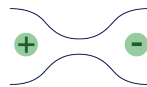
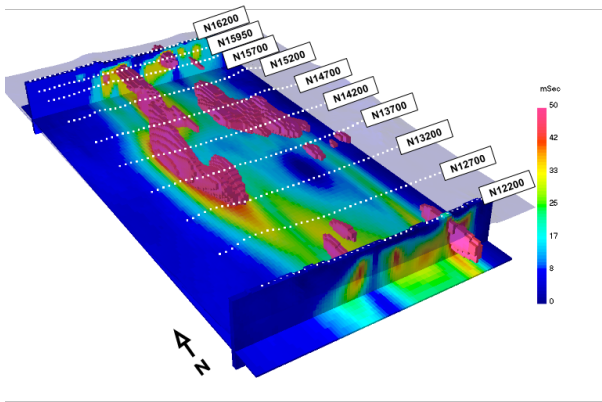


Induced Polarization

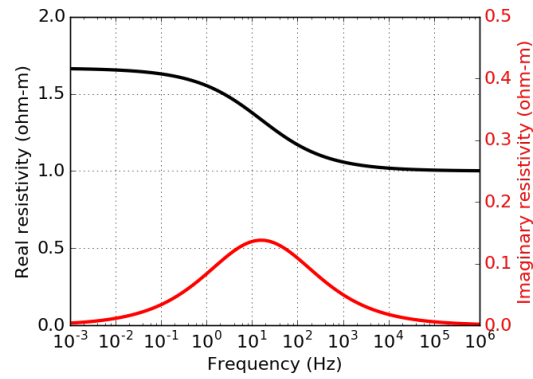


Motivation

Minerals



Complex resistivity



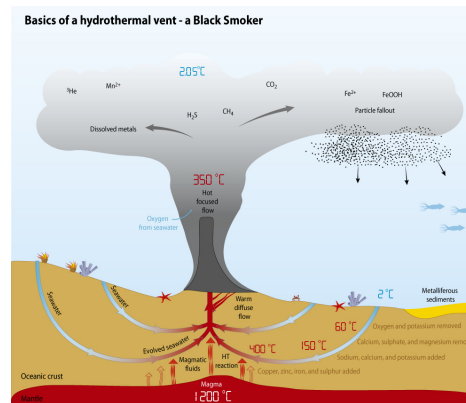
Permafrost



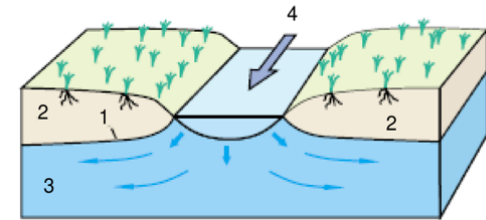
Geotechnical



Seafloor massive sulfide



Groundwater

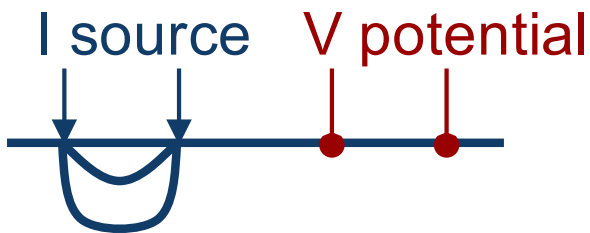


Outline

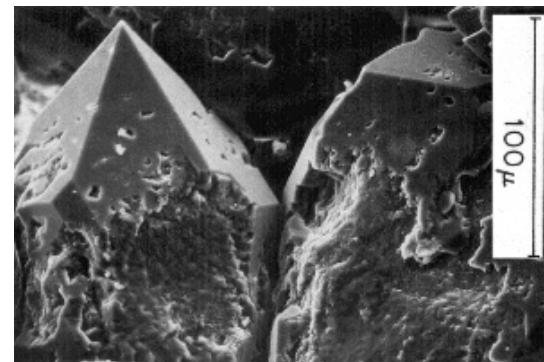
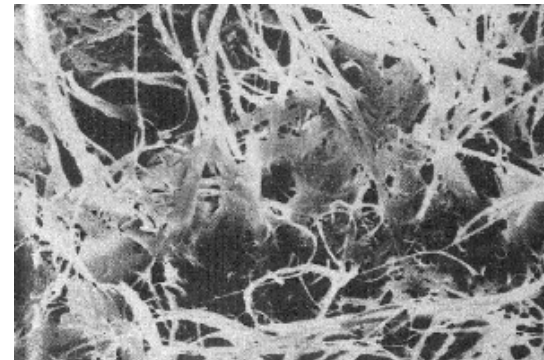
- Sources of IP
- Conceptual model of IP
- Chargeability
- IP data
- Pseudosections
- Two stage DC-IP inversion
- Case history: Mt. Isa
- Example: Landfills

Induced Polarization

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



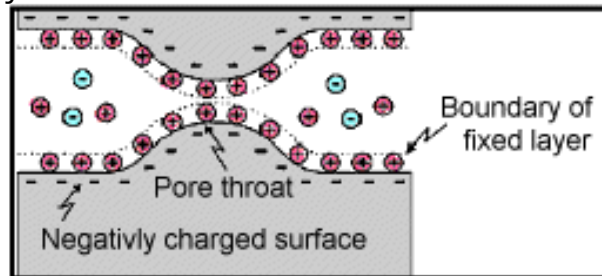
	Not chargeable	Chargeable
Source (Amps)		
Potential (Volts)		



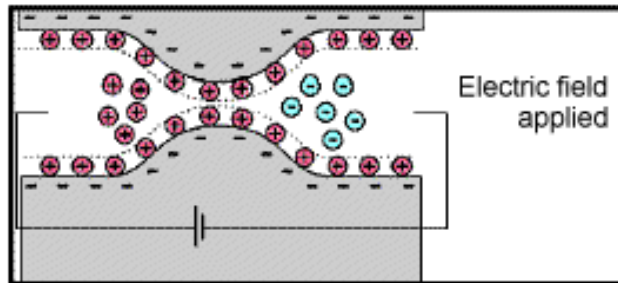
Conceptual Model of IP

Membrane polarization

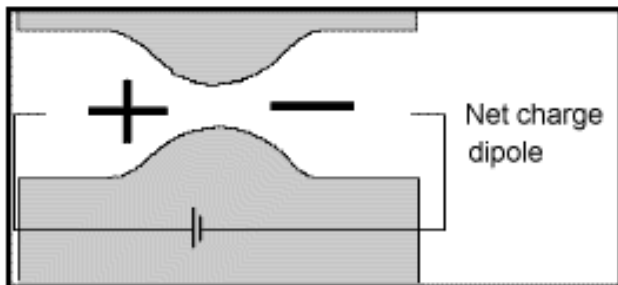
Initially - neutral



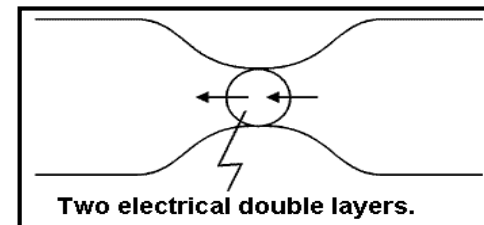
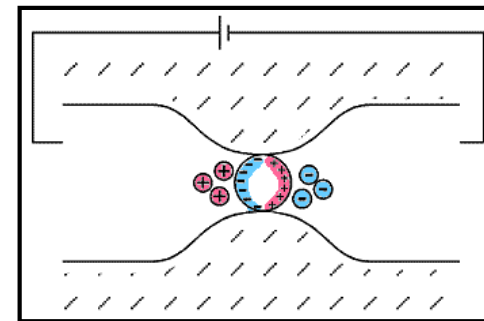
Apply electric field, build up charges



Charge polarization, Electric dipole

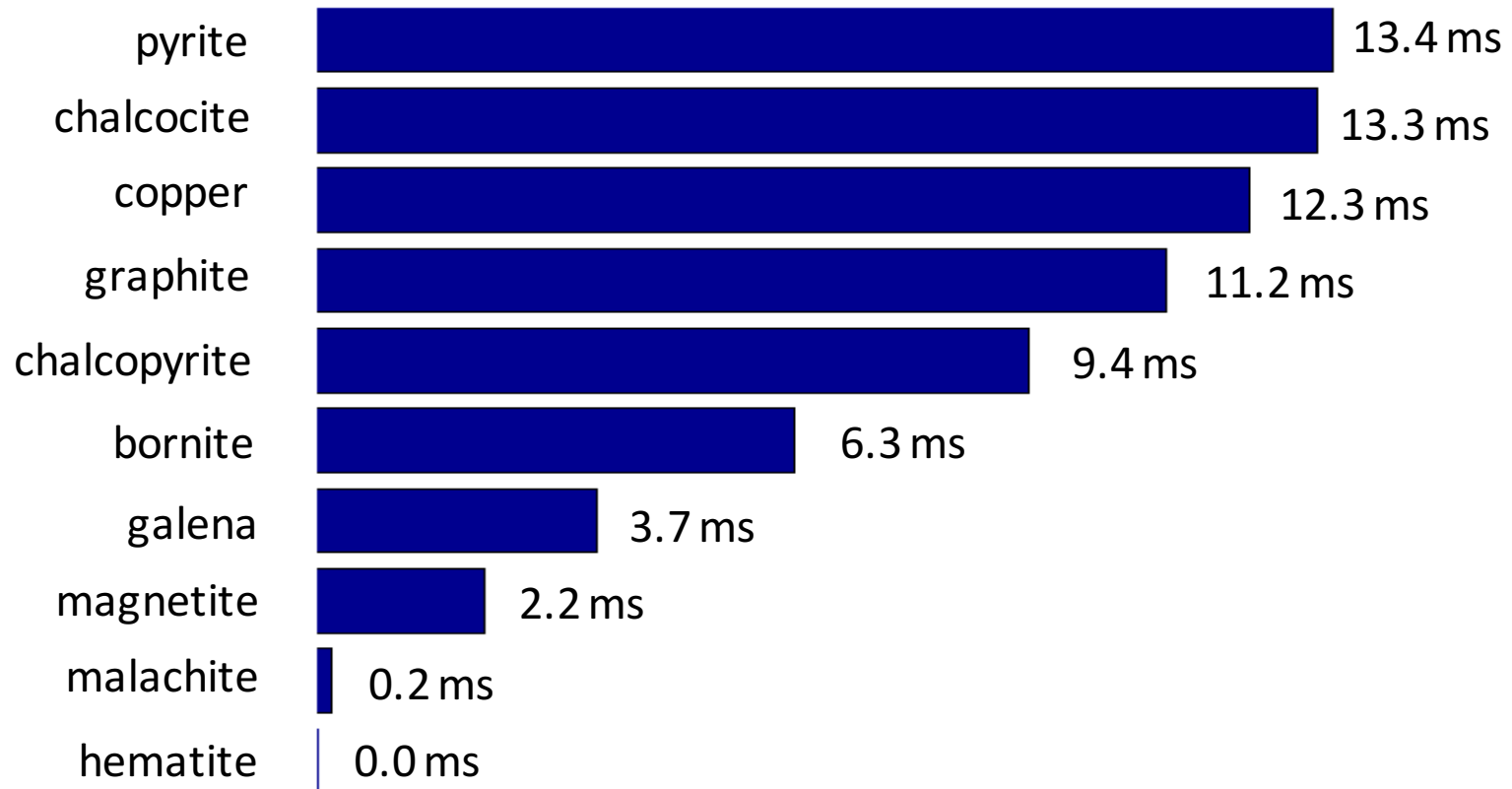


Electrode polarization



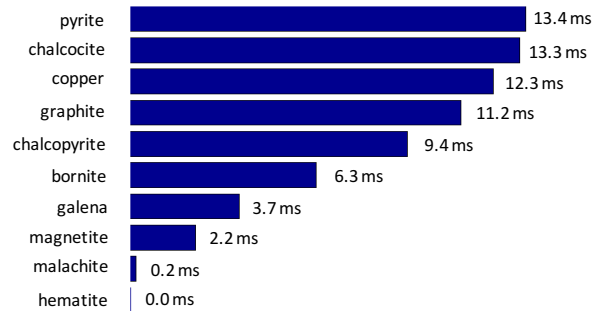
Chargeability

Minerals at 1% Concentration in Samples



Chargeability

Minerals at 1% Concentration in Samples

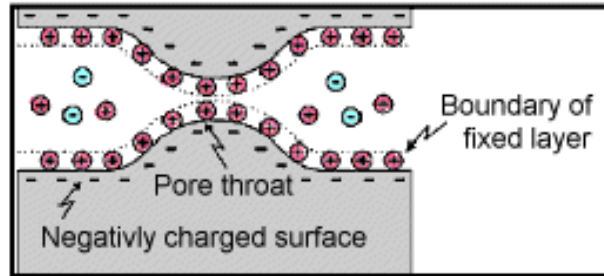


Material type	Chargeability (msec.)
20% sulfides	2000 - 3000
8-20% sulfides	1000 - 2000
2-8% sulfides	500 - 1000
volcanic tuffs	300 - 800
sandstone, siltstone	100 - 500
dense volcanic rocks	100 - 500
shale	50 - 100
granite, granodiorite	10 - 50
limestone, dolomite	10 - 20

