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3D MT Imaging for Conventional and Unconventional Geothermal Exploration

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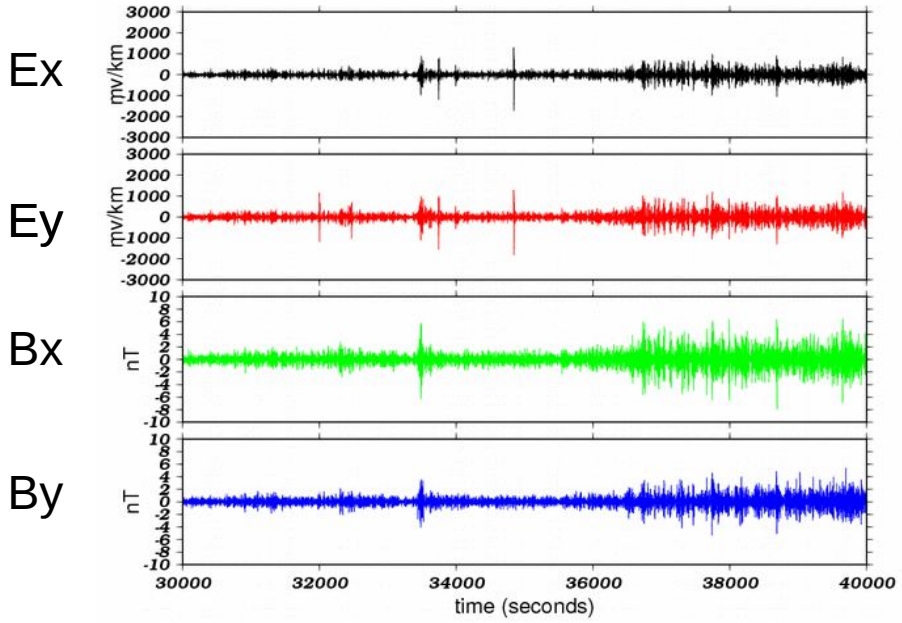
Outline

- Quick review of the MT method
- Challenges in MT when applied to geothermal exploration
  - Data acquisition and processing
  - High resolution 3D imaging tools for complex geothermal targets
- 3D inversion of MT data: Two case studies
  - Conventional geothermal system : Carribean Sea
  - Unconventional geothermal system : Massif Central, France
- Conclusion

A quick review of the Magnetotelluric method

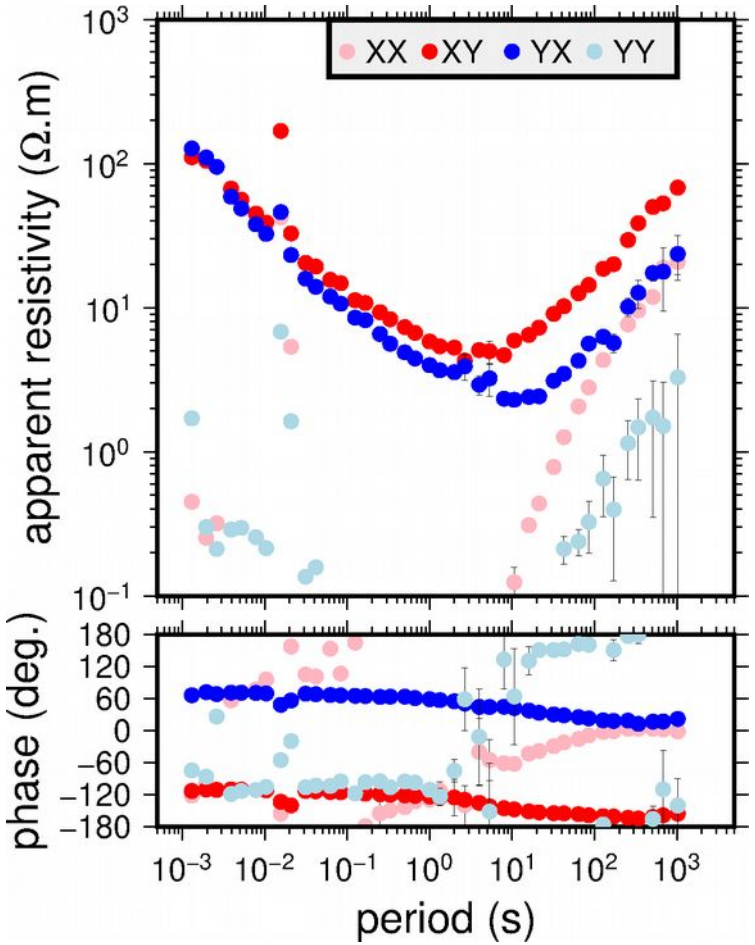
- A passive imaging technique
- Data collected are time series : Fluctuations of the natural electric and magnetic fields on Earth's surface
- Data processing in the frequency domain to derive the electrical resistivity structure of the subsurface



