A decade of SimPEG

connecting research & industry through open-source software

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challenges & opportunities for EM in mineral exploration

challenges:

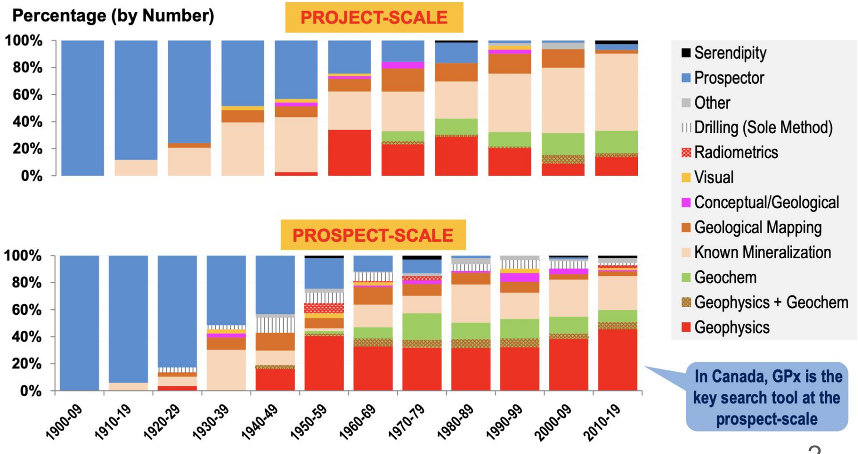
- need to see deeper
- rugged topography
- highly conductive targets
- multiple surveys types (diff. resolution, physical properties)
- other factors: infrastructure, …

but have

- high quality data
- multiple data types (geophysical, geology, geochemistry…)
- computational machinery

opportunities…

Primary search methods used by Country
Non-Bulk mineral discoveries in CANADA : 1900-2019



Note: Analysis based on detailed analysis of 628 discoveries (out of 914 known discoveries)

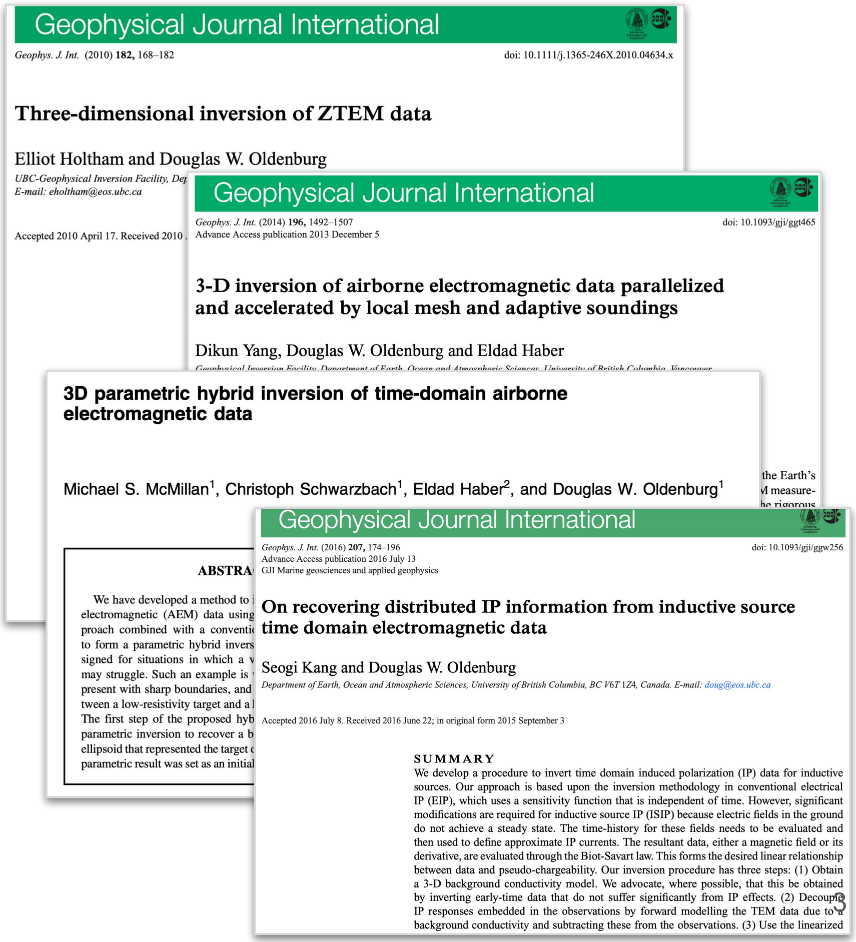
Source: MinEx Consulting © March 2020

Schodde, 2020

GIF over the decades

(we can even invert Geotech data!)

- developed codes to invert individual types of geophysical data
- goal: extract information about physical properties, generate models relevant to mineral exploration
- connections with industry core to research
    - data & research problems
    - transfer of software & technology


Geophysical Journal International

Geophys. J. Int. (2010) 182, 168–182 doi: 10.1111/j.1365-246X.2010.04634.x

Three-dimensional inversion of ZTEM data

Elliot Holtham and Douglas W. Oldenburg

UBC-Geophysical Inversion Facility, Dep

E-mail: eholtham@eos.ubc.ca

Accepted 2010 April 17. Received 2010

Geophysical Journal International

Geophys. J. Int. (2014) 196, 1492–1507 doi: 10.1093/gji/ggt465

Advance Access publication 2013 December 5

3-D inversion of airborne electromagnetic data parallelized and accelerated by local mesh and adaptive soundings

Dikun Yang, Douglas W. Oldenburg and Eldad Haber

3D parametric hybrid inversion of time-domain airborne electromagnetic data

Michael S. McMillan[1], Christoph Schwarzbach[1], Eldad Haber[2], and Douglas W. Oldenburg[1]

ABSTRA

We have developed a method to i electromagnetic (AEM) data using proach combined with a conventi to form a parametric hybrid invers signed for situations in which a v may struggle. Such an example is present with sharp boundaries, and tween a low-resistivity target and a l The first step of the proposed hyb parametric inversion to recover a b ellipsoid that represented the target parametric result was set as an initial

Geophysical Journal International

Geophys. J. Int. (2016) 207, 174–196 doi: 10.1093/gji/ggw256

Advance Access publication 2016 July 13

GJI Marine geosciences and applied geophysics

On recovering distributed IP information from inductive source time domain electromagnetic data

Seogi Kang and Douglas W. Oldenburg

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Accepted 2016 July 8. Received 2016 June 22; in original form 2015 September 3

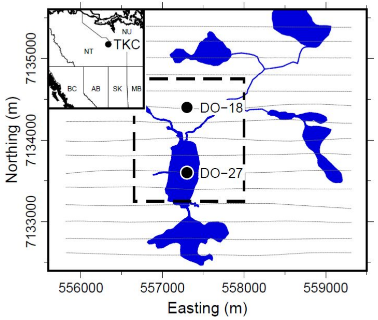
SUMMARY

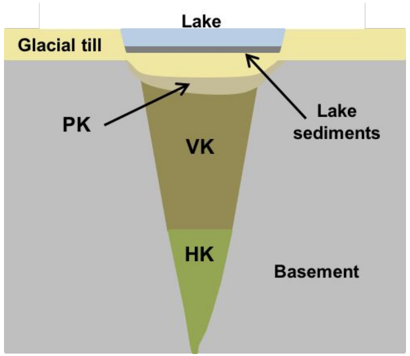
We develop a procedure to invert time domain induced polarization (IP) data for inductive sources. Our approach is based upon the inversion methodology in conventional electrical IP (EIP), which uses a sensitivity function that is independent of time. However, significant modifications are required for inductive source IP (ISIP) because electric fields in the ground do not achieve a steady state. The time-history for these fields needs to be evaluated and then used to define approximate IP currents. The resultant data, either a magnetic field or its derivative, are evaluated through the Biot-Savart law. This forms the desired linear relationship between data and pseudo-chargeability. Our inversion procedure has three steps: (1) Obtain a 3-D background conductivity model. We advocate, where possible, that this be obtained by inverting early-time data that do not suffer significantly from IP effects. (2) Decouple IP responses embedded in the observations by forward modelling the TEM data due to a background conductivity and subtracting these from the observations. (3) Use the linearized

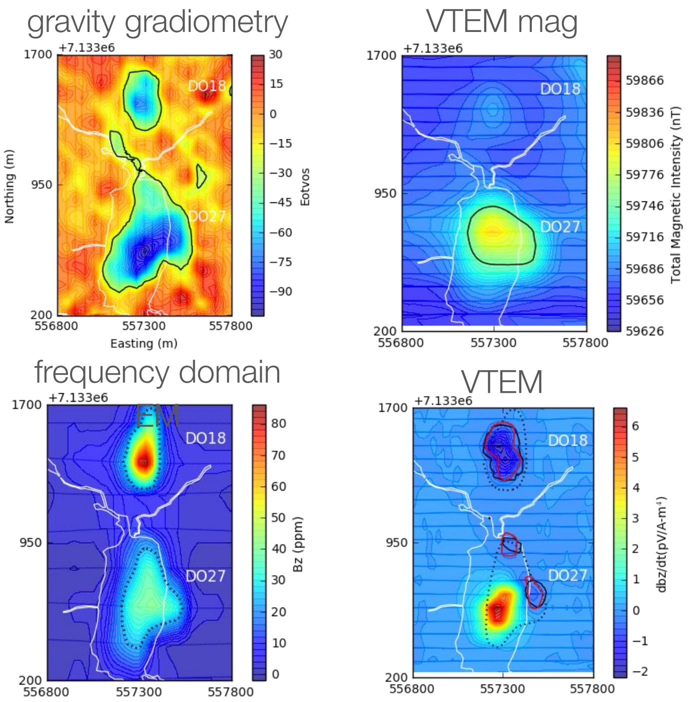
an example: Tli Kwi Cho Kimberlite (TKC) complex

- Geophysical discovery in 90's
- airborne mag and EM
- 2 kimberlite pipes

- invert to obtain physical property models
- interpret to build quasi-geology model







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
Chargeability	Low	Low	?	?	?

