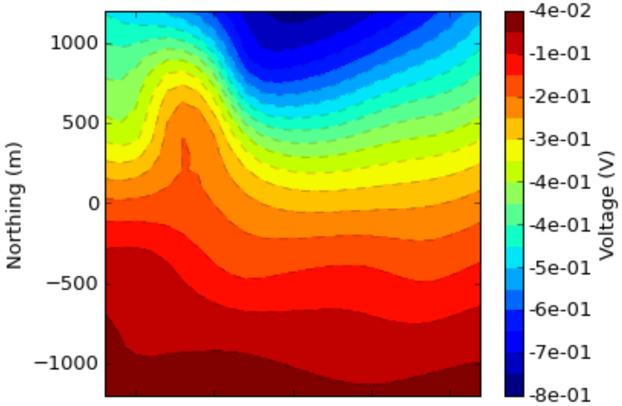

(b) Apparent conductivity
A1
A2
A3
Easting (m)
Apparent conductivity (S/m)
0.021
0.014
0.008
−1000
−500
0
500
1000

Off-time data

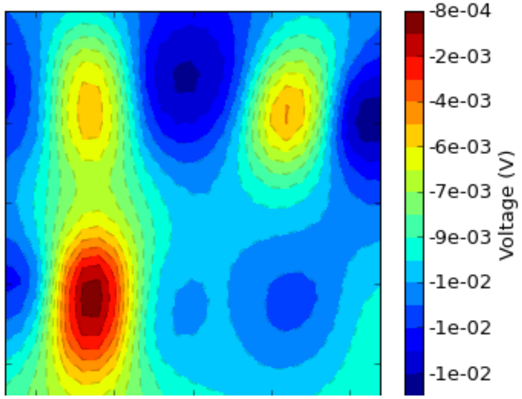




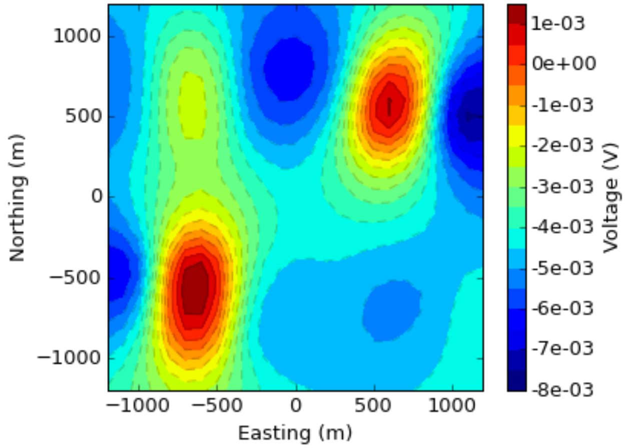
5 ms



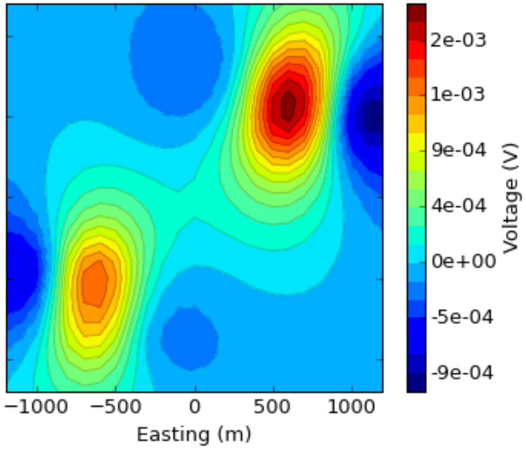
80 ms



130 ms



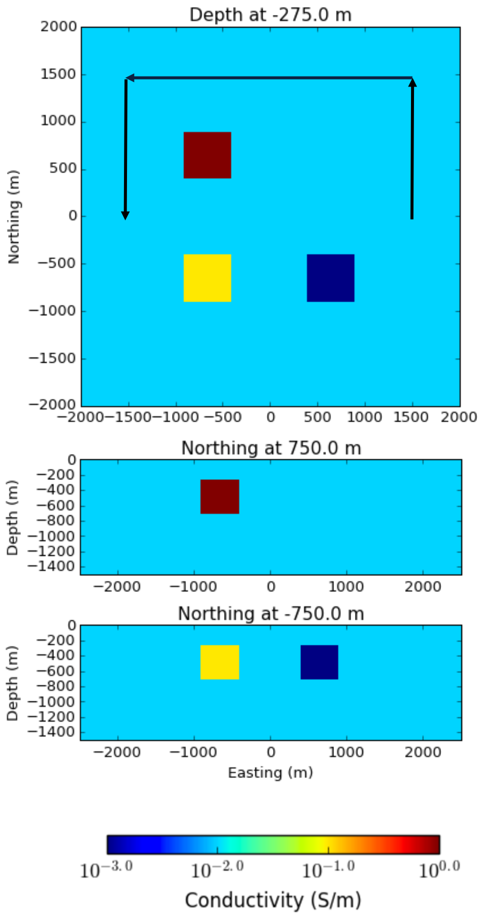
650 ms



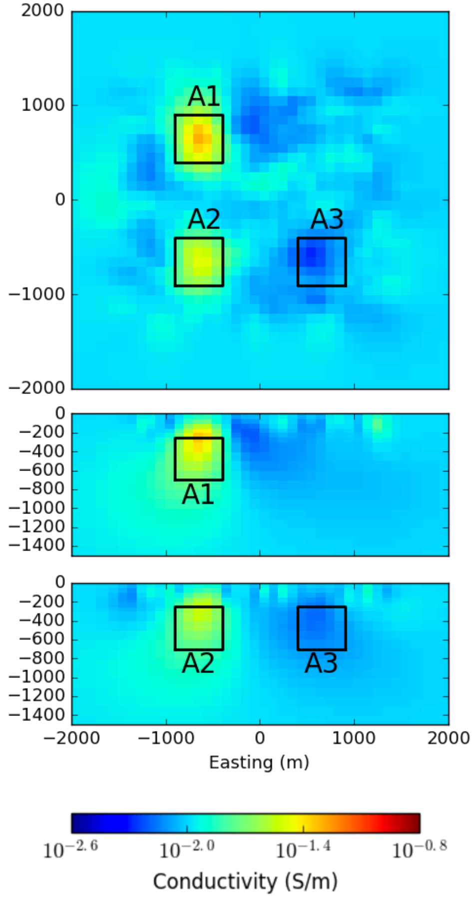
DC inversion

- Recovered 3D conductivity

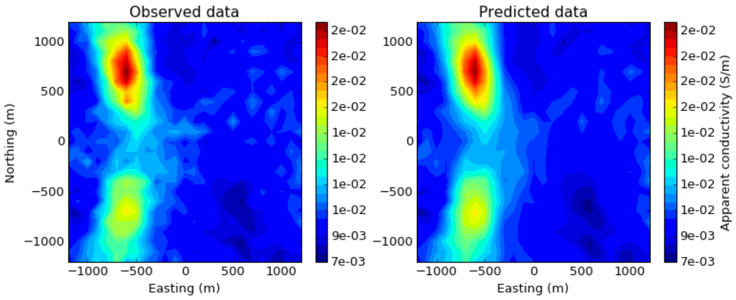
True



Recovered



Apparent conductivity



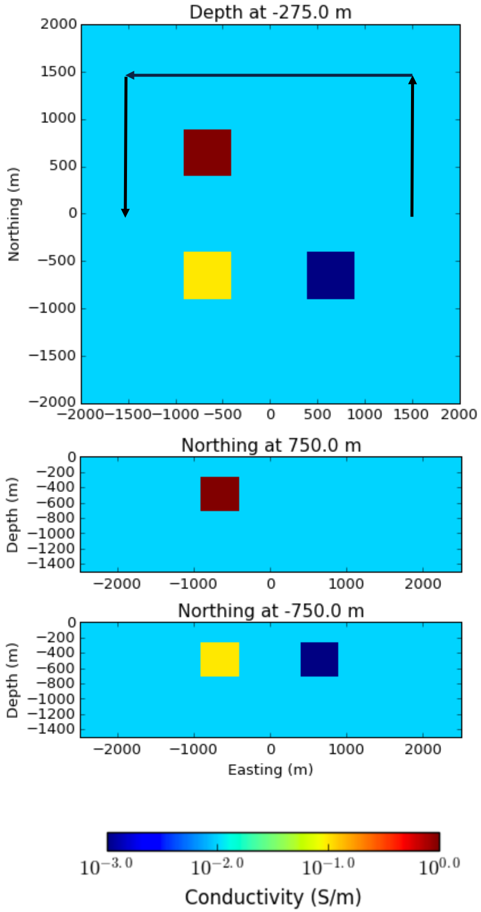
- Depth weighting
  - Compensate for high sensitivity near surface (similar to mag.)

