

# Summary and the Future



# Roadblocks

In general, geoscientists...

- Don't realize that EM can play a role in solving the problem
- Don't understand the technique
  - Confusing terminology
  - Seems complicated and unintuitive

What is the connection between my problem and the physical properties?

So many types of surveys, how to choose?

- DC, frequency, time?
- Surveys in air on ground, downhole?
- What to expect for resolution?

Are there situations, similar to mine, in which EM has been applied?

# Many applications

Electromagnetics can be used for ...



minerals



contaminants



water



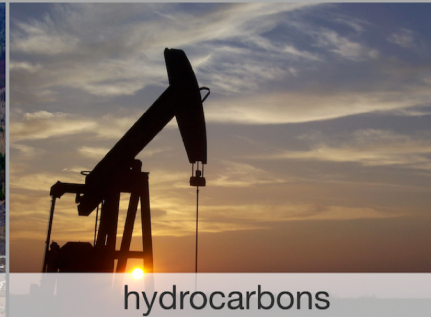
geothermal



geotechnical



slope stability

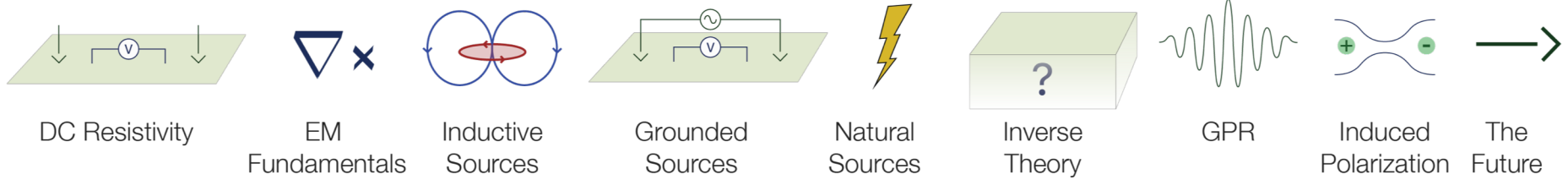


hydrocarbons



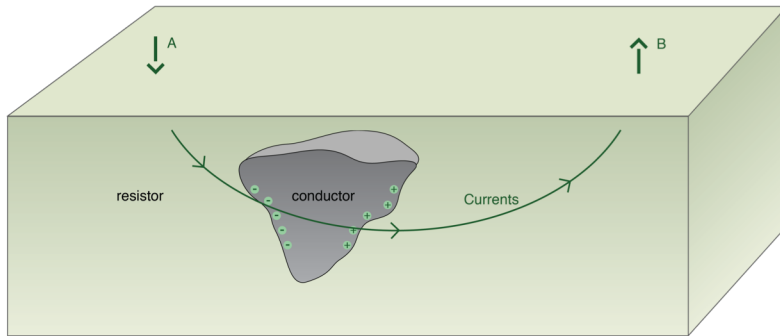
unexploded ordnance

# Summary

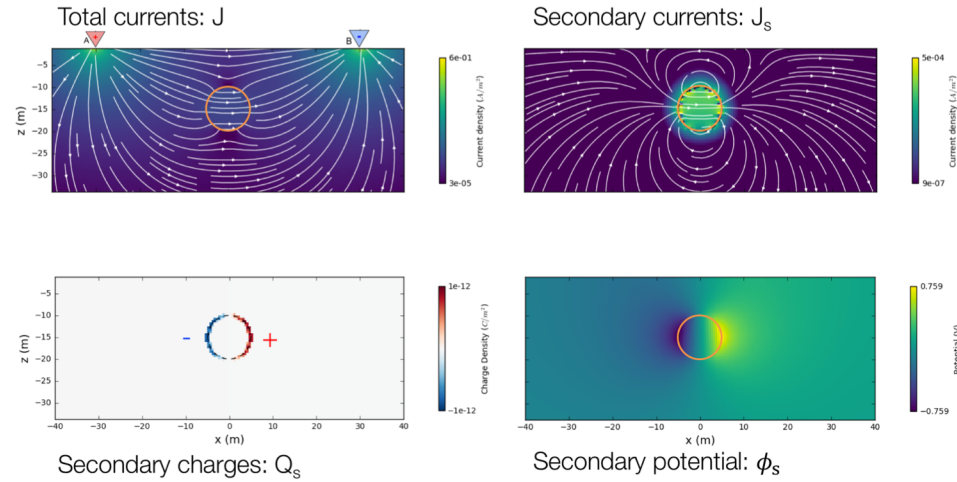


# DC Resistivity

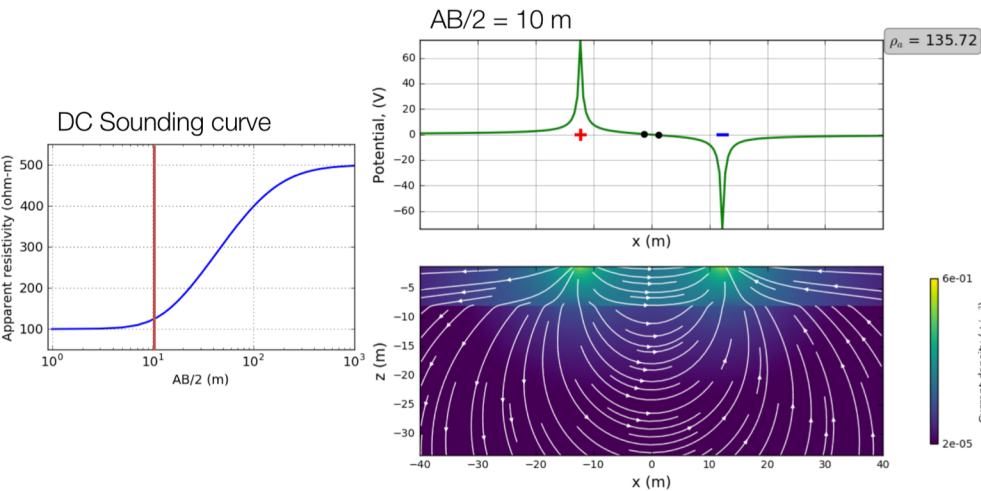
## Basic experiment



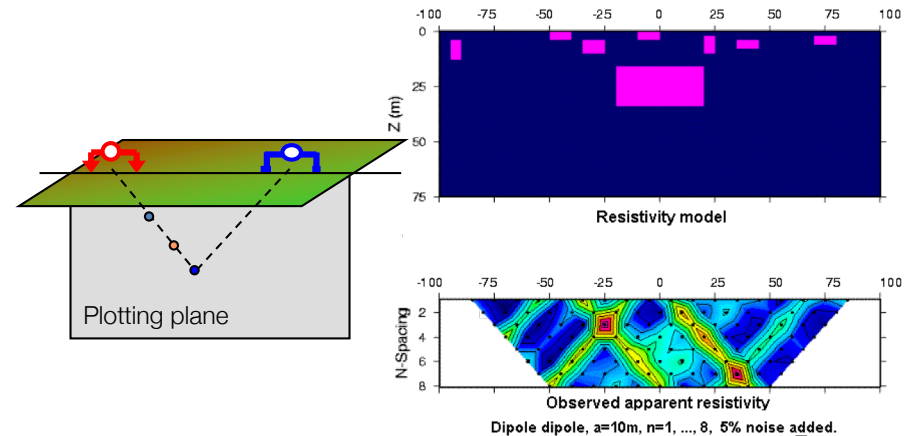
## Currents, charges and potentials



## Soundings and arrays

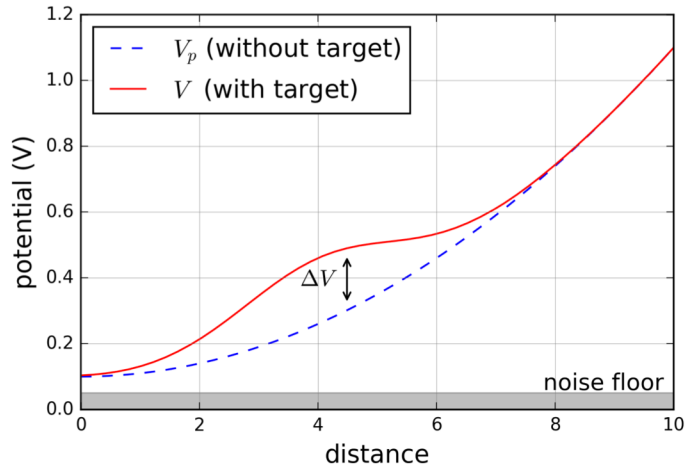


## Pseudosections

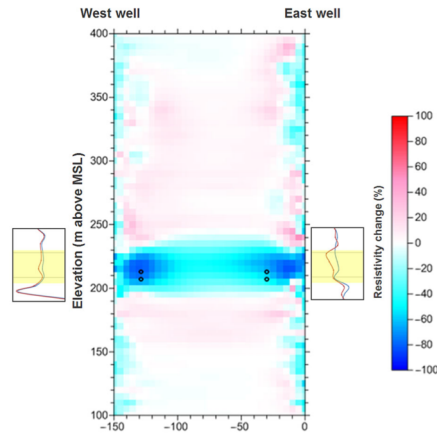


# DC Resistivity

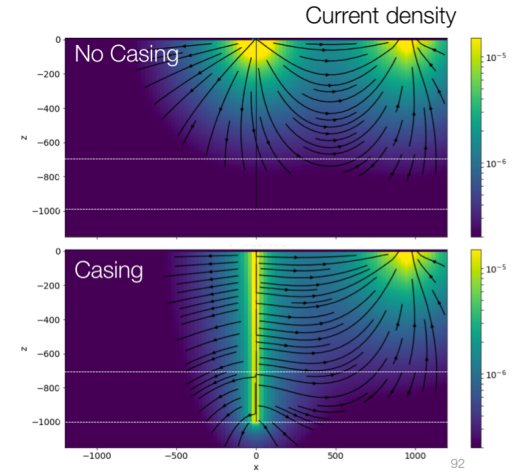
## Survey design and sensitivity



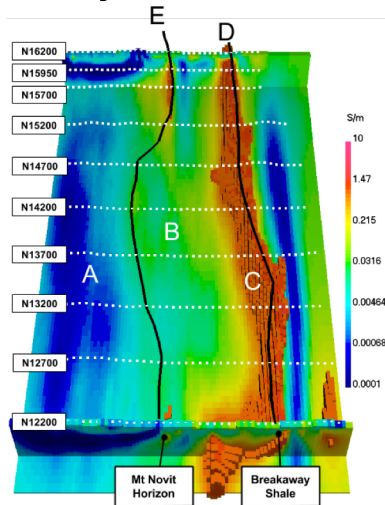
## Case History: Reservoir Monitoring



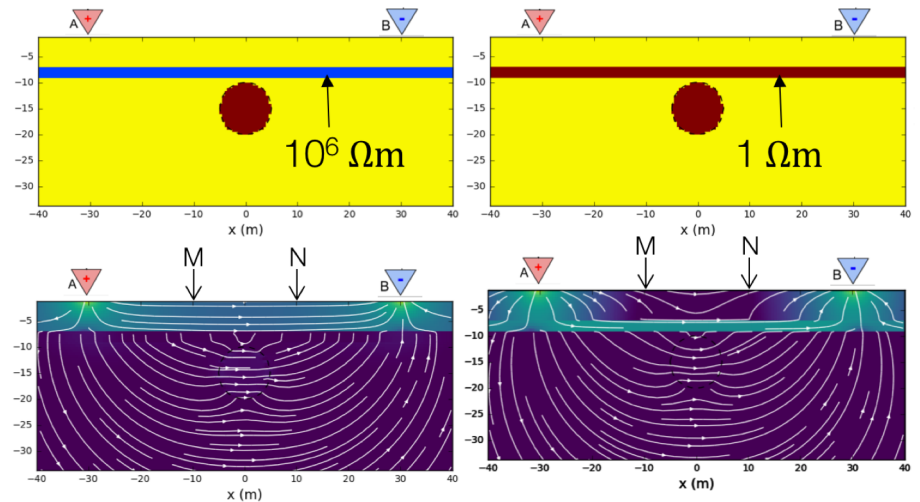
## DC with steel cased wells



## Case History: Mt. Isa

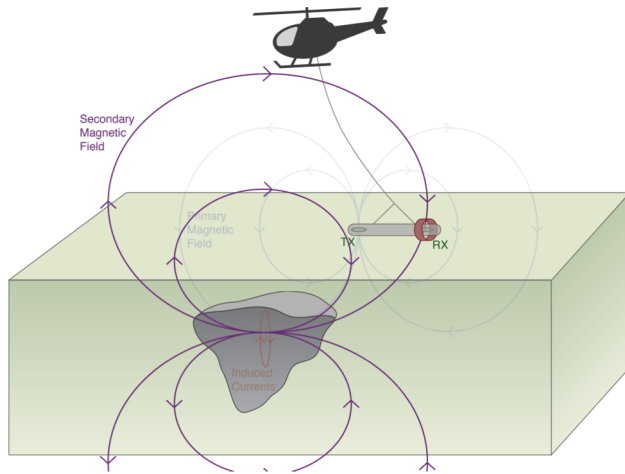


## Shielding

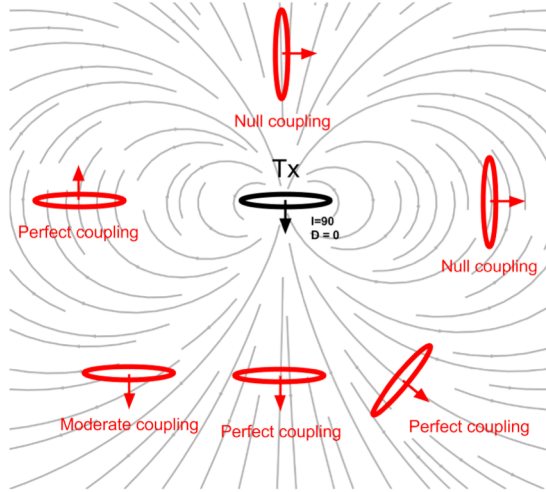


# EM Fundamentals

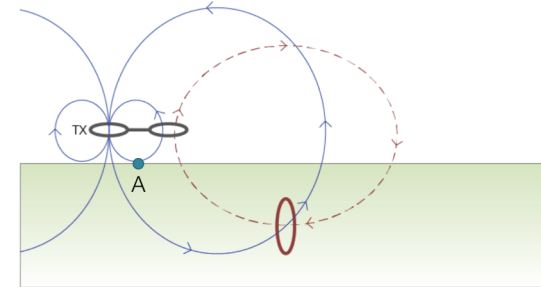
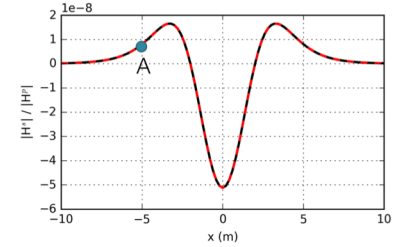
## Basic experiment



