pyGIMLi

Geophysical Inversion & Modelling Library

Combining near-surface geophysical data with the open-source library pyGIMLi

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Our plan for today

Time	Session	Lead
09:00-10:30	1. Introduction	F. Wagner
10:30-11:00	*Break*	
11:00-12:30	2. Advanced inversion	N. Menzel
12:30-13:30	*Lunch*	
13:30-15:00	3. Joint inversion	A. Jaron
15:00-15:30	*Break*	
15:30-17:00	4. Additional topics & assisted data processing	

Note

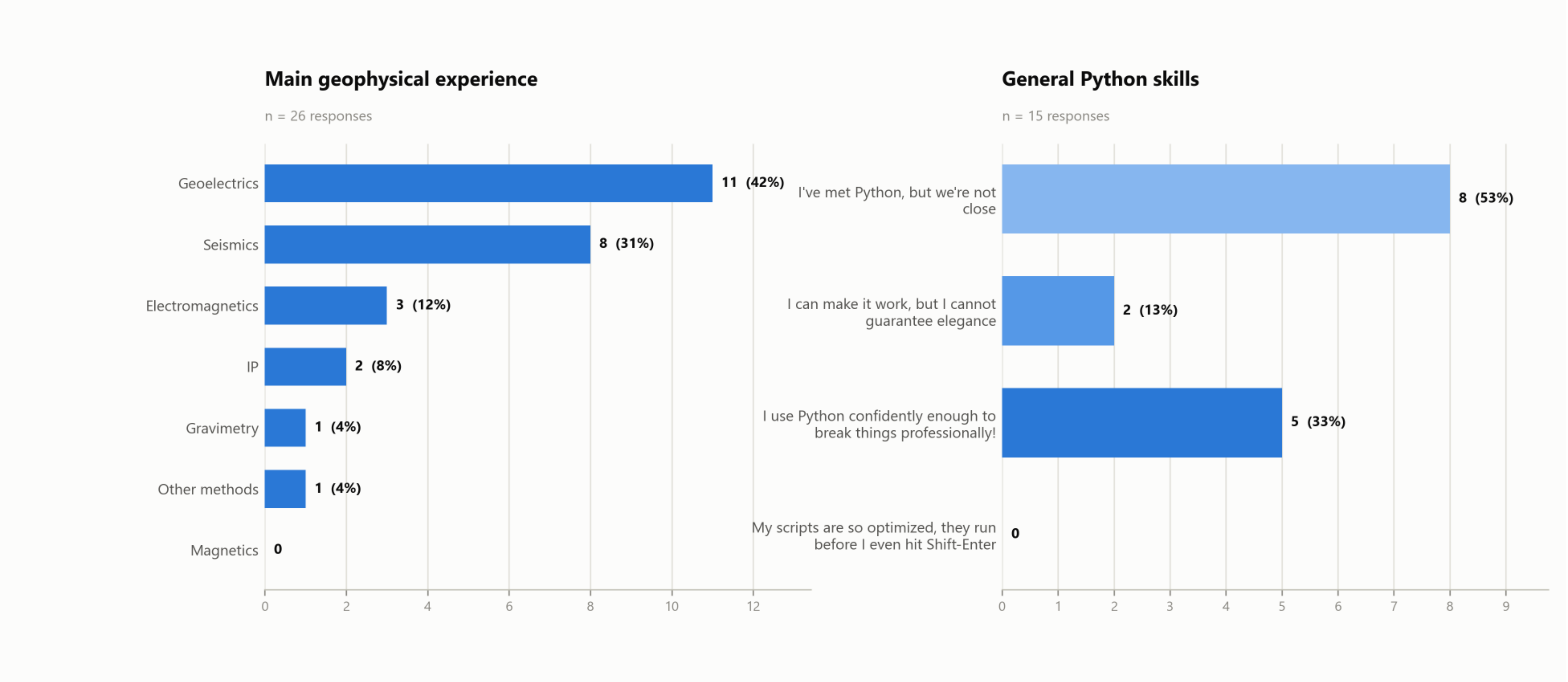
Feel free to ask questions at any time during the workshop. We will also have a Q&A session at the end of each part of the workshop.

Interactive slides available here

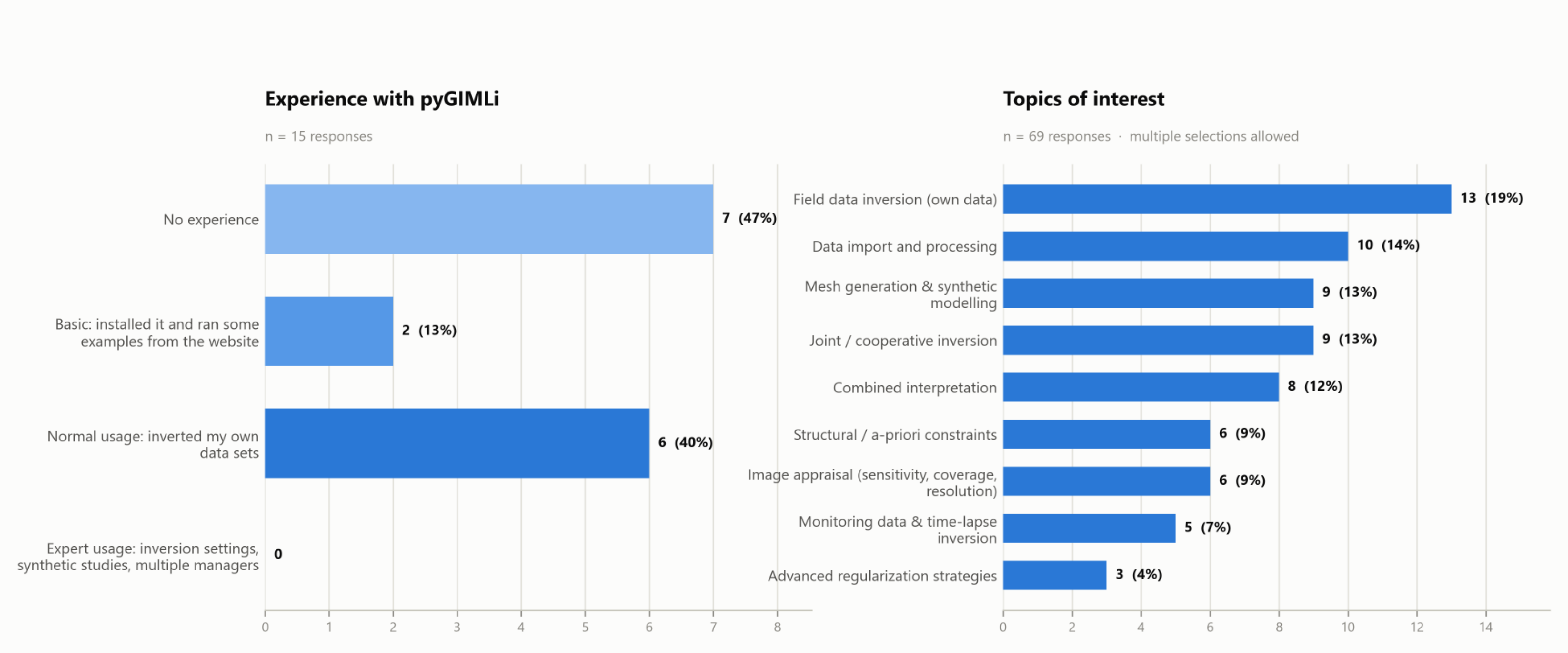
Code & slides here:

