Airborne IP for Kimberlite

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IP workshop 2016

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Acknowledgements

- Ken Witherly, Joel Jansen, Sean Walker
- Pereguine Diamonds

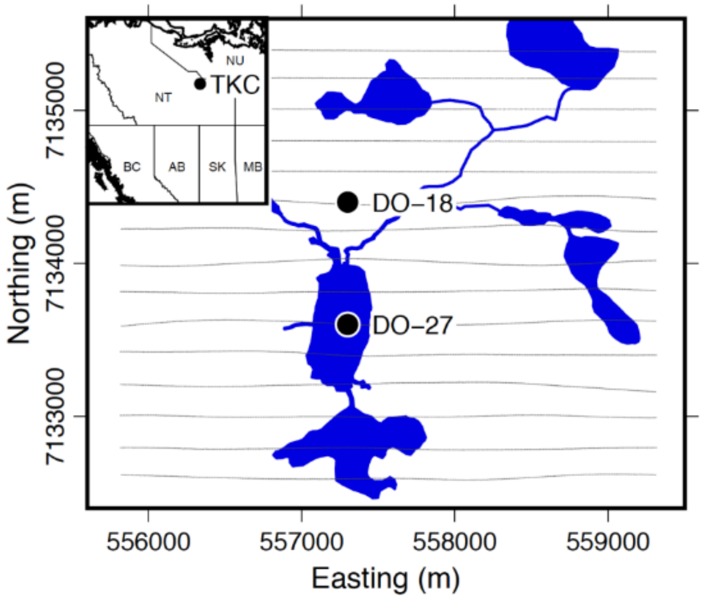
- S Devriese, K. Davis D. Fournier, M. McMillan
- Others in the UBC-Gif group

Motivation: negative transients

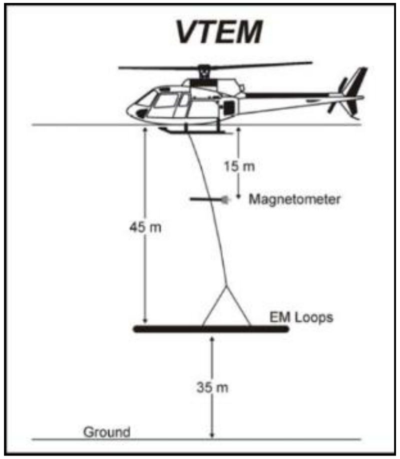
- Tli Kwi Cho (TKC) VTEM data

Signature of chargeable rock (Weidelt, 1982)

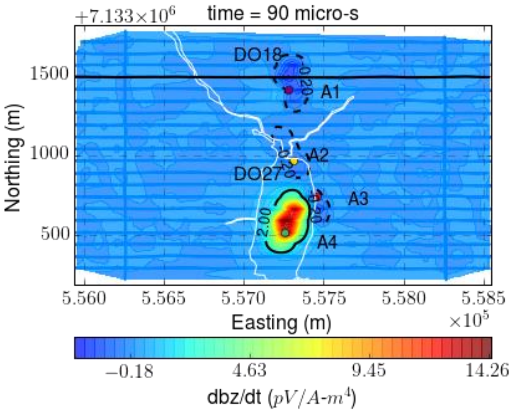
TKC kimberlite complex



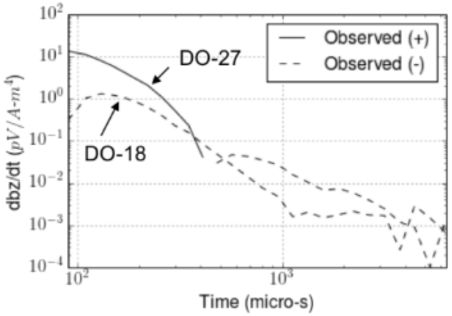
VTEM set-up



At 90 micro-s

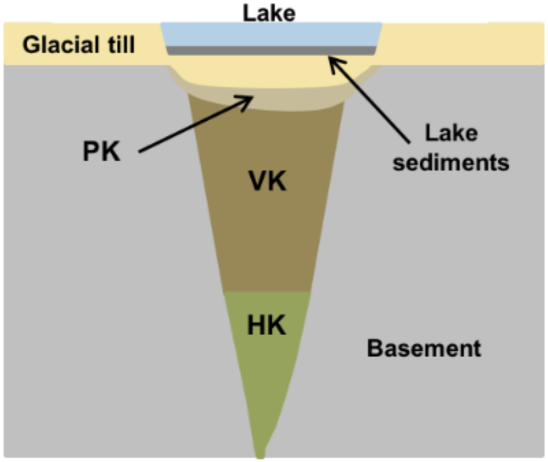


Decay curve



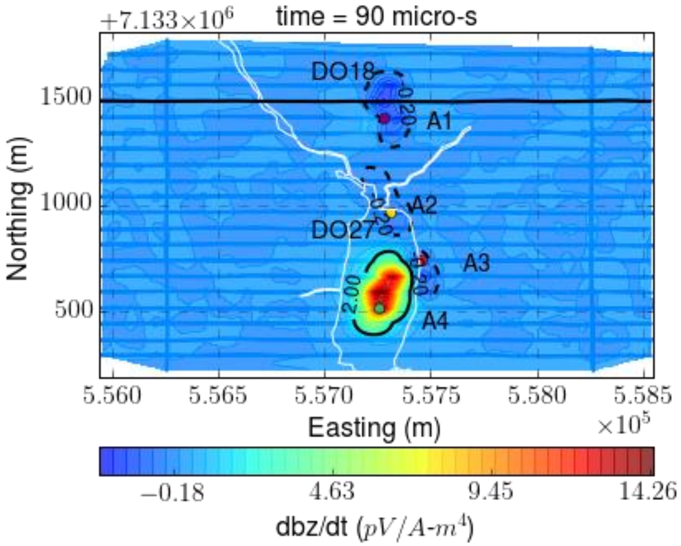
Kimberlite exploration

Kimberlite pipe structure



Devriese et al. (2016)

ATEM data



- **Questions:**
– How to deal with negatives in airborne time domain EM (ATEM) data
– Can we recover a 3D chargeability distribution?
– Does it have practical utility in diamond exploration?”

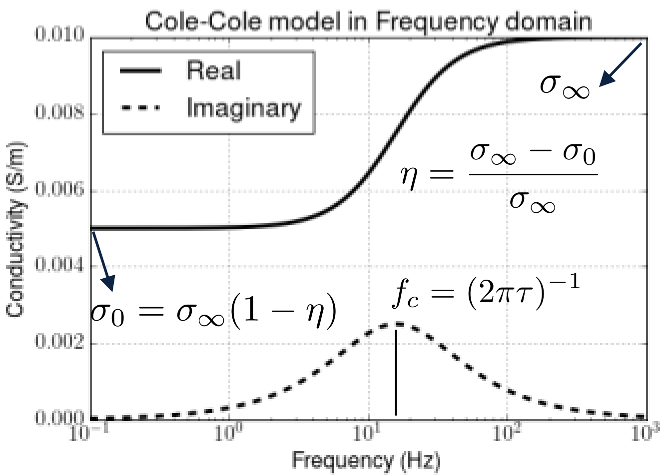
Outline

- Complex conductivity for kimberlites
- IP for inductive sources
- 3D TEM-IP inversion workflow
- Airborne IP inversion for VTEM data at TKC
- A 3D rock model at TKC
- Summary

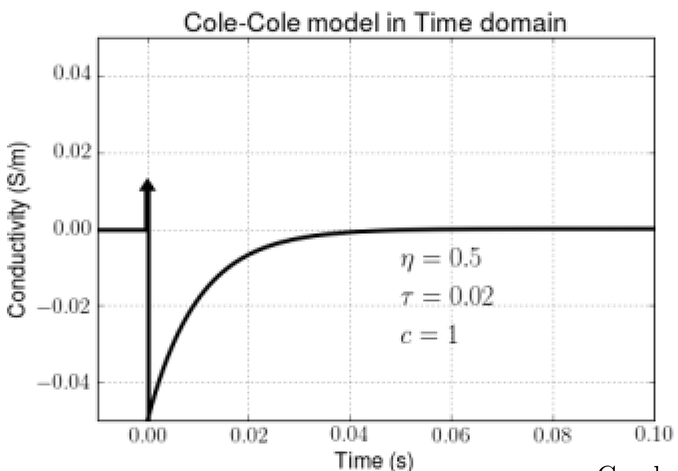
Complex conductivity

- Cole-Cole model (Pelton et al., 1978)

Frequency domain



Time domain



σ_∞: Conductivity at infinite frequency
σ_0: Conductivity at zero frequency
η: Chargeability
τ: Time constant (s)
c: Frequency dependency

