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

An example of creating a geologic rock model from geophysical data

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

Setup

Physical Properties

Surveys

Data

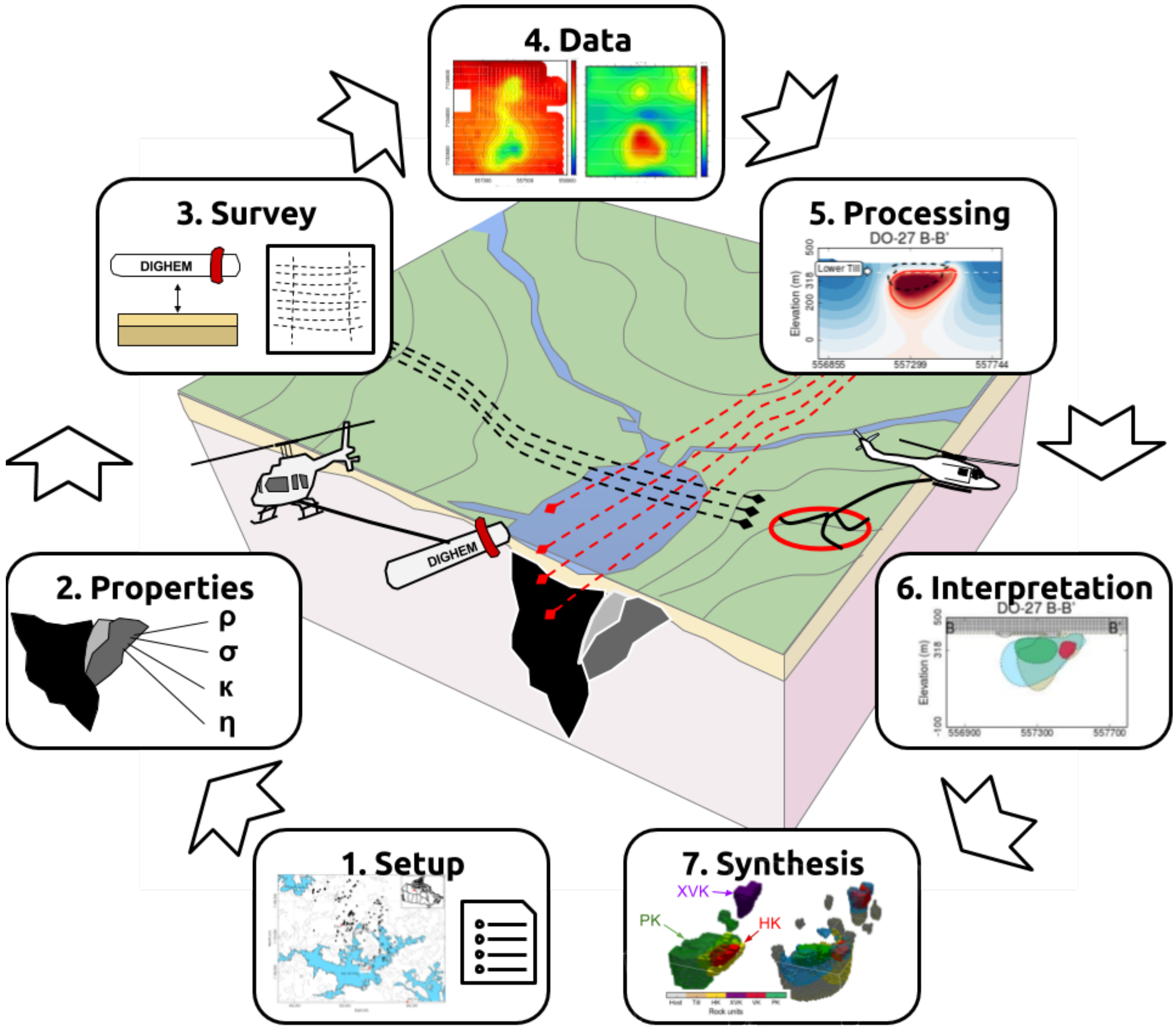
Inversion

κ	ρ	σ	η

Interpretation

Synthesis

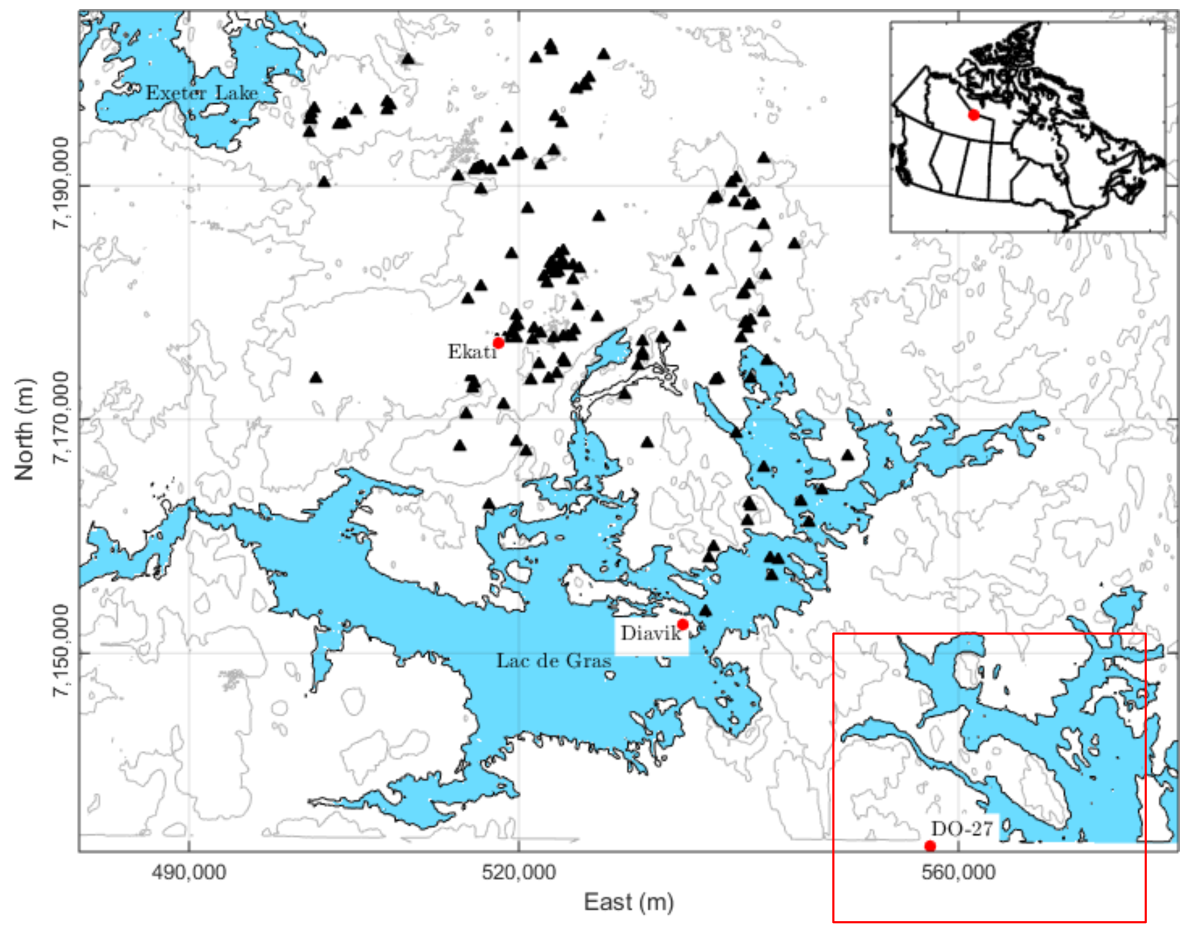
Seven steps



1. Setup
2. Properties
ρ
σ
κ
η
3. Survey
DIGHEM
4. Data
5. Processing
DO-27 B-B'
Lower Till
Elevation (m)
6. Interpretation
DO-27 B-B'
7. Synthesis
XVK
PK
HK
Rock units
DIGHEM

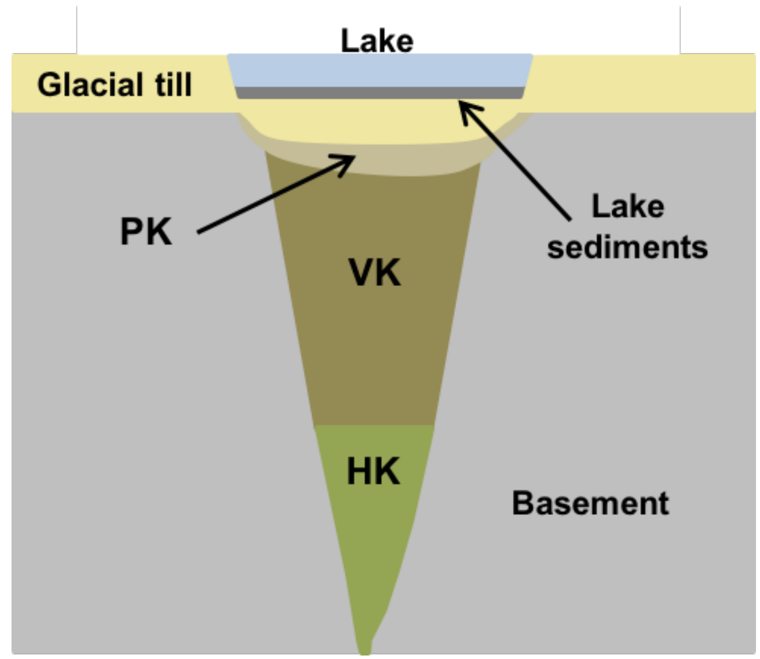
Diamonds in NWT

- Canada:
  - world's 3rd largest diamond producer
- Northwest Territories:
  - Ekati and Diavik,
- Tli Kwi Cho (TKC)
  - 2 kimberlite pipes

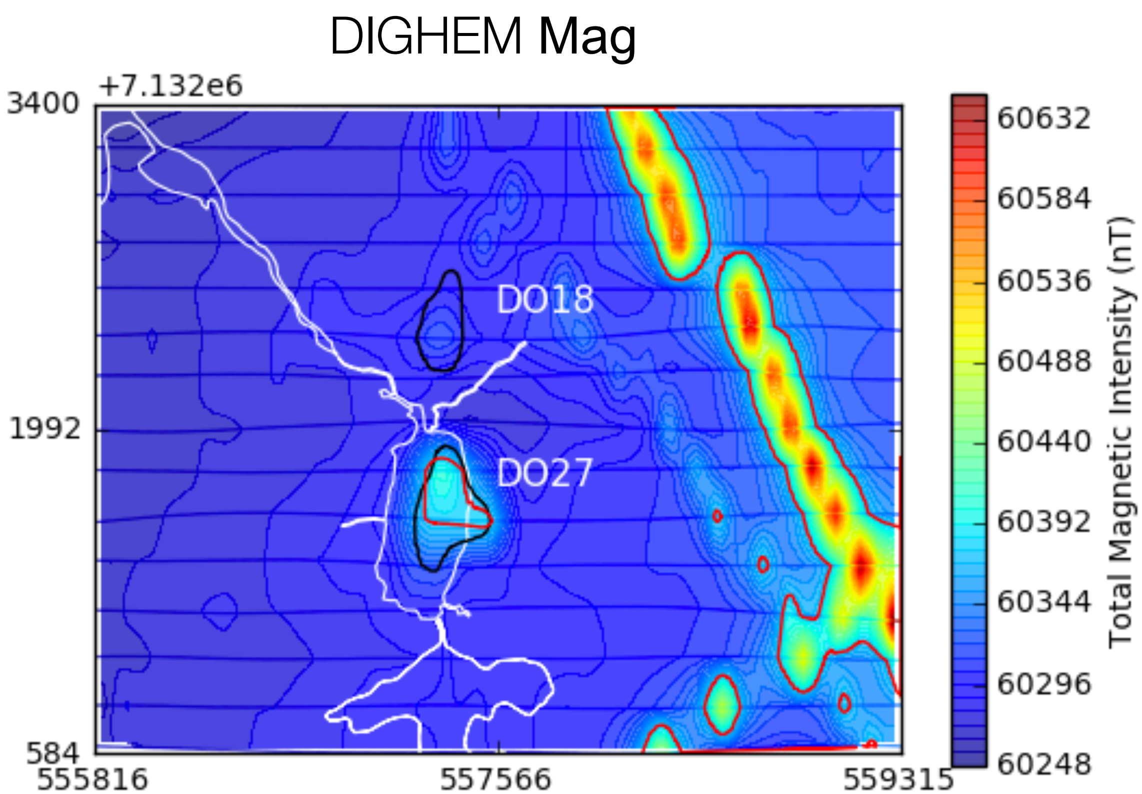


Geology of kimberlite pipes

- Kimberlites emplaced in granite
- Three main kimberlite units
  - Hypabyssal (HK): intrusive, igneous, non-fragmented
  - Volcaniclastic (VK): extrusive and fragmental
  - Pyroclastic (PK): similar to VK, more violent, and deposited after an explosive event



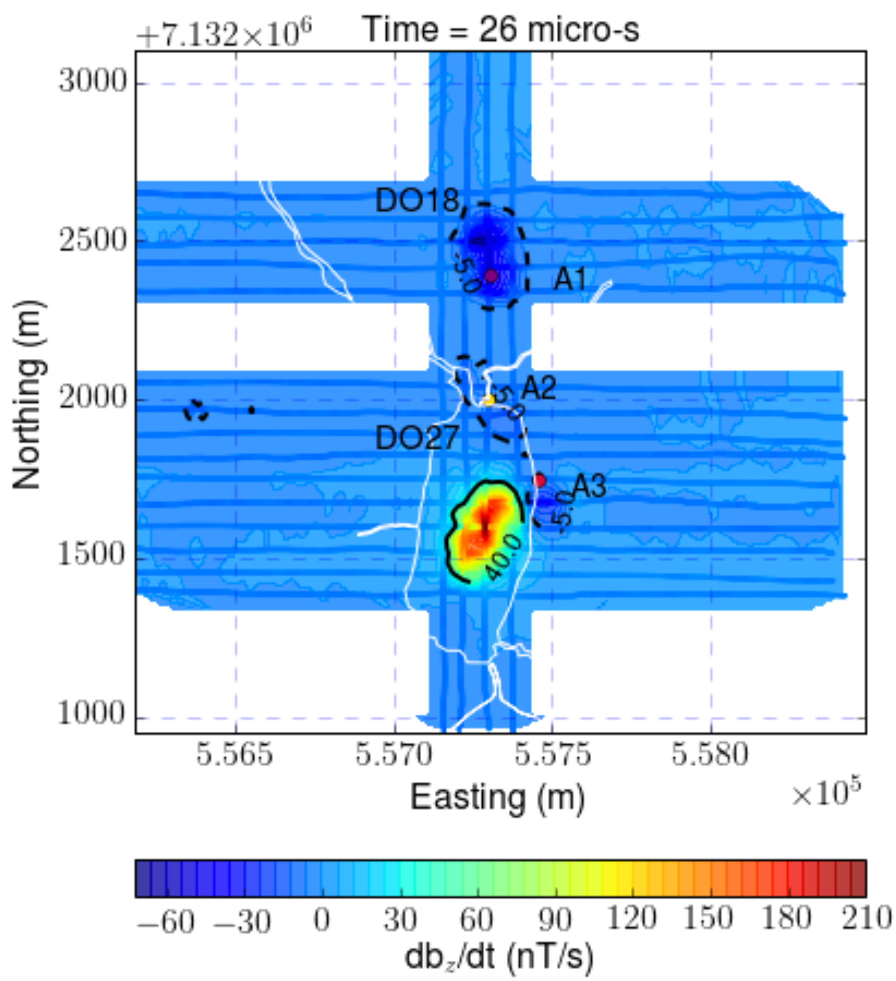
Exploration challenge



- 1992: drilled based on mag anomaly
  - disappointing diamond content
  - Poor location of initial drill holes
- How much information can be obtained using airborne geophysical data and 3D inversion technology?

Technical challenge

AeroTEM II data

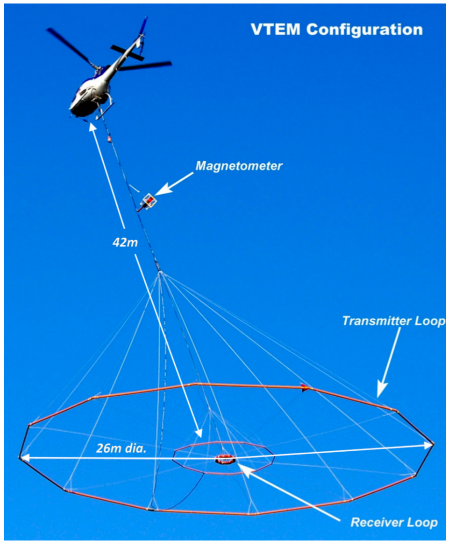


- Negative transients
  - AeroTEM (I and II), and VTEM
- How do we invert:
  - Conductivity
  - Chargeability
- What impact can polarization information have on kimberlite exploration?

Questions

Using only airborne geophysics:

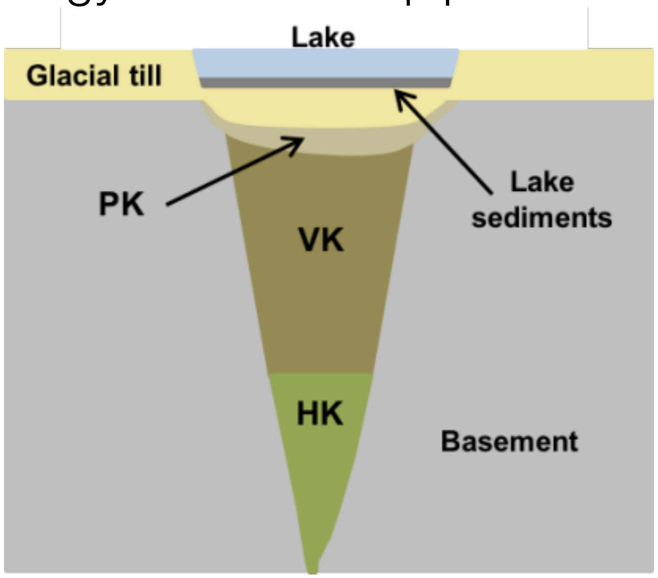
- gravity
- magnetics
- EM



- How much information about a kimberlite complex can be extracted with modern 3D inversion techniques?
- Can we create a geologic rock model using airborne geophysical data sets?