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

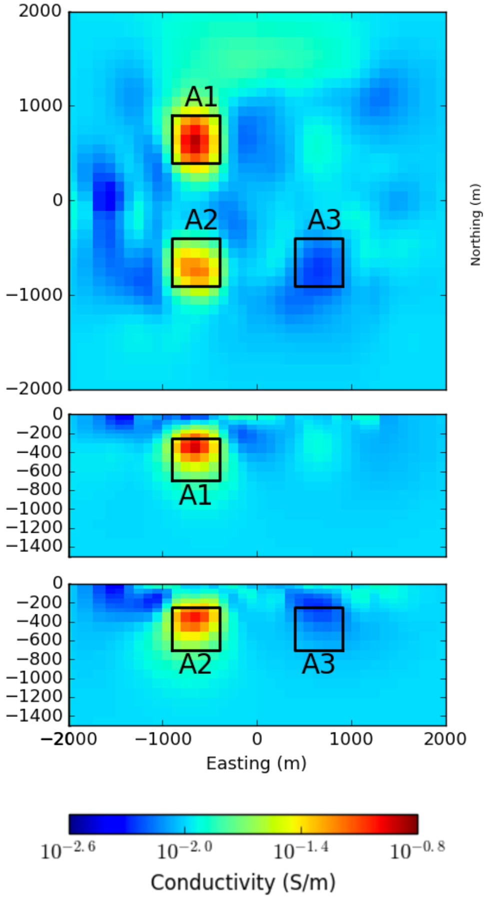
EM inversion

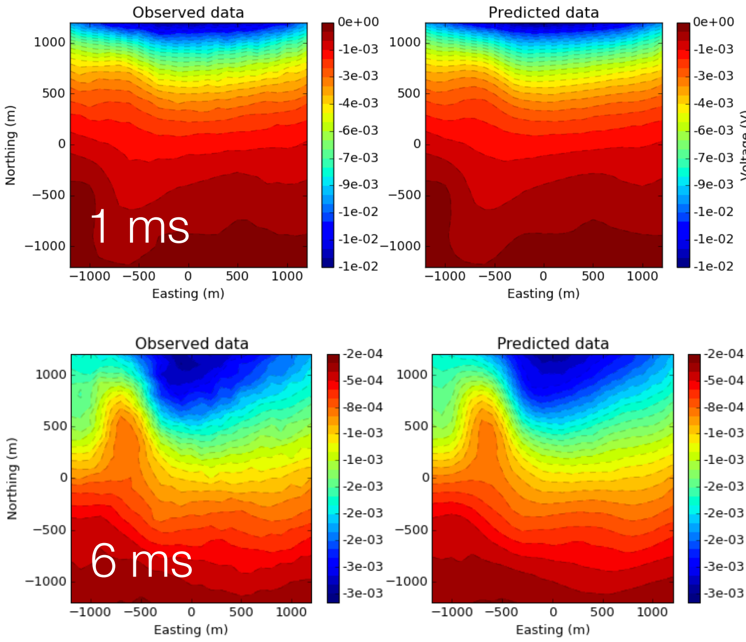
- Recovered 3D conductivity

True

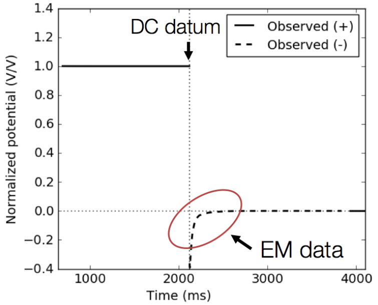


Recovered



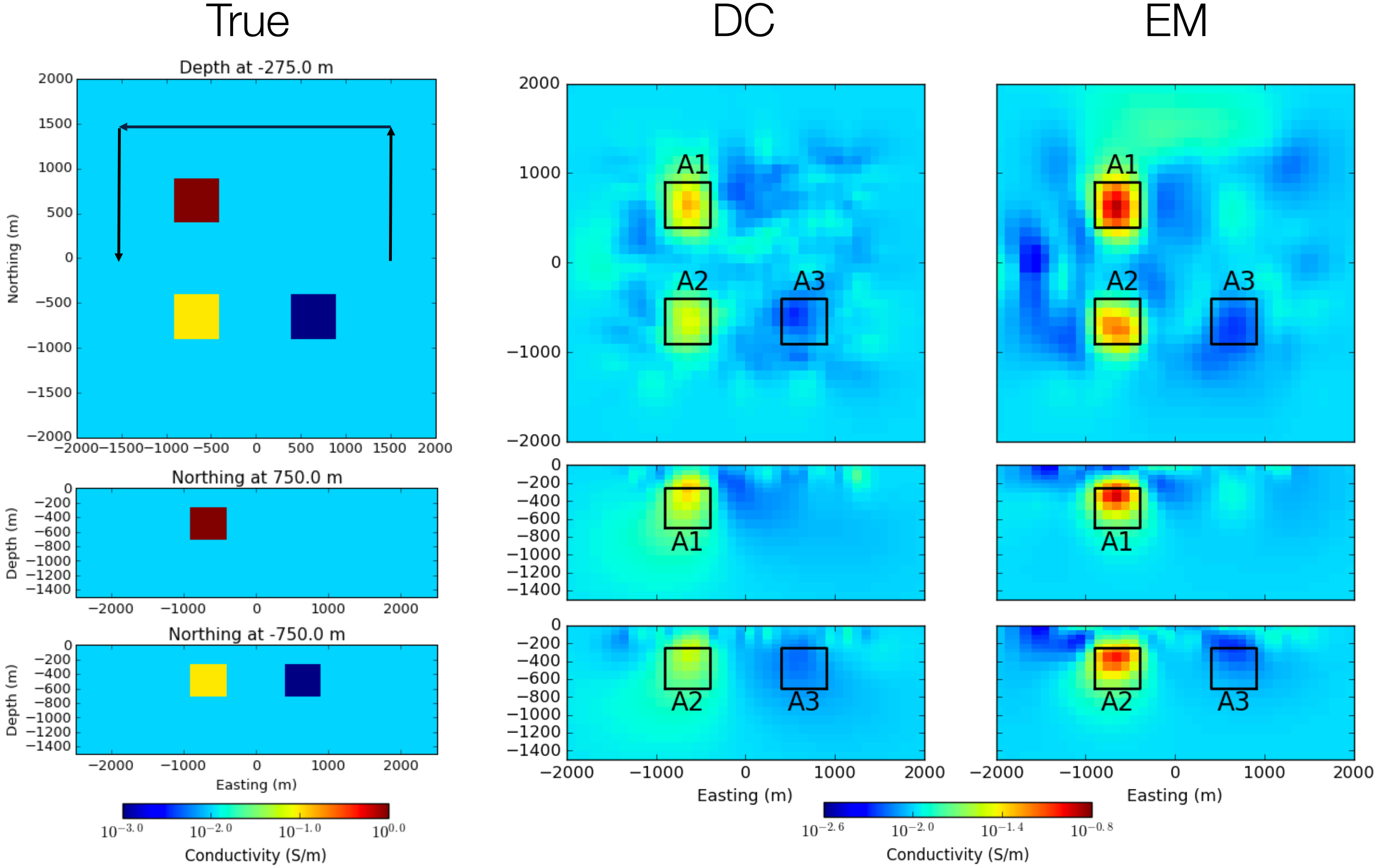


- No depth weighting



Conductivity models

- True, DC, and EM conductivities



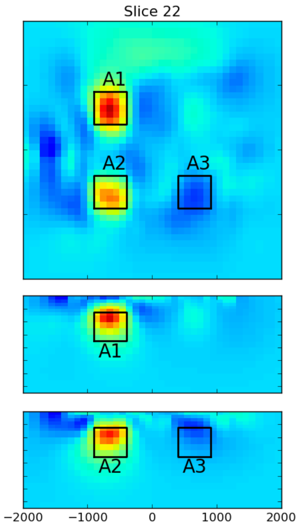
EM data contain signal

EM decoupling

- Off-time at 80 ms

IP = Observation – EM

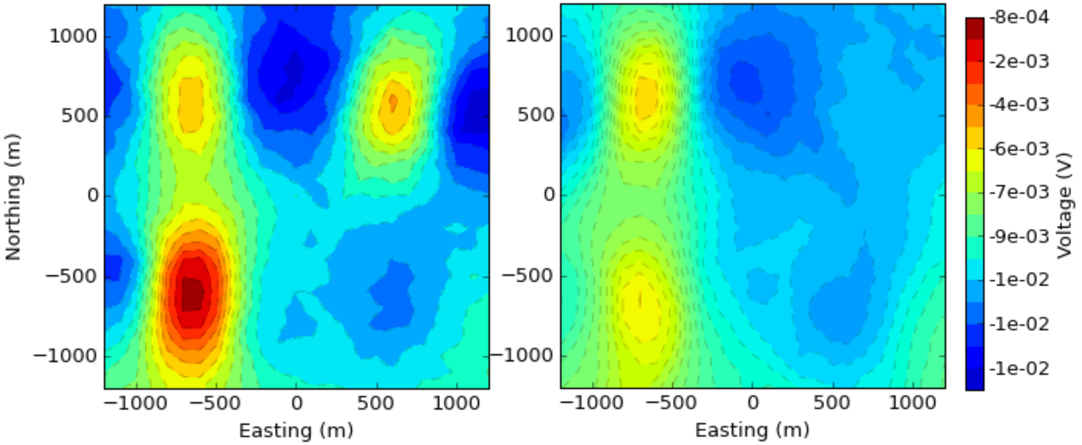
EM conductivity



TDEM simulation

Observation

Predicted EM

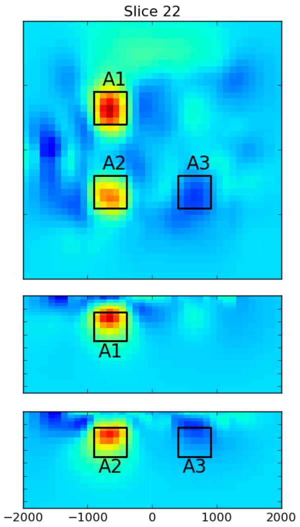