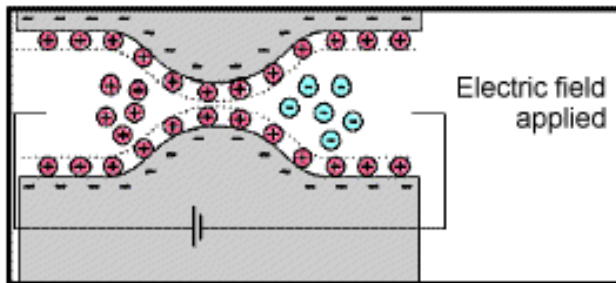
Material type	Chargeability (msec.)
ground water	0
alluvium	1 - 4
gravels	3 - 9
precambrian volcanics	8 - 20
precambrian gneisses	6 - 30
schists	5 - 20
sandstones	3 - 12

Chargeability

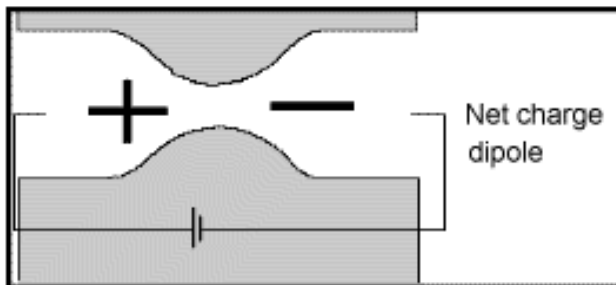
Initially - neutral



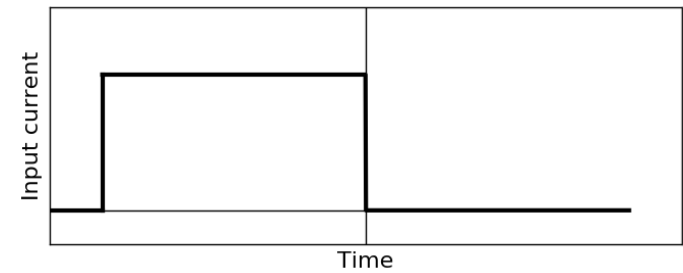
Apply electric field, build up charges



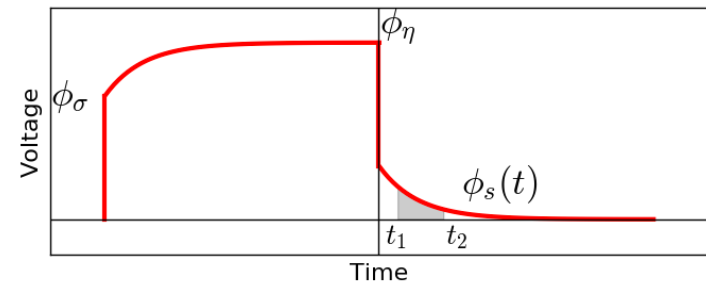
Charge polarization, Electric dipole



Input current



Measured voltage



IP data

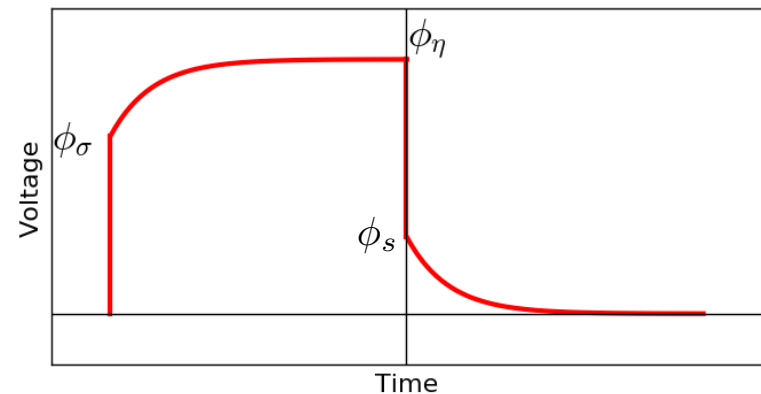
- Seigel (1959):
 - Introduced chargeability: η
 - Effect reduces conductivity

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

- Theoretical chargeability data

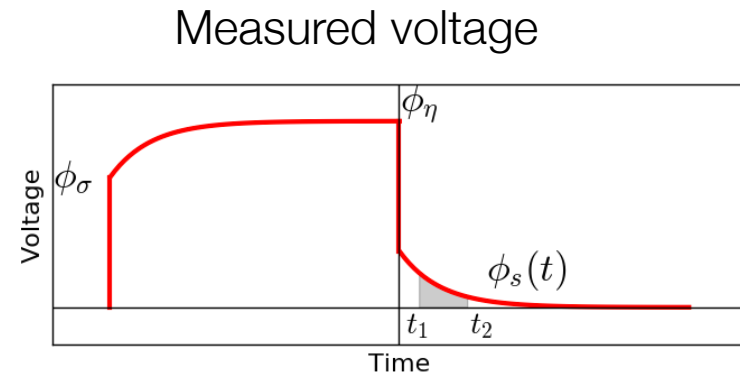
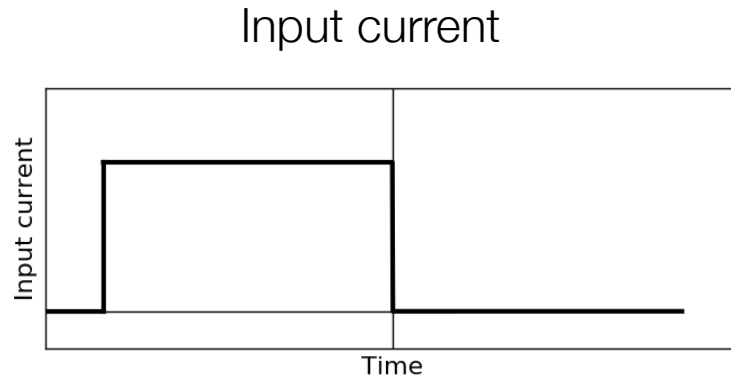
$$d^{IP} = \frac{\phi_s}{\phi_{\eta}} = \frac{\phi_{\eta} - \phi_{\sigma}}{\phi_{\eta}}$$

- Not directly measureable



IP data: time domain

- IP decay



- IP datum

Dimensionless:

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

Value at individual time channel:

$$\phi_s(t)$$

Area under decay curve:

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

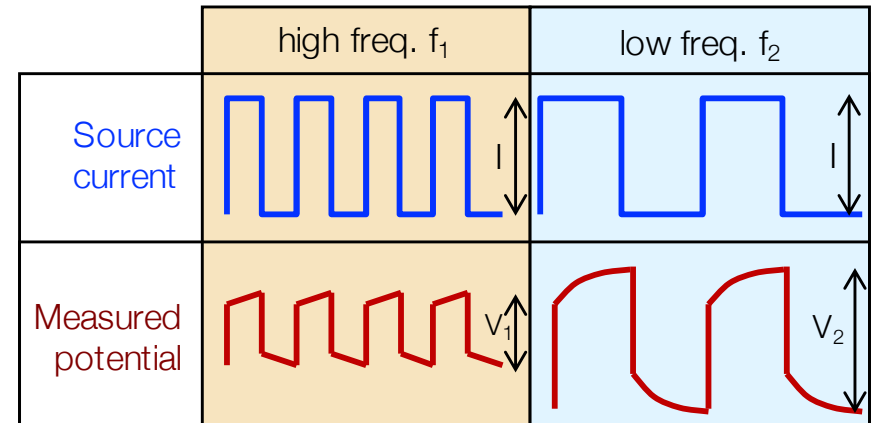
IP data: frequency domain

- Percent frequency effect:

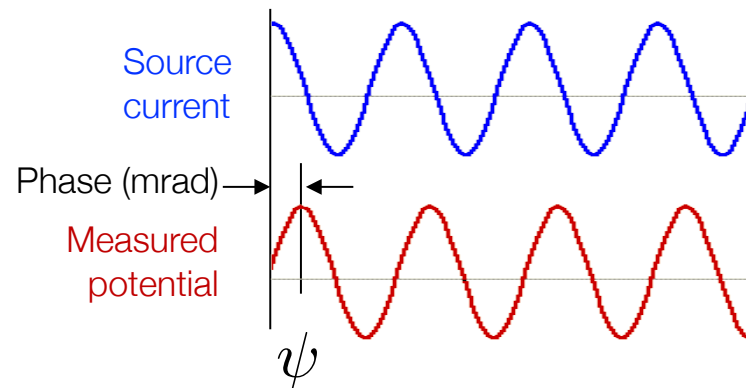
$$PFE = 100 \left(\frac{\rho_{a2} - \rho_{a1}}{\rho_{a1}} \right)$$

ρ_{a1} : apparent resistivity at f_1

ρ_{a2} : apparent resistivity at f_2



- Phase ψ



IP data

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

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

- An IP datum can be written as

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

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

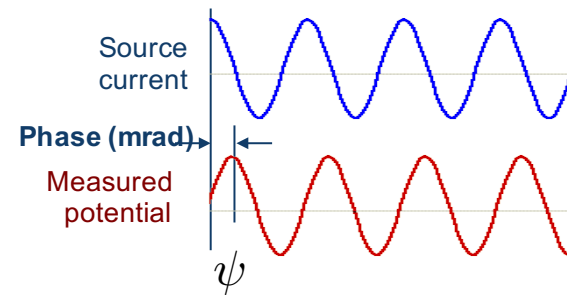
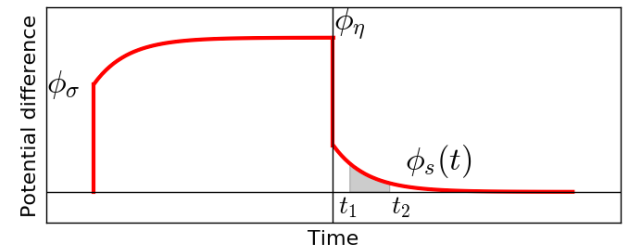
- In matrix form