$$\begin{pmatrix} E_{x(\omega)} \\ E_{y(\omega)} \end{pmatrix} = \begin{pmatrix} Z_{xx(\omega)} & Z_{xy(\omega)} \\ Z_{yx(\omega)} & Z_{yy(\omega)} \end{pmatrix} \begin{pmatrix} B_{x(\omega)} \\ B_{y(\omega)} \end{pmatrix}$$

Impedance tensor **Z=**f(ρ_a,Φ,f)

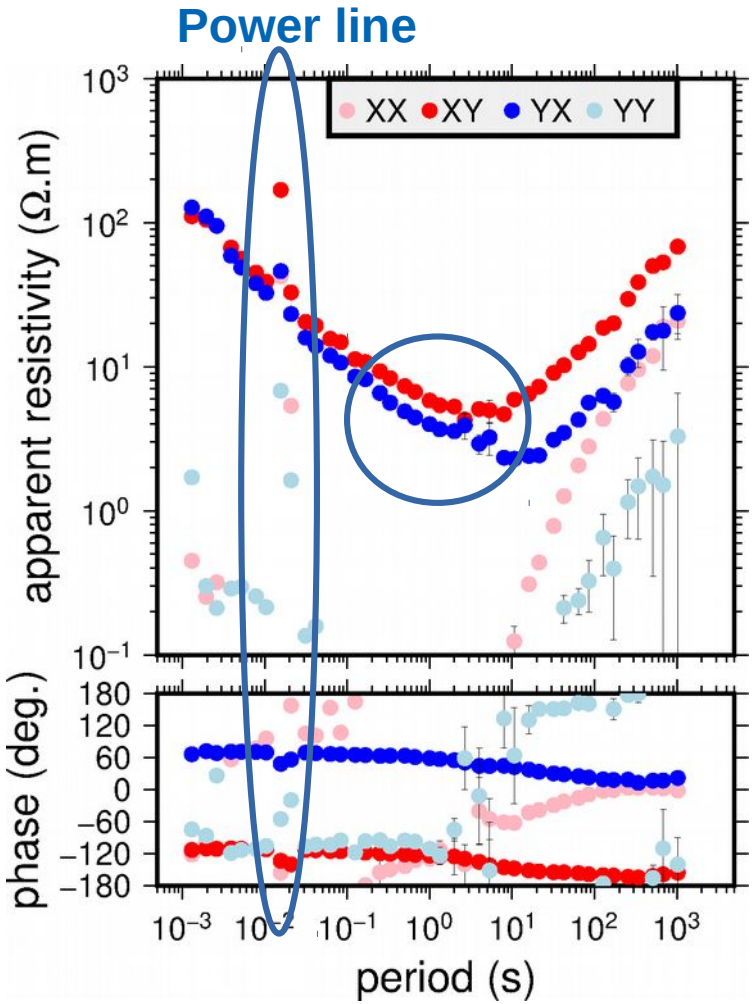
A quick review of the Magnetotelluric method



- Penetration depth is a function of frequency (1/period)
- In geothermal exploration : ~1000 Hz – 1000 seconds → Penetration down to several kilometers
- $Z_{xy} = -Z_{yx}$ and $Z_{xx} = Z_{yy} = 0$ in 1D
- $Z_{xy} \neq Z_{yx} \neq Z_{xx} \neq Z_{yy}$ in 3D

- MT is particularly sensitive to highly conductive materials, hence a standard technique in geothermal exploration (fluids, clay cap, heat source, ..)
- Quality dependent on the energy source and anthropic noise.