EM decoupling

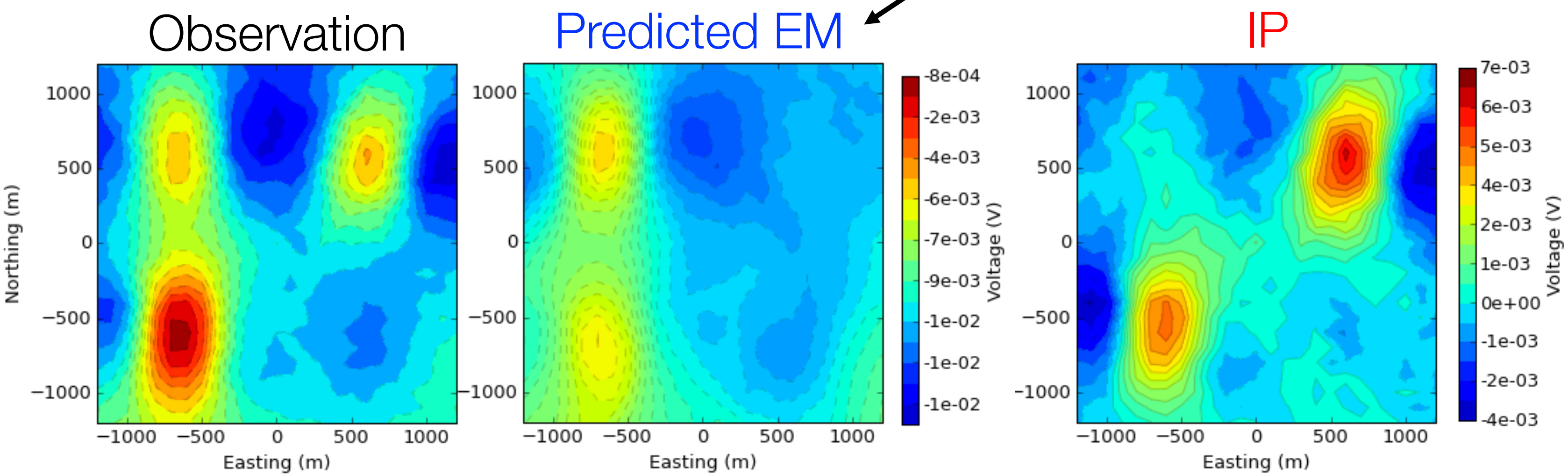
- Off-time at 80 ms

IP = Observation – EM

EM conductivity



TDEM simulation

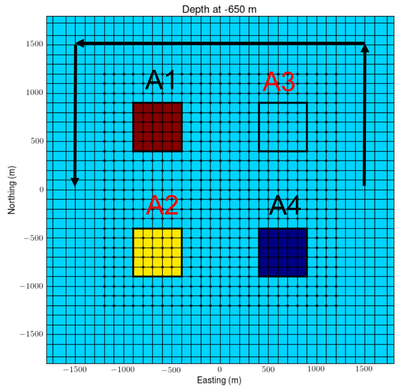


Observation

Predicted EM

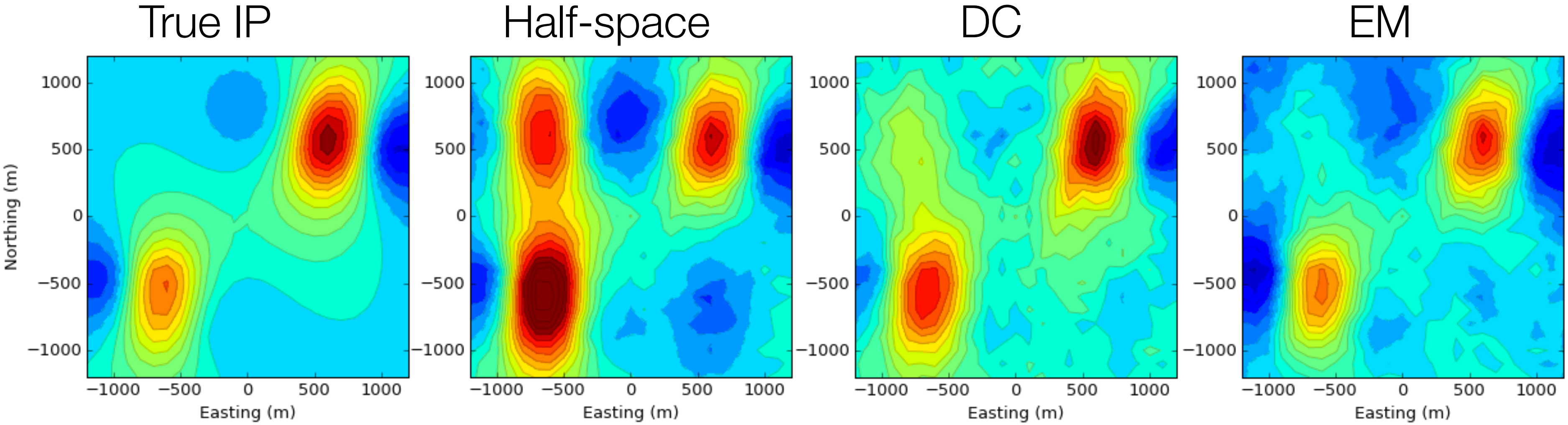
IP

EM decoupling



IP = Observation – EM

IP data at 80 ms


True IP

Half-space

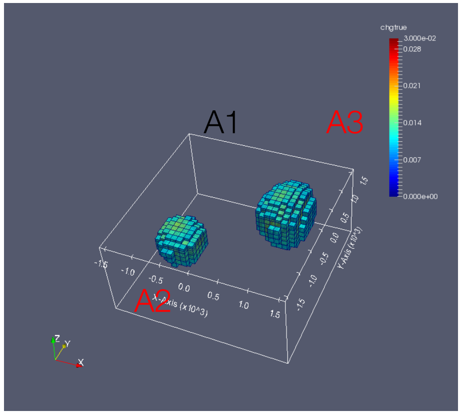
DC

EM

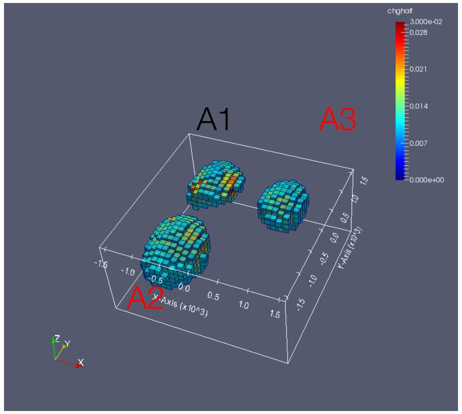
IP inversion

Chargeability > 0.015

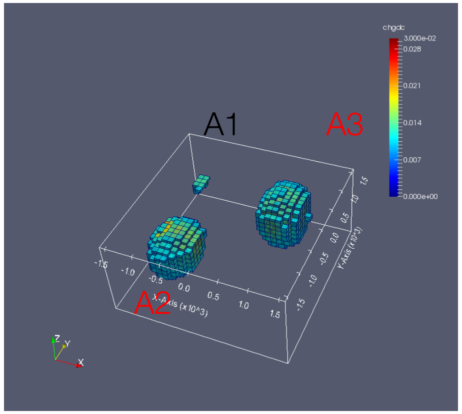
True IP



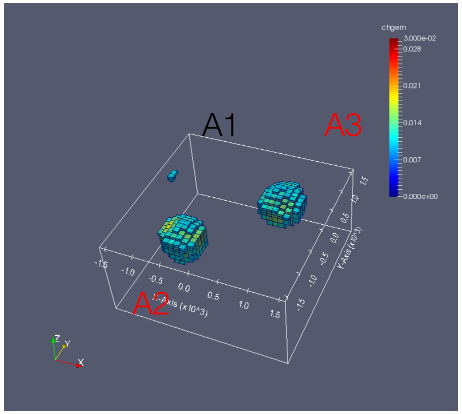
Half-space



DC



EM

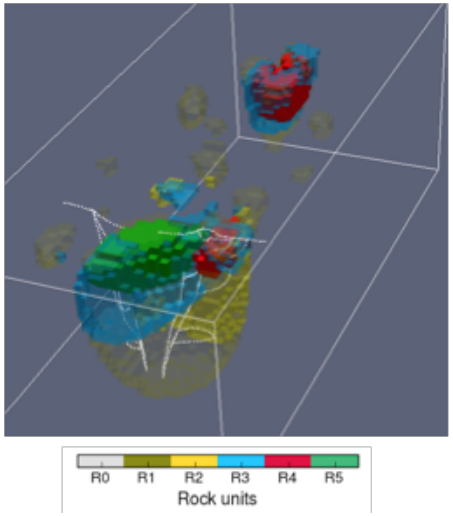


Case History:

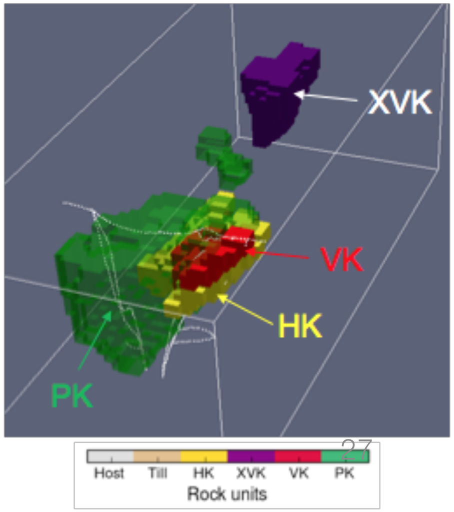
Inversion of airborne geophysical data over the Tli Kwi Cho kimberlite complex

Devriese et al, 2017; Fournier et al, 2017; Kang et al, 2017

Rock Model from Geophysics

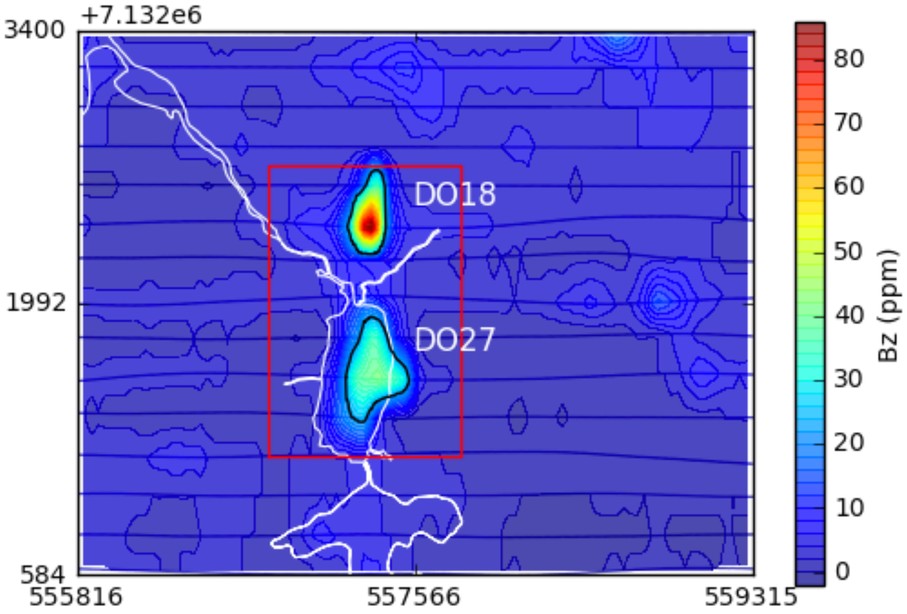


Rock Model from Drilling

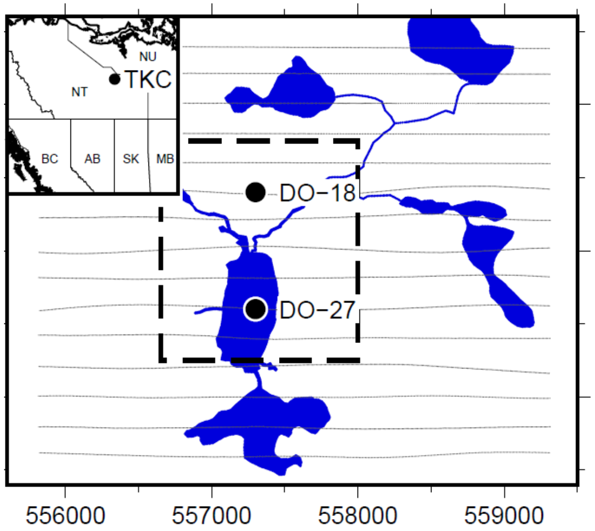


Discovery of Tli Kwi Cho (TKC)

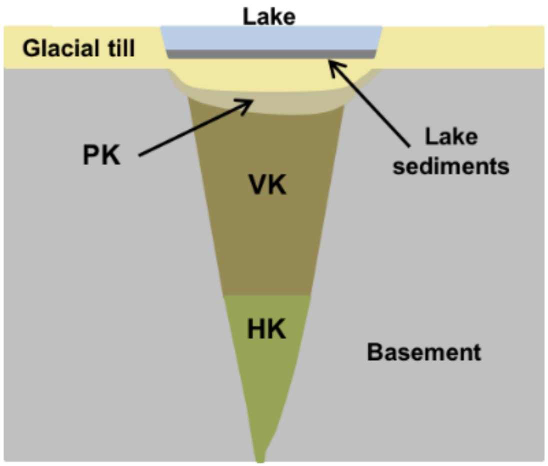
DIGHEM Q7200Hz



Location of TKC, NWT



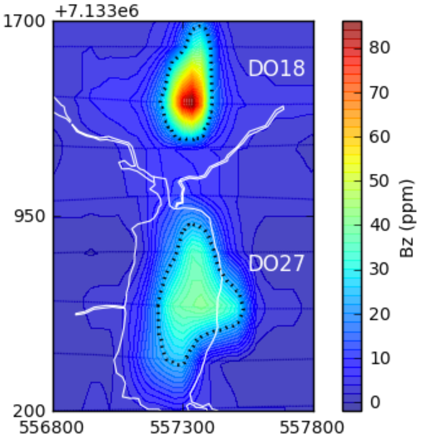
Kimberlite pipe structure

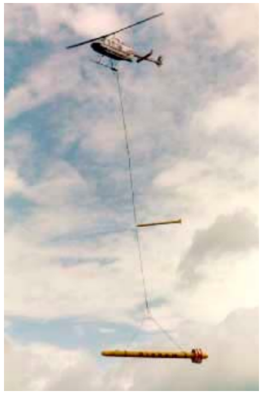


Devriese et al. (2016)

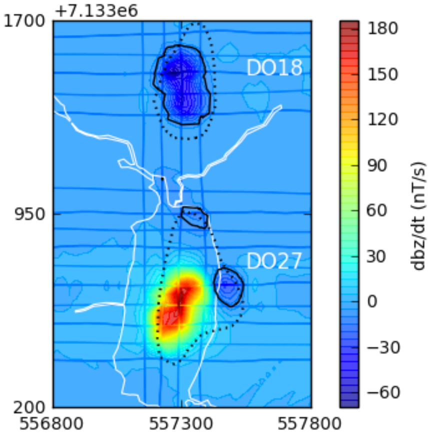
Time domain EM data

DIGHEM
(1992)

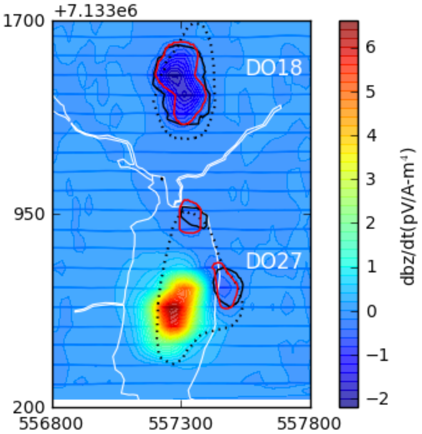


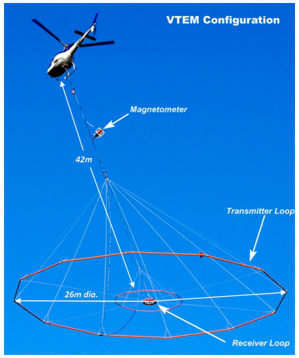


AeroTEMII
(2003)