Physical Properties

Geology of Diamond pipe



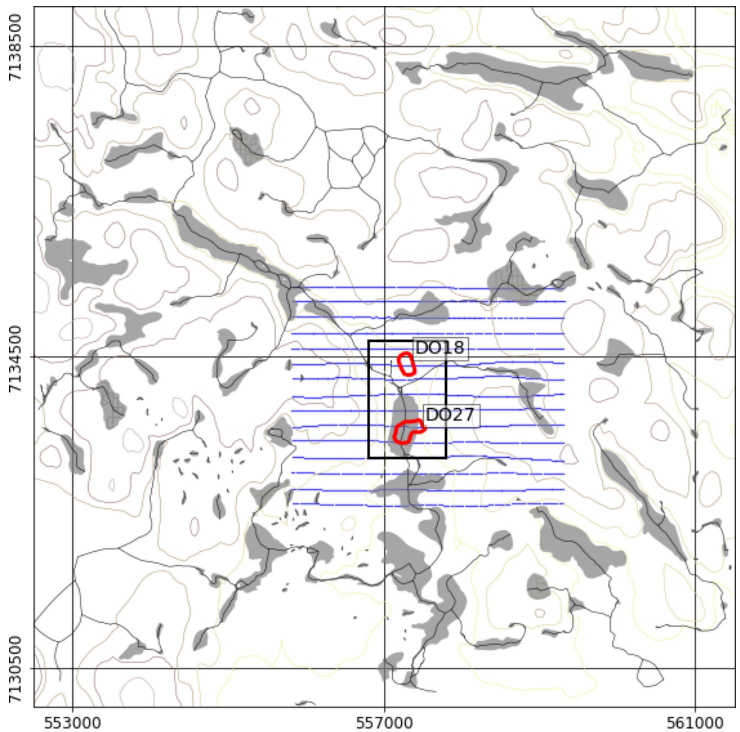
- Overall kimberlite: low density
- HK: high susceptibility
- VK and PK:
  - Low-moderate susceptibility
  - Moderate-high conductivity

Physical property table

Rock Unit	Density	Susceptibility	Conductivity	Chargeability
Glacial till	Moderate	None	Moderate-high	Low
Host rock	Moderate	None	Low	Low
HK	Low-moderate	High	Low-moderate	Low
VK	Low	Low-moderate	Moderate-high	High
PK	Low	Low-moderate	Moderate-high	Moderate-high

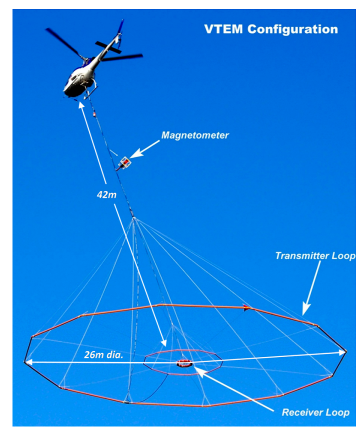
Table of physical properties for typical kimberlitic rocks found in the Lac de Gras region.

Surveys



System	Year	Data
DIGHEM	1992	FEM, mag
Falcon	2001	Grav grad
AeroTEM II	2003	TEM, mag
VTEM	2004	TEM, mag

DIGHEM

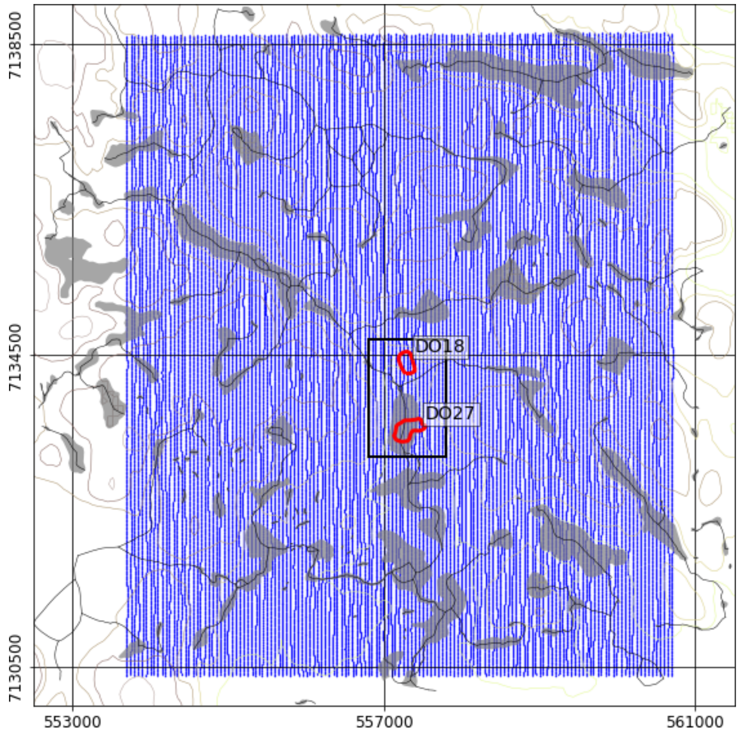


VTEM

AeroTEM

Various ground surveys as well: NanoTEM, magnetic, and gravity

Surveys



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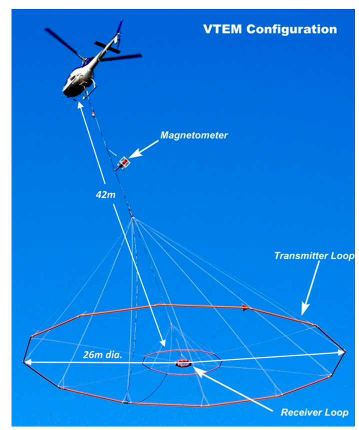
DIGHEM



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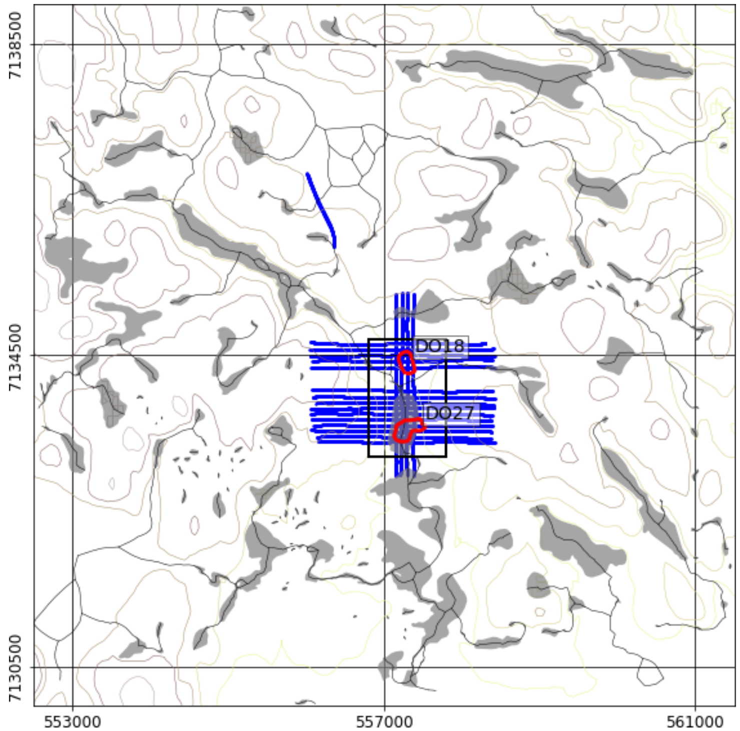

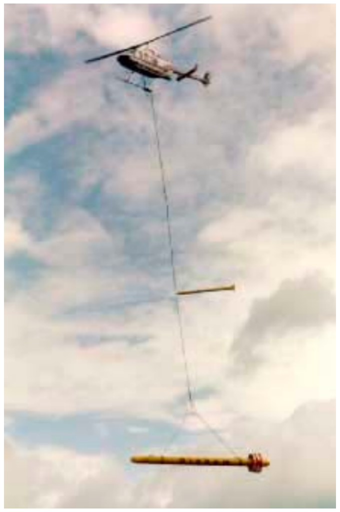

DIGHEM

System	Year	Data
DIGHEM	1992	FEM, mag
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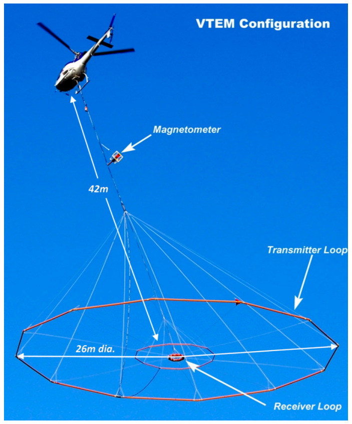
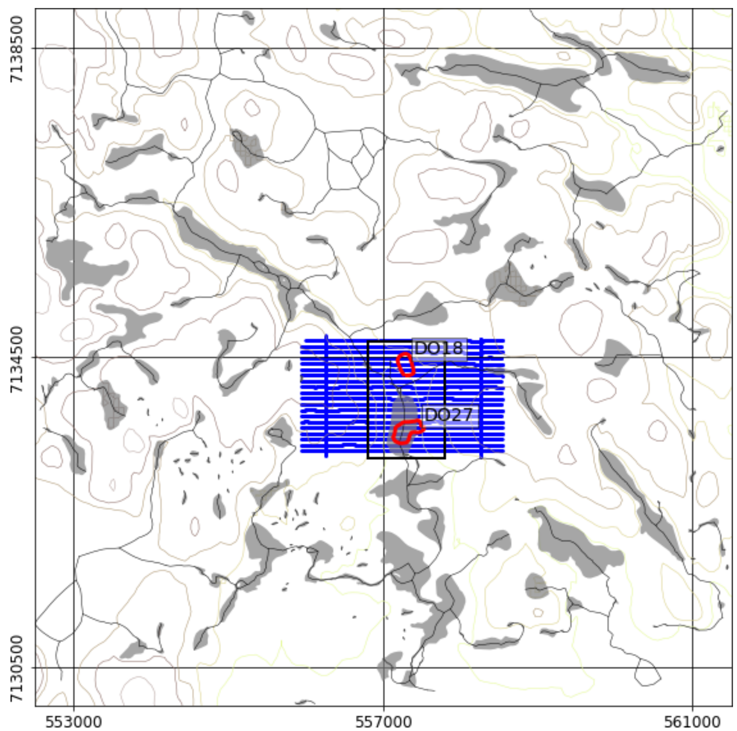


VTEM

AeroTEM

Various ground surveys as well: NanoTEM, magnetic, and gravity

Surveys



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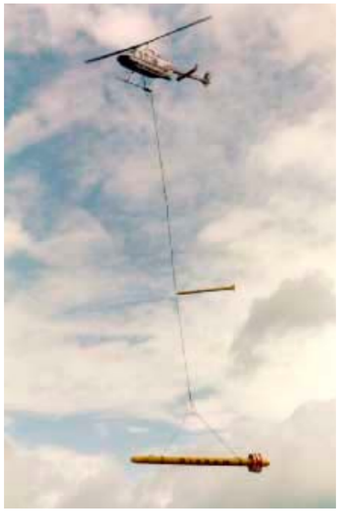
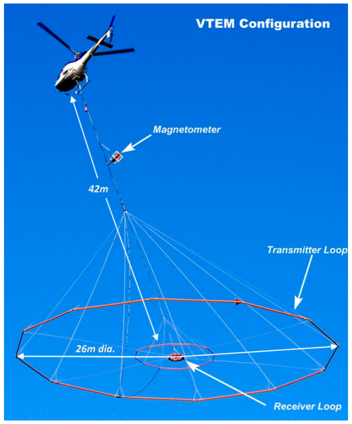


DIGHEM

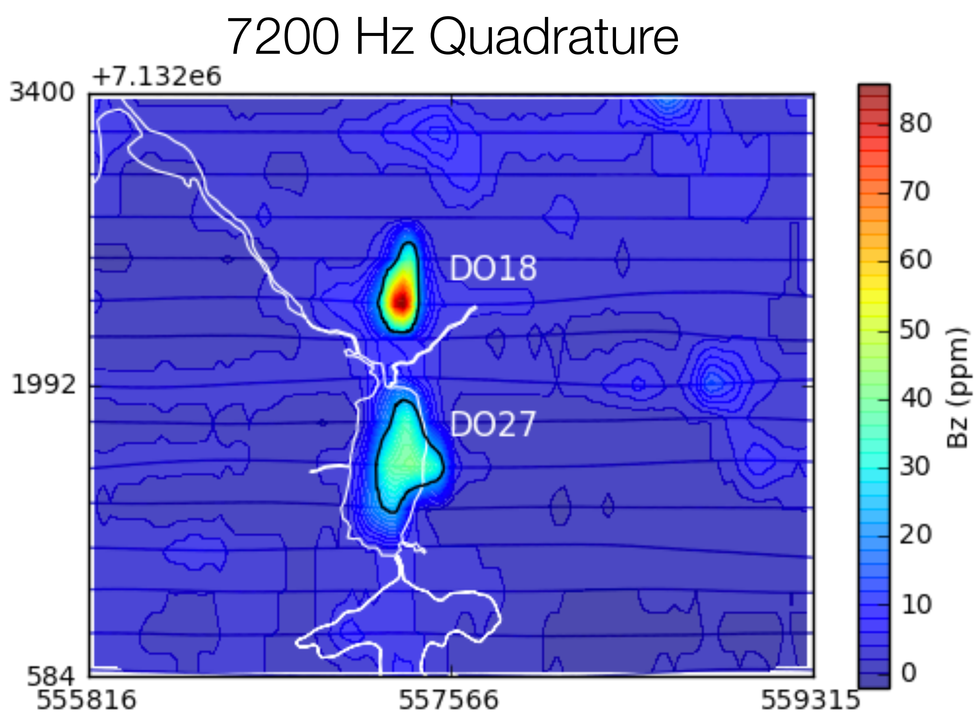


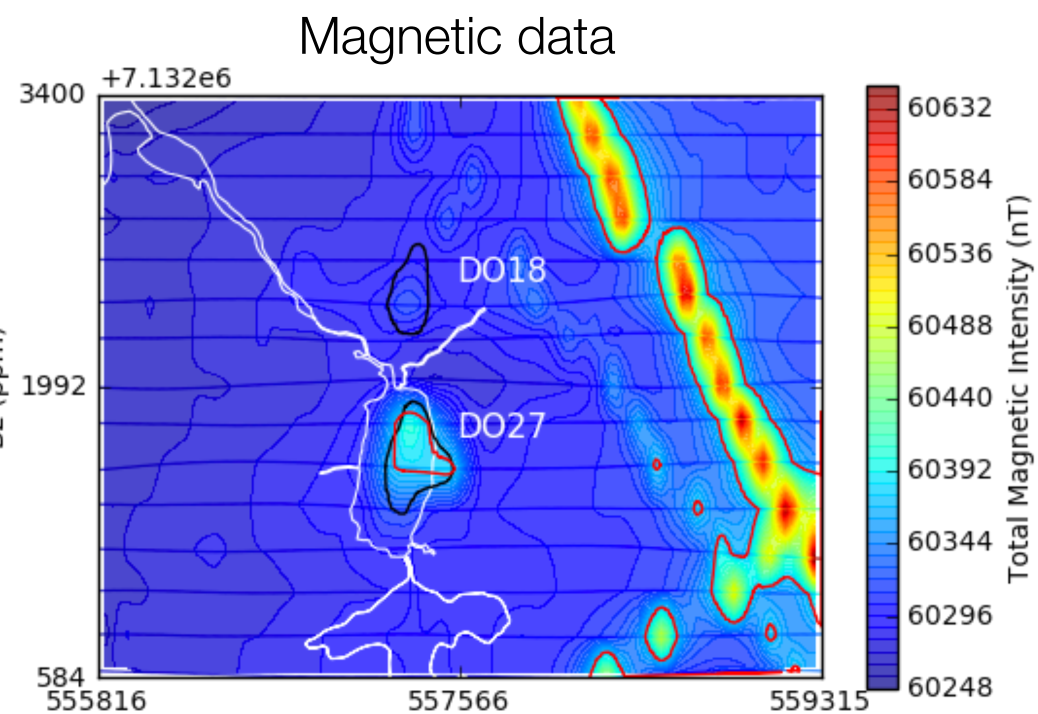
VTEM

AeroTEM

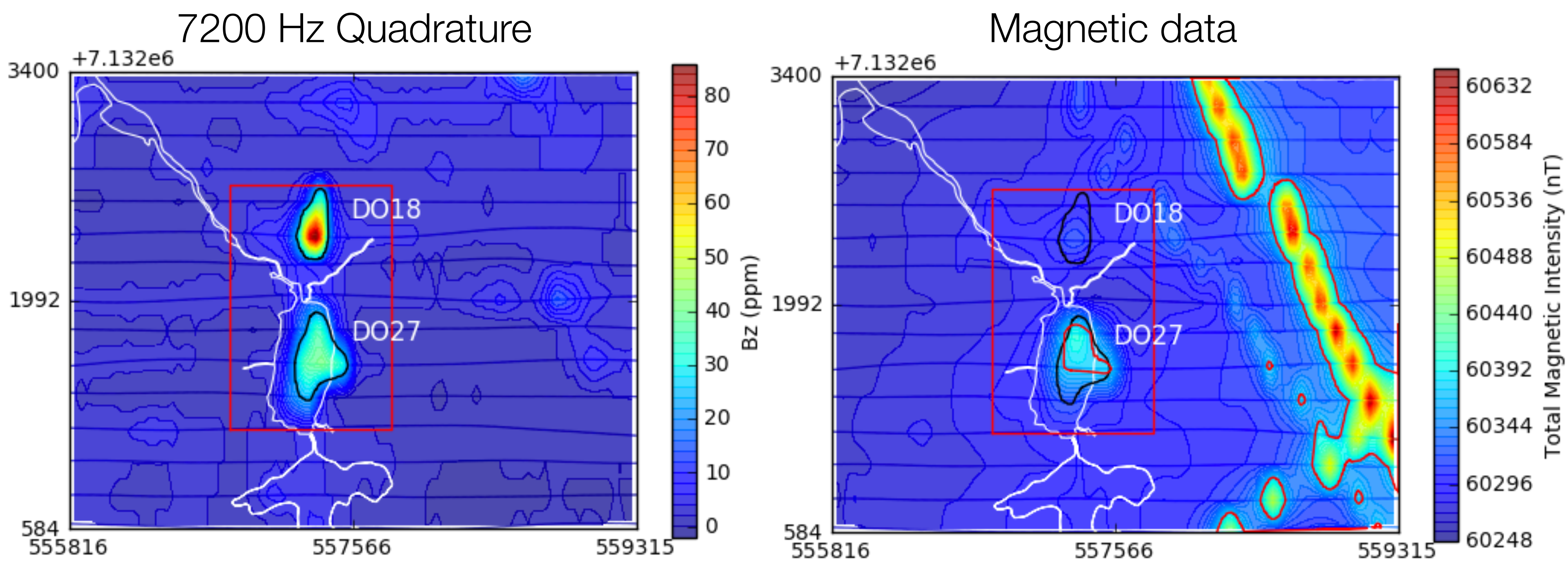
Various ground surveys as well: NanoTEM, magnetic, and gravity