https://nsg26.pygimli.org

Survey evaluation

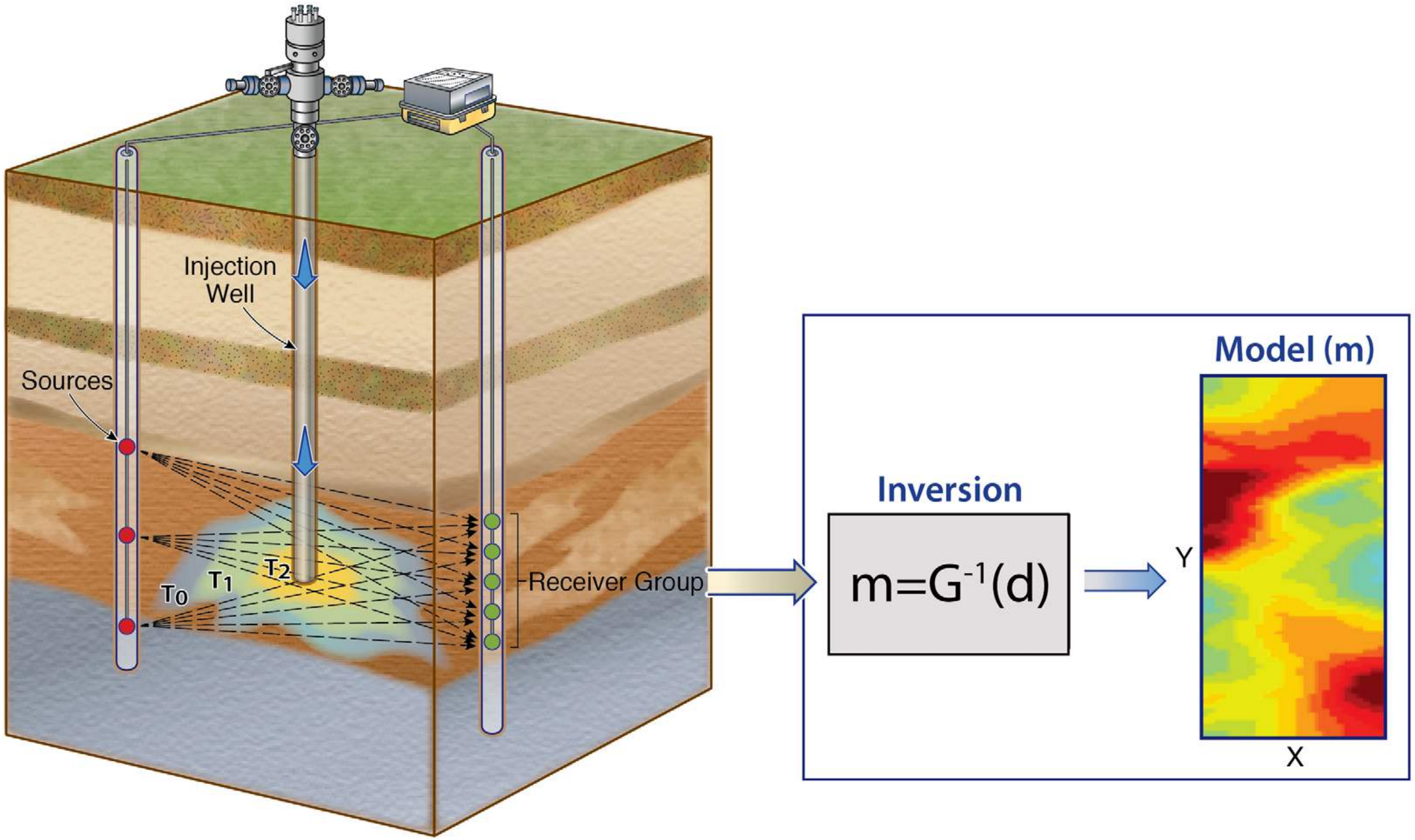


Survey evaluation



Introduction

Geophysical monitoring of subsurface processes

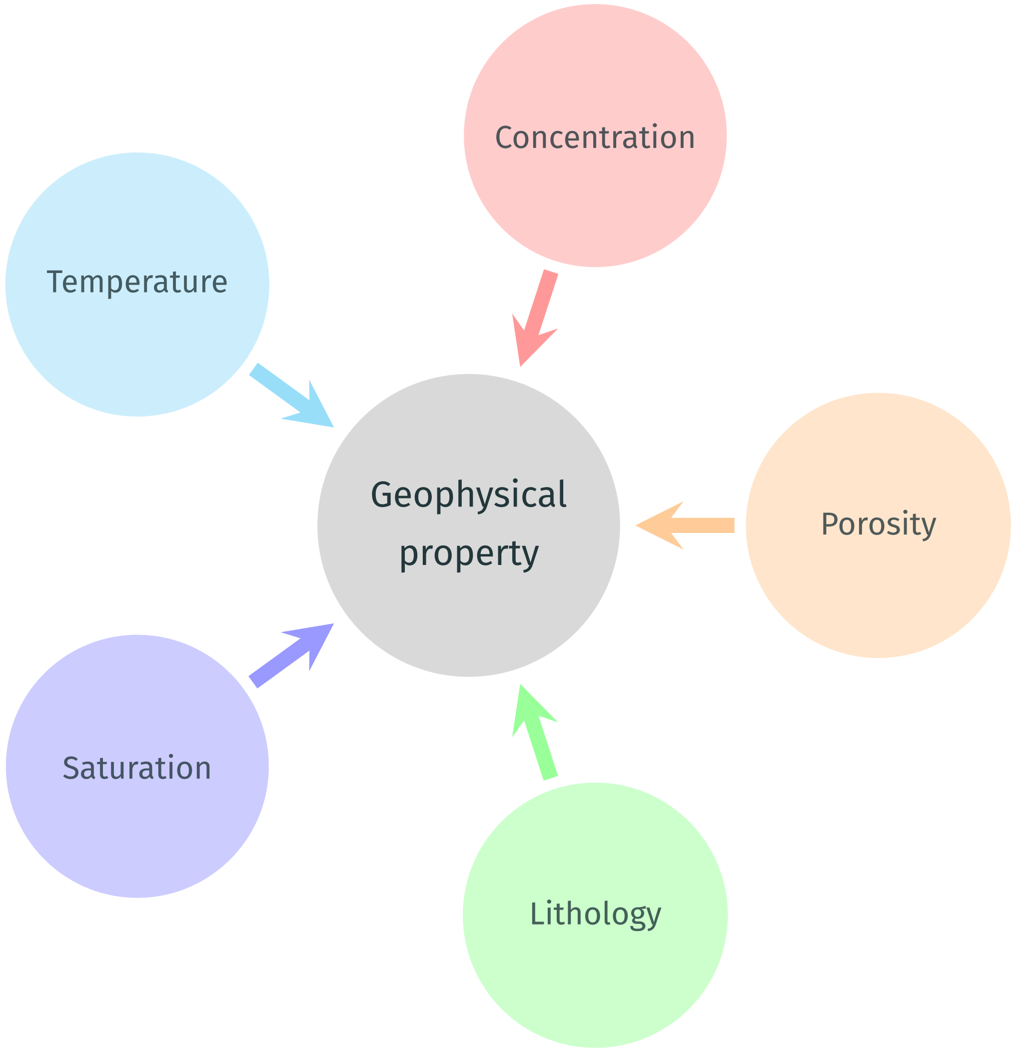


Binley et al. (2015)

Quantitative imaging and monitoring is challenging

Understanding subsurface processes is difficult due to:

- strong **heterogeneity** on different spatial scales
- highly **dynamic behavior** at different temporal scales, including critical transitions
- manifold **process couplings** and feedbacks involving, e.g., pedosphere, hydrosphere, cryosphere, biosphere

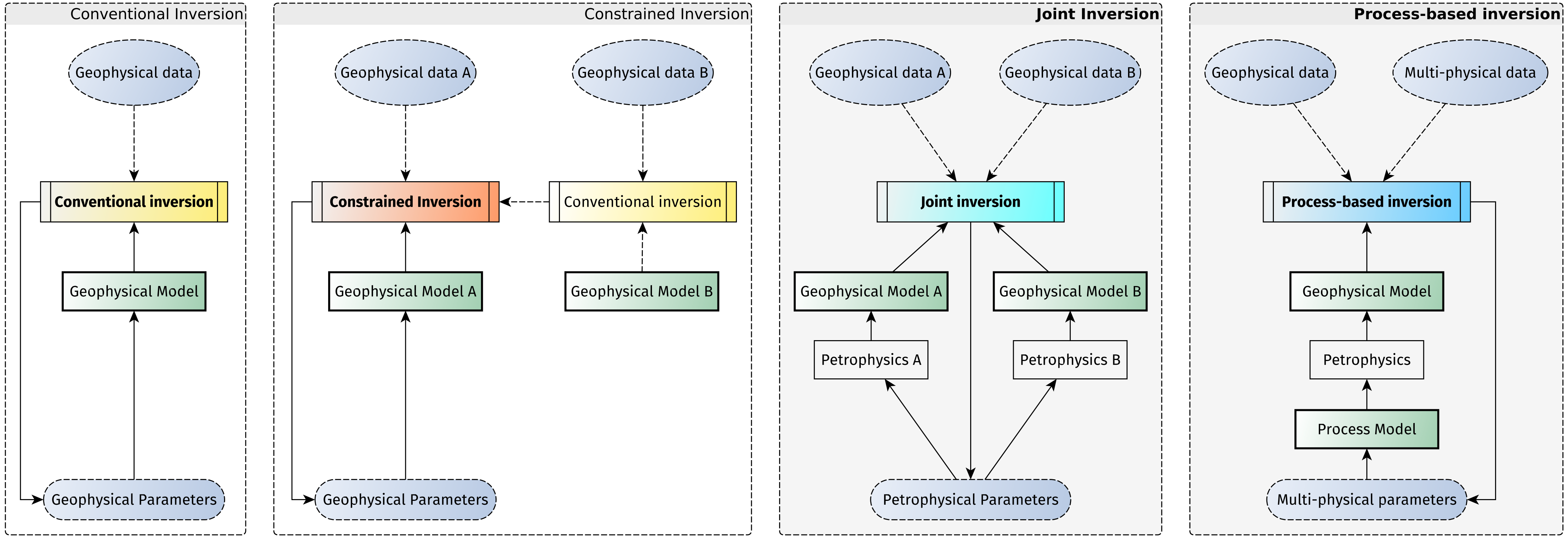


Quantitative information from geophysical images is promising, yet challenged by:

- inherent **petrophysical ambiguities**
- **limited sensitivity** and resolution