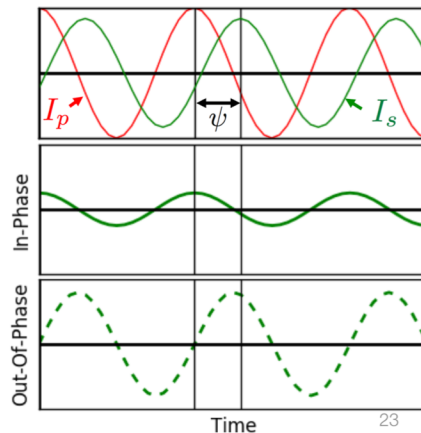
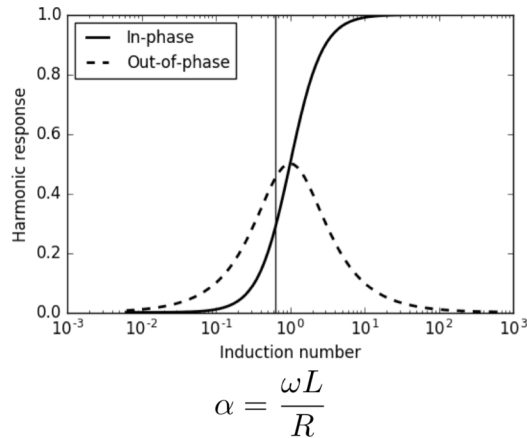
## Coupling



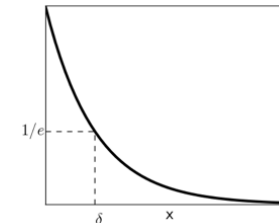
## 3 loop model



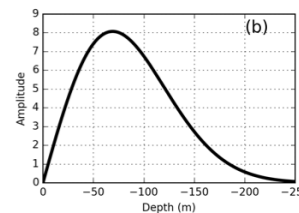
## Response function



## Skin depth and diffusion distance



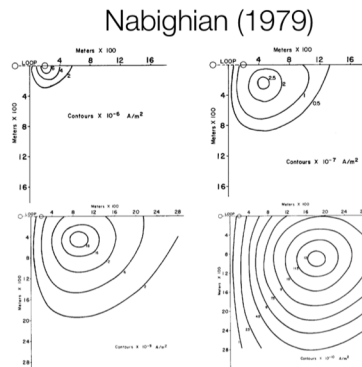
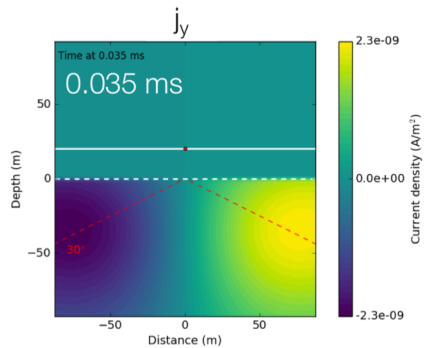
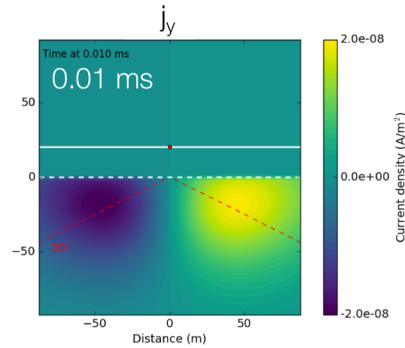
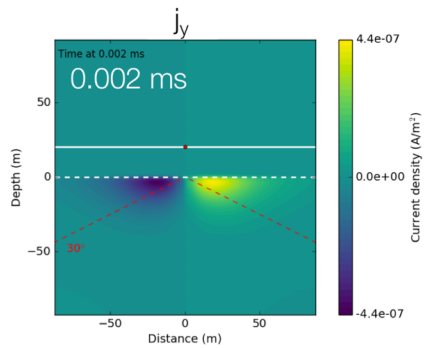
$$\delta = \sqrt{\frac{2}{\omega \mu \sigma}} = 503 \sqrt{\frac{1}{\sigma f}}$$



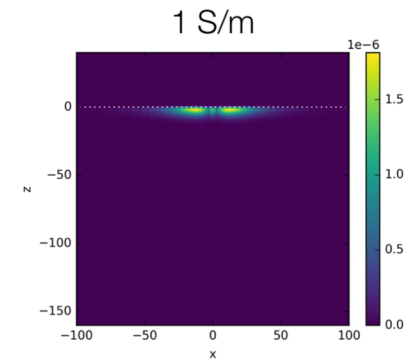
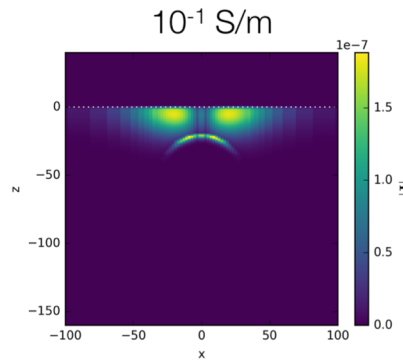
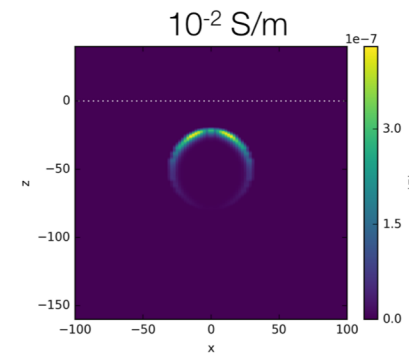
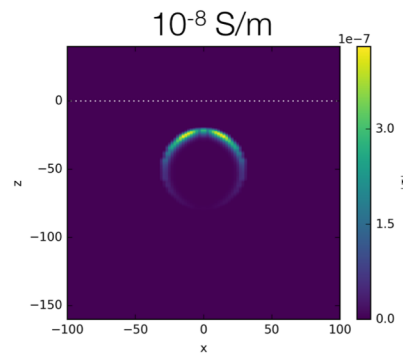
$$d = \sqrt{\frac{2t}{\mu \sigma}} \approx 1260 \sqrt{\frac{t}{\sigma}}$$

# EM Fundamentals

## Dipole sources



## Background conductivity

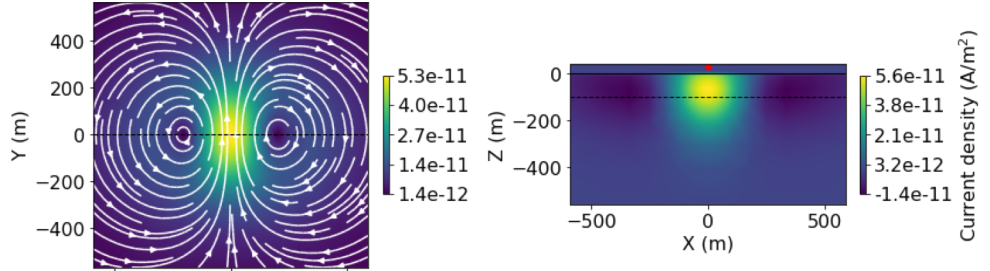
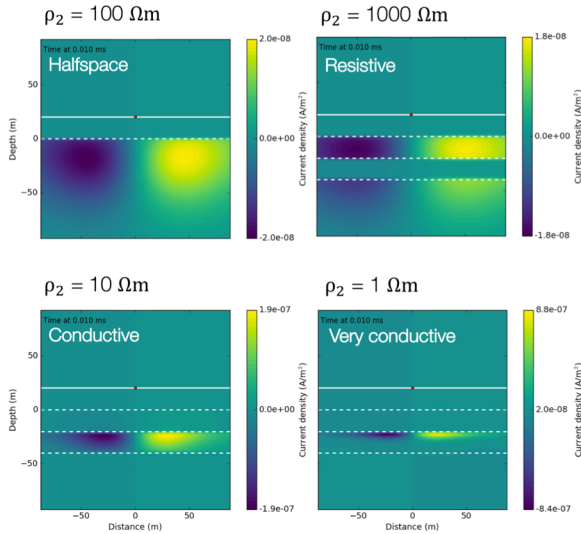




# Inductive Sources

VMD over a layered earth

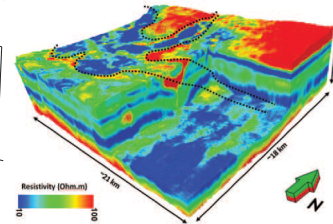
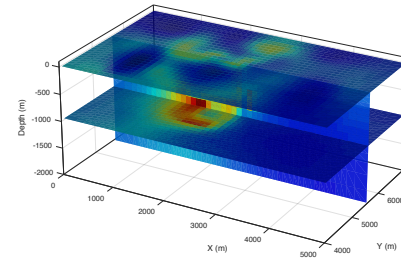
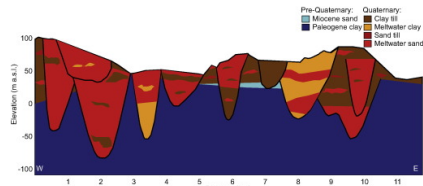
Horizontal magnetic dipole