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

\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

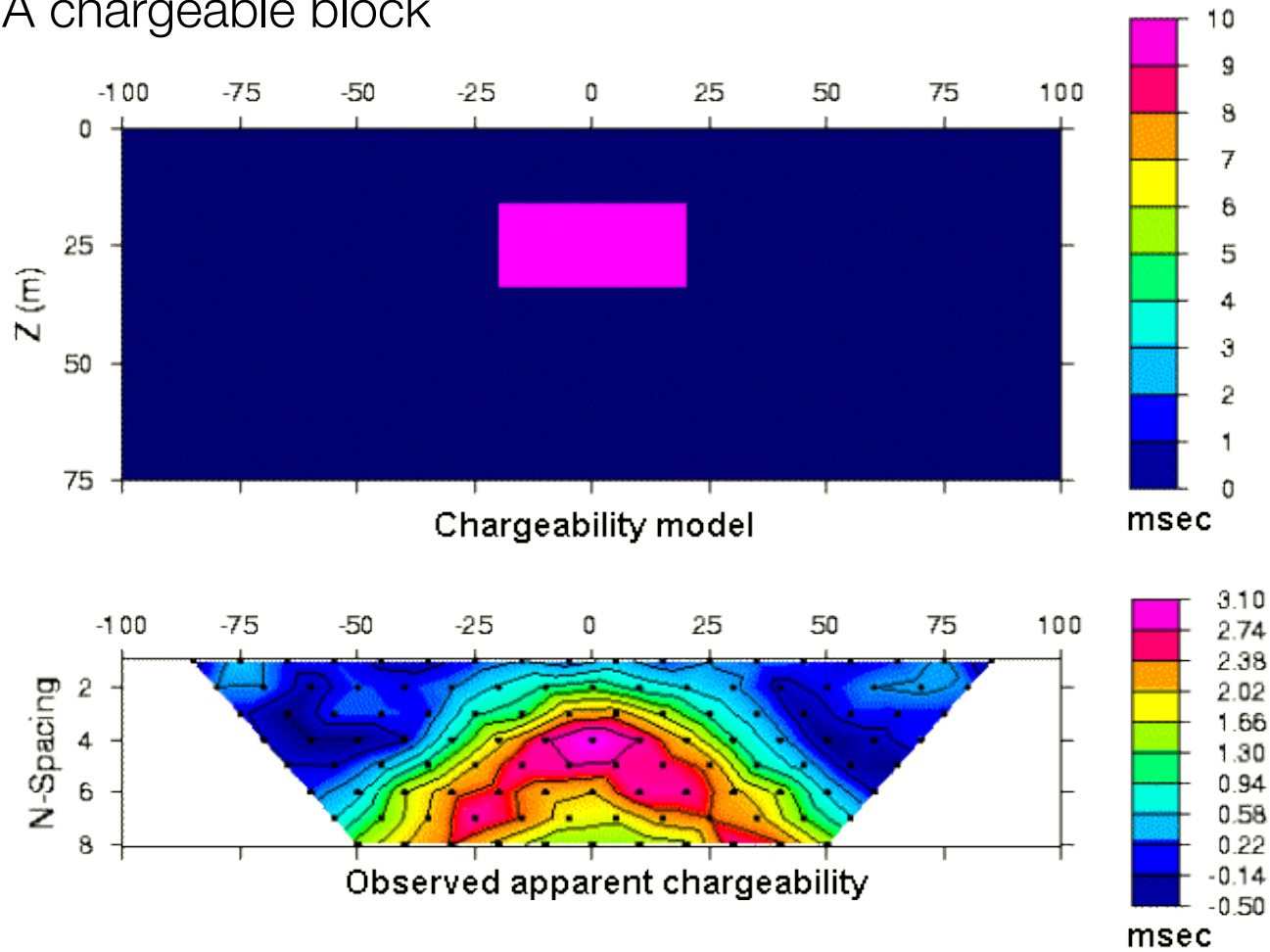


$$\mathbf{d}^{IP} = \mathbf{J}\boldsymbol{\eta}$$

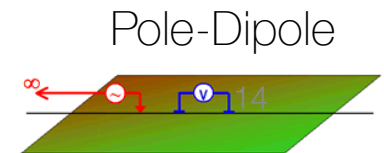
J is an N×M matrix

IP pseudosections

1) A chargeable block

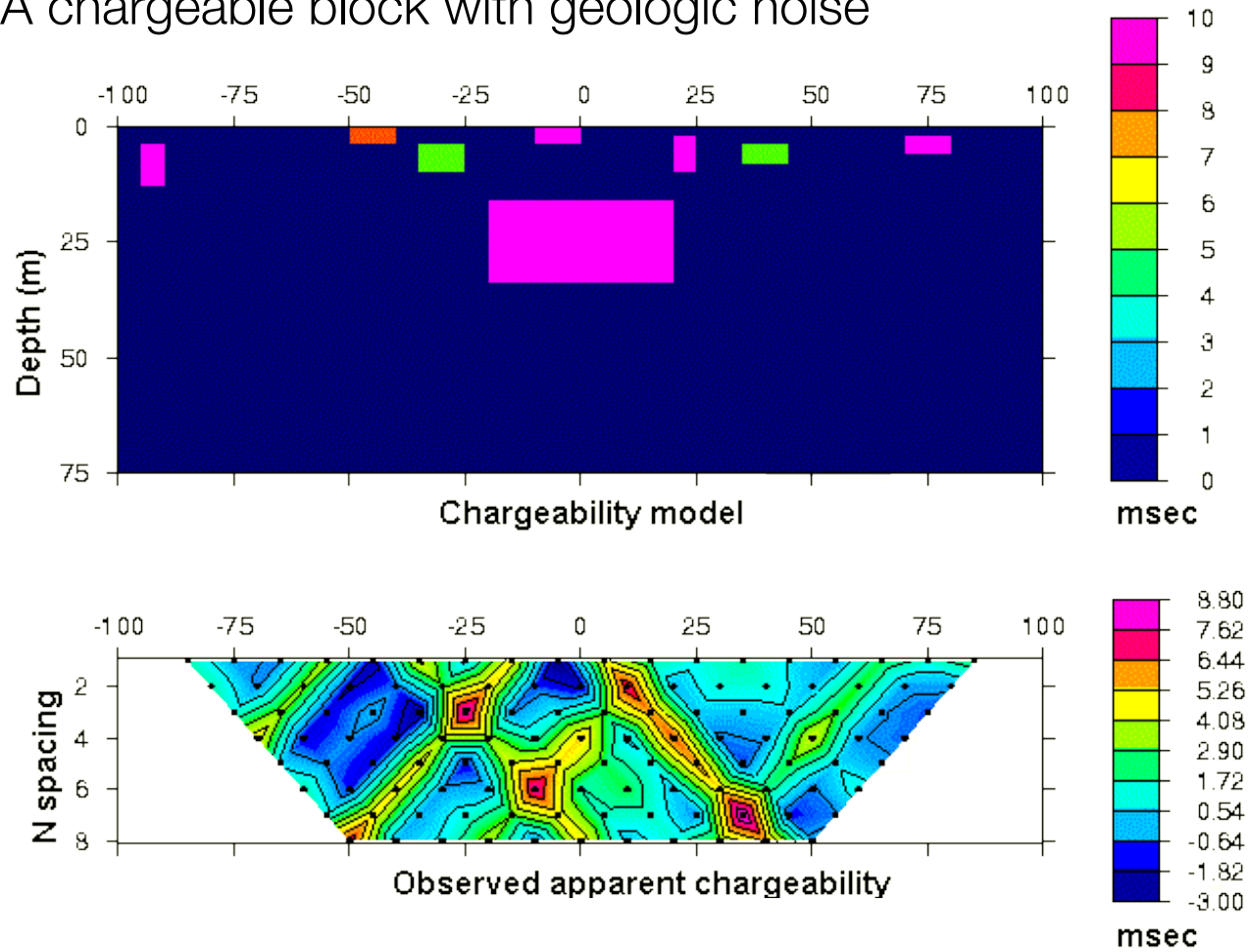


- Pole-dipole; $n=1,8$; $a=10\text{m}$; $N=316$

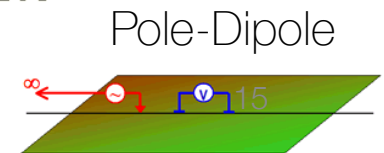


IP pseudosections

2) A chargeable block with geologic noise

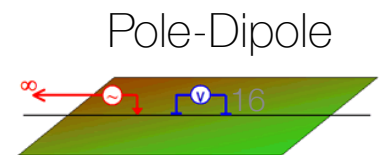
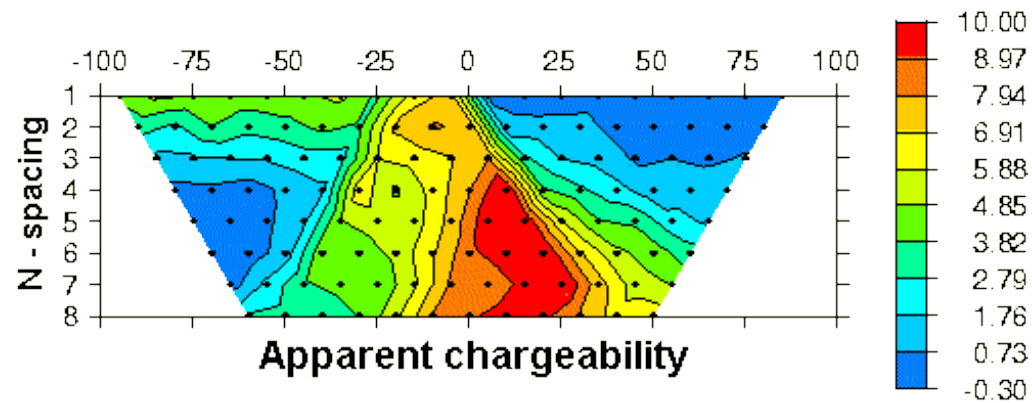
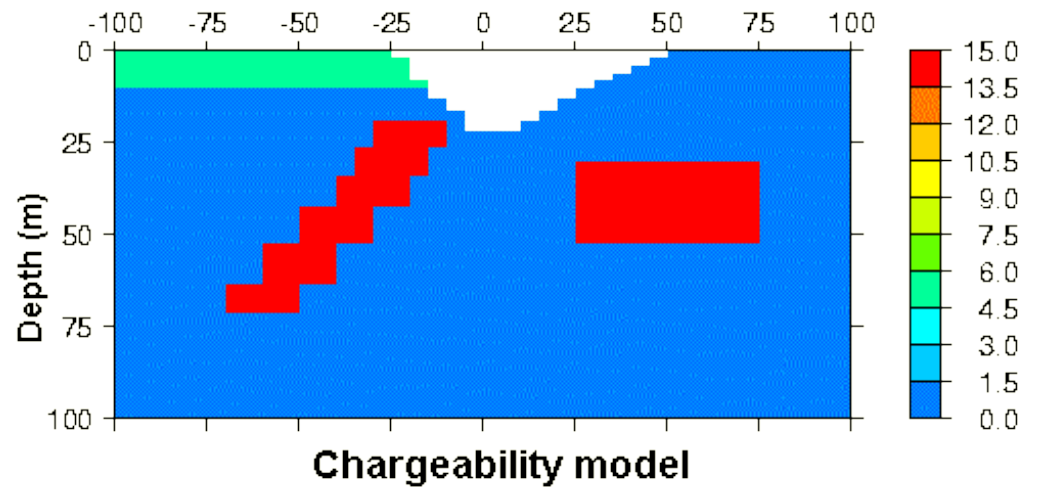