→ **requires integration of different complementary methods**

The evolution of geophysical imaging for subsurface characterization

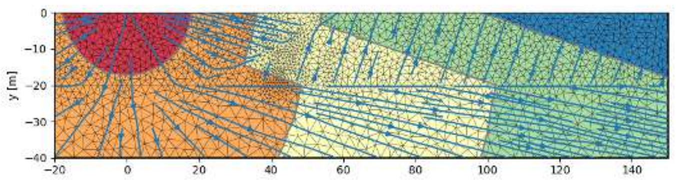


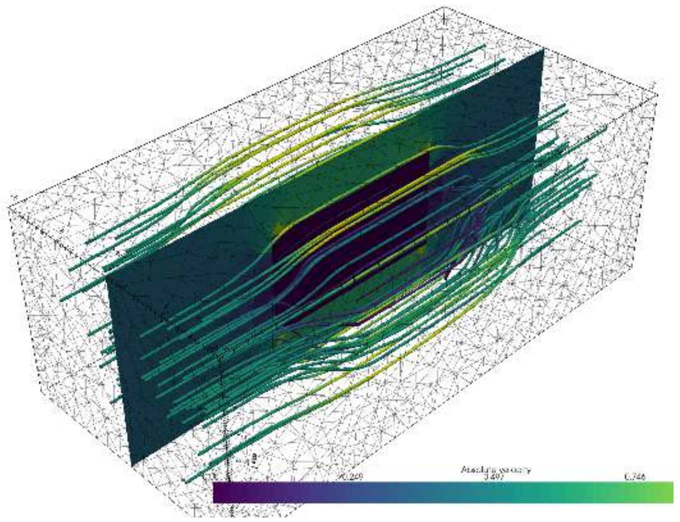
–> model coupling is challenging and requires versatile open-source software

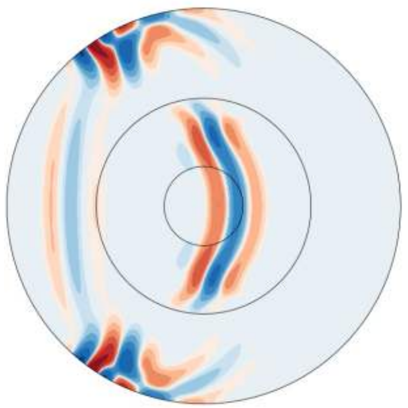
(Wagner & Uhlemann, 2021)

pyGIMLi is a versatile open-source toolbox with:

- management tools for **structured and unstructured meshes** in 2D & 3D
- computationally efficient **finite-element and finite-volume solvers**
- **various geophysical forward operators**: ERT/IP, Traveltime, Gravimetry, Magnetics, SP, EM
- frameworks for **constrained, joint and process-based inversions** with **region-specific regularization**
- **open-source, platform compatible**, documented & tested code
- suitability for **teaching & reproducible research**
- v1.0 published in *Computers and Geosciences* (Rücker et al., 2017) (among 5 *Most Downloaded* papers and > 700 citations) and broadly used since
- **Website and documentation:** https://pygimli.org







Implemented geophysical methods

All available in `pygimli.physics`:

Method	Forward	Inverse	Dimension
EM	✓	✓	*1D*
ERT	✓	✓	*2D, 3D, 4D*
Gravimetry	✓	✓	*2D, 3D*
Magnetics	✓	✓	*2D, 3D*
Petrophysics	✓	✓	*dimensionless*
Seismics	✓	-	2D
SIP	✓	✓	*1D, 2D, 3D*
sNMR	✓	✓	*1D*
Traveltime	✓	✓	*2D, (3D)*
VES	✓	✓	*1D*

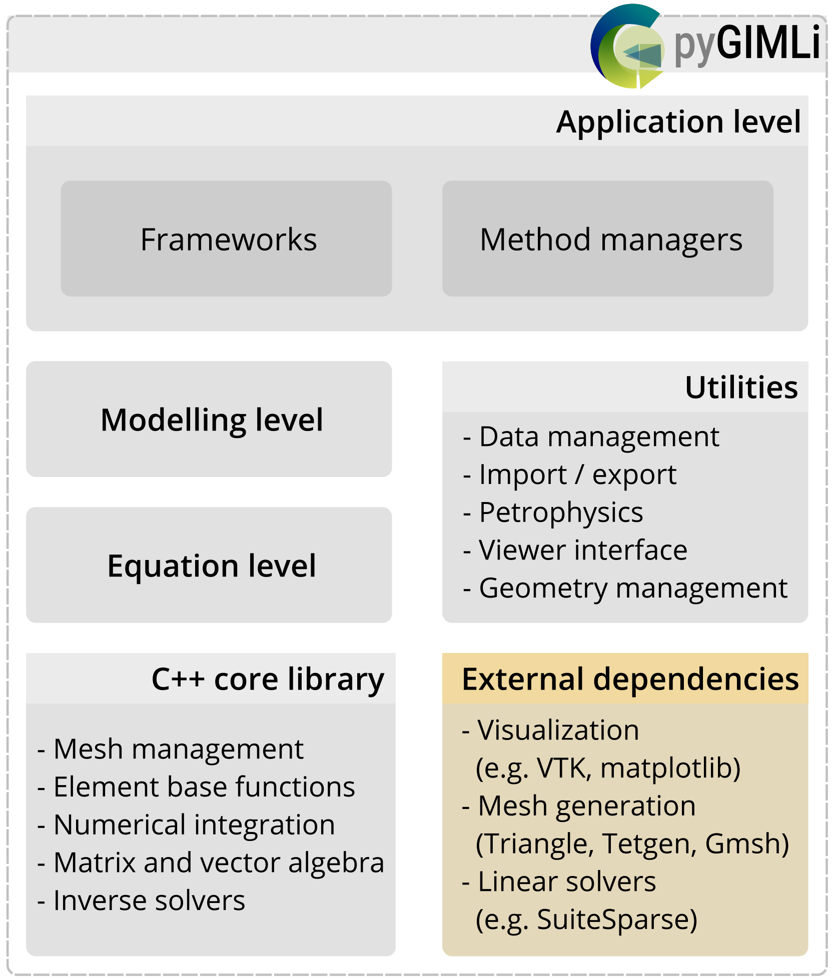
Software design

pyGIMLi is organized in three different abstraction levels:

Application level | Modelling level | Equation level

In the application level, ready-to-use method managers and frameworks are provided.

```
from pygimli.physics import ert
mgr = ert.ERTManager("mydata.dat")
mgr.showData()
mgr.invert(lam=50)
mgr.showResult()
```



Rücker et al. (2017)

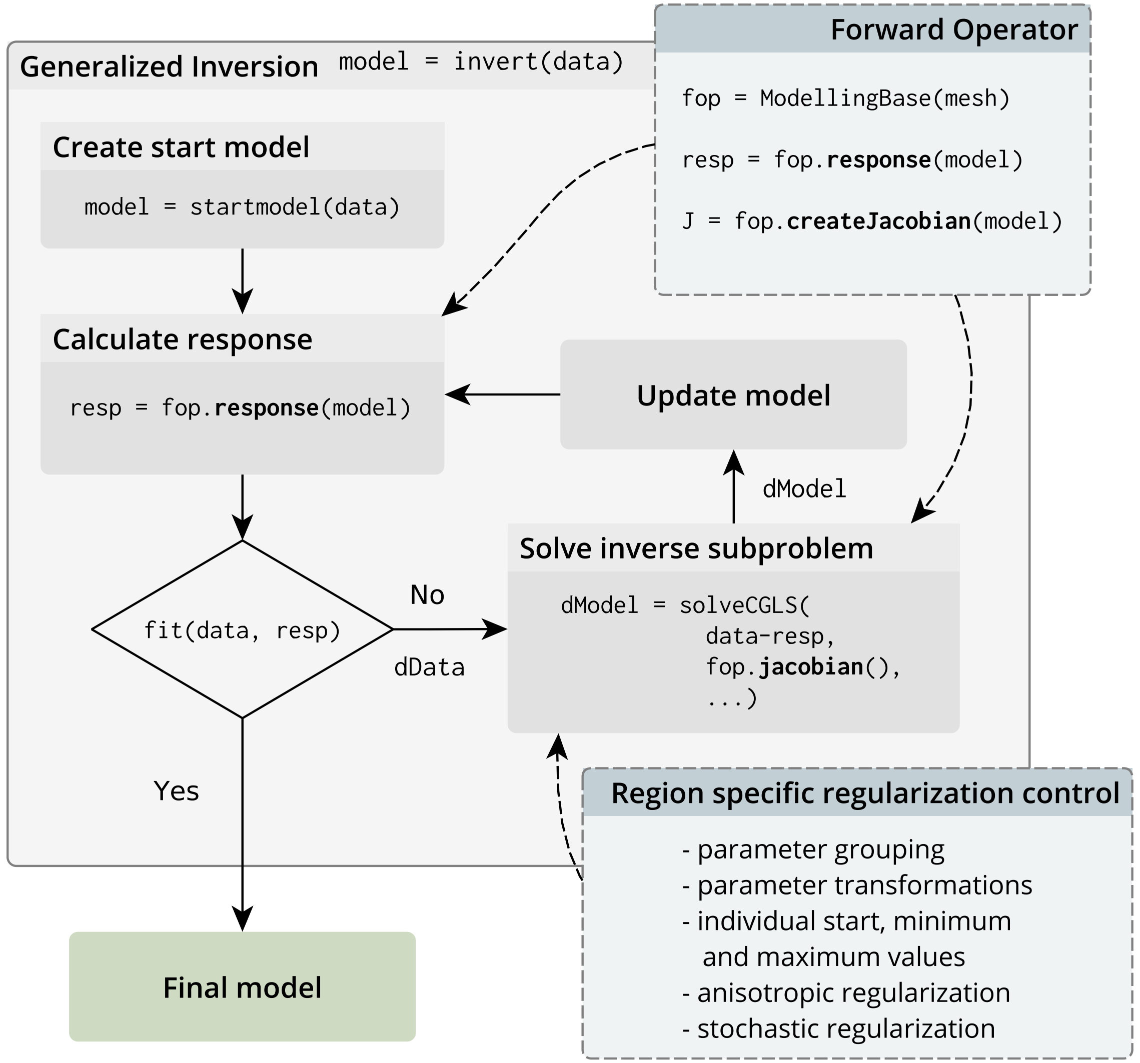
Basic inversion framework

The default inversion framework is based on the generalized Gauss-Newton method and is compatible with any given forward operator and thus applicable to various physical problems.

$$\|\mathbf{W}_d(\mathbf{F}(\mathbf{m}) - \mathbf{d})\|_2^2 + \lambda \|\mathbf{W}_m(\mathbf{m} - \mathbf{m}_0)\|_2^2 \rightarrow \min$$

Note

The inversion is physics-independent and very flexible in terms of adding prior information, regularization and integrating different geophysical methods.