Devriese *et al.* 2017, Fournier *et al.* 2017, Kang *et al.* 2017

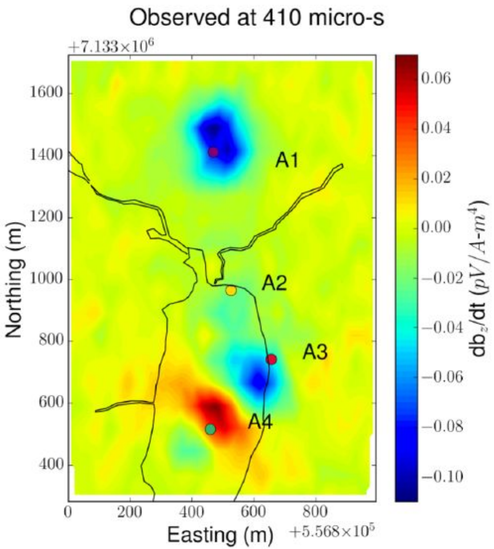
IP effects in time domain EM data

Seogi Kang

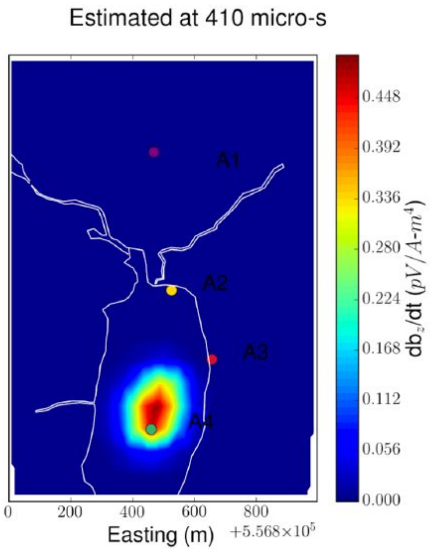
Negative transients in VTEM presents a challenge → motivates research

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

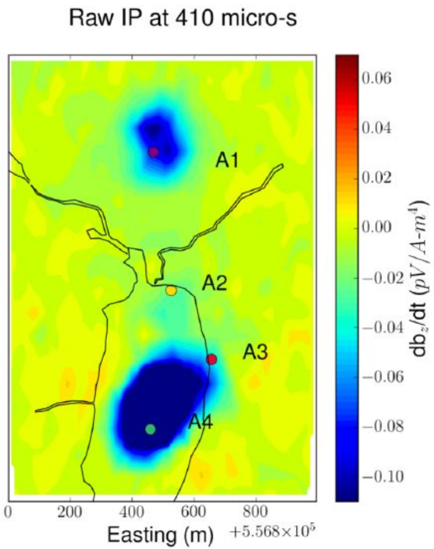
Observed



Fundamental (EM)

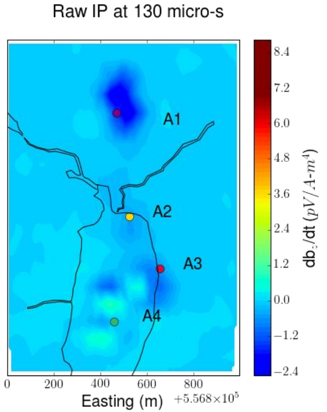


IP



TKC: IP inversion (early time)

IP data



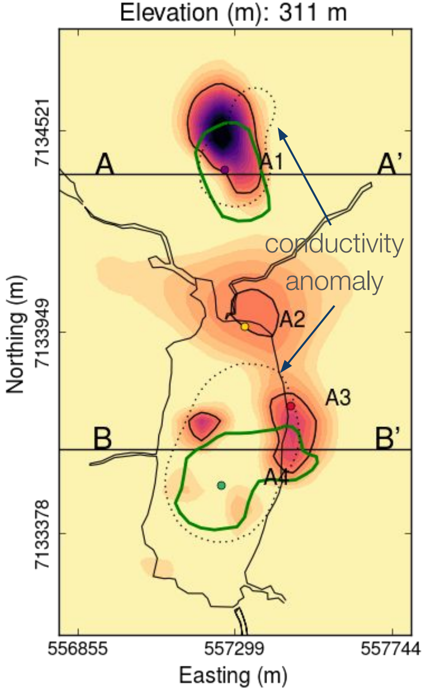
invert

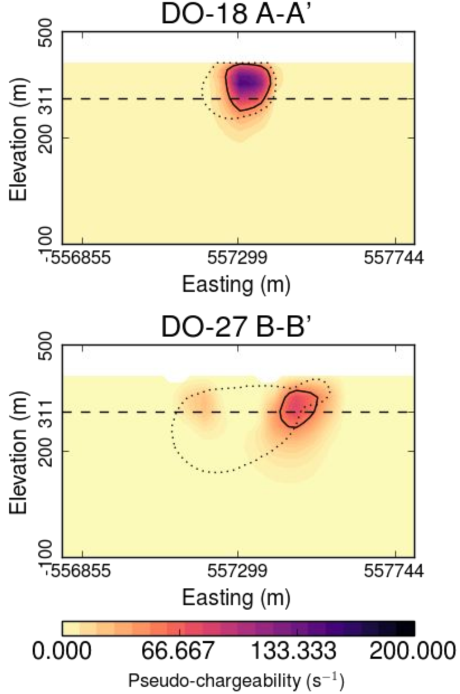
$$d^{IP}(t) = G\tilde{\eta}(t)$$

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

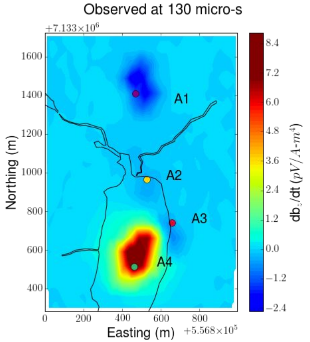
Kang et al. (2016)

Recovered 3D model

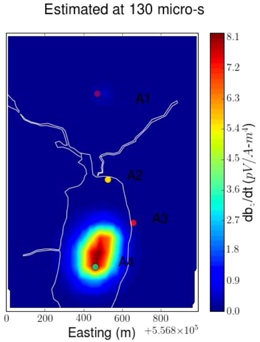




Observation



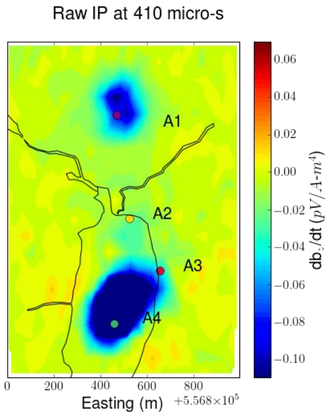
Fundamental



IP = Observation – Fundamental (EM)

TKC: IP inversion (late time)

IP data



invert

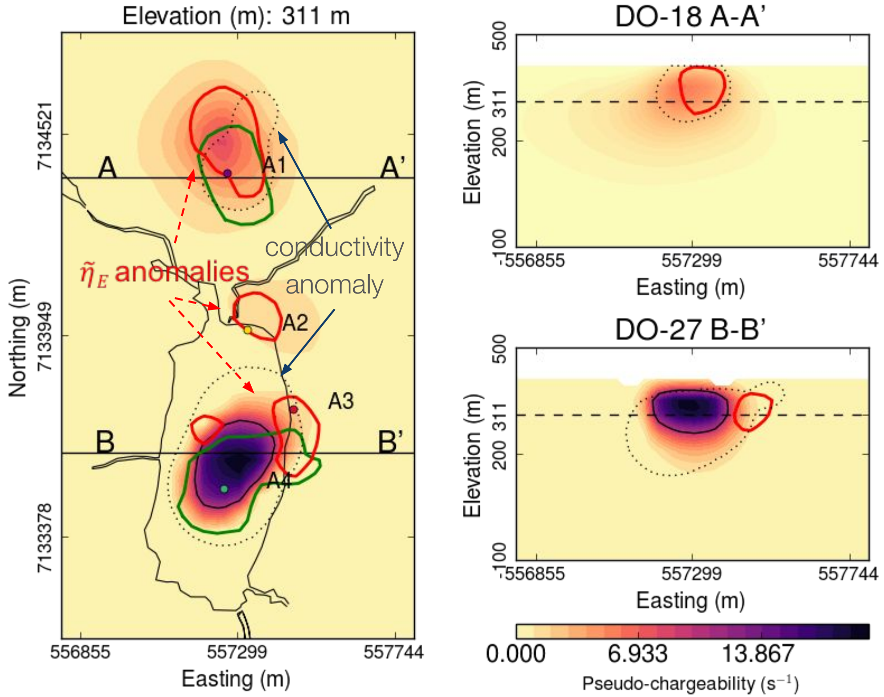
$$d^{IP}(t) = G\tilde{\eta}(t)$$

$G(\sigma_\infty)$: Sensitivity function

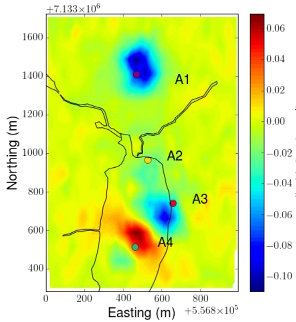
$\tilde{\eta}$: Pseudo-chargeability

Kang et al. (2016)

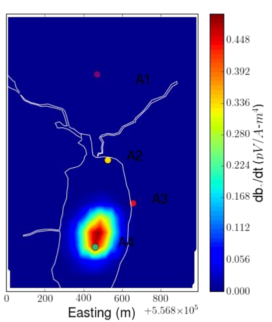
Recovered 3D model



Observation



Fundamental



IP = Observation – Fundamental (EM)

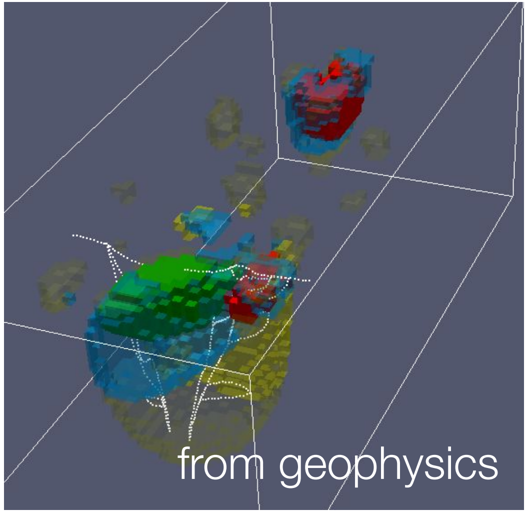
A quasi-geology model from physical properties

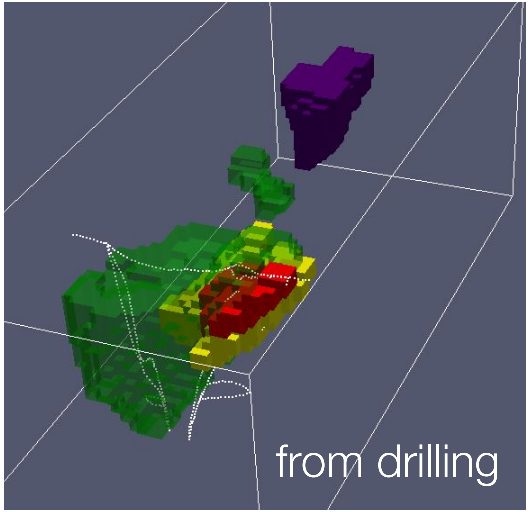
Rock type	Glacial till	Host rock	HK	VK	PK
Density	Moderate	Moderate	Low	Low	Low
Susceptibility	None	None	High	Low-moderate	Low-moderate
Conductivity	Moderate-high	Low	Low-moderate	Moderate-high	Moderate-high
Chargeability	Low	Low	?	?	?