DIGHEM data (broad scale)



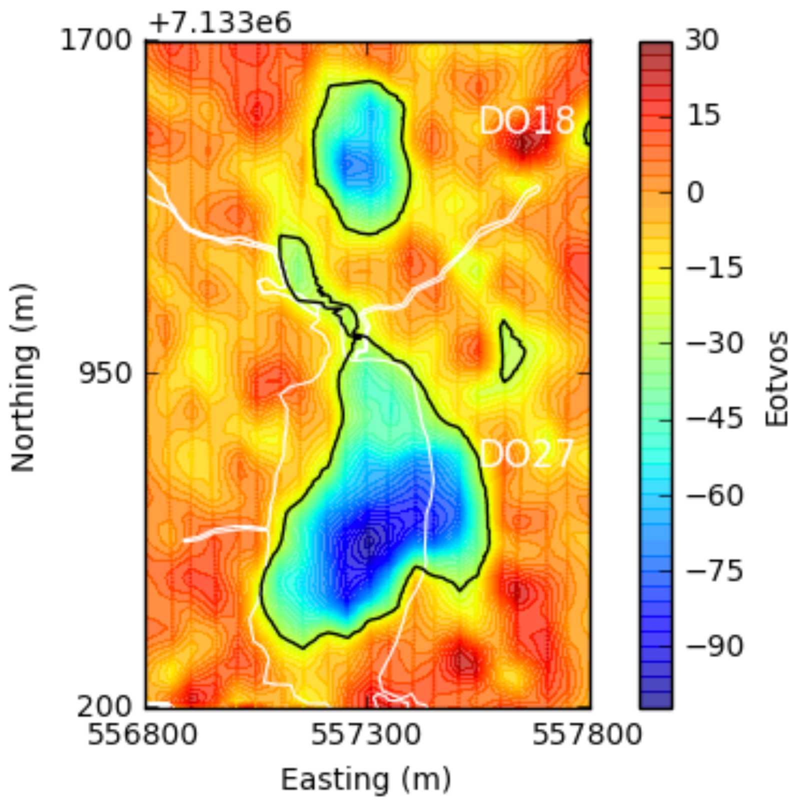


DIGHEM data (broad scale)

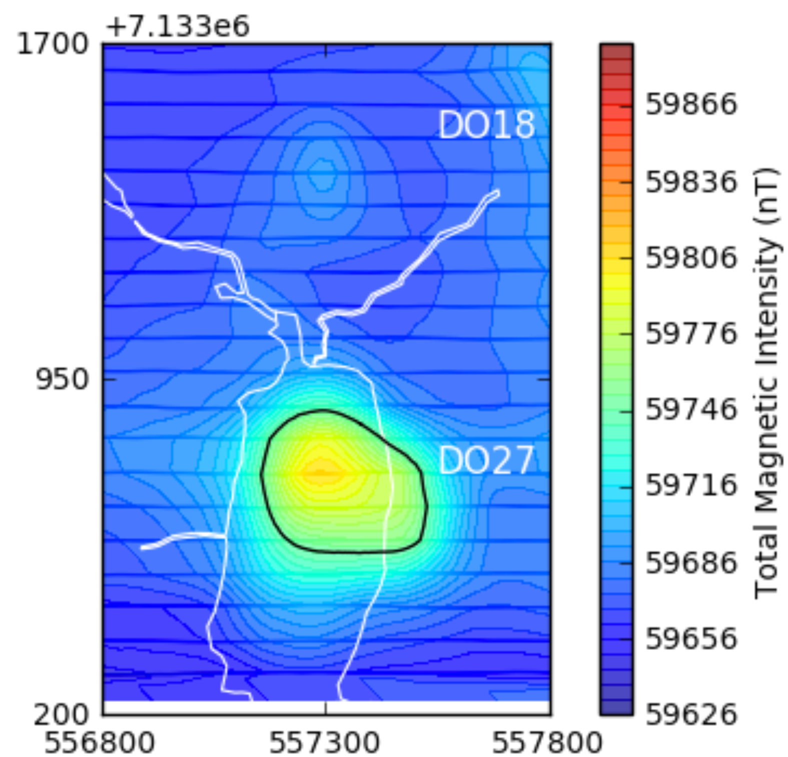


Potential field data

Gravity gradiometry data

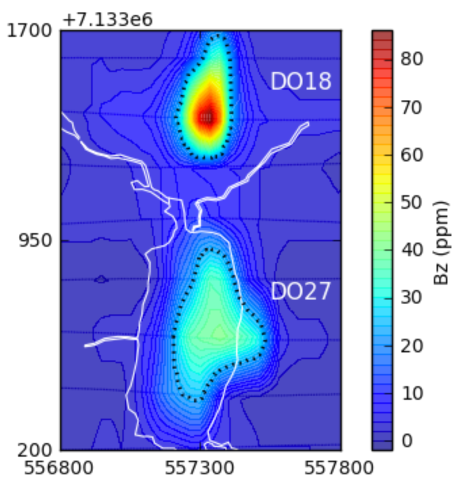


VTEM mag data

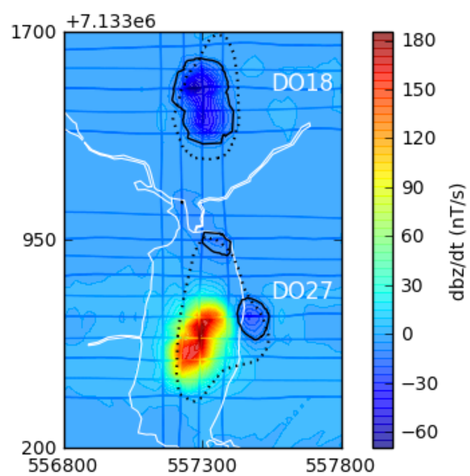


EM data (close to two pipes)

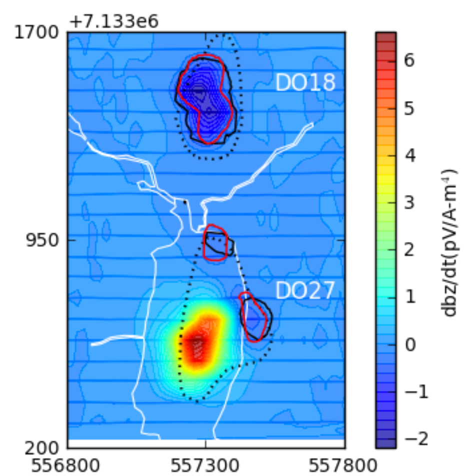
Dighem
(1992)



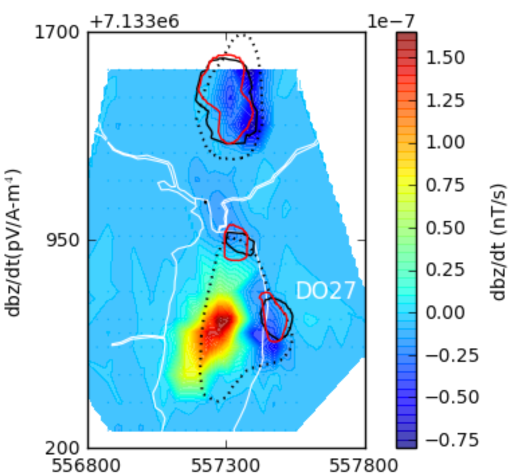
AeroTEMII
(2003)



VTEM
(2004)



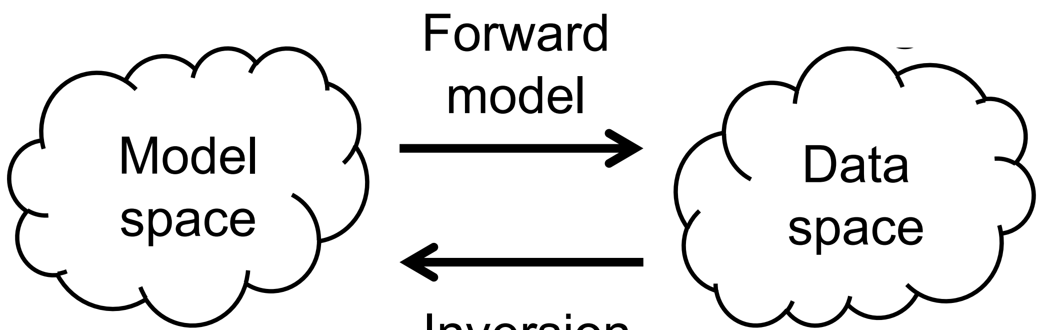
NanoTEM
(1993)



Inversion: a quick overview

- Forward modeling

$$\mathcal{F}[m] = d$$

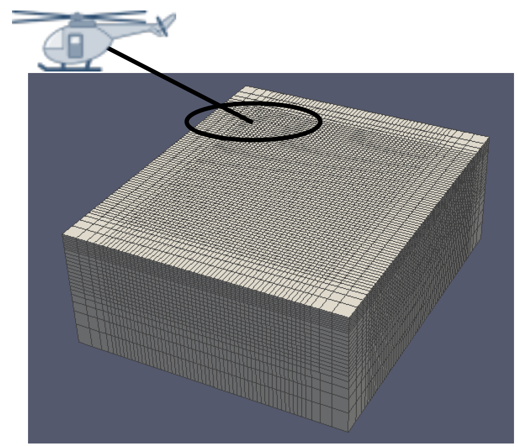


- Minimize objective function

$$\phi = \phi_d + \beta\phi_m$$

$$\phi_d = \|W_d(\mathcal{F}[m] - d)\|_2^2$$

$$\phi_m = \alpha_s\|W_s(m - m_0)\|_2^2 + \sum_{i=1}^{3} \alpha_i\|W_i(m - m_0)\|_2^2$$