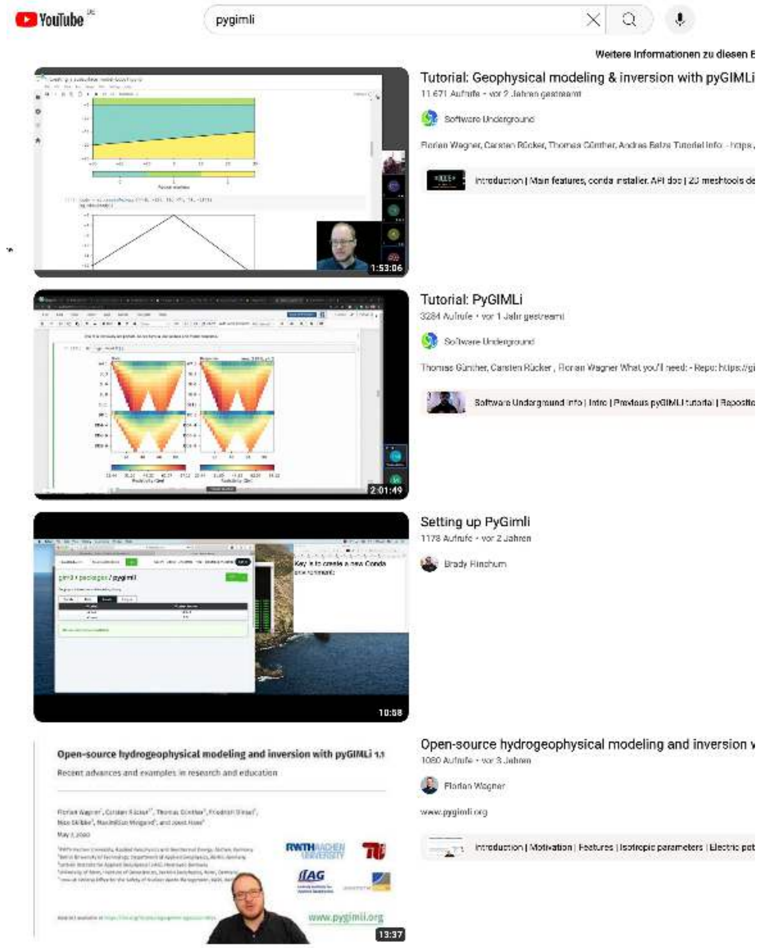
Rücker et al. (2017)

Recent developments in pyGIMLi

- **Improved 3D visualization** powered by pyvista (including filters, slices and interactive notebook compatibility)
- **3D gravity and (full-tensor) magnetics** operators and managers
- `LSQRinversion` framework enabling additional parameter relations (from Wagner et al., 2019)
- `MultiFrameModelling` framework for temporally/spectrally/spatially constrained inversion
- `TimelapseERT` class with different strategies, e.g. **4D inversion**
- **New examples** on ERT (2D/3D crosshole, 3D surface, timelapse), IP, 3D magnetics
- **Improved website** and new user-guide
- enabled `pip install pygimli` for easier installation (e.g. on Google Colab)
- fully **complex-valued** (FD) ERT-IP inversion (also for TD)
- Structurally-coupled cooperative (SCCI) inversion framework

Existing tutorials

- Transform 2021: creating **geometries & meshes**, **modeling** PDEs, **synthetic data**, **inversion** (also with **external forward operator**).
- Transform 2022: fundamental `pyGIMLi` objects (`Mesh`, `DataContainer`, matrix types, etc.), **geostatistical** vs. smoothness regularization, treatment of subsurface **regions**, adding **prior data**.
- SEG webinar 2024: invert **real-life 3D data** (Hübner et al., 2017) to tweak your **inversion beyond the standard** practice.
- GELMON 2025: ERT time-lapse data processing and inversion + image appraisal
- Today we focus on **combining near-surface geophysical data** for joint interpretation and inversion.



Join the pyGIMLi user community!

> "In open source, we feel strongly that to really **do something well**, you have to get a lot of people involved."
>
> – *Linus Torvalds*

1. **Join the `#pyGIMLi` chat** on Mattermost!
2. **Open a discussion** or **raise an issue** on GitHub.
3. **Contribute to the website** via the "Improve this page" button in the right sidebar.
4. **Add your** pyGIMLi-powered **publication** to this database.
5. **Send your example** to mail@pygimli.org.
6. **Contribute to the code** as described in our contribution guidelines.

A typical ERT workflow

Everything is exposed through

```
import pygimli.physics.ert as ert
```

and the high-level `ert.ERTManager` class — but every step can also be customized at the modelling or equation level.

1. **Survey design** — electrode geometry & measurement scheme
2. **Forward modelling** — predict data from a resistivity model
3. **Loading and inspecting data** — apparent-resistivity pseudosections
4. **Quality control** — filter unreliable measurements
5. **Error model** — weights that enter the inversion
6. **Mesh generation** — discretize the parameter domain
7. **Inversion** — recover the subsurface resistivity model
8. **Appraisal** — coverage, data fit, sensitivity

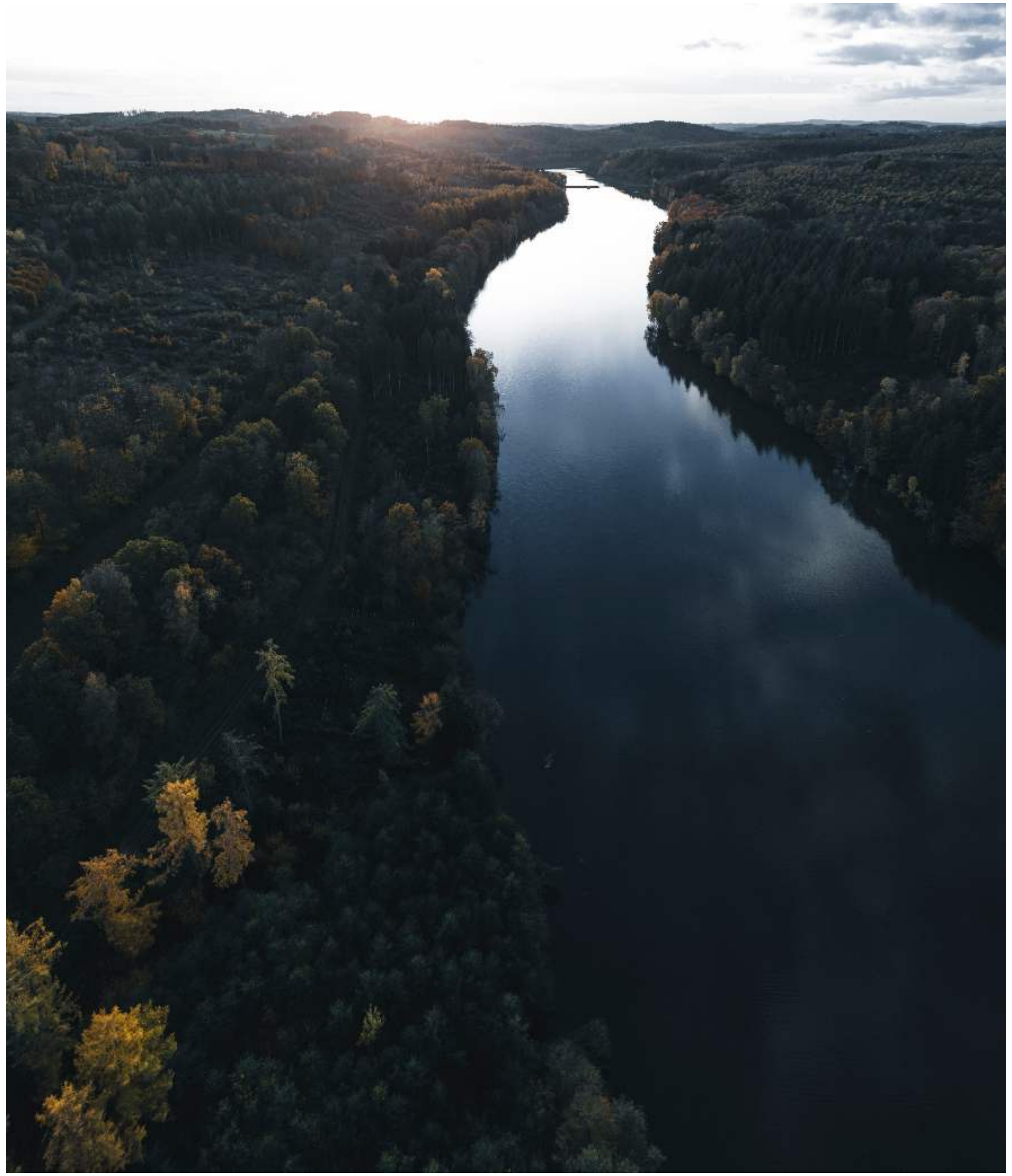
Unified data format

pyGIMLi can read various system formats, but internally the unified data format is the basis of the `DataContainer` class, which is used for all data management and processing steps.

