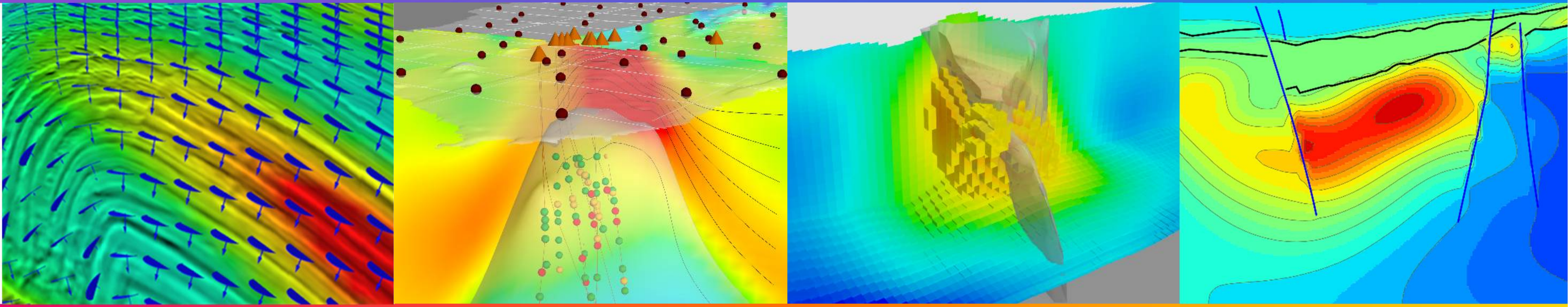


GEOLOGICALLY CONSISTENT INVERSION OF GEOPHYSICAL DATA: A ROLE FOR JOINT INVERSION

Randall Mackie

CGG Geoscience – Multi-Physics Imaging

Milan, April 28, 2021

cgg.com

CGG

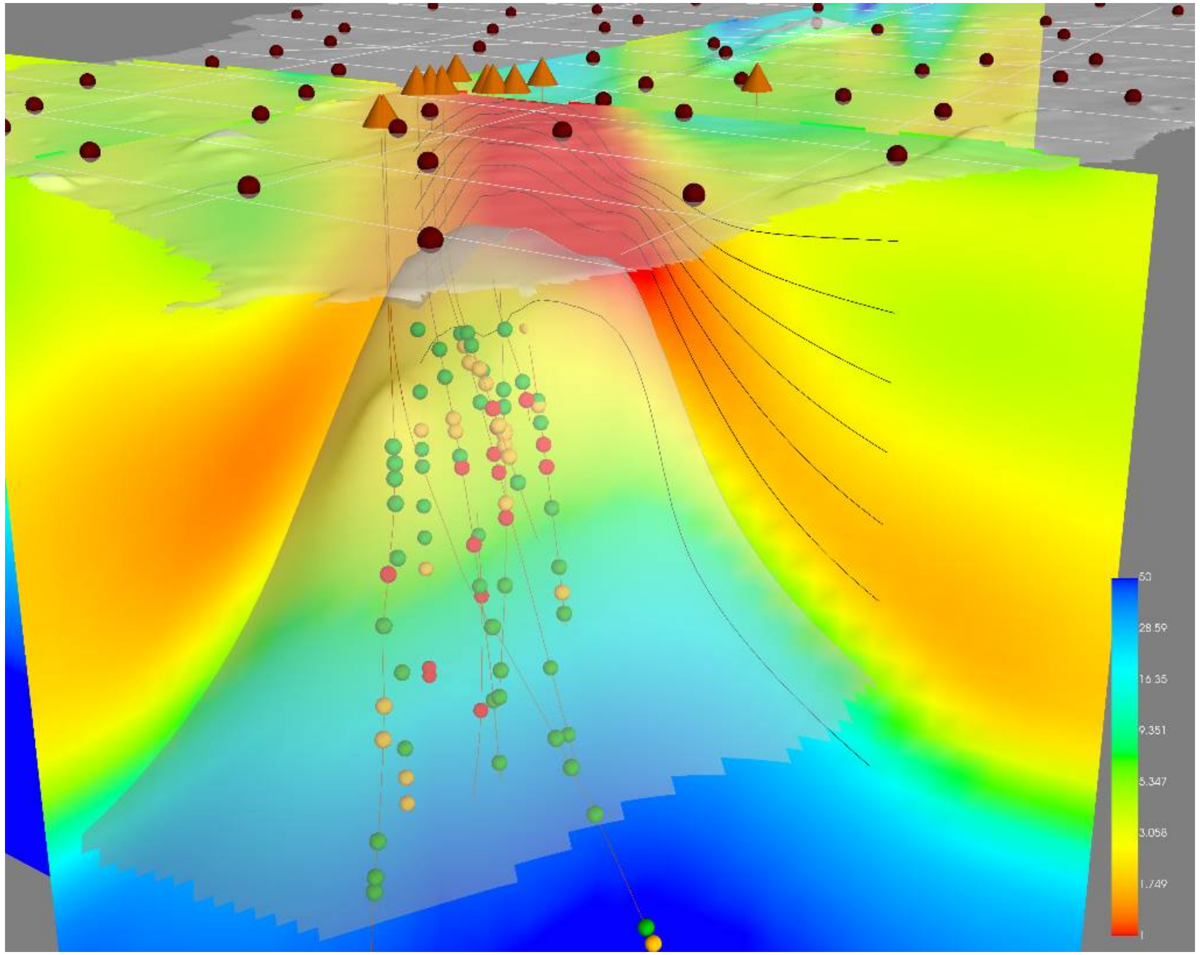
This is a collaborative effort

- The CGG Multi-Physics Group in Milan includes:
  - Stephen Hallinan (Manager)
  - Randall Mackie (RLM-3D, multi-physics software)
  - Wolfgang Soyer
  - Federico Miorelli
  - Carsten Scholl (Otze, multi-physics software)
  - Stefano Garanzini
  - Alice Pavesi
  - Marianne Parsons
  - Efrem Verderio
  - Geotools™ programming group

Outline

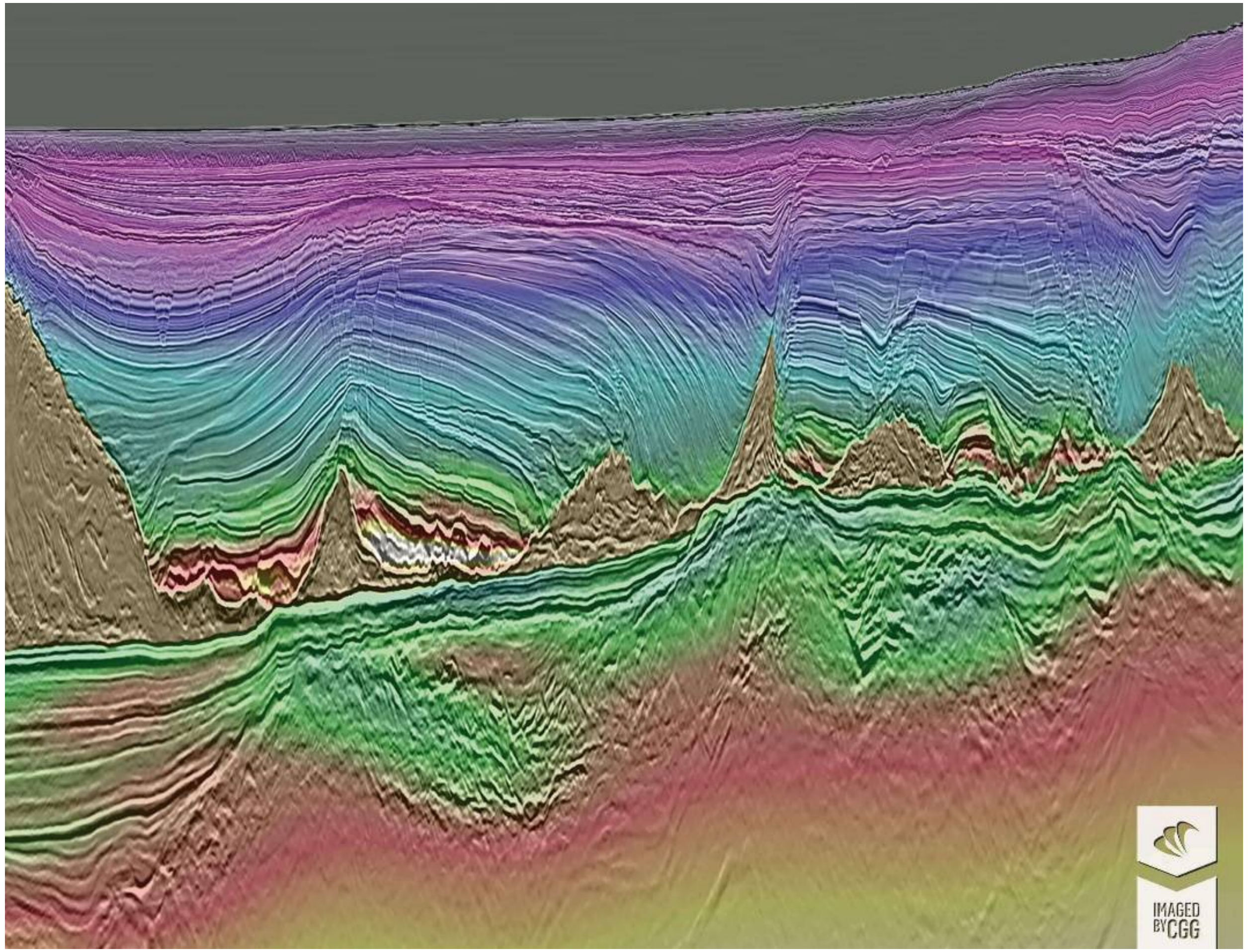
- Motivation
- Overview of joint inversion approaches
- Examples from geothermal and O&G

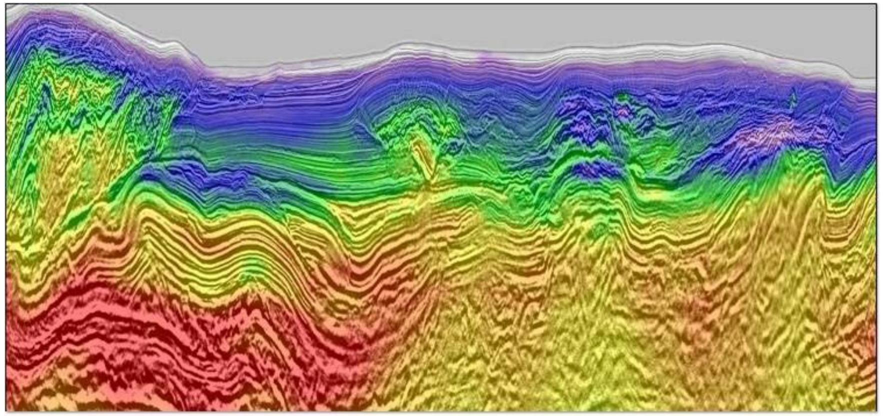
Motivation

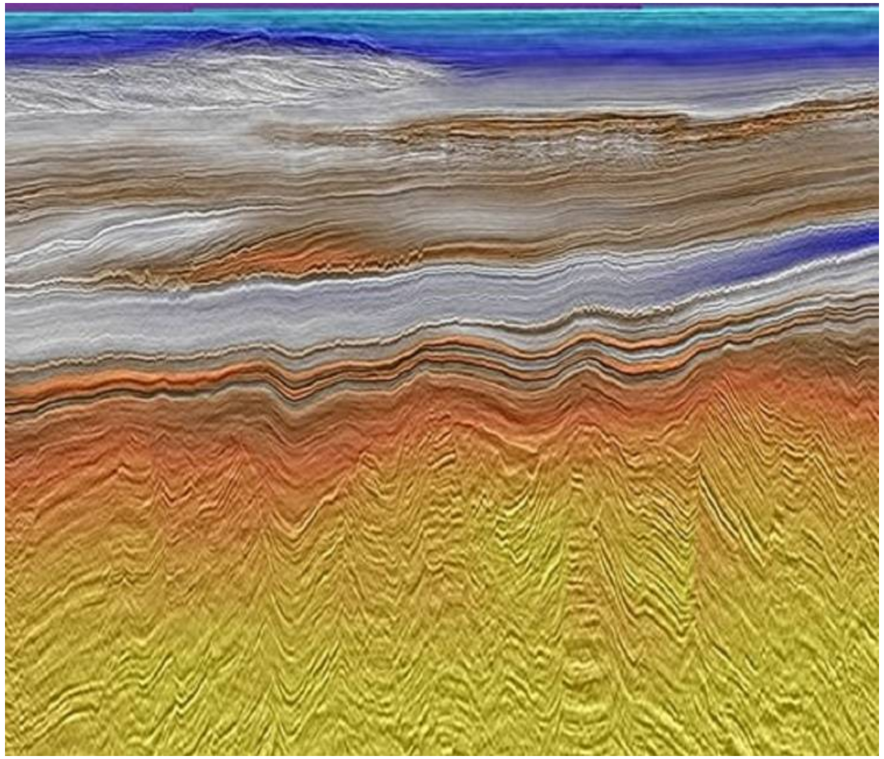


Goal: to jointly interpret multiple datasets for a more geologically reasonable earth model.