A quick review of the Magnetotelluric method



- Geothermal prospects close to inhabited areas (power lines, road traffic,..)
- Signal/Noise low when small resistivity in 0.1-1 second range (weak natural signals)
- Special care for data acquisition and processing are essential before interpretation
  - Set up of sensors
  - Length of time series
  - Noise correction

MT data interpretation

- Commercial 3D MT inversion is young (~15 years)
- Until recently, 3D inversion was performed only by experts in academics and Oil&Gas major companies

- In geothermal exploration :

  - 1D inversion was popular to image conventional geothermal systems (target = clay cap) : Fast and cheap interpretation tools.

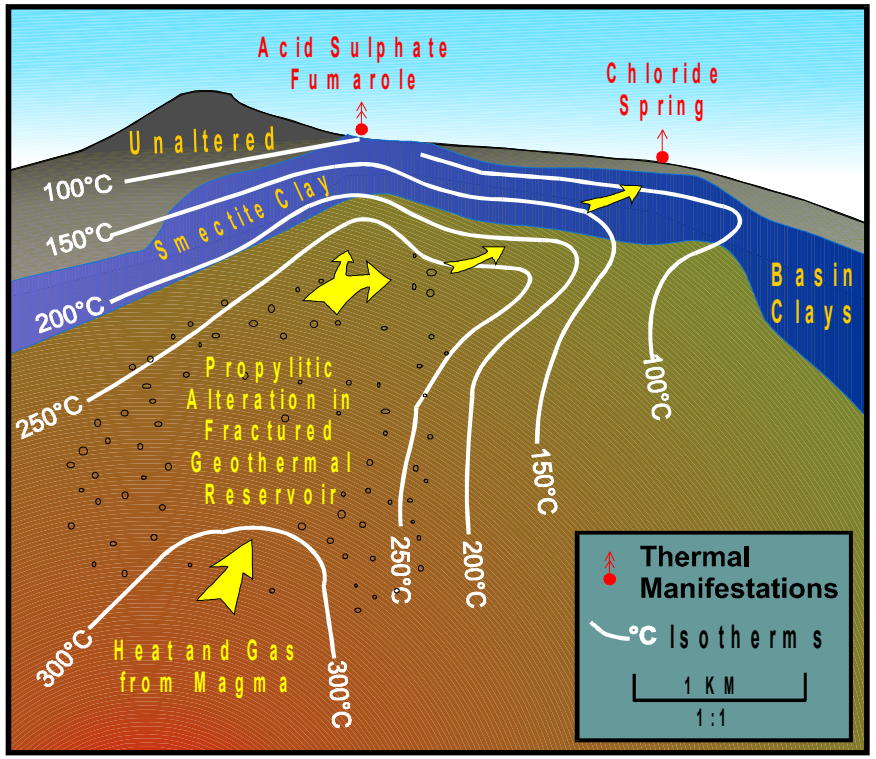
  - But 1D should be interpreted carefully.

  - 3D MT imaging becomes a standard : Easier access to 3D inversion codes. Also, the complexity of potential geothermal targets increases.