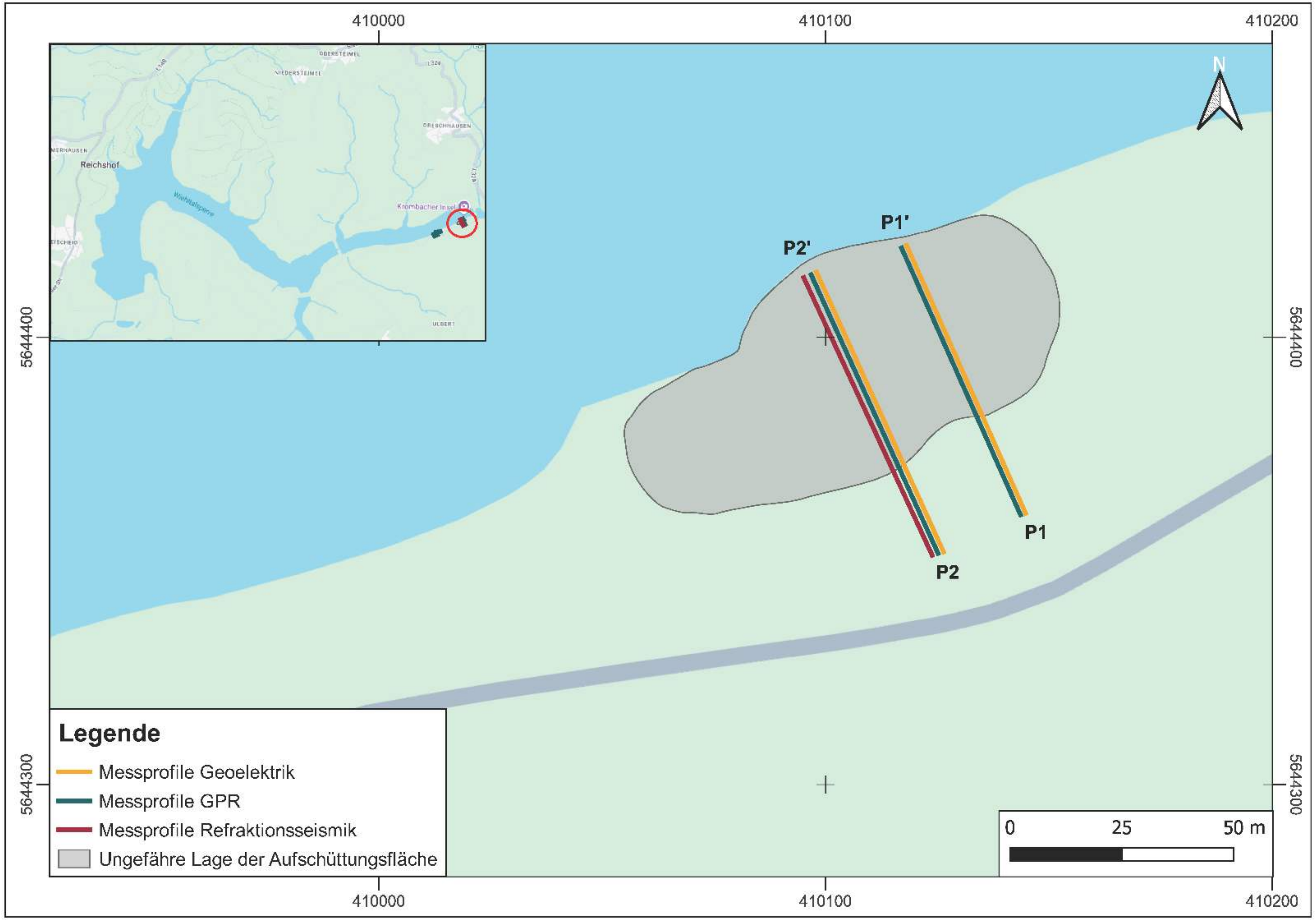
```
6 # Number of electrodes
# x z
0     0
1     0
2     0 # loose ground
3     0
4     0
5     0
6 # Number of data
# a b m n u i/mA err/%
  1   2   3   4  -0.5305165 102.2 2.4
  2   3   4   5  -0.5305165 99.9  1.4
  3   4   5   6  -0.5305165 95.6  2.6
  1   2   4   5  -0.1326291 100.1 7.6
  2   3   5   6  -0.1326291 80.2 8.6 # possibly an outlier
  1   2   5   6  -0.05305165 77.3 7.5
```

The field site - Wiehltalsperre

- Drinking water reservoir near Cologne, Germany
- Severe **drought and beetle infestation** lead to massive **forest diebacks** close to reservoir
- Geophysical surveys should help to answer questions regarding **hydrological settings in near-surface areas** at potential reforesting sites
- Can we use geophysics in combination with other soil parameter measurements to **make suggestions regarding the reforestation** of certain areas?



Quantitative imaging and monitoring is challenging



Goals of this part of the workshop

1. Get familiar with pyGIMLI's method managers for ERT and traveltime data.
2. Learn basic operations such as data import, data filtering, and topography addition.
3. Perform your first inversion using either your own field data or our provided data sets.
4. Get to know the basic image appraisal techniques.
5. Apply tools to compare and jointly interpret individual geophysical data sets.

Note

If you have pyGIMLi and Jupyter installed, please open an empty notebook.

Takeaway messages:

- We familiarized ourselves with the method managers to process and invert ERT and SRT data.
- We loaded, filtered, and inverted field data using pyGIMLi and qualitatively evaluated the results
- We applied tools that allow us to quantitatively compare and qualitatively evaluate the single inversion results, such as...
  - → 1D interpolation tools to generate synthetic geoelectrical and acoustic logs
  - → data point - wise misfit examination to identify regions of decreased model goodness.
- We implemented ways to further improve our individual inversions by penalizing individual data points with increased misfit.

Advanced inversion

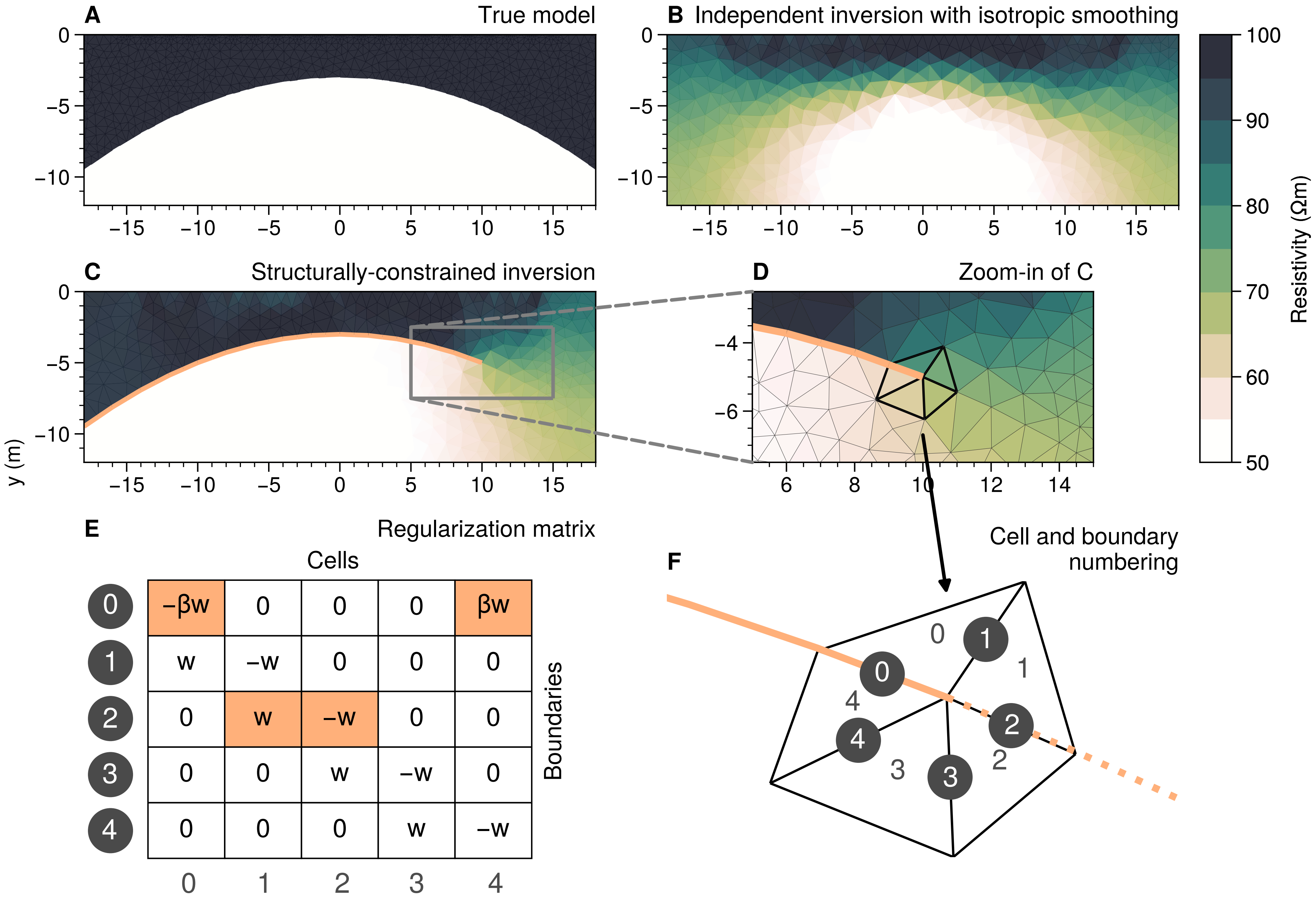
Goals of this part of the workshop

- Get to know the possibilities of **including a-priori information** as constraints into inversions.
- Incorporate **geological and structural** a-priori information into regularization.
- Incorporate reflectors visible in **GPR measurements** as constraints in ERT.
- Apply **interactive tools** to extract constraints from images or models.