Motivation



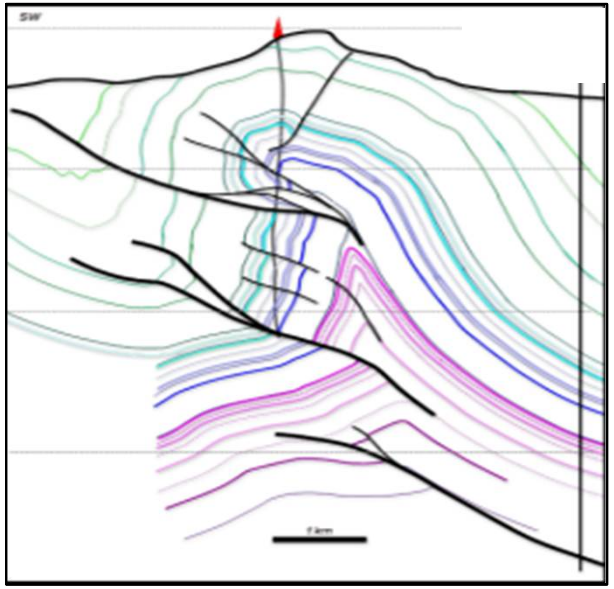


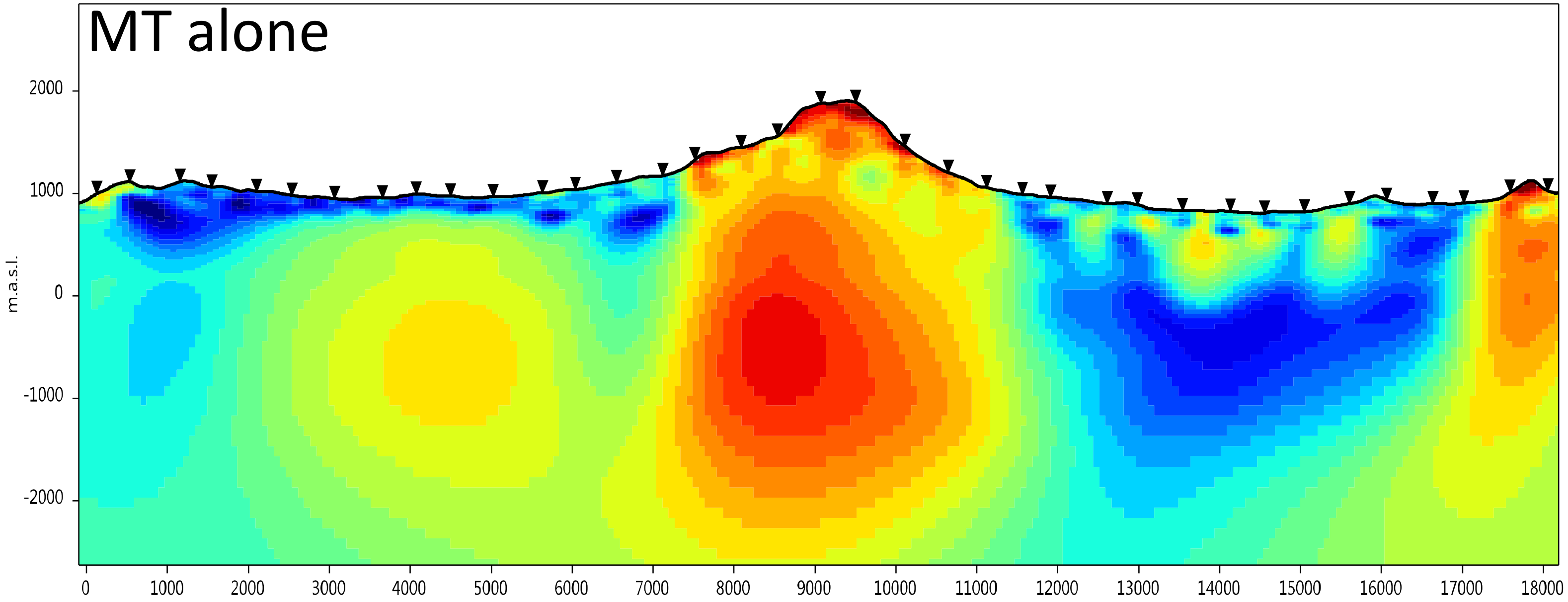


Current seismic reflection state of the art

Meanwhile, over in the MT world…

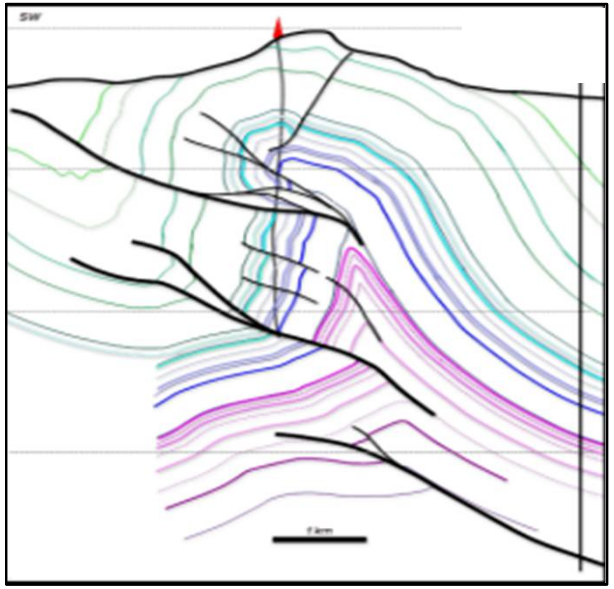
Structural model

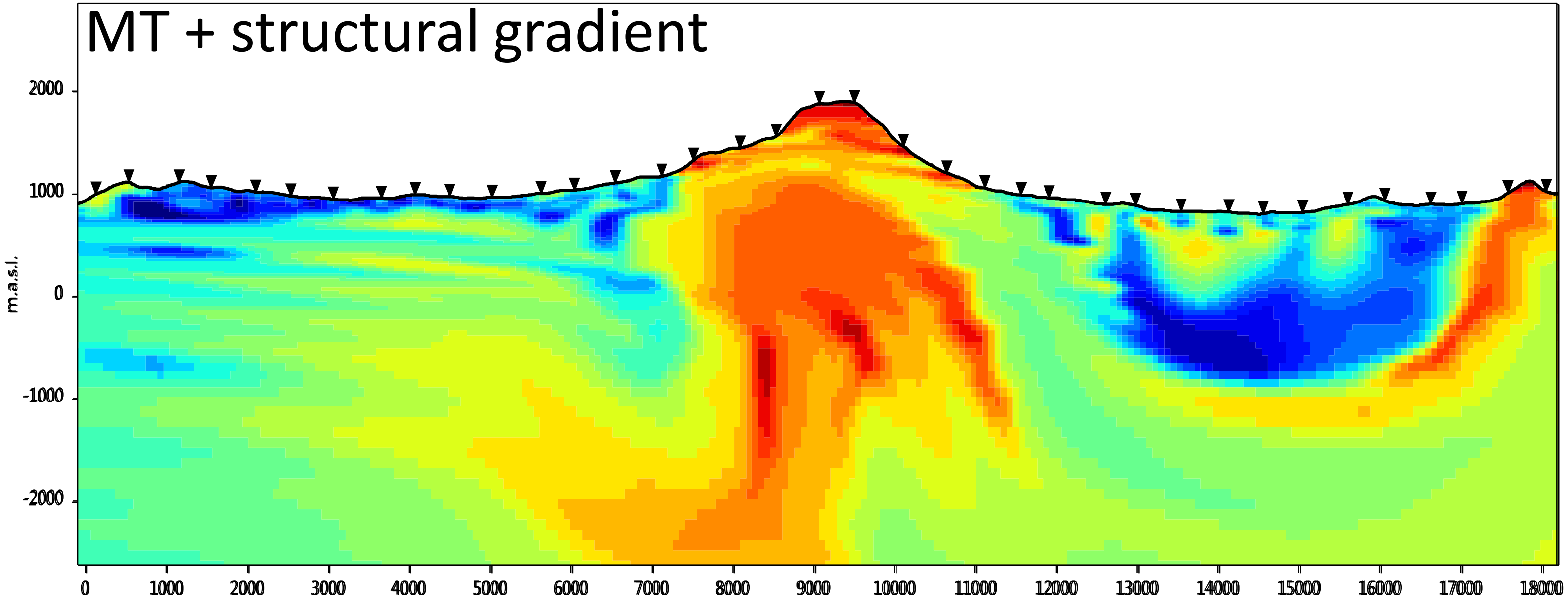




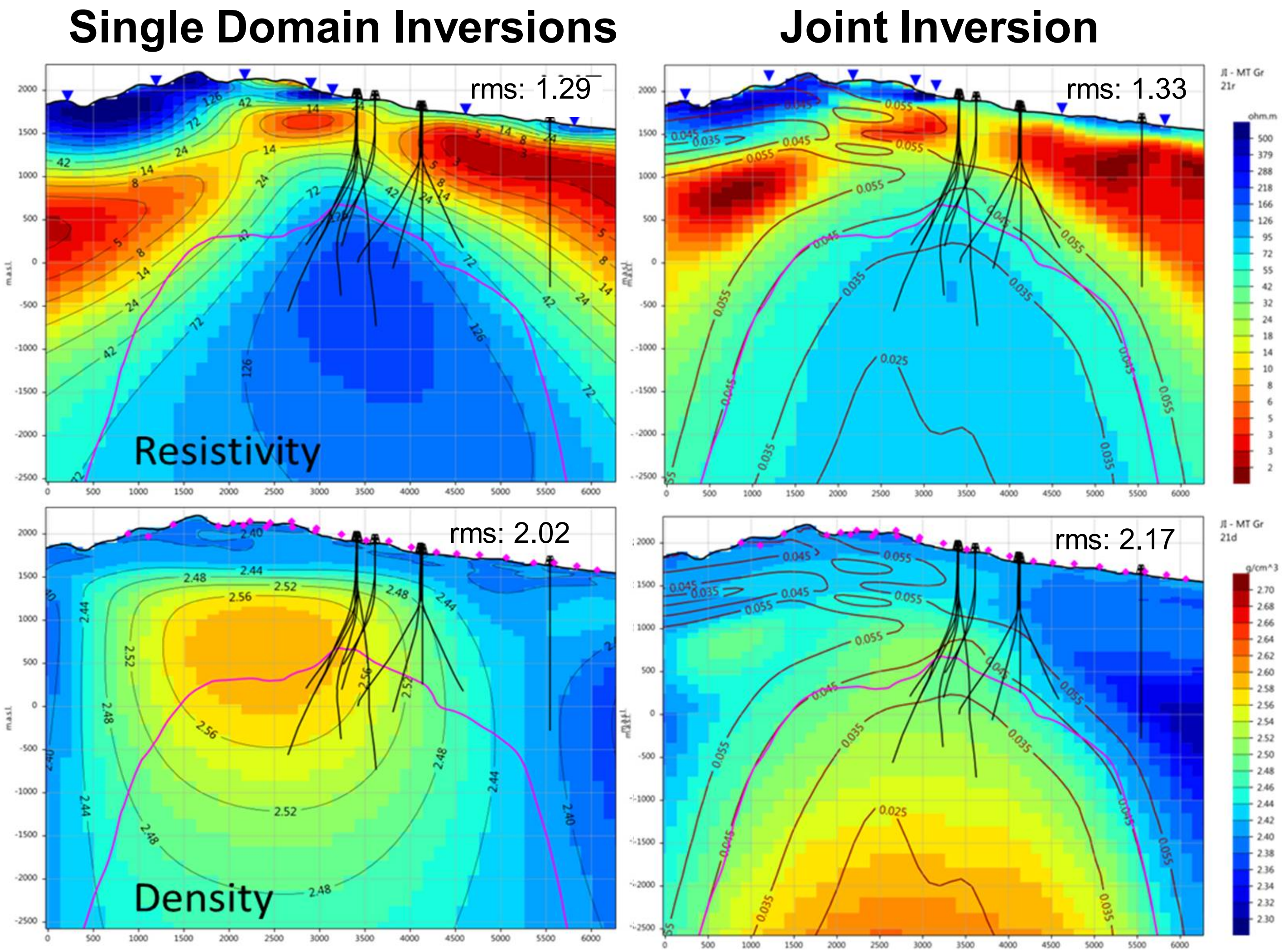
Meanwhile, over in the MT world…

Structural model





Joint Inversion for increased geological fidelity



Detailed resistivity model from MT alone.

Poor definition of density without additional constraints.

Line contours from external porosity model

Soyer et al (2017 GRC)

Inversion posed as a minimization

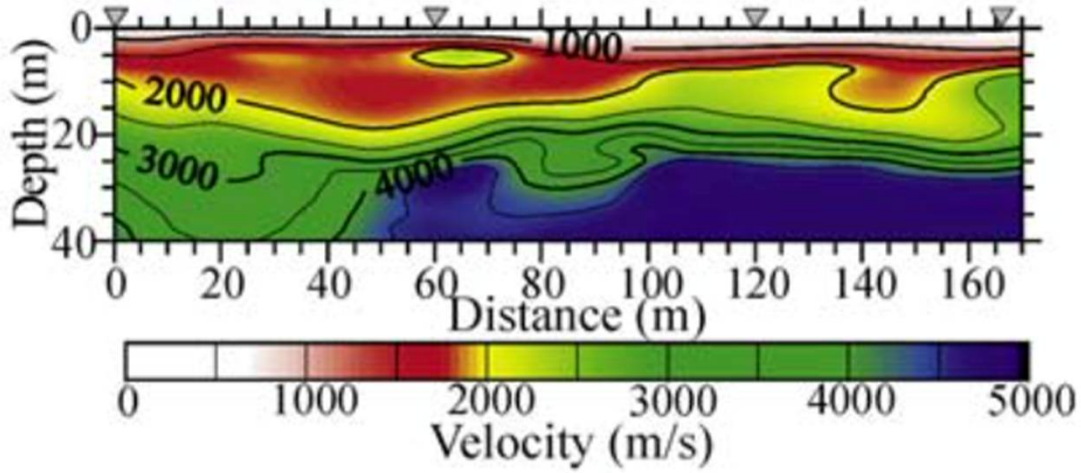
- Objective function: $\Psi(\mathbf{m}) = \varphi_d + \lambda\varphi_m$
  - **Data misfit**: $\varphi_d = \left(\mathbf{d} - F(\mathbf{m})\right)^T \mathbf{W}\left(\mathbf{d} - F(\mathbf{m})\right)$
  - **Model smoothness**: $\varphi_m = \mathbf{m}^T \mathbf{K}\mathbf{m}$

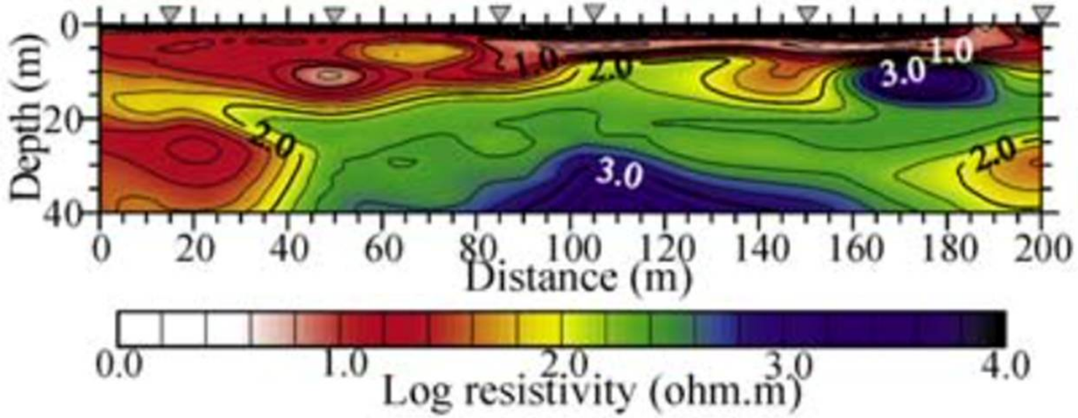
- Joint Inversion (**single property**): $\Psi(\mathbf{m}) = \varphi_{d_1} + \varphi_{d_2} + \cdots + \lambda\varphi_m$
  - Example: MT and mCSEM

- Joint Inversion (**multiple properties**): $\Psi(\mathbf{m}) = \varphi_{d_1} + \varphi_{d_2} + \lambda_1\varphi_{m_1} + \lambda_2\varphi_{m_2} + \gamma\varphi_{cpl}$
  - Example: MT and gravity

- Coupling to external reference models: $\Psi(\mathbf{m}) = \varphi_{d_1} + \varphi_{d_2} + \lambda_1\varphi_{m_1} + \lambda_2\varphi_{m_2} + \gamma\varphi_{cpl} + \tau\varphi_{ref}$

Cross-Gradients



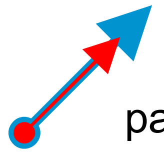


Gallardo and Meju (2003)

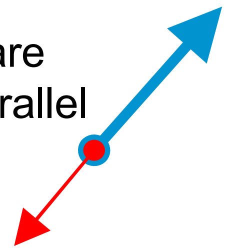
When there is no intrinsic relationship between model properties

$$\Phi_{a,b}^{xg}(\vec{\mathrm{m}}) = \int_V \|\nabla\vec{m}_a \times \nabla\vec{m}_b\|^2$$

The X-gradient term is zero if:

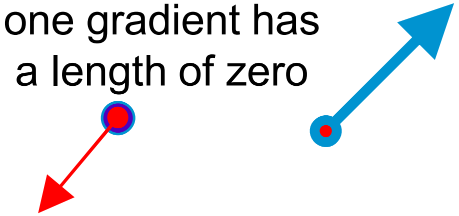


the gradients are parallel or antiparallel



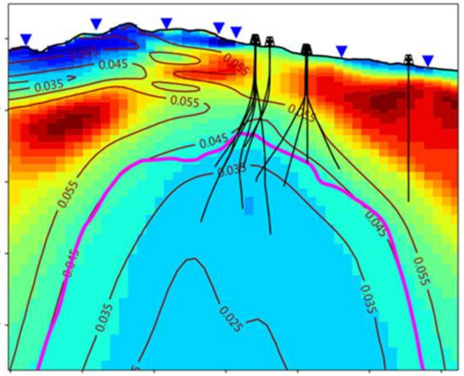
or

one gradient has a length of zero

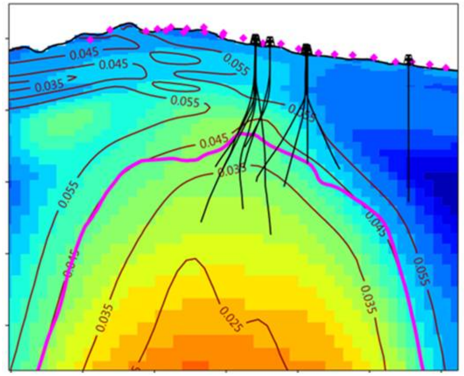


Cross-Gradients in Geophysical Inversions

1. Promote structural similarity between domains



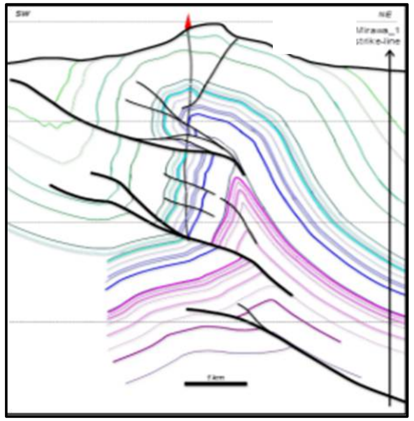
Resistivity



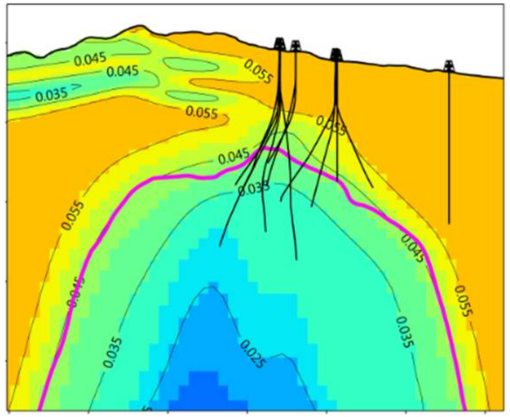
Density

2. Other structural information to steer model gradients

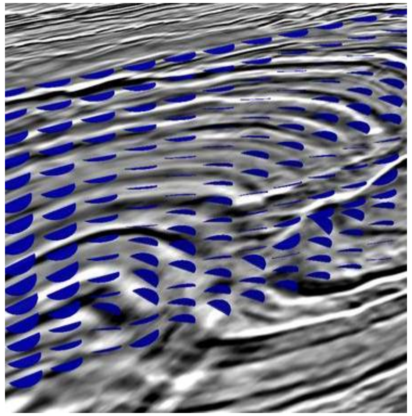
Surface geology



Geological model



Reservoir model (e.g. porosity)

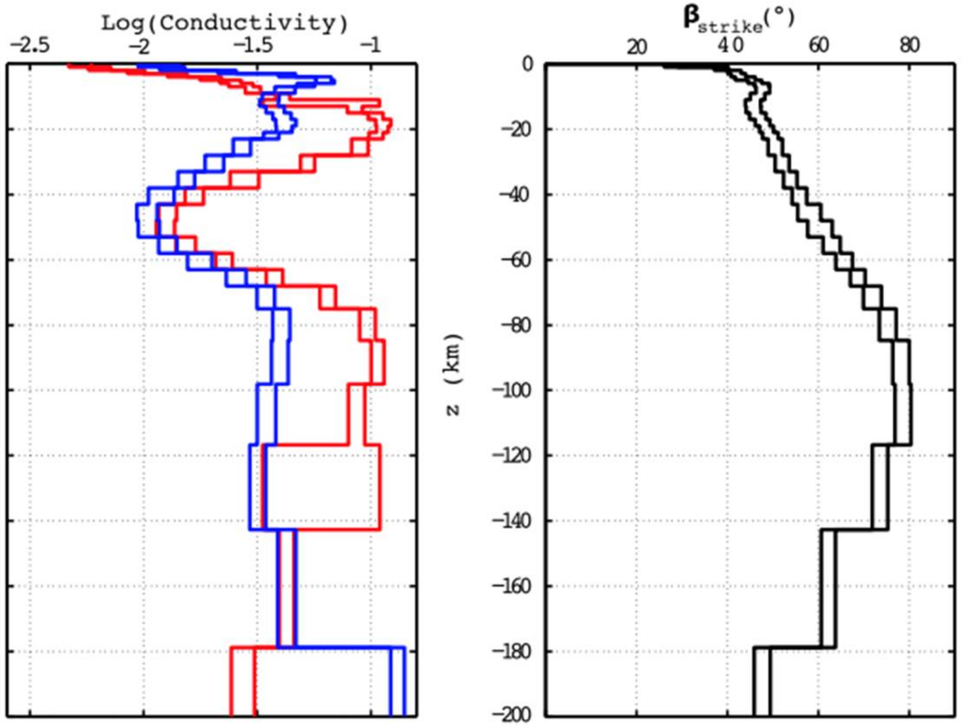


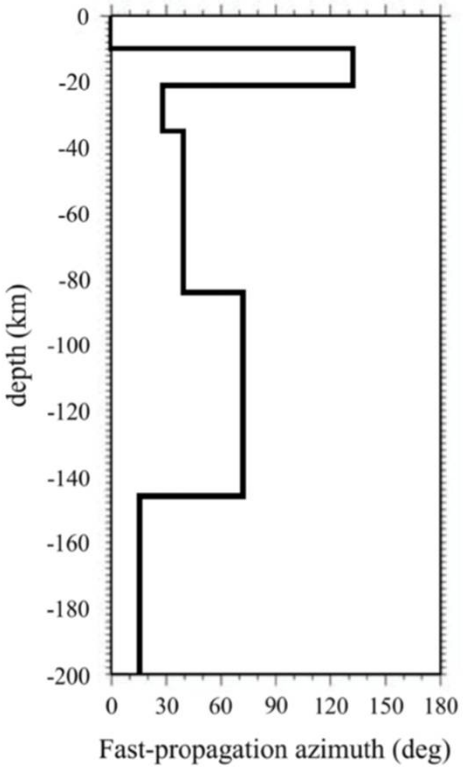
Structural tensor

Mutual Information

A distance metric used for image registration

$$I(X;Y) := \sum_{y \in Y} \sum_{x \in X} p(x,y) \log_2 \frac{p(x,y)}{p(x)p(y)}$$





$$\Phi_{\mathrm{MI}} = [b - I(X;Y)]^2$$

Reference model

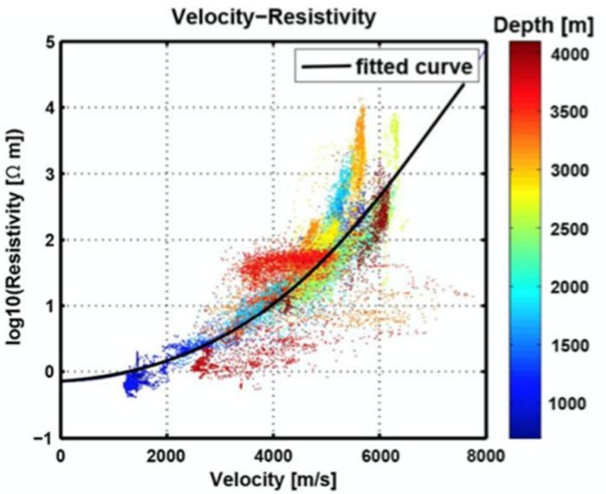
Mandolesi and Jones (2014); see also the talk by Max Moorkamp (2020)