small time constant

large time constant

- Independently inverted multiple airborne geophysical data sets in 3D, built a representative 3D rock model
- Importance of conductivity, chargeability & related computational tools
- Research grounded in data: helps prioritize questions
- Challenges…?





research model: challenges & opportunities

Limitations to research mode

- Production code (Fortran) decoupled from research code (Matlab)
  - difficult to alter (even for small changes)
- Fortran software an end-product, structured to carry out one task
  - connecting multiple physical properties would require a complete rewrite

Needs

- extensible, adaptable software → modular software in a “friendly” language
- collaboration → testing, software practices

Tools

GitHub Python open source initiative

motivations for open-source

develop + deploy in same programming language
→ research and tech transfer tightly coupled

community-driven development
→ users can also be contributors
→ reduces “bus-factor” risk

open license facilitates use, adaptation
→ flexibility to extend to new use cases
→ commercial and academic use

interoperate with broader open-source ecosystem
→ leverage advances in other tools
→ more integrated workflows

simpeg

fatiando a terra
open-source library for modeling and inversion in geophysics

GemPy

PyTorch

scikit learn

simpeg

Simulation and parameter estimation in geophysics

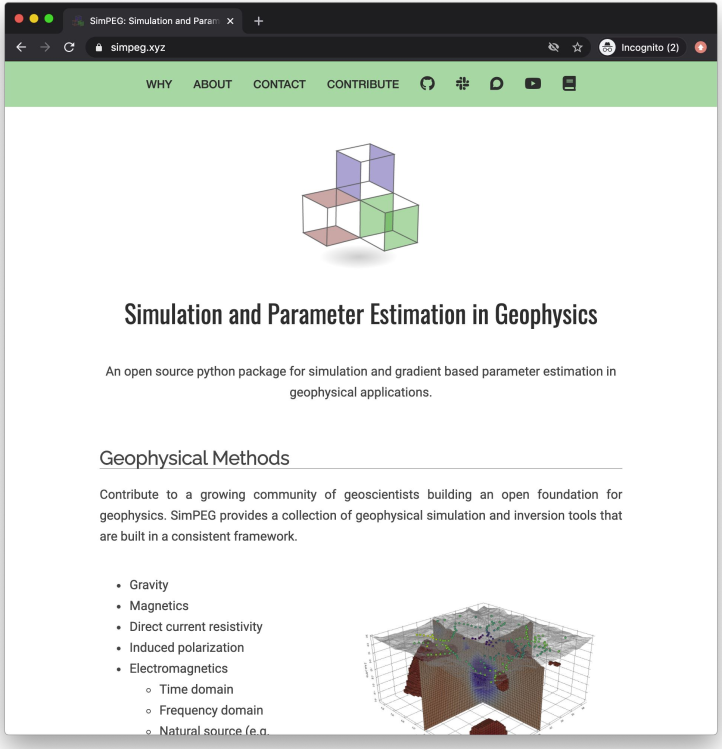
common framework for simulations & inversions

accelerate research: build upon others work

facilitate reproducibility of results

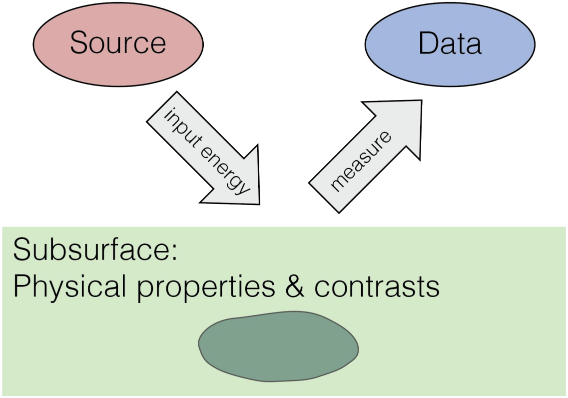
build & deploy in python

open-source



10 years coming soon!

goal of developing a common framework for inversions in geophysics

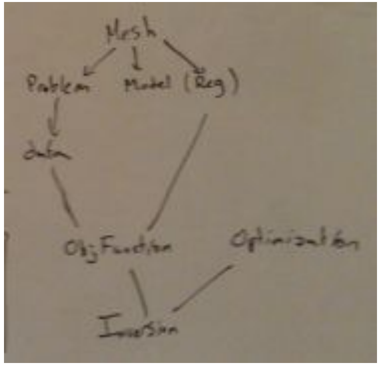


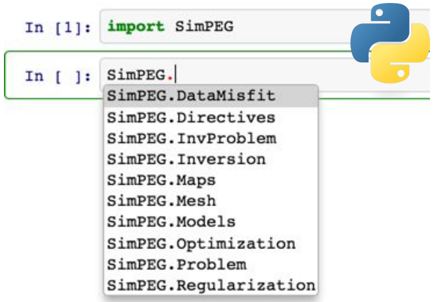
founders

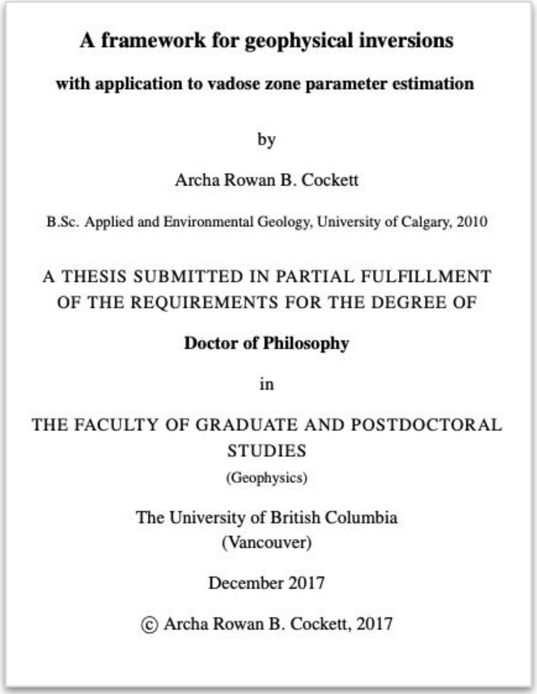
Rowan Cockett

Seogi Kang

Lindsey Heagy







A framework for geophysical inversions

with application to vadose zone parameter estimation

by

Archa Rowan B. Cockett

B.Sc. Applied and Environmental Geology, University of Calgary, 2010

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

Doctor of Philosophy

in

THE FACULTY OF GRADUATE AND POSTDOCTORAL STUDIES

(Geophysics)

The University of British Columbia (Vancouver)

December 2017

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what simpeg solves

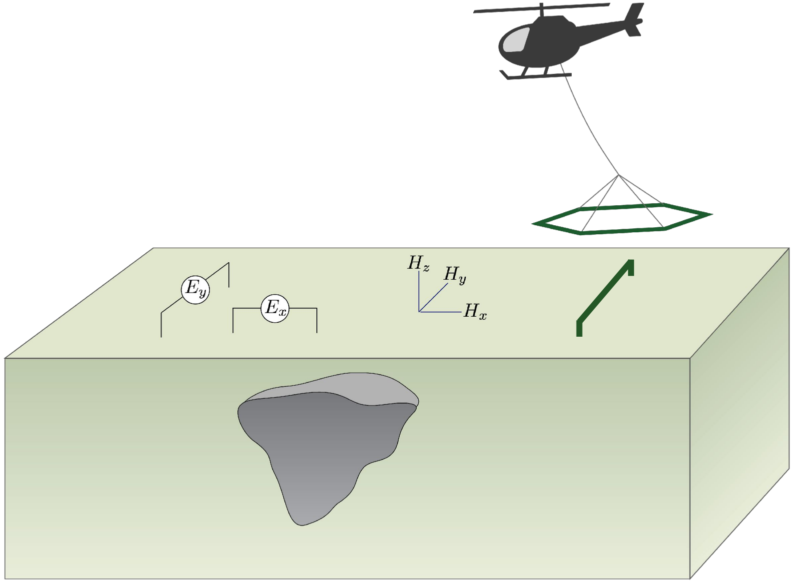
Given

- observations: $d_j^{obs}, \quad j = 1, \ldots, N$
- uncertainties: ϵ_j
- ability to forward model: $\mathcal{F}[m] = d$

Inverse problem: Find the Earth model that gave rise to the data

$$\min_{\mathbf{m}} \phi(\mathbf{m}) = \phi_d(\mathbf{m}) + \beta \phi_m(\mathbf{m})$$

$$\text{s.t. } \phi_d \leq \phi_d^* \quad \mathbf{m}_L \leq \mathbf{m} \leq \mathbf{m}_U$$