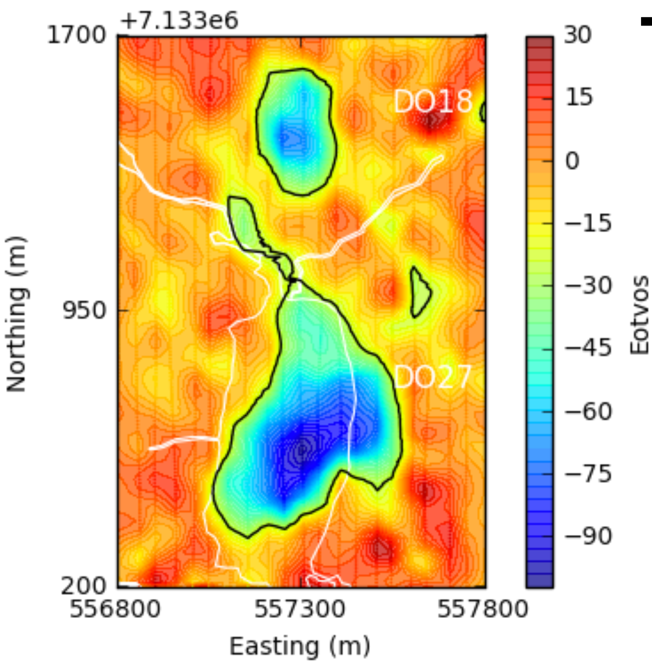
UBC codes

SimPEG

Potential fields

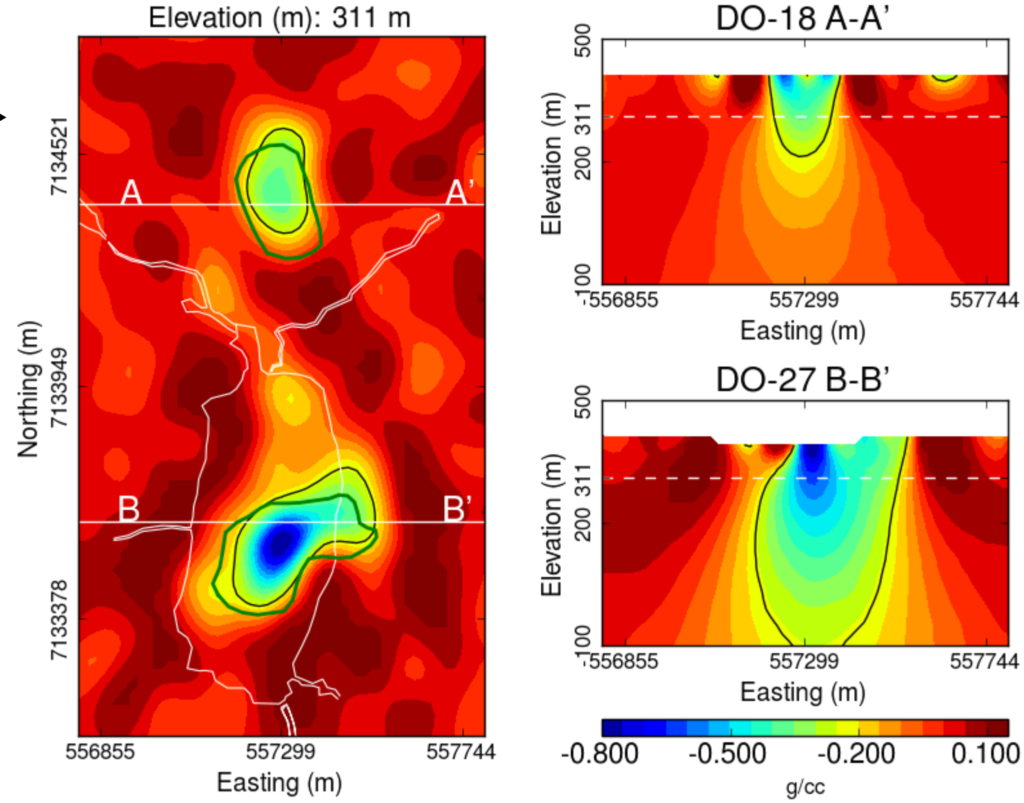
Density: ρ

Gravity gradiometry data



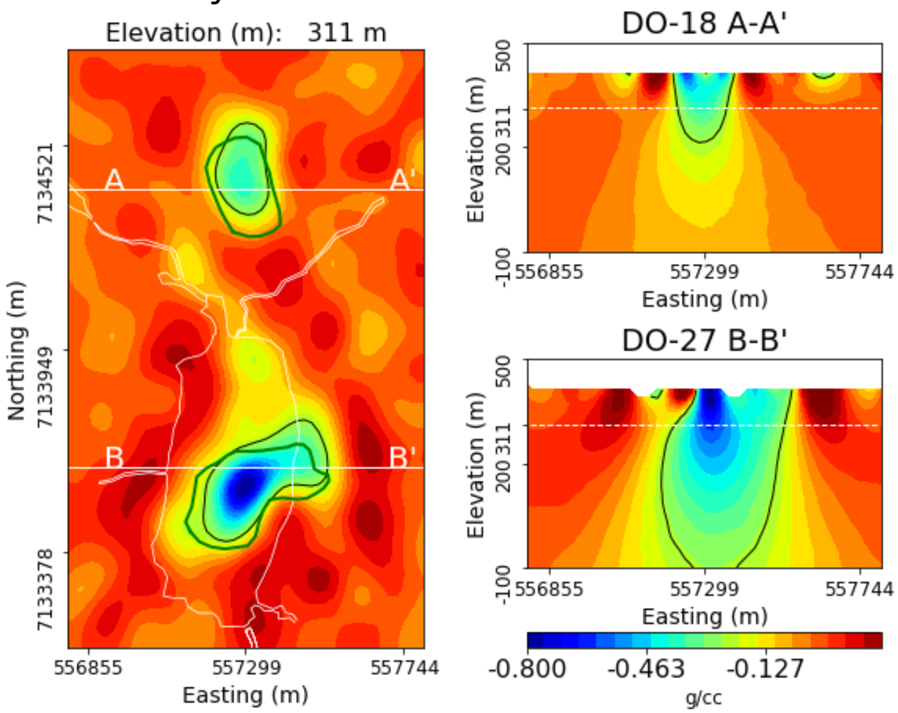
Inversion

Recovered 3D model

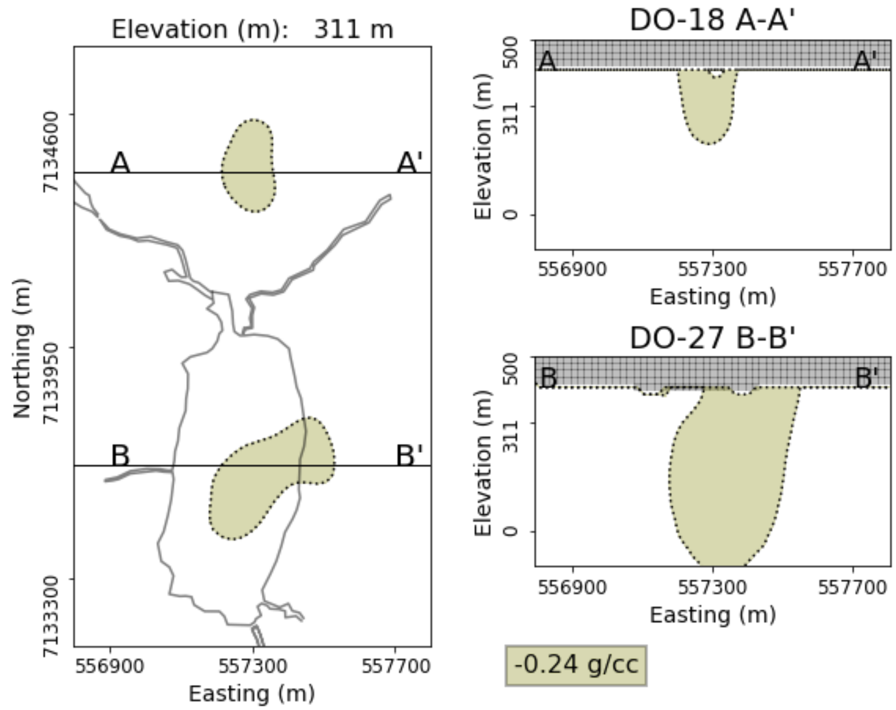


ρ anomalies

Density model

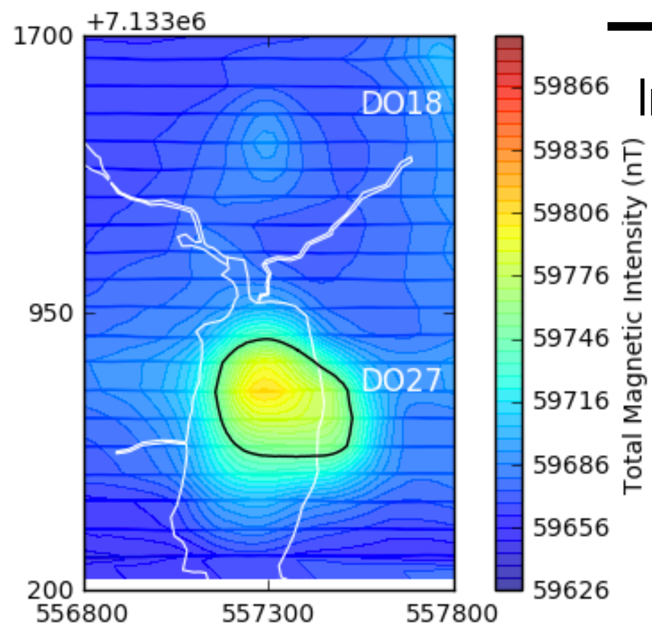


Anomaly contours



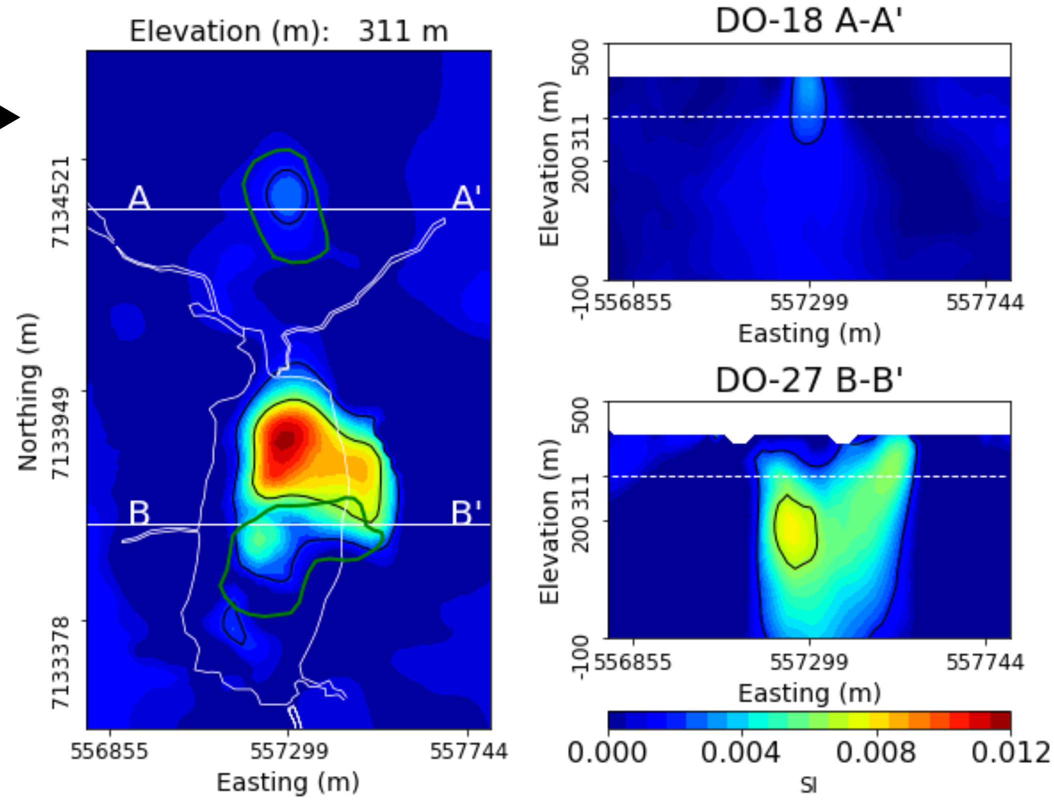
Susceptibility: κ

VTEM Mag data



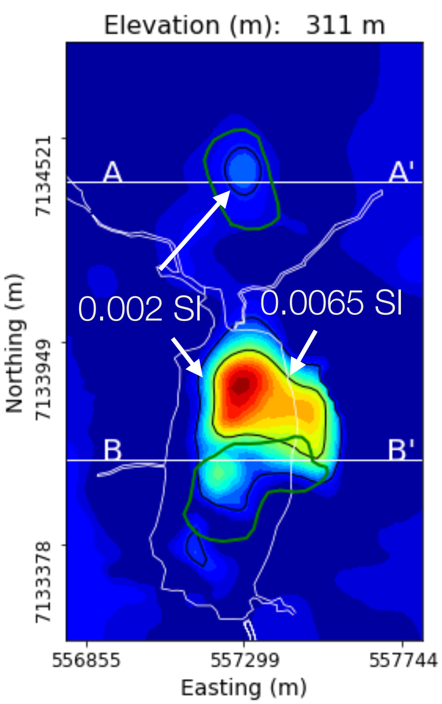
Inversion

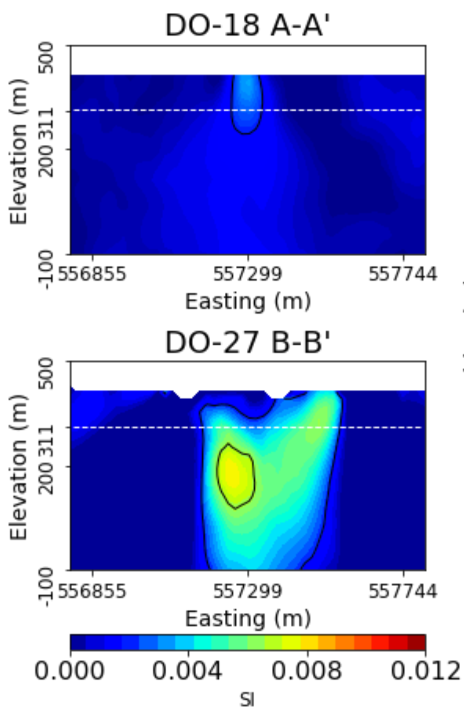
Recovered 3D model



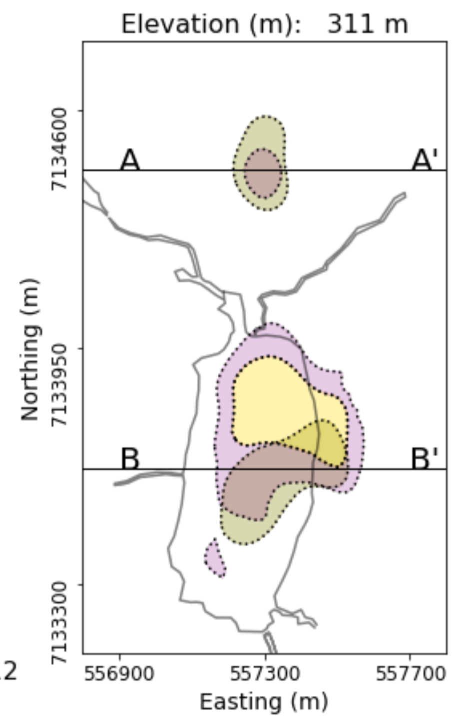
κ and ρ anomalies

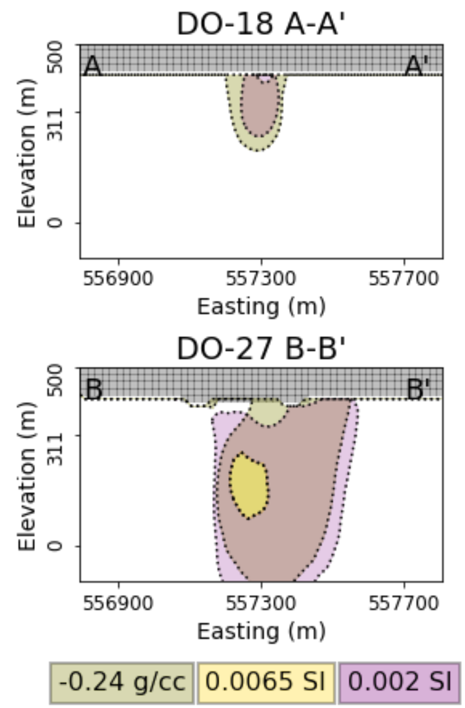
Susceptibility model





Anomaly contours

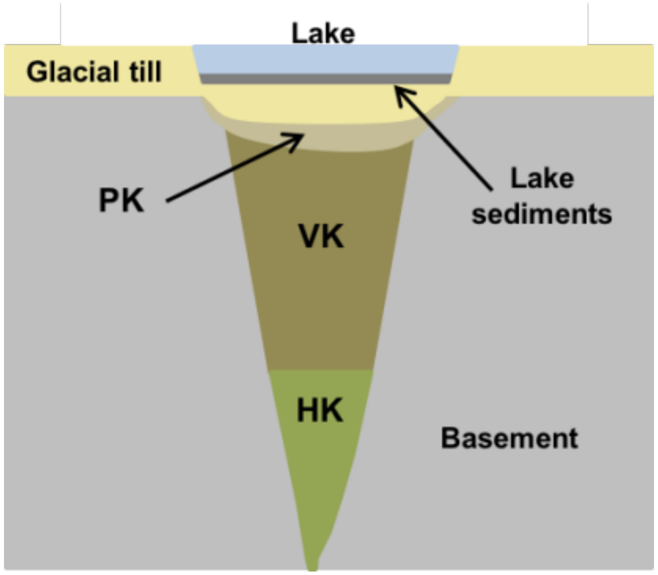




Note: remanent magnetization is considered in the MVI inversion

Interpretation

Geology of Diamond pipe



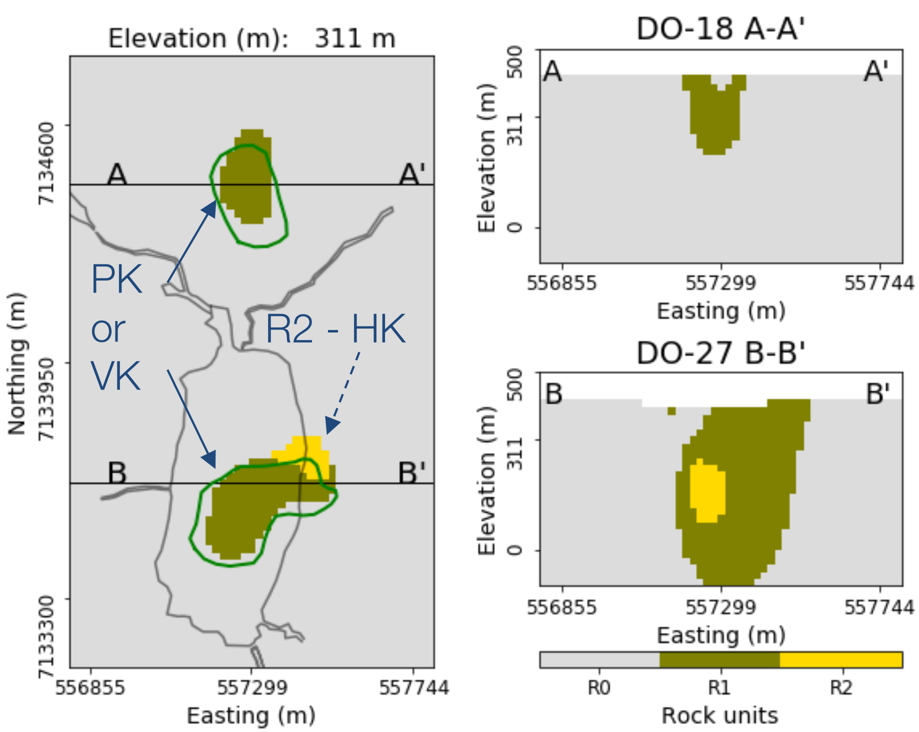
Physical property table

Rock Unit	Density	Susceptibility
Glacial till	Moderate	None
Host rock	Moderate	None
HK	Low-moderate	High
VK	Low	Low-moderate
PK	Low	Low-moderate

- Overall kimberlite: low density
- HK: high susceptibility
- VK and PK: Low-moderate susceptibility

Summary: potential fields data

Petrophysical model



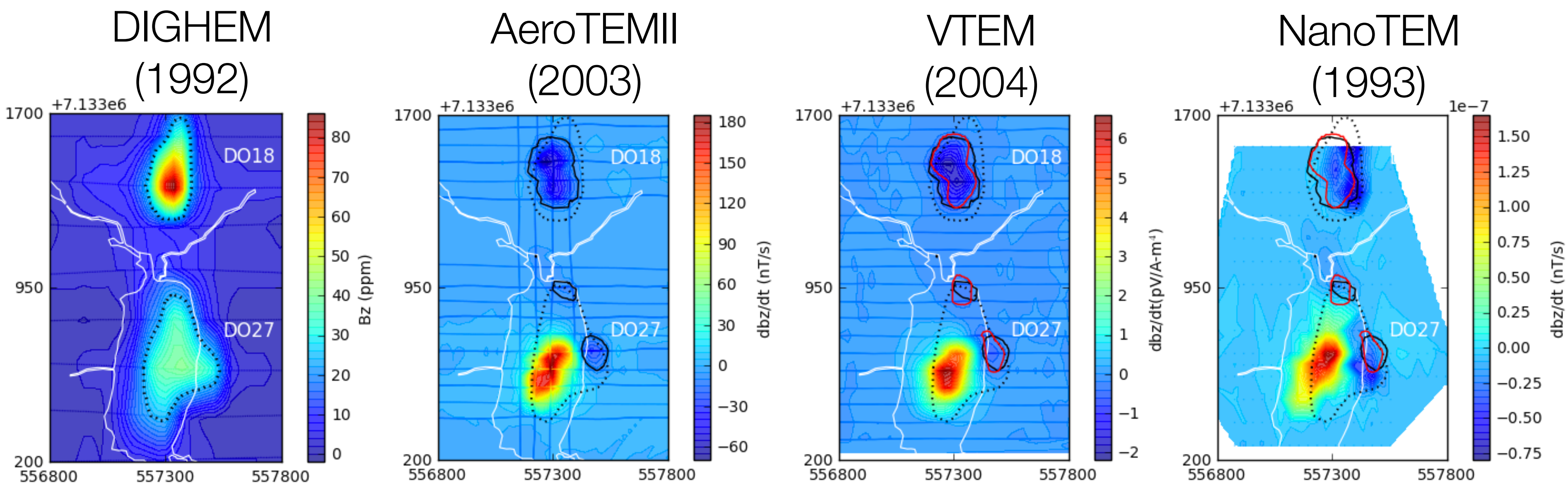
Rock Unit	Density	Susceptibility
Glacial till	Moderate	None
Host rock	Moderate	None
HK	Low-moderate	High
VK	Low	Low-moderate
PK	Low	Low-moderate

- Density
  - Overall kimberlites (R1)
  - Less dense then host
- Density + susceptibility
  - High sus. (R2) → "HK"
  - Moderate sus. and low density→ Either PK or VK
  - But cannot distinguish PK and VK!