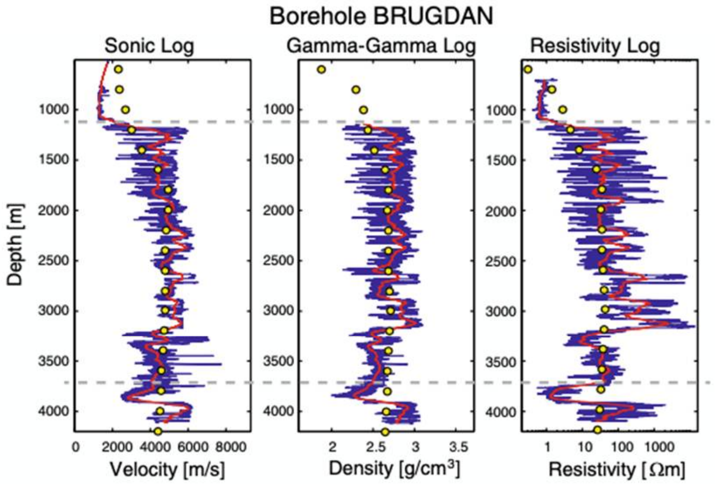
Parameter relationships

When we can derive an empirical relationship between model parameters

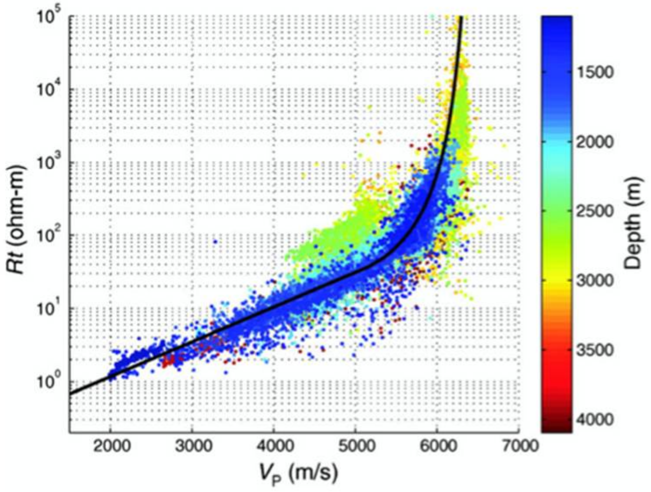
[also called correspondence maps Haber (2012)]

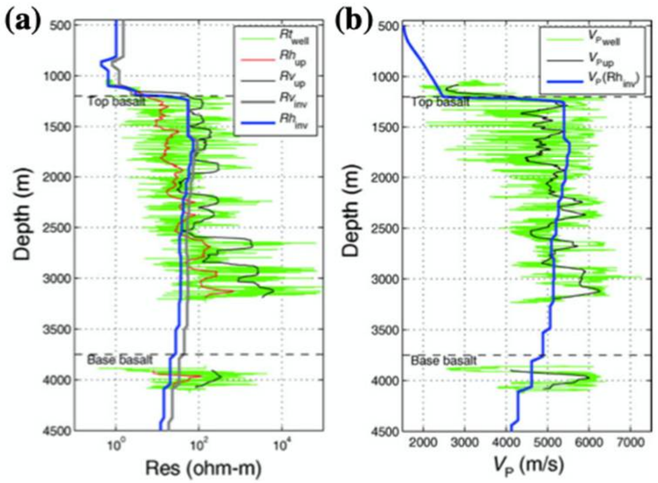
Heincke et al (2017)





Panzner et al (2016)

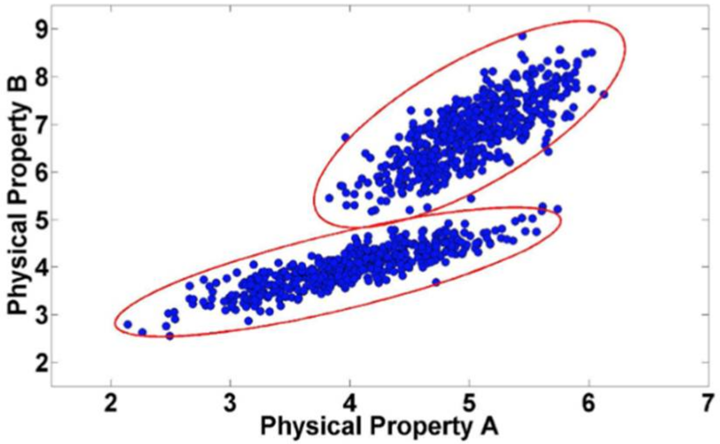




Moorkamp (2017)

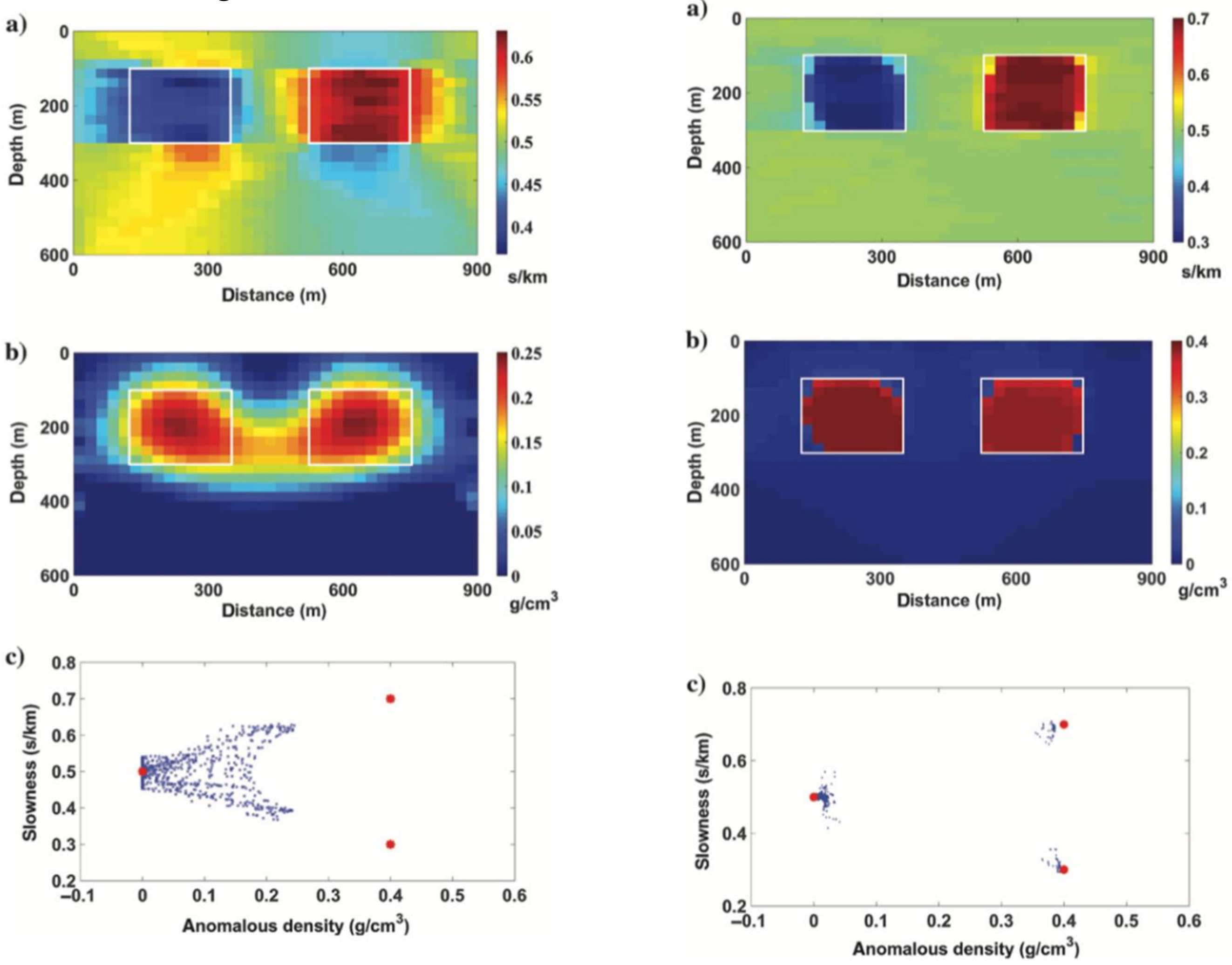
Fuzzy c-means clustering

If we expect physical properties to be in discrete clusters, we can use the concept of fuzzy c-means clustering



$$\Phi_{\mathrm{FC}} = \sum_{i=1}^{C} \sum_{k=1}^{N} u_{ik}^{q} d_{ik}^{2}$$

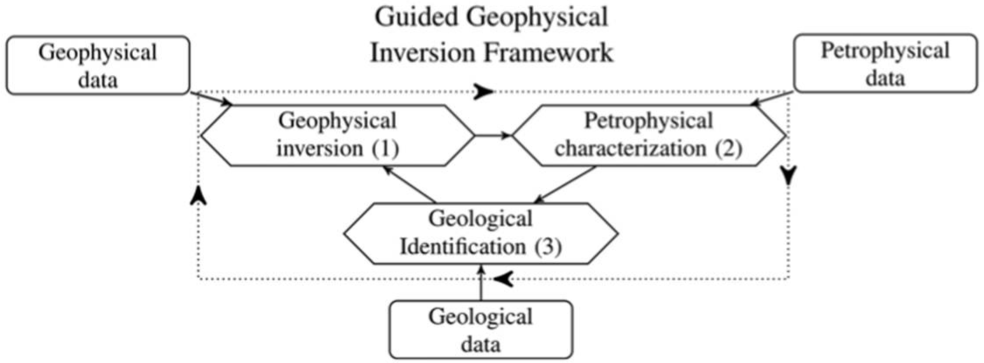
$$d_{ik}^{2} = (x_i - v_k)^T (x_i - v_k)$$

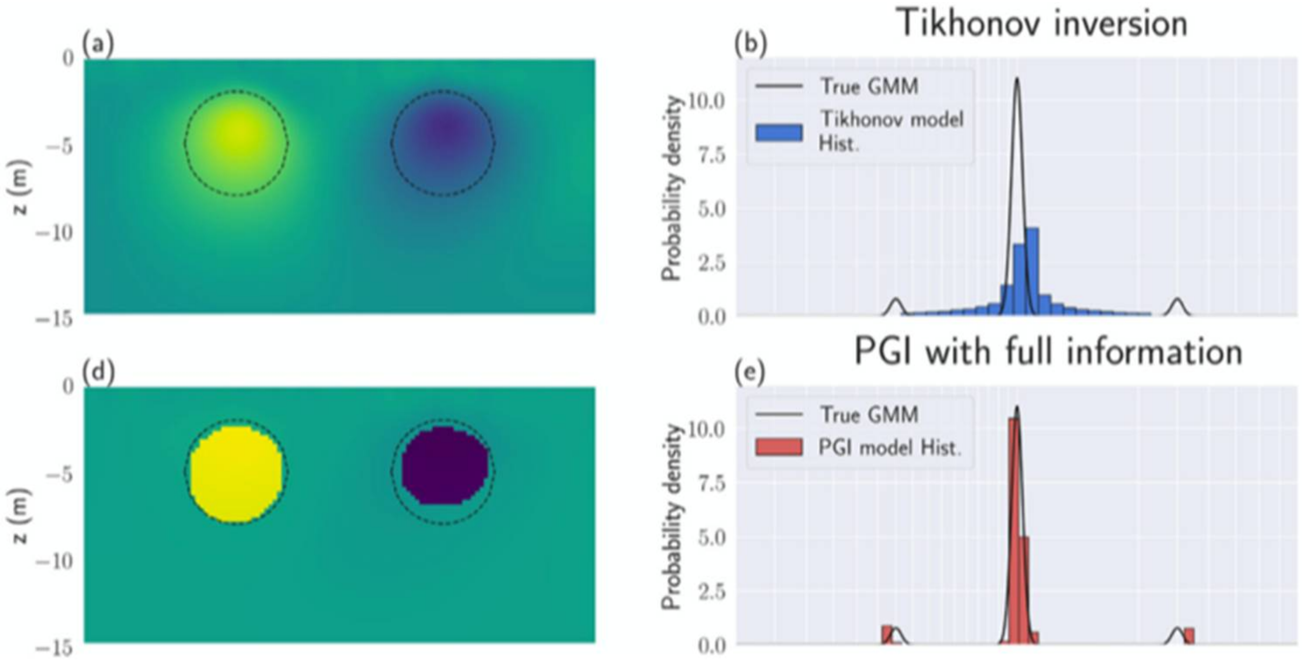


Sun and Li (2016)

Gaussian mixture model

A way to include physical property information in inversion where each property is represented by a Gaussian distribution





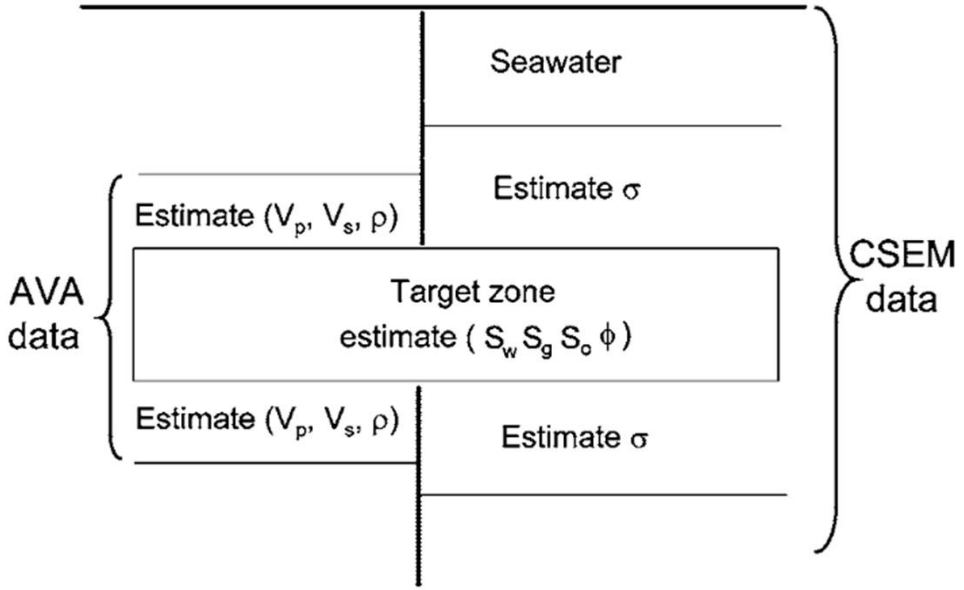
resistivity

Astic et al (2020, 2019)

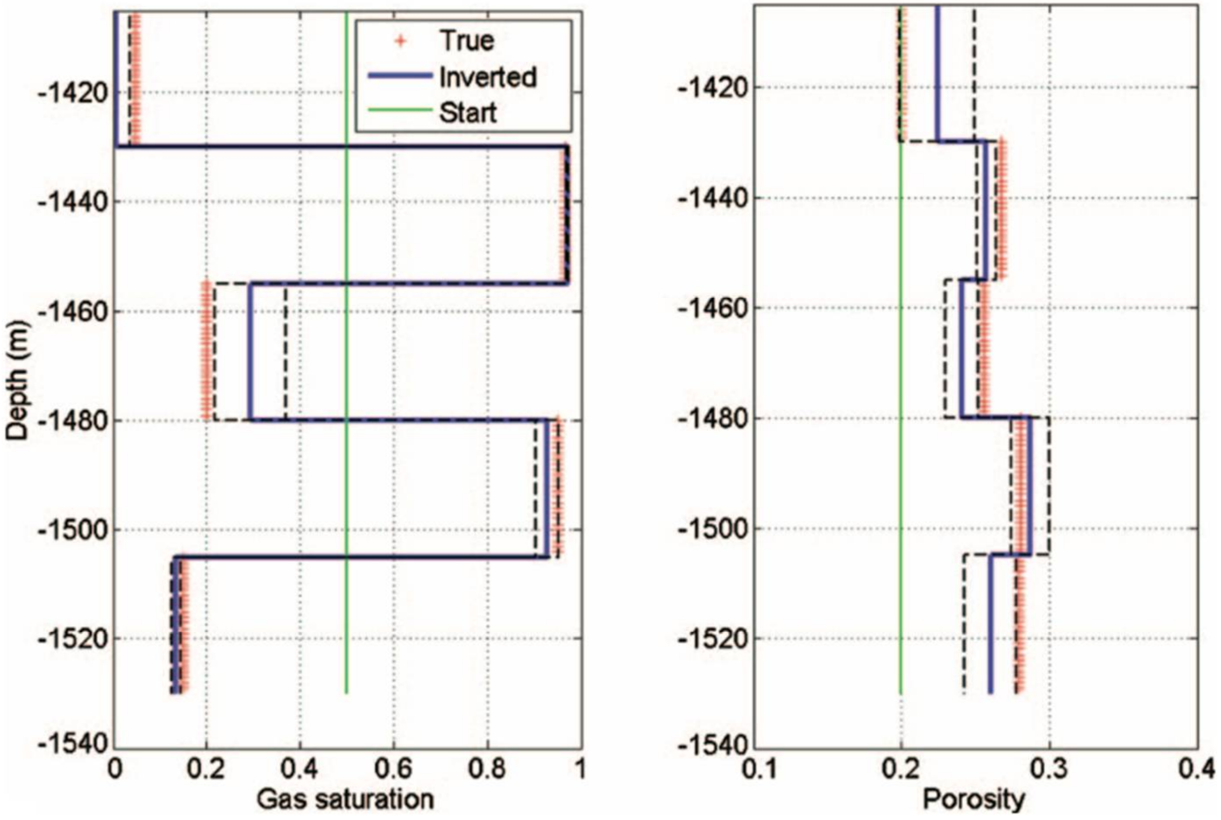
Petrophysical links

Inversion for parameters like porosity and fluid saturation through petrophysical relationships

$$\sigma = \frac{1}{a}\,\sigma_w \phi^m S_w^n$$ *Archie's Law*



$$\frac{\partial\theta}{\partial S_g} = \frac{\partial\theta}{\partial\sigma}\cdot\frac{\partial\sigma}{\partial S_g} + \frac{\partial\theta}{\partial V_p}\cdot\frac{\partial V_p}{\partial S_g} + \frac{\partial\theta}{\partial V_s}\cdot\frac{\partial V_s}{\partial S_g} + \frac{\partial\theta}{\partial\rho}\cdot\frac{\partial\rho}{\partial S_g}$$