- Pole-dipole; $n=1,8$; $a=10\text{m}$; $N=316$

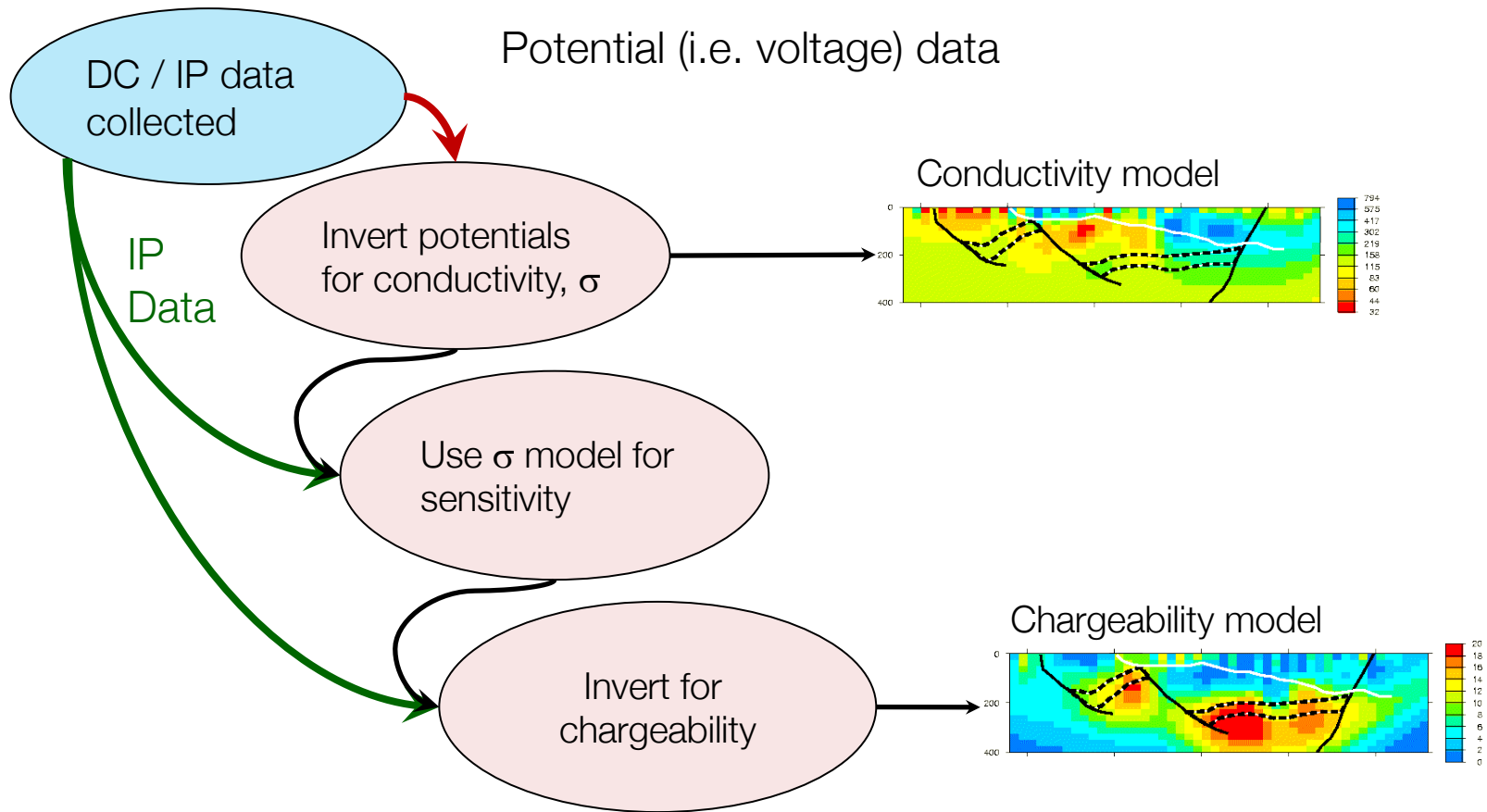


IP pseudosections

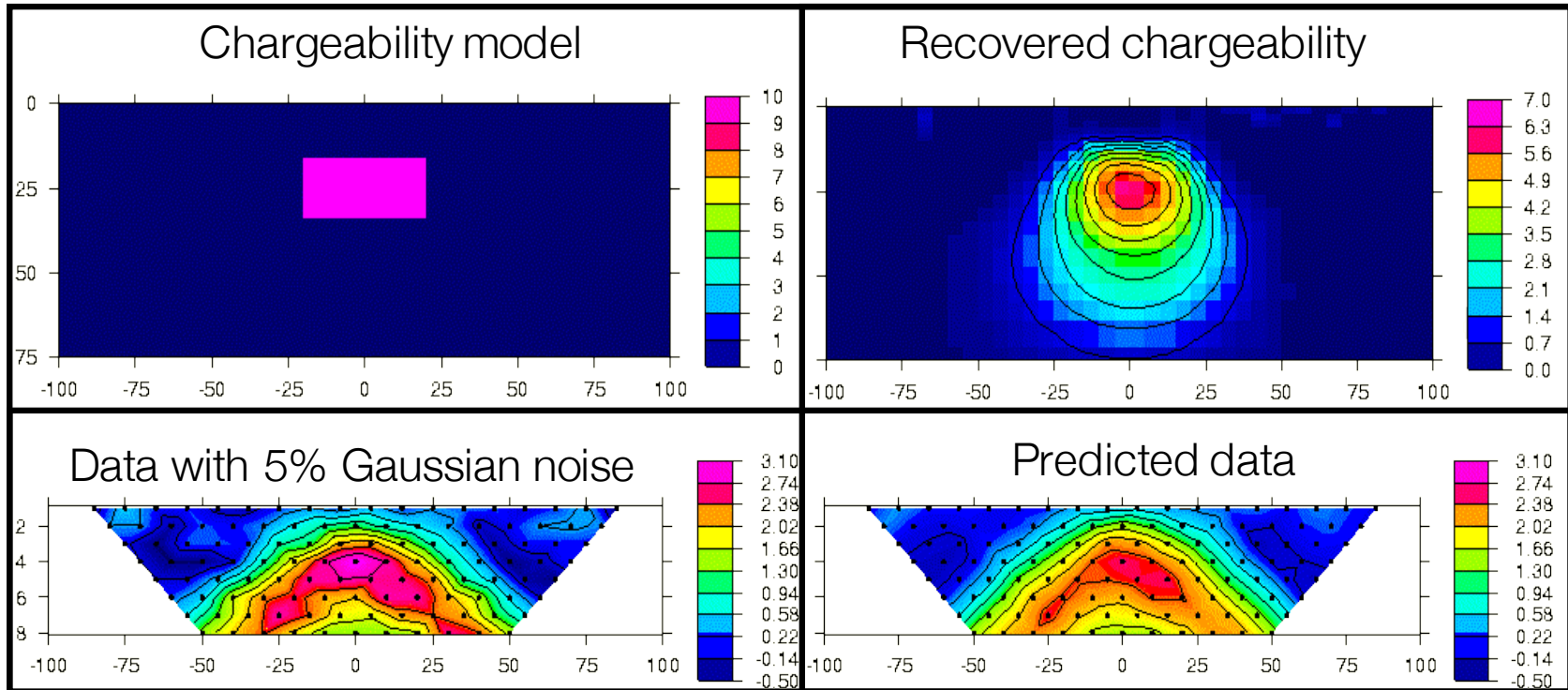
3) The “UBC-GIF model”



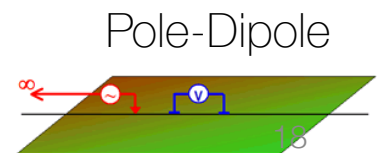
IP Inversion



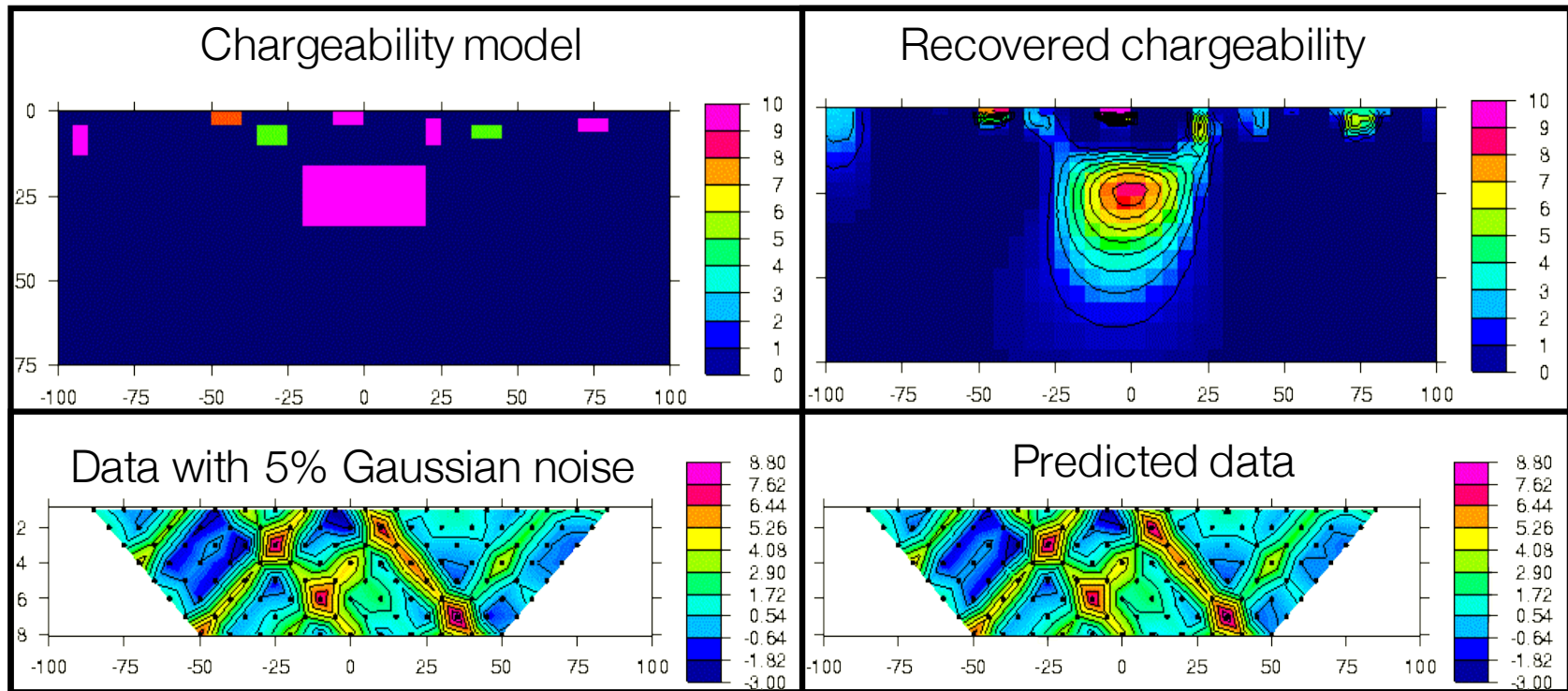
Example 1: buried prism



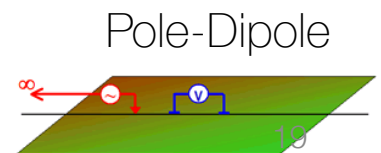
- Pole-dipole; $n=1,8$; $a=10\text{m}$; $N=316$; $(\alpha_s, \alpha_x, \alpha_z)=(.001, 1.0, 1.0)$



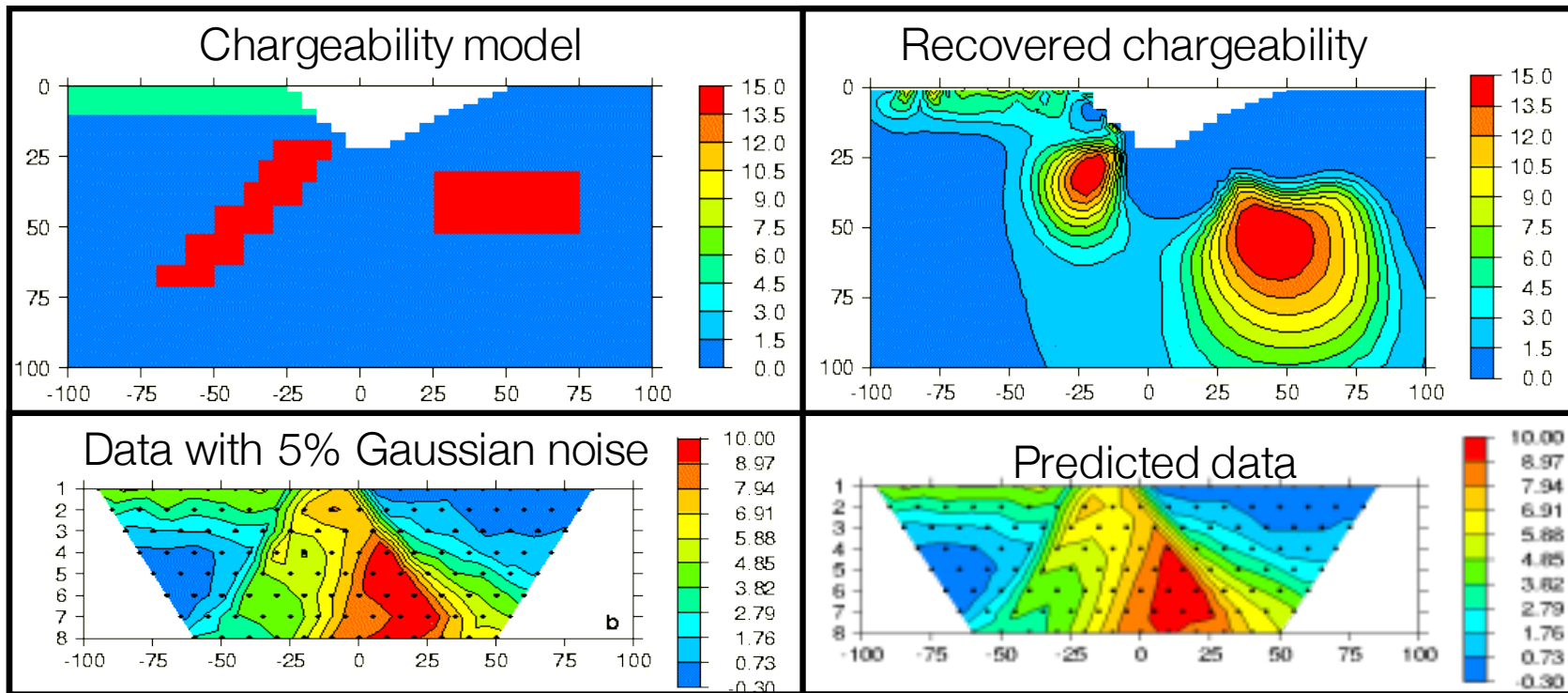
Example 2: prism with geologic noise



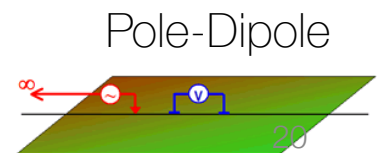
- Pole-dipole; $n=1,8$; $a=10\text{m}$; $N=316$; $(\alpha_s, \alpha_x, \alpha_z)=(.001, 1.0, 1.0)$



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

- Questions

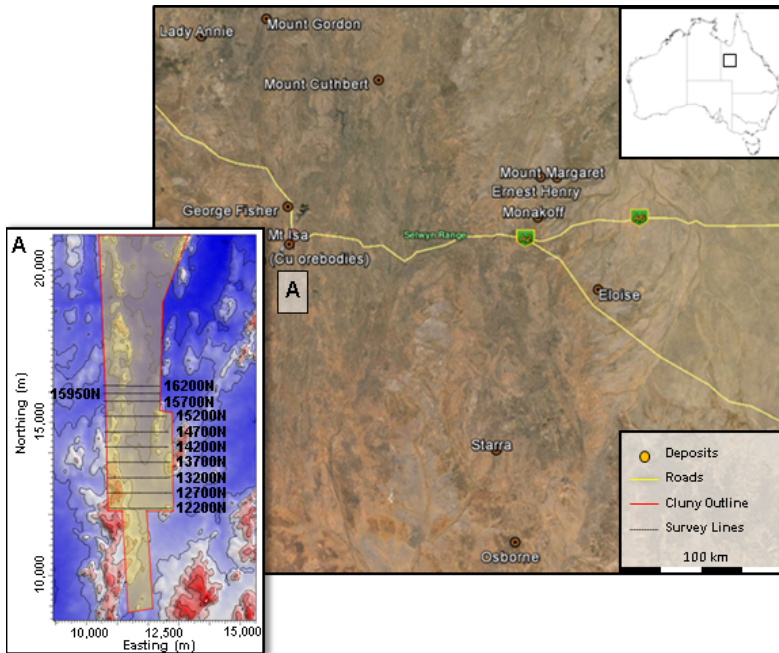
- Case history: Mt. Isa
- Example: Landfills

Case history: Mt. Isa

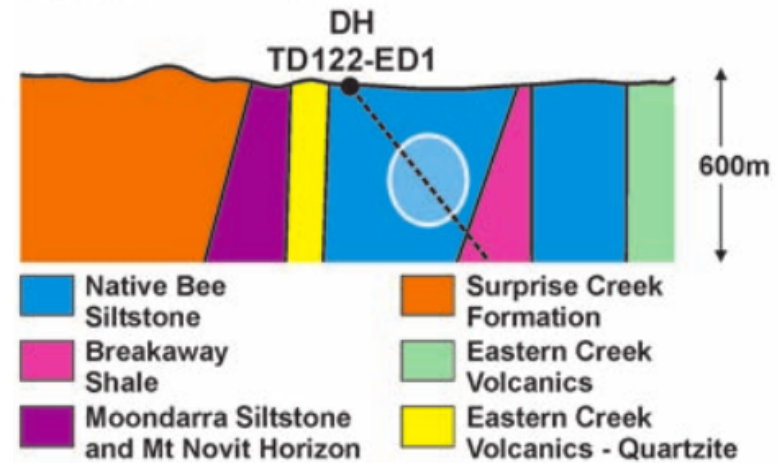
Rutley et al., 2001

Setup

- Mt. Isa (Cluny project)