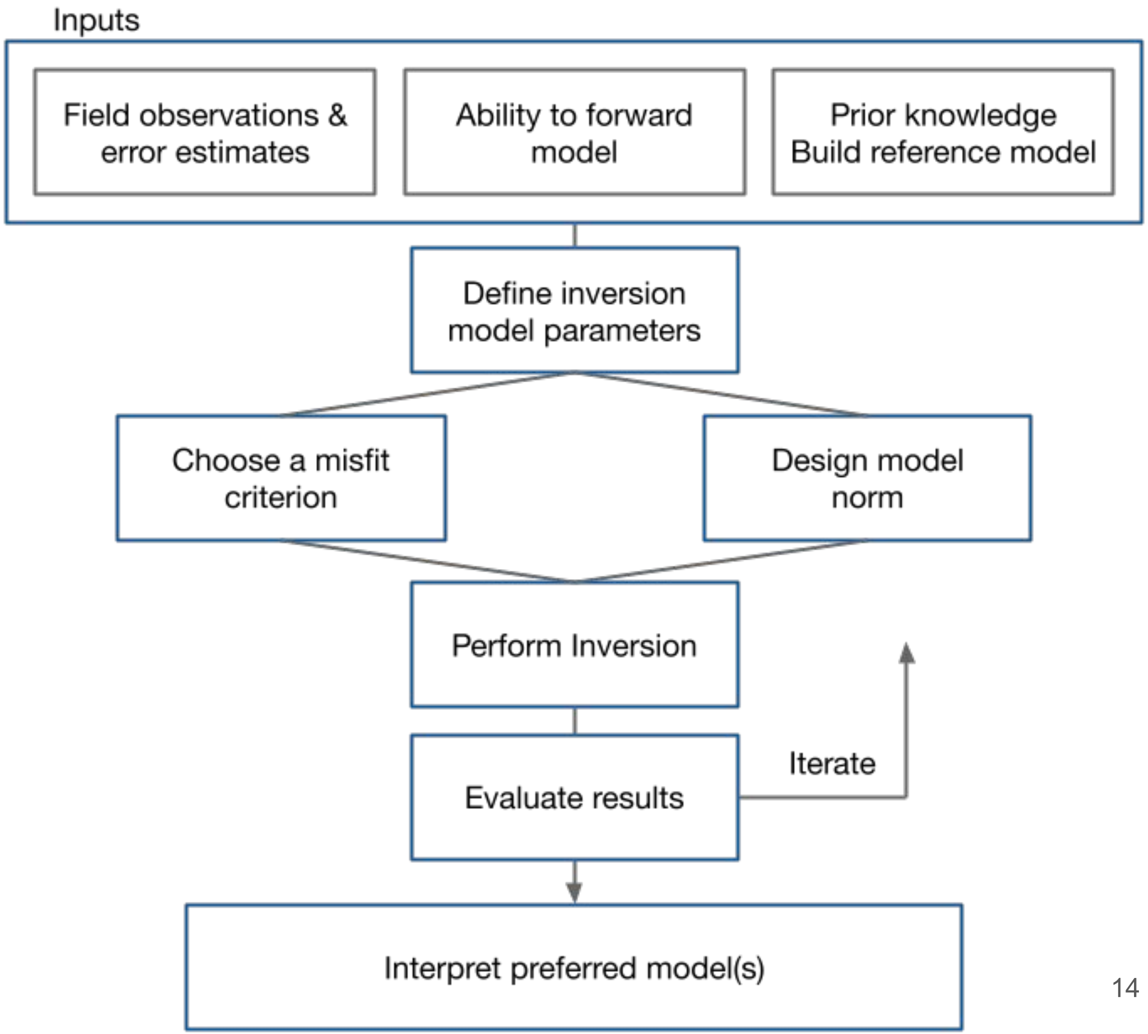


flow chart for the inverse problem

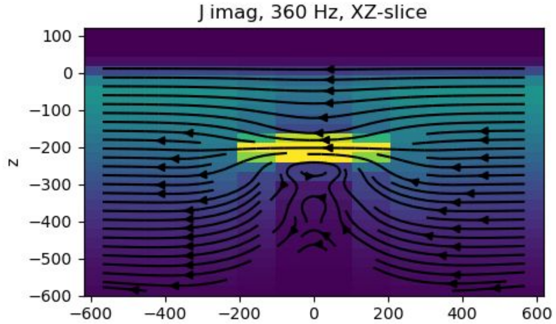
- many components
- iterative process to obtain solution
- each component requires evaluation, adjustment by user



Fundamentals of Inversion – D. Oldenburg
Capturing knowledge in code – L. Heagy
http://www.mtnet.info/EMinars/EMinars.html



the forward simulation: discretize and solve



frequency domain electromagnetics

$$\nabla \times \mu^{-1} \nabla \times \vec{E} + i\omega\sigma\vec{E} = -i\omega\vec{J}_s$$

discretize (finite volume)

$$\underbrace{\left(\mathbf{C}^\top \mathbf{M}^f_{\mu^{-1}} \mathbf{C} + i\omega \mathbf{M}^e_\sigma\right)}_{\mathbf{A}} \mathbf{e} = -i\omega \mathbf{j}_s$$

```python
ω = 2 * np.pi * frequency
C = mesh.edgeCurl
Mfμi = mesh.getFaceInnerProduct(1./mu_0)
Meσ = mesh.getEdgeInnerProduct(sigma)

A = C.T * Mfμi * C + i * ω * Meσ
Ainv = Solver(A)  # acts like A inverse

rhs = - i * ω * js

e = Ainv * rhs
```

forward simulation: discretize and solve

frequency domain electromagnetics

$$\nabla \times \mu^{-1} \nabla \times \vec{E} + i\omega\sigma\vec{E} = -i\omega\vec{J}_s$$

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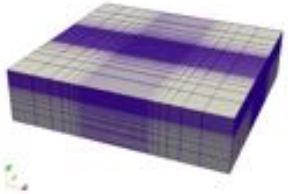
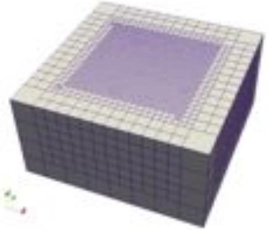


Tensor



OcTree

J. Capriotti

```
ω = 2 * np.pi * frequency
C = mesh.edgeCurl
Mfμi = mesh.getFaceInnerProduct(1./mu_0)
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A = C.T * Mfμi * C + i * ω * Meσ
Ainv = Solver(A)  # acts like A inverse

rhs = - i * ω * js

e = Ainv * rhs
```

simpeg electromagnetics

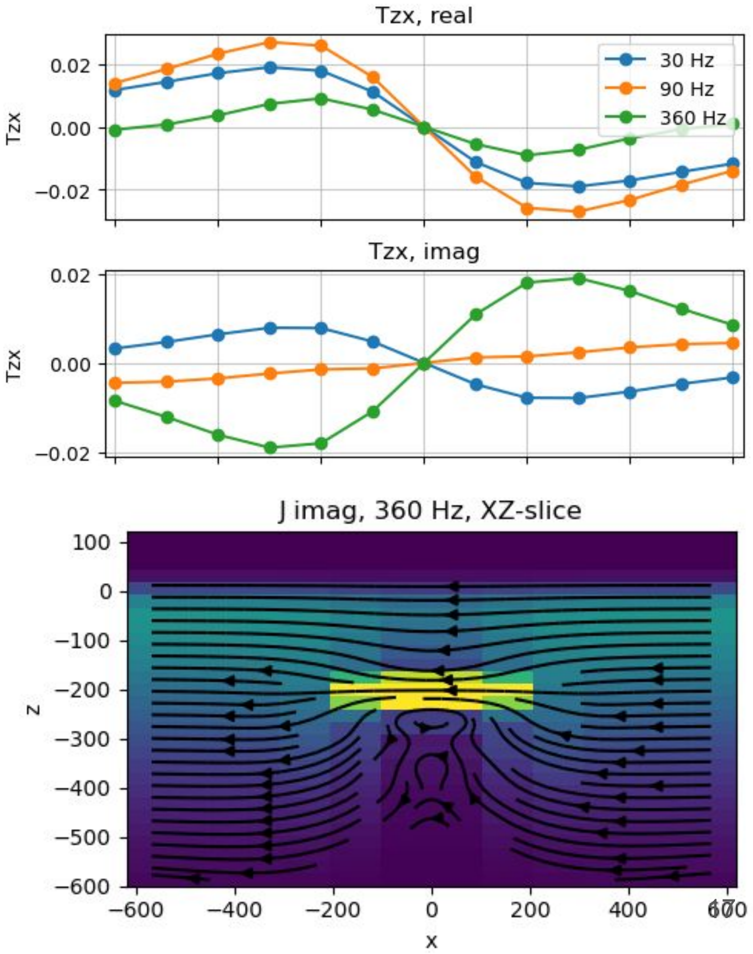
time and frequency domain

Controlled source + natural source methods

- Rely on the same methods for calculating fields, sensitivities
- 1D, 2D (in progress), 3D simulation on Tensor, OcTree meshes
    - Primary-secondary approach
    - Boundary-conditions in progress

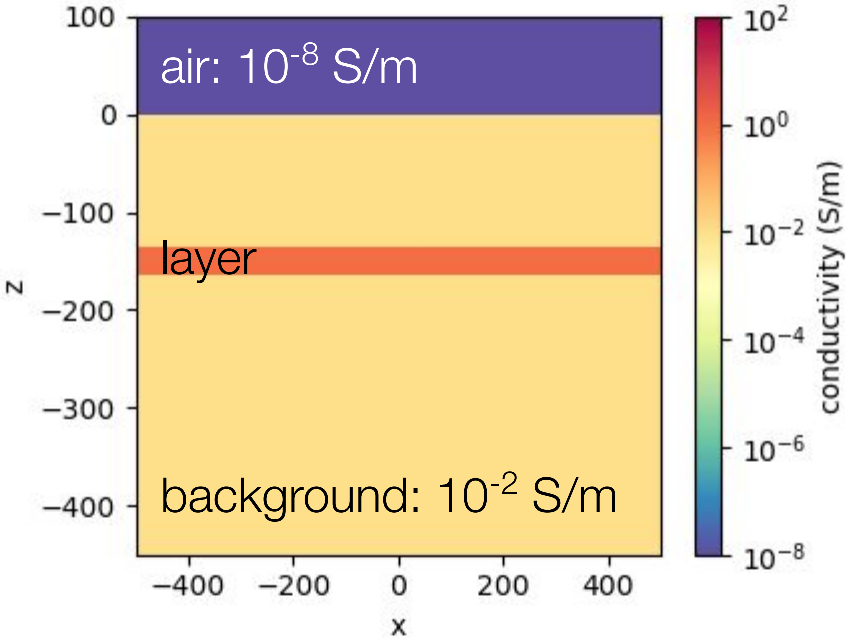
Conventions:

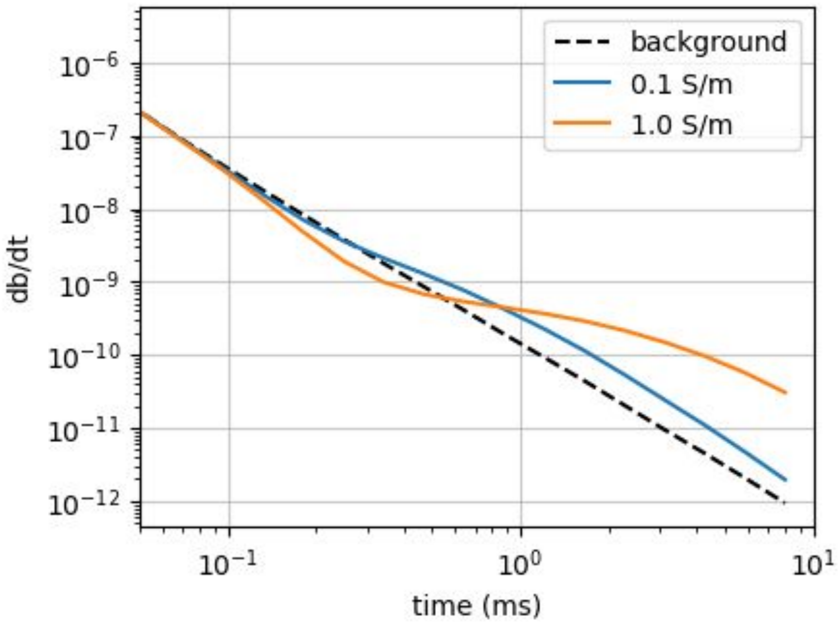
- right handed coordinate system
- z positive up
- e+iwt Fourier transform