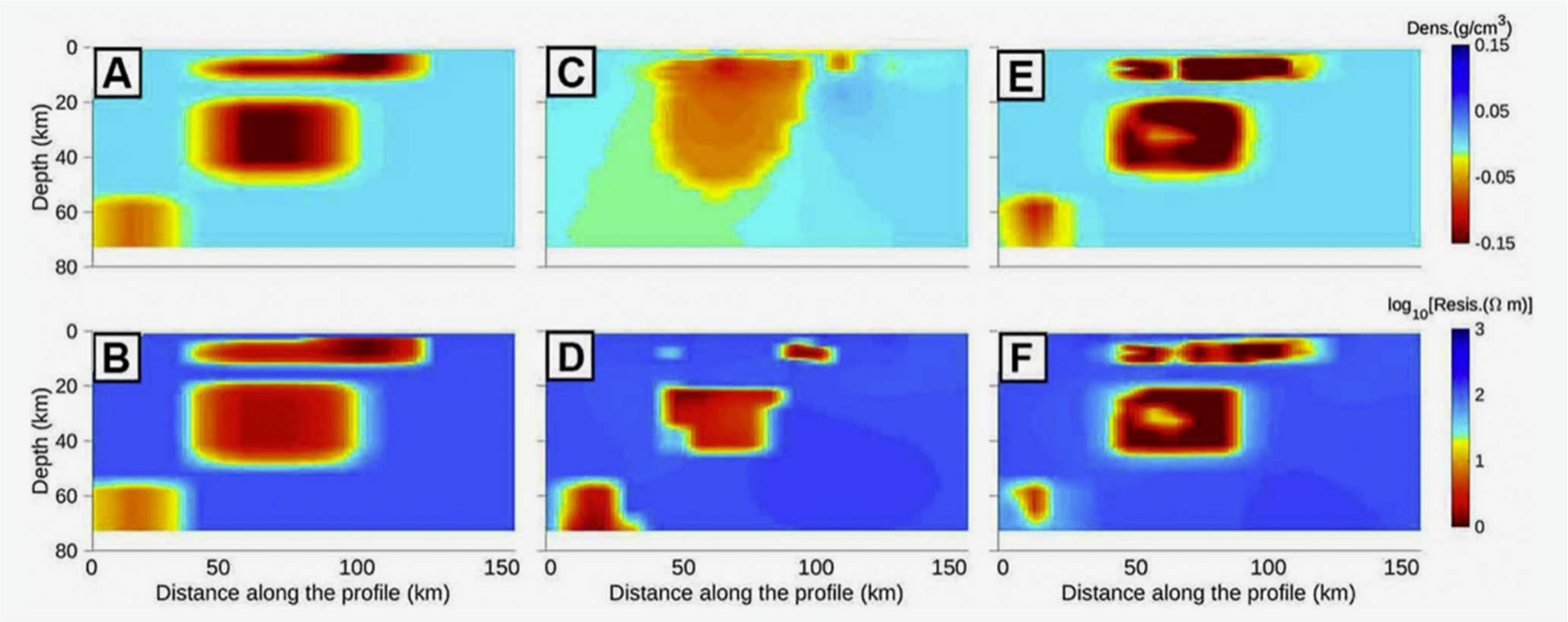
Hoversten et al (2006), see also Abubakar et al (2012)

Gramian constraints

Based on the minimization of the determinant of the Gram matrix of a system of different model parameters

$$s_G(\nabla \mathbf{m}^{(1)}, \nabla \mathbf{m}^{(2)}) = \begin{vmatrix} (\nabla \mathbf{m}^{(1)}, \nabla \mathbf{m}^{(1)}) & (\nabla \mathbf{m}^{(1)}, \nabla \mathbf{m}^{(2)}) \\ (\nabla \mathbf{m}^{(2)}, \nabla \mathbf{m}^{(1)}) & (\nabla \mathbf{m}^{(2)}, \nabla \mathbf{m}^{(2)}) \end{vmatrix}$$

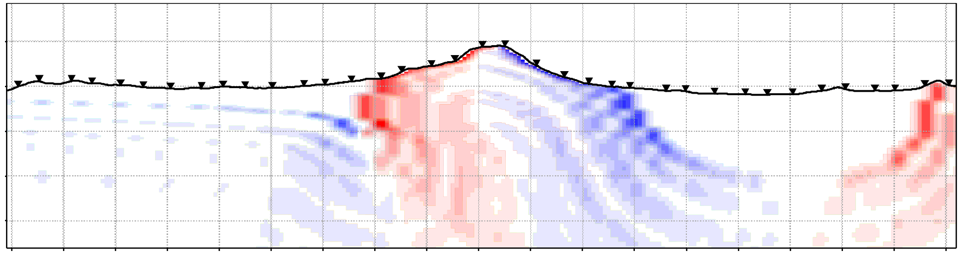
The determinant is a measure of how parallel the gradients are



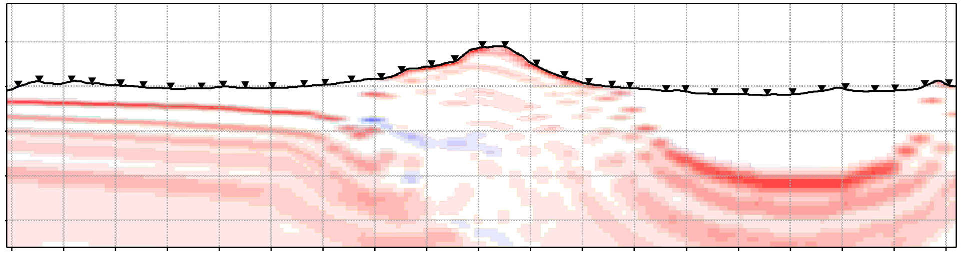
Zhdanov et al (2012), Jorgensen and Zhdanov (2019)

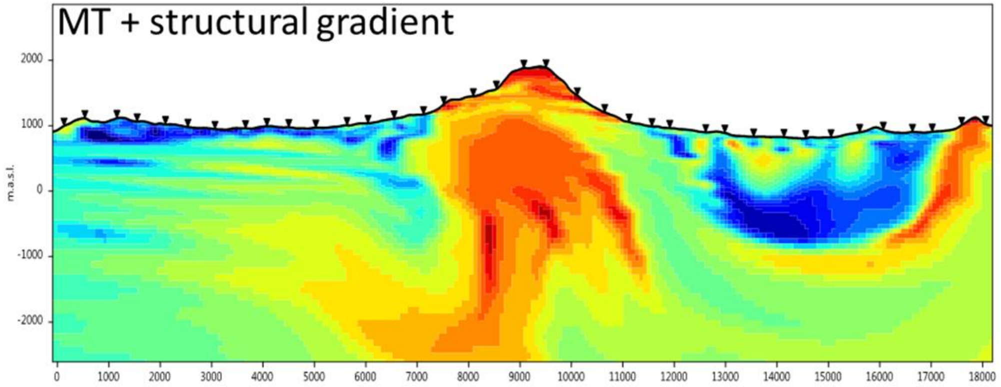
Image-guided inversion

Horizontal gradient

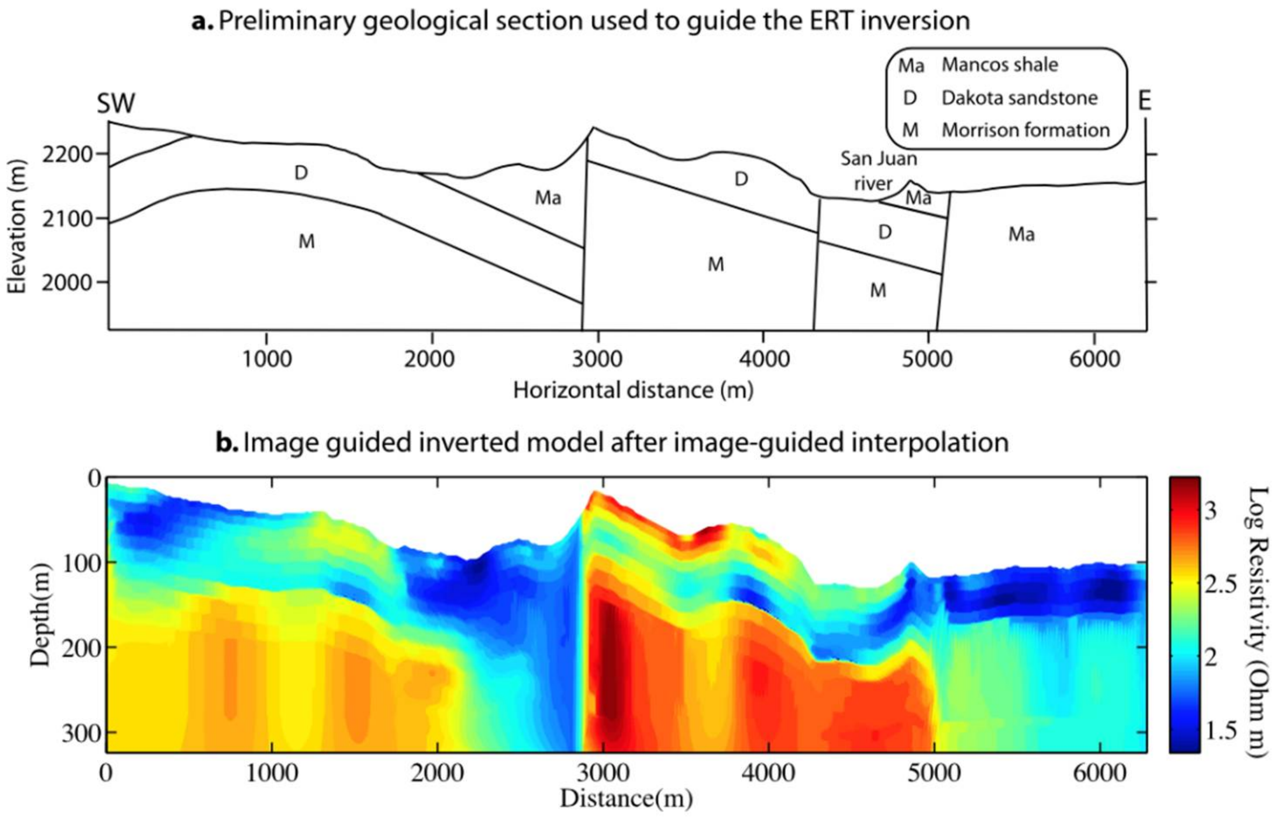


Vertical gradient





Coupled via cross gradients to external gradients



Structure tensors used to modify regularization

Zhou et al (2014)

Minimizing joint inversion objective functions

$$\Psi(\mathbf{m}) = w_1\varphi_{d_1} + w_2\varphi_{d_2} + \lambda_1\varphi_{m_1} + \lambda_2\varphi_{m_2} + \gamma\varphi_{cpl}$$

- Need to estimate tradeoff parameters: data weights, model weights, and coupling weights

- Data weights:
  - Keep constant
  - Values based on number of data points or norms of gradients (*Commer et al, 2009)*
  - Values based on Jacobian (sensitivity) values (*Abubakar et al, 2009)*
  - L curve analysis (*Giraud et al, 2019*)
  - Values determined dynamically during the inversion (*Lelièvre et al, 2012; Astic et al, 2020*)
  - Values included as parameters to be estimated during the inversion (*Capriotti and Li, 2019*)

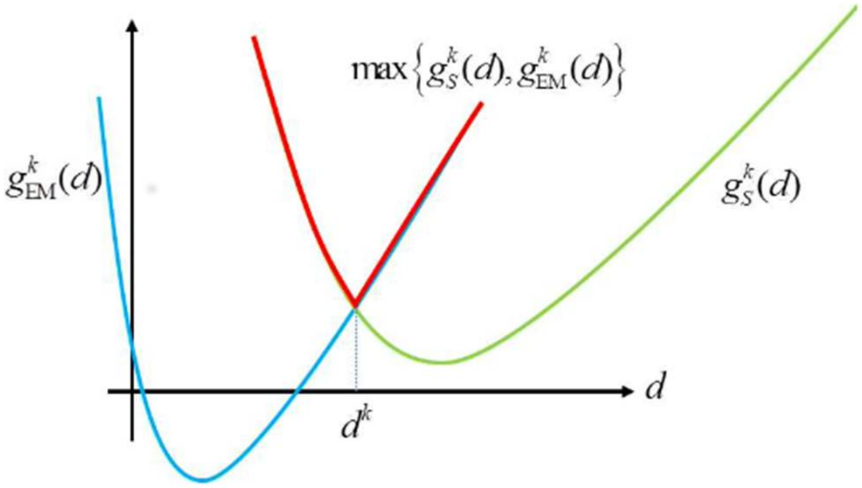
Minimizing joint inversion objective functions

$$\Psi(\mathbf{m}) = w_1\varphi_{d_1} + w_2\varphi_{d_2} + \lambda_1\varphi_{m_1} + \lambda_2\varphi_{m_2} + \gamma\varphi_{cpl}$$

- Simultaneous joint inversion: minimize single objective function
- Sequential joint inversion: alternate single domain inversions using other model as constraint
- Cooperative joint inversion: using fixed external information

Minimizing joint inversion objective functions

$$\Psi(\mathbf{m}) = f(\mathbf{m})_1 + f(\mathbf{m})_2$$



Semerci et al (2014)

$f(\mathbf{m})_1$ = EM objective function

$f(\mathbf{m})_2$ = seismic objective function

No **m** that minimizes both functions

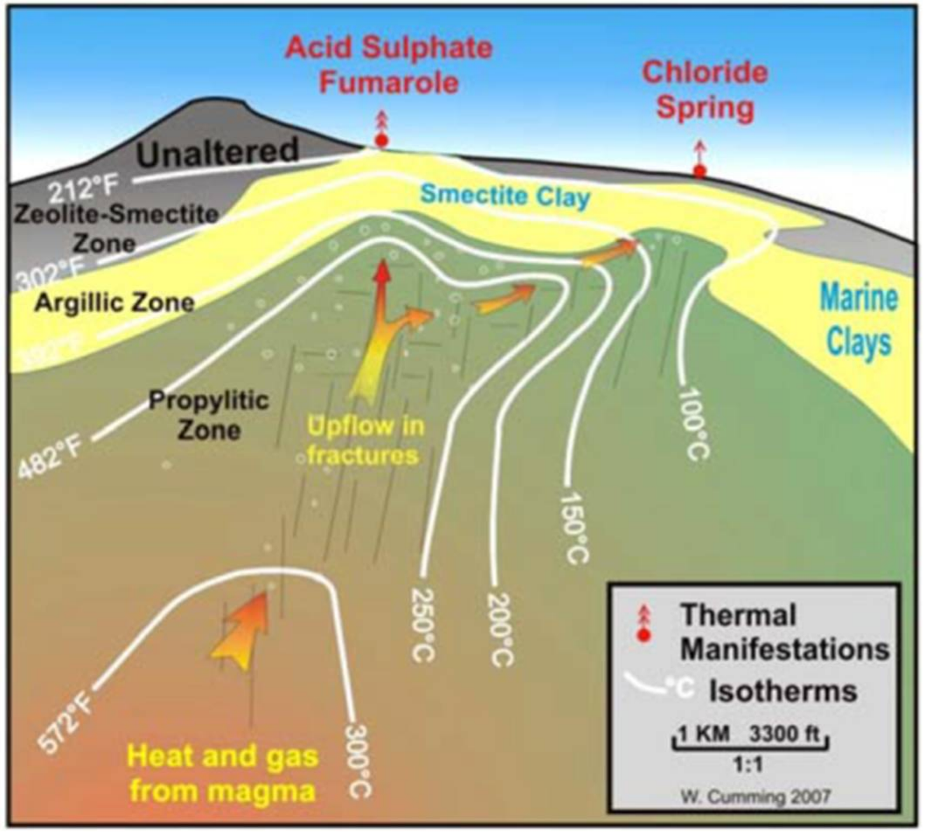
Can be solved using multi-objective optimization as done in Semerci et al (2014) and Filege et al (2009)

JOINT INVERSION

Examples from geothermal areas

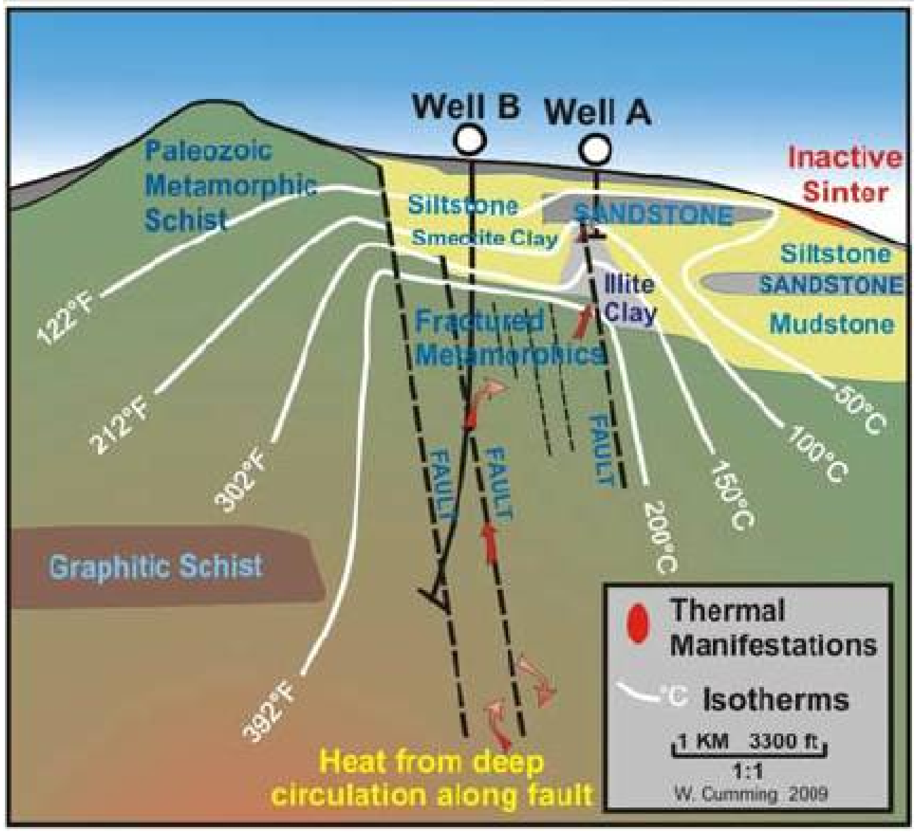
Geothermal Resource Concept Models

Volcanic-hosted



e.g. Iceland, Indonesia

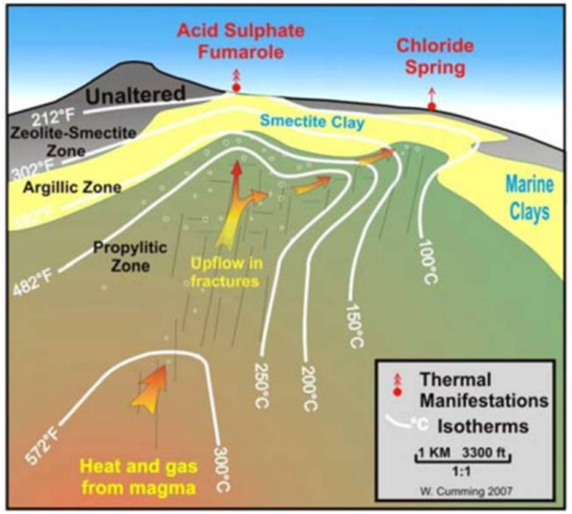
Fault-controlled



e.g. Basin & Range US, Turkey

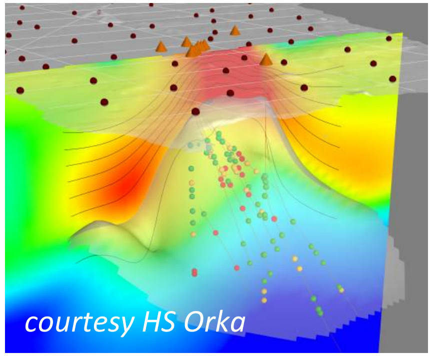
Cumming, Stanford Geothermal Workshop, 2009