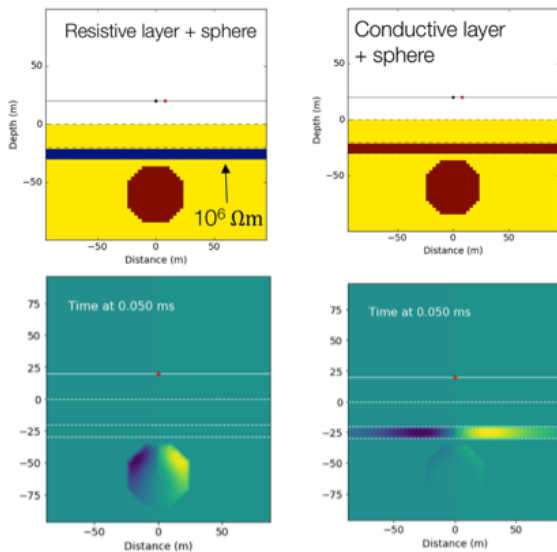
Kasted

Lalore

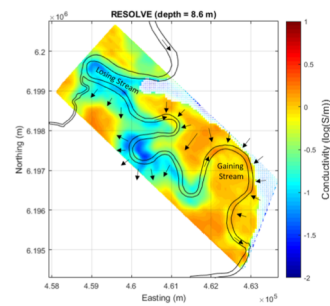
Wadi Sahba



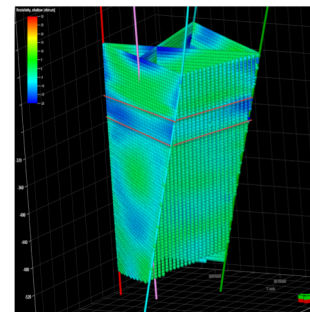
Shielding



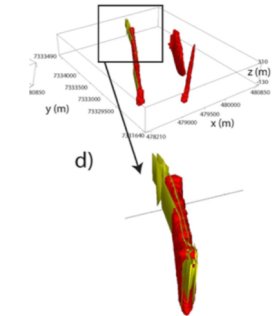
Bookpurnong



Dom João



Westplains

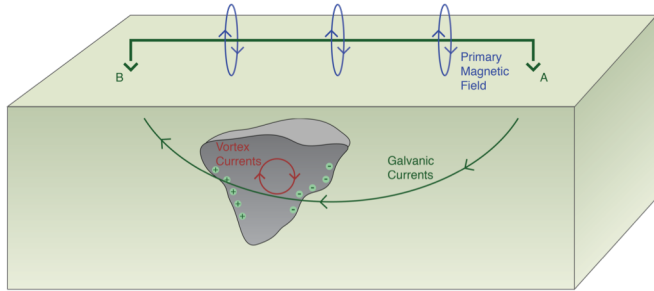


LWD

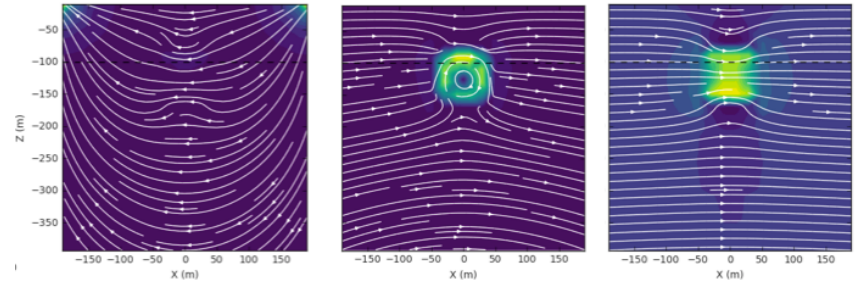


# Grounded Sources

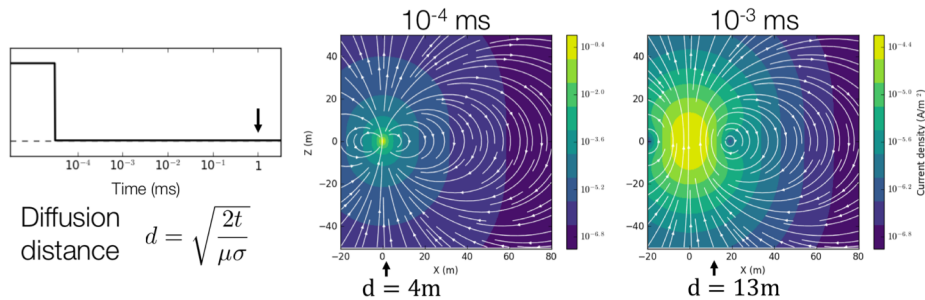
## Basic Experiment



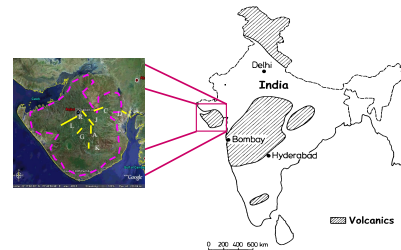
## Grounded sources with a target



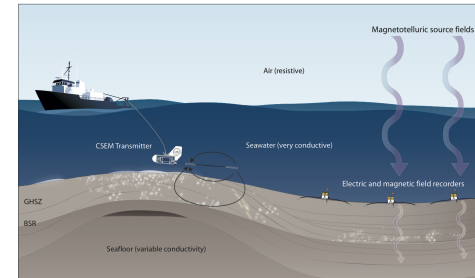
## Electric dipole in a wholespace



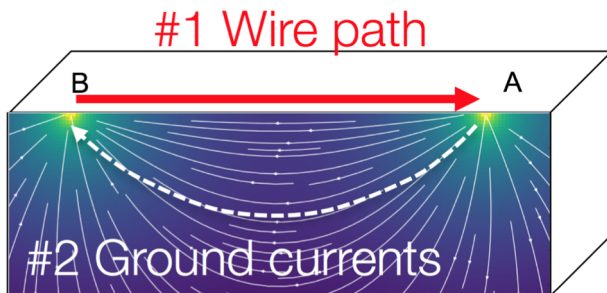
## Deccan Traps



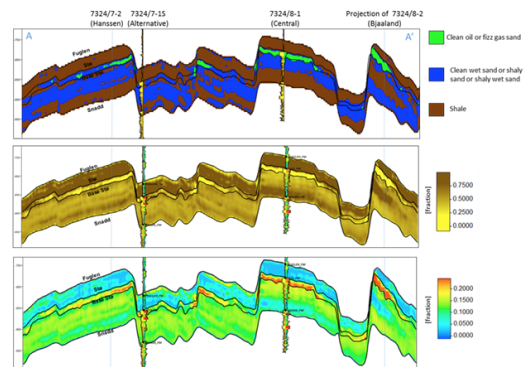
## Marine CSEM



## Currents in a TDEM experiment



## Barents Sea

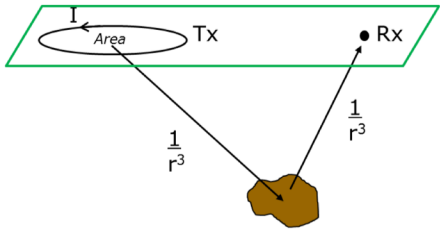


## Hydrate Ridge

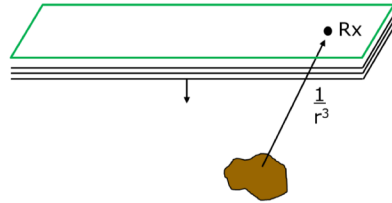
# Natural Sources

Seeing deeper

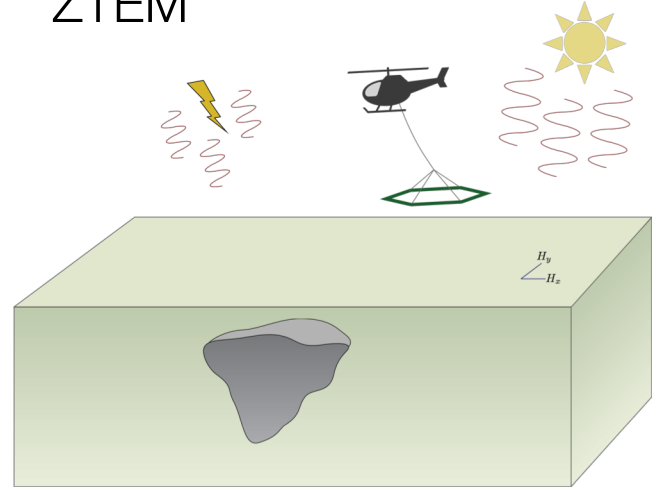
$$\sim \frac{1}{r^6}$$



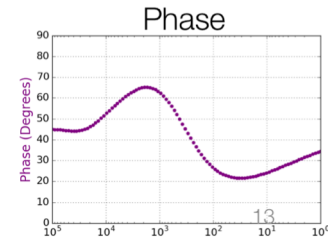
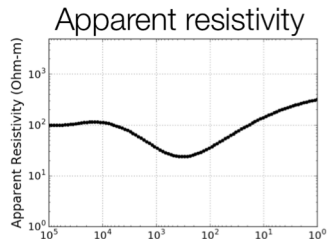
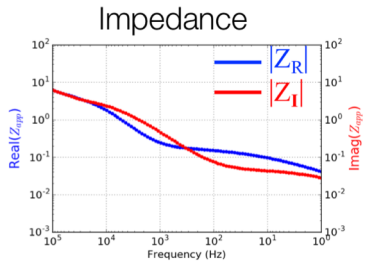
$$\sim \frac{1}{r^3}$$



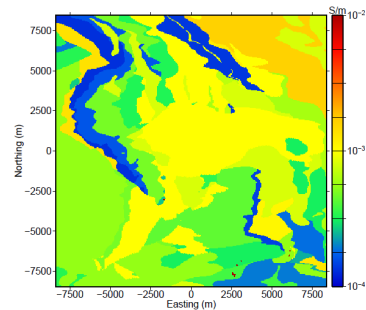
ZTEM



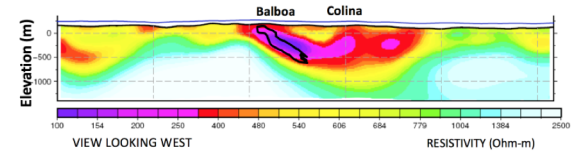
Data



Noranda



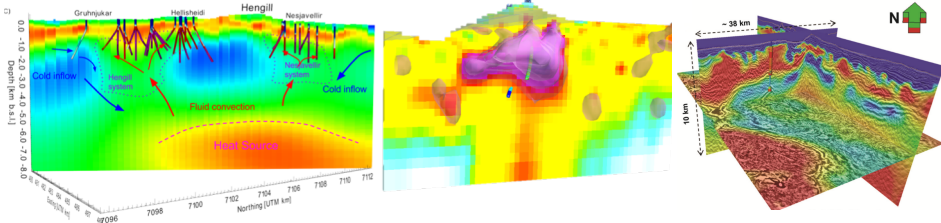
Balboa



Hengill

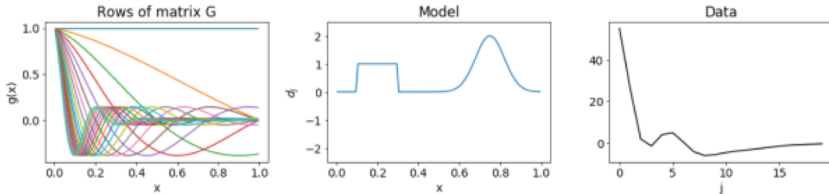
Santa Cecilia

Red Sea

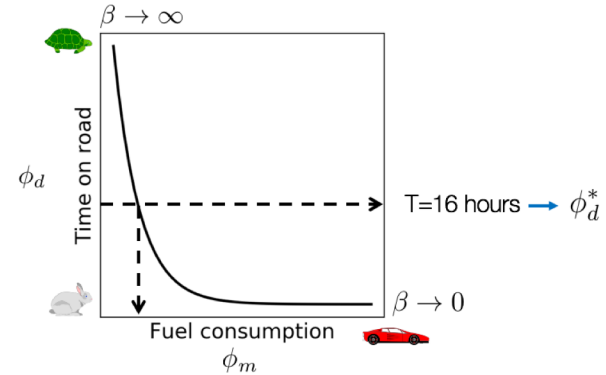


# Inverse Theory

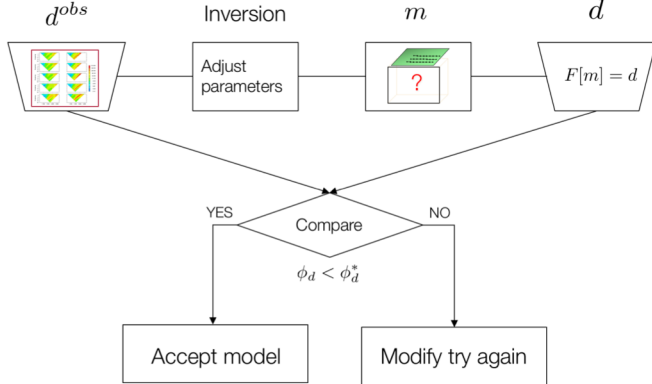
## Linear problem



## Tikhonov curve



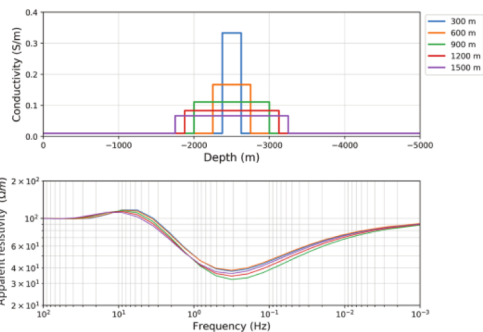
## Inversion with misfit only



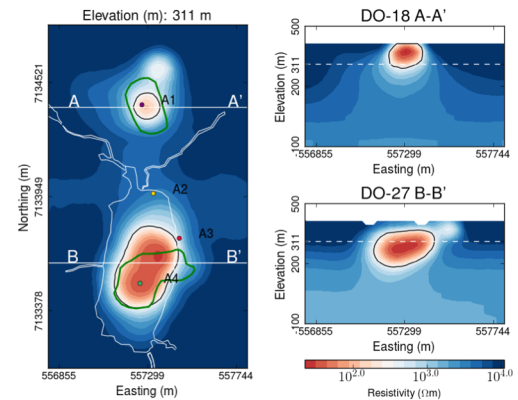
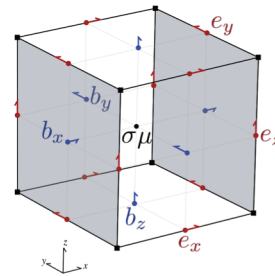
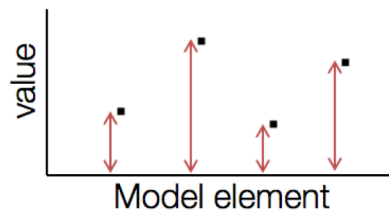
$$\phi_d = \sum_{j=1}^N \left( \frac{d_j - d_j^{obs}}{\epsilon_j} \right)^2$$