Time domain simulation: VTEM

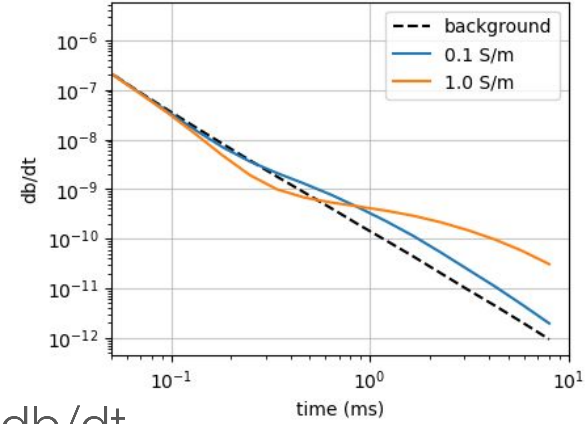
response of a layered Earth





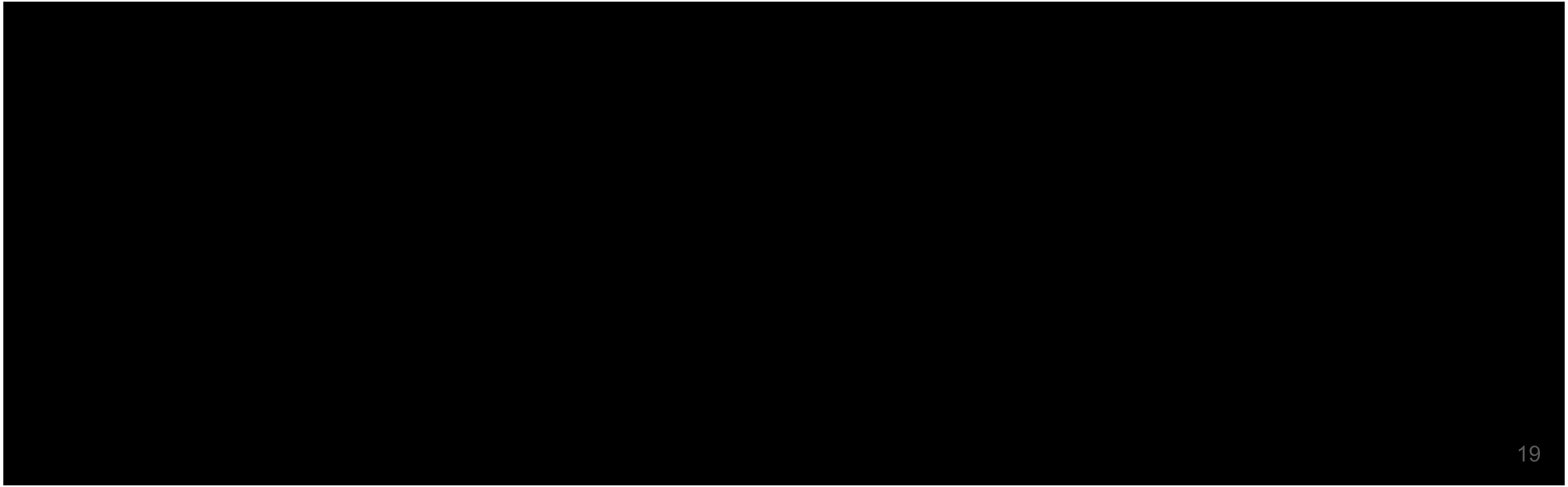
Time domain simulation:VTEM

halfspace



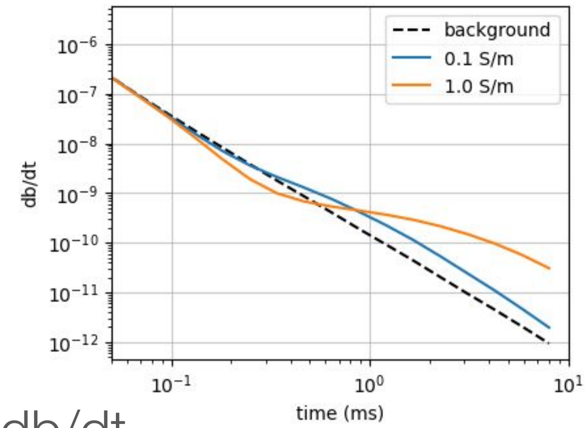
current density

db/dt



Time domain simulation:VTEM

halfspace with a conductive layer



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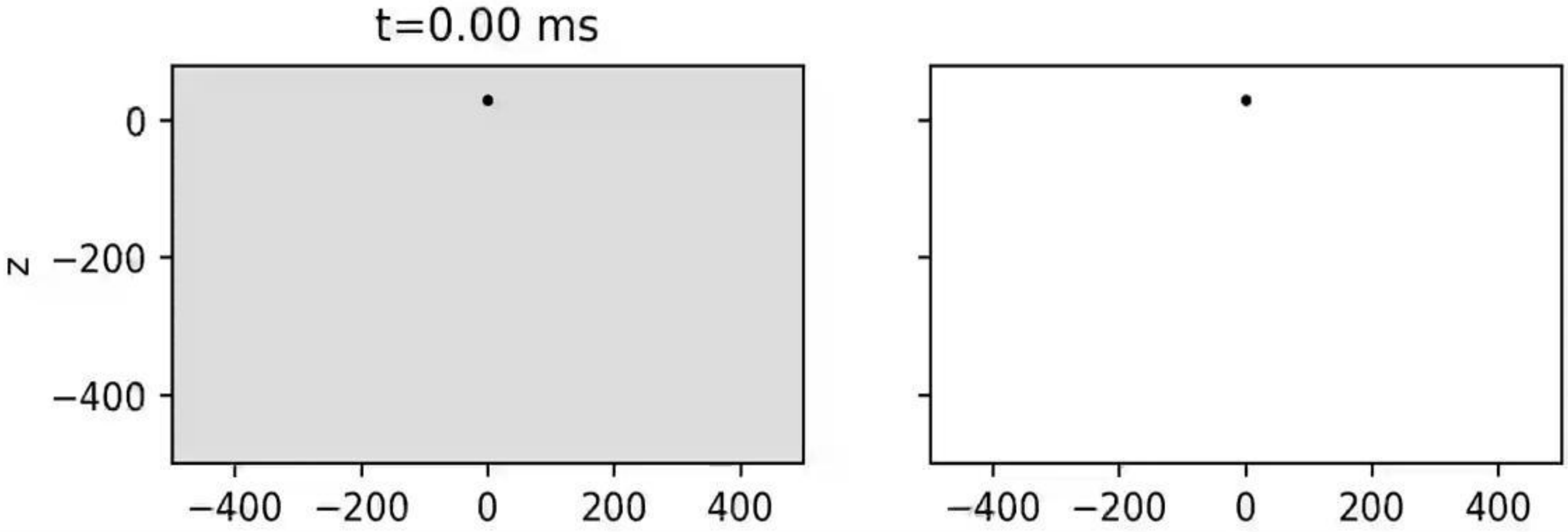
db/dt



Time domain inversion: VTEM

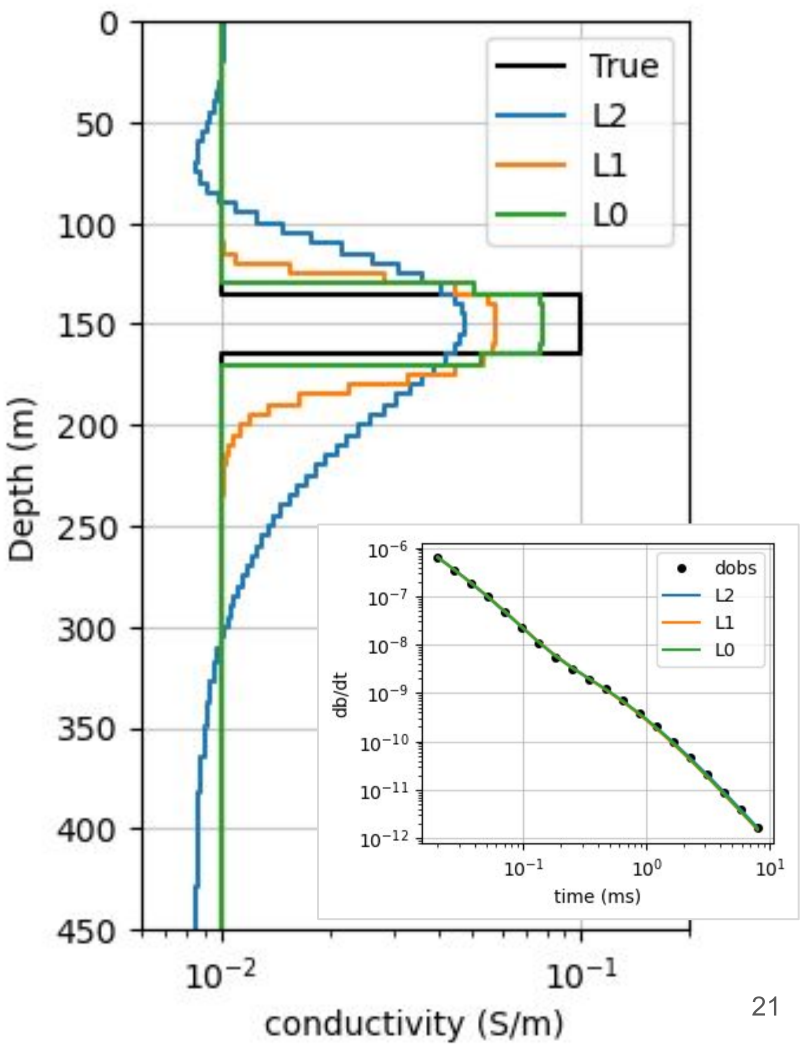
solving the inverse problem

$$\min_{\mathbf{m}} \phi(\mathbf{m}) = \phi_d(\mathbf{m}) + \beta\phi_m(\mathbf{m})$$

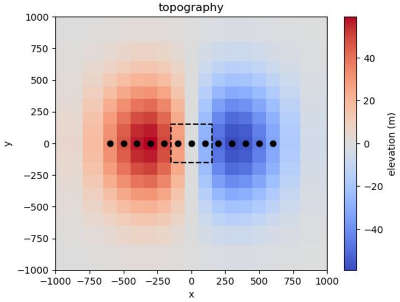
$$\text{s.t. } \phi_d \leq \phi_d^* \quad \mathbf{m}_L \leq \mathbf{m} \leq \mathbf{m}_U$$