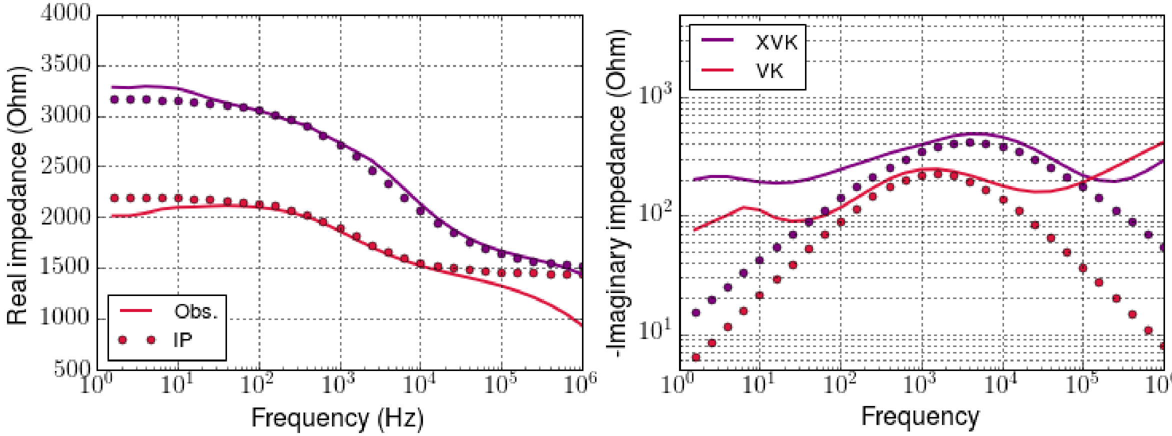
Inverse Fourier transform

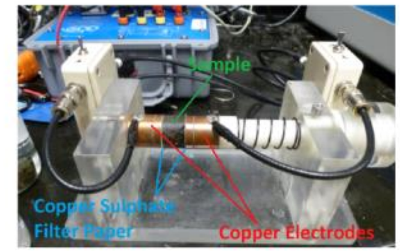
$$\sigma(\omega) = \sigma_\infty + \sigma_\infty \frac{\eta}{1 + (1-\eta)(\imath\omega\tau)^c} \longrightarrow \mathcal{F}^{-1}[\sigma(\omega)] = \sigma(t)$$

Complex impedances at TKC

- From GSC Lab

Two kimberlite samples: XVK and VK



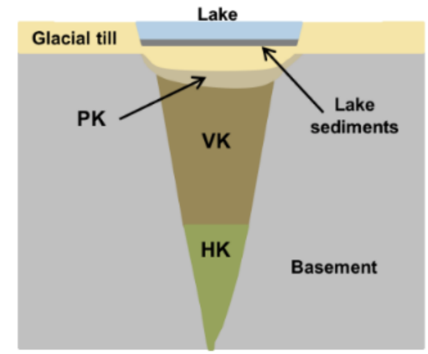


Geological Survey of Canada (2016)

Estimated Cole-Cole parameters

Division	Depth (mbsf)	ϱ_∞ (ohm-m)	σ_∞ (S/m)	η (V/V)	τ (micro-s)	c
XVK	266	81.3	2.77×10^{-2}	0.539	3.97×10^{1}	0.6
VK	78	49.0	3.13×10^{-2}	0.337	10.6×10^{1}	0.7

Kimberlite pipe structure



Devriese et al. (2016)

3D TEM inversion workflow: grounded source

Workflow

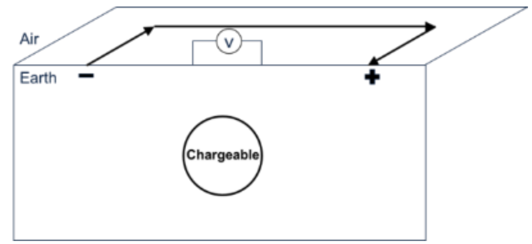
Invert TEM data,
to recover σ_∞

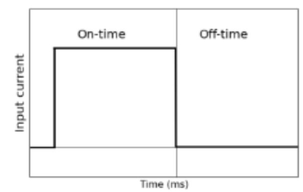
Compute IP datum
Remove EM responses

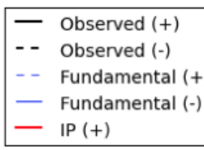
Linearized equations

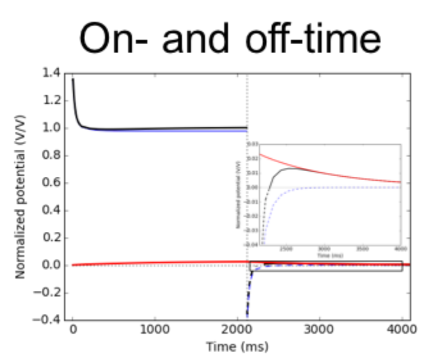
Invert d^{IP} data,
recover pseudo-chargeability

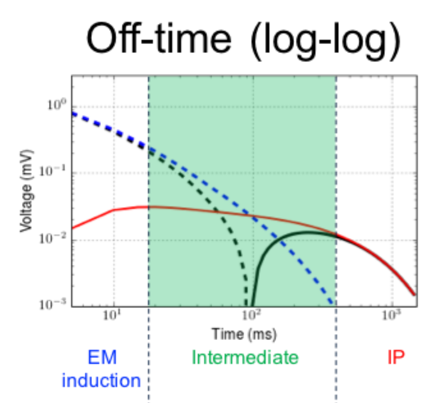
Estimate intrinsic
IP parameters











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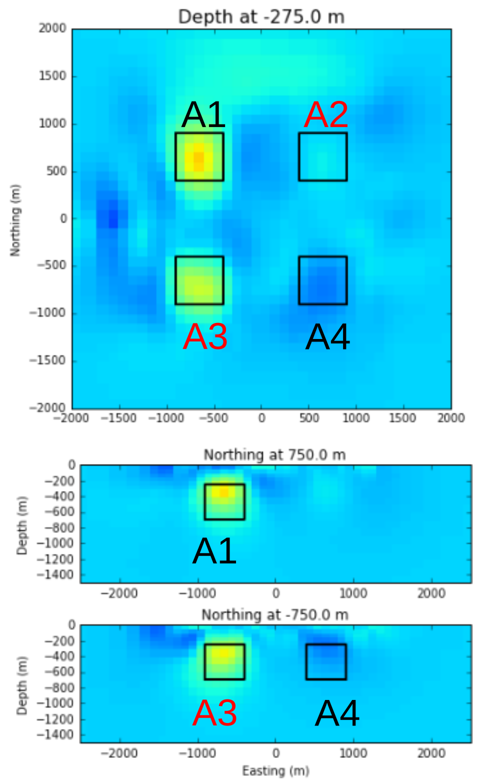
Estimated $\sigma_\infty (= \sigma_{est}^{EM})$



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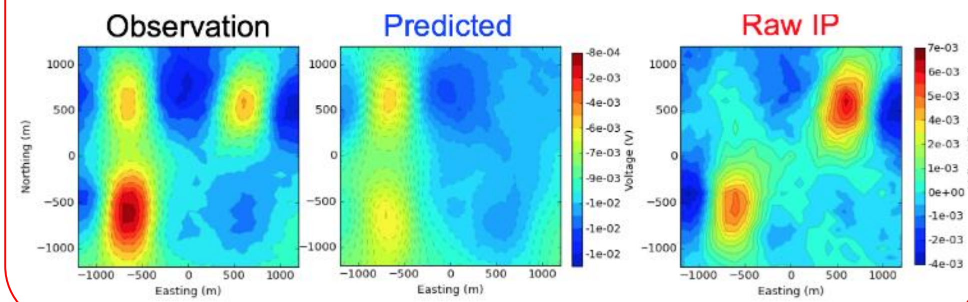
Estimate intrinsic
IP parameters

IP = Observation - Fundamental

$$d^{IP}(t) = F[\sigma(t)] - F[\sigma_\infty]$$



3D TEM inversion workflow: grounded source

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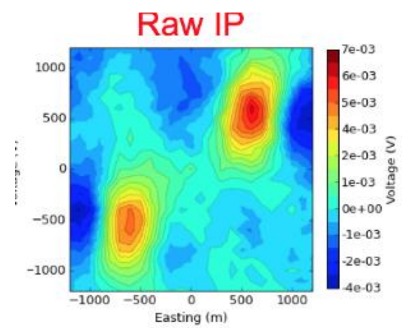

$$d^{IP}(t) = G\tilde{\eta}(t)$$

$G(\sigma_\infty)$: Sensitivity function
$\tilde{\eta}$: Pseudo-chargeability

Seigel (1959)
Oldenburg and Li (1994)

3D TEM inversion workflow: grounded source

Workflow

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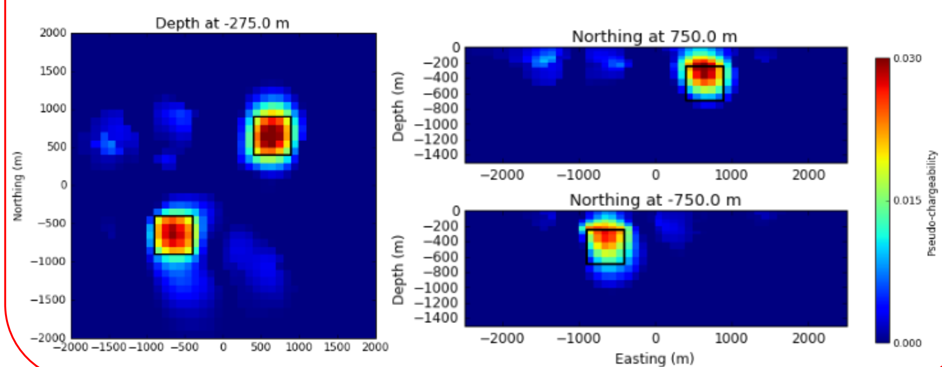
$$d^{IP}(t) = G\tilde{\eta}(t)$$

$G(\sigma_\infty)$: Sensitivity function
$\tilde{\eta}$: Pseudo-chargeability

Recovered pseudo-chargeability (80 ms)



3D TEM inversion workflow: grounded source

Workflow

Invert TEM data,
to recover σ_∞

Compute IP datum
Remove EM responses

Linearized equations

Invert d^{IP} data,
recover pseudo-chargeability

Estimate intrinsic
IP parameters

Recovered intrinsic IP parameters:

Pseudo-chargeability at i-th pixel

$$\tilde{\eta}_i = f(\sigma_\infty, \eta, \tau, c; t)$$

σ_∞: Conductivity at infinite frequency
η: Chargeability
τ: Time constant (s)
c: Frequency dependency

Inductive source IP

Workflow

Invert TEM data,
to recover σ_∞

Compute IP datum
Remove EM responses

Linearized equations

Invert d^{IP} data,
recover pseudo-chargeability

Estimate intrinsic
IP parameters

Workflow is the same but …

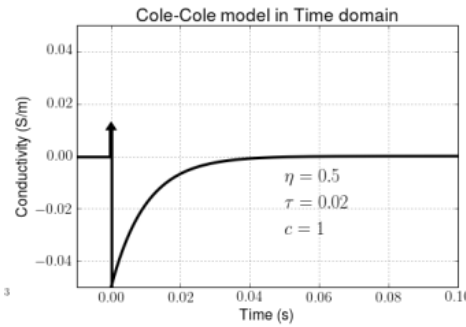
- Polarization currents generated by a transient electric field
- Airborne IP data have many Tx-Rx pairs

IP currents

- Ohm's law

$$\vec{j}(t) = \sigma(t) \otimes \vec{e}(t)$$

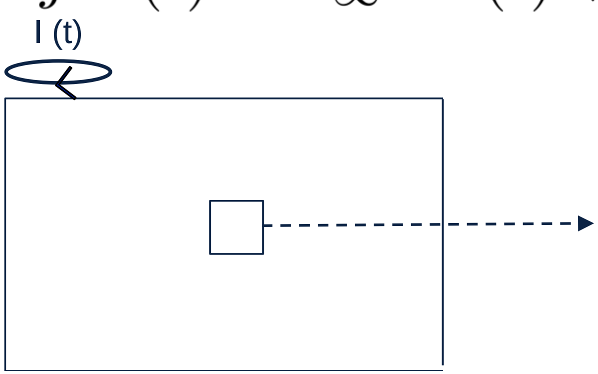
$$= \sigma_\infty \vec{e}^{F}(t) + \vec{j}^{IP}$$

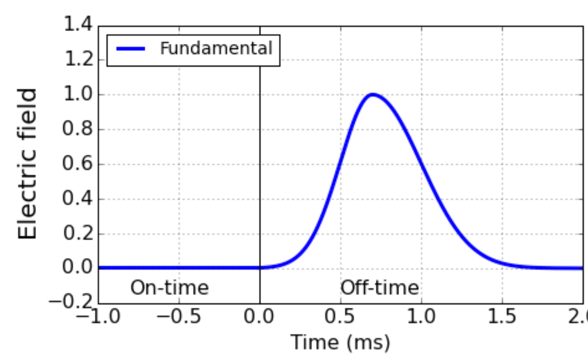


Superscripts:
F: Fundamental
IP: Induced polarization

where

$$\vec{j}^{IP}(t) = \sigma_\infty \vec{e}^{IP}(t) + \boxed{\triangle\sigma(t) \otimes \vec{e}(t)}$$





Linearization

- IP current density

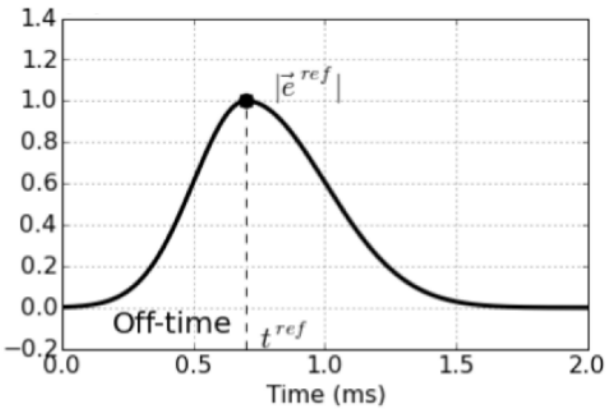
$$\vec{j}^{IP}(t) = \sigma_\infty \vec{e}^{IP}(t) + \triangle\sigma(t) \otimes \vec{e}(t)$$

Pseudo-chargeability

Approximating $\vec{e}(t) \approx \vec{e}^{\,ref} w^e(t)$

$$w^e(t) = \frac{\vec{e}(t) \cdot \vec{e}^{\,ref}}{\vec{e}^{\,ref} \cdot \vec{e}^{\,ref}}$$

$$\vec{j}^{IP}(t) = \sigma_\infty \vec{e}^{IP}(t) - \tilde{\eta}(t)\vec{j}^{\,ref}$$



$$\tilde{\eta}(t) = -\frac{\triangle\sigma(t) \otimes w^e(t)}{\sigma_\infty}$$

$$\vec{j}^{\,ref} = \sigma_\infty \vec{e}^{F}_{max}$$

Linearization

- By applying Biot-Savart's law (similar to MIP)

$$\vec{b}^{IP}(\vec{r};t) = \frac{\mu_0}{4\pi}\int_{\Omega}\frac{\vec{j}^{IP}\times\hat{r}}{|\vec{r}-\vec{r}_s|^2}dv_s \qquad \text{where } \hat{r} = \frac{\vec{r}-\vec{r}_s}{|\vec{r}-\vec{r}_s|}$$

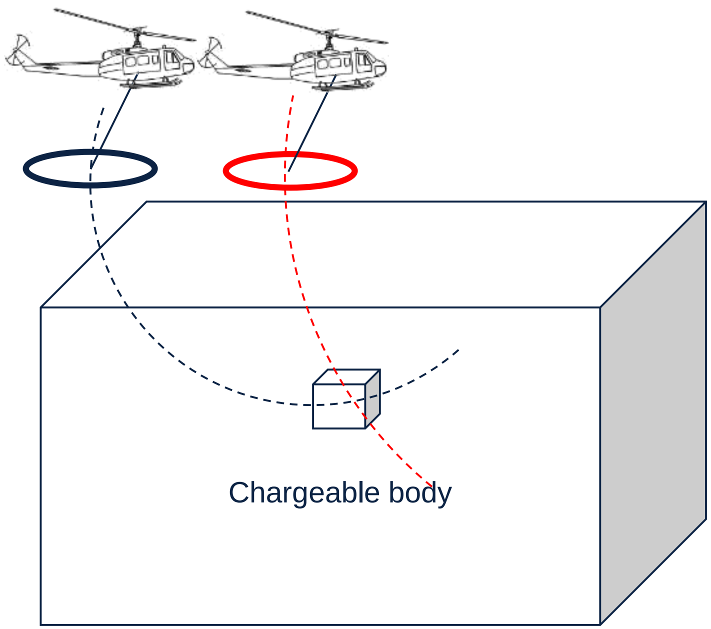
- We can have linear form:

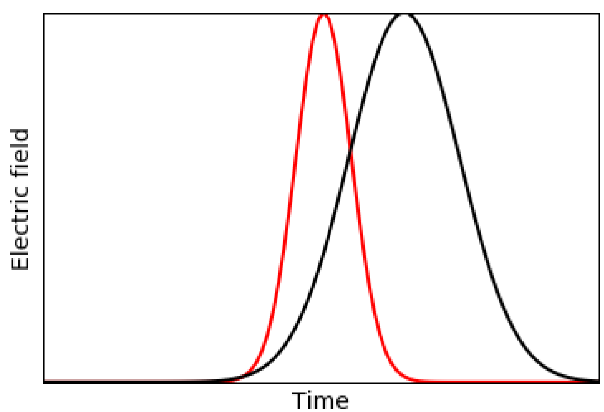
$$d^{IP}(t) = G\tilde{\eta}(t)$$

$G(\sigma_\infty)$: Sensitivity function
$\tilde{\eta}$: Pseudo-chargeability

(Seigel, 1974; Chen et al., 2006)

Challenge: multiple Tx-Rx pairs





$$\vec{e}(t) \approx \vec{e}^{\,ref} w^e(t)$$

$$w^e(t) = \frac{\vec{e}(t)\cdot\vec{e}^{\,ref}}{\vec{e}^{\,ref}\cdot\vec{e}^{\,ref}}$$

$$\tilde{\eta}(t) = -\frac{\triangle\sigma(t)\otimes w^e(t)}{\sigma_\infty}$$

Every transmitter has different excitation …

$$d_k^{IP}(t) = \sum_{i=1}^{nC} J_{k,i}\tilde{\eta}_i^k(t), \quad k = 1,\ldots,nTx$$

i-th cell (i=1,…,nC)
k-th transmitter (k=1, …, nTx)

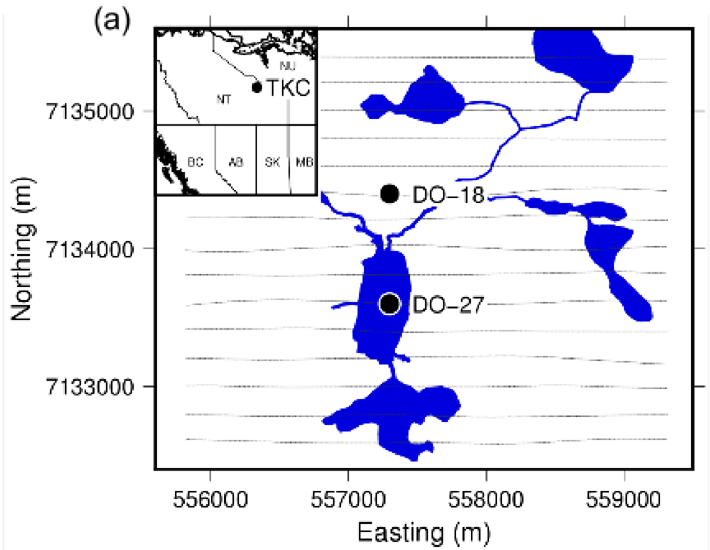
$$d_k^{IP}(t) = \sum_{i=1}^{nC} J_{k,i}\tilde{\eta}_i(t)$$