- Geologic model

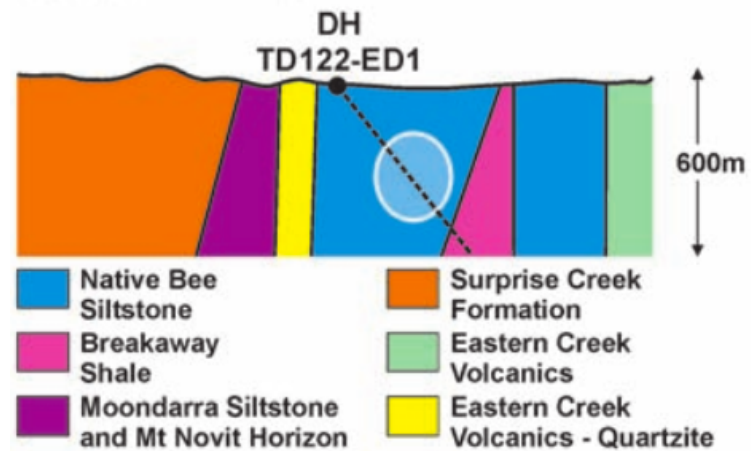


Question

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

Properties

Geologic model



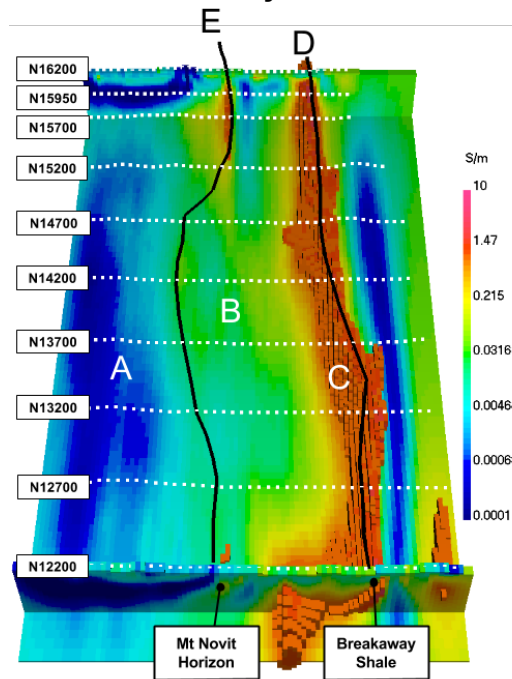
Resistivity and Chargeability

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

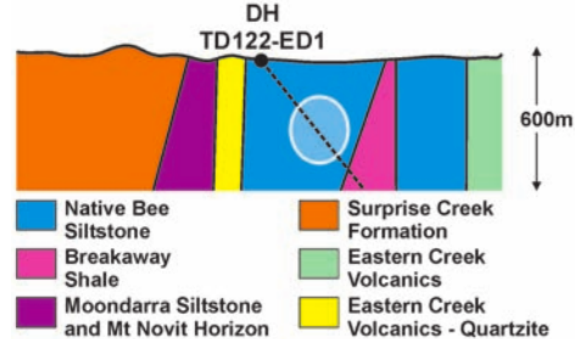
Recap: Synthesis from DC

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

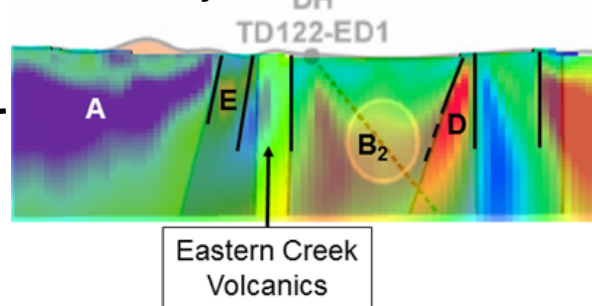
3D resistivity model



Geologic section



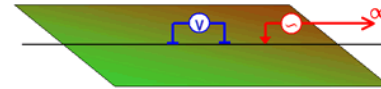
Resistivity section



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

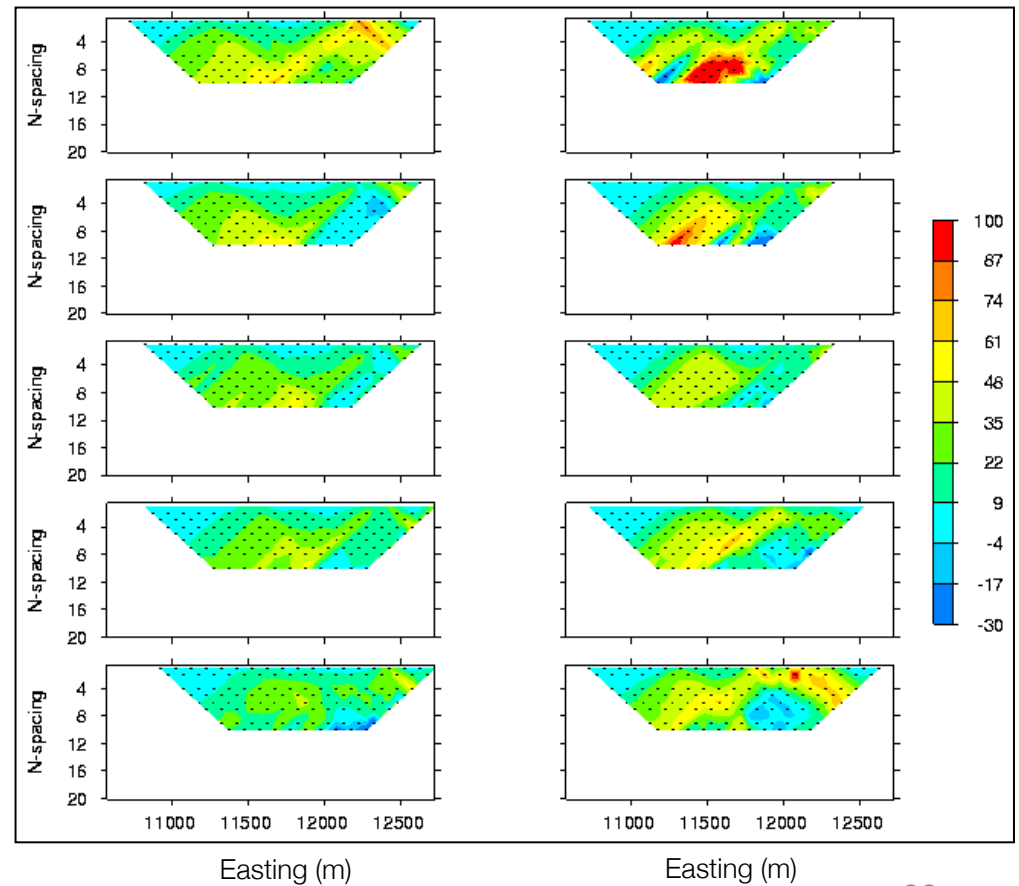
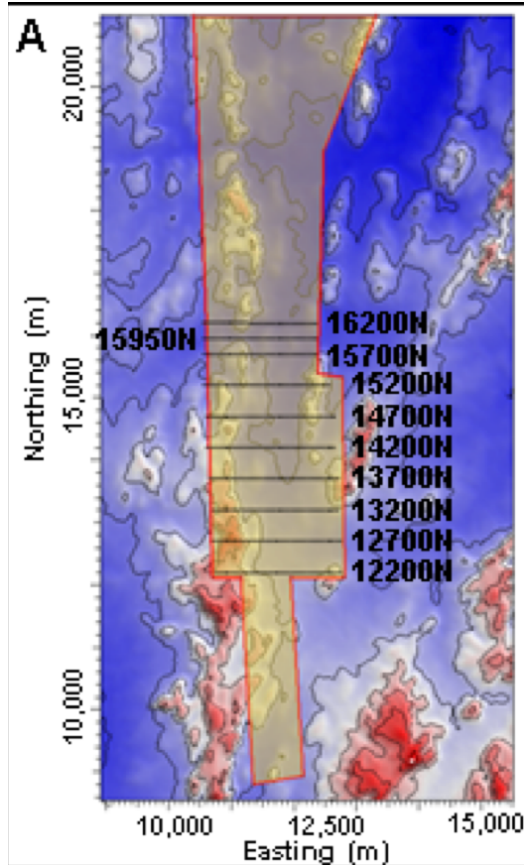
Survey and data

- Eight survey lines
- Two configurations



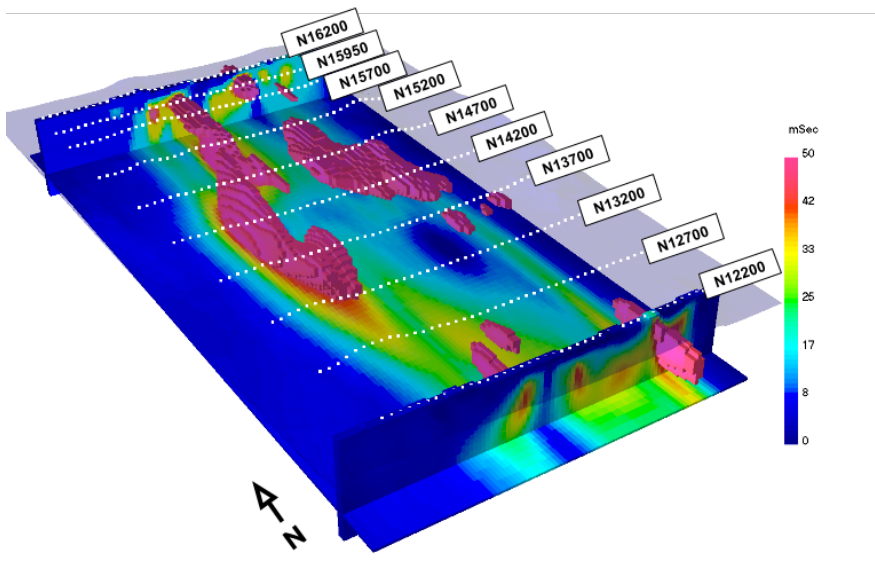
Apparent chargeability, dipole- pole.