## Modelling Maxwell's equations & Non linear inversions

## Non-uniqueness

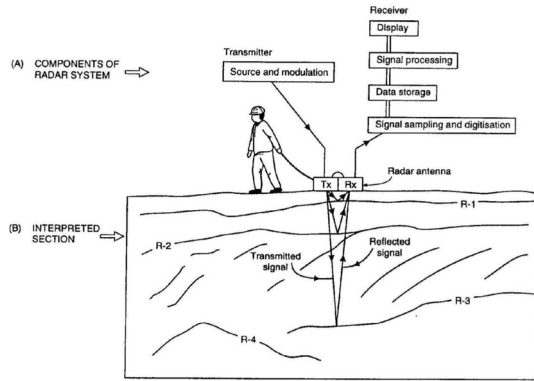


## Model norms

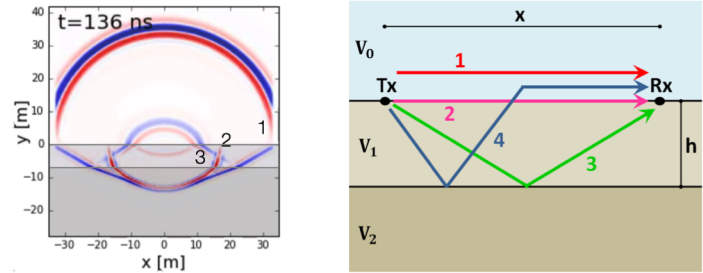


# Ground Penetrating Radar

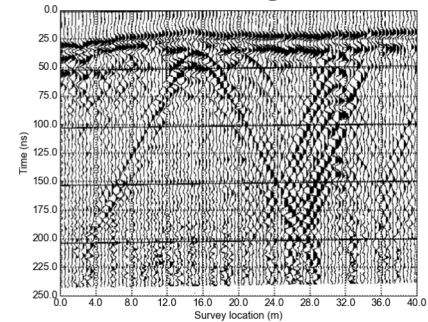
## Basic Experiment



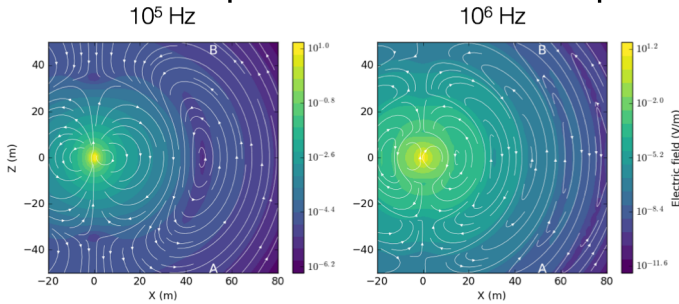
## Waves and Rays



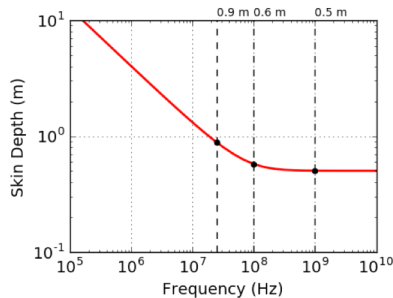
## Radargrams



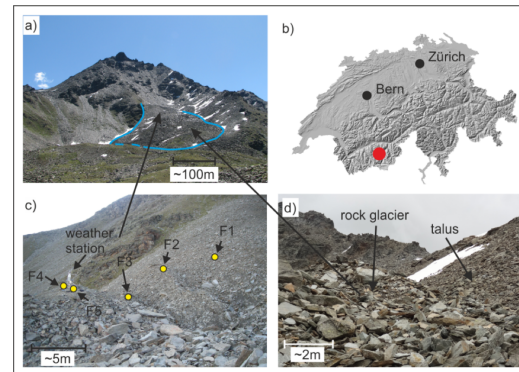
## Electric dipole in a wholespace



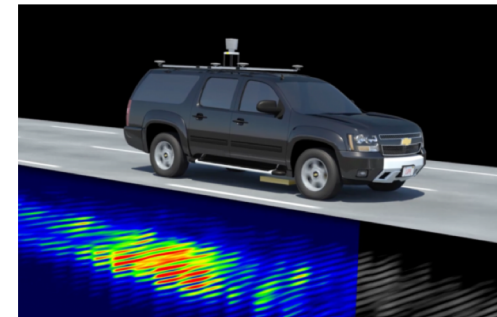
## Attenuation



## Rock Glaciers

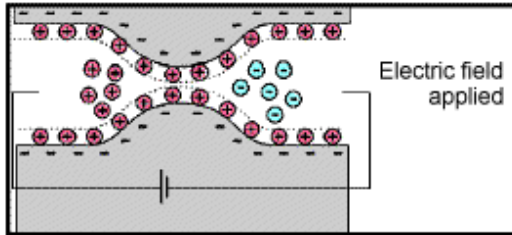


## Driverless Cars

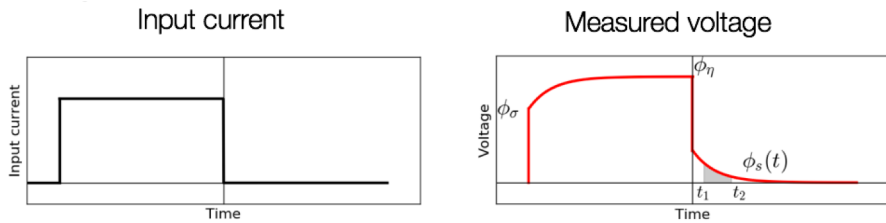


# Induced Polarization

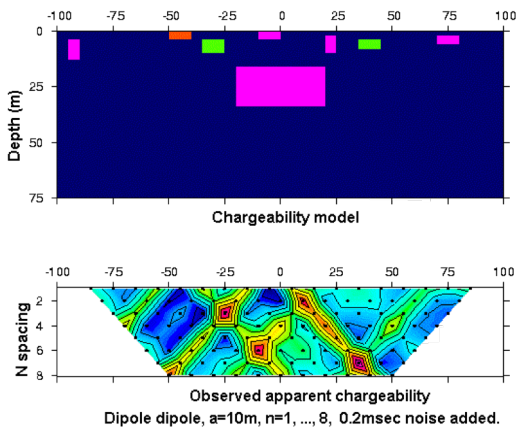
## Conceptual model



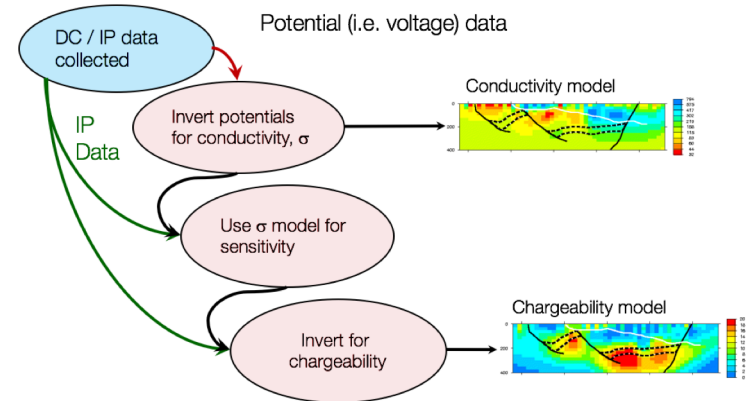
## IP data



## Pseudosections



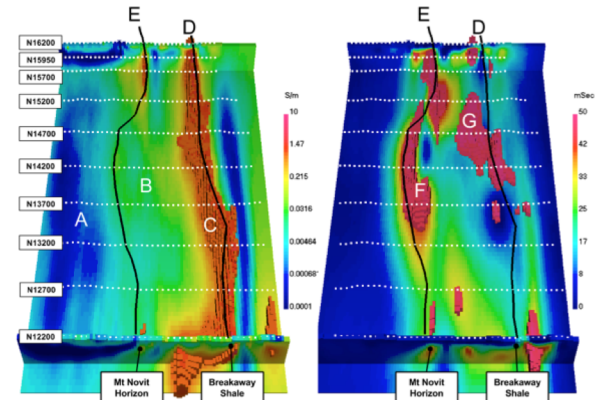
## IP inversion



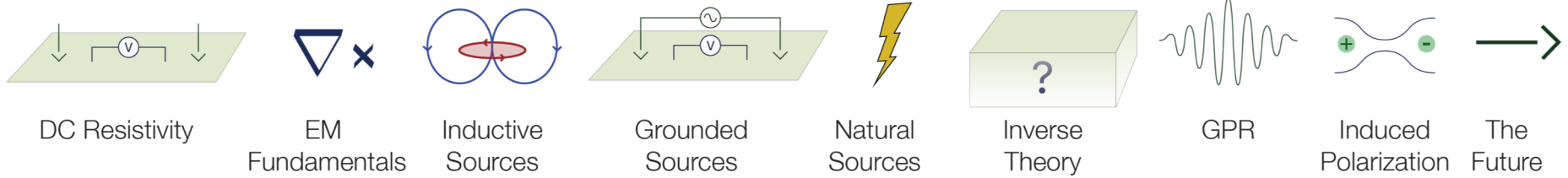
## Mt Isa

### Resistivity model

### Chargeability model



# Summary



What does the future hold?



What does the future hold?

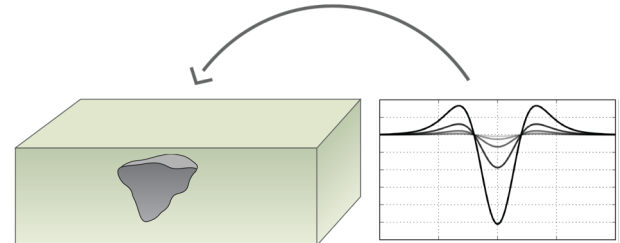


# What does the future hold?

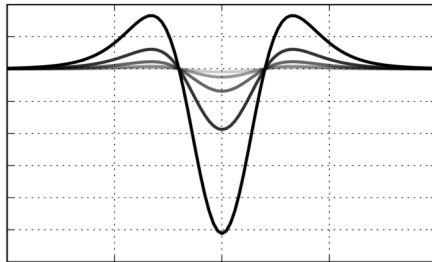
Problems



Inversion capabilities



High quality data



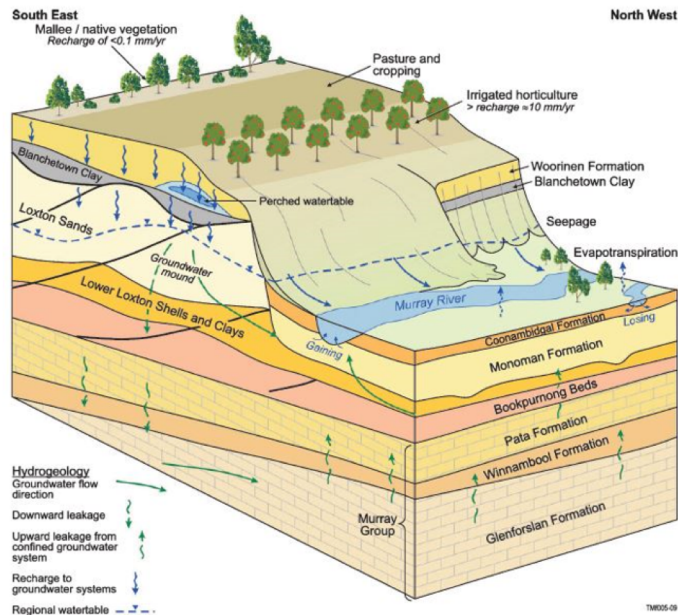
Web tools to  
communicate



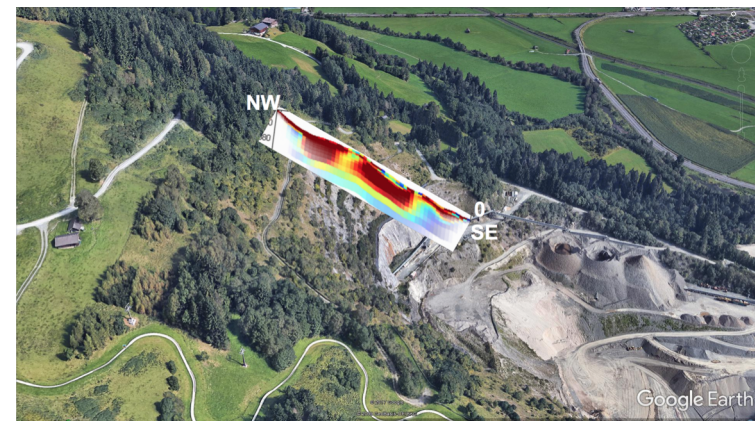
# The Future: Monitoring

- Dam integrity
- Slope stability
- Aquifers
- Coal seam gas
- Enhanced oil recovery

Mt. Polly tailings dam collapse



Water infiltration and slope stability

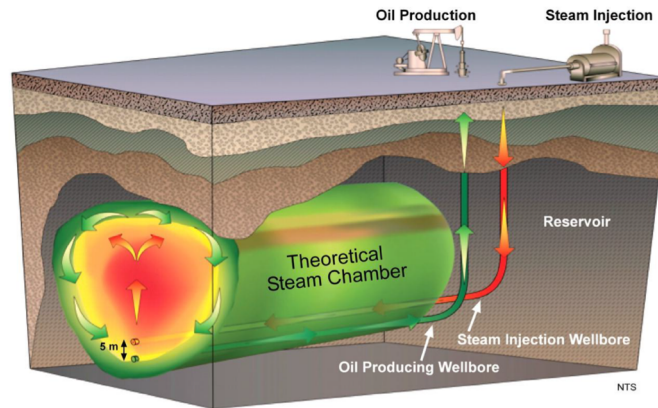


Florian Bleibinhaus

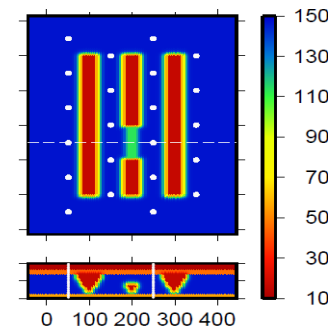
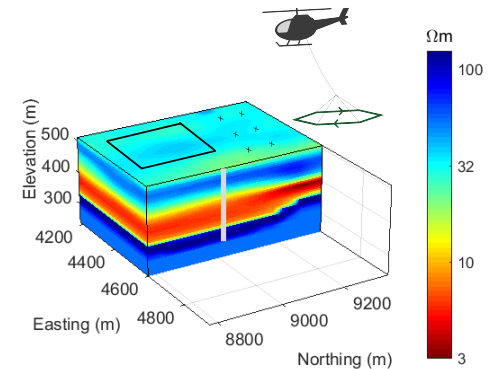
# Monitoring: Choosing the appropriate survey