Seek for Effective pseudo-chargeability

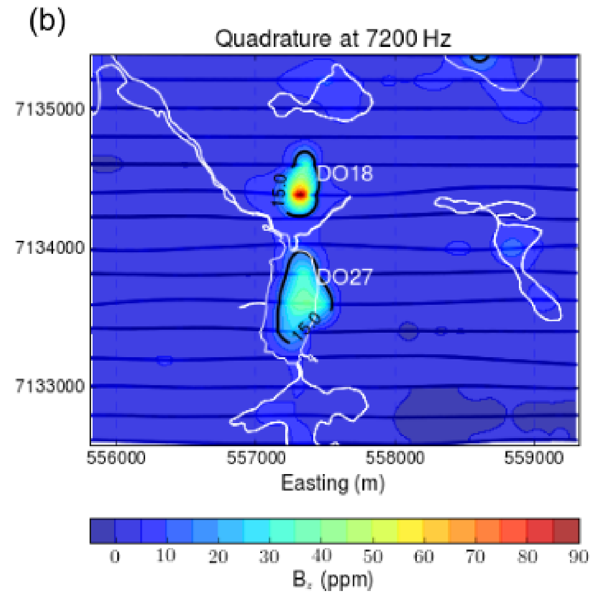
Field example: TKC

Backgrounds of TKC

TKC kimberlite complex



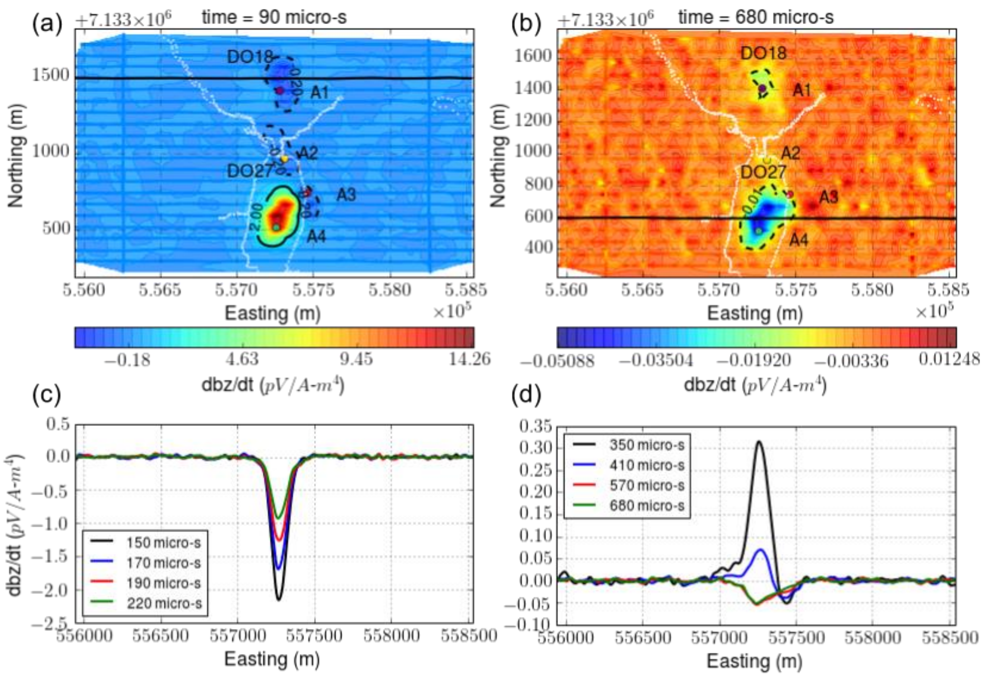
Dighem map



- Kimberlite deposit located 360 km north east Yellowknife, NWT
- Discovered by airborne geophysics
- Two pipes:
  - DO-18 (north)
  - DO-27 (south)

VTEM data at TKC

VTEM data



- DO-18: even the earliest time is negative (A1)
  - No data for TEM inversion
- DO-27: late time has strong negatives (A4)
- Resistive background
  - Away from pipes data are noisy

Step 1: Conductivity inversion

Invert TEM data, to recover

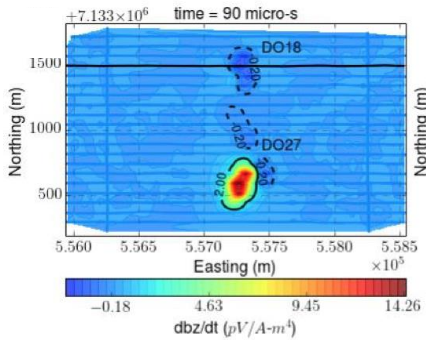
Compute IP datum Remove EM responses

Linearized equations

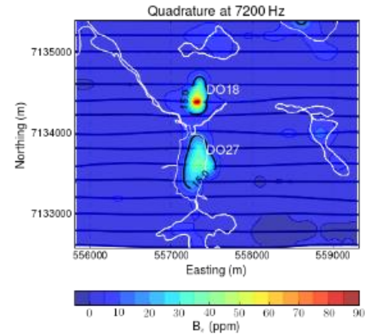
Invert d^{IP} data, recover pseudo-chargeability

Estimate intrinsic IP parameters

Cooperative inversion of VTEM and Dighem



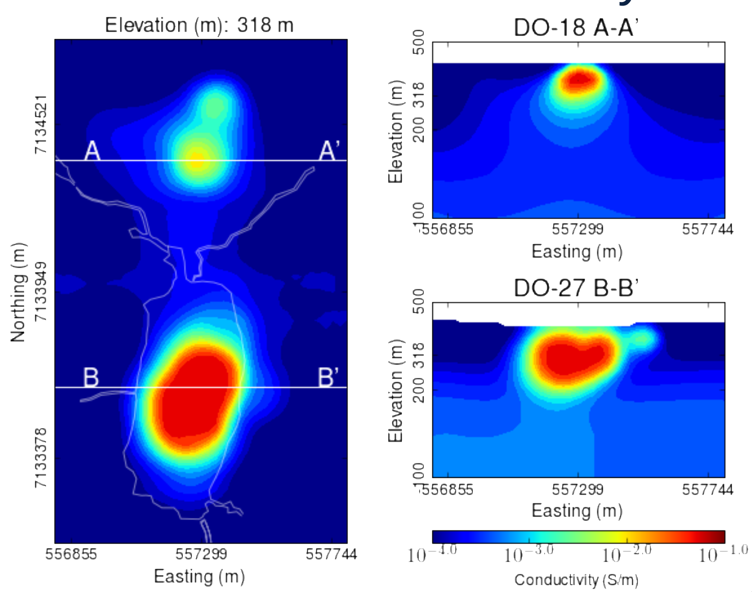
+



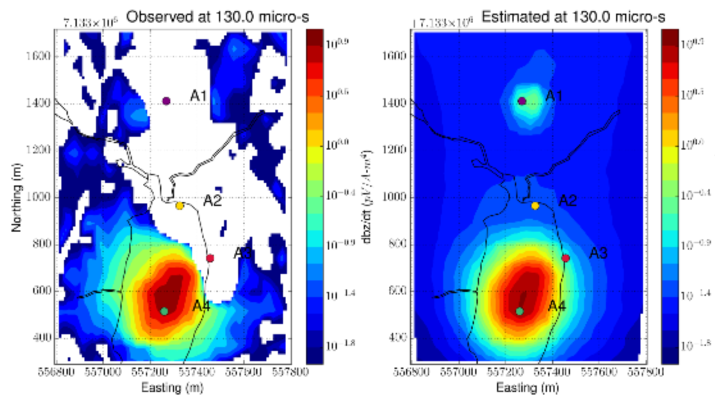
Dighem: no negatives

Fournier et al. (2016)

Estimated 3D conductivity



Observed. vs. Estimated



Step 2: EM-decoupling

Invert TEM data, to recover

Compute IP datum Remove EM responses

Linearized equations

Invert d^{IP} data, recover pseudo-chargeability

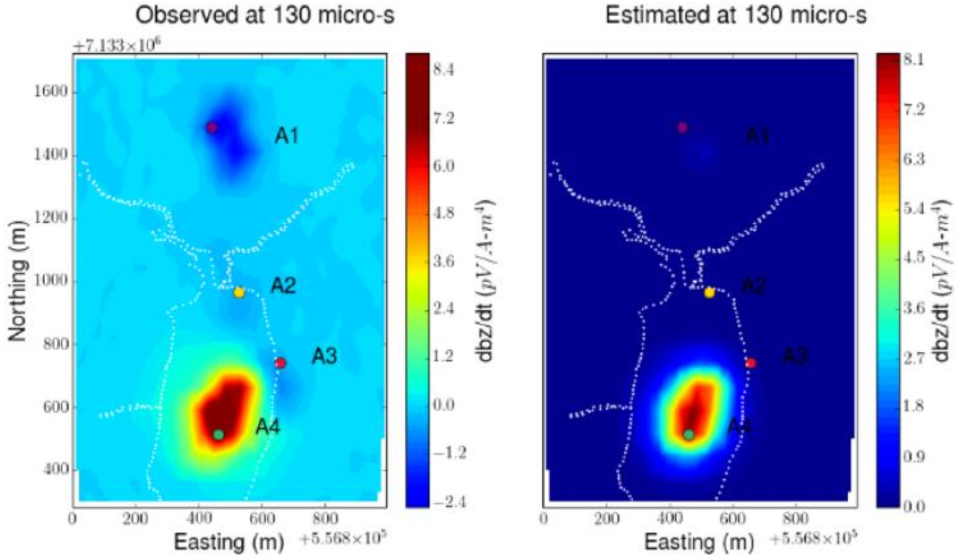
Estimate intrinsic IP parameters

IP = Observation - Fundamental

$$d^{IP} = F[\sigma(t)] - F[\sigma_\infty] \qquad F[\cdot] : \text{Maxwell's operator}$$