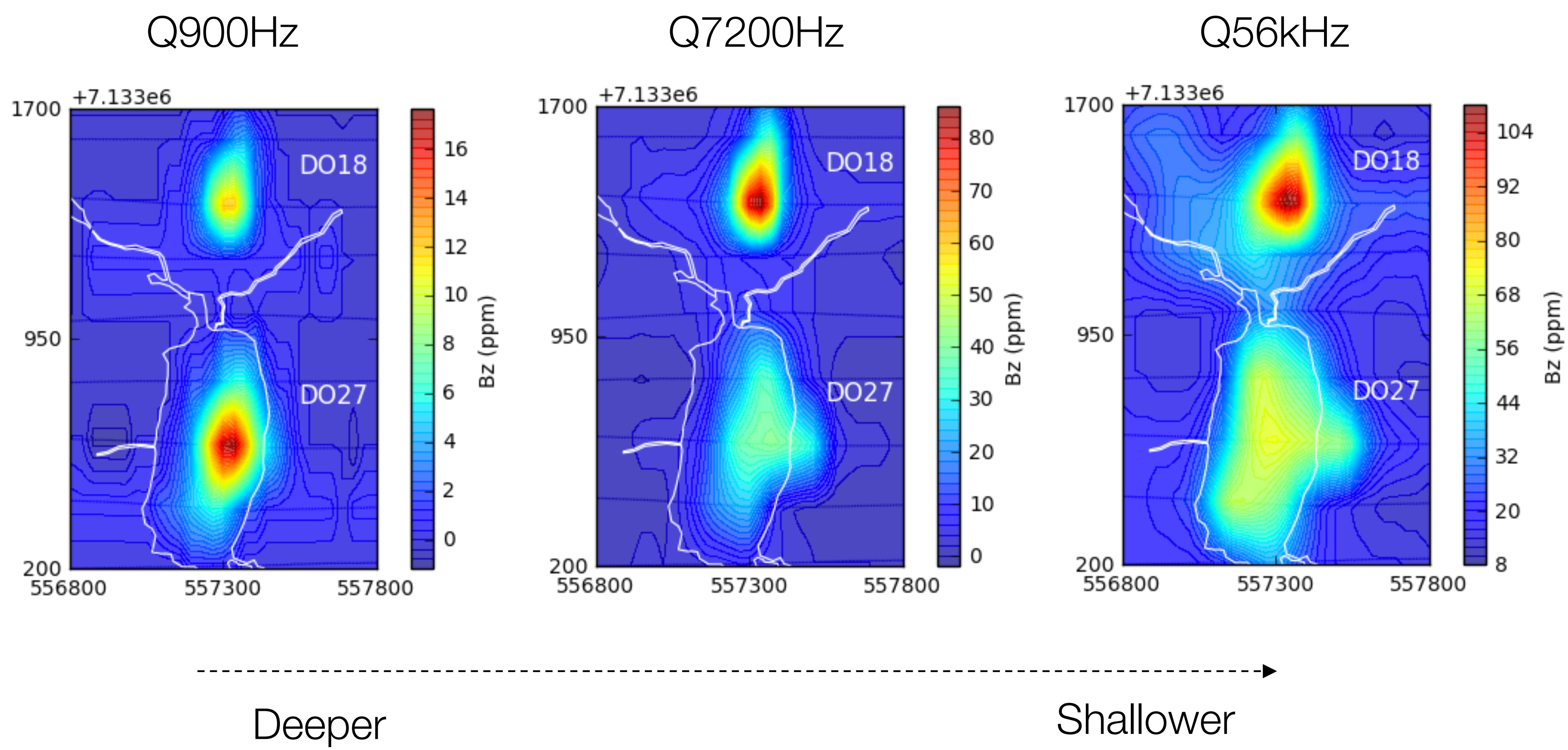
Electromagnetics

EM data

- Focus on DIGHEM and VTEM data
- Negatives in VTEM data is a challenge



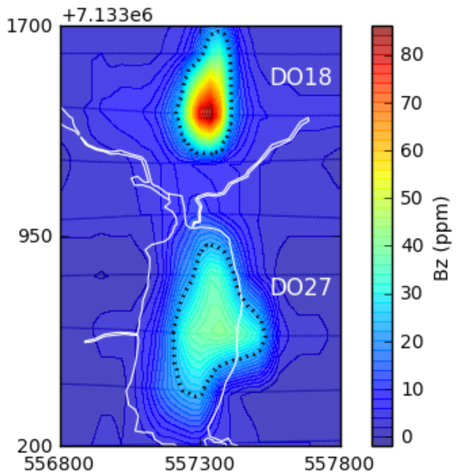
DIGHEM data


Q900Hz
Q7200Hz
Q56kHz
+7.133e6
1700
950
200
556800
557300
557800
DO18
DO27
16
14
12
10
8
6
4
2
0
Bz (ppm)
80
70
60
50
40
30
20
10
0
104
92
80
68
56
44
32
20
8
Deeper
Shallower

VTEM data

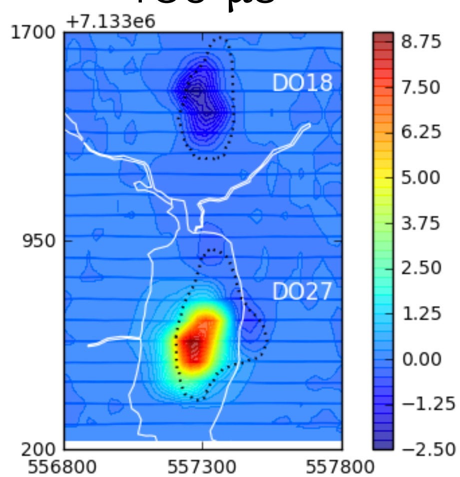
FEM data

Q7200 Hz

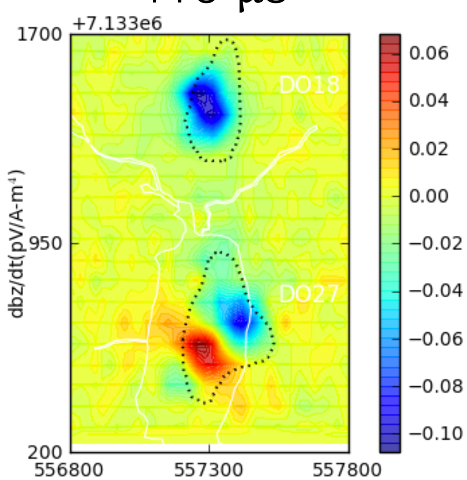


TEM data

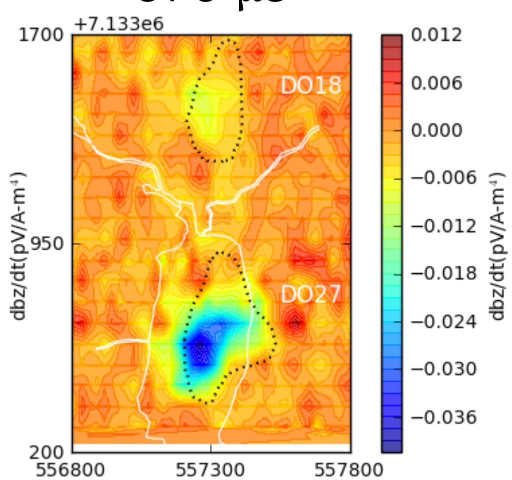
130 μs



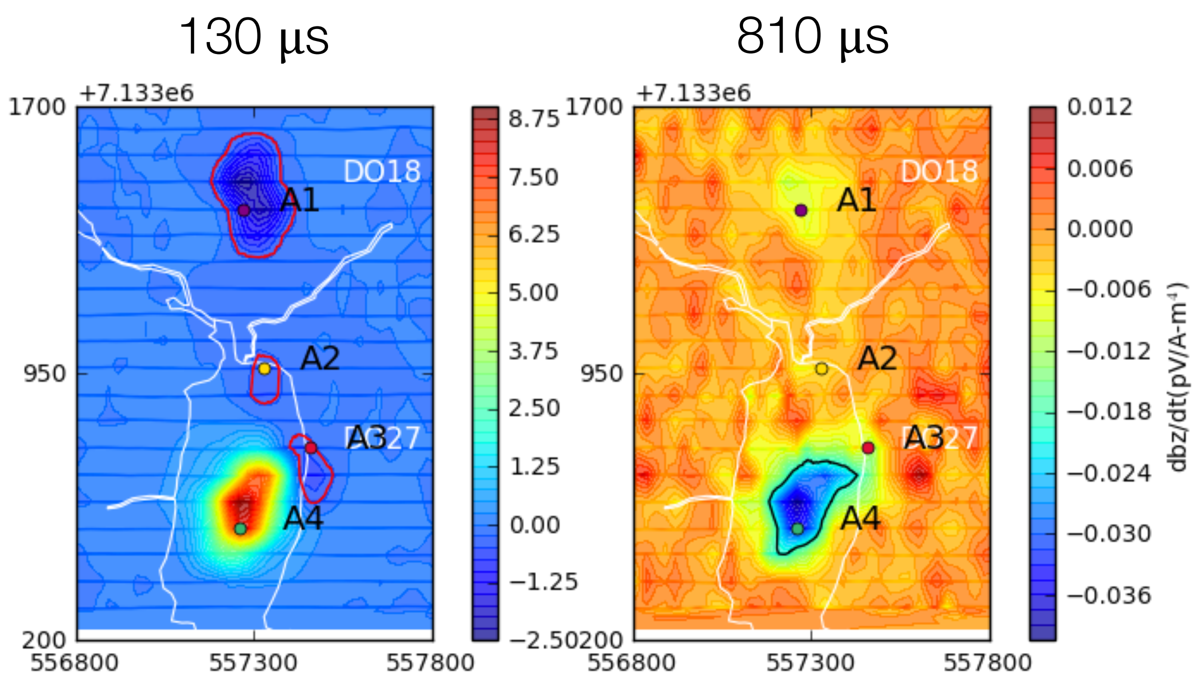
410 μs

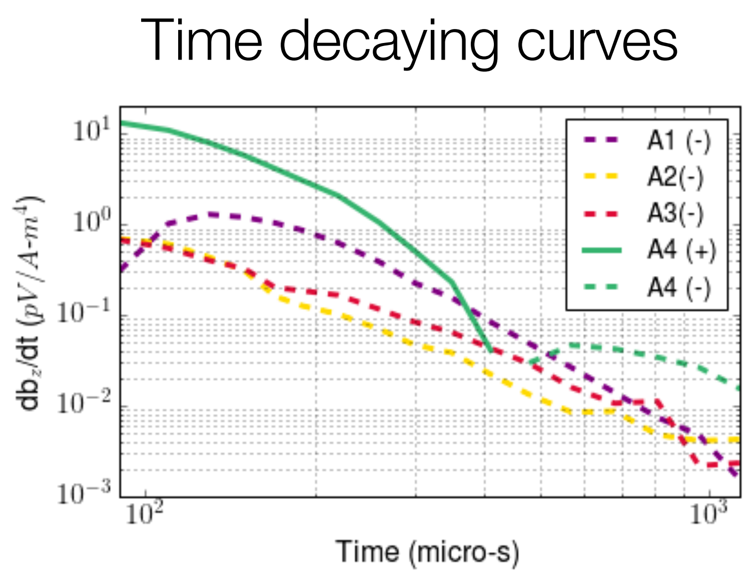


570 μs



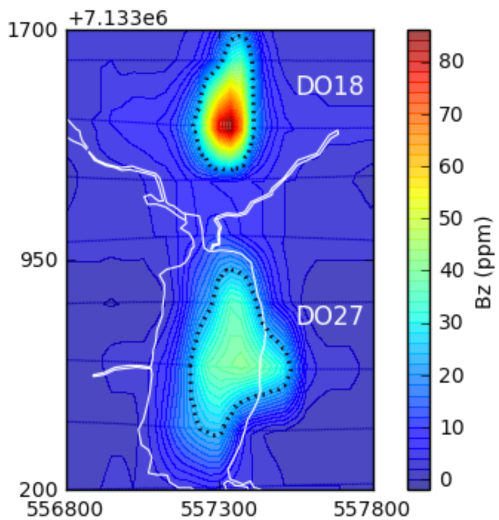
Four chargeable anomalies: A1-A4



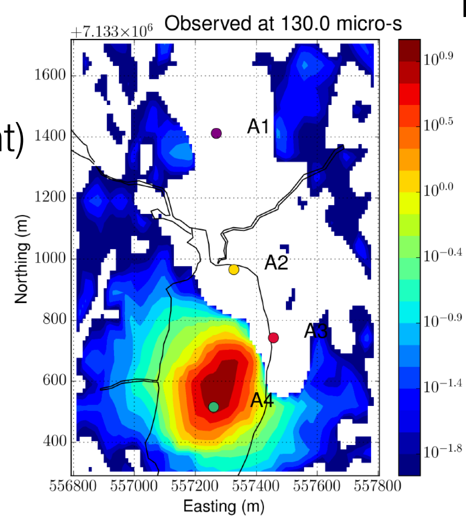


Conductivity inversion

DIGHEM

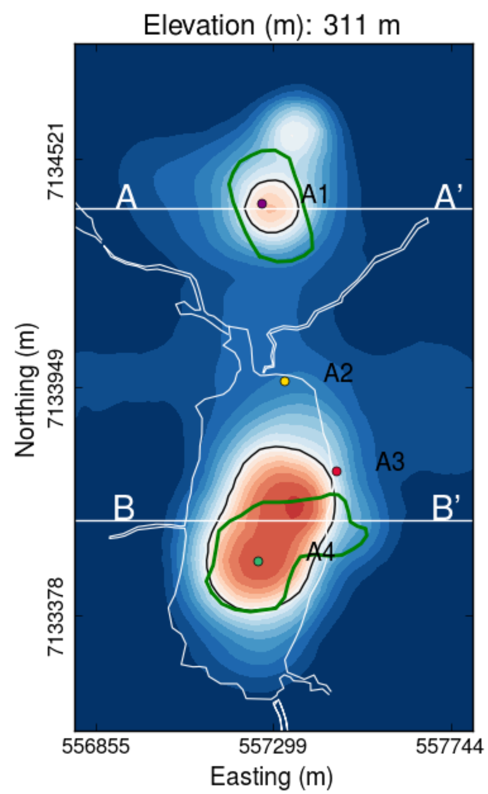


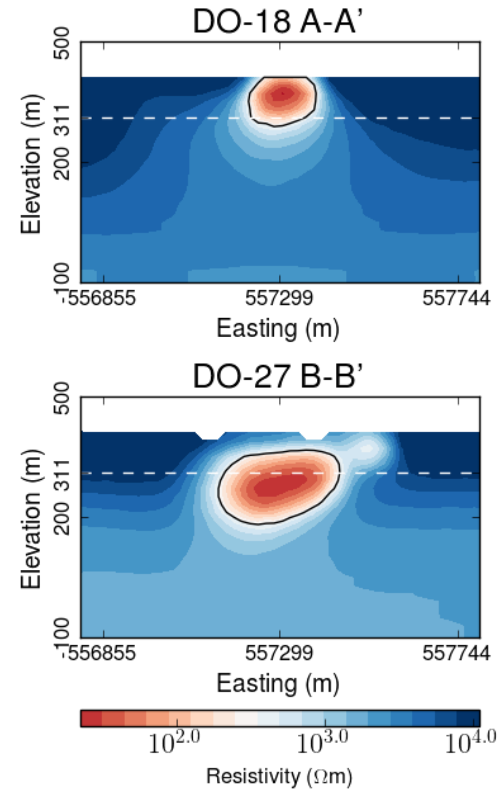
Positive
VTEM
(EM-dominant)