Different EM surveys needed to answer different questions

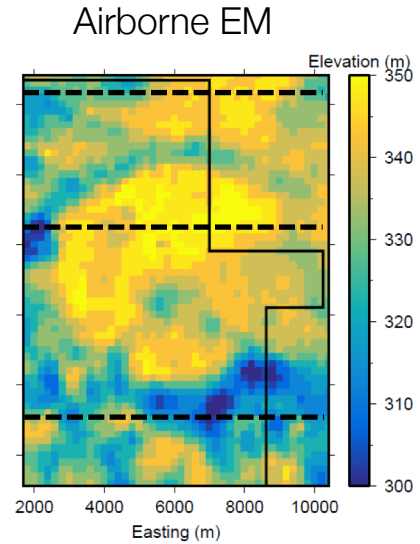
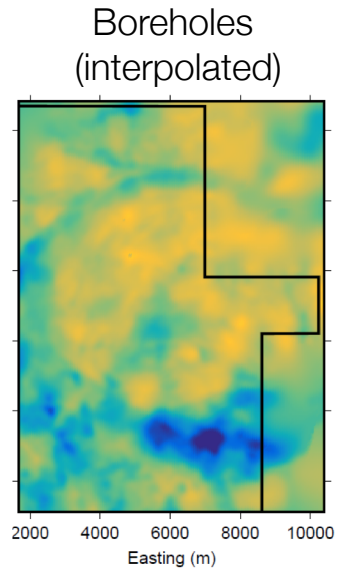
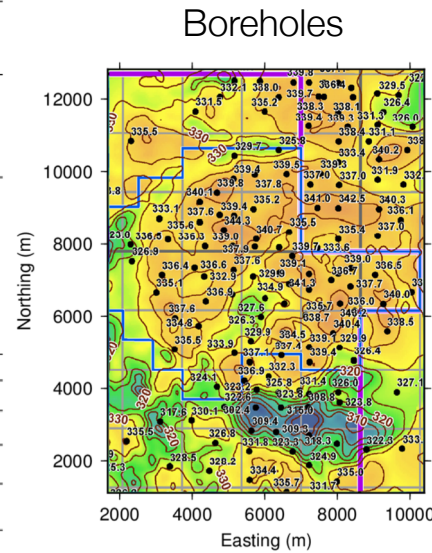
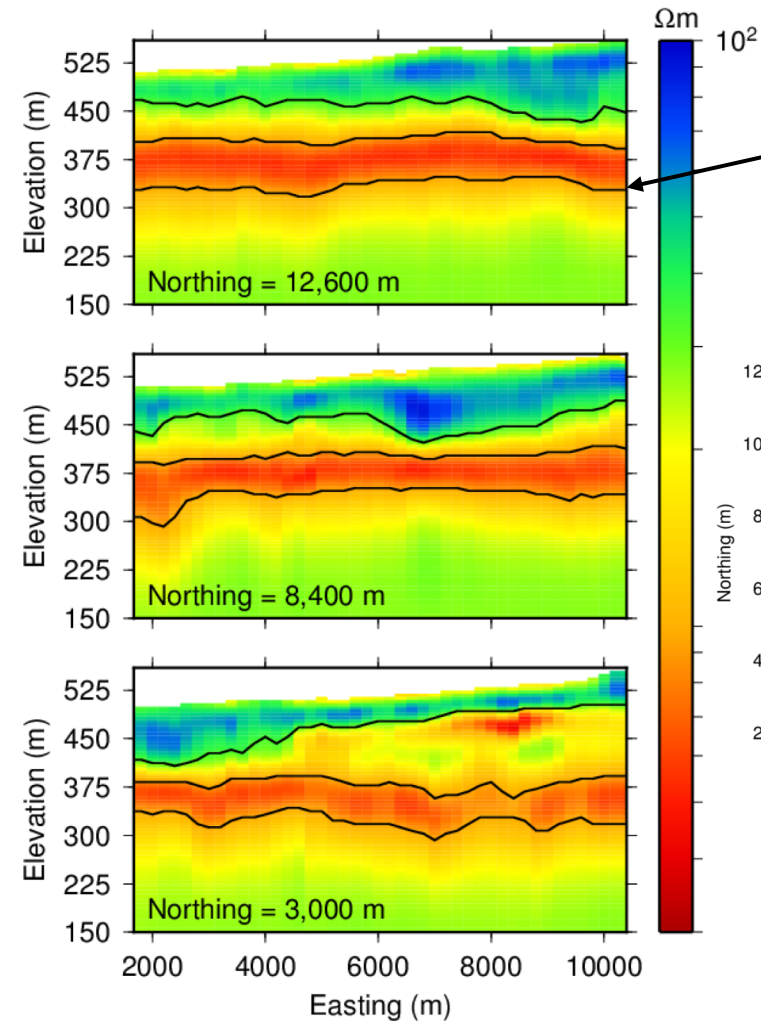
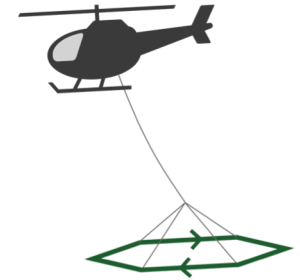
SAGD (Injection and monitoring steam flooding)



- Stage 1: Airborne reconnaissance survey
- Stage 2: Surface and borehole for pre-injection
- Stage 3: Monitoring array

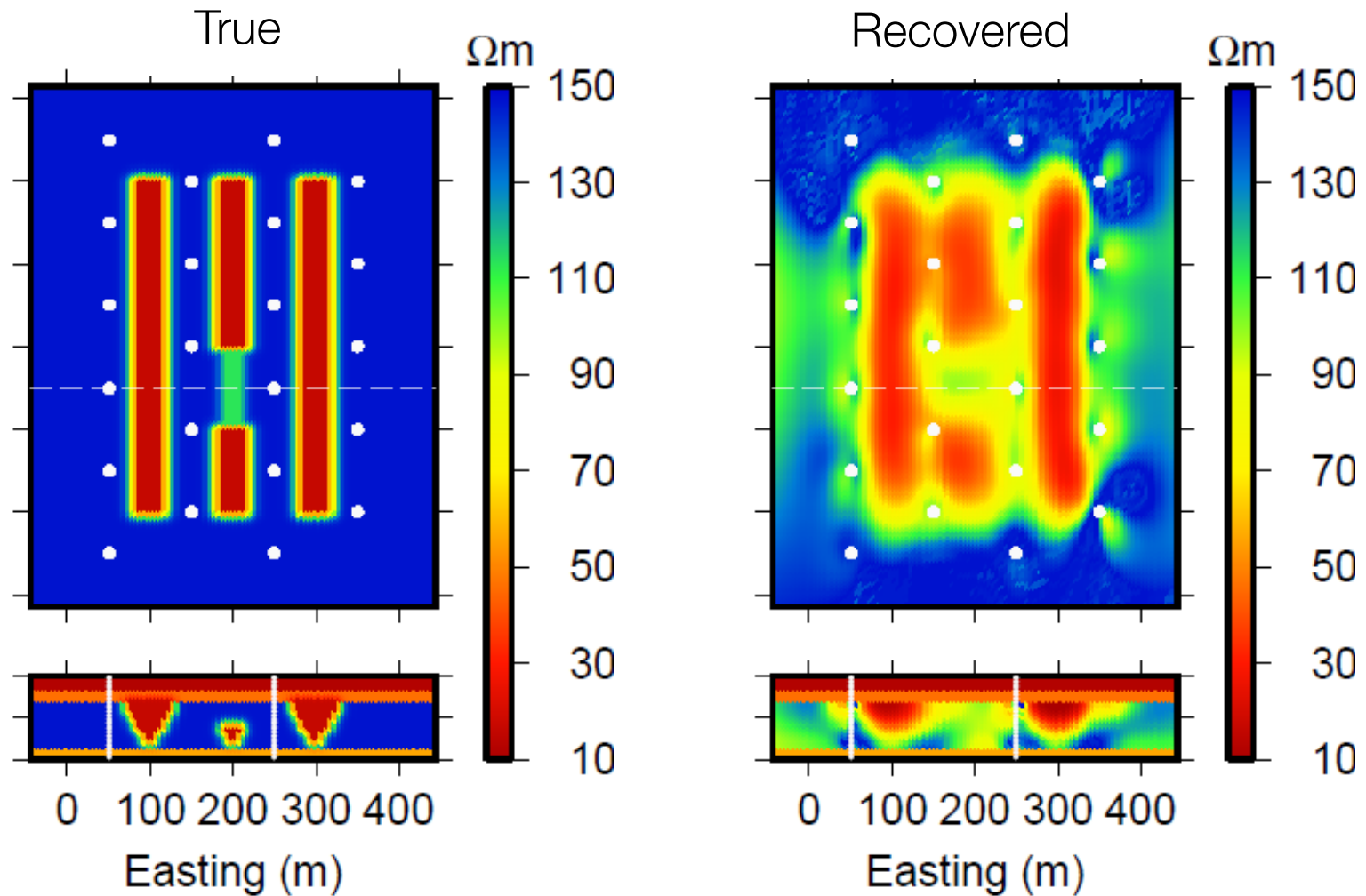


# Large scale reconnaissance (SAGD)



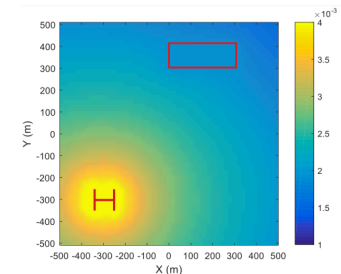
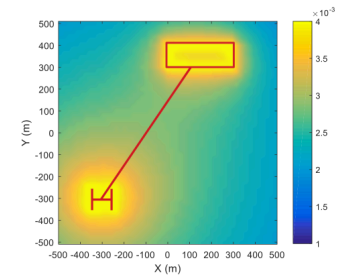
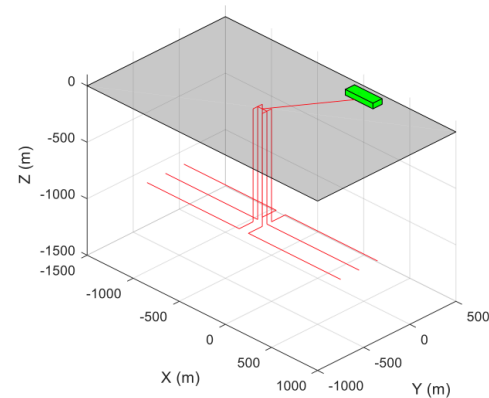
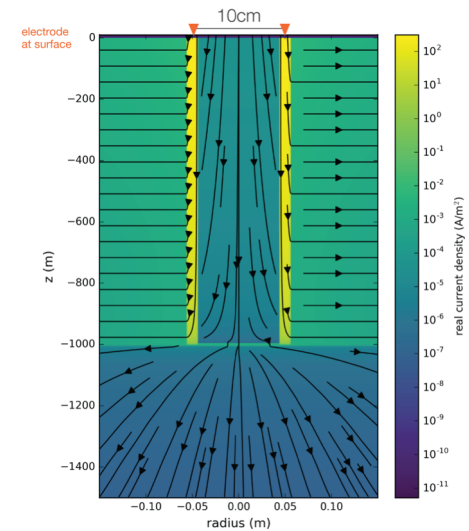
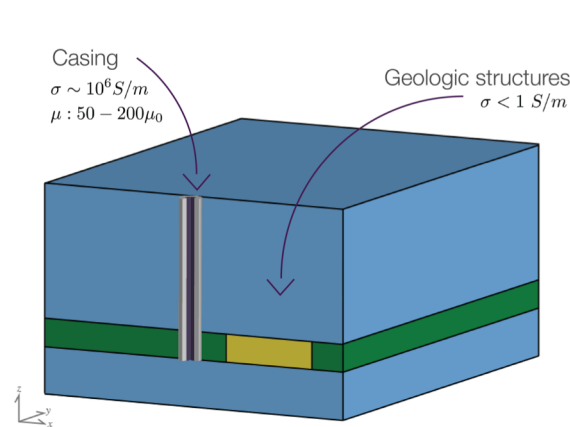
# Multi-stage EM for monitoring

Post-injection: surface sources, borehole receivers



# The Future: Large Contrasts

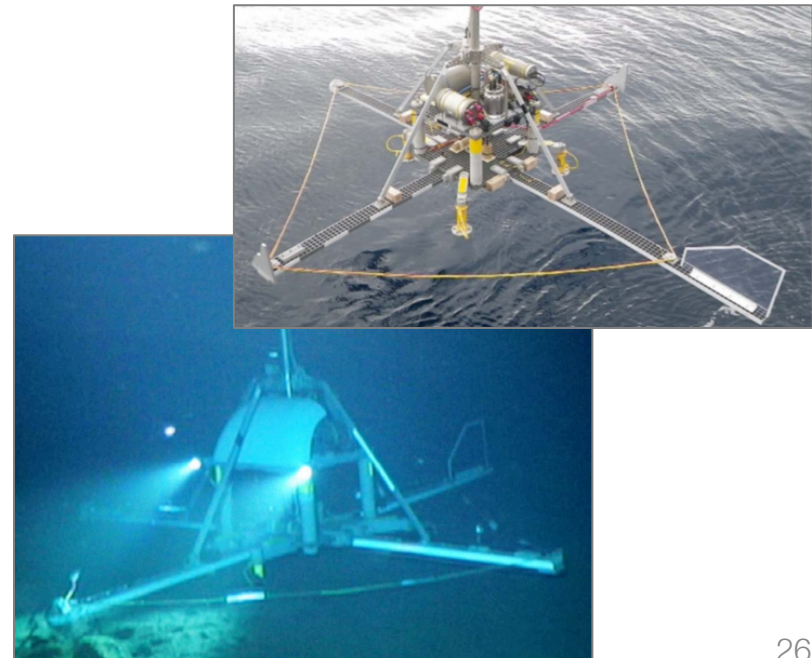
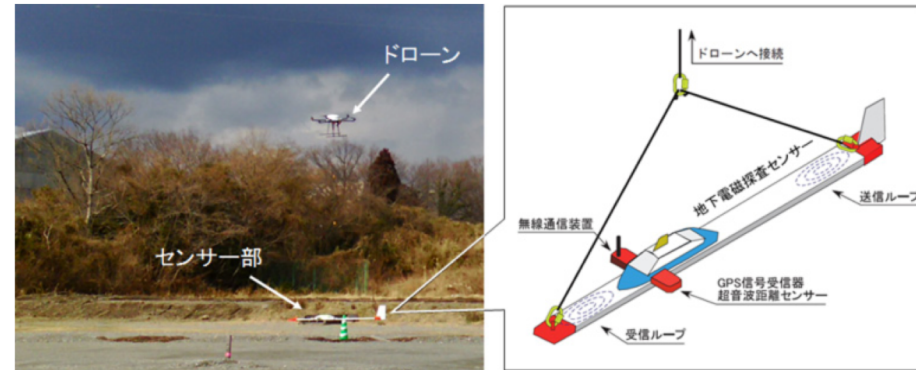
- Conductivity contrasts
- Permeability contrasts
- eg. Steel Casing
  - Mechanism for getting current to depth
  - Challenges:
    - Scales
    - Physical properties



eg. Sudbury basin

# The Future: High Quality Data

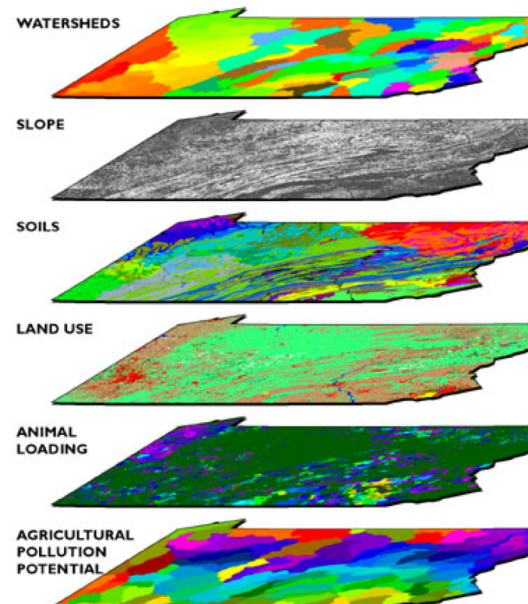
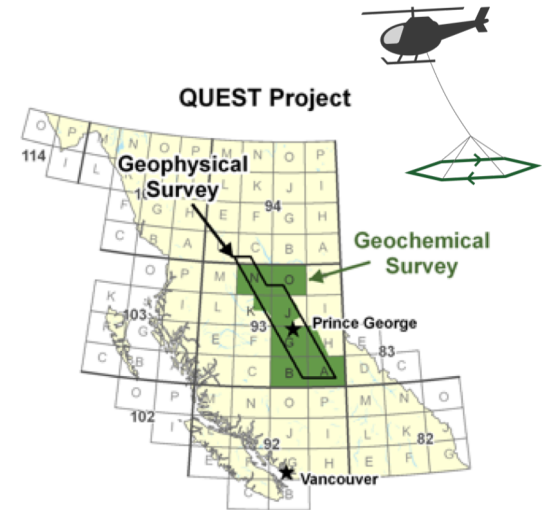
- Improved instrumentation
  - Lower noise
  - More power
  - Better control on transmitters and receivers
    - Current waveform
    - Filtering parameters
    - Position and orientation
    - Higher sampling rates
    - ...
- Data collection
  - Drones
  - AUVs
  - ROVs
- Mathematical modelling requires that we know all the details.