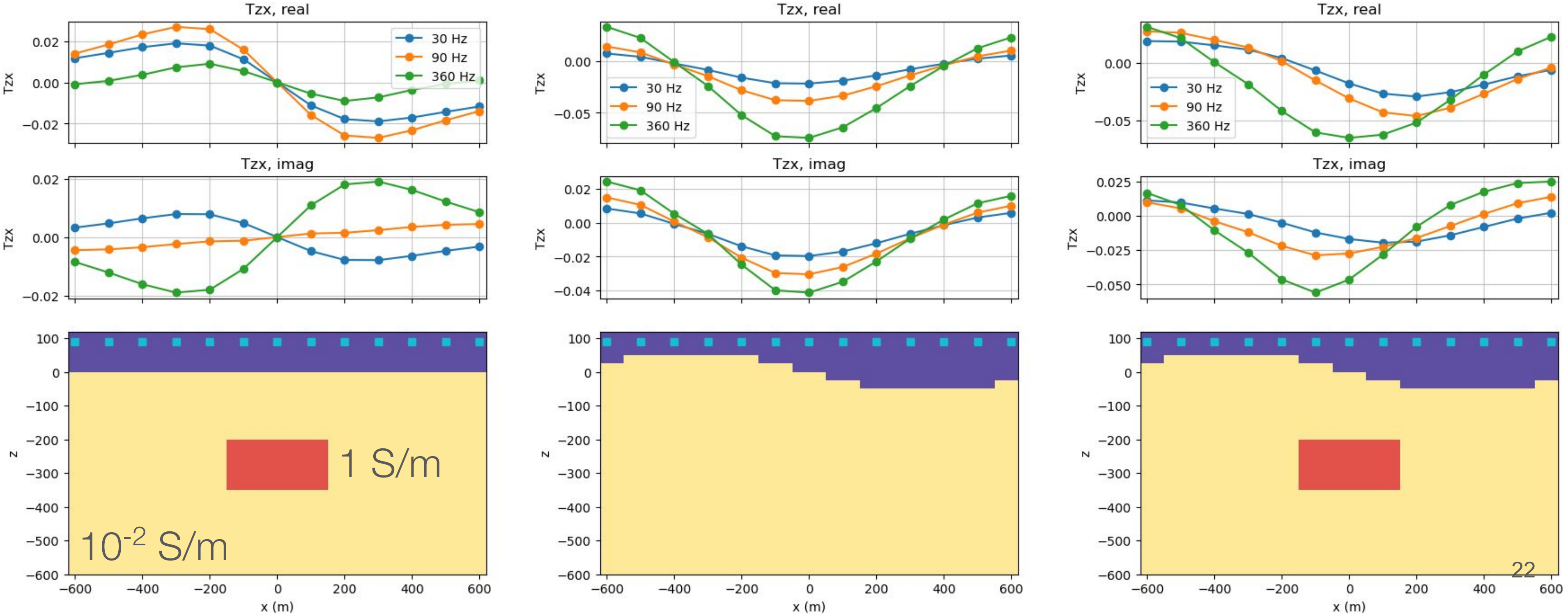
choice of model norm

$$\phi_m = \alpha_s \int_v w_s \left|\mathbf{m} - \mathbf{m}_{ref}\right|^{p_s} dV + \alpha_x \int_V w_x \left|\frac{d\mathbf{m}}{dz}\right|^{q_z} dV$$



Frequency domain: ZTEM





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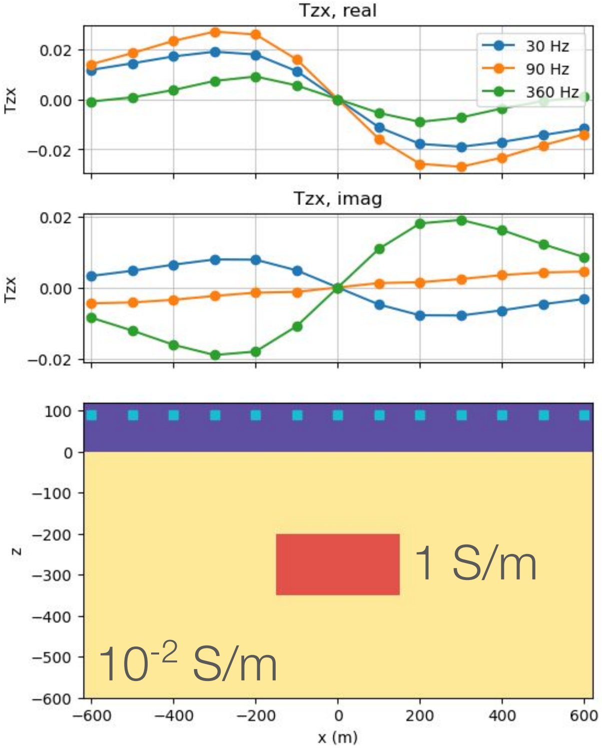

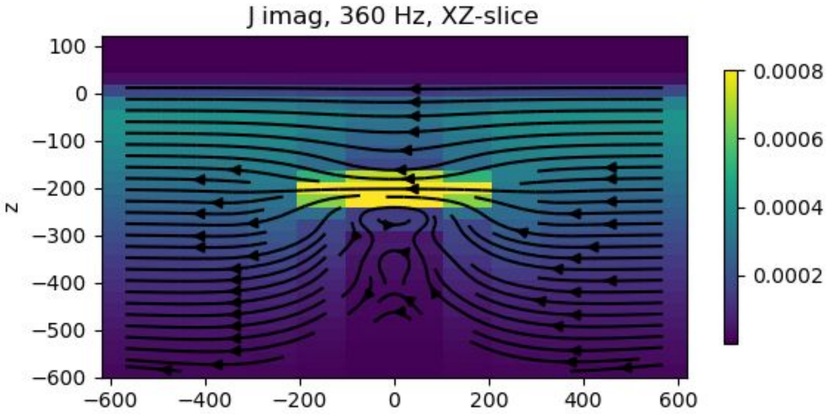

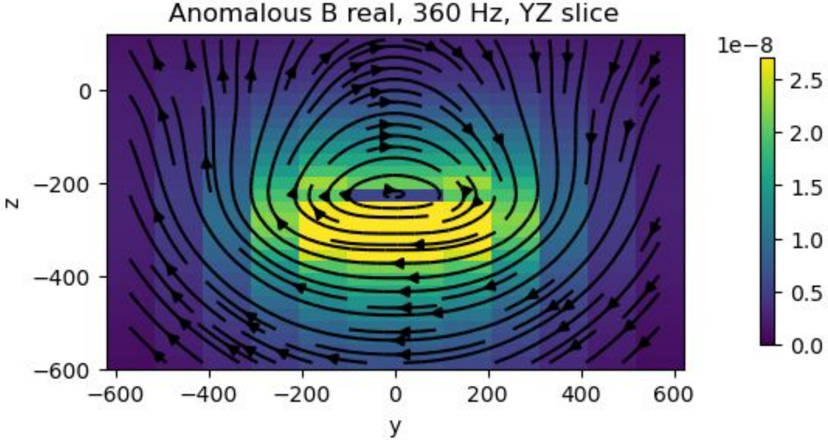

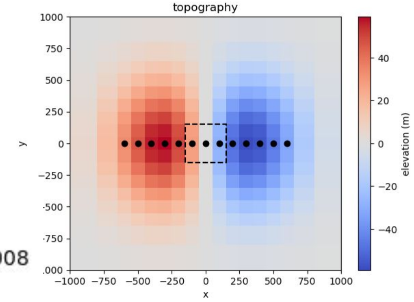

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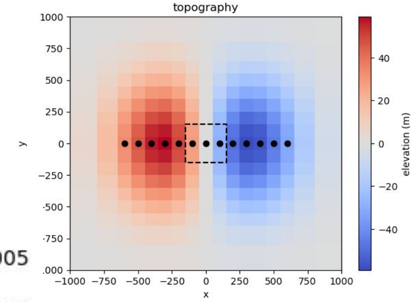
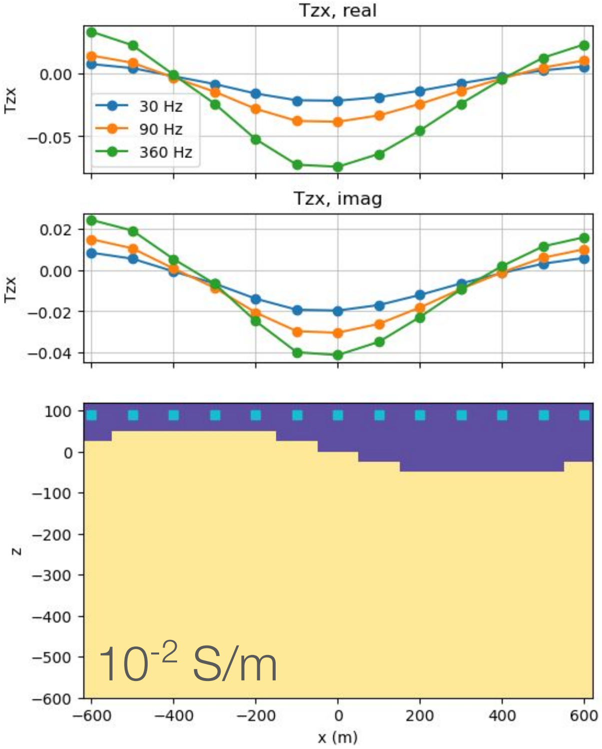
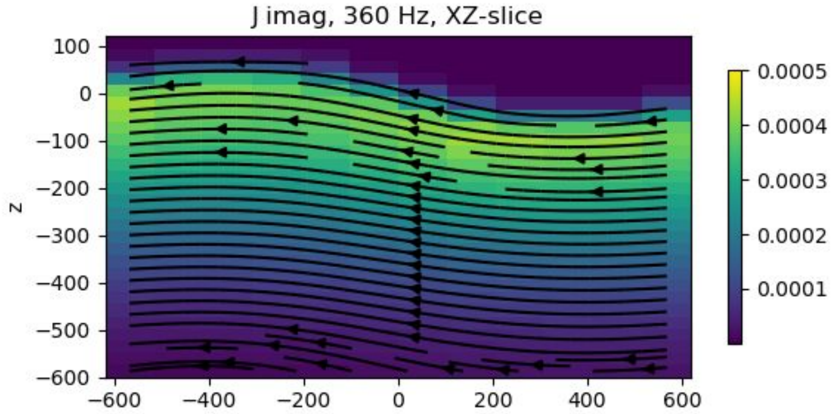
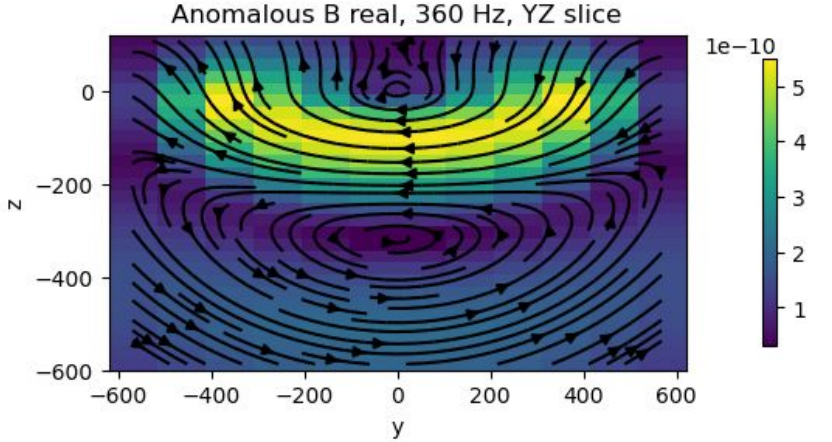
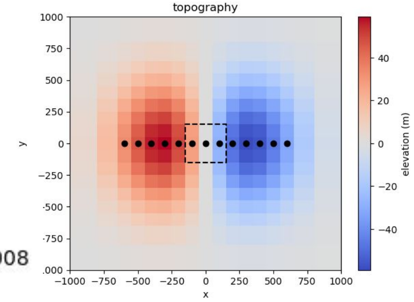