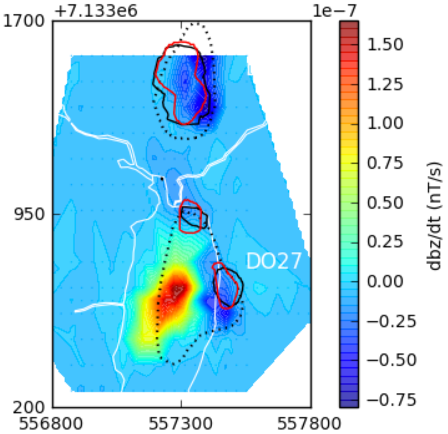


VTEM
(2004)

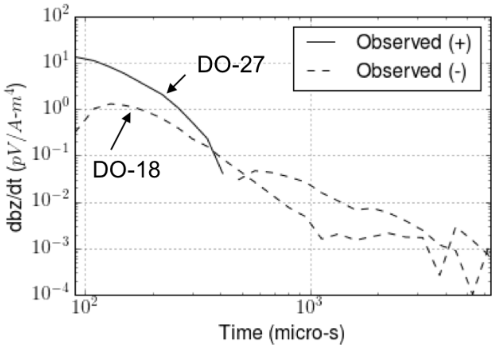




NanoTEM
(1993)

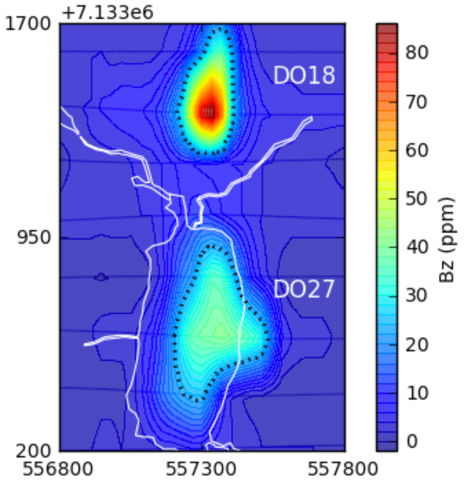


Decay curve



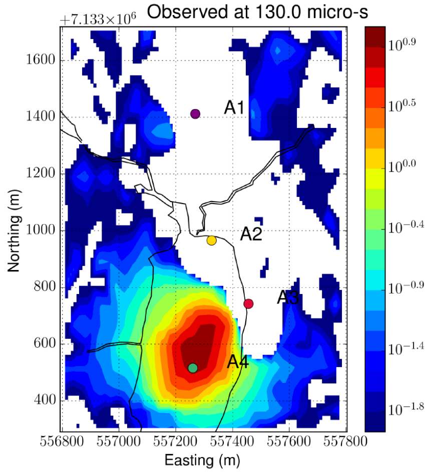
Step 1: Conductivity inversion

DIGHEM



Positive VTEM

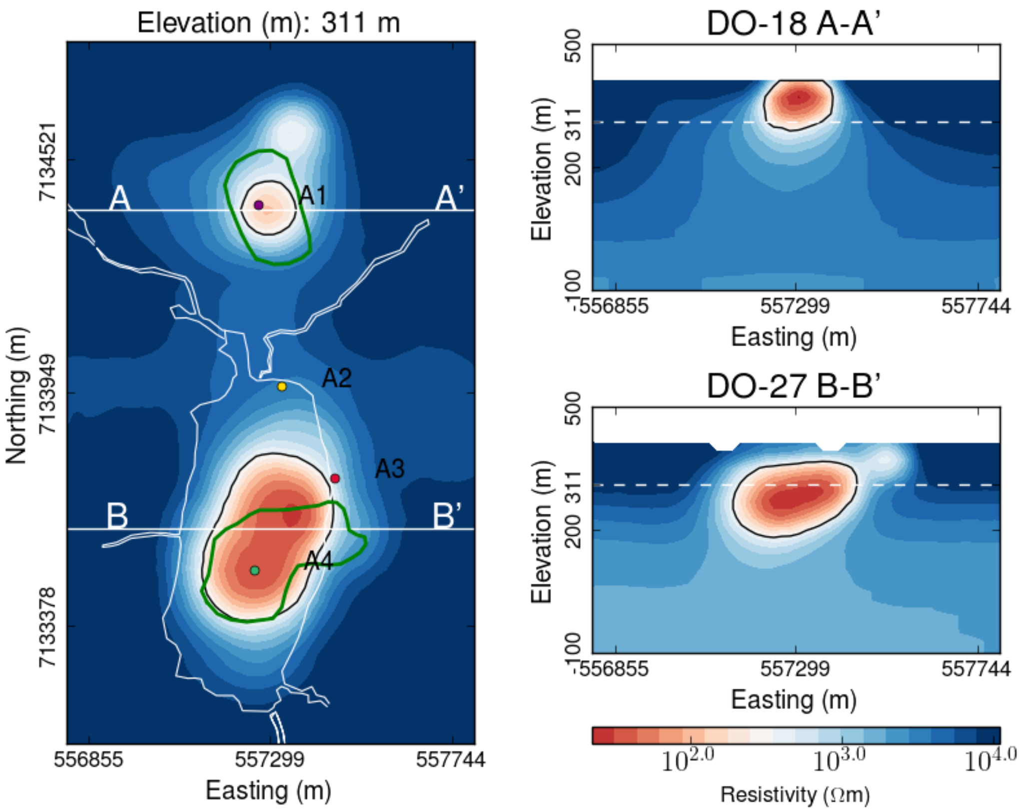
(EM-dominant)