Geophysical Signature

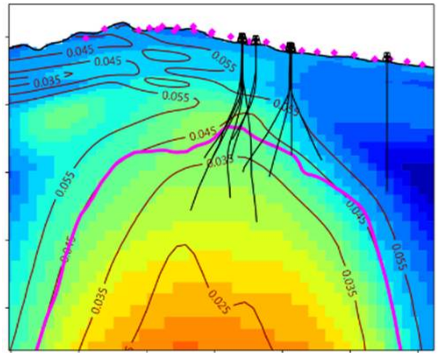


clay cap = *conductive*

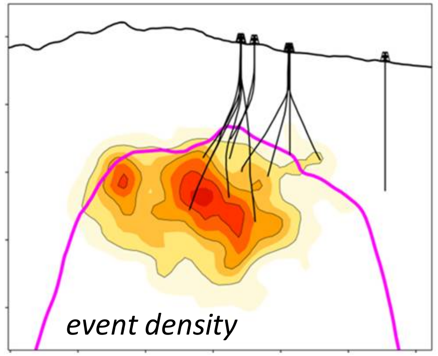
reservoir = *resistive* *dense*



Magnetotellurics / *resistivity*



Gravity / *density*



Micro-Earthquakes / *event locations* *velocity*

courtesy Star Energy (Soyer et al, First Break, 6, 2018)

Darajat

40+ years of exploration
23 years of production

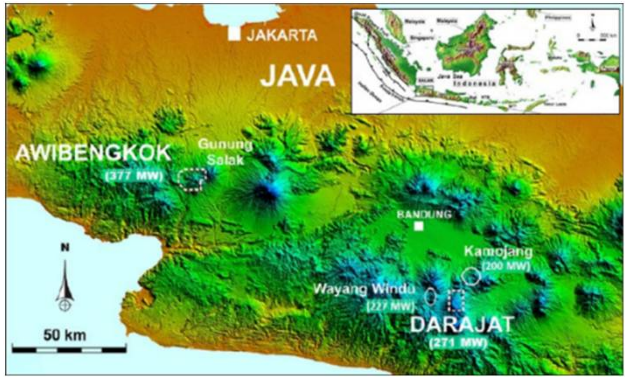
Darajat I, 1994:	55 MW
Darajat II, 2000:	90 MW
Darajat III, 2007,	110 MW

Combined current output: ~271 MW

Amoseas (Chevron) / PLN / Chevron
2017: acquired by Star Energy

Dry steam at well heads

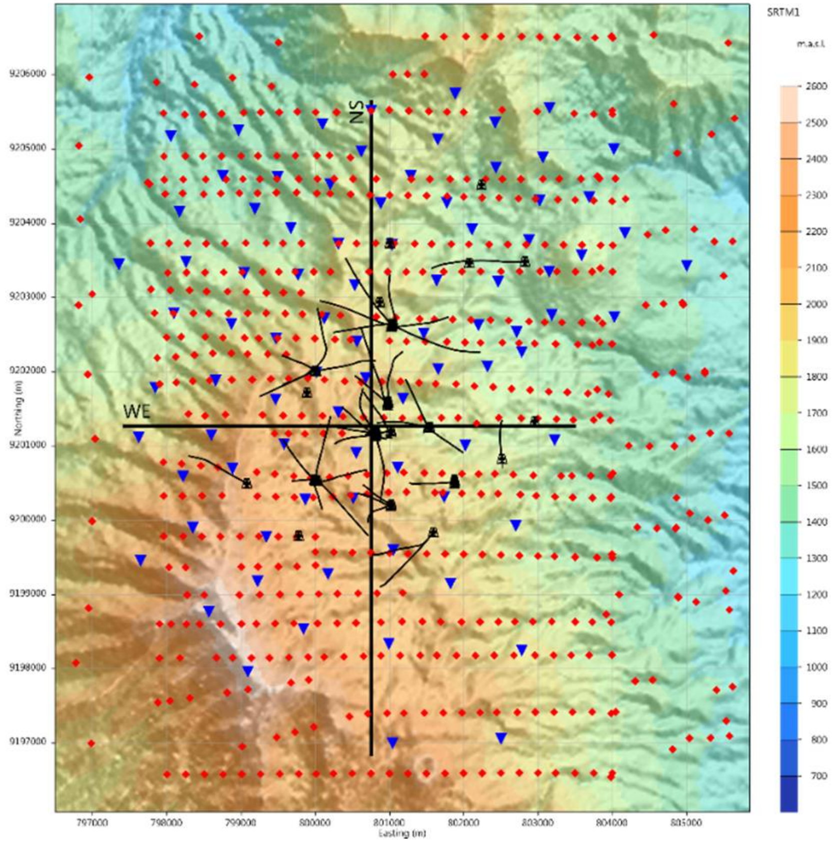
Chevron, 2015



Satya et al., WGC, 2015

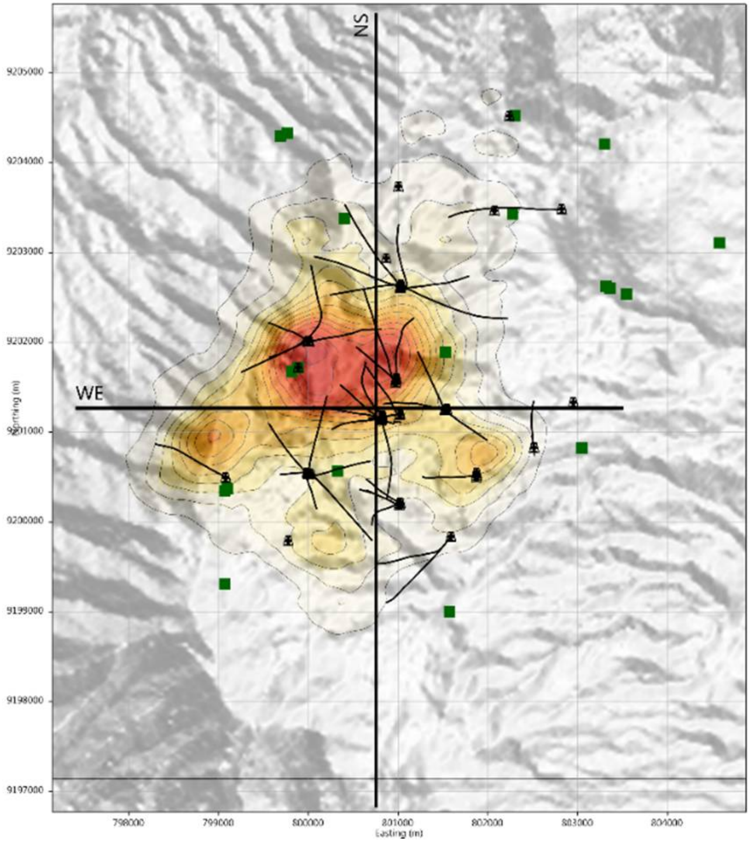
3 x Geophysical Data Sets

▼ MT station #84 (1996, 2004)
◆ Gravity station #538 (1996)



Broad-band MT:
0.001-100 / 10000Hz (1996 / 2004)

■ MEQ seismic receiver #21 (2005-2015)
3-component, buried ~1m.



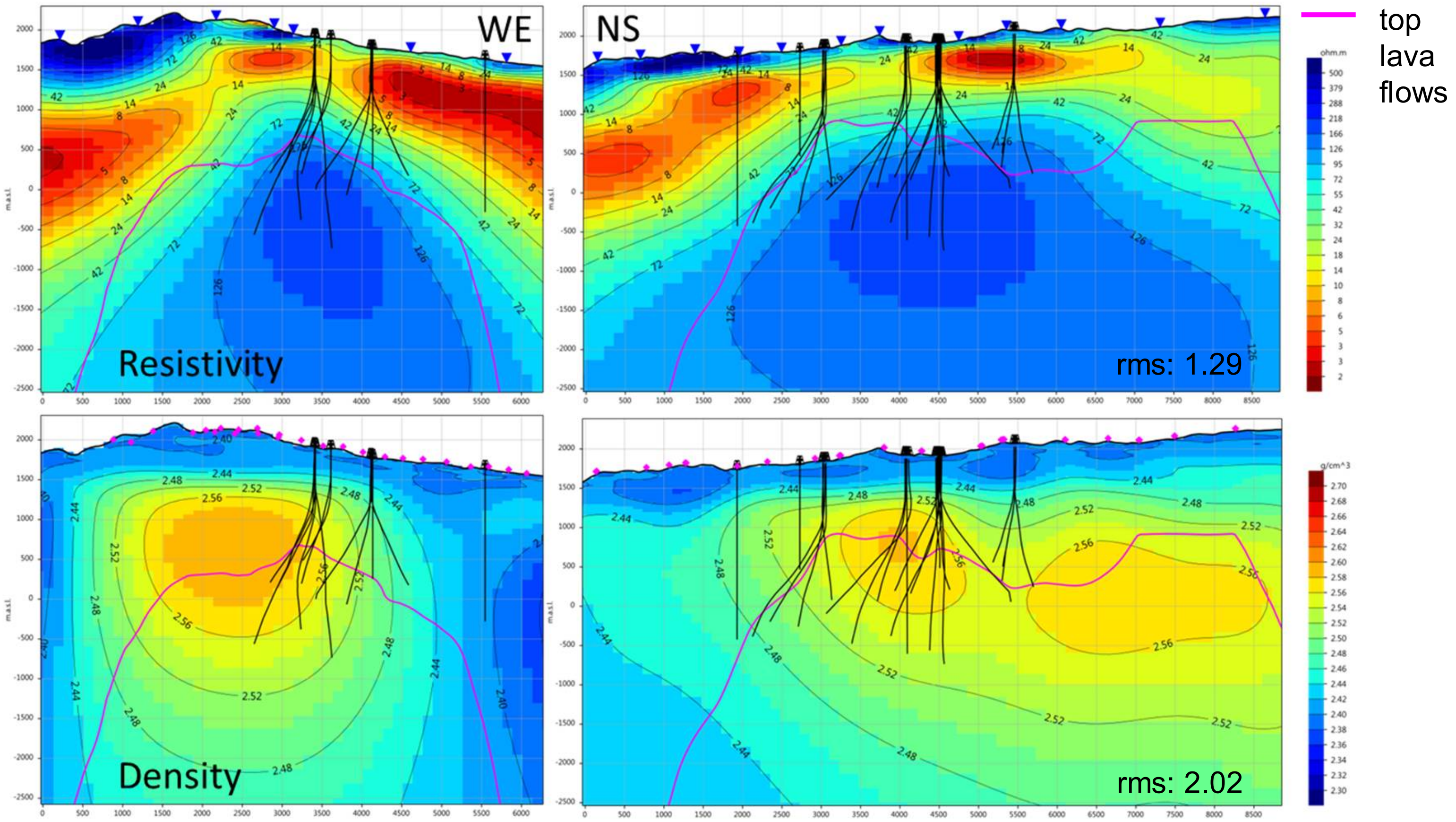
Color = MEQ event density

~5,100 MEQ events
Data = ~33,000 P- and S-wave arrival times.

Soyer et al (2017 GRC)

Single Domain 3D Inversions – MT, Gravity

Blind inversions, from homogeneous starting properties

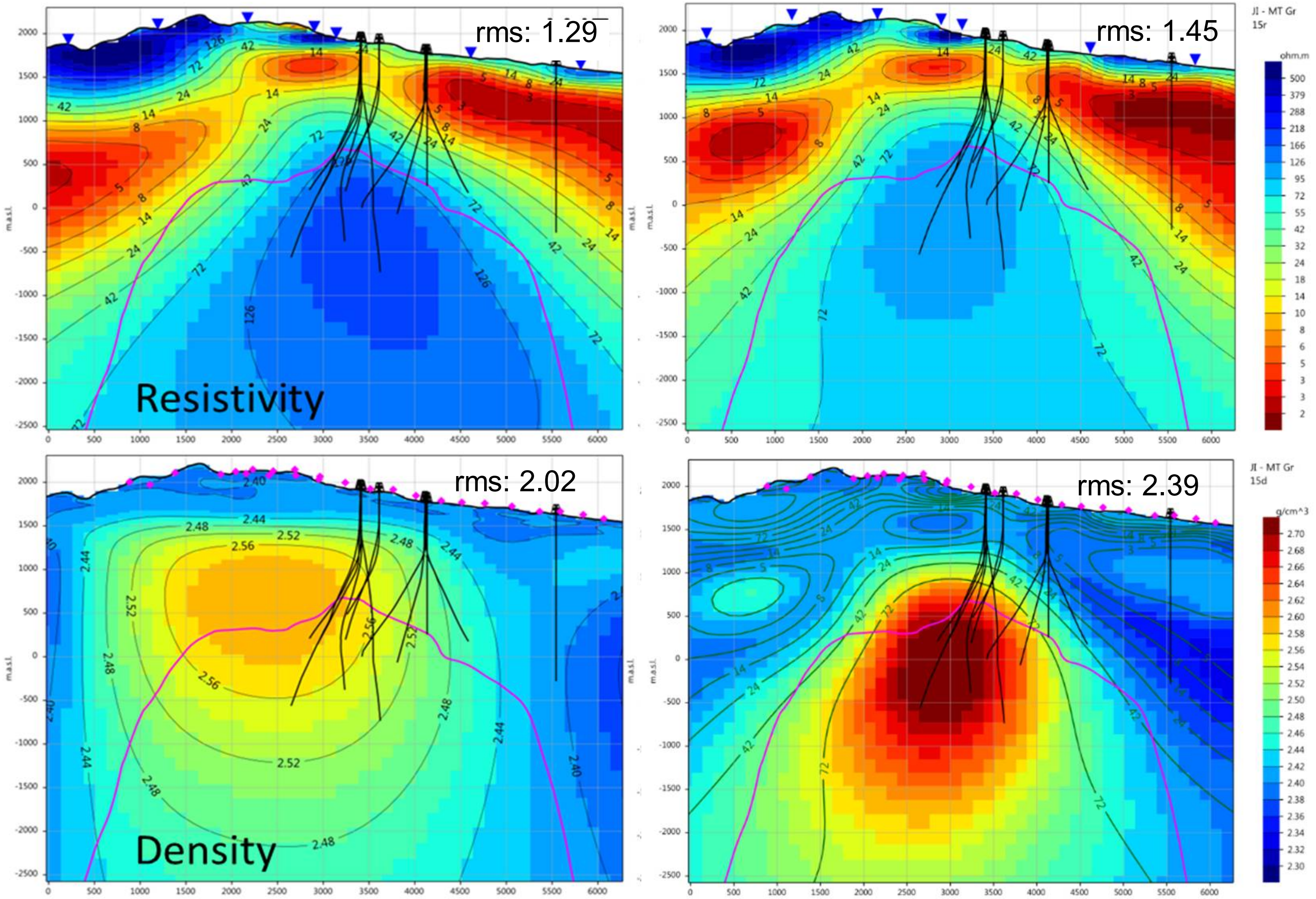


→ Detailed resistivity model from MT alone.
→ Poor definition of density without additional constraints.

Joint Inversion – MT + Gravity

All Starting Models = homogeneous half space

Single Domain Inversions | **X-gradient Joint Inversion**



Detailed resistivity model from MT alone.

Poor definition of density without additional constraints.

Line contours from resistivity model

Inversion Cost Function – Reference Model XG

regularization (smoothing)

reference / porosity cross-gradients

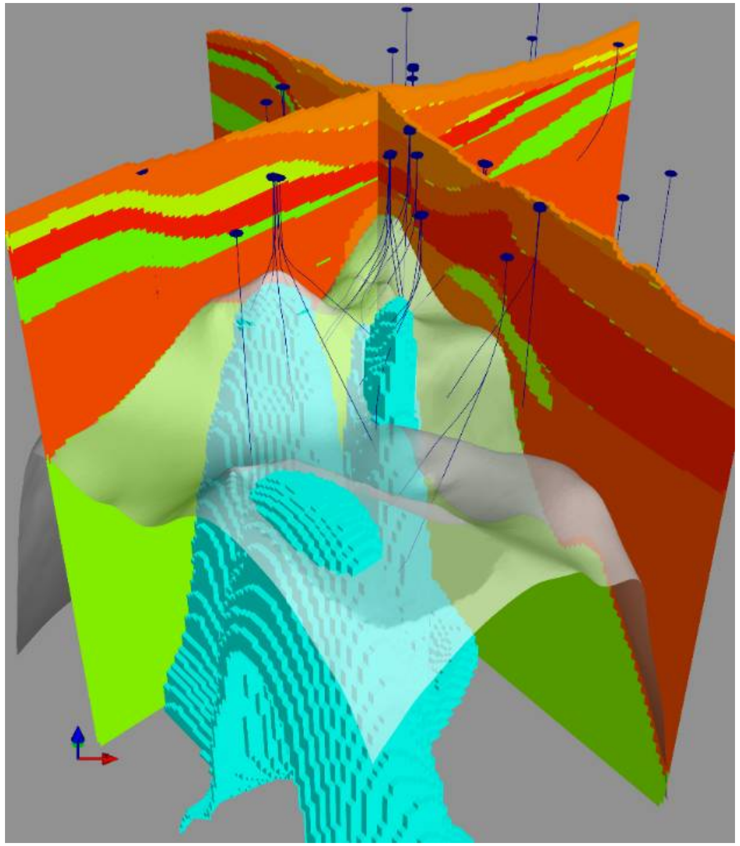
property cross-gradients

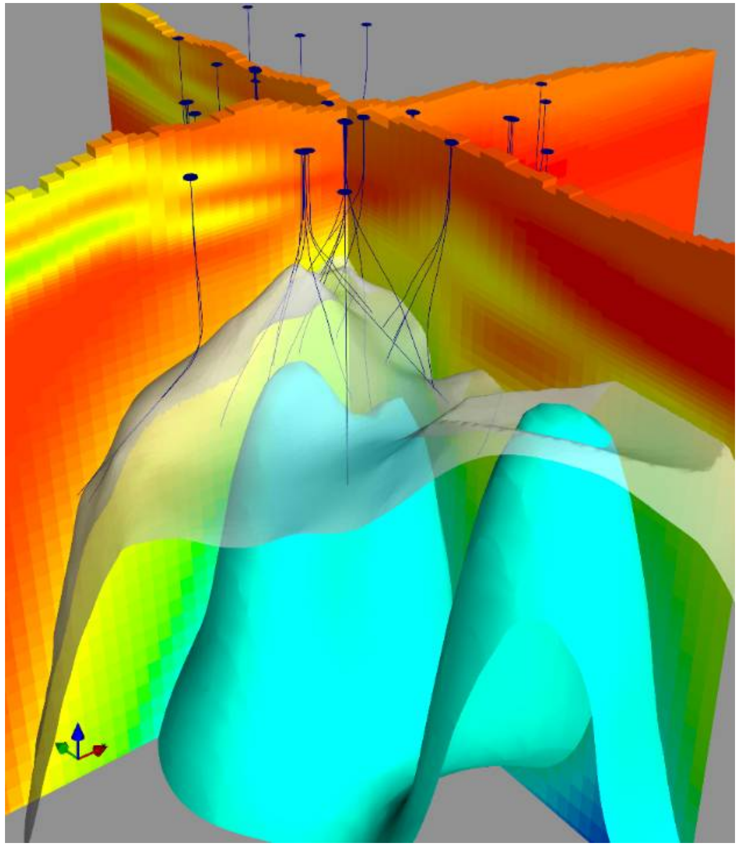
data misfits

$$\Psi(\vec{m}) = \sum_{j=1,2} \alpha_j \Phi_j^{data} + \sum_{i=a,b} \lambda_i \Phi_i^{reg} + \tau_{a,b}\, \Phi_{a,b}^{xg} \quad \left[+ \sum_{i=a,b} \tau_{i,ref} \Phi_{i,ref}^{xg}\right]$$

weights, to balance

Porosity Volume = Reference Model





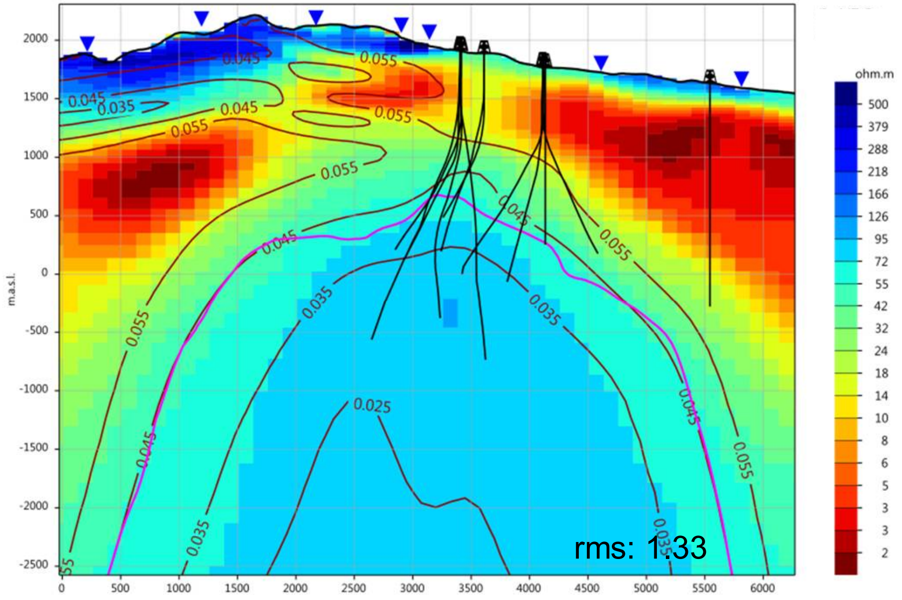
Porosity model on different mesh than inversion mesh → paint to 3D modeling mesh
Cross-gradients required for support in joint inversion → smoothing applied.