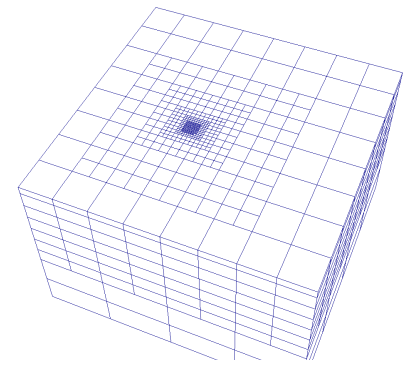


# The Future: Lots of Data

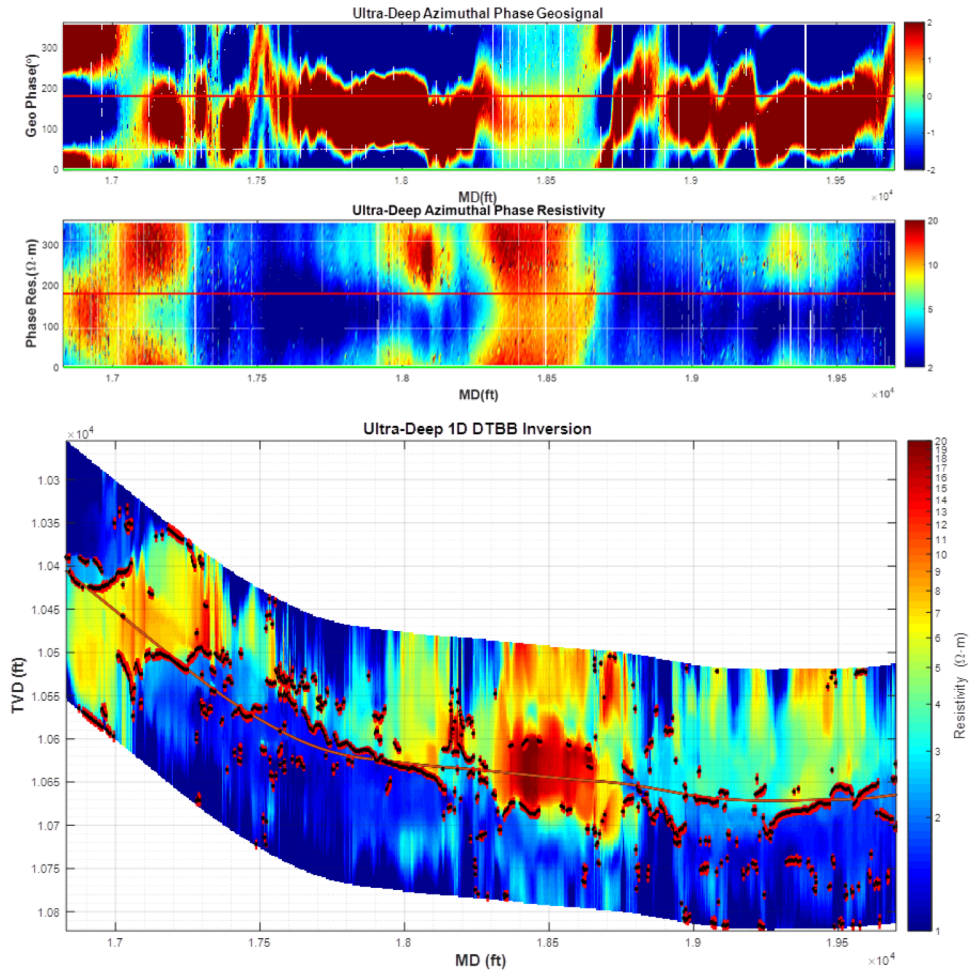
- Big data
  - Multicomponent receivers
  - Many transmitters, receivers
  - High sampling rates
  - Large areas
- Multiple types of data
  - geophysical surveys
  - Physical properties
  - Geochemistry
  - Geology
  - ...
- Machine learning



# Real-time 3D inversions



Logging while drilling

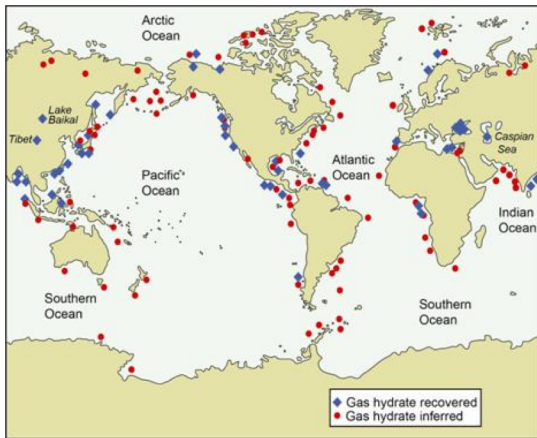
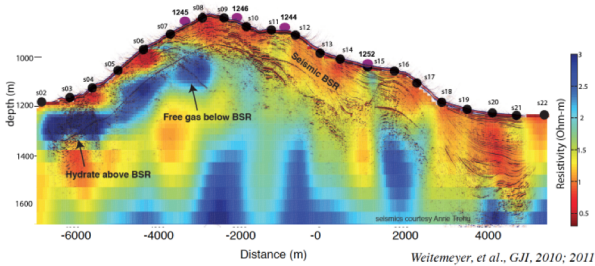


Tunnel boring machines

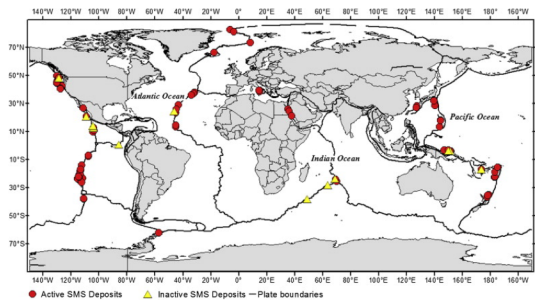
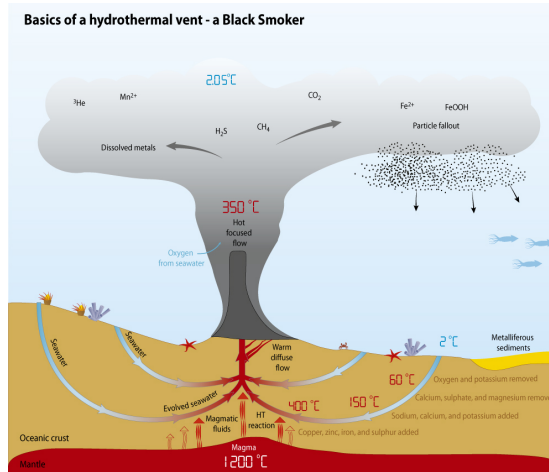