Inversion

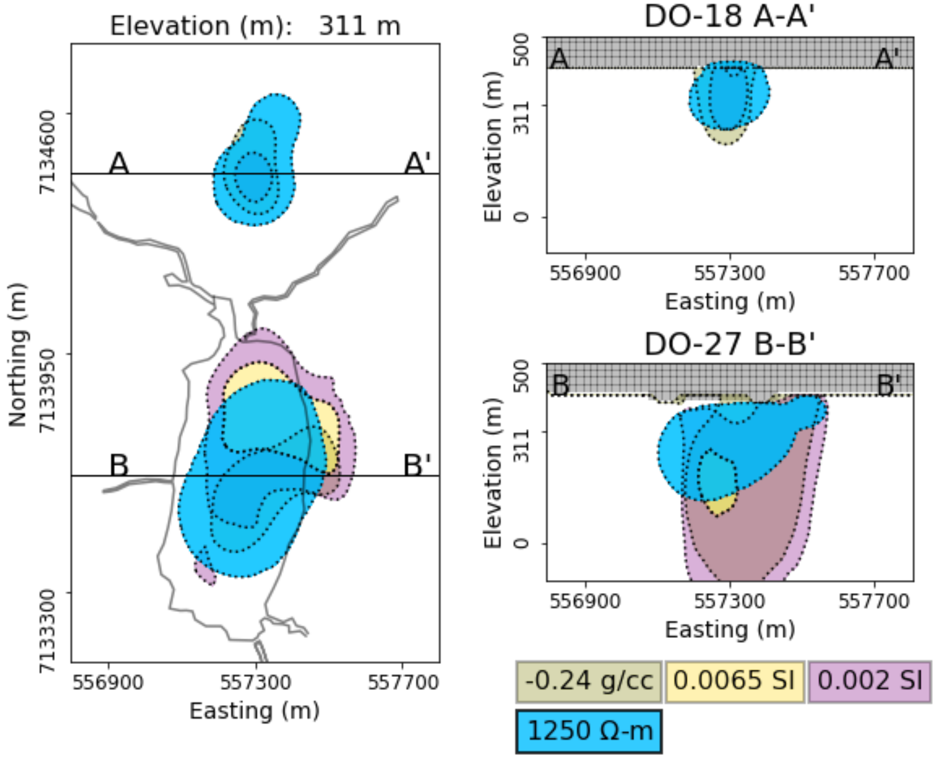
Recovered 3D model



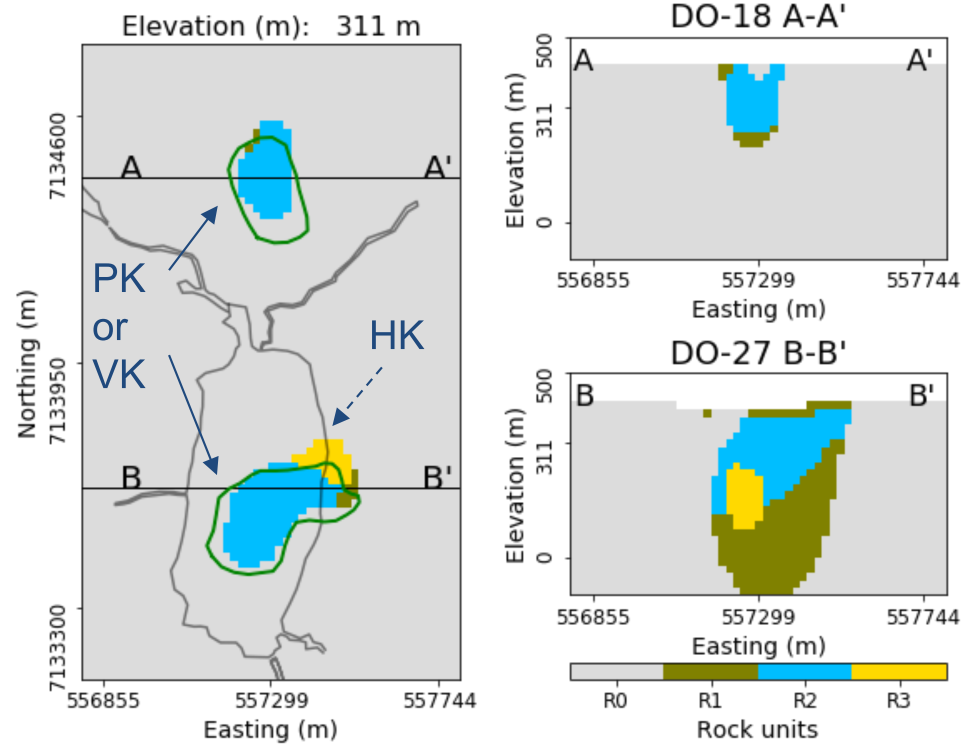


Interpretation: κ, ρ, and σ

Anomaly contours



Petrophysical model



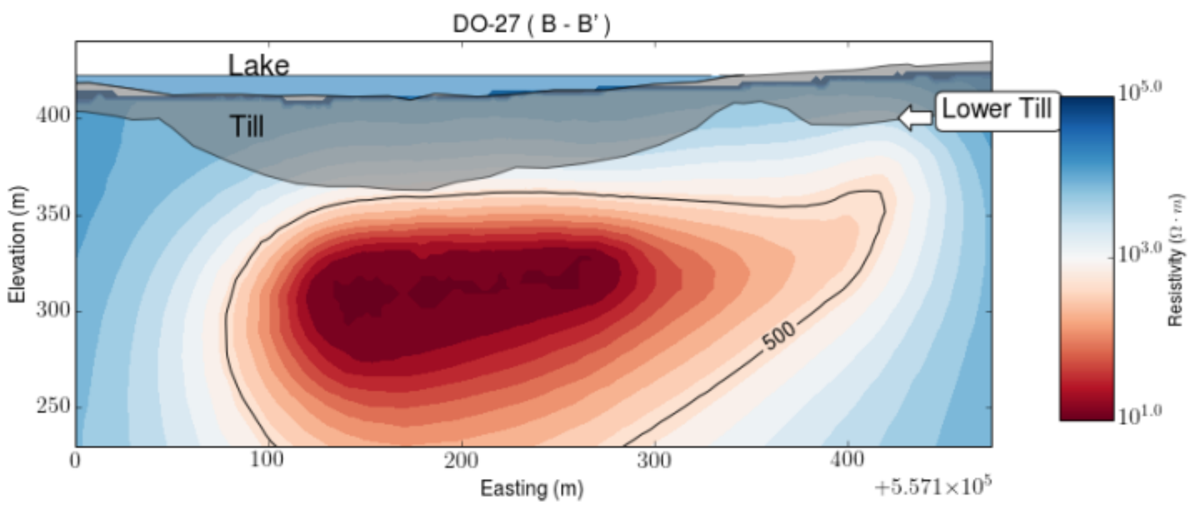
- Helps to delineate top part of DO-27 (Till)
- R1 and R3 could still be either **PK or VK**

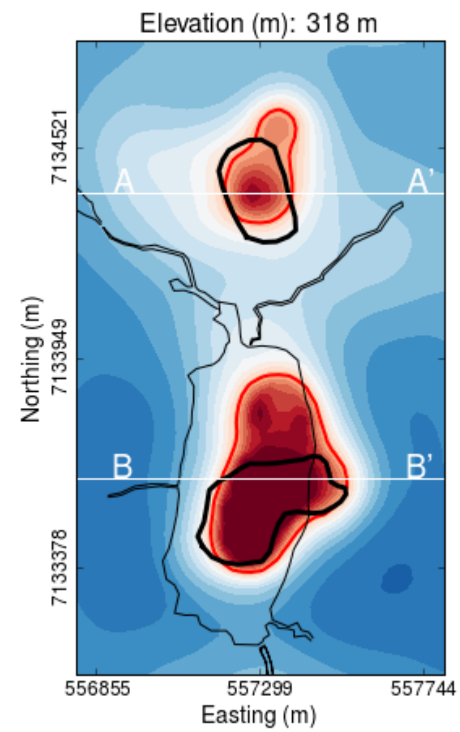
R3: Low ρ
Moderate κ
High σ

Conductivity: kimberlite or lake sediments?

Can we see a conductive pipe below the till?

Rock type	Glacial till	Host rock	HK	VK	PK
Density	Moderate	Moderate	Low	Low	Low
Susceptibility	None	None	High	Low-moderate	Low-moderate
Conductivity	Moderate-high	Low	Low-moderate	Moderate-high	Moderate-high



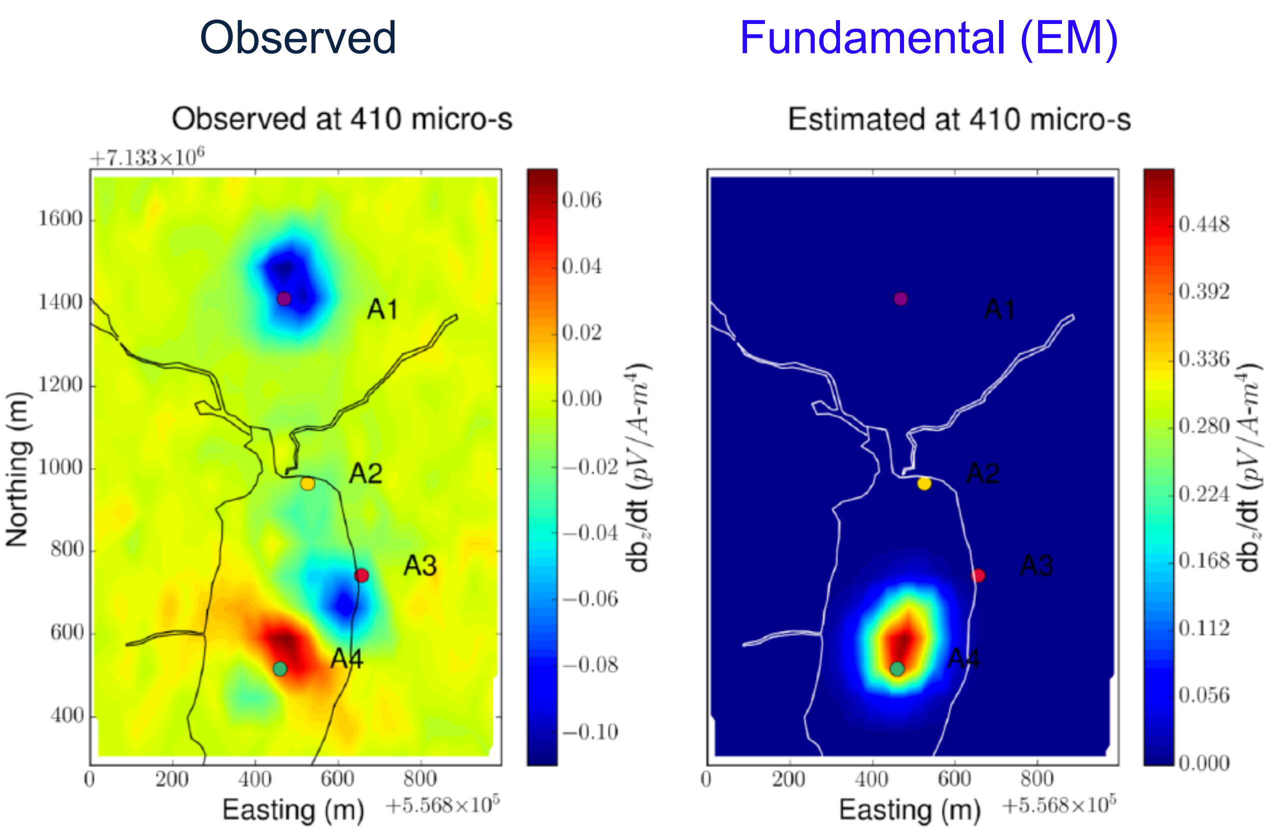


One more physical property

Chargeability

Obtain IP data

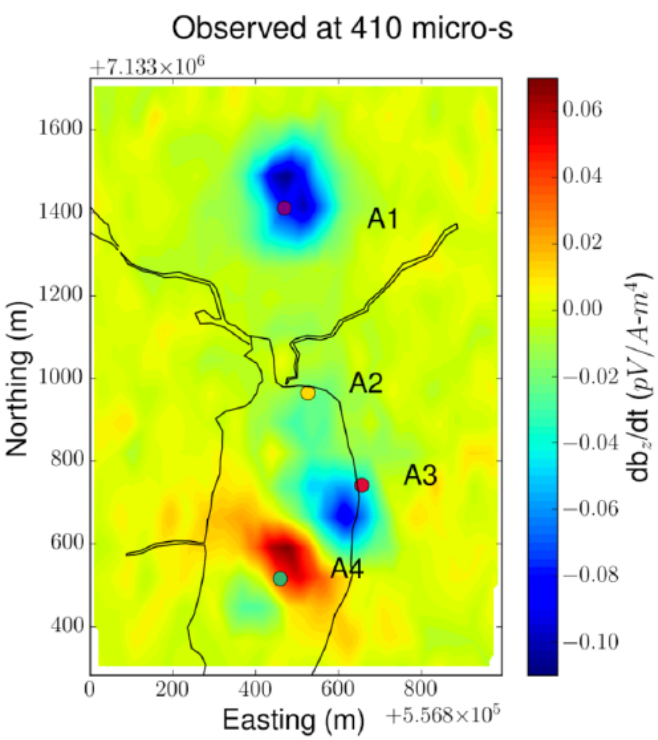
- EM-decoupling: IP = Observation – Fundamental (EM)



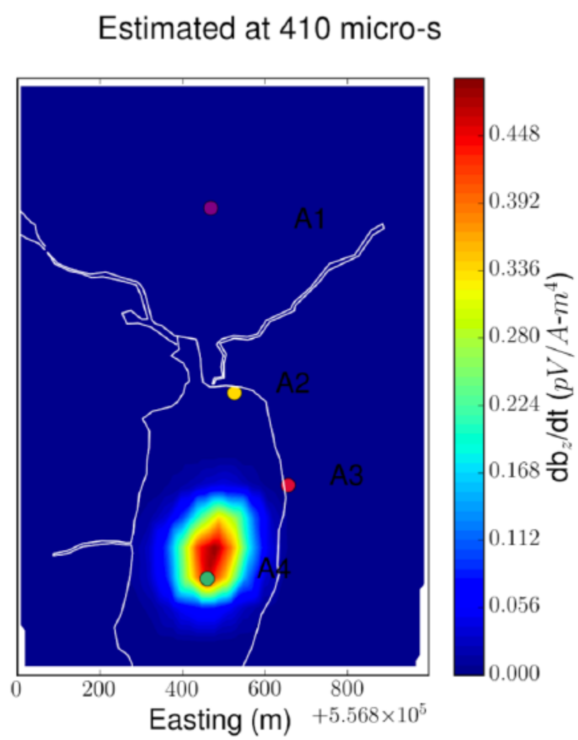
Obtain IP data

- EM-decoupling: IP = Observation – Fundamental (EM)

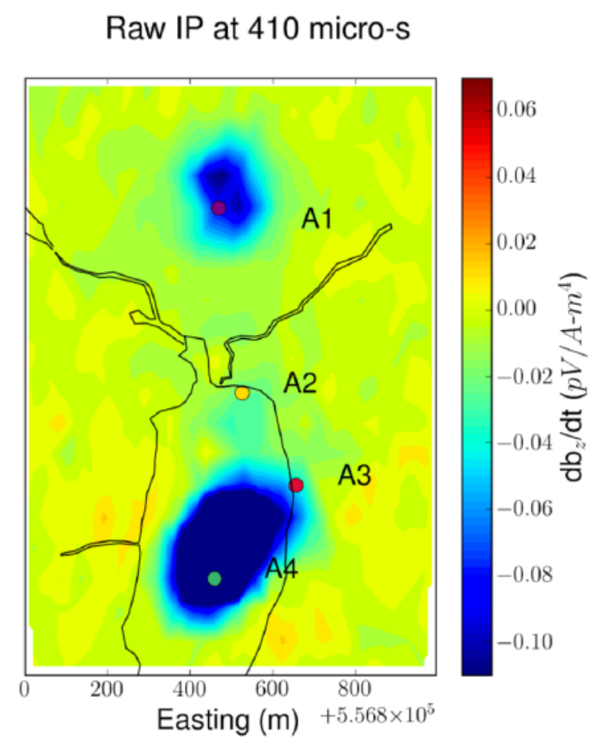
Observed



Fundamental (EM)

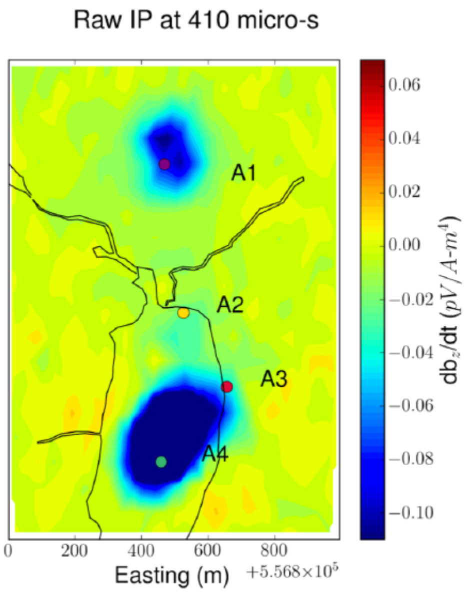


IP



3D IP inversion

IP data



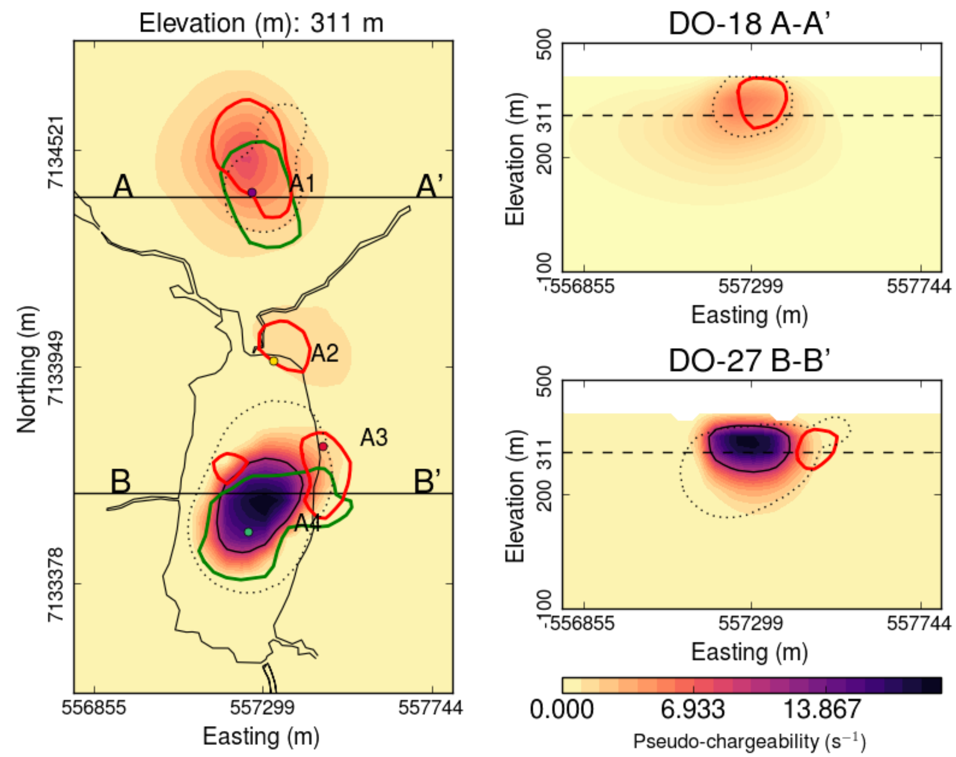
$$d^{IP}(t) = G\tilde{\eta}(t)$$

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

Kang et al. (2016)