Surface topography

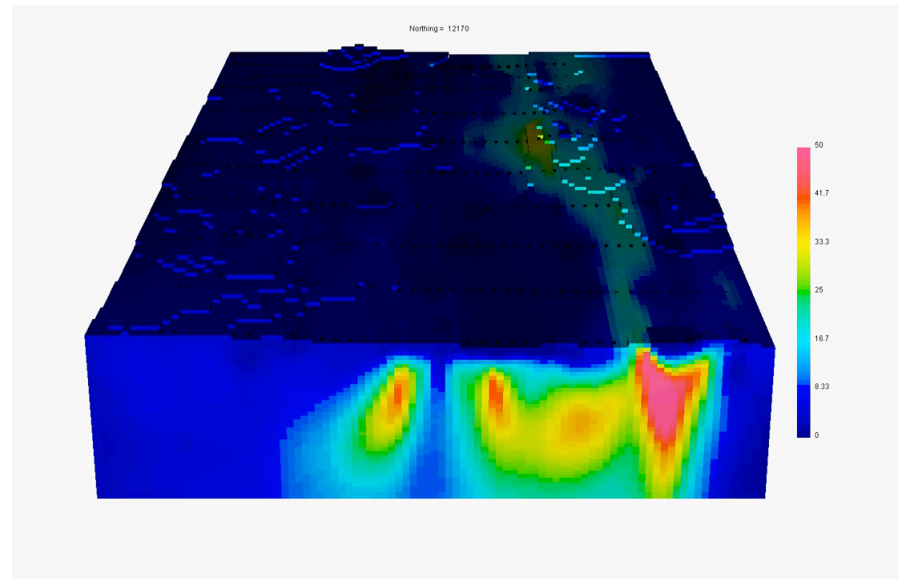


Processing

3D chargeability model



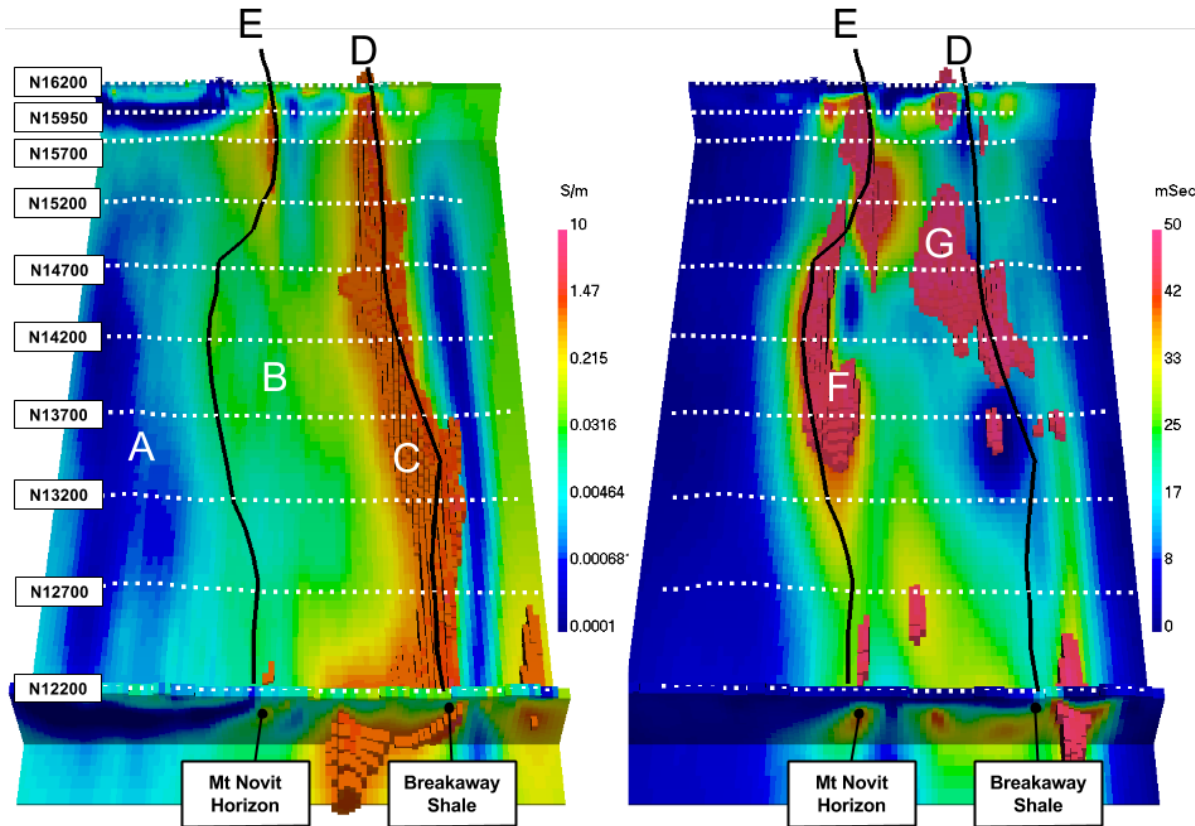
Animation



Interpretation

Resistivity model

Chargeability model



A: Resistive, Non-chargeable

B: Moderate conductivity; low chargeability

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

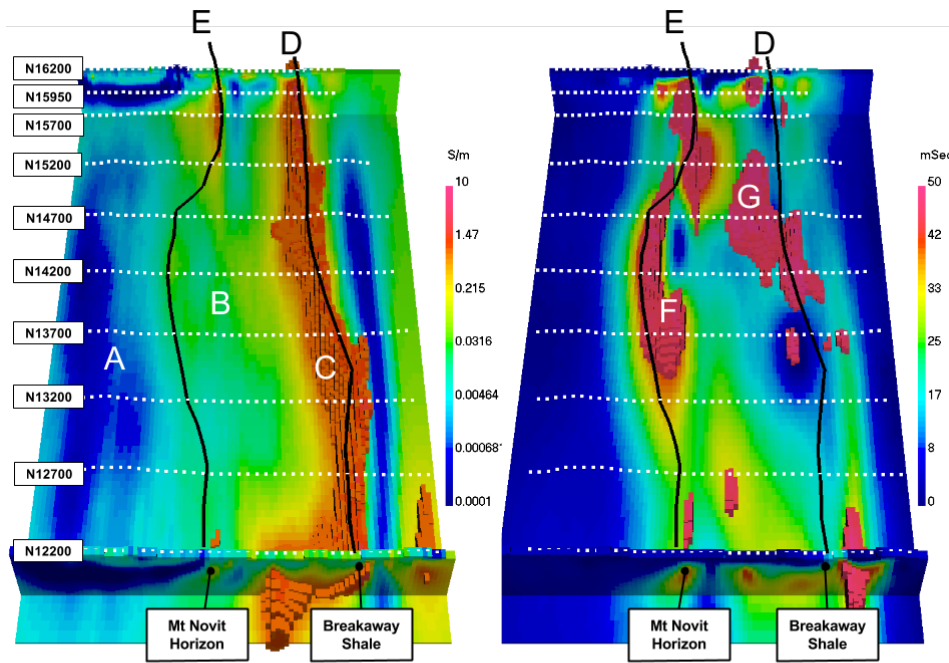
E and F: High conductivity and high chargeability

G: Other chargeable regions

Synthesis

Resistivity model

Chargeability model



A: Surprise Creek Formation
– Resistive, non-chargeable

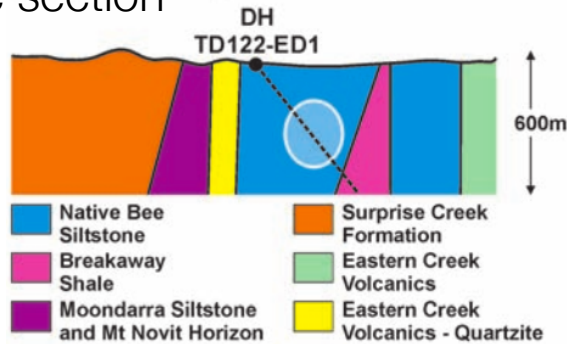
B: Moondarra and Native Bee siltstones

C: Breakaway Shales
– Very high conductivity

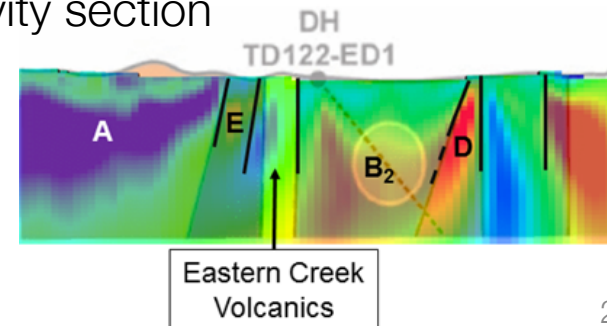
E and F: Mt Novit Horizon
– High conductivity and high chargeability

G: Other chargeable regions within siltstone complex

Geologic section



Resistivity section



Induced Polarization: Summary

- Sources of IP
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- Case history: Mt. Isa

- Questions

- Example: Landfills

IP over Landfills

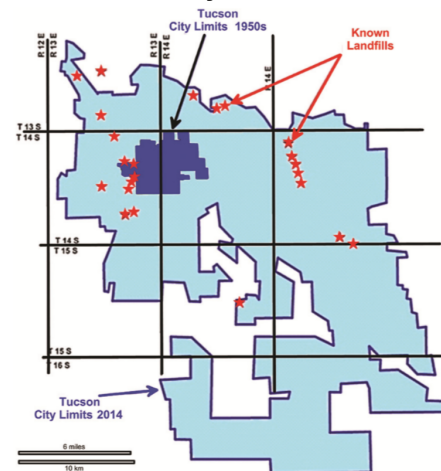
Landfills: Hazards and Goals

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

Nearmont and Congress landfills, Tucson, Arizona



Tucson city limits and regional landfills



Physical Properties



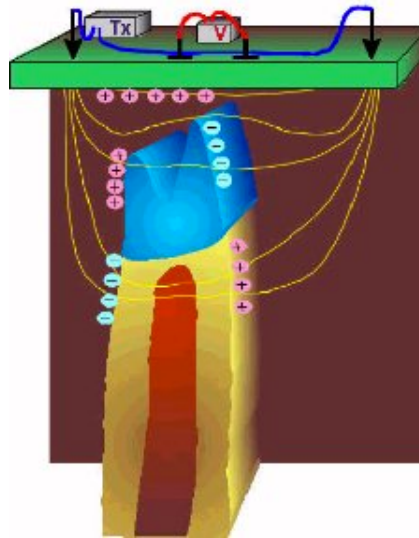
Waste Type	Description	Resistivity	Susceptible	Chargeable
Electronic/ Technological	Metallic objects, heavy metals in solution	Low	Yes	Yes
Construction Debris	Wood, cement, iron rebar, wall board, asbestos, glass, plastics	High	Frequently	Weakly
Earth Materials	Clays, various fill	Low/Moderate	Occasionally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

Traditional Landfill Surveys

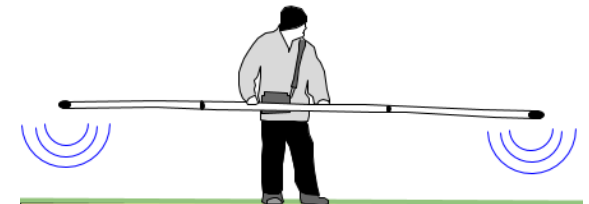
Magnetic



DC Resistivity



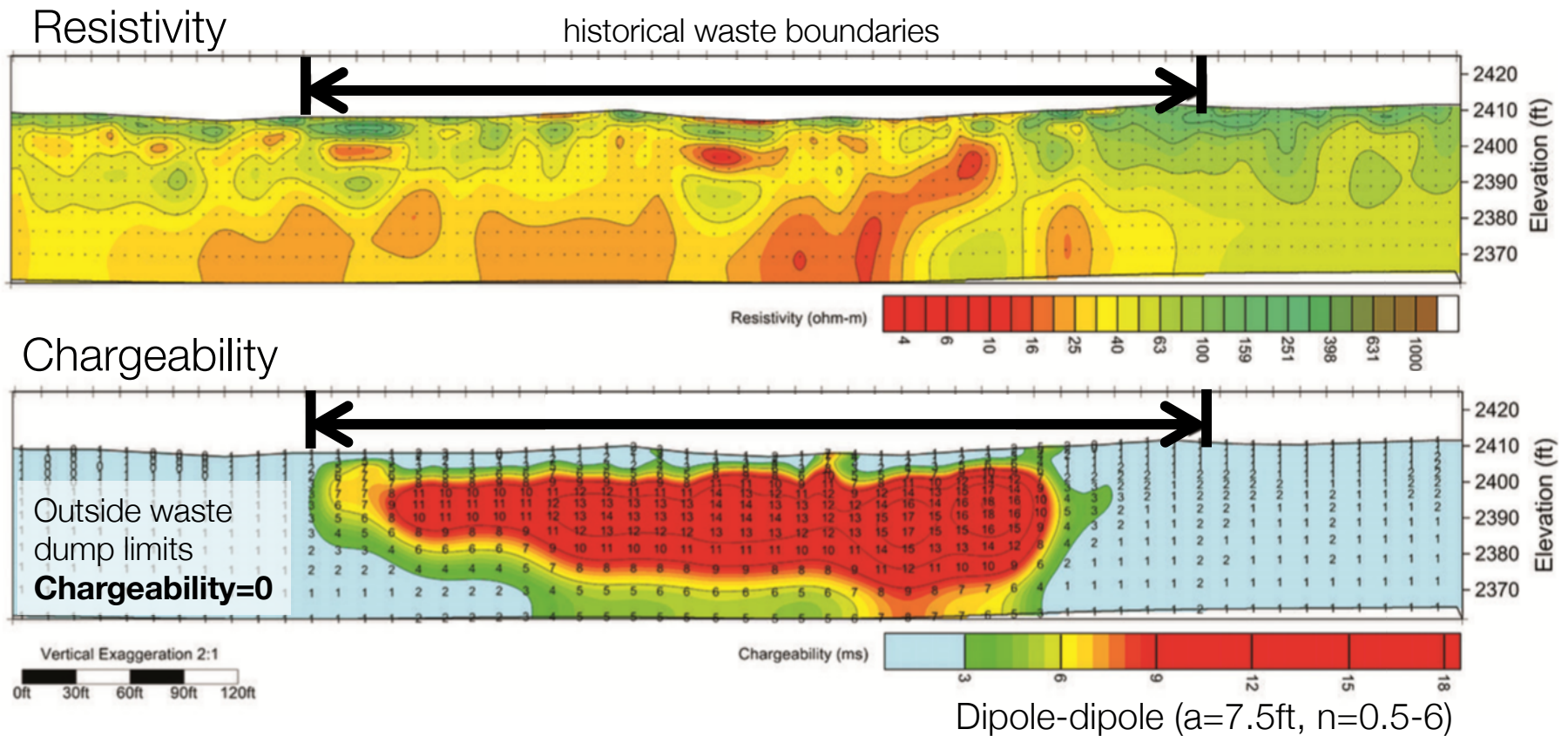
Near-Surface Electromagnetic



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

Ryan Airfield (Eastern Pit)

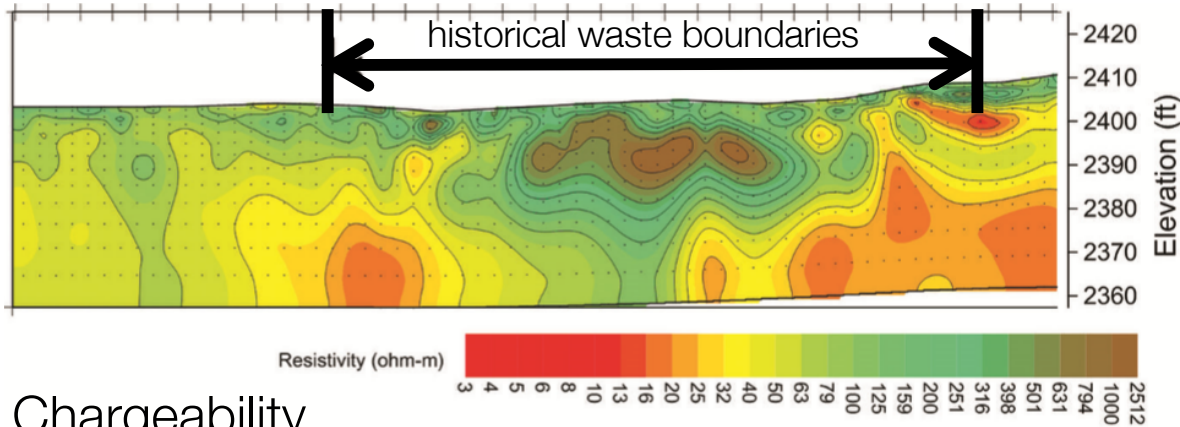
- Waste material: Mixed solid waste (MSW)
- Observations:
 - Resistivity not correlated with pit margins (non-diagnostic)
 - Chargeability (IP) correlates well with historical pit margins (diagnostic)