# The Future: Marine EM

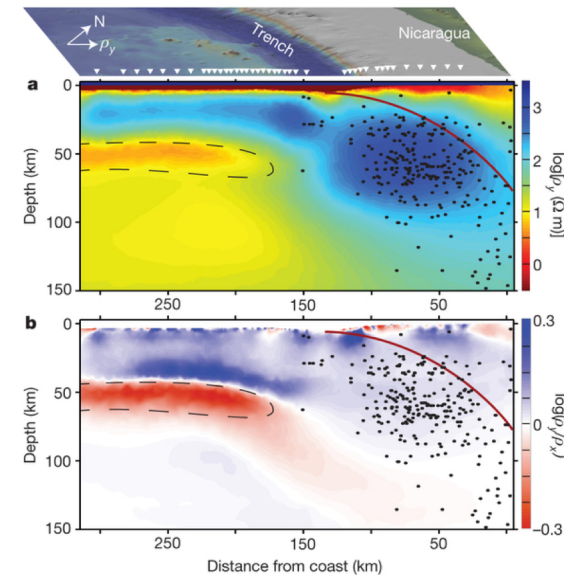
## Gas hydrates



## Seafloor massive sulfides



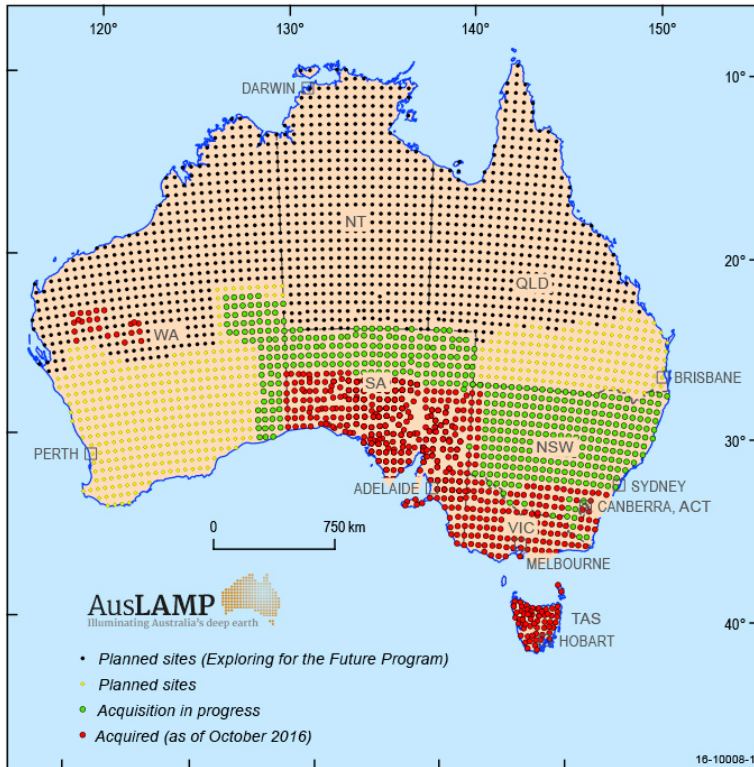
## Tectonic studies, natural hazards



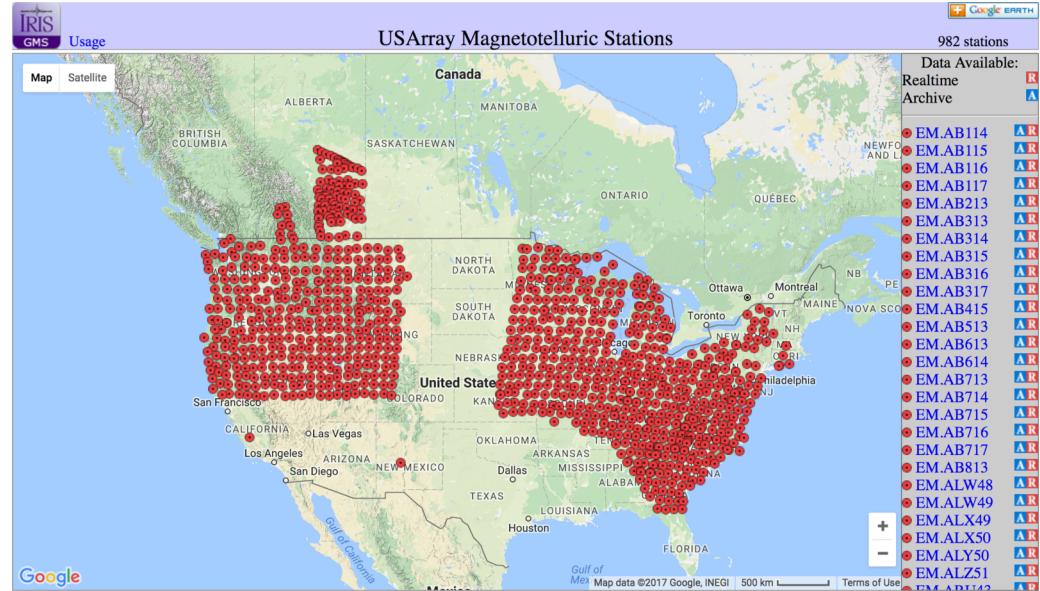
Naif et al., 2013

# The Future: Large Scale EM

## AusLamp

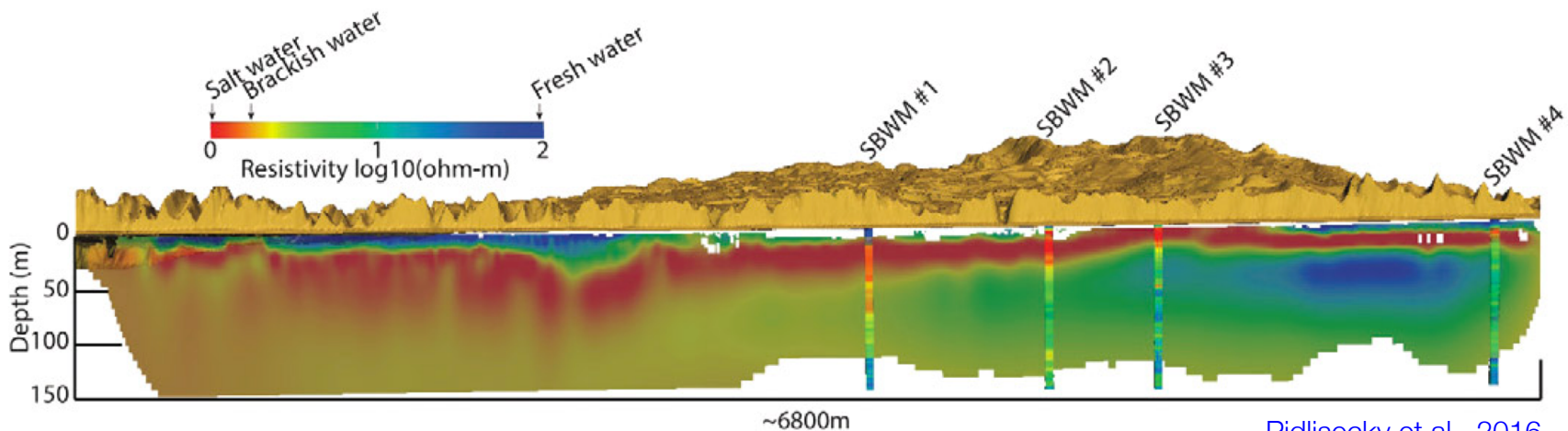
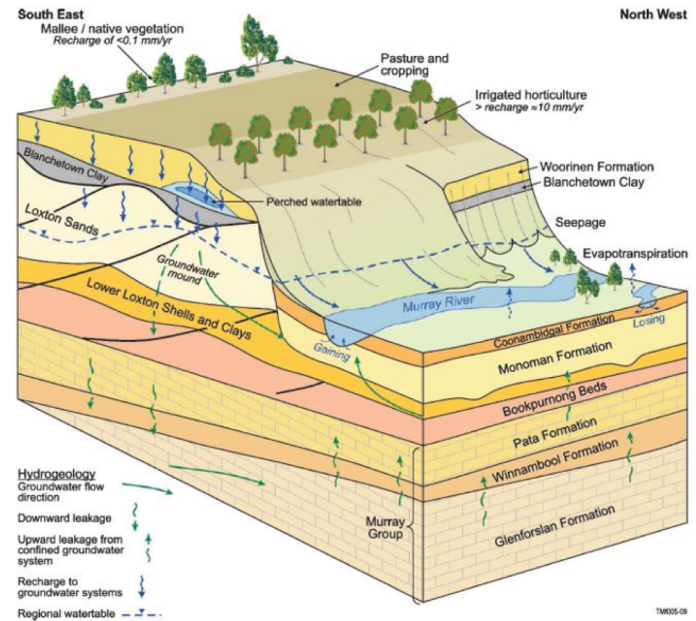


## Earth scope



# The Future: Water

- Finding and delineating water
- Aquifer monitoring and management
- Salt water intrusions
- Pollutants

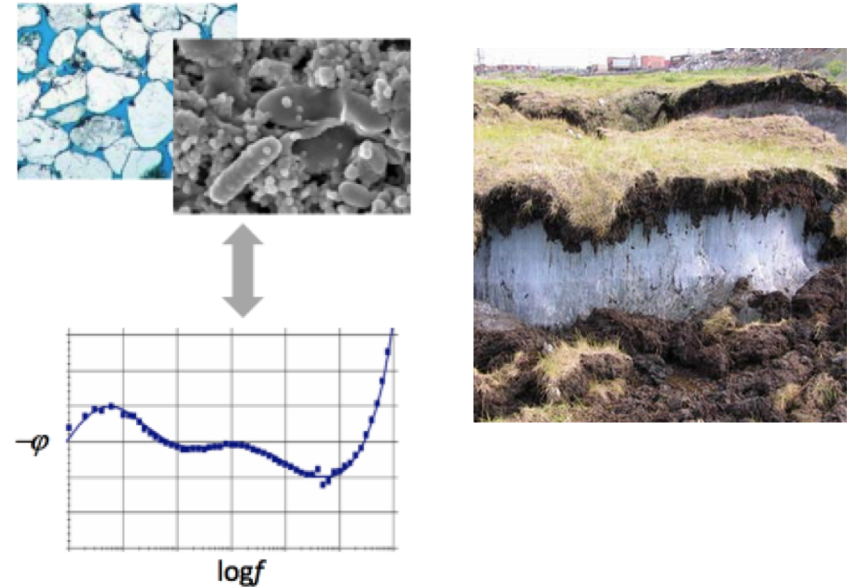


[Pidlisecky et al., 2016](#)

# The Future: Physical Properties

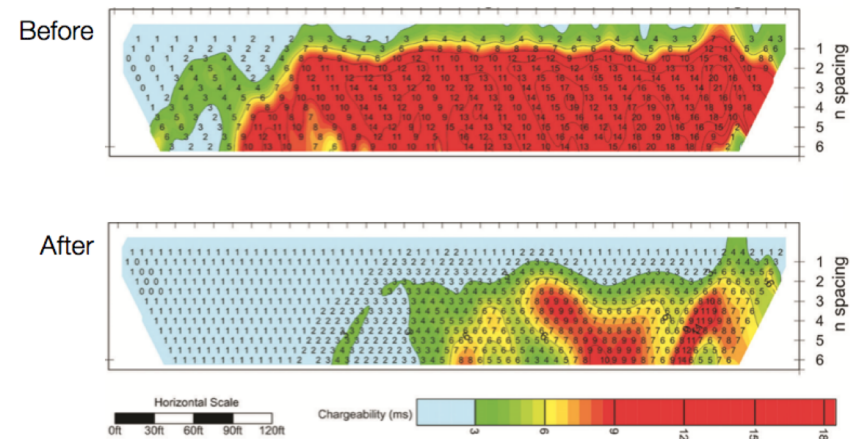
## Dispersive Conductivity (IP)

- Ice / water, permafrost
- Organic materials
- Bioremediation
- Hydraulic permeability
- Characterizing materials based on spectral IP response



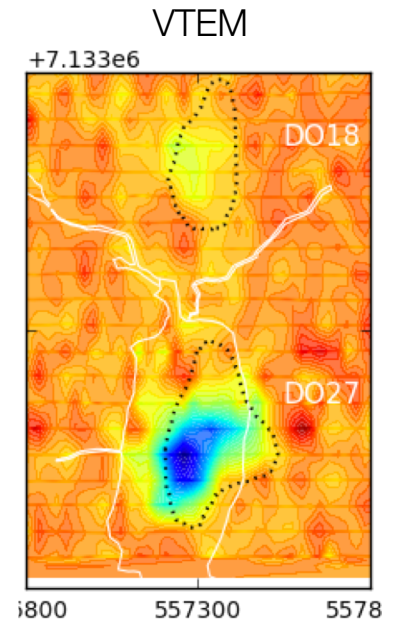
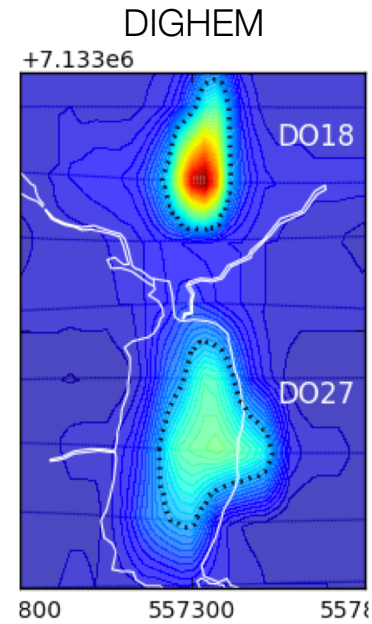
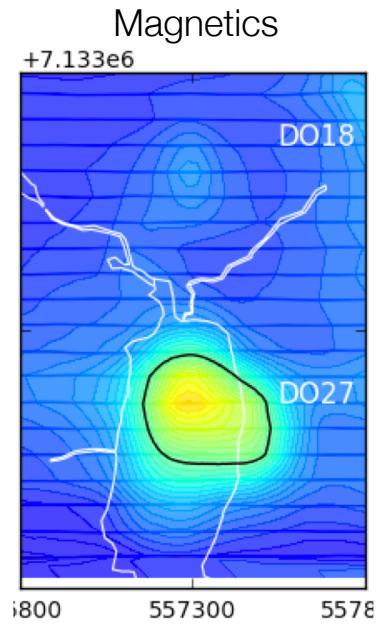
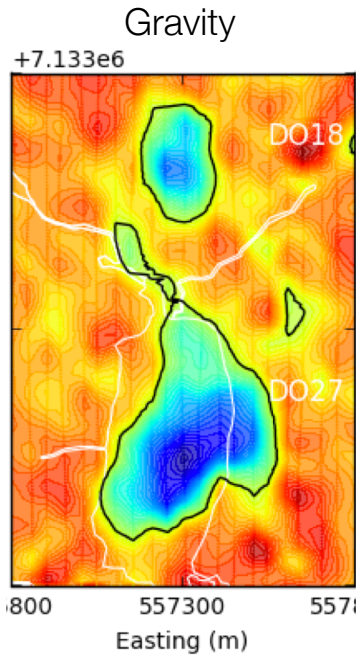
## Dispersive Magnetic Permeability (Viscous Remanent Magnetization)

- Soils
- Bioremediation (?)

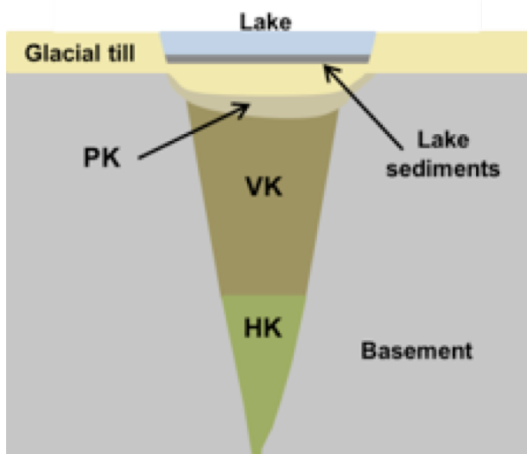


## Numerical Modelling

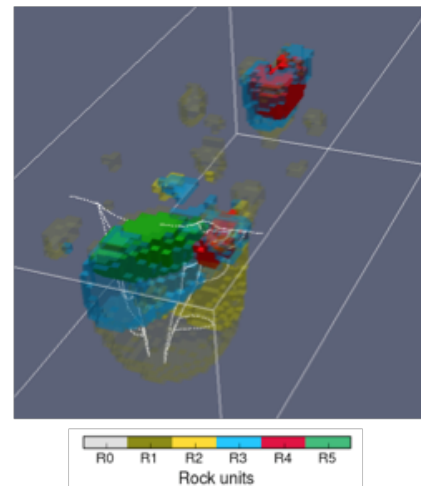
# The Future: Data Integration & Multi-physics



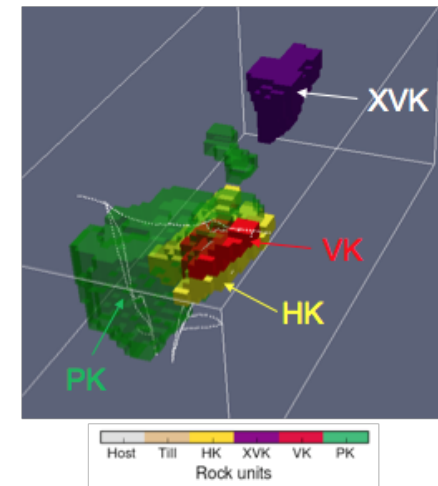
Kimberlite Model



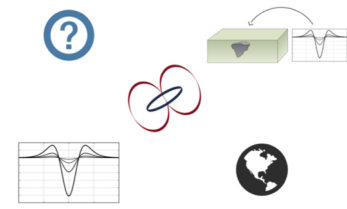
Rock Model from Geophysics



Rock Model from Drilling



# The Future: Modelling and Inversion



- HPC, Cloud computing
- Collaborative development
- Open source



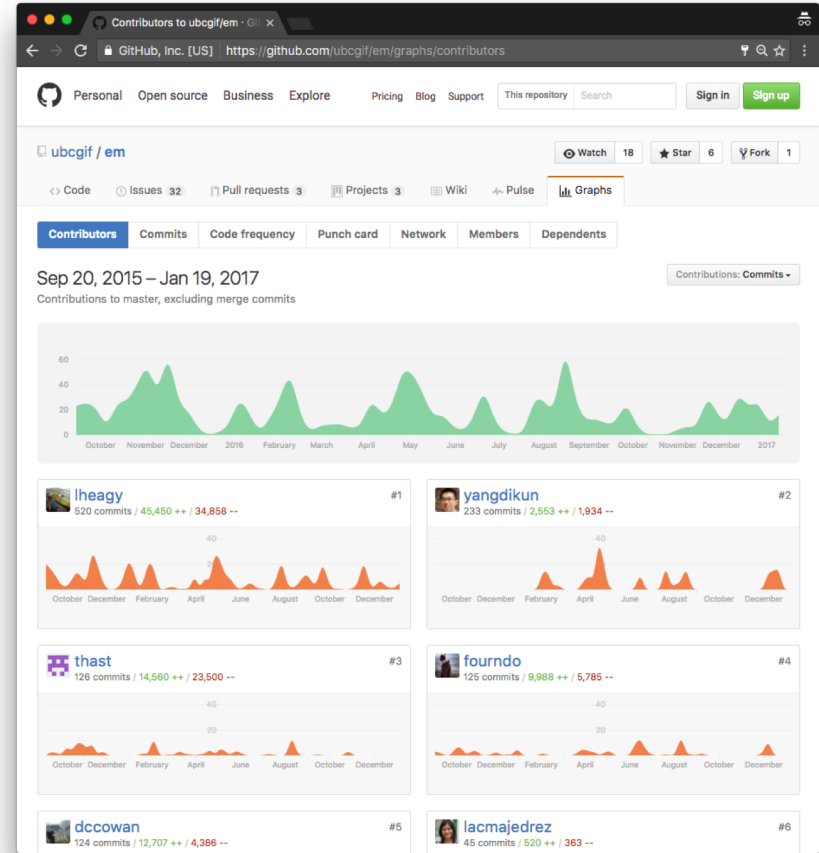
Simulation and Parameter Estimation in Geophysics