conventional and unconventional geothermal systems

Conventional

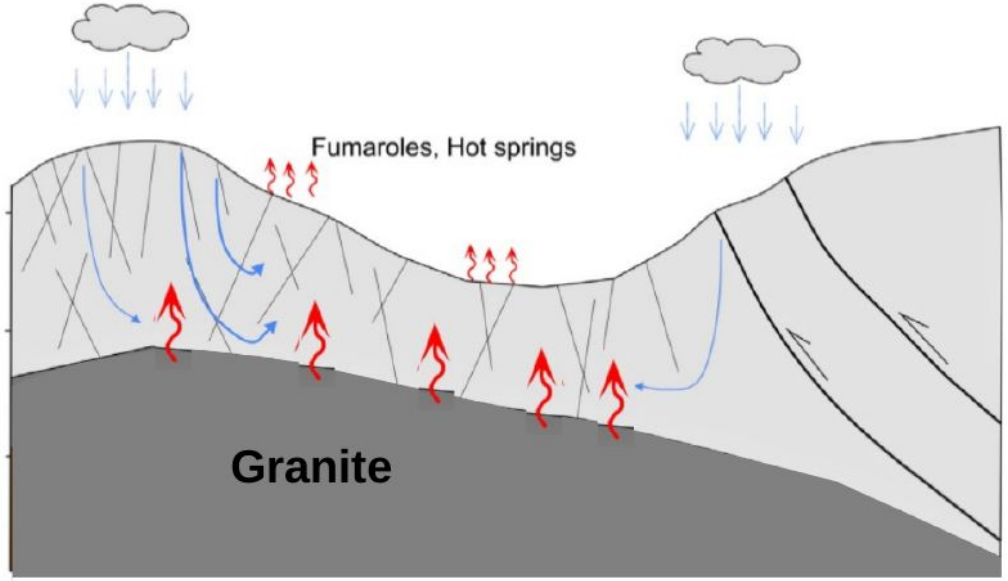
Classical convective hydrothermal system
MT well adapted to image the clay cap, hydrothermal fluids, in some cases magma,..



after Cumming et al. 2000

Unconventional

Any other geothermal target different from the classical convective hydrothermal system
- Can be in sedimentary or cristalline context
- Geothermal fluids circulate through fracture networks.
- System more complex to image