→

Cooperative Inversion

Recovered 3D conductivity



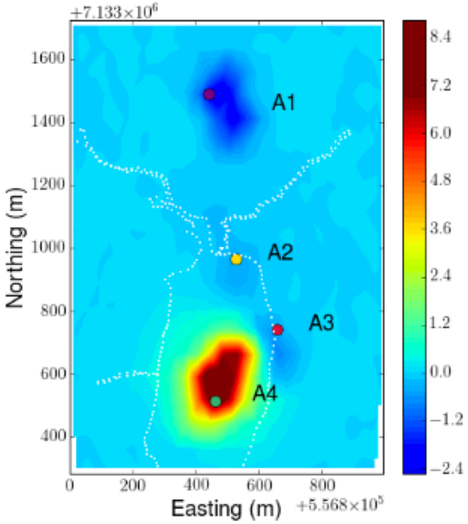
— Outline of two pipes

Step 2: EM-decoupling

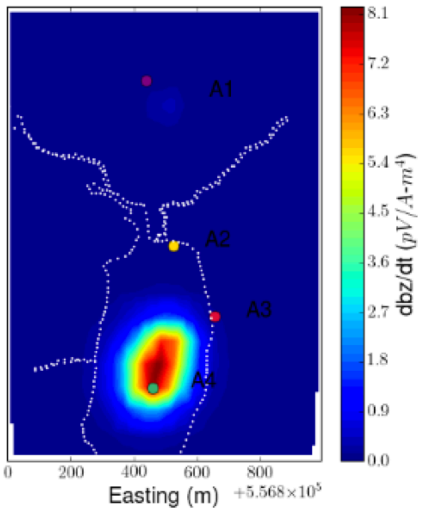
IP = Observation - EM

130 micro-s

Observed



Predicted EM

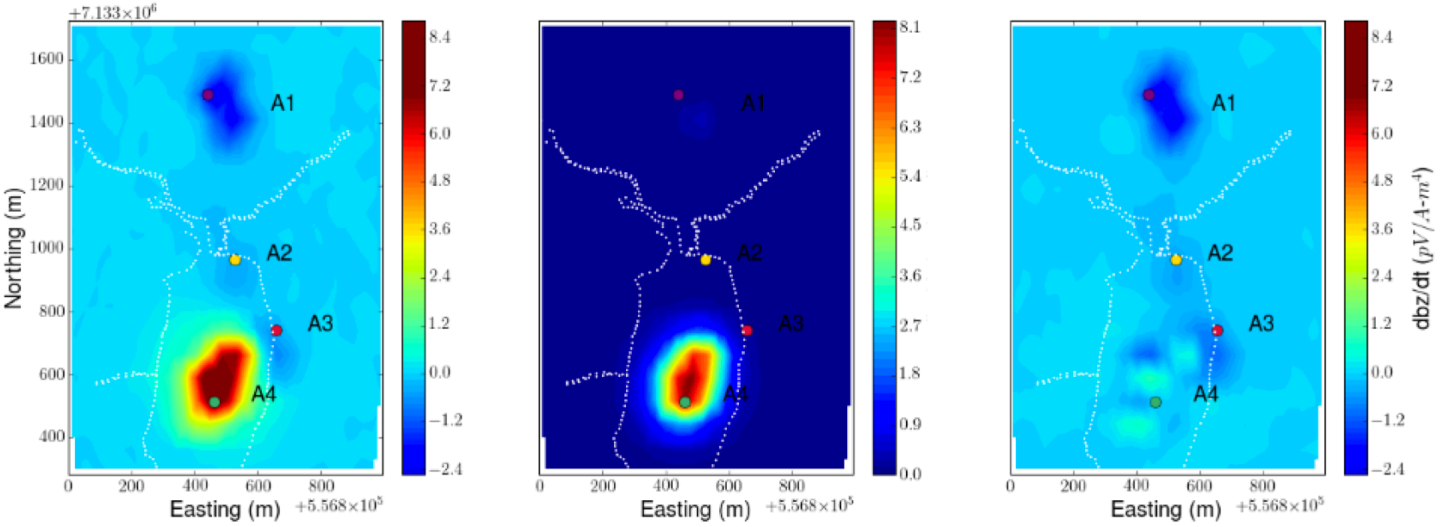


Step 2: EM-decoupling

IP = Observation - EM

130 micro-s

Observed Predicted EM IP

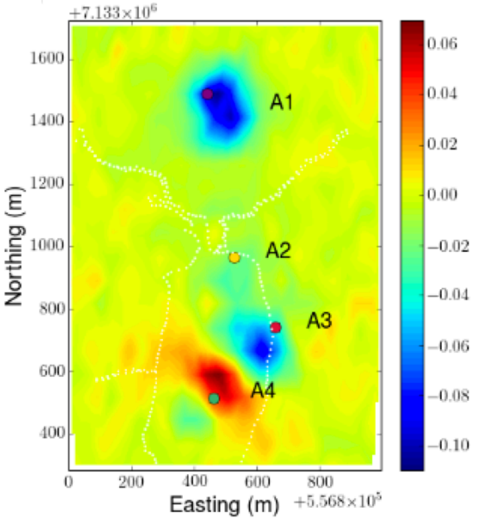


Step 2: EM-decoupling

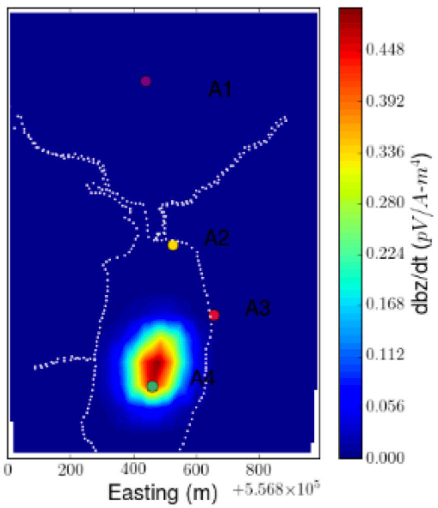
IP = Observation - EM

410 micro-s

Observed



Predicted EM



Step 2: EM-decoupling

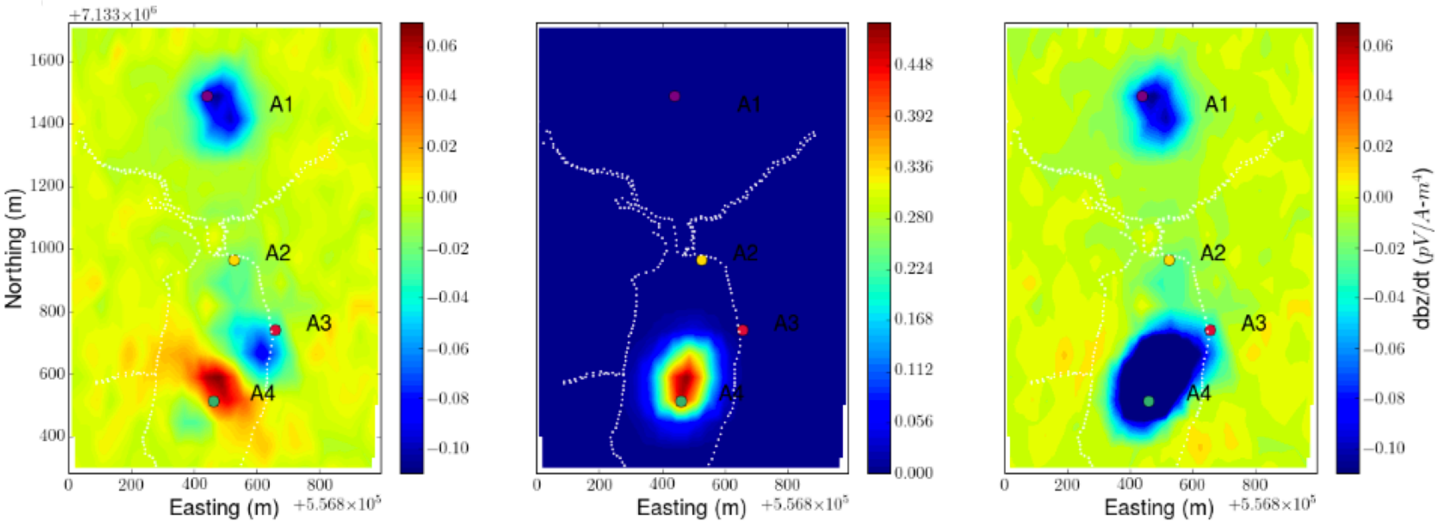
IP = Observation - EM

410 micro-s

Observed

Predicted EM

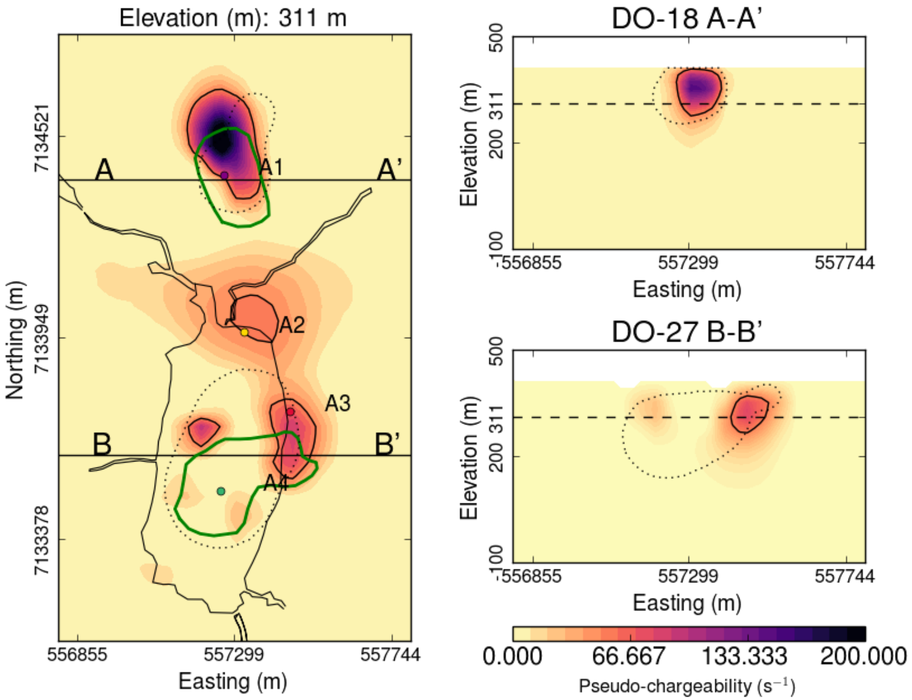