Including structural information

- Structural information can be a **useful addition** to any inversion to **reduce ambiguity**.
- Goal: give **“hints”** to the inversion as to **where we expect parameter jumps / contrasts**.
- Possible sources of information:
  - → **wave methods (seismics, GPR,...)**
  - → point-wise **lithological borehole information**
  - → **geological maps** or models / cross sections
  - → ...
- Those information can be **easily integrated** into the mesh used for inversion

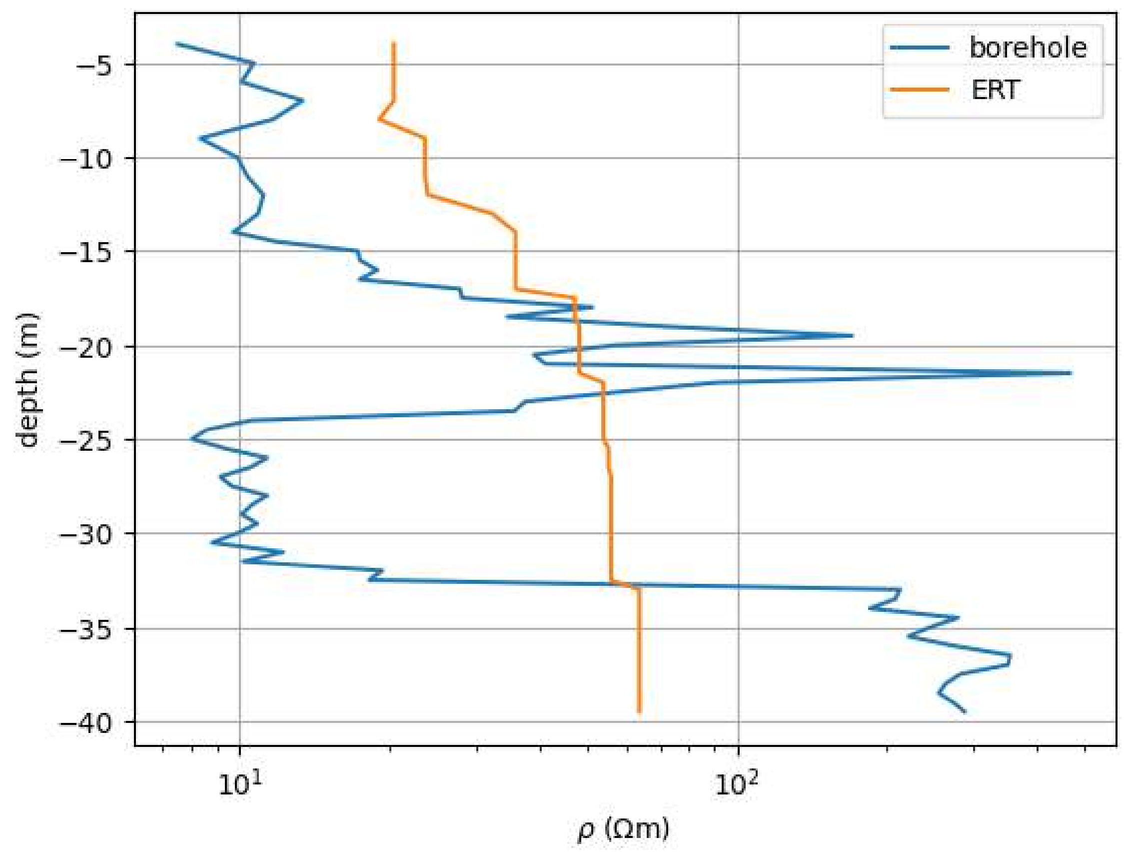
Implementation via smoothing matrix



Wagner & Uhlemann (2021)

Constraints from borehole data

- Most commonly applied constraints: including one or multiple **1D point sources** of information
- Structural / geological information or geophysical data from well logging
- In most cases, borehole data give **sharp boundaries** between lithologies that can be utilized to **constrain the inversion**
- Goal: by including borehole data, the inversion also aims at **explaining the additional information within its error bounds**, leading to an oftenmost more refined model



Geostatistical regularization

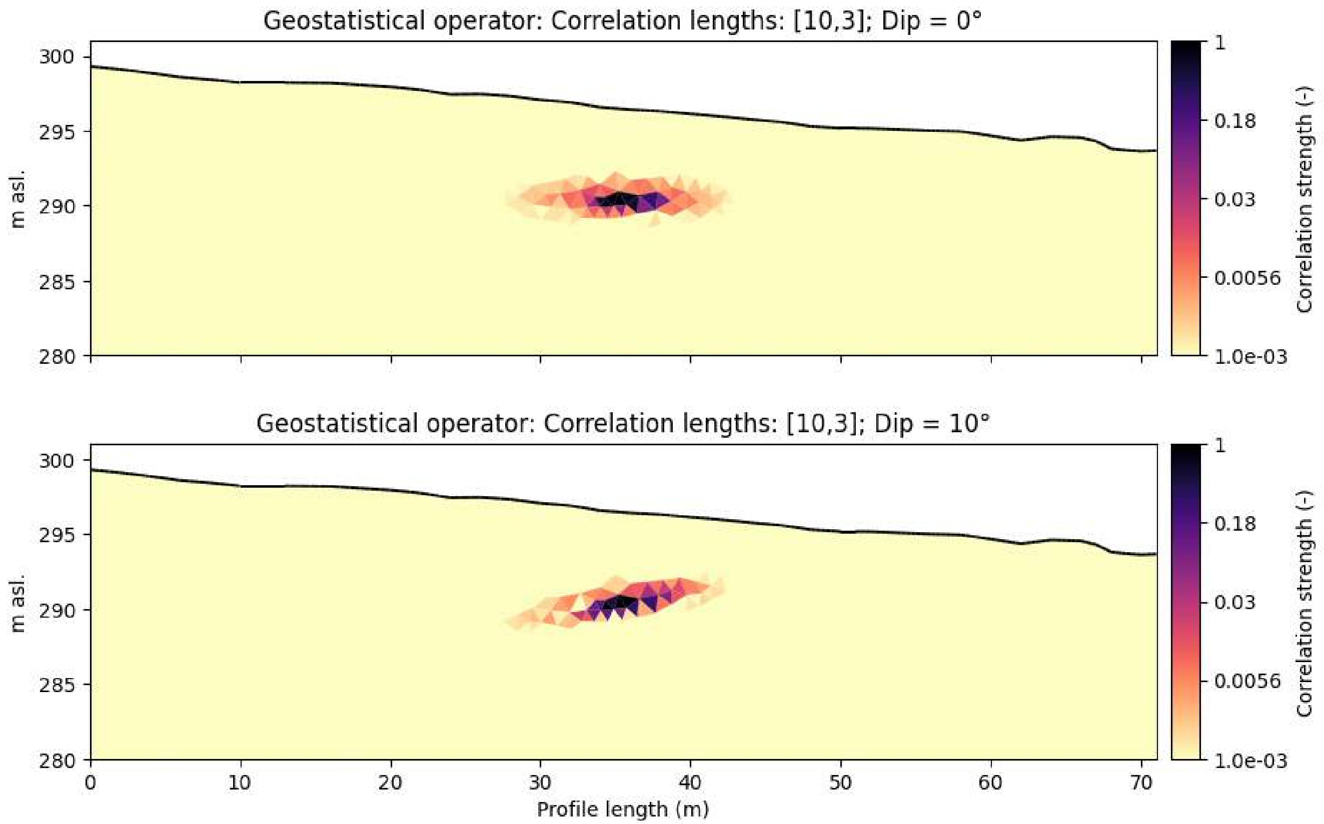
- **Alternative way to smoothness-constrained inversions** using a covariance matrix to quantify the correlation of model parameters in different cells (Jordi et al., 2018)
- Based on **geological or structural analysis**, an estimation of *i) vertical and horizontal correlation lengths, ii) the dip angle* and *iii) the strike direction* (in 3D) is included into the inversion
- The resulting **covariance matrix** is given as:

$$\mathbf{C}_{\mathrm{M,i,j}} = \sigma^2 exp\left(-3\sqrt{\left(\frac{\mathbf{H}_{\mathrm{x,i,j}}}{I_x}\right)^2 + \left(\frac{\mathbf{H}_{\mathrm{y,i,j}}}{I_y}\right)^2 + \left(\frac{\mathbf{H}_{\mathrm{z,i,j}}}{I_z}\right)^2}\right) \quad (1)$$