Ryan Airfield (Western Pit)

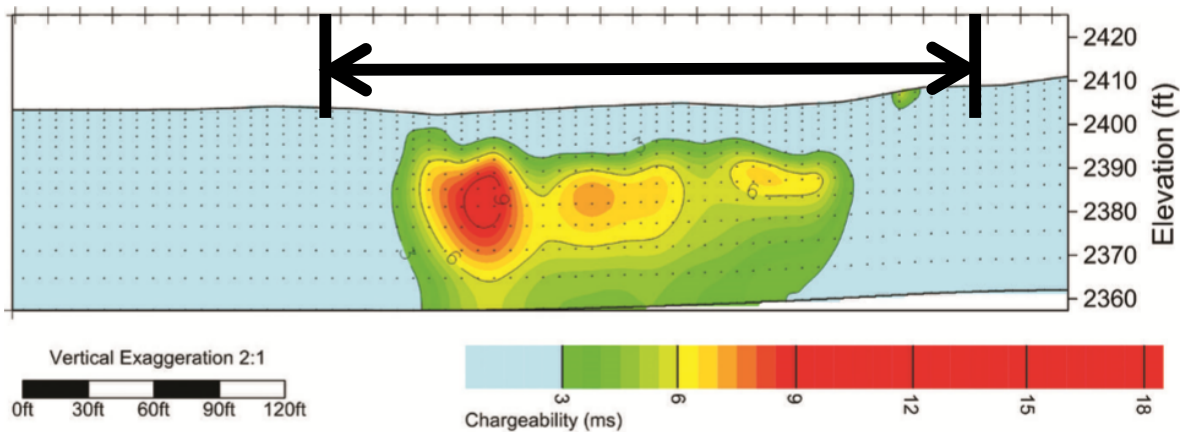
- Waste material: Construction / demolition
- Observations:
 - Waste correlates with region of high resistivity
 - Waste correlates with chargeable region (significant IP anomaly).

Resistivity



Resistive waste within landfill

Chargeability

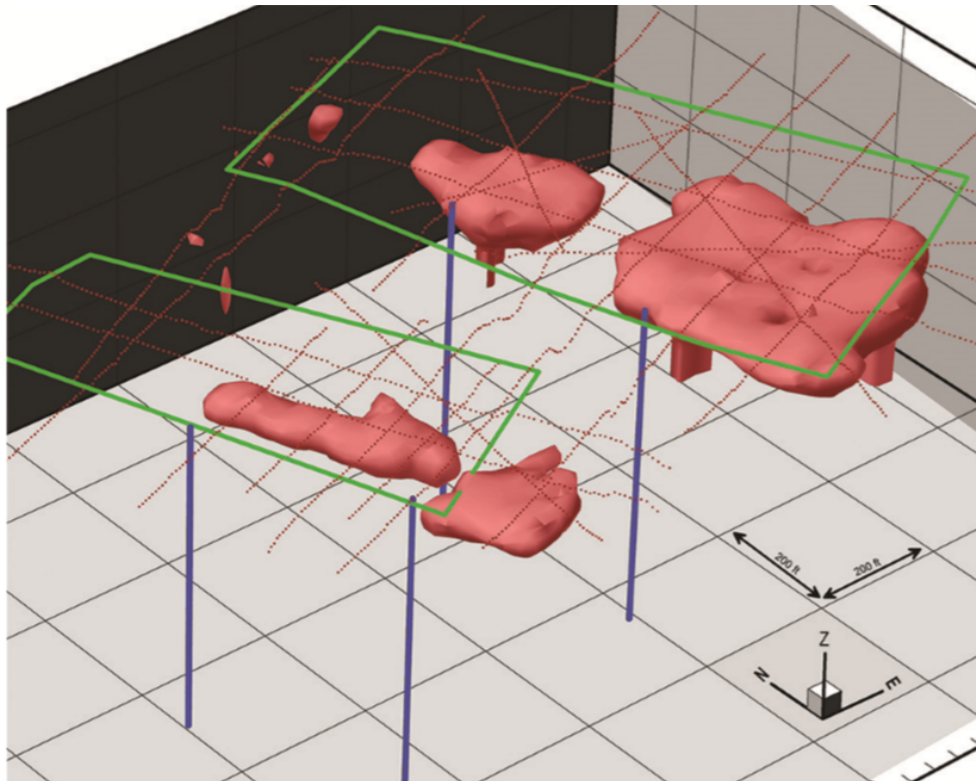


IP correlates with landfill

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

Ryan Airfield (Composite)