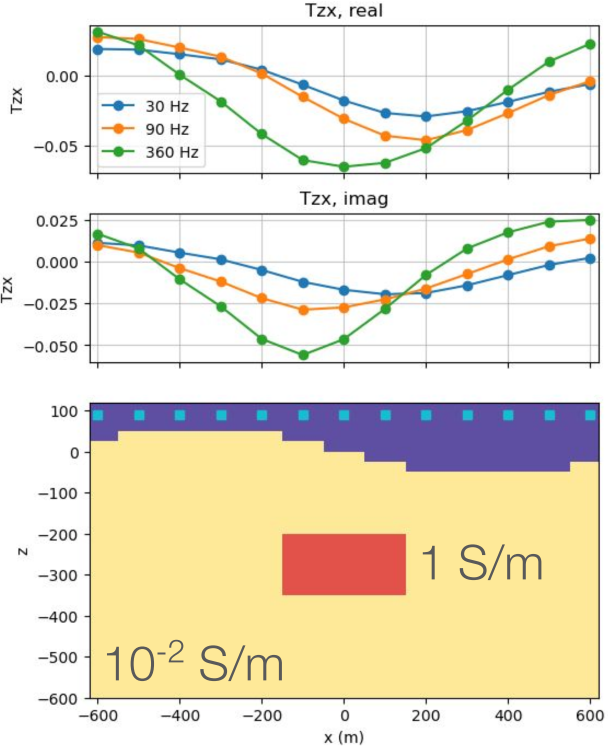


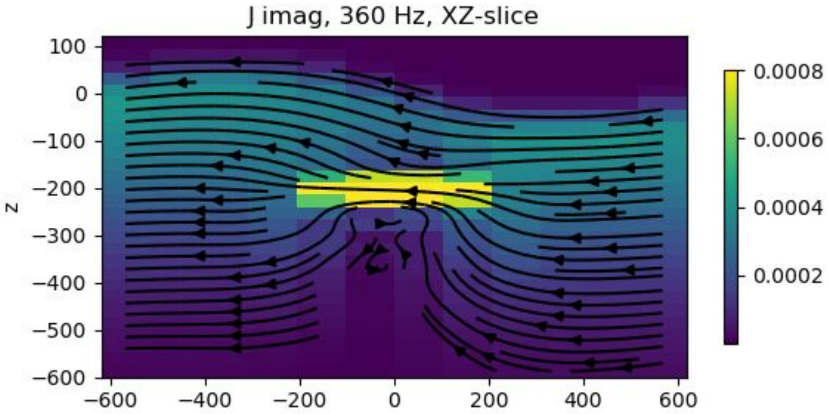


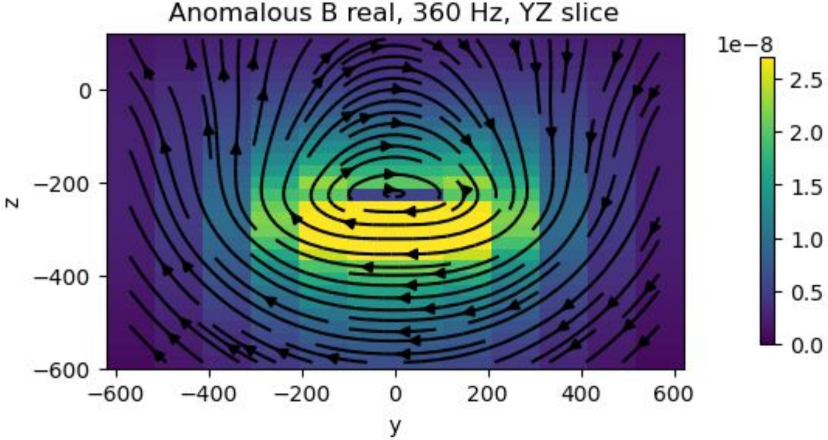


Frequency domain: ZTEM









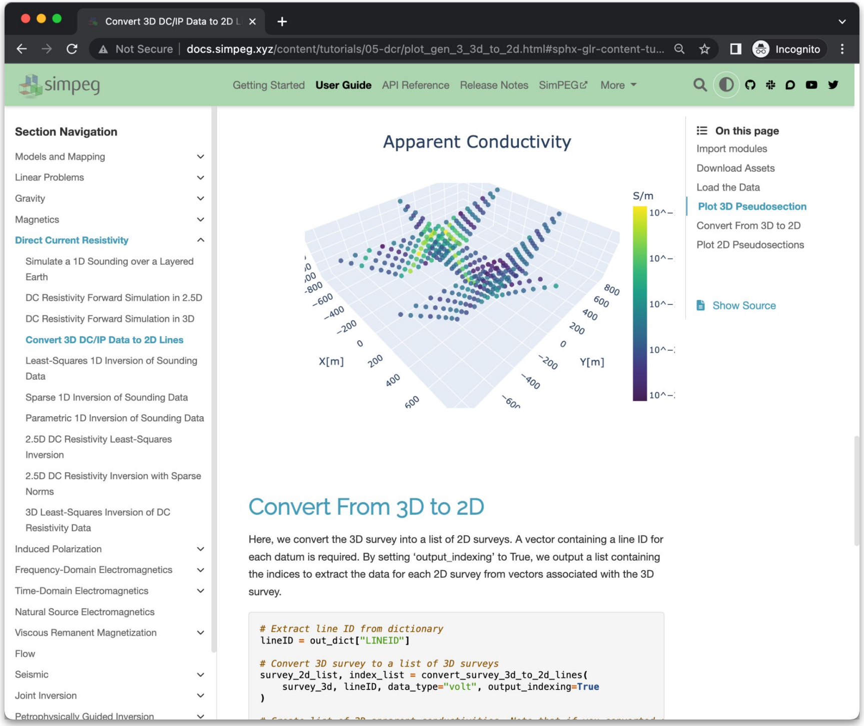
functionality & status

Many aspects production-ready

- OcTree meshes
- Gravity
- Magnetics
- DC Resistivity
- Induced Polarization
- EM1D

Other areas in research and development

- 3D FDEM
- 2D, 3D NSEM
- 3D TDEM
- Joint Inversions



simpeg & GIF Fortran codes

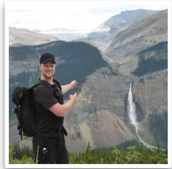
GIF Fortran codes: widely used, applied, and trusted

- plan to maintain Fortran codes and make functional improvements
- code validations project: comparing, testing Fortran & simpeg codes

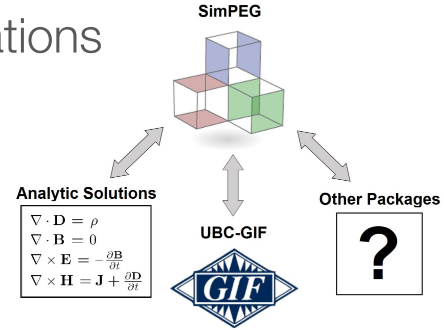
Moving forwards with open source

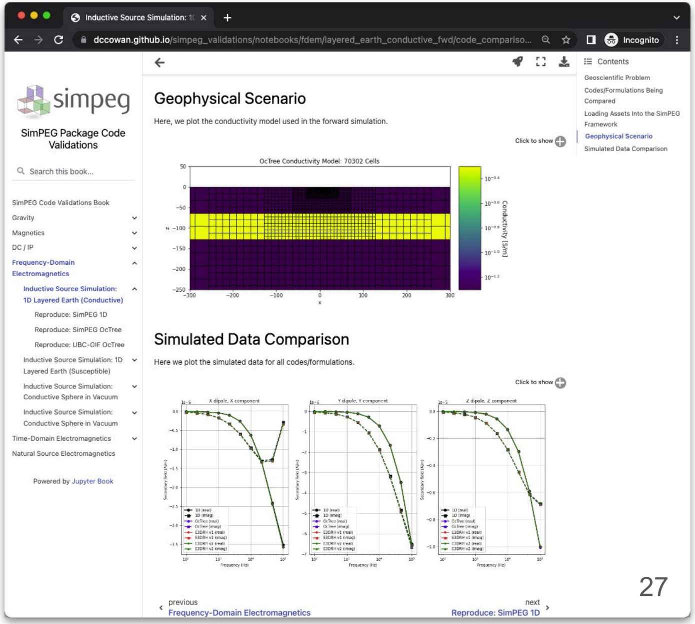
- focus of new research & development efforts
- streamlines technology transfer
- accelerates research…?

code validations



Devin Cowan

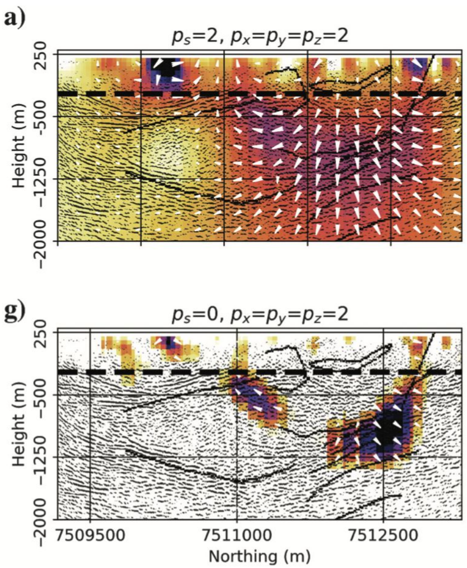




sparse norms

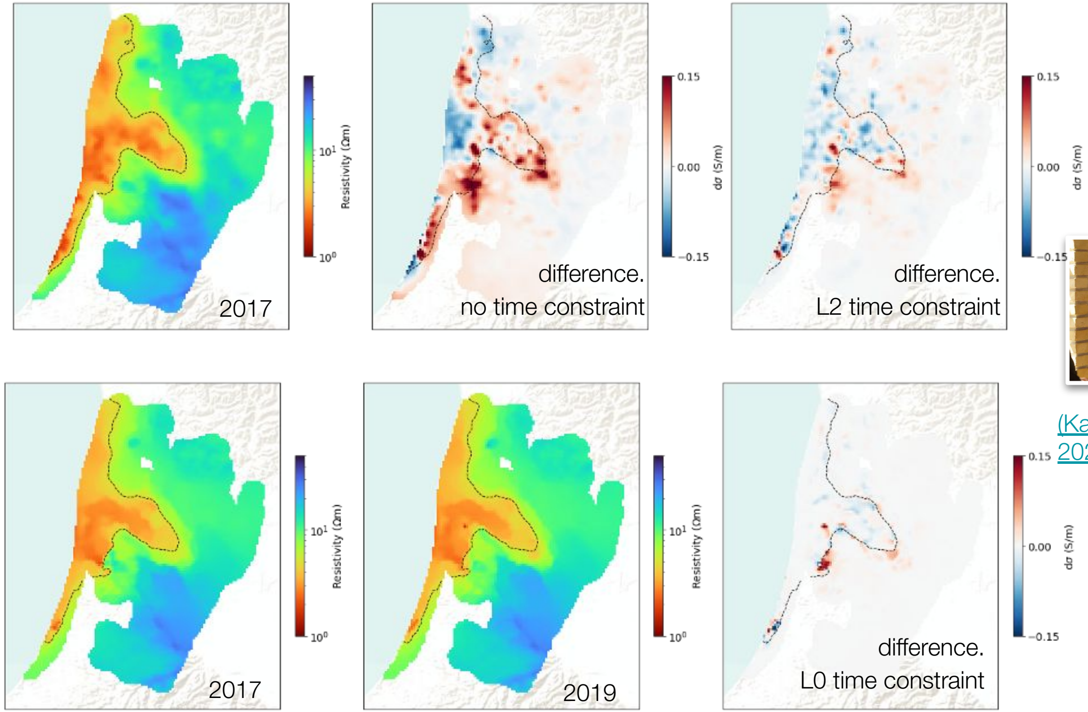
$$\phi_m = \alpha_s \int_v w_s \left|\mathbf{m} - \mathbf{m}_{ref}\right|^{p_s} dV + \alpha_x \int_V w_x \left|\frac{d\mathbf{m}}{dz}\right|^{q_z} dV$$