- Each **row** of the covariance matrix contains the **spatial correlation function for one particular cell**.
- Example notebook: `Applying geostatistical constraints`

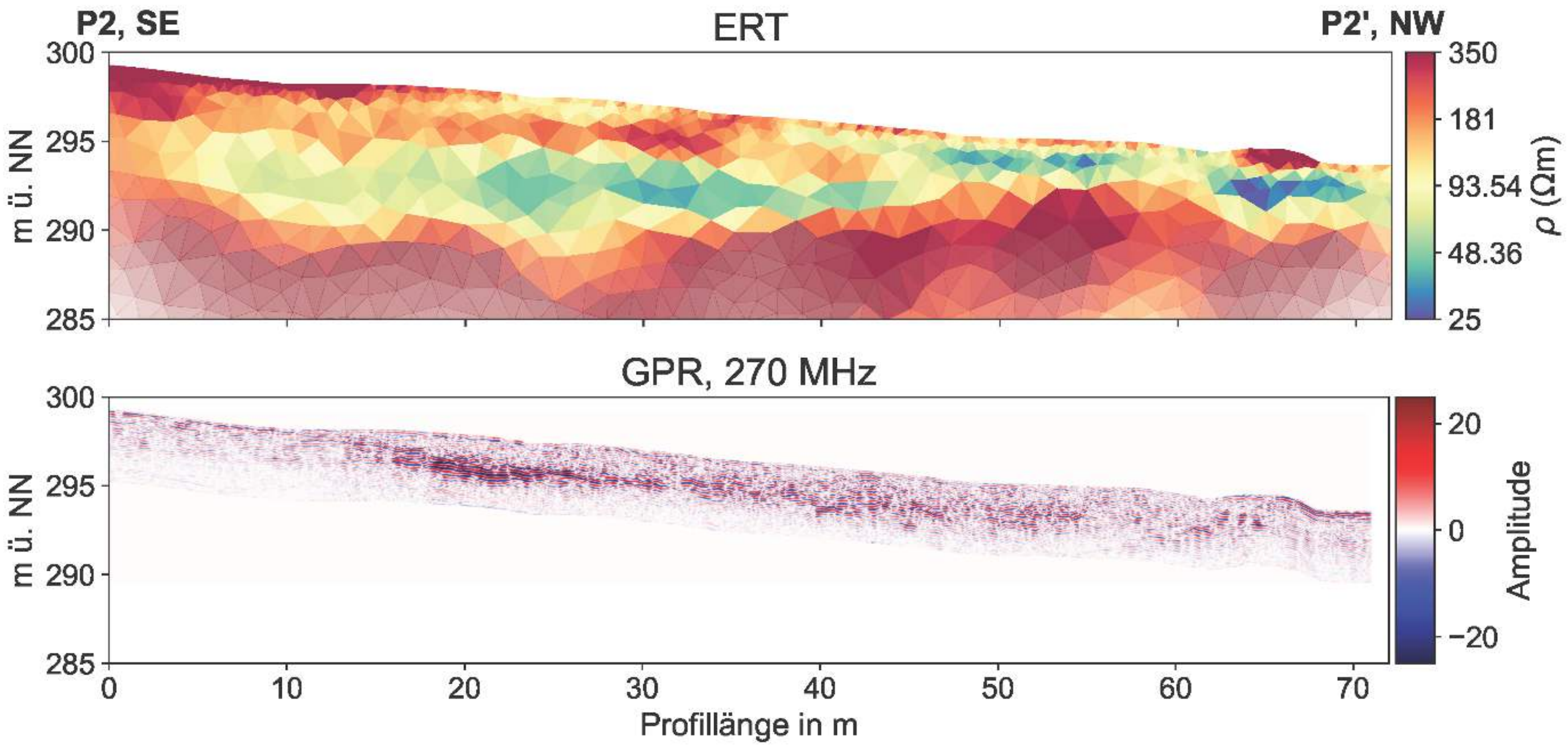
Geostatistical regularization

- **Alternative way to smoothness-constrained inversions** using a covariance matrix to quantify the correlation of model parameters in different cells (Jordi et al., 2018)
- Based on **geological or structural analysis**, an estimation of *i) vertical and horizontal correlation lengths*, *ii) the dip angle* and *iii) the strike direction* (in 3D) is included into the inversion
- The resulting **correlation for a single model cell** looks as follows:



Inversion with two-dimensional structural constraints

- Structural information can not only be derived from geological or structural information, but also from **measurements using other geophysical methods**.
- In our case: measured **GPR data** are loaded and **reflector is picked** to define a structural constraint to further refine an ERT inversion.
- Other possibilities: **1D downhole geophysical measurements**, other wave methods (reflection seismics), ...



Takeaway messages:

- We **applied advanced regularization techniques** to our individual inversions
- We **constrained the individual inversions** using
  - → **structural information** on dip and geological layering
  - → **1D borehole data**
  - → **2D GPR reflections**
- We **evaluated and compared** the constrained models and quantified the effect of adding a-priori information

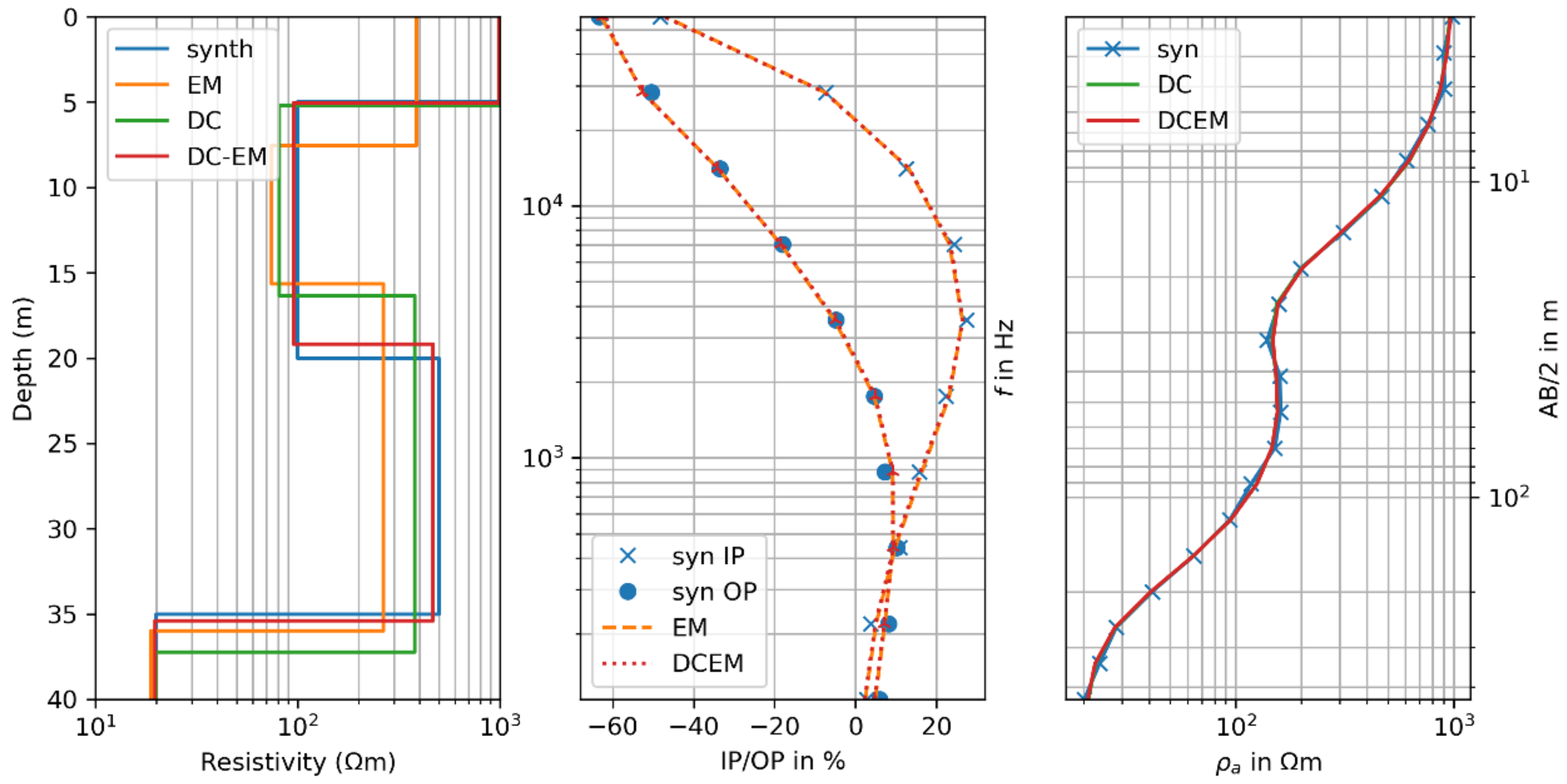
Joint inversion

Goals of this part of the workshop

- Learn the necessary steps to successfully perform a joint inversion.
- Apply the cross-gradient algorithm to jointly invert SRT and ERT using actual field data.
- Evaluate and compare the joint inversion results to individually inverted data sets.
- **Optional:** Apply the algorithm to your own data sets!