<http://simpeg.xyz>



pyGIMLi

*Geophysical Inversion & Modelling Library*



Github  
versioning, collaborating



Travis CI  
testing, deploy



Jupyter  
interactive computing



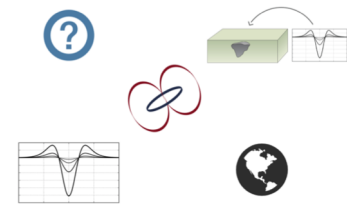
Creative Commons  
licensing, reuse



Python  
computation



# The Future: Modelling and Inversion

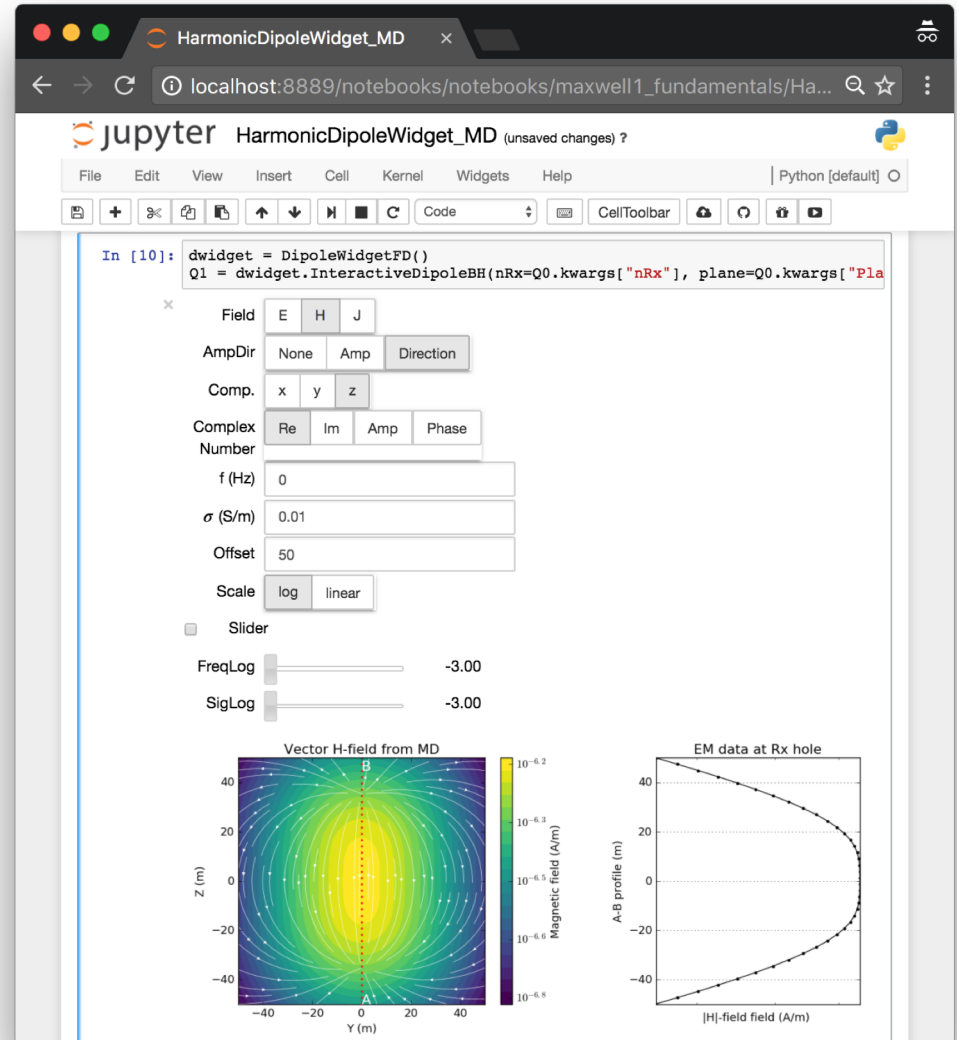


- Interactive computing
- Visualization

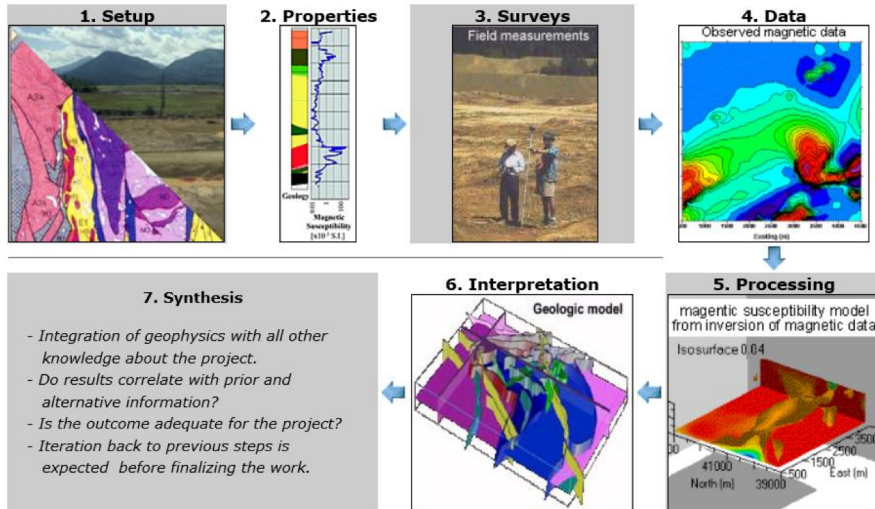
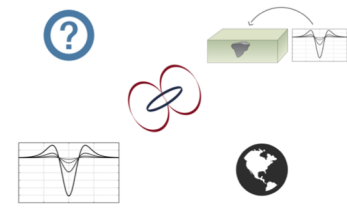
$$\nabla \times \mathbf{e} = - \frac{\partial \mathbf{b}}{\partial t}$$



$$\nabla \times \mathbf{h} = \mathbf{j} + \frac{\partial \mathbf{d}}{\partial t}$$



# The Future: Collaboration



<http://slack.geosci.xyz>

**Edit on GitHub**

Case Histories — Electromag: x

em.geosci.xyz/content/case\_histories/index.html

em

Search docs

Contributors

Introduction

Physical Properties

Maxwell I: Fundamentals

Maxwell II: Static

Maxwell III: FDEM

Maxwell IV: TDEM

Geophysical Surveys

Inversion

Case Histories

- Mt. Isa
- Bookpurnong
- Aspen
- Lalor
- Elevenmile Canyon
- Albany
- West Plains
- Furggwanhorn
- Norsminde
- Barents Sea
- Kasted
- The Balboa ZTEM Cu-Mo-Au porphyry discovery at Cobre Panama

Equation Bank

References

**Case Histories**

Case histories provide the context for our development of educational and research materials presented in em.geosci. Each case history focuses upon a particular problem to be solved and provides the motivation for working with particular surveys and shows the effectiveness of electromagnetics in answering the posed questions. For many people, a case history will be the entry point to this site. To facilitate transfer of knowledge we have developed a common framework (Seven Step Process) in which each case history is presented. Links are provided so that a reader can investigate fundamental aspects of EM, the survey, or interpretation. In some cases we are able to provide data sets and analysis/inversion software to enhance the user experience and to address important issues regarding reproducibility. Case histories for our initial launch of em.geosci are those that have been developed by past and present students at the Geophysical Inversion Facility. The titles, and EM systems used are provided below.

**Gallery**

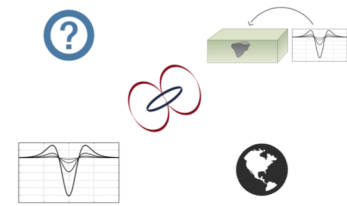
**Mt. Isa**

- **Mt. Isa**
- **Contributors**
  - author: Dom Fournier
- **Tags**
  - geophysical survey: DC, IP
  - application: Mining
  - location: Australia

**Bookpurnong**

- **Bookpurnong**
- **Contributors**
  - author: Dikun Yang
- **Tags**
  - geophysical survey: Airborne FDEM, Airborne TDEM
  - application: Groundwater
  - location: Australia

# Goals for the Course



- Inspire
  - See the variety of potential applications
  - Illustrate effectiveness using case histories
- Build a foundation
  - Basic principles of EM
  - Exploration and visualization with interactive apps
  - Open source resource: <http://em.geosci.xyz>
- Set realistic expectations
- Promote development of an EM community
  - Open source software
  - Capturing case histories world-wide

# Resources

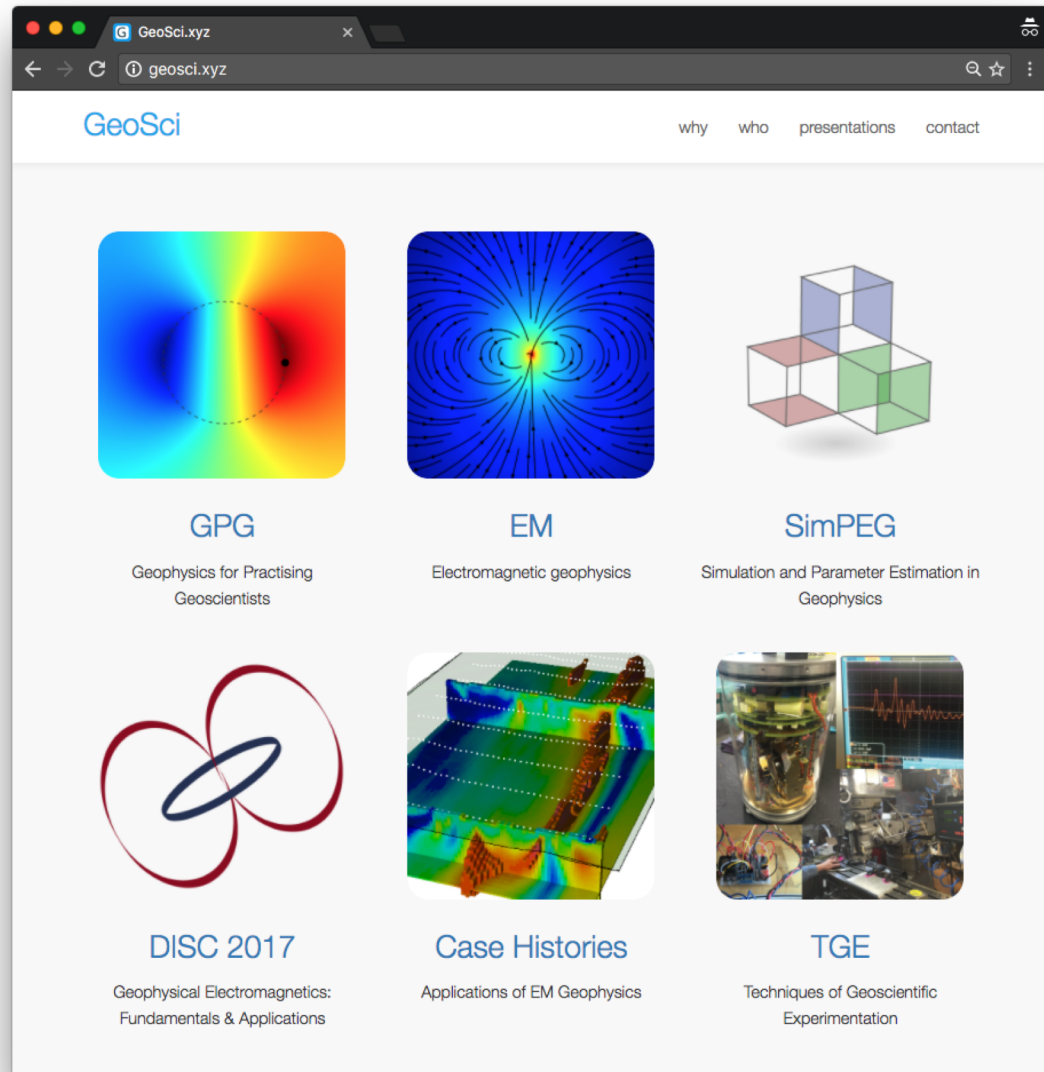
- GeoSci

<http://geosci.xyz>

- Web-textbooks
- Software
- Apps

- Apps:

<http://em.geosci.xyz/apps.html>



# GeoSci Team



doug



lindsey



seogi

## UBC GIF Team



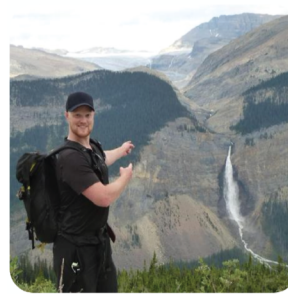
Thibaut



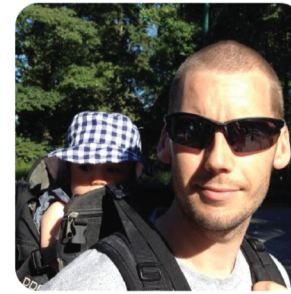
Patrick



Rowan



Devin



Kris



Sarah



Dom



Mike



Mike



Gudni



Dikun

# Thank You!

<http://geosci.xyz>



minerals



contaminants



water



geothermal



geotechnical



slope stability



hydrocarbons



unexploded ordnance