130 micro-s

Observed **Fundamental**



Step 2: EM-decoupling

- Invert TEM data, to recover
- **Compute IP datum Remove EM responses**
- Linearized equations
- Invert d^{IP} data, recover pseudo-chargeability
- Estimate intrinsic IP parameters

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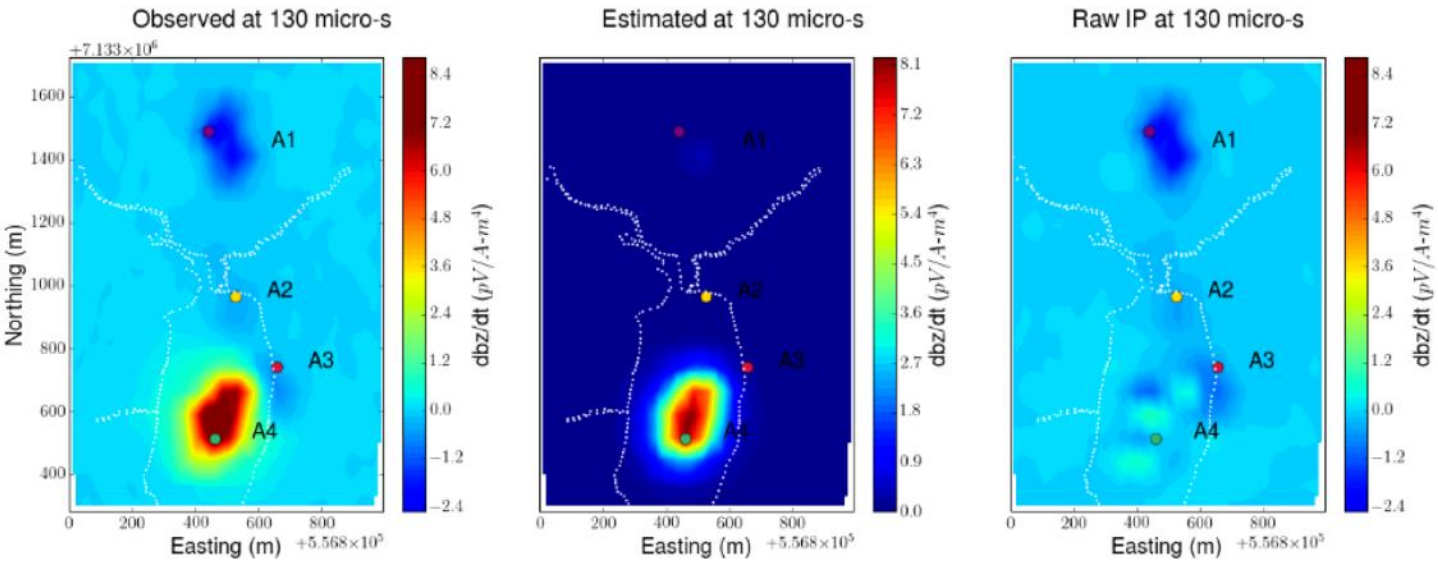
130 micro-s

Observed **Fundamental** **IP**



Step 2: EM-decoupling

Invert TEM data, to recover

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Linearized equations

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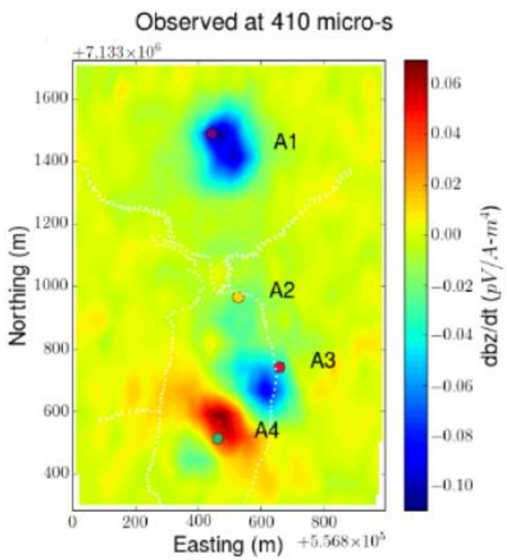
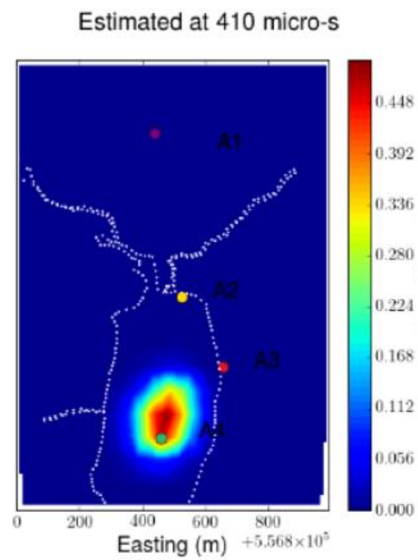
410 micro-s

Observed



Fundamental



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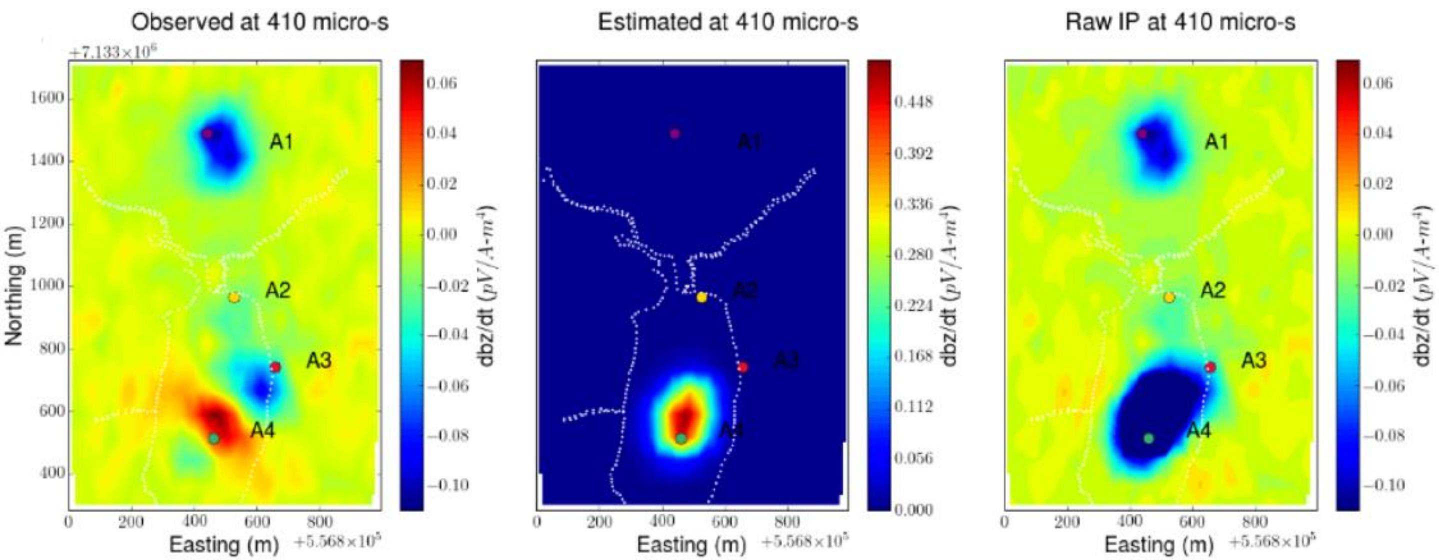
410 micro-s

Observed **Fundamental** **IP**



Step 3: 3D IP inversion

Invert TEM data, to recover

Compute IP datum Remove EM responses

Linearized equations

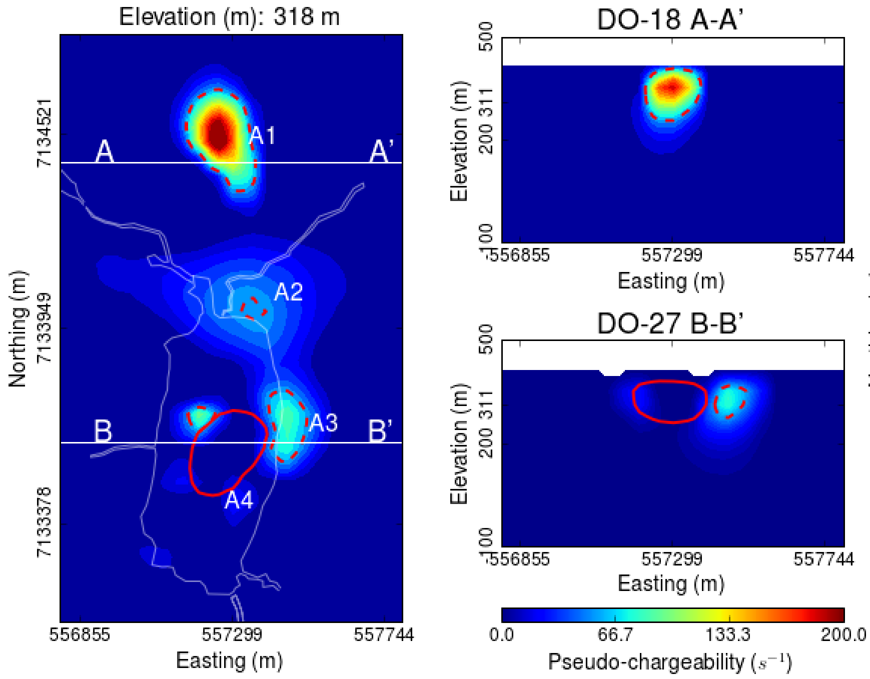
Invert d^{IP} data, recover pseudo-chargeability