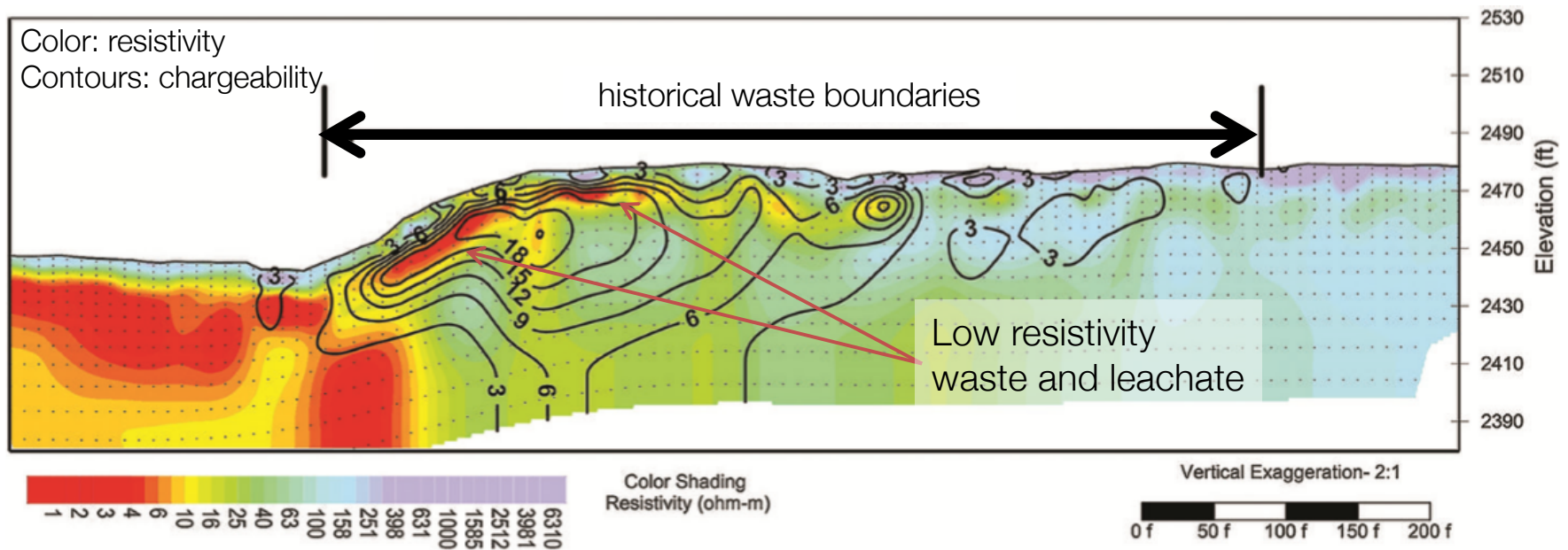
Chargeability isosurface



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

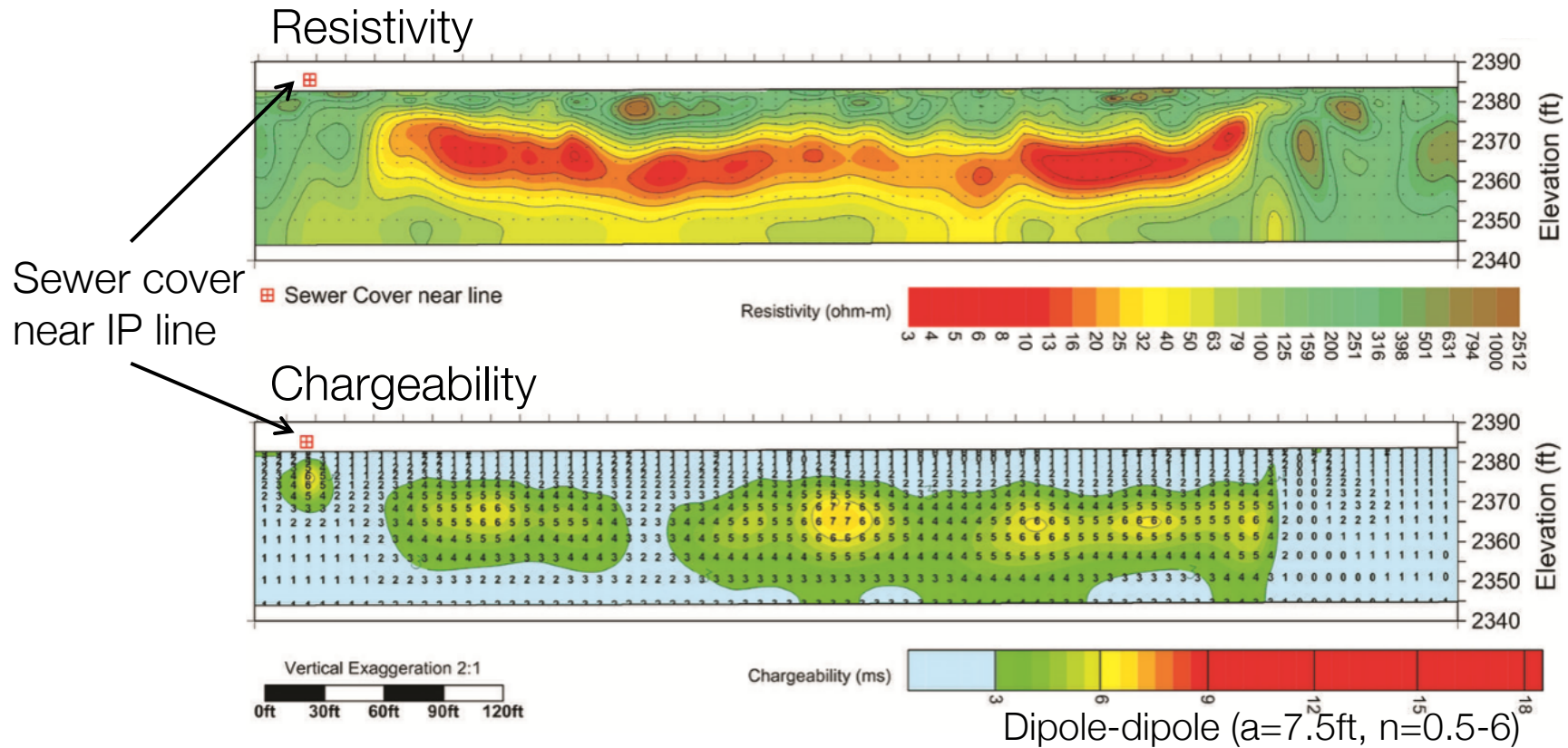
Tumamoc Landfill

- 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



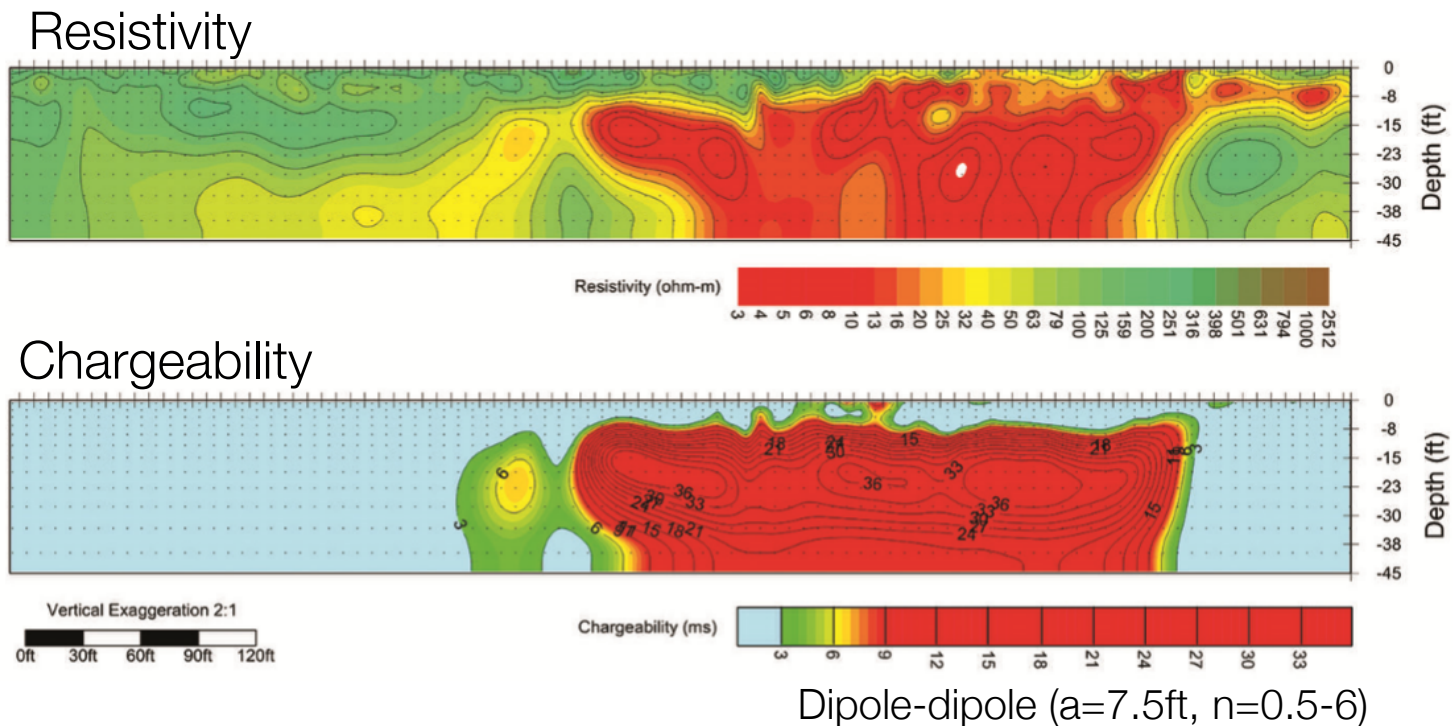
Tucson region: Organic material

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



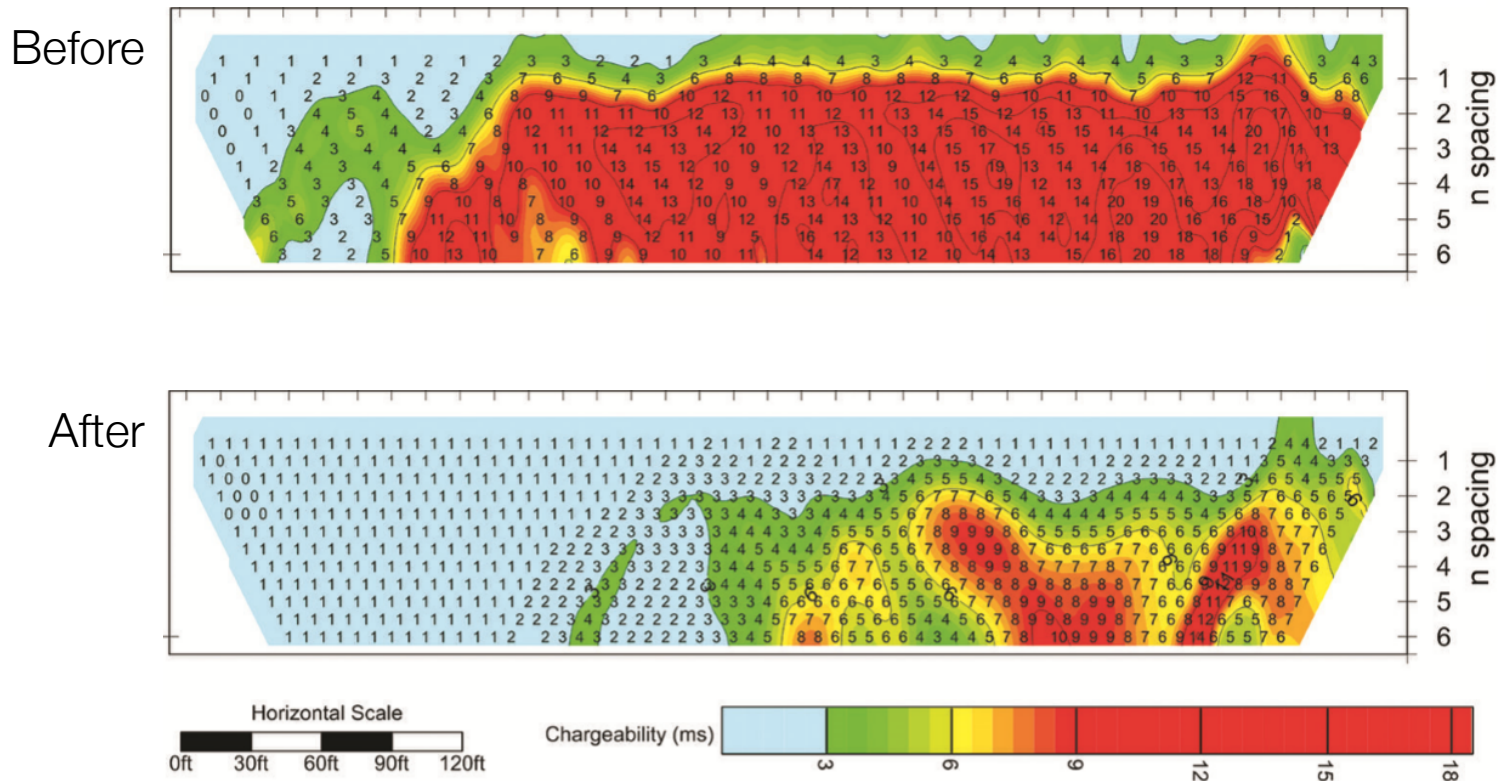
Nearmont Landfill

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



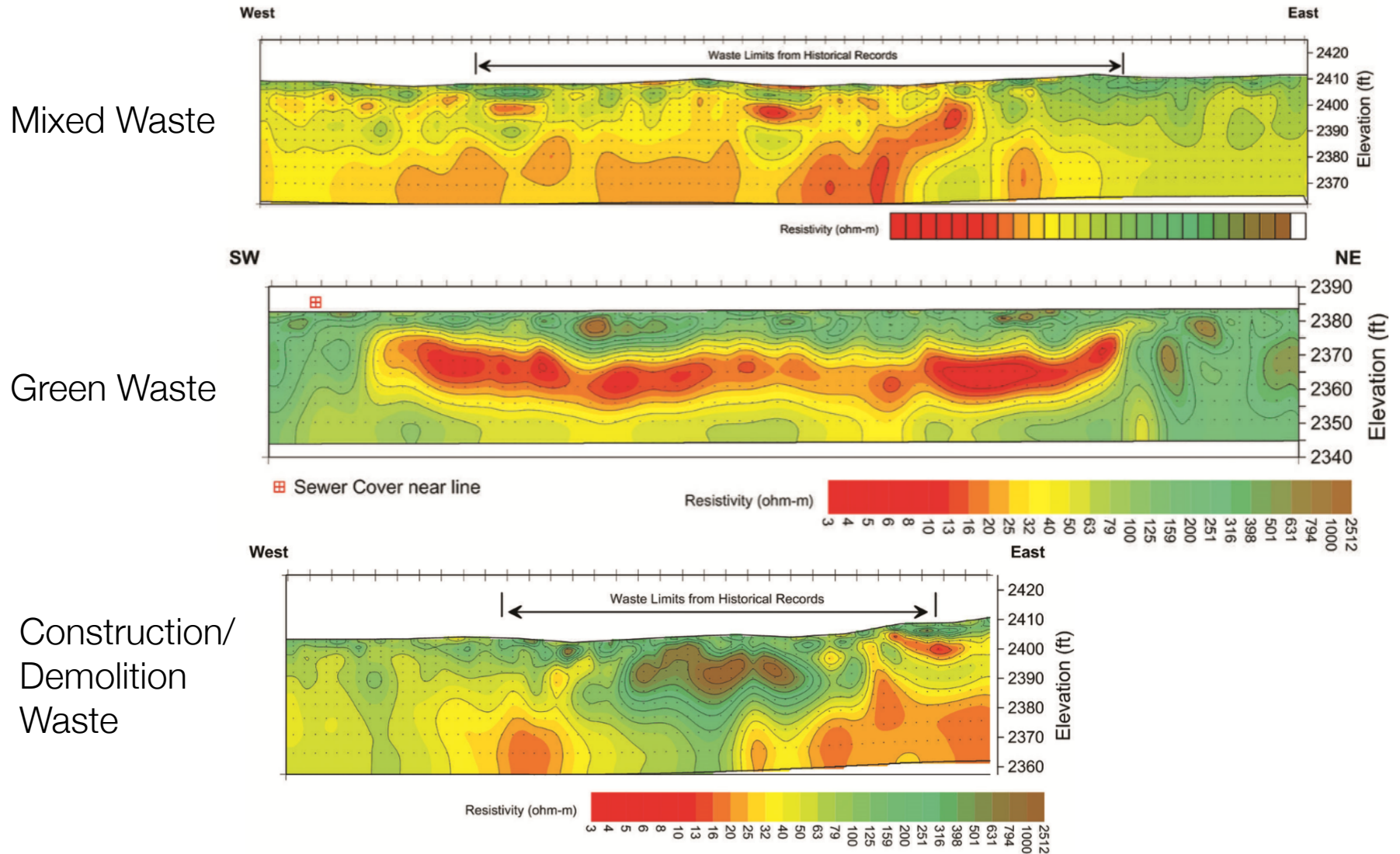
Example: Landfill Monitoring

- 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

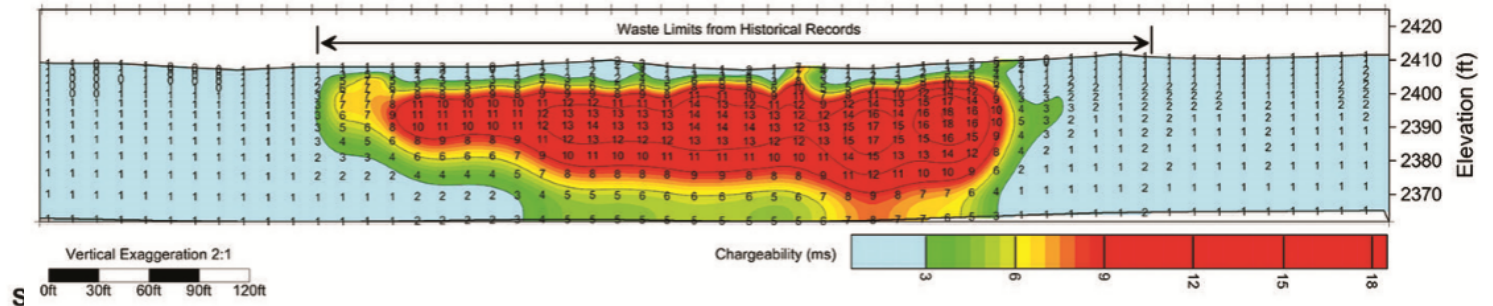
- Resistivity may not be a good indicator of waste



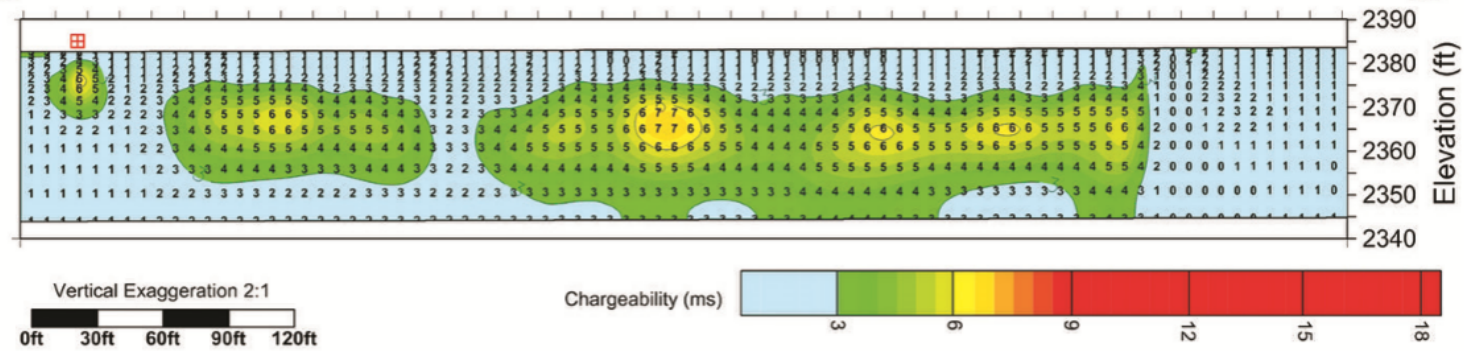
Summary

- Chargeability may be a more consistent indicator of waste

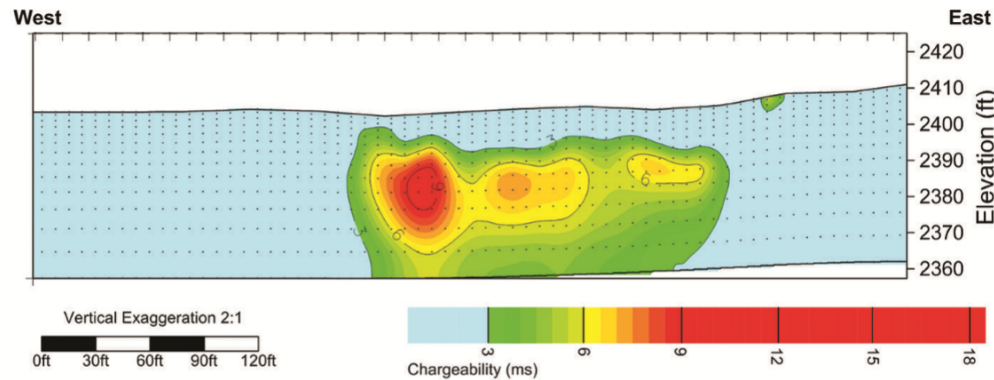
Mixed Waste



Green Waste



Construction/
Demolition
Waste



End of IP