IP



Step 3: 3D IP inversion

Recovered 3D pseudo-chargeability

130 micro-s



— Outline of two pipes

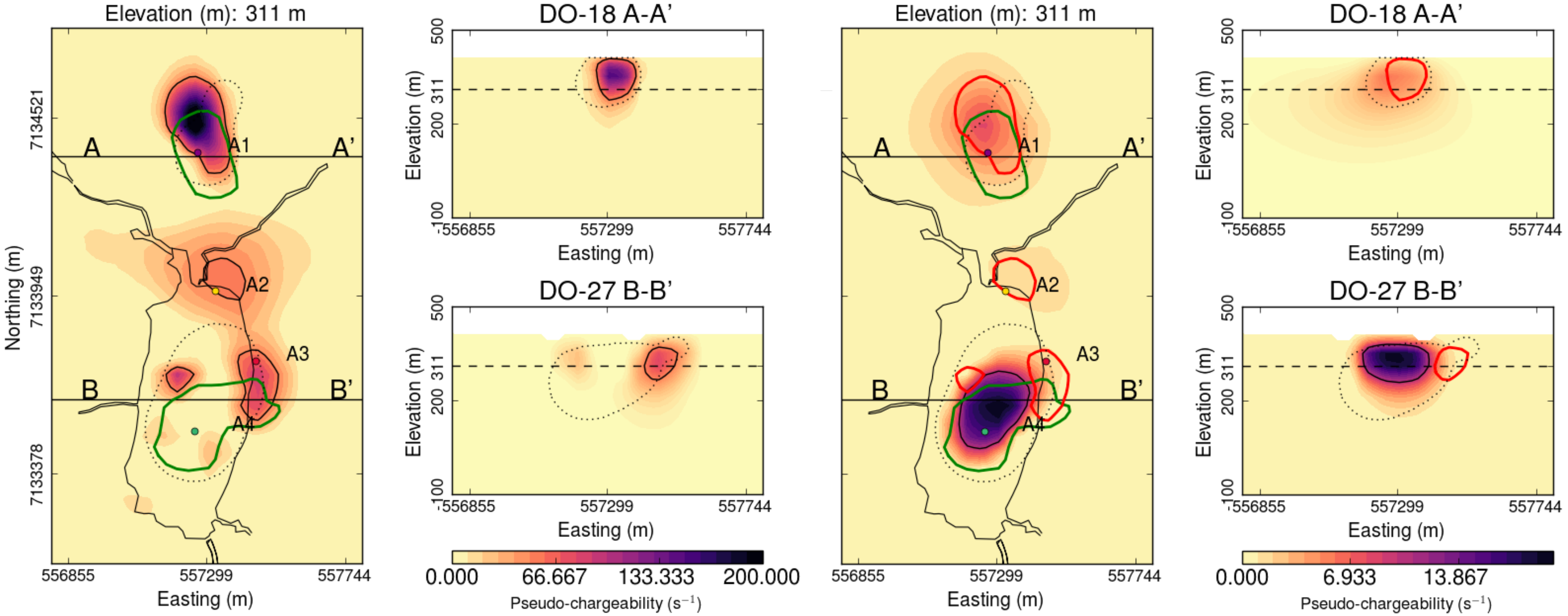
⋯ Conductivity contour

Step 3: 3D IP inversion

Recovered 3D pseudo-chargeability

130 micro-s

410 micro-s

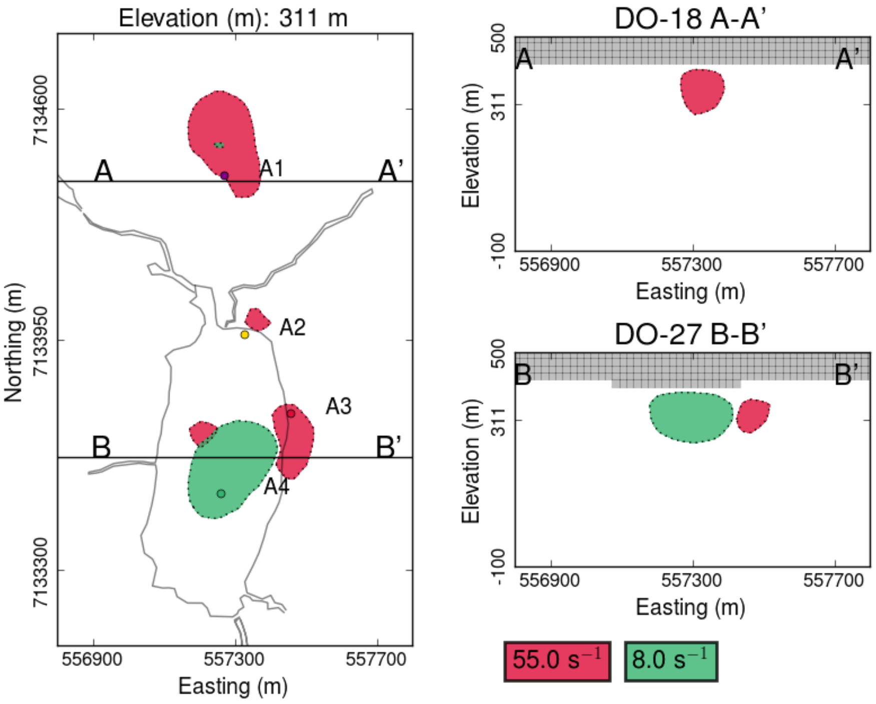


▬ Outline of two pipes

⋯ Conductivity contour

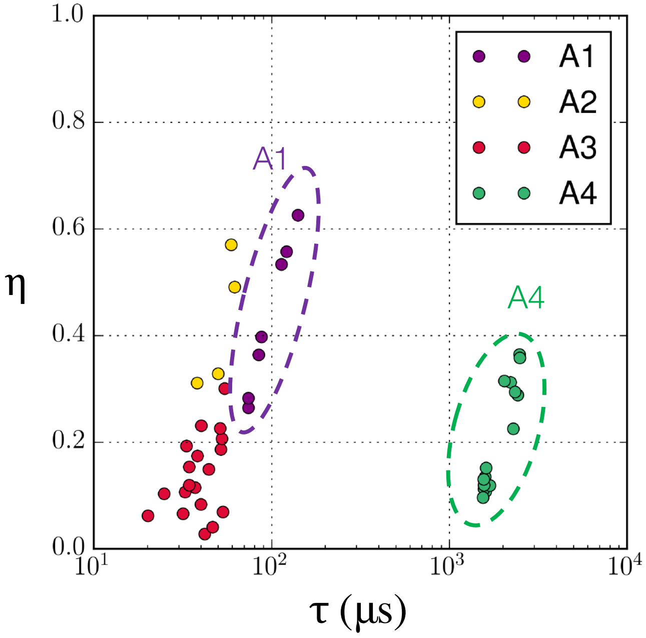
Step 4: Estimate η and τ

Anomaly contours



Cole-Cole model

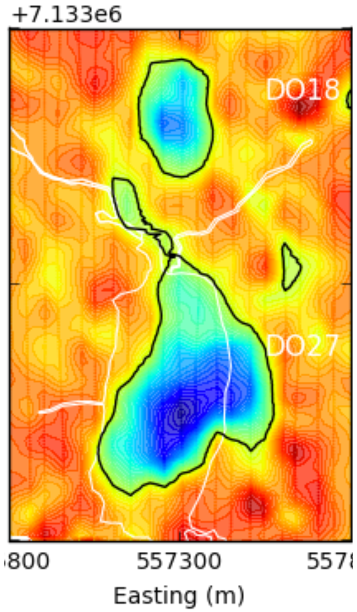
$$\sigma(\omega) = \sigma_\infty + \sigma_\infty \frac{\eta}{1+(1-\eta)(\imath\omega\tau)^c}$$



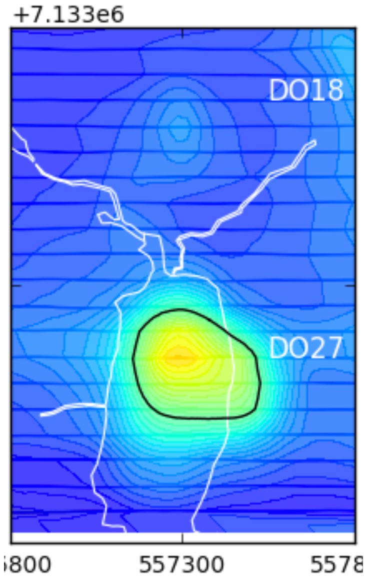
- A1-A3 has small time constant
- A4 has greater time constant