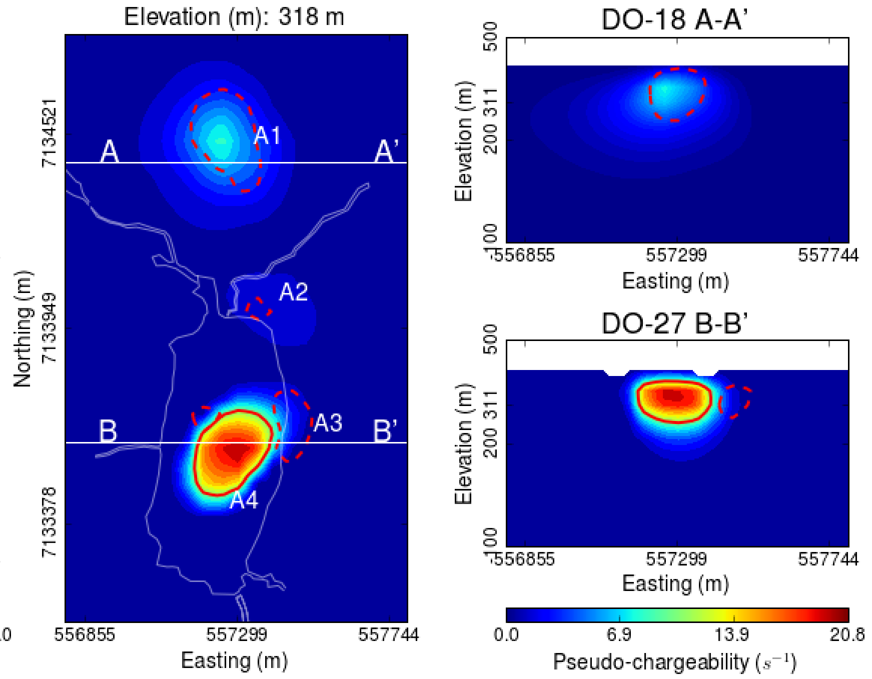
Estimate intrinsic IP parameters

Recovered 3D pseudo chargeability

130 micro-s

410 micro-s





Step 4: Estimate η and τ

Invert TEM data, to recover

Compute IP datum Remove EM responses

Linearized equations

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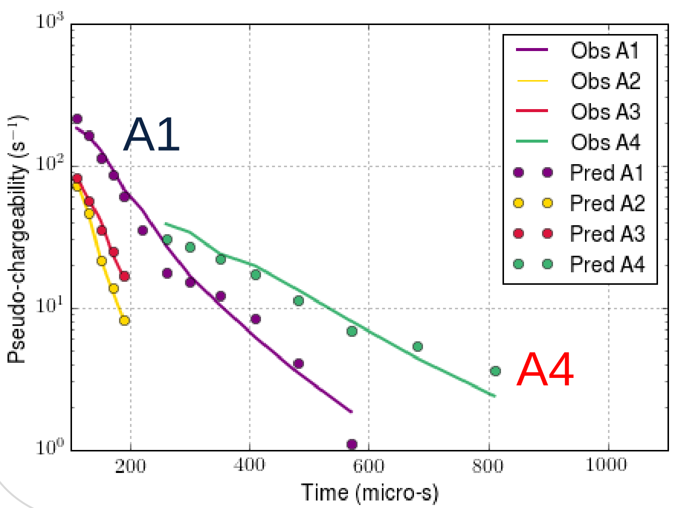
Estimate intrinsic IP parameters