developed in potential fields



(Fournier et al, 2019)

adapted to time-lapse AEM



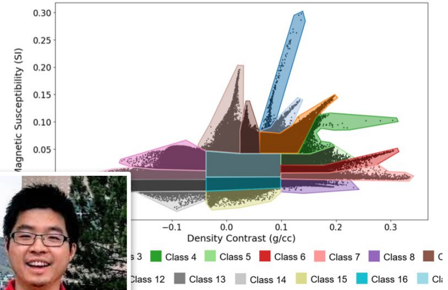
(Kang & Knight, 2022)

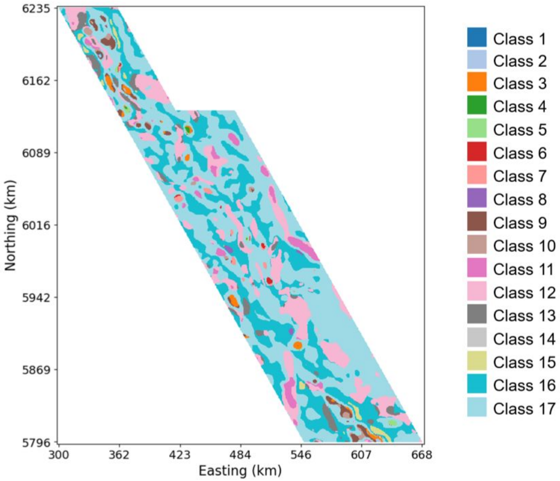
joint inversions

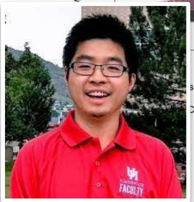
`ϕ_data = ϕ_grav + ϕ_mag  # one earth?`

- modular framework enables extension to joint inversions
- PGI, cross-gradient, joint total variation implemented

Cross gradient & geologic differentiation at QUEST [Kim et al., 2020](#)

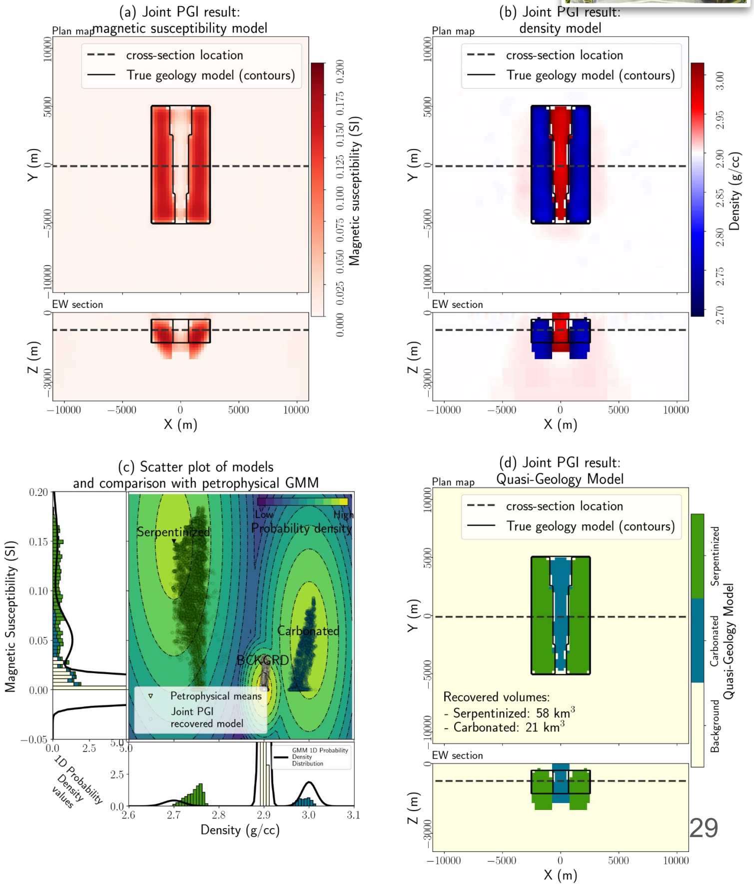






Jiajia Sun

Petrophysically and Geologically guided Inversion (PGI). [Astic et al., 2021](#)

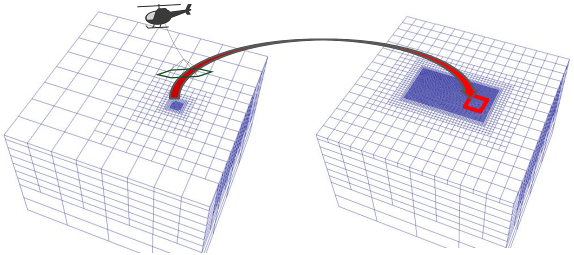


parallelization: an industry-academic collaboration

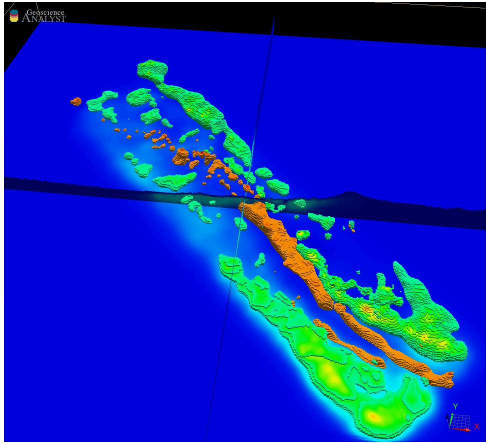
parallelization motivated initially by large scale 3D DCIP

use of dask for parallelization (on any architecture)

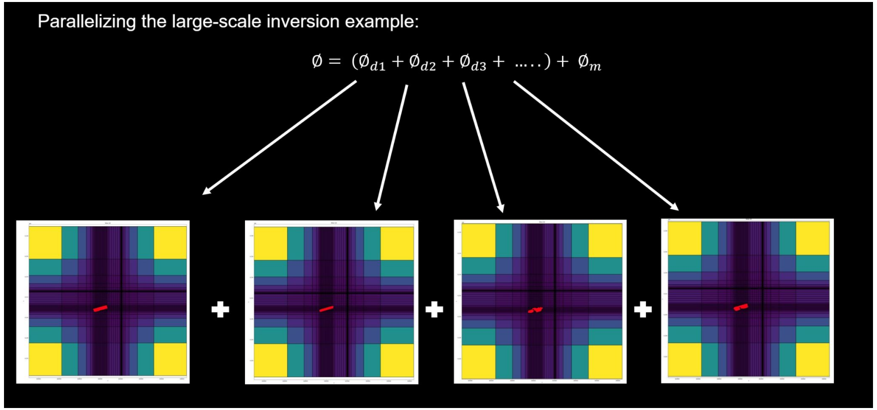
now adapted for Mag, Grav, and working on AEM, MT



John Kuttai



17.1 million cells 783 injections

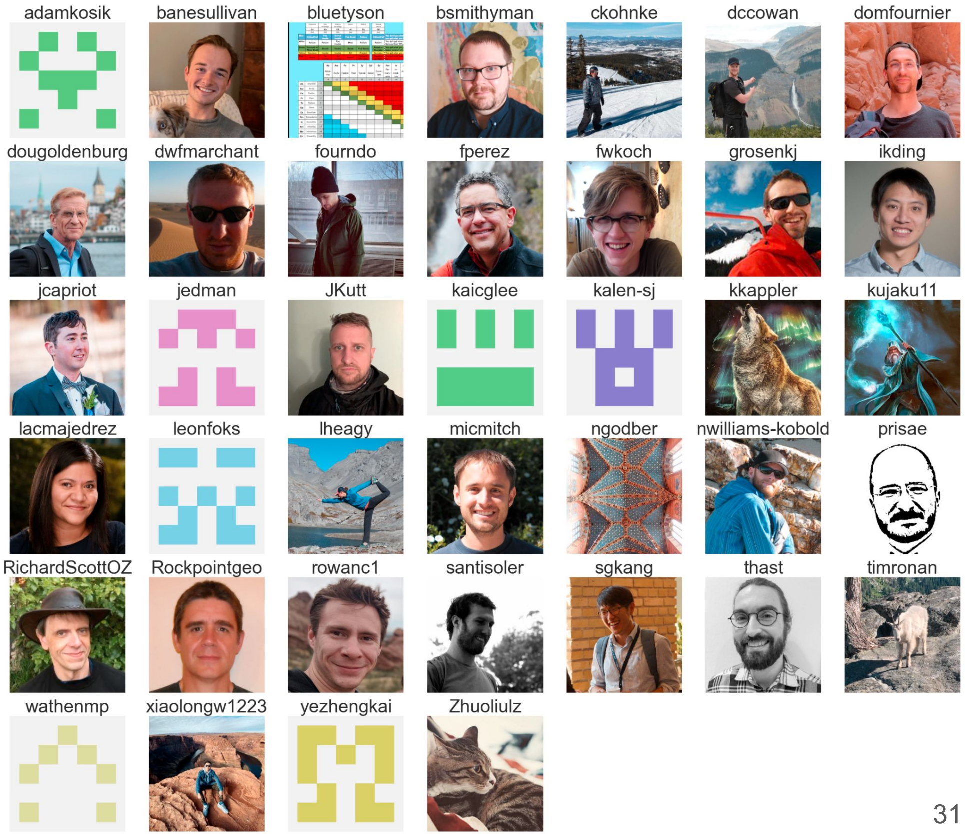


what have we done in 10 years?

built a foundation for new research
→ framework & code

importantly, growth of the community
→ academic & industry

facilitated by open-source approach:
→ enables collaboration, adaptation,
re-use and so much more!



simpeg

thank you and questions

GEOTECH

Jean Legault

Paolo Berardelli

David Hitz