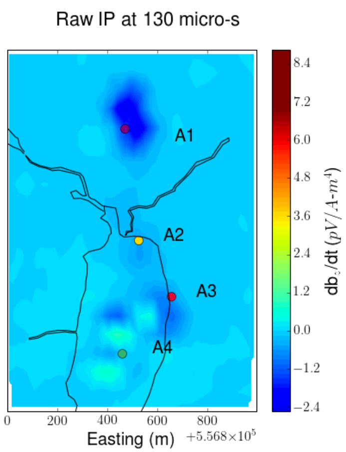
Inversion

Recovered 3D model



Pseudo-chargeability (Early): $\tilde{\eta}_E$

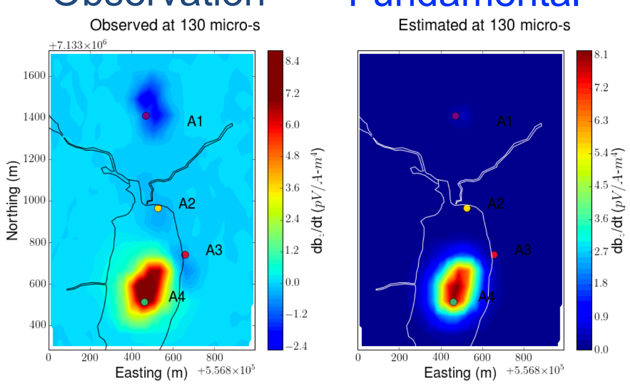
IP data



Inversion

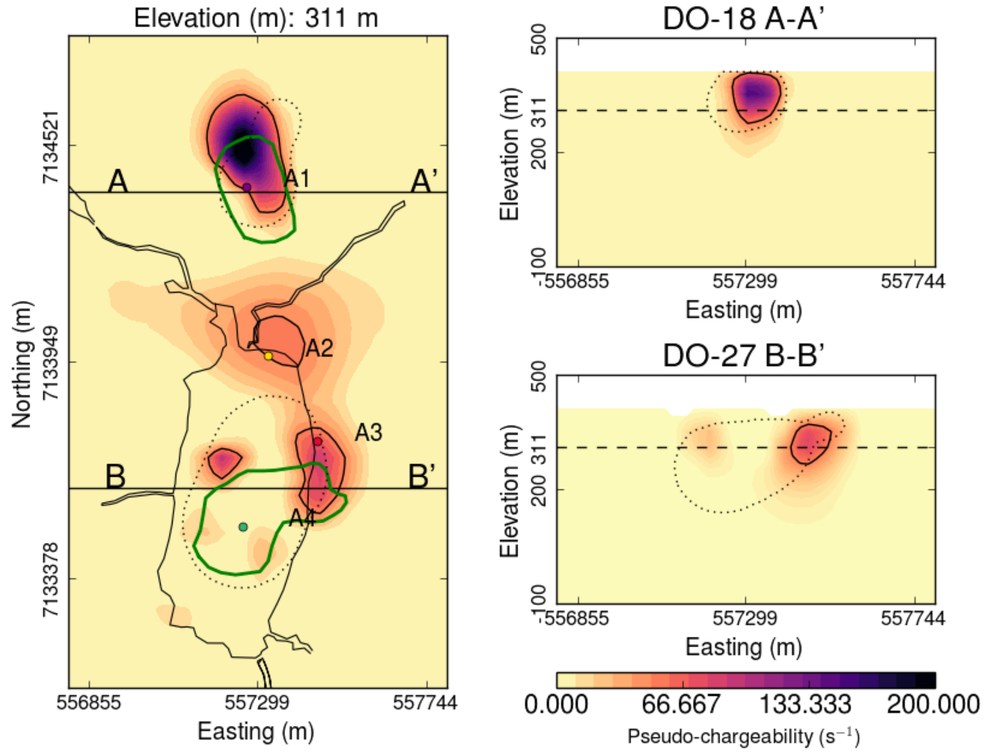
Observation

Fundamental



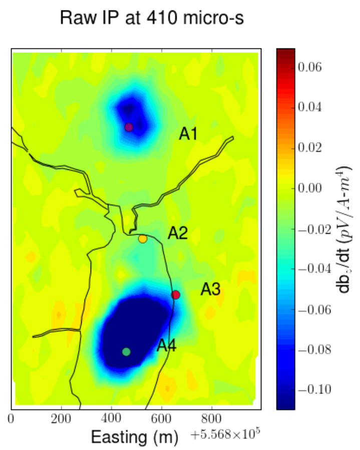
IP = Observation - Fundamental

Recovered 3D model



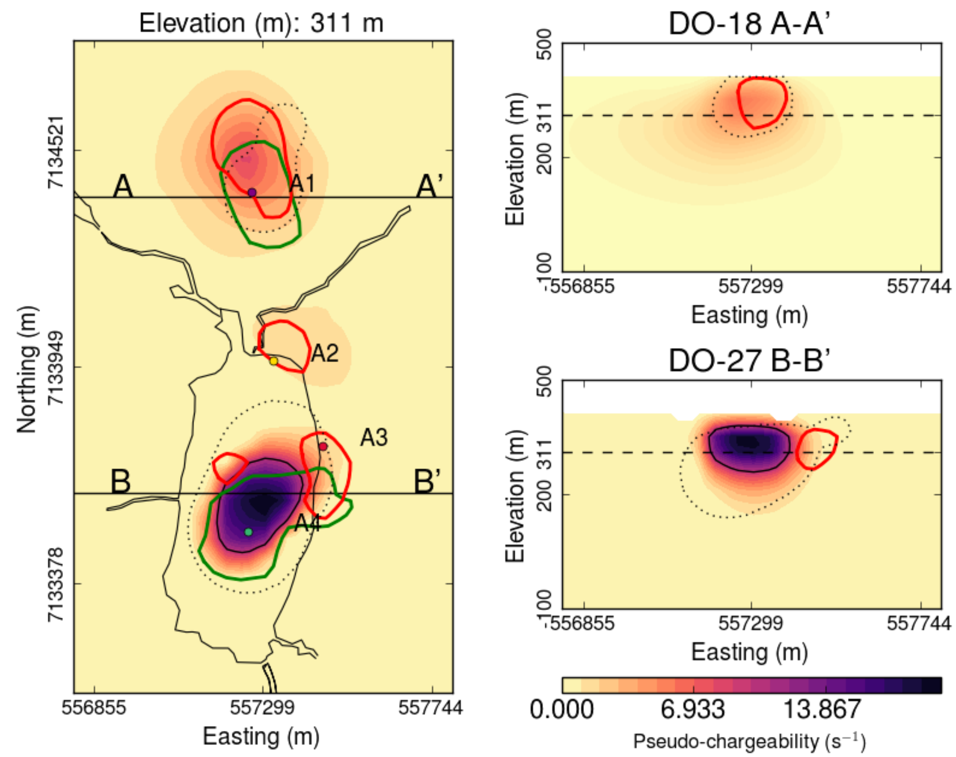
Pseudo-chargeability (Late): $\tilde{\eta}_L$

IP data

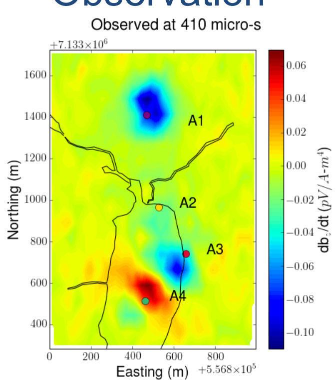


Inversion

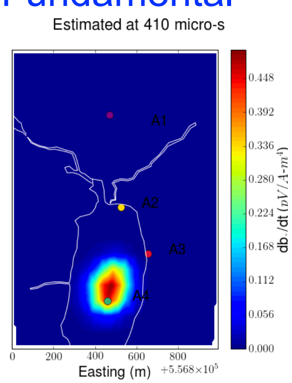
Recovered 3D model



Observation



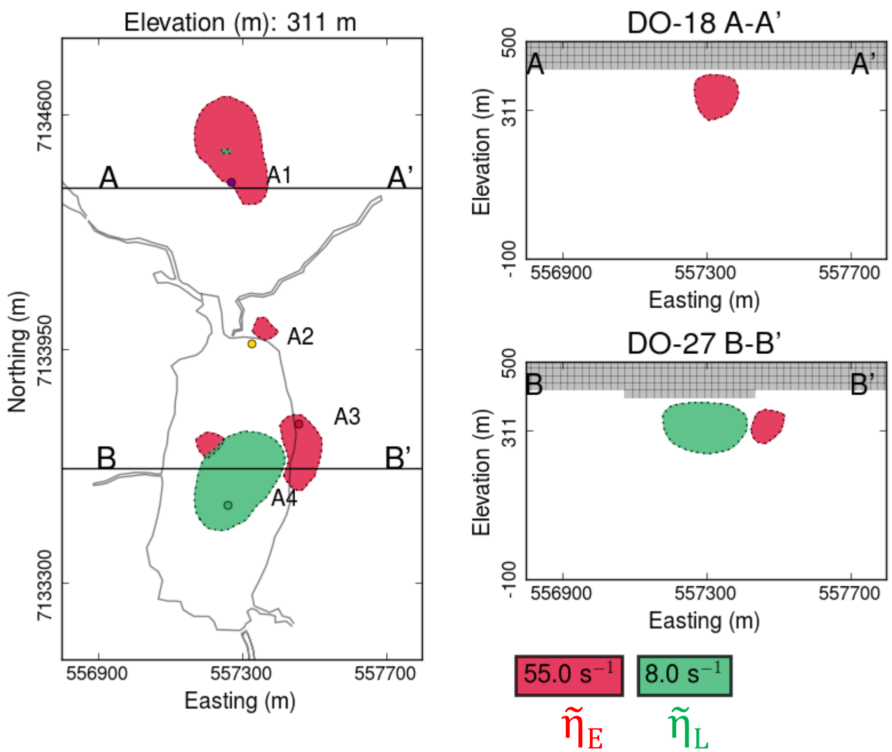
Fundamental



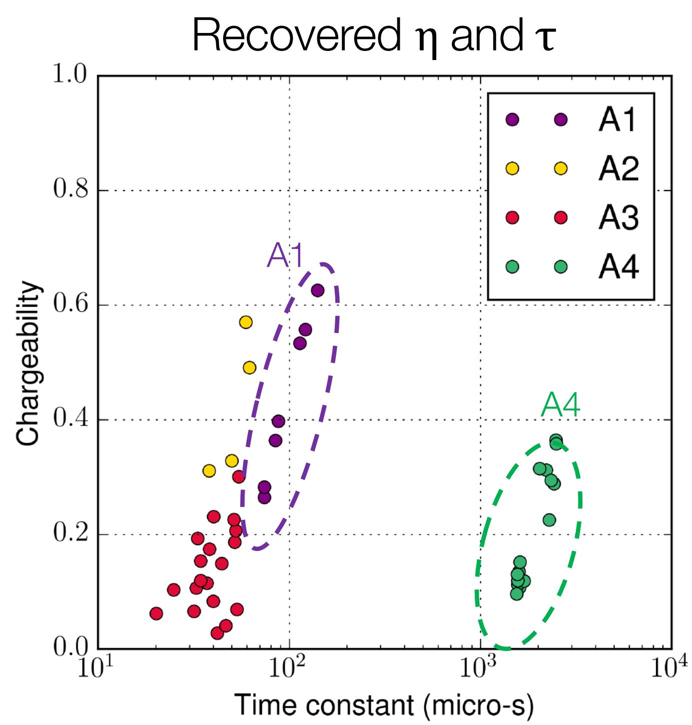
IP = Observation - Fundamental

EM and IP summary

Anomaly contours



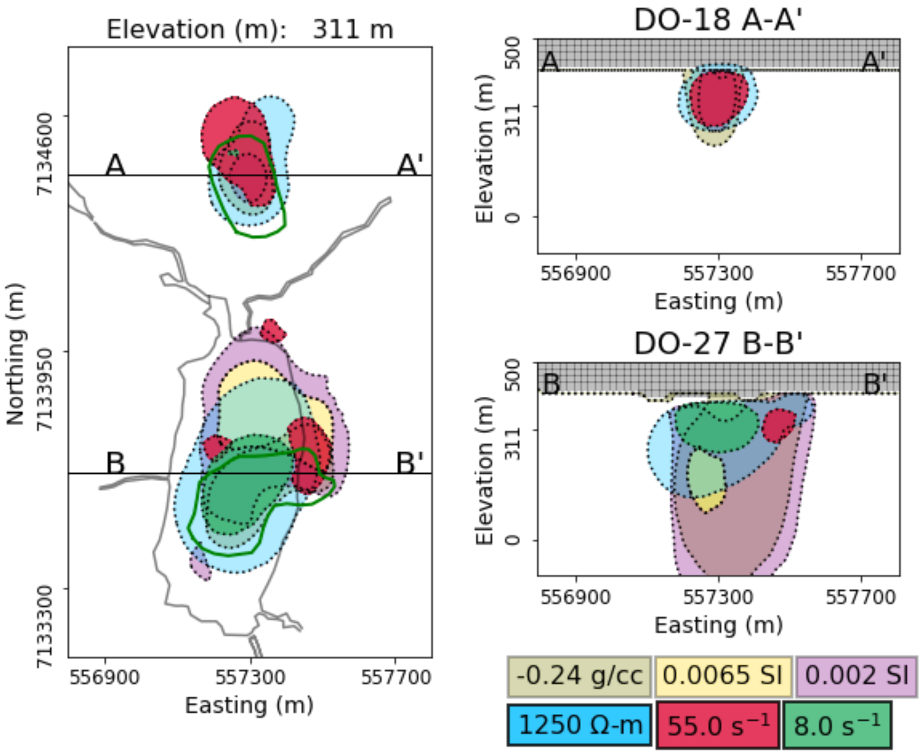
Cole-Cole parameters



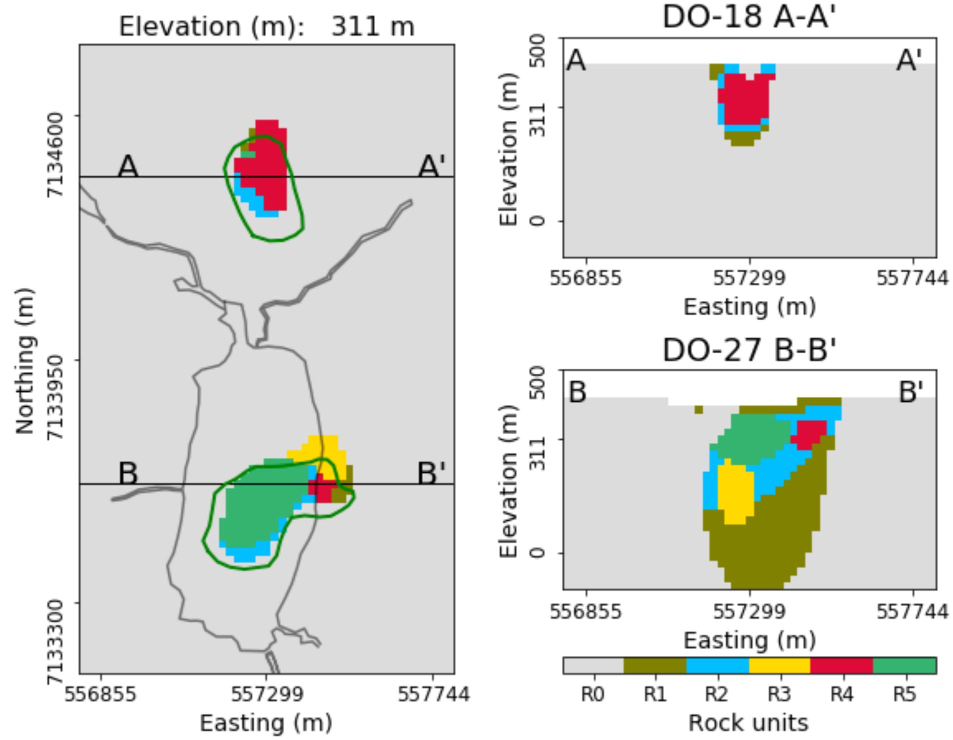
- A4 has greater time constant
- A1-A3 have small time constant

Interpretation: adding $\tilde{\eta}_E$ and $\tilde{\eta}_L$

Anomaly contours



Petrophysical model

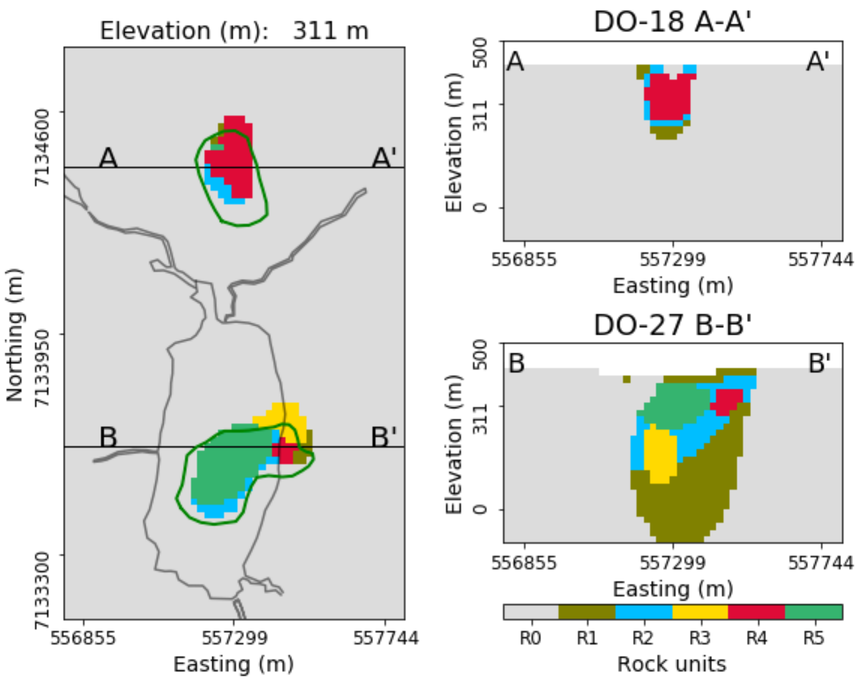


Distinction between PK and VK

- PK deposited after an explosive event
- PK has greater pore size than VK
- Result in greater time constant: τ
- R4 (small τ) – VK, R5 (greater τ) – PK

Final Interpretation

Petrophysical model



- From airborne geophysics

Rock Unit	Density	Susceptibility	Conductivity	Chargeability
Glacial till	Moderate	None	Moderate-high	Low
Host rock	Moderate	None	Low	Low
HK	Low-moderate	High	Low-moderate	Low
VK	Low	Low-moderate	Moderate-high	High
PK	Low	Low-moderate	Moderate-high	Moderate-high