Joint Inversion: MT + Gravity + Porosity (ref)

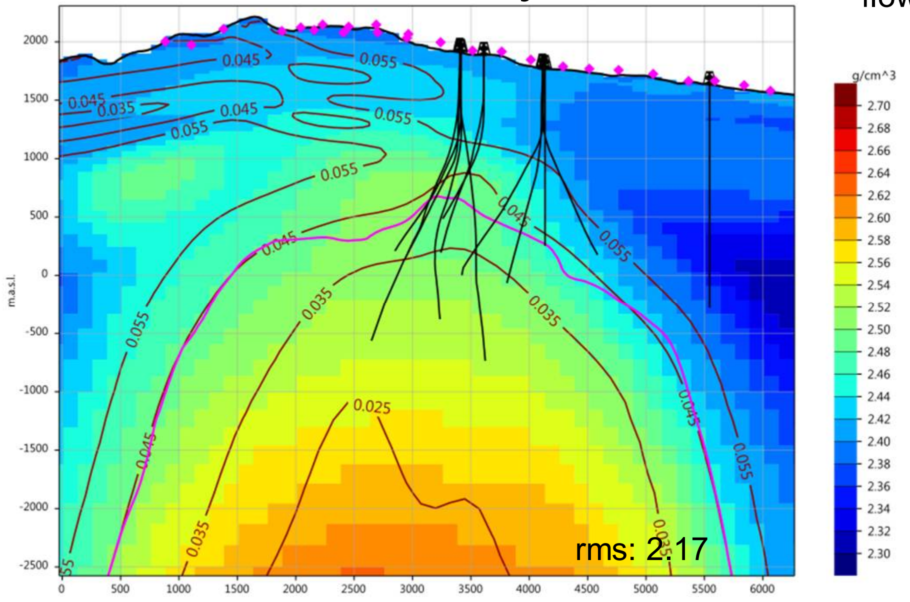
Coupling to an external porosity model via cross gradients

top lava flows

Resistivity



Density

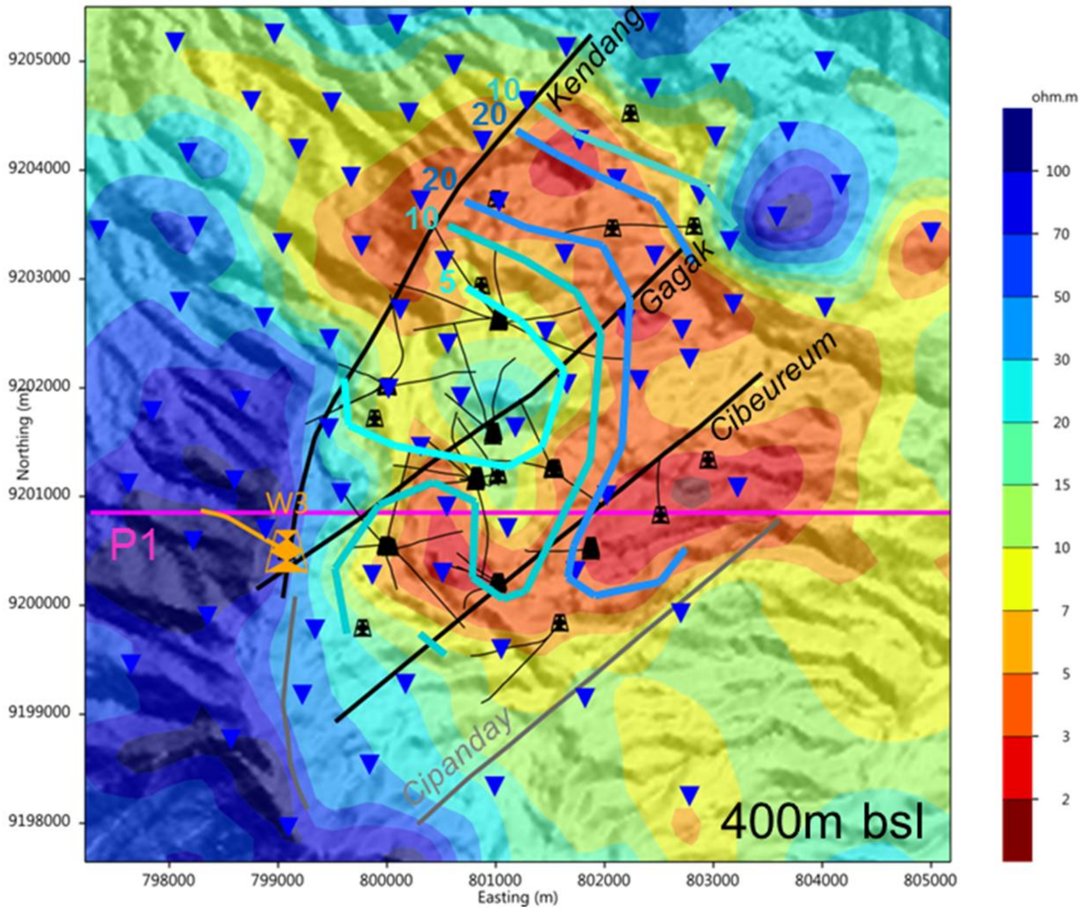


contours from smoothed porosity model

modified starting density with density increase below top lava.

Interpretation – Correlation with Methylene Blue

3D JI MT-gravity with porosity cross-gradients



Thick contours:

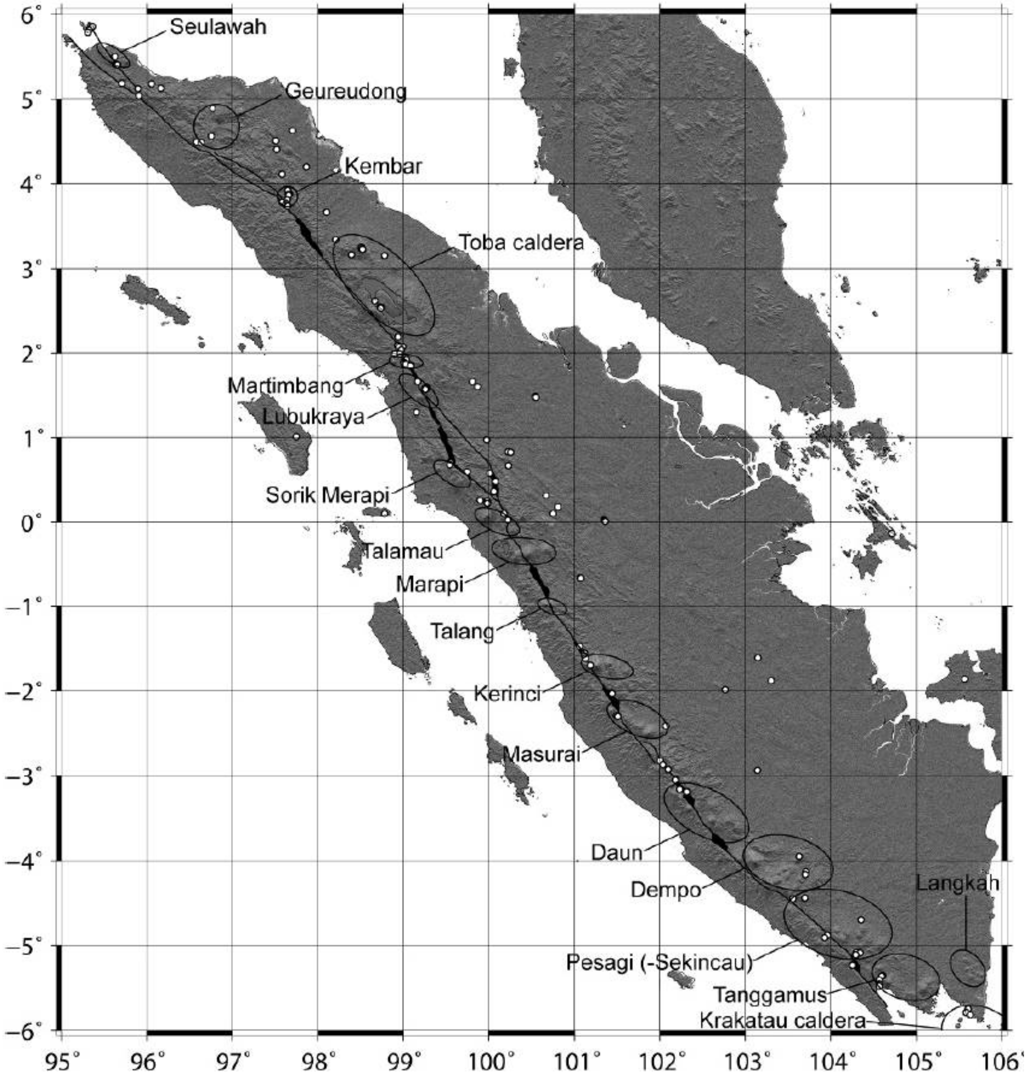
% of methylene blue analysis

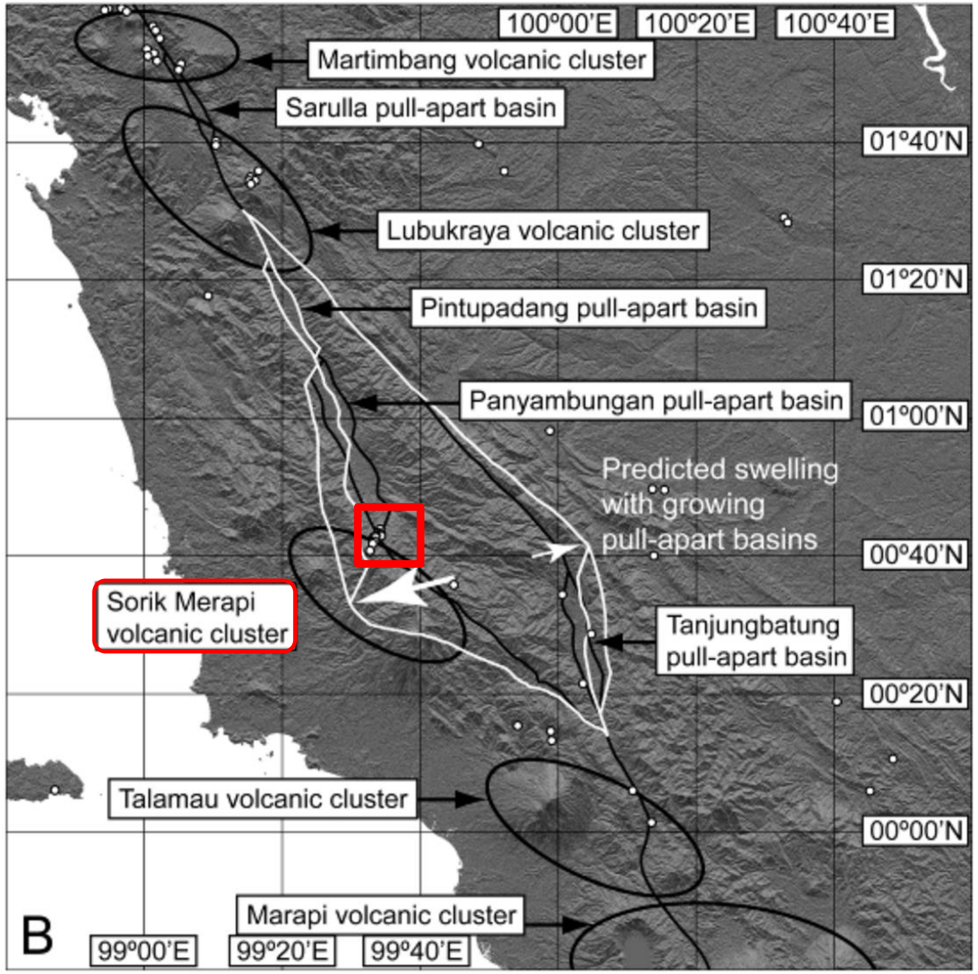
→ High values mark increased smectite clay mineral

→ Smectice is electrically conductive

→ Good correlation between conductor and high MB values.