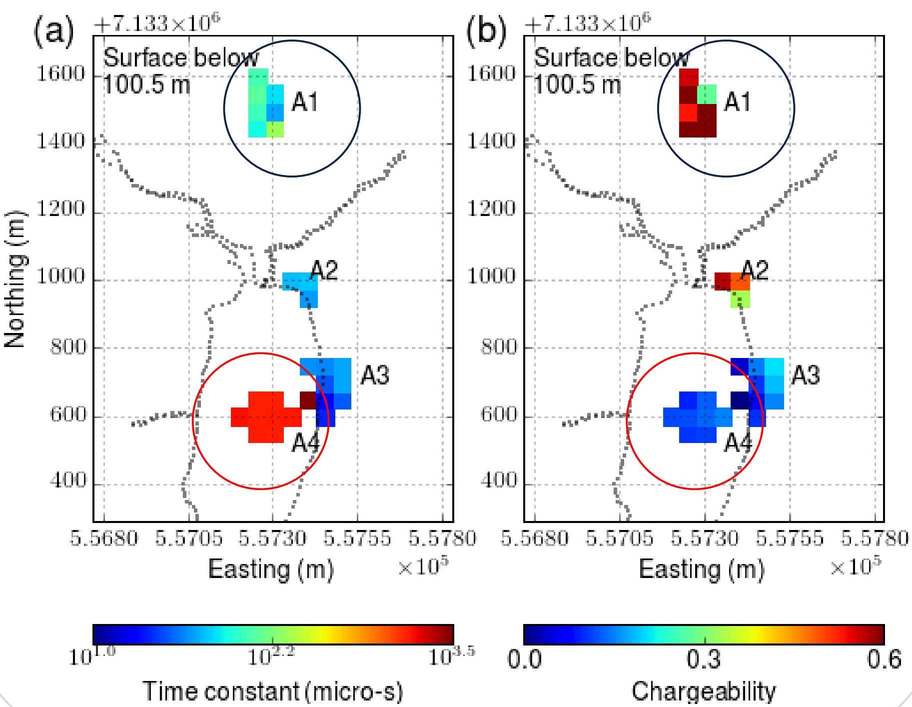
Pseudo-chargeability at i-th pixel

$$\tilde{\eta}_i = f(\sigma_\infty, \eta, \tau, c; t)$$

Time curves

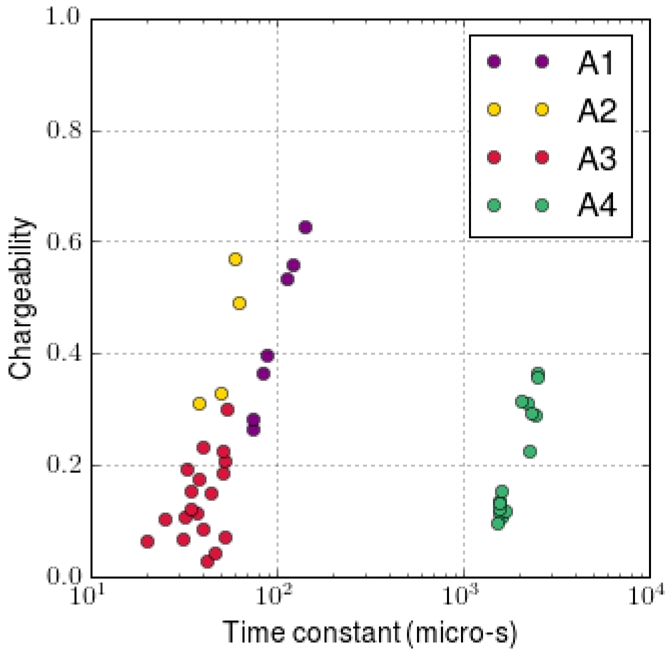


Recovered τ and η



Step 4: Estimate η and τ

- Comparison with rock samples



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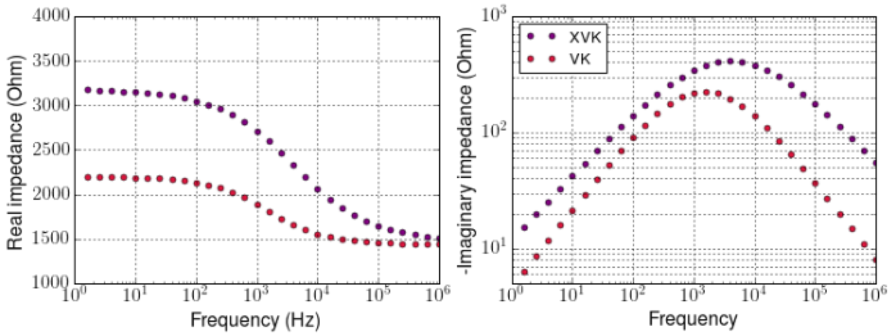
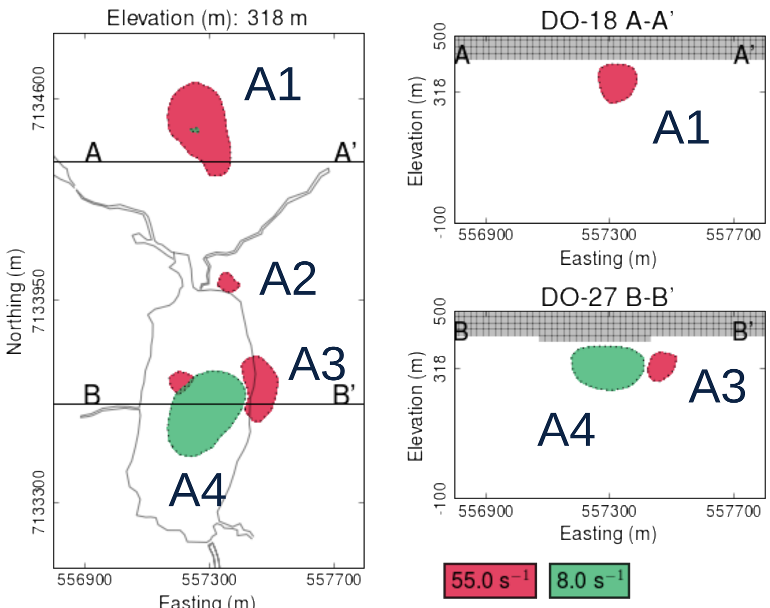
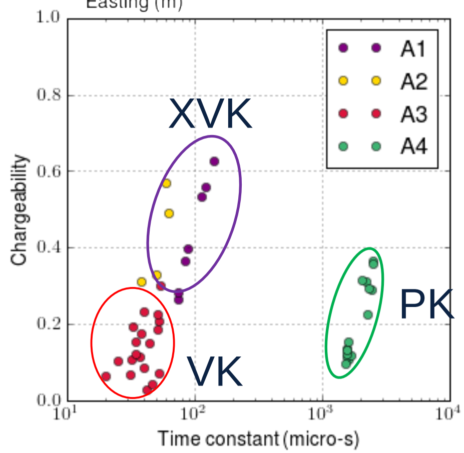


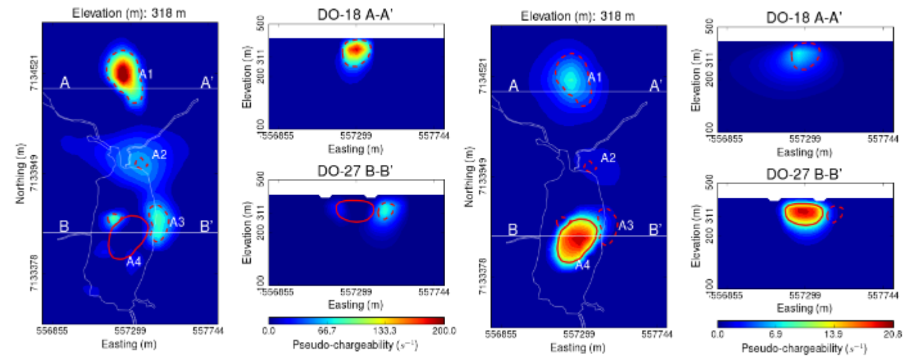
What can we infer from IP?

Anomalous pseudo-chargeability





Pseudo-chargeability

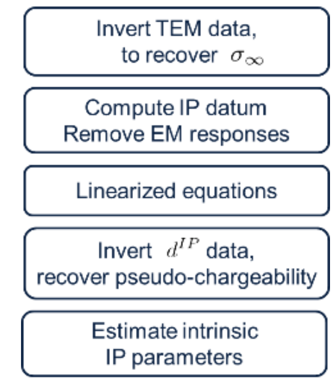


- A4 can be distinguished from A1-A3 (time constant)
- A3 can be distinguished from A1-A2 (chargeability)

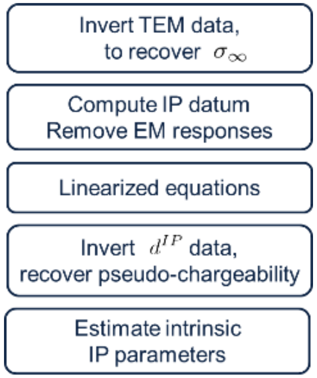
- DO-18 pipe: small time constant
- DO-27 pipe: two different chargeable bodies (small and large time constant)

Conclusions

- We can invert airborne TEM data
  - 3D TEM-IP inversion workflow

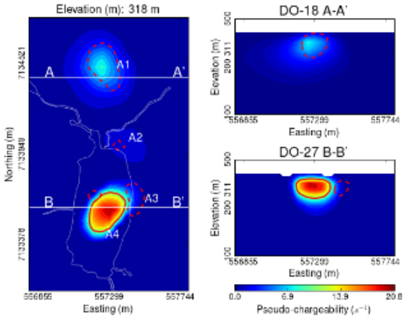


Conclusions



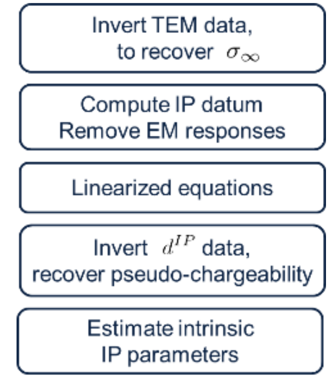
- We can invert airborne TEM data
  - 3D TEM-IP inversion workflow

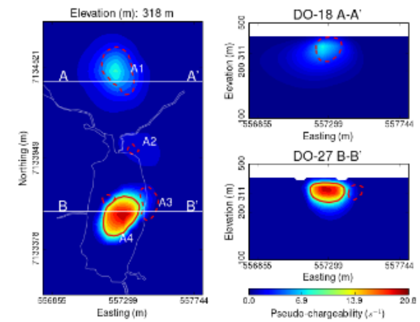
- Apply this to TKC field example

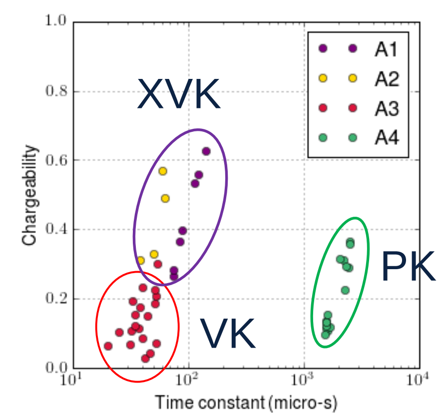


Conclusions

- We can invert airborne TEM data
  - 3D TEM-IP inversion workflow
- Apply this to TKC field example
- Is our question answered?
  - “Can airborne IP helps kimberlite exploration?”



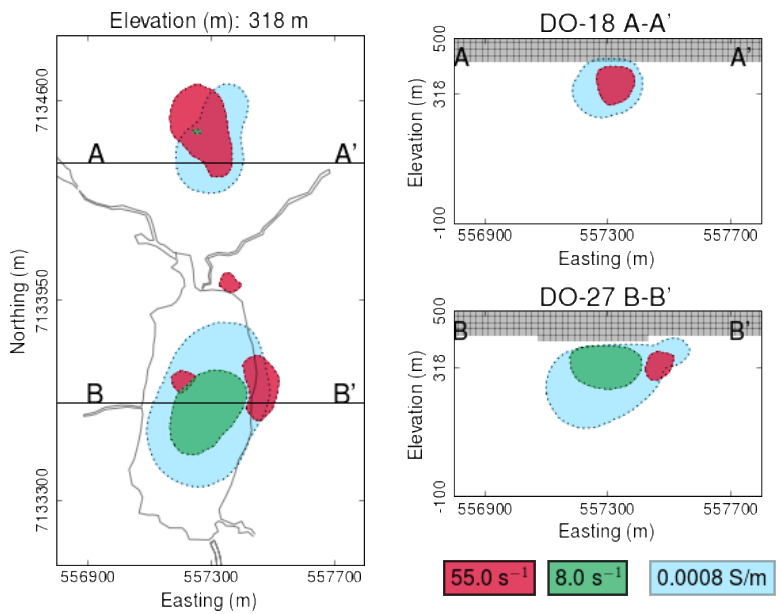


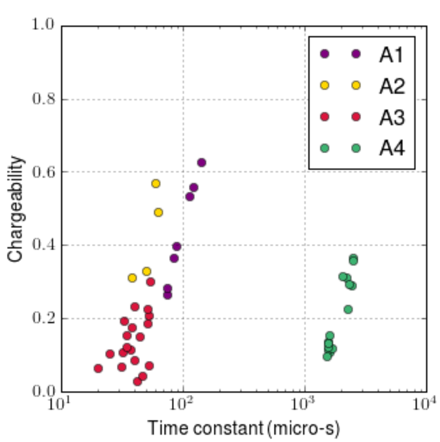


Thank you

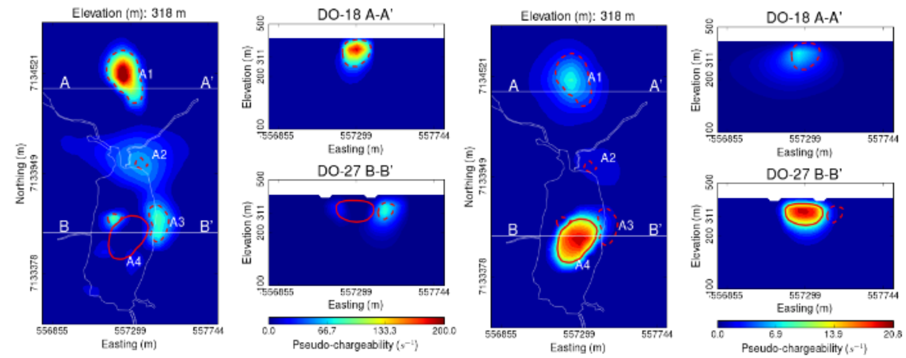
What can we infer from IP and σ ?