Joint inversion of methods working in same parameter space

- If two methods are sensitive to the same physical property (e.g. electrical resistivity ρ by using ERT and a electromagnetic method) we can use the same model parameter space for both methods and perform a classical **joint inversion**.
- In the following example we will use vertical electrical sounding (VES) and EM data to jointly invert for the electrical resistivity distribution of the subsurface in a 1D model.



pyGIMLi

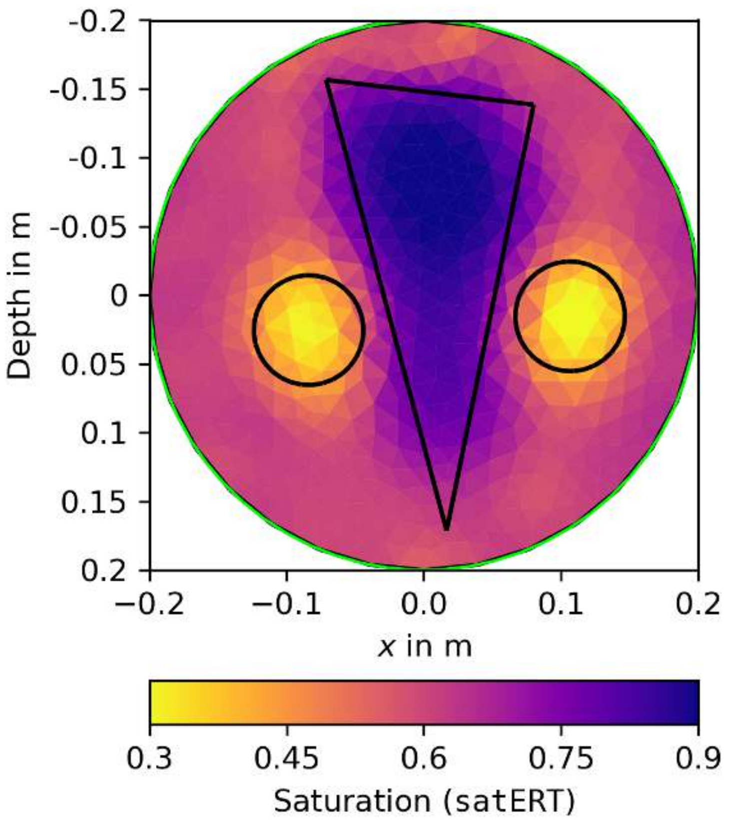
Joint inversion of methods working in different parameter spaces

Petrophysically coupled joint inversion

- If two methods are sensitive to different physical properties (e.g. electrical resistivity ρ by using ERT and acoustic velocity v by using SRT) we can use different types of joint inversion algorithms to link the two model parameter spaces.
- One possible approach is to couple both methods by using a petrophysical relationship between the two physical properties. This is called **petrophysically coupled joint inversion**. For example the water saturation can be used to link the electrical resistivity and acoustic velocity of the subsurface.

Joint inversion of methods working in different parameter spaces

- Finally, we invert again in the same parameter space.



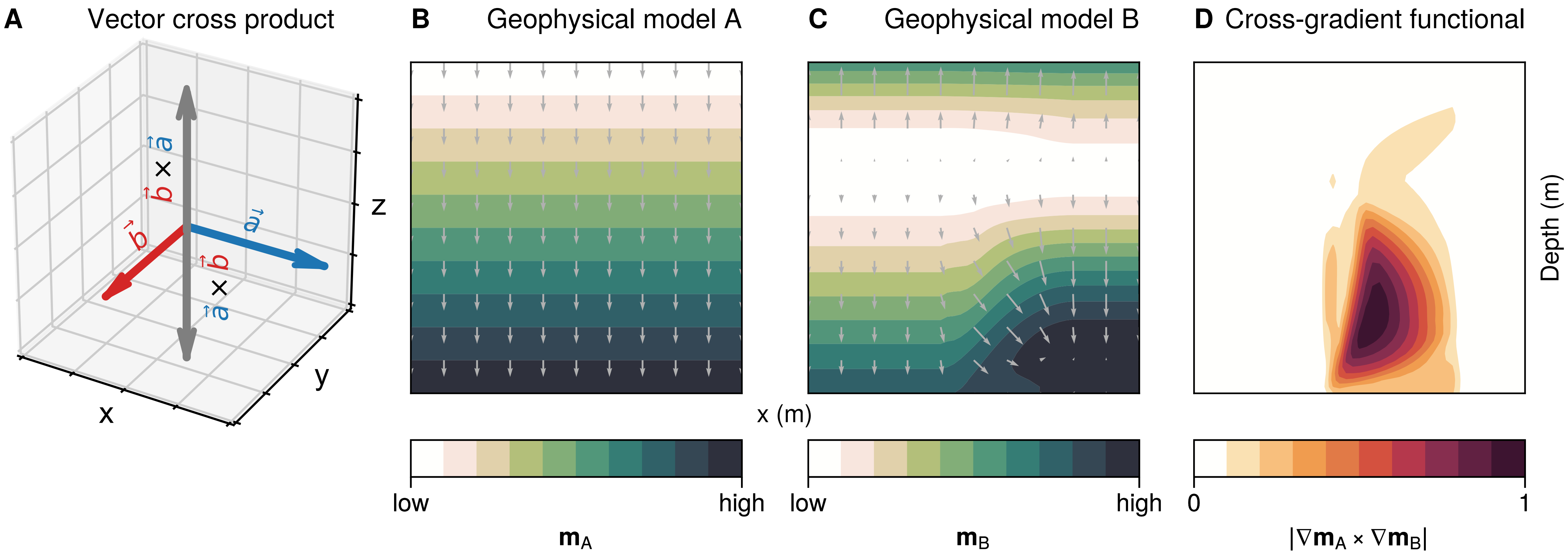
Joint inversion of methods working in different parameter spaces

Structurally coupled joint inversion

- If a petrophysical relationship is not known or cannot be applied, we can use a **structurally coupled joint inversion**. In this case, we assume that the two physical properties are structurally related, i.e. they have similar spatial distributions. This can be achieved by using a **cross-gradient constraint** in the inversion.
- For this purpose, we define the cross-gradient function Φ_{cg} as the integral of the squared magnitude of the cross product of the gradients of the two physical properties:

$$\Phi_{cg} = \int |\nabla \rho(i) \times \nabla \mathbf{v}(i)|^{2}$$

The idea of cross-gradients

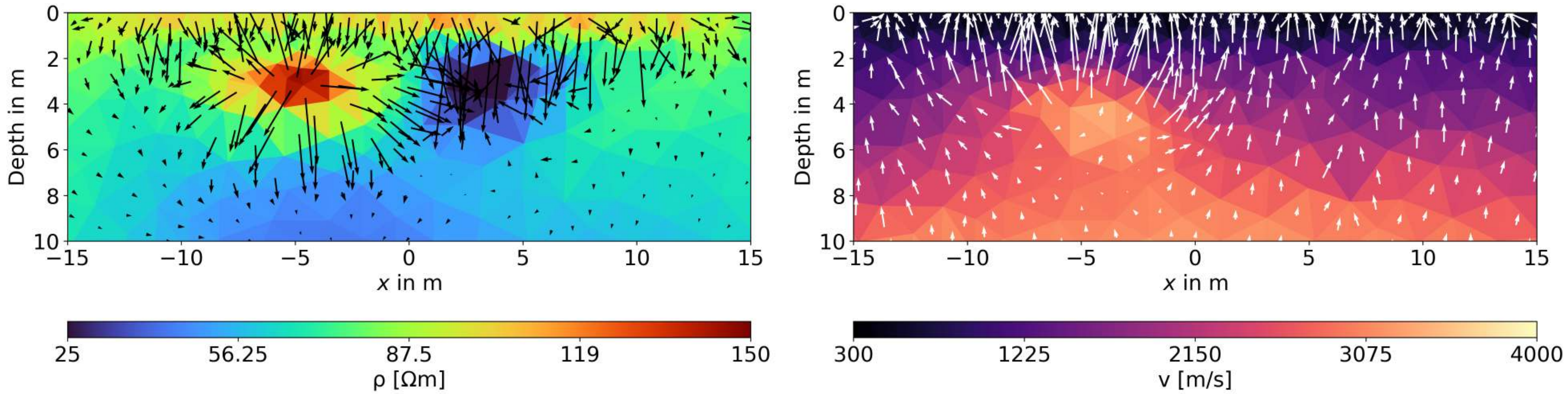


Wagner & Uhlemann (2021)

Joint inversion of methods working in different parameter spaces

Structurally coupled joint inversion

- The gradients of two models in different parameter spaces are parallel if the cross-gradient function Φ_{cg} is zero. In this case, the two models are structurally quite similar.



Takeaway messages:

- which type of joint inversion to use depends on the physical properties of the methods used.
- If the methods are sensitive to the same physical property, a classical joint inversion can be used.
- If the methods are sensitive to different physical properties, a petrophysically coupled or structurally coupled joint inversion can be used.
- A petrophysically coupled joint inversion requires a known petrophysical relationship between the two physical properties.
- Often, a structurally coupled joint inversion is used, which requires no petrophysical relationship between the two physical properties.

References

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