Sumatra Fault – Graben-hosted and Volcanic Systems

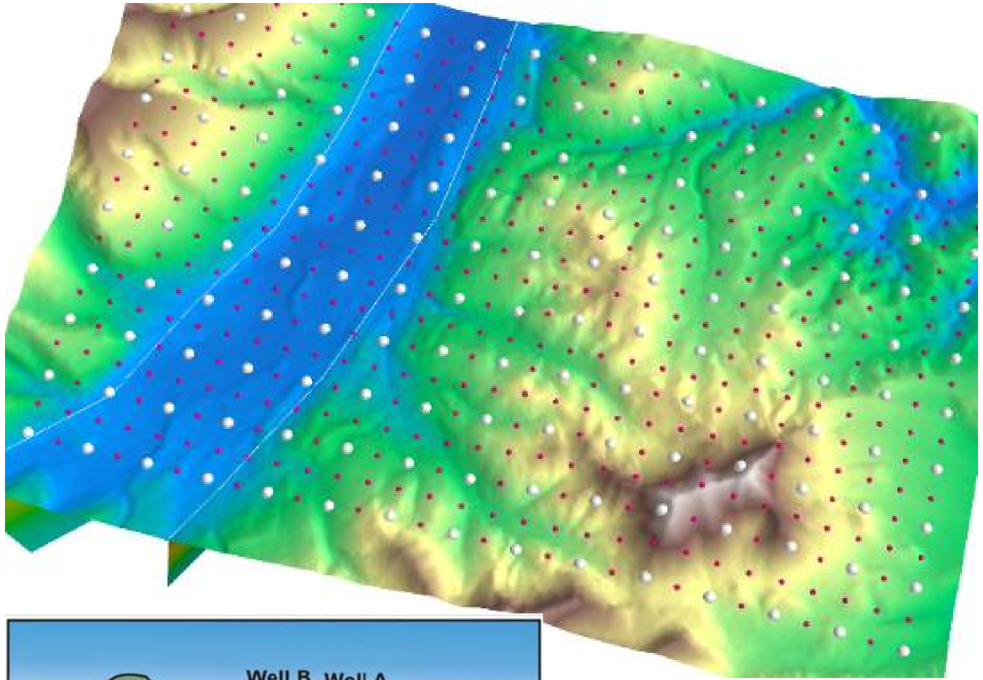


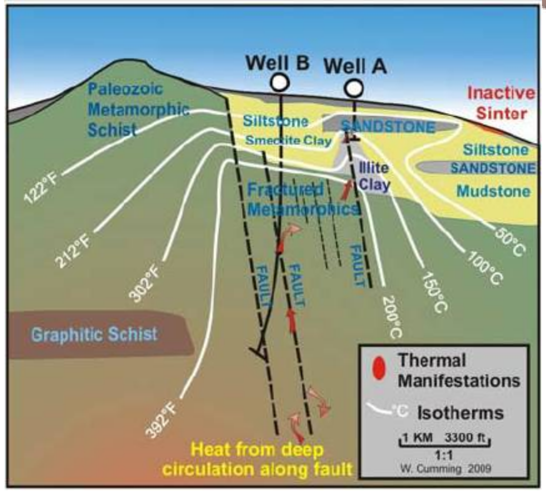


Muraoka et al, 2010 WGC

Simulation – Graben-hosted & Volcanic-hosted Field

Topography



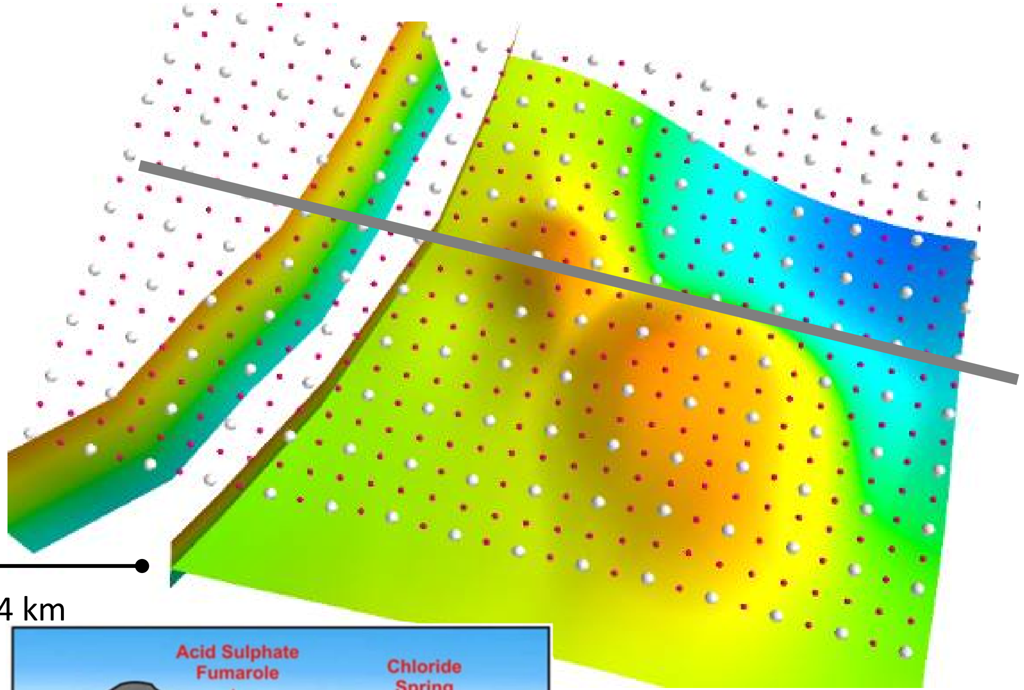


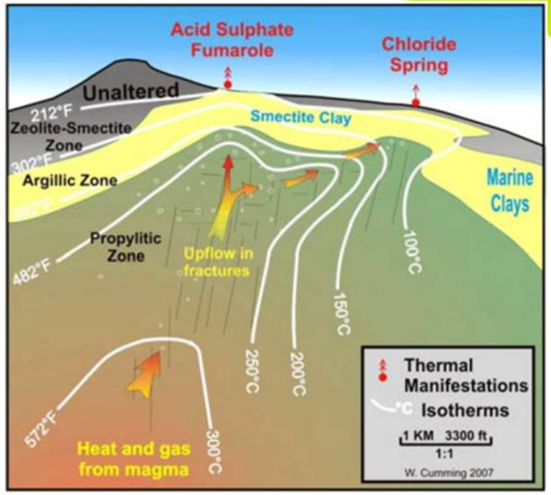
m asl

400 1700

4 km

Base of Conductor





m asl

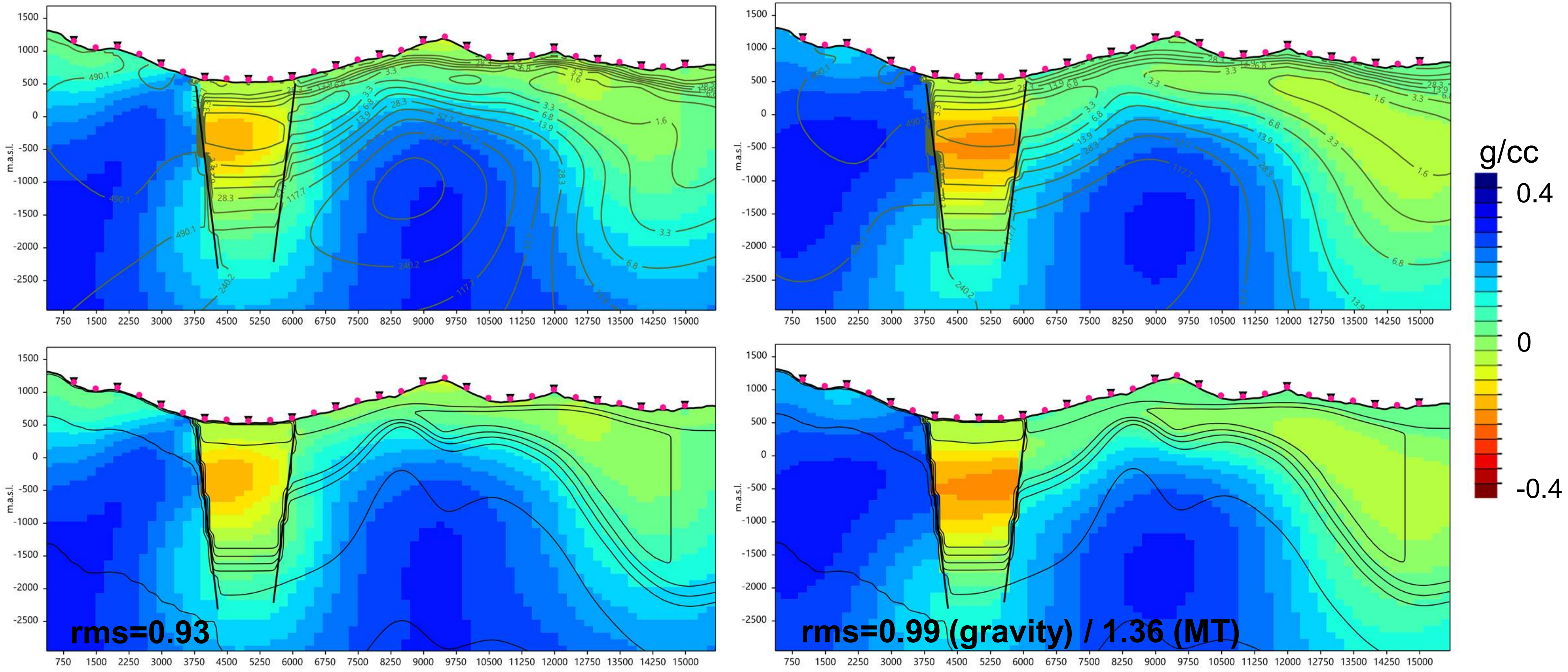
-3400 1000

Soyer et al (2020 WGC)

Gravity 3D Inversions using XG – Resitivity Reference vs JI

MT Resistivity as Reference

Direct MT+Gravity JI

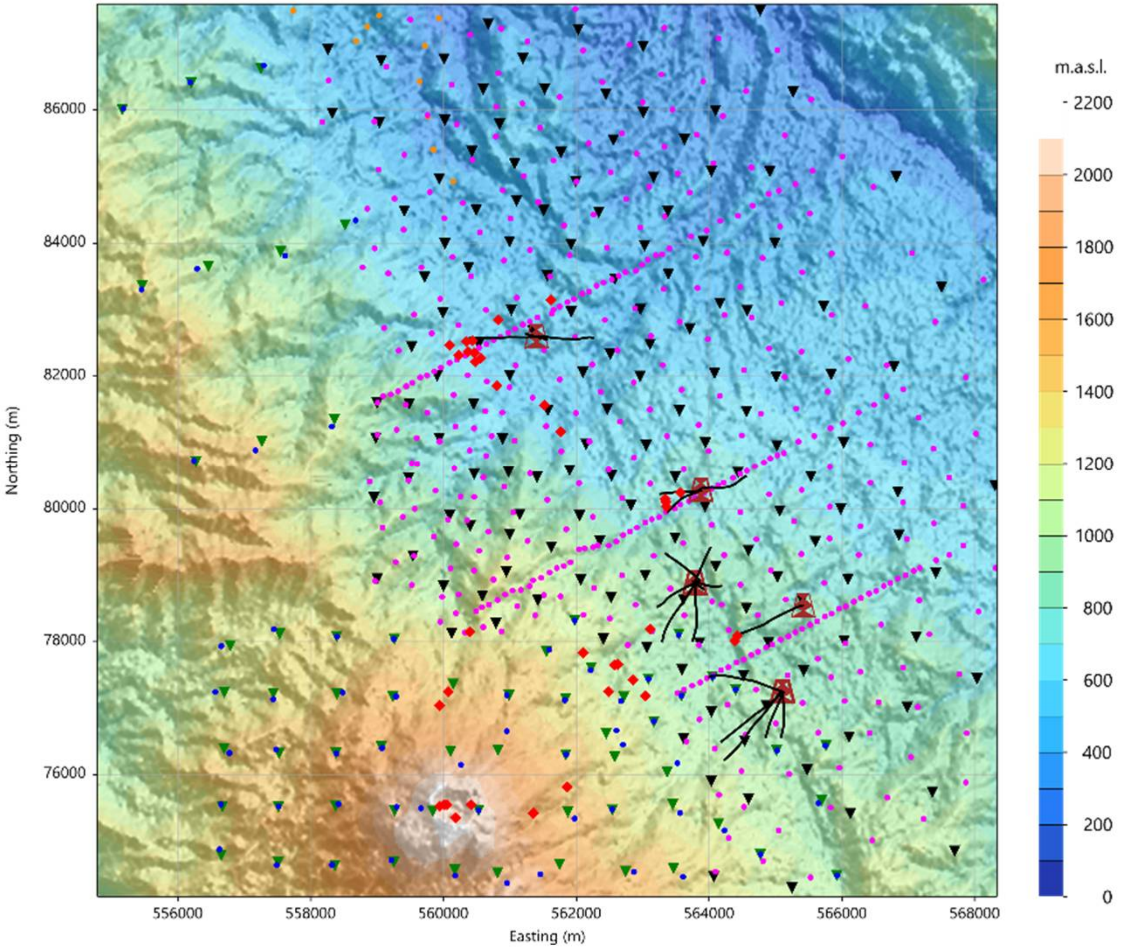


color: density.

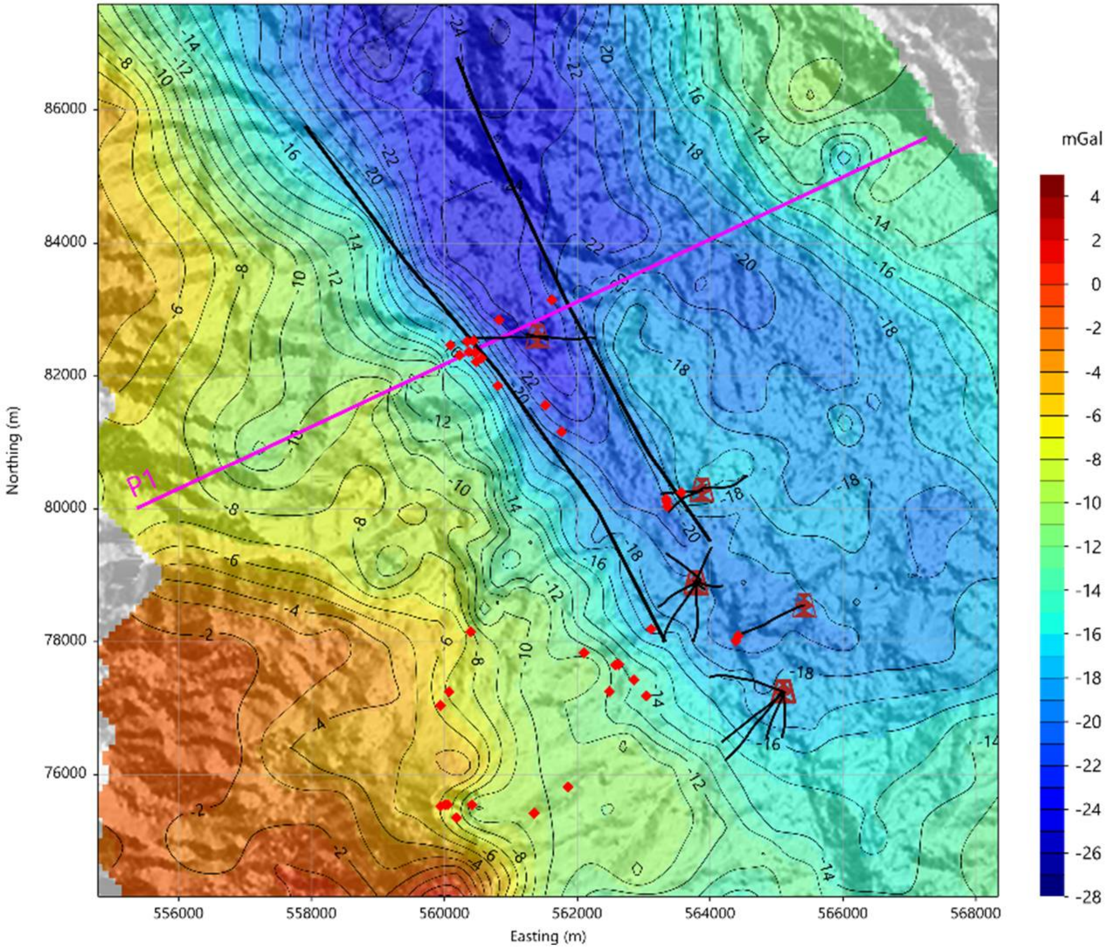
top contours: corresponding resistivity model
bottom contours: true density model