Anomalous contour map

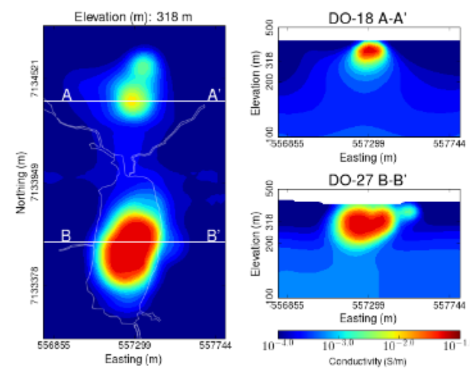




Pseudo-chargeability



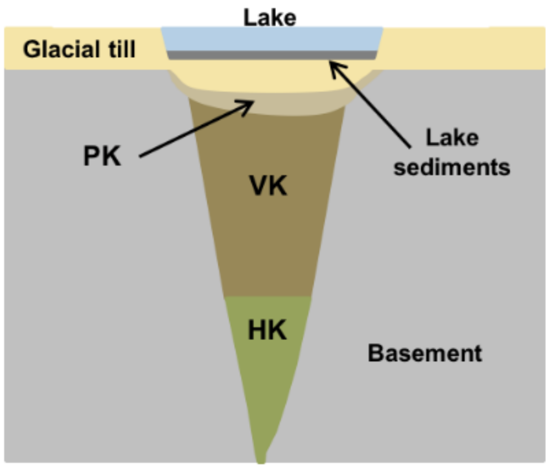
Conductivity



- Most of IP bodies have high conductivity

"Can airborne IP help?"

Kimberlite pipe structure



Devriese et al. (2016)

Physical Properties

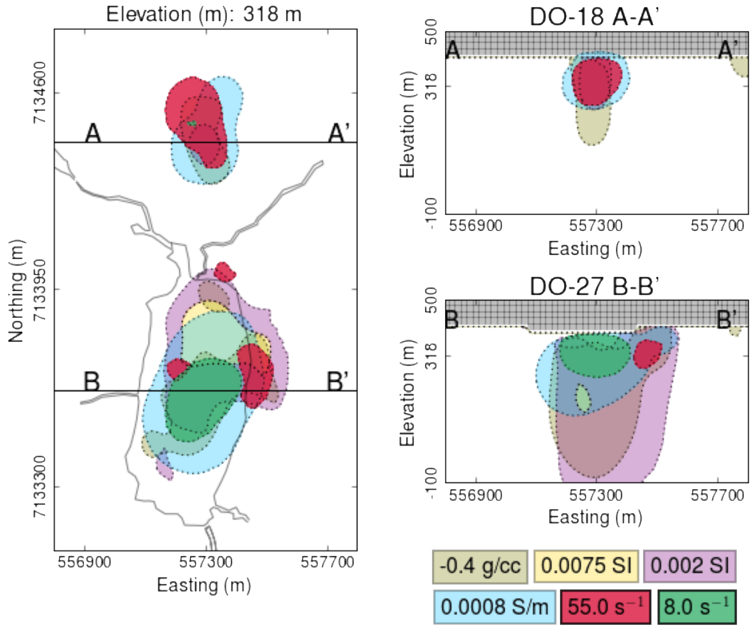
Division	Dens.	Susc.	Cond.	**Charg.**
XVK	Low	Med.	High	?
VK	Low	Med.	High	?
PK	Low	Med.	High	?
HK	Low	High	Med.	?
Till	Med.	Low	Med.	?
Host rock	Med.	Low	Low	?

- Various Rock units:
  - Kimberlites: XVK/VK/PK/HK
  - Till, Host rock
- Different physical prop.
- Various airborne geophysical surveys:
  - Mag / Gravity
  - AFEM / ATEM

"Everything inverted in 3D"

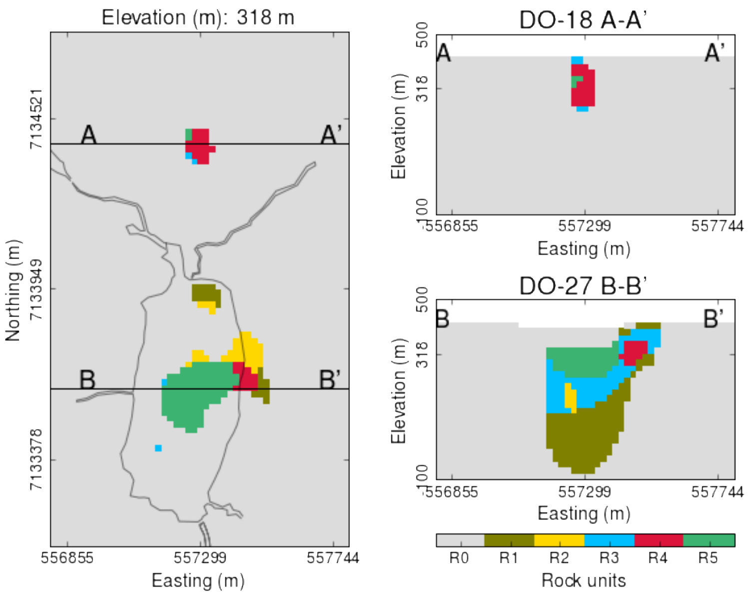
A final petro physical model

From **Geophysics**



A final petro physical model

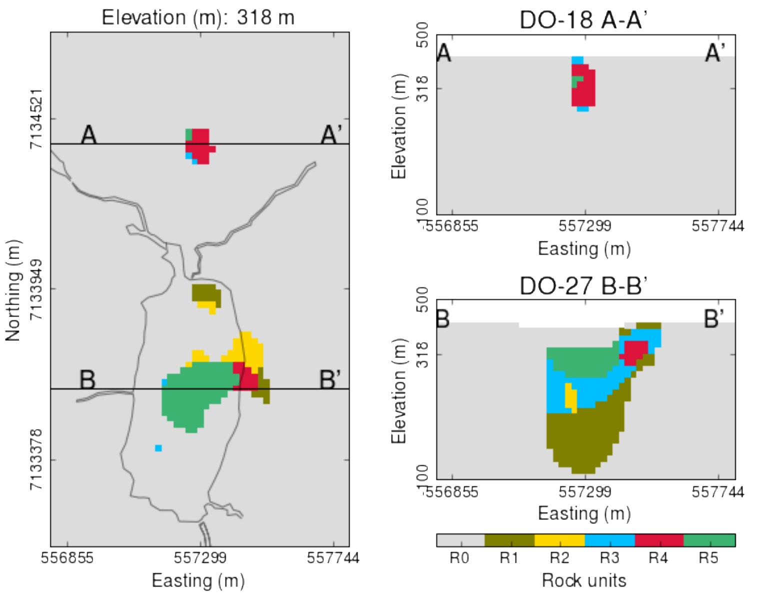
From **Geophysics**



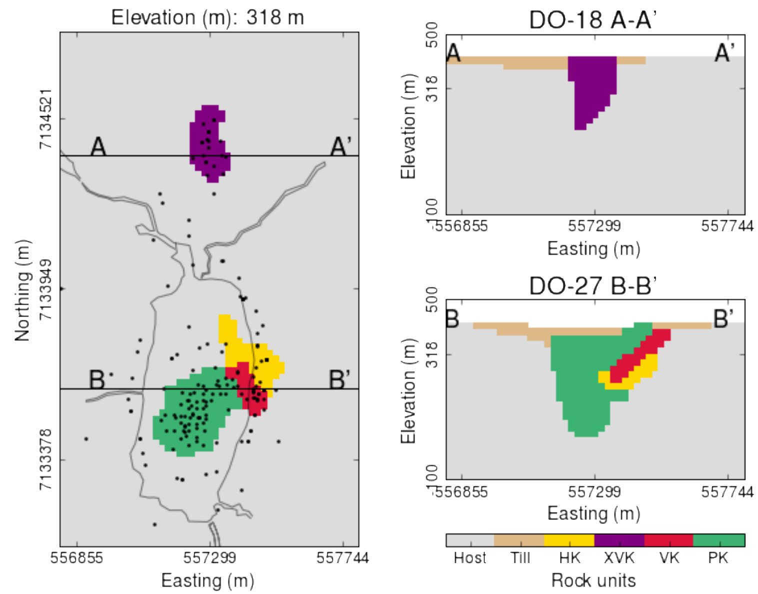
Division	Dens.	Susc.	Cond.	Early Charg.	Late Charg.
R0	Med.	Low	Low	Low	Low
R1	Low	Med.	Low	Low	Low
R2	Low	High	Low	Low	Low
R3	Low	Med.	High	Low	Low
R4	Low	Med.	High	Low	High
R5	Low	Med.	High	High	Low

A final petro physical model

From **Geophysics**



From **Drillings**



Division	Dens.	Susc.	Cond.	Early Charg.	Late Charg.	**Kimberlites**
R0	Med.	Low	Low	Low	Low	?
R1	Low	Med.	Low	Low	Low	?
R2	Low	High	Low	Low	Low	HK
R3	Low	Med.	High	Low	Low	?
R4	Low	Med.	High	Low	High	PK
R5	Low	Med.	High	High	Low	VK, XVK