Data Integration

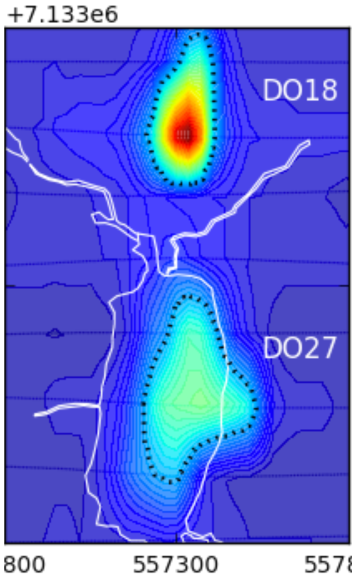
Gravity



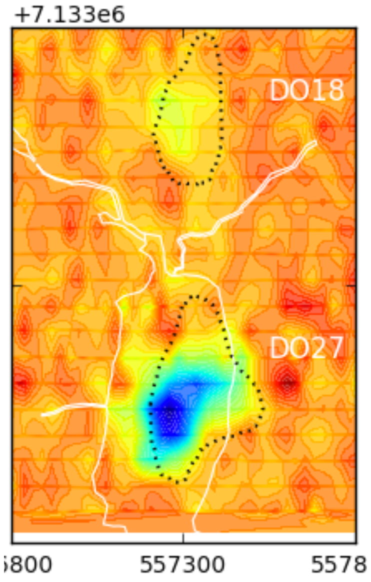
Magnetics



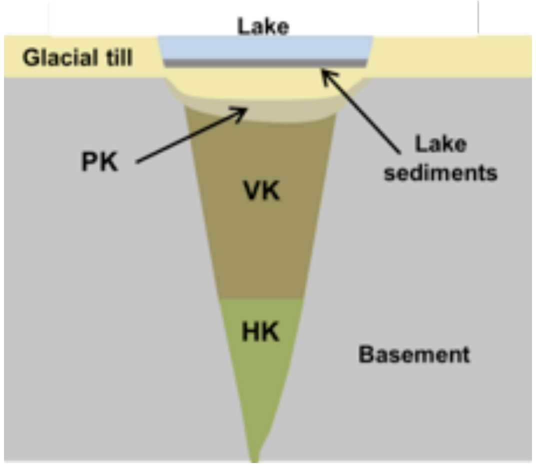
DIGHEM

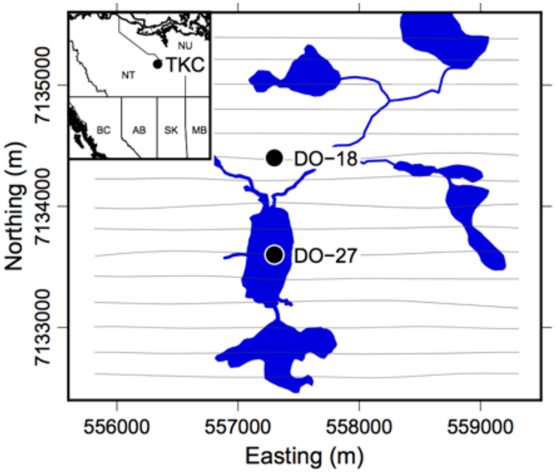


VTEM



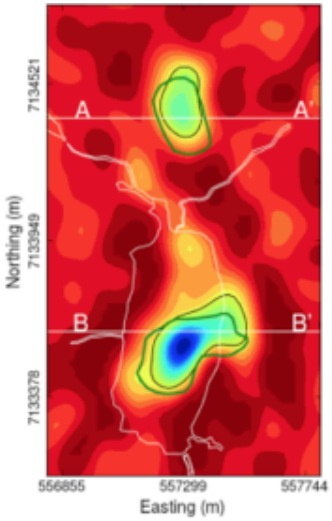
Kimberlite Model



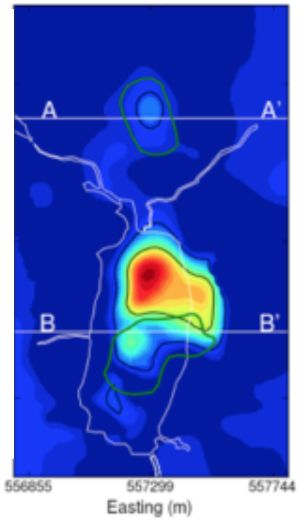


Data Integration: 5 physical property models

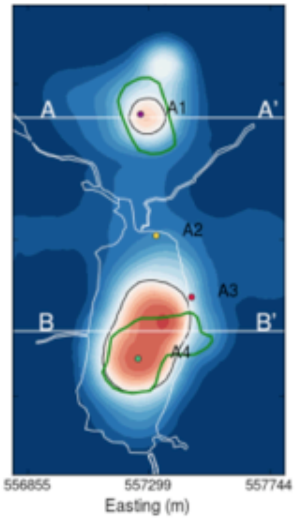
Density



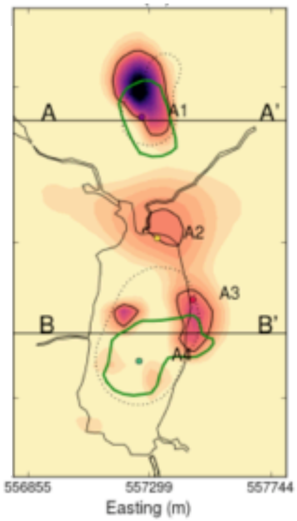
Susceptibility



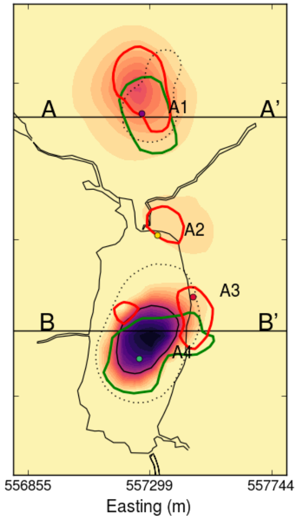
Conductivity



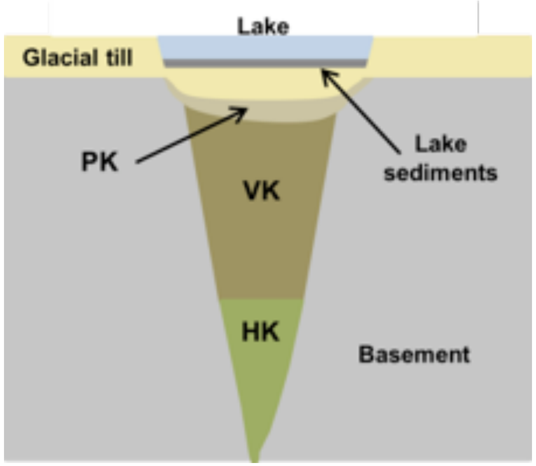
Early chargeability



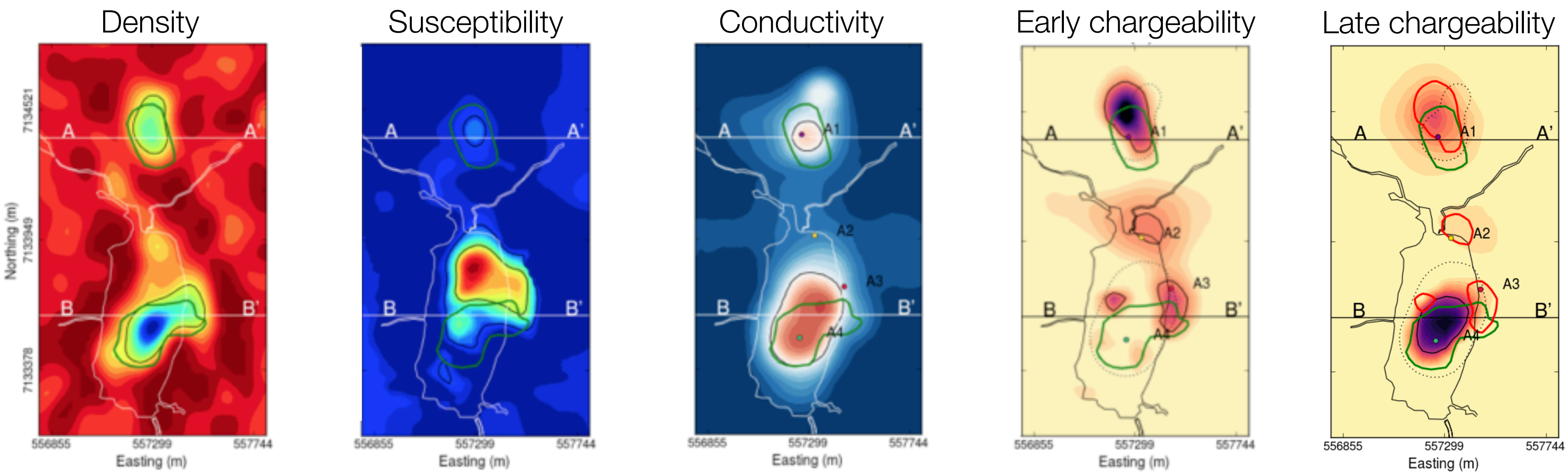
Late chargeability



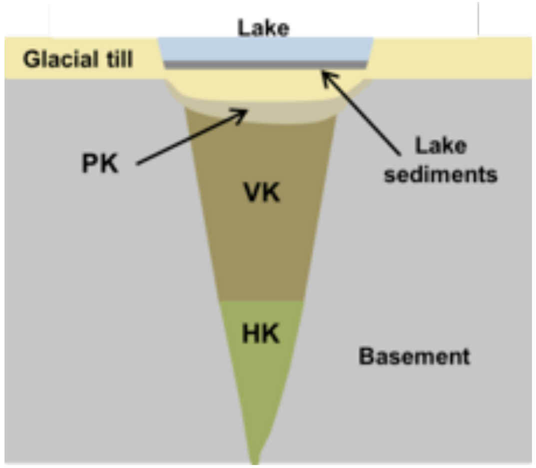
Kimberlite Model



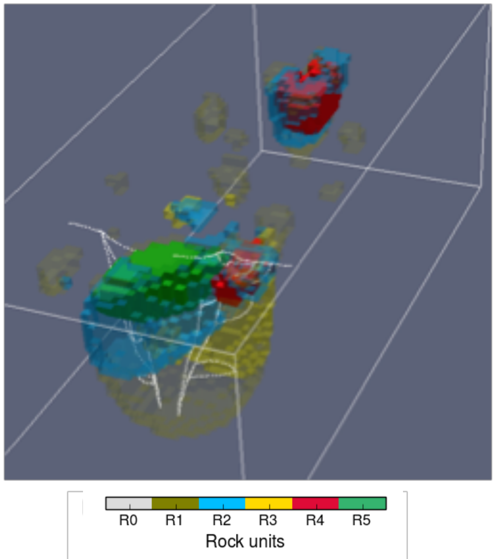
Data Integration: 5 physical property models



Kimberlite Model



Rock Model from Geophysics



Rock Model from Drilling