Real Data Case: Sorik Marapi, Sumatra: MT+Gravity, Faults

Topography



Bouguer Gravity

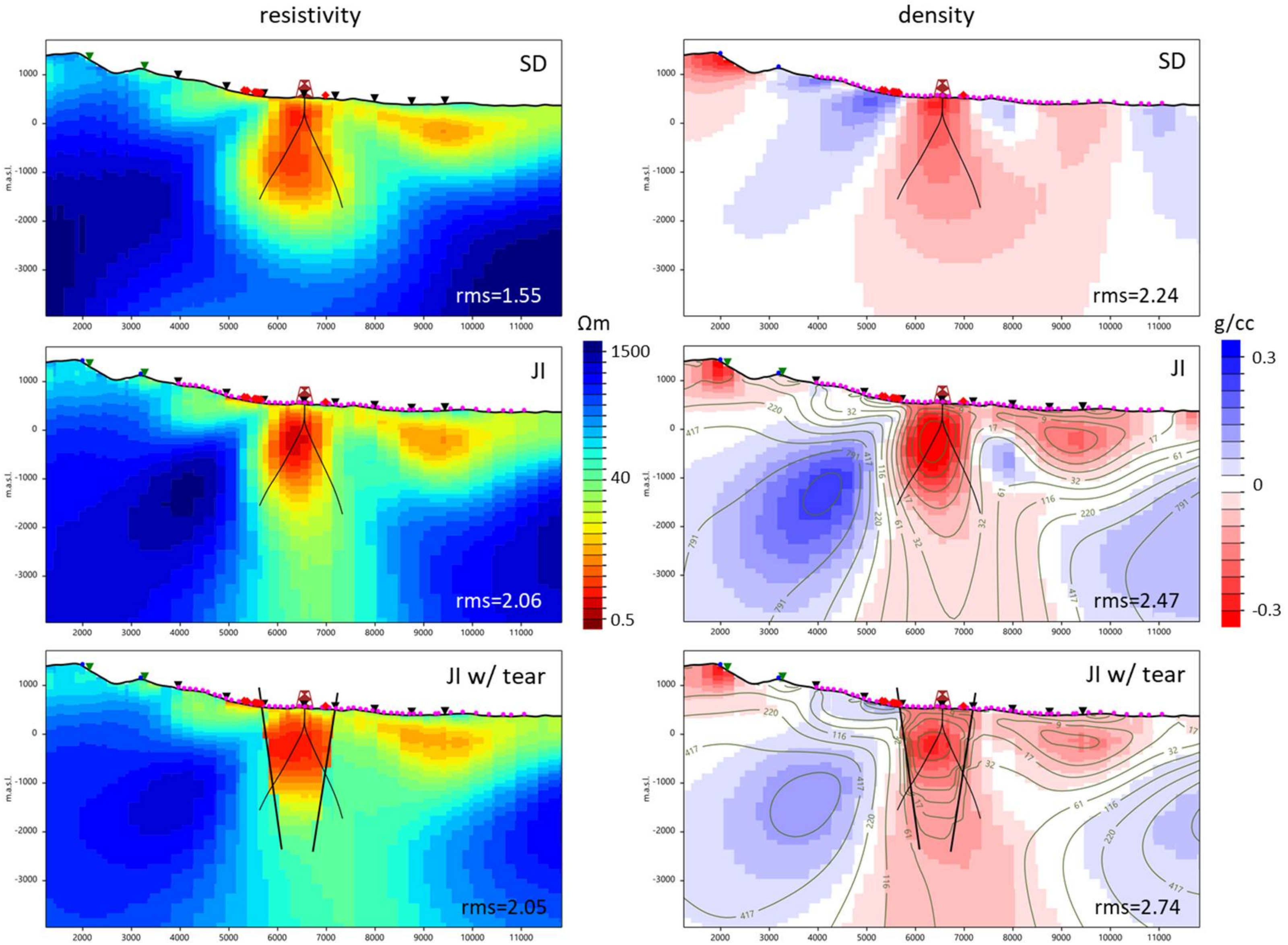


Sorik Marapi – MT+Gravity Inversions

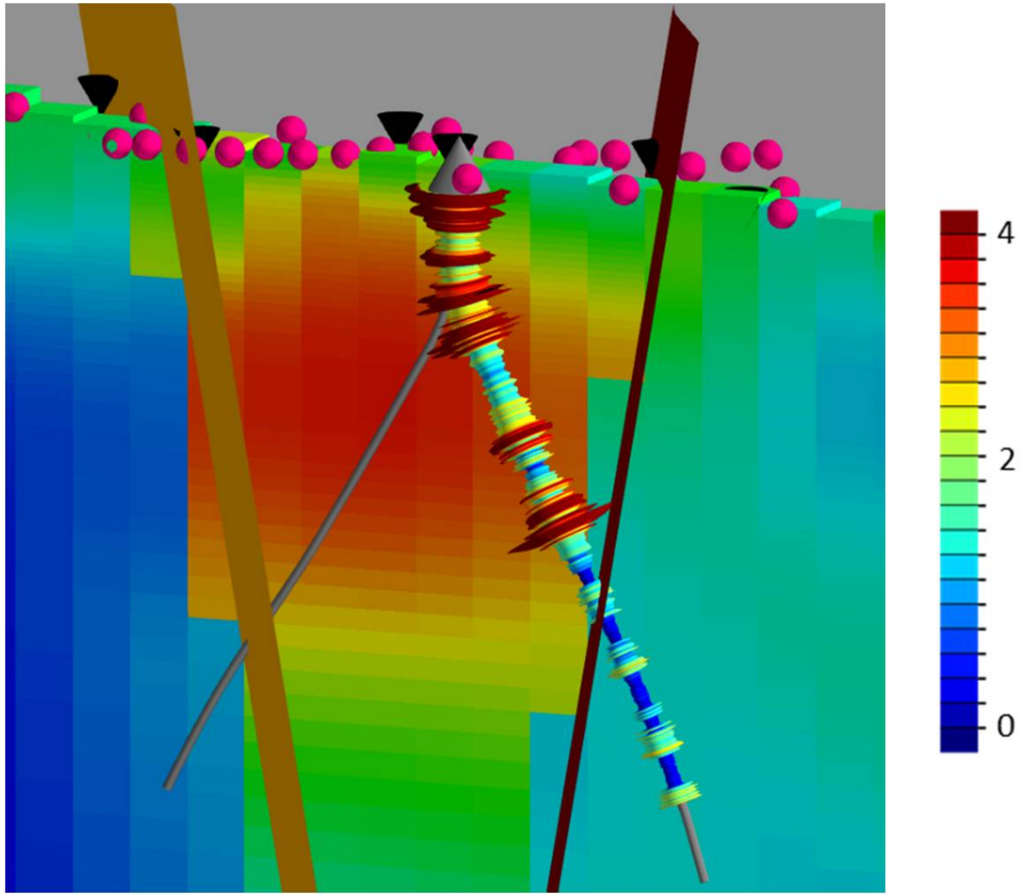
Single domain inversions

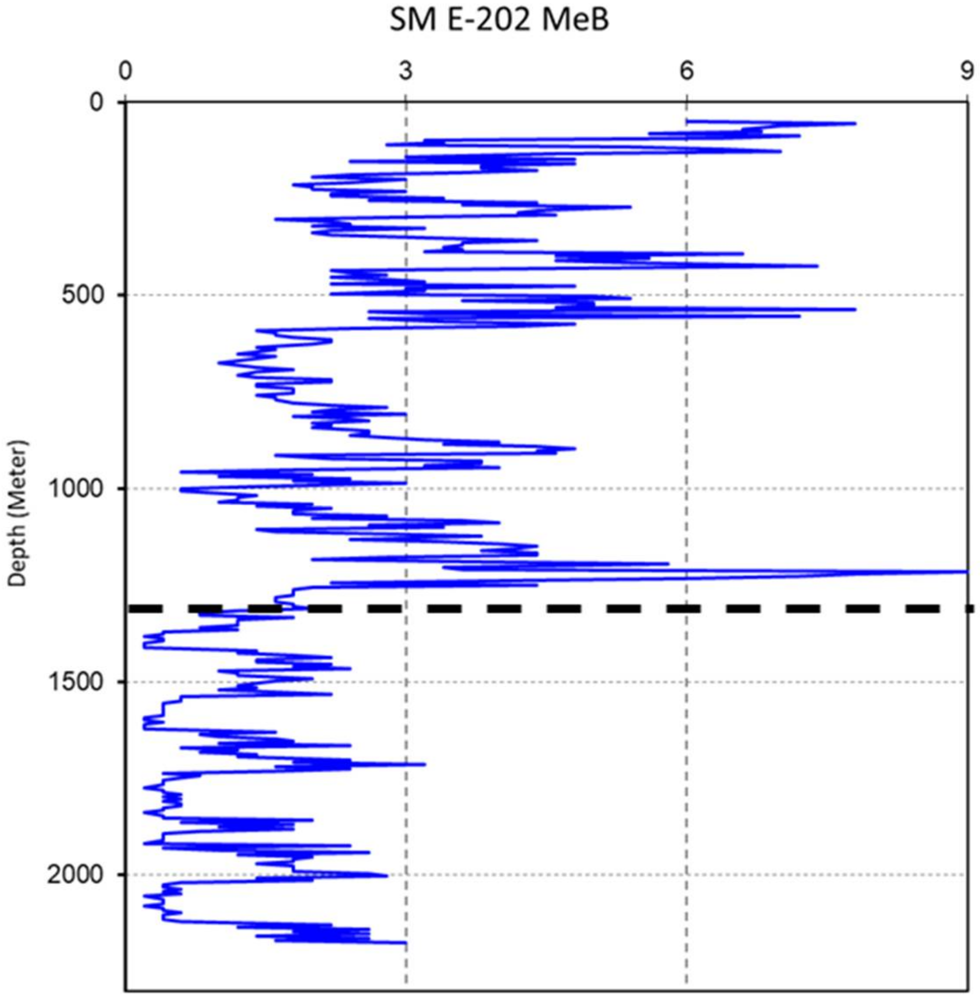
Joint MT+Gravity with X-gradient

Joint MT+Gravity with X-gradient **and fault tears**



3D JI Resistivity vs. Methylene Blue Well Cuttings





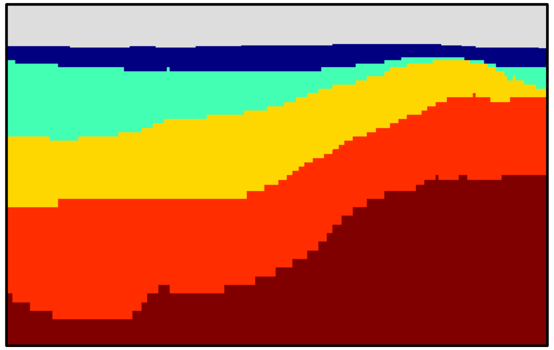
SEISMIC IMAGE-GUIDED INVERSION WITH STRUCTURE TENSOR

Example from O&G

Using seismic data to constrain EM inversions

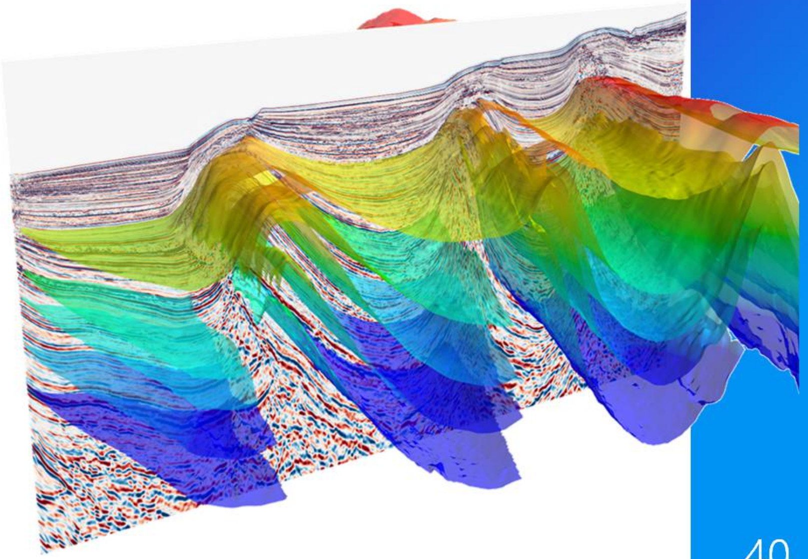
Typical workflows for constrained 3D inversion use seismic horizons

- A priori models with values between interfaces
- Tear surfaces to impose sharp discontinuities



Problems:

- Complex structures result in multi-Z surfaces, which make model building very hard
- Requires interpretation of rock units to assign *a priori* values between interfaces
- May result in too strong a constraint if used as tear surfaces
- Potential inconsistency of interpreted horizons with seismic data



Using seismic data to constrain EM inversions

- Use a 3D migrated seismic image directly
- Skip interpretation of horizons and units
- Cross-gradients regularization promotes consistency between EM image and seismic image
- We need to solve the problem of scale:
  - Typical Seismic: 6.25 - 12.5m horizontal, 2-4m vertical
  - Typical EM values: 250m horizontal, 10 to 100m vertical

Solving the scale issue: Structure Tensor

- Fine-scale variations below the EM resolution are not relevant
- Need to "average" the gradients to extract a **representative direction** at the scale of the EM model
- Robust estimator of local direction: **Structure Tensor**

$$S = \begin{bmatrix} \sum I_x^2 & \sum I_x I_y & \sum I_x I_z \\ \sum I_y I_x & \sum I_y^2 & \sum I_y I_z \\ \sum I_z I_x & \sum I_z I_y & \sum I_z^2 \end{bmatrix}$$

Image gradients (first difference)

Summation window

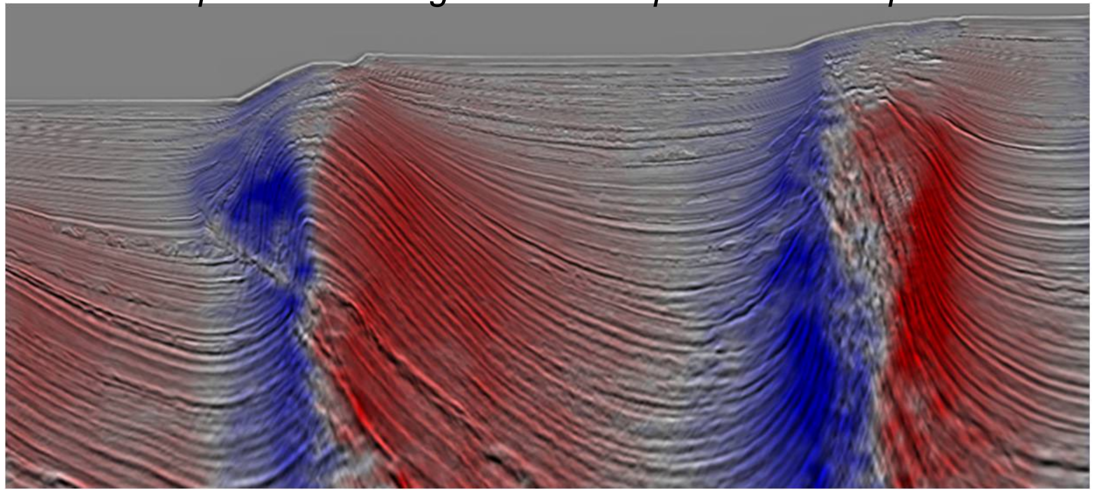
- The eigenvectors of this tensor represent the **principal directions**

Seismic image-guided inversion

- Instead of using cross-gradients against a model, we feed the **gradient field** that we just derived from structure-tensors

$$\Phi(\mathbf{m}) = \left\|\left(\mathbf{d} - \mathbf{f}(\mathbf{m})\right)\right\|^2 + \beta \int_V \|\nabla\mathbf{m} \times \nabla\mathbf{m}_{\mathrm{SEIS}}\|^2 dV$$

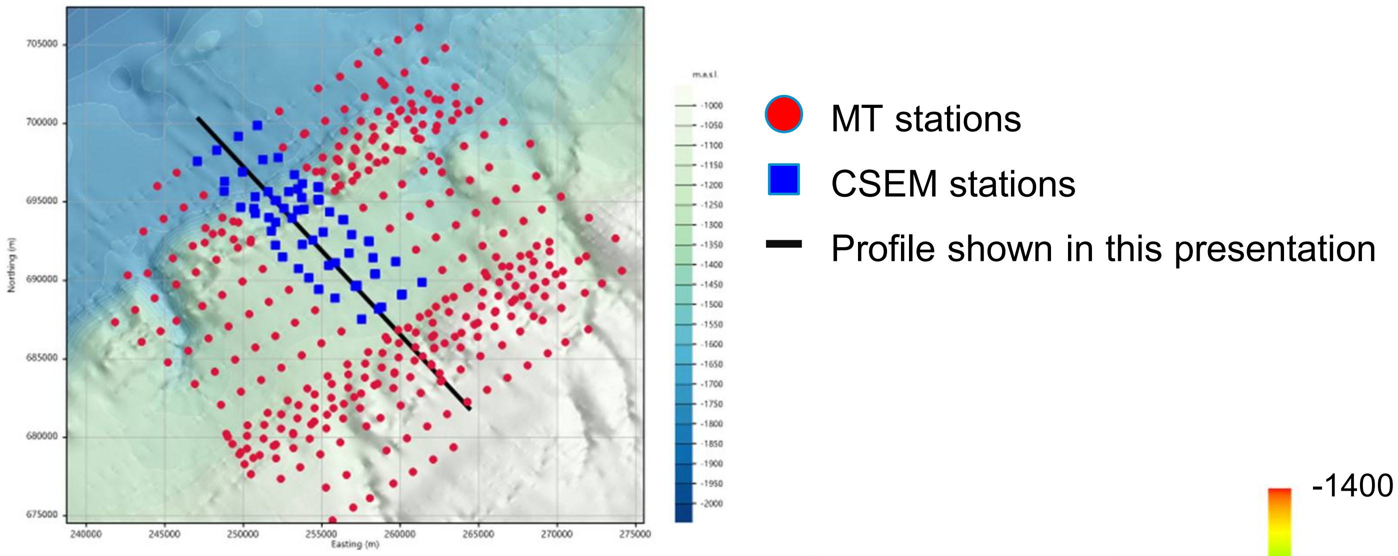
Component of the gradient field parallel to the plane

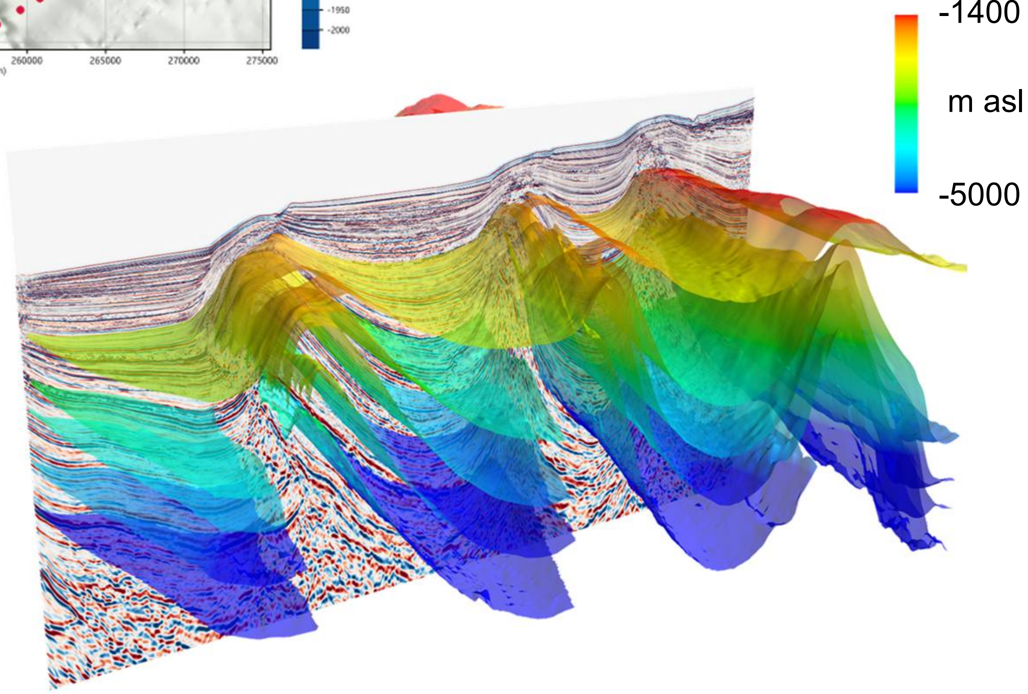


Since the gradients are fixed throughout the inversion, the operator is linear

Application to field data from fold-thrust belt (Sabah)

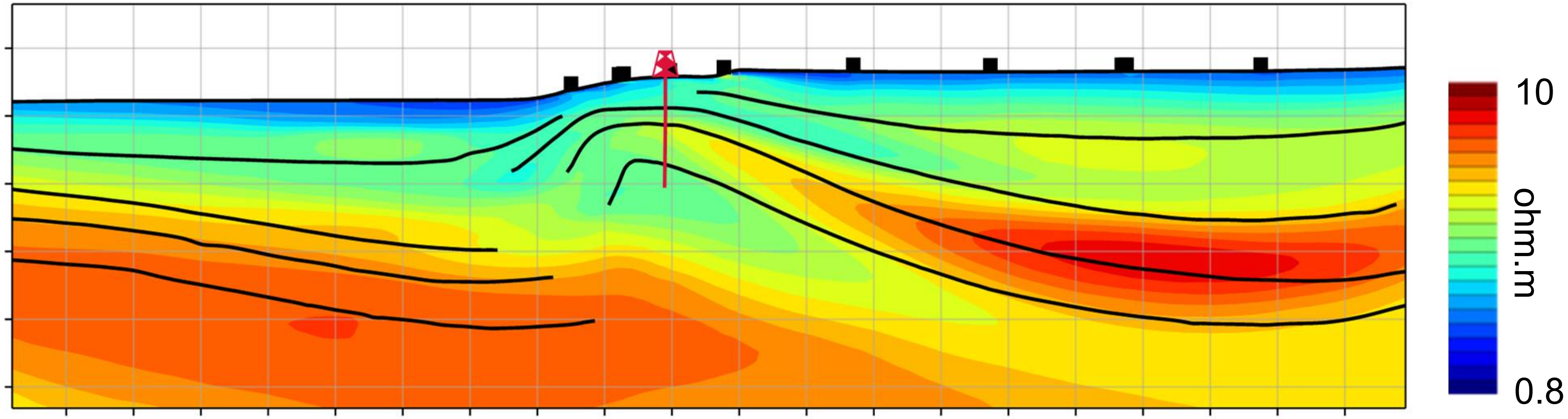
- CSEM
  - 63 sites, 26 towlines (subset used for this test)
  - Valid offset to about 12 km
  - Ex + Ey, 0.125 Hz to 2.5 Hz
- MT
  - 398 sites
  - Good quality data between 1 and 1000 s
- Seismic:
  - Velocity modeling: Refraction + Reflection FWI
  - Migration: TTI KPSDM
  - Horizontal sampling: 12.5 m x 9.375 m
  - Vertical sampling: 3 m



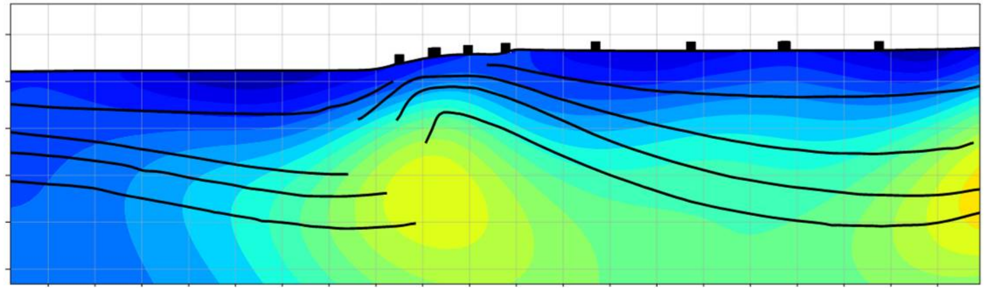


Application: Fold-thrust belt (offshore Borneo)

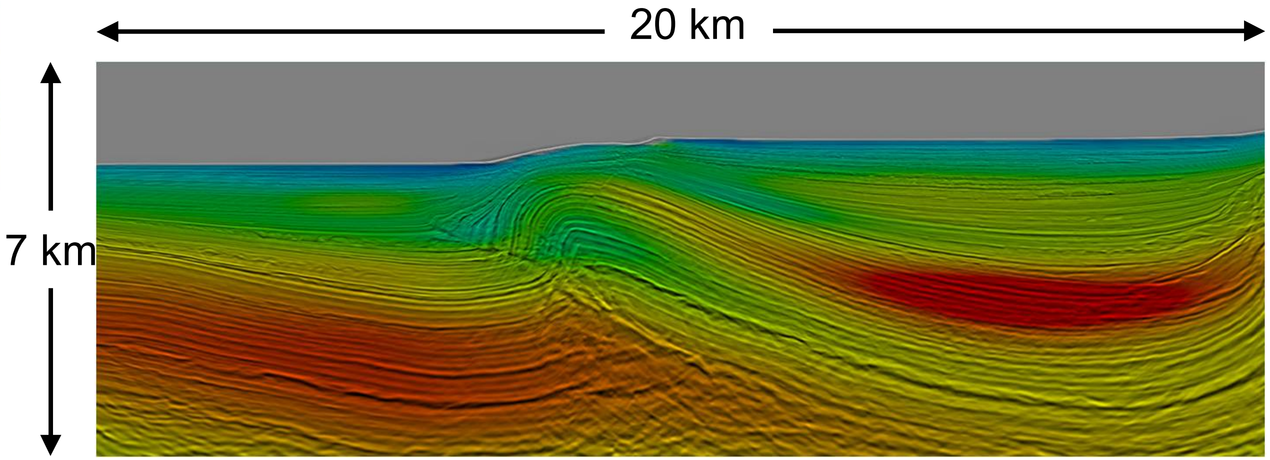
PETRONAS



Horizons displayed, but not used in inversion



Unconstrained MT inversion



Seismic and resistivity co-rendering

Mackie et al (2020 Interpretation)

Conclusions

- We should always include as much data as possible into our inversions.
- Adding different types of data can improve resolution.
- Geological data should also be included, such as geology strikes/dip, faults, horizons.

- ***Goal:*** assimilate all available data into one geologically consistent and reasonable model.

Geologically consistent inversion of geophysical data: a role for joint inversion

Thank You