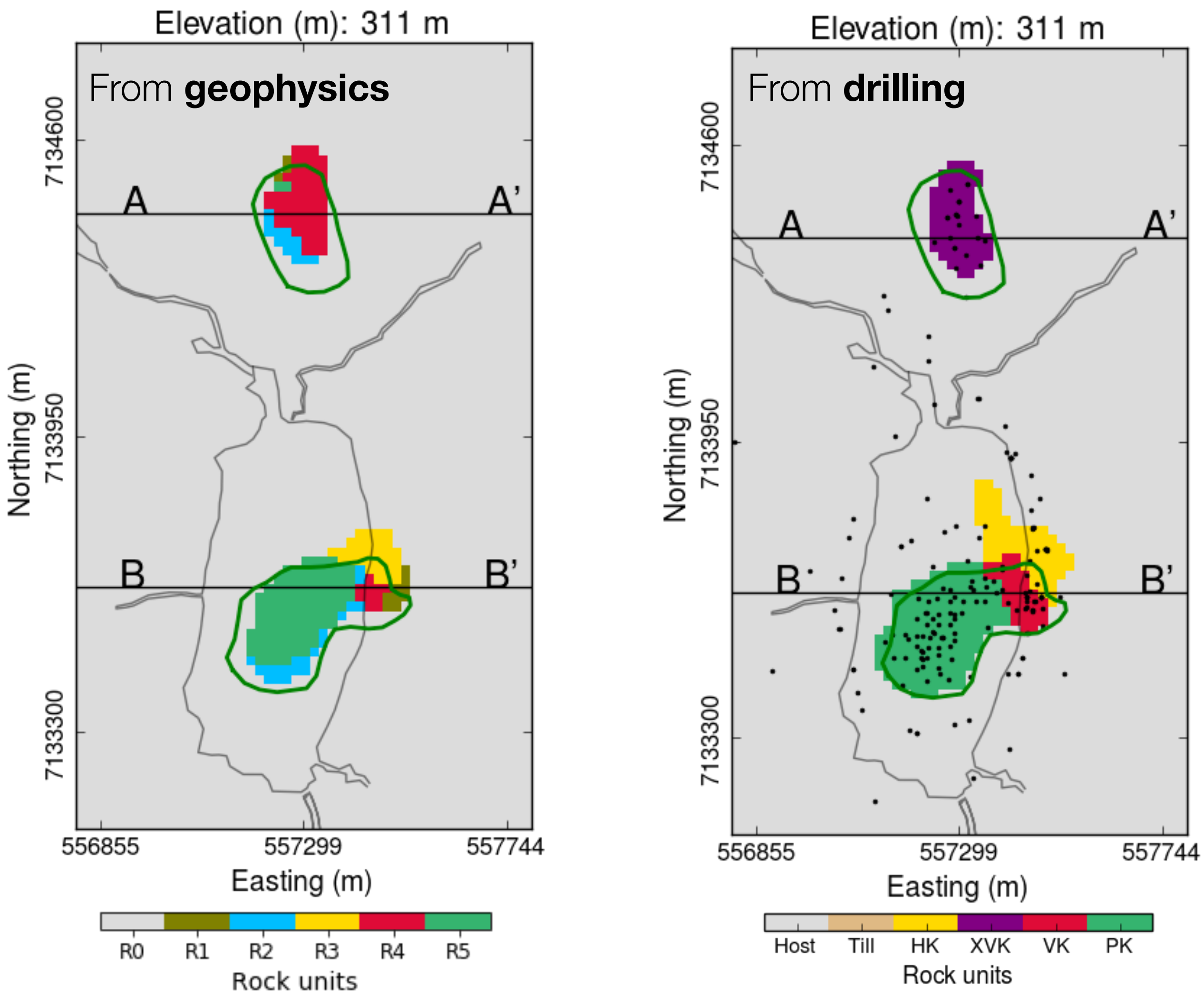
Table of physical properties for typical kimberlitic rocks found in the Lac de Gras region.

Interpreted rock table (R0-R5)

Rock Unit	ρ	κ	σ	$\tilde{\eta}_E$	$\tilde{\eta}_L$	τ	Interpretation
R0	Mod.	Low	Low	Low	Low	N/A	Host Rock
R1	Low	Low	Low	Low	Low	N/A	Kimberlite
R2	Low	Mod.	Mod.	Low	Low	N/A	PK or VK
R3	Low	High	Low	Low	Low	N/A	HK
R4	Low	Mod.	Mod.	High	Low	Small	VK
R5	Low	Mod.	Mod.	Low	High	Large	PK

Comparison with 3D geologic model

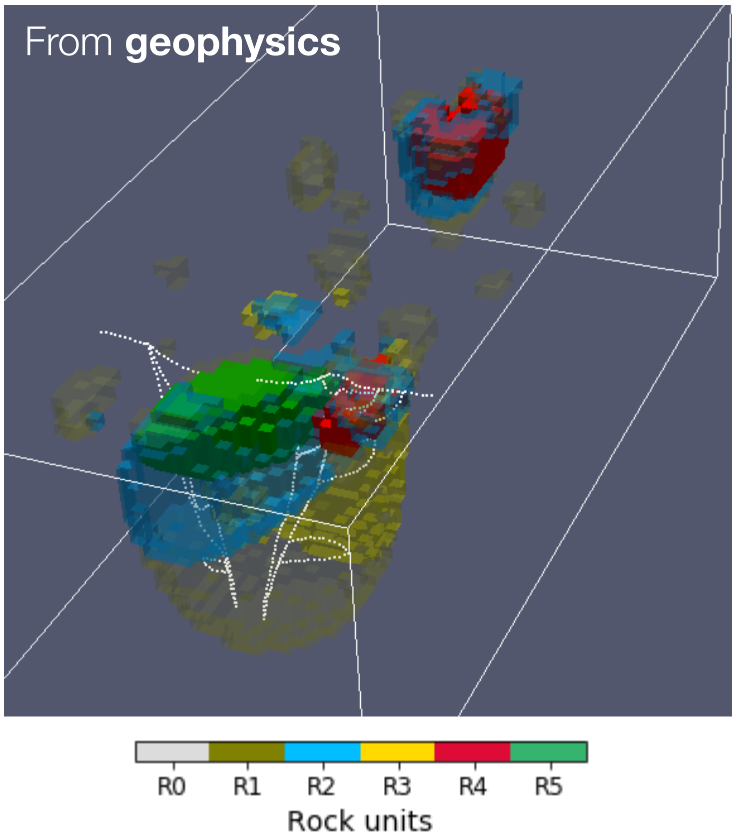
Plan map (100 mbsf)

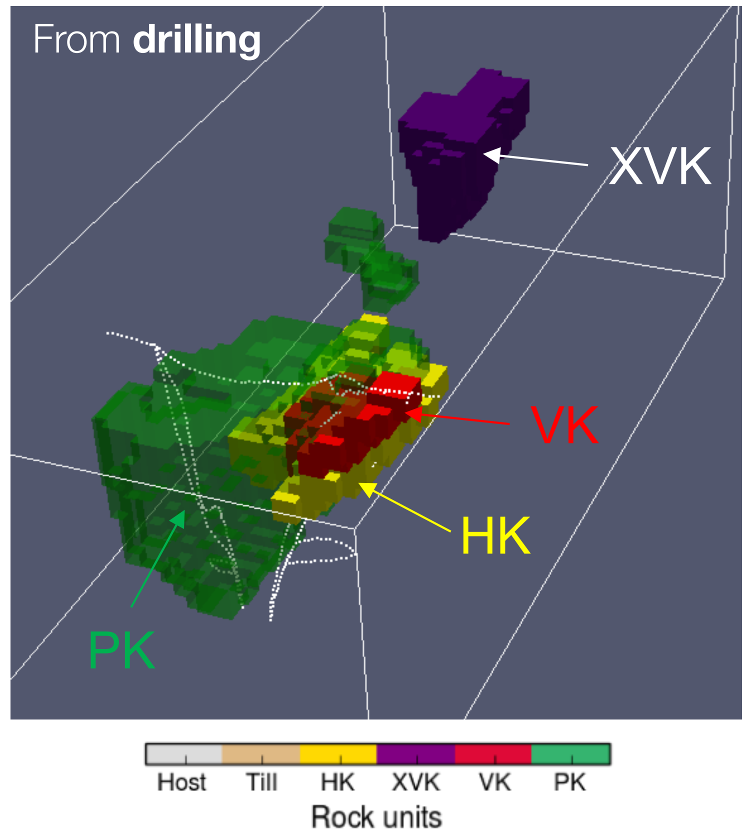


- HK, PK, and VK are delineated in 3D

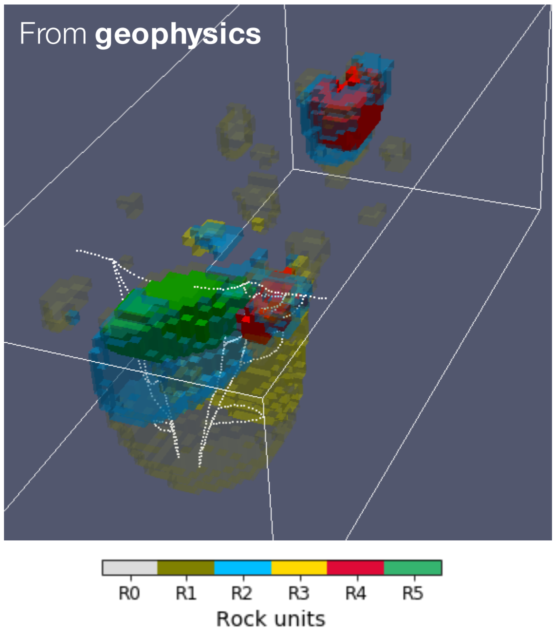
Comparison with 3D geologic model

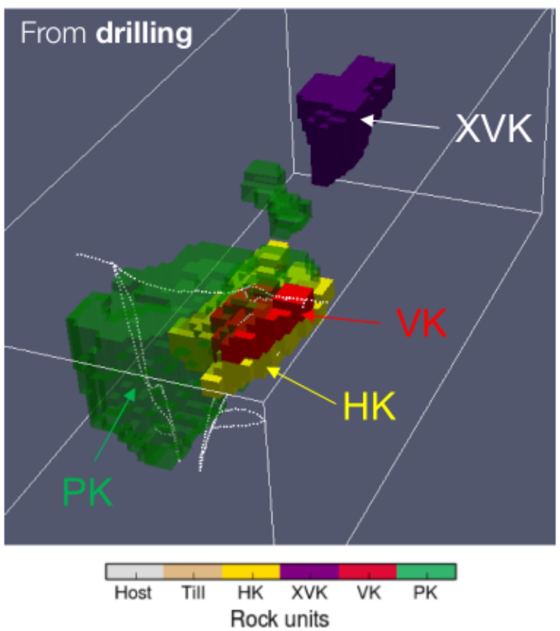
3D cut-off volume





Synthesis





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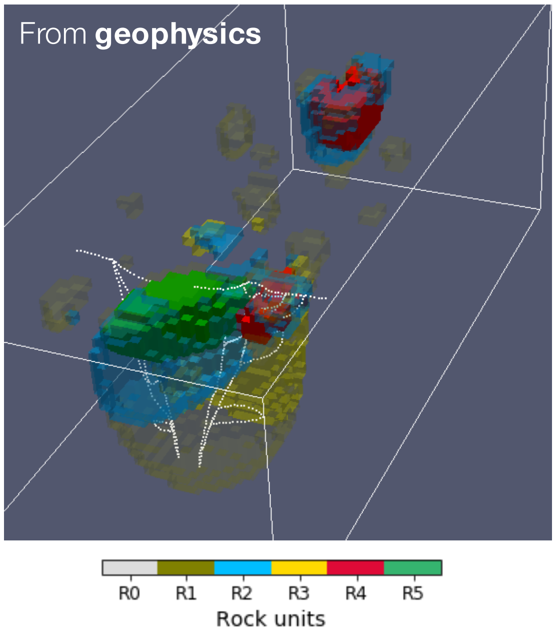
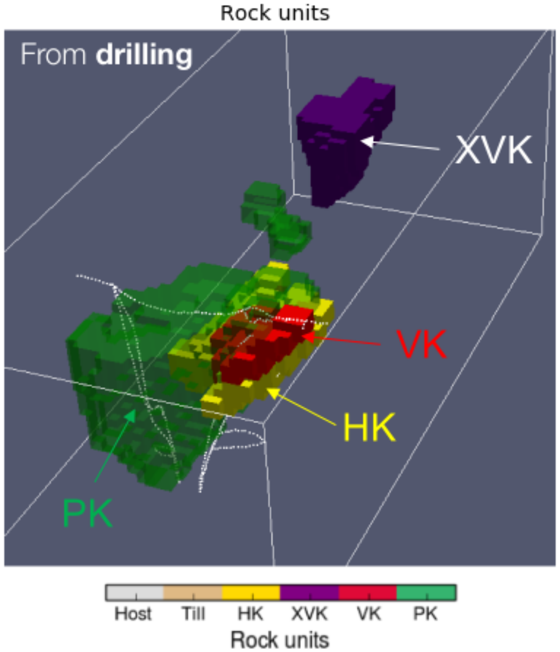
R5	Low	Mod.	Mod.	Low	High	Large	PK

Main source of information

- R1 (kimberlite): from density (gravity)
- R2 (PK or VK): from conductivity (EM)
- R3 (HK): from susceptibility (mag.)
- R4 (VK): from IP (small $\boldsymbol{\tau}$)
- R5 (PK): from IP (large $\boldsymbol{\tau}$)

Synthesis





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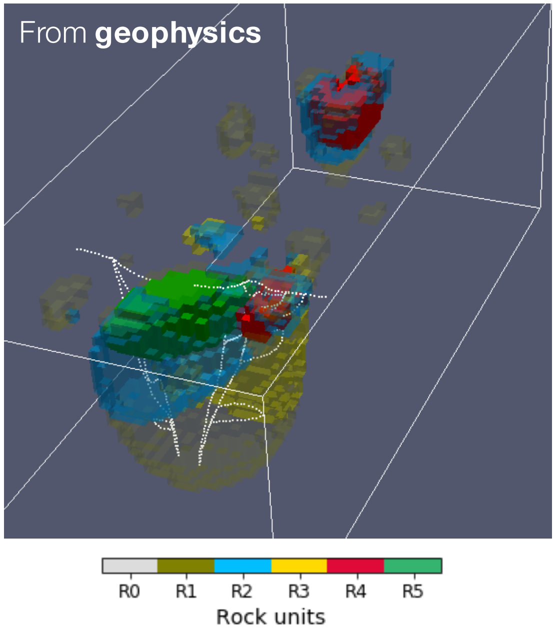
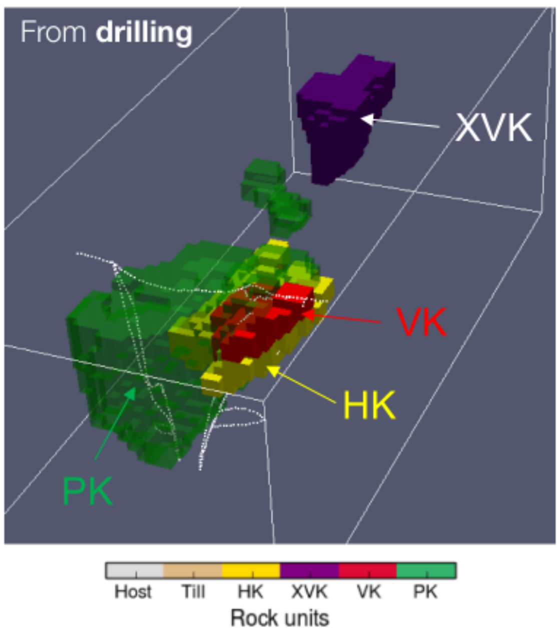
- R5 (PK): from IP (large $\boldsymbol{\tau}$)

Limitations for kimberlite characterization

- PK: only recognized upper portion
- HK: dipping sheets; magnetics does not have resolution
- In general, limited depth resolution

How could we improve the interpretation?

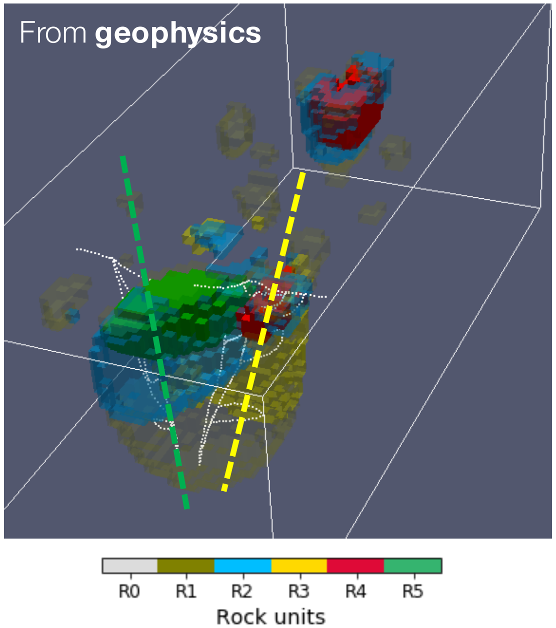


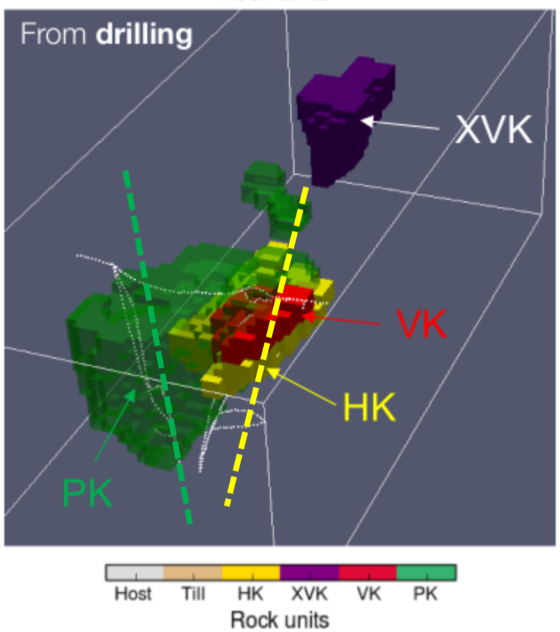


What if drill holes were available?

- Geologic logs
    - Identifies rock units
    - Structural constraints
- Geophysical logs
    - bound constraints

How could we improve the interpretation?





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Update geophysical inversions and interpretation