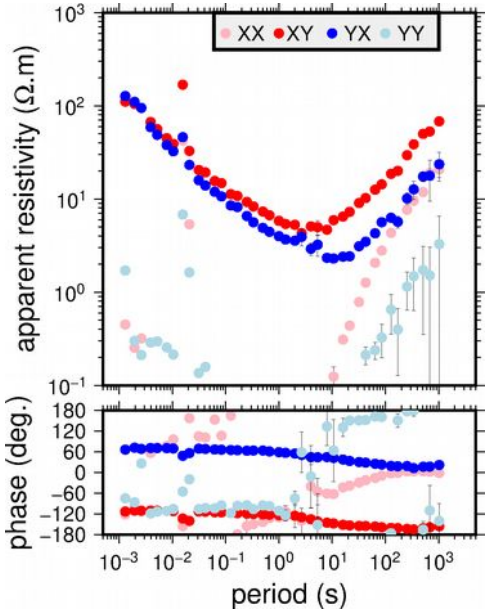


Modified after Moeck, 2014

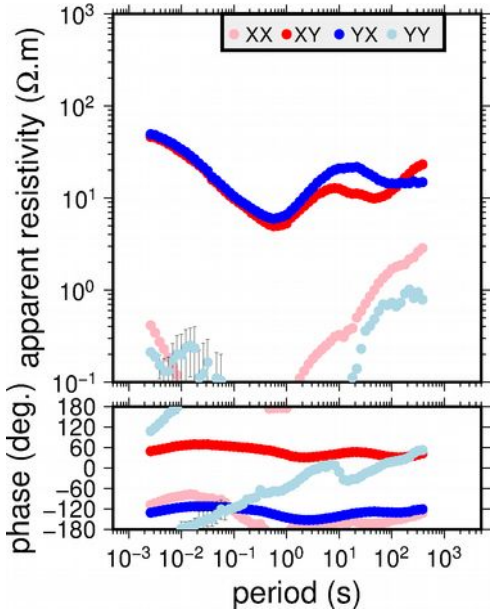
conventional geothermal systems

MT data collected in conventional geothermal prospects around the world

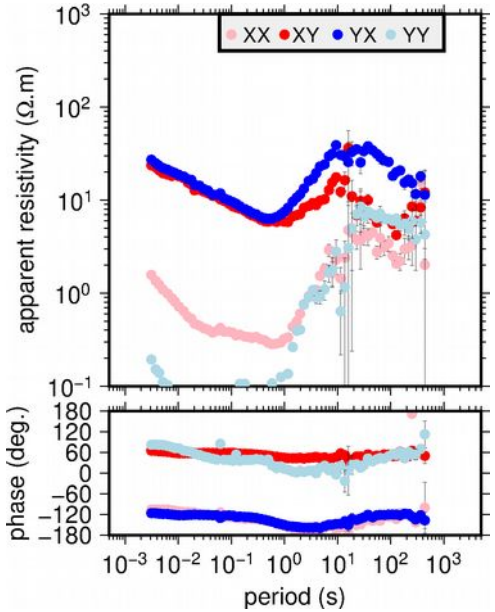
Carribean Sea



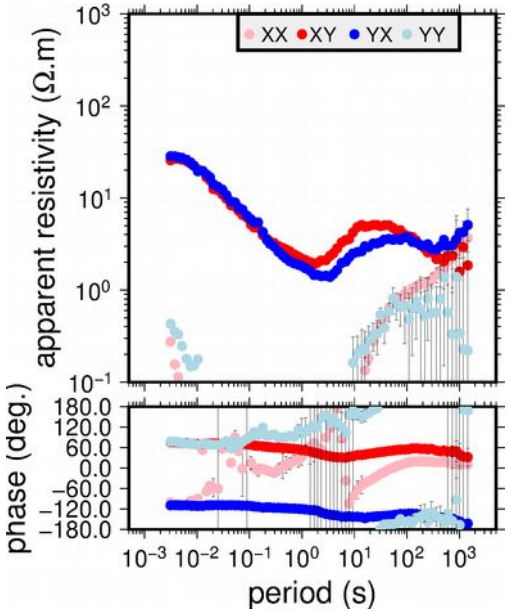
South America



Kenya



Republic of Djibouti



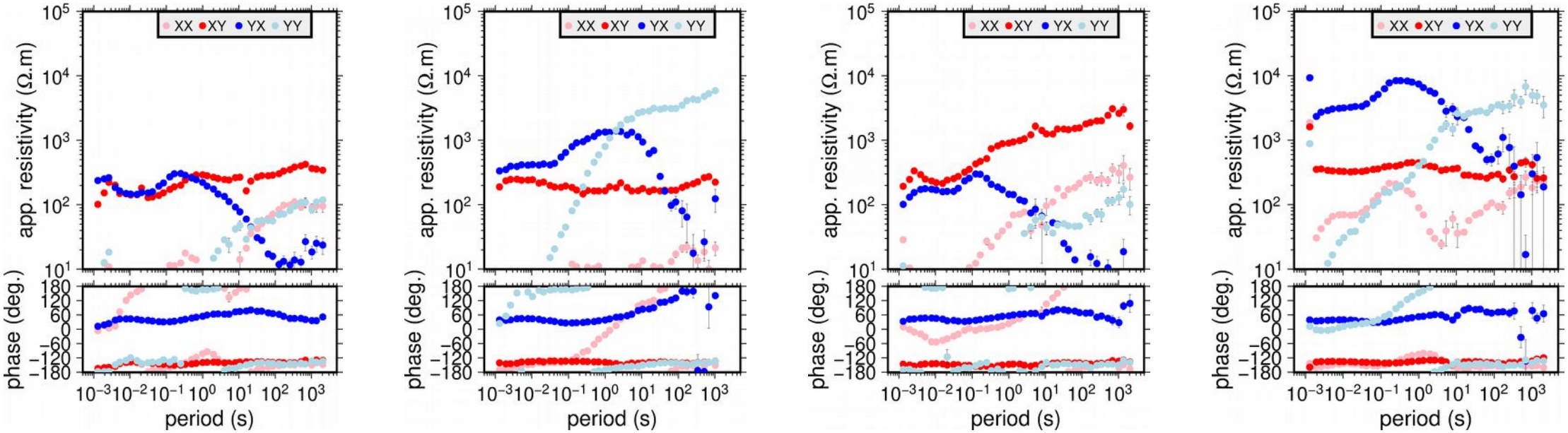
Clear signature from short to longer periods :

Volcanics – Clay cap – Reservoir – potentially, heat source

Diagonals terms (Zxx and Zyy) frequently ignored but amplitude not negligible

Unconventional geothermal systems

MT data collected in one unconventional geothermal prospect



MT soundings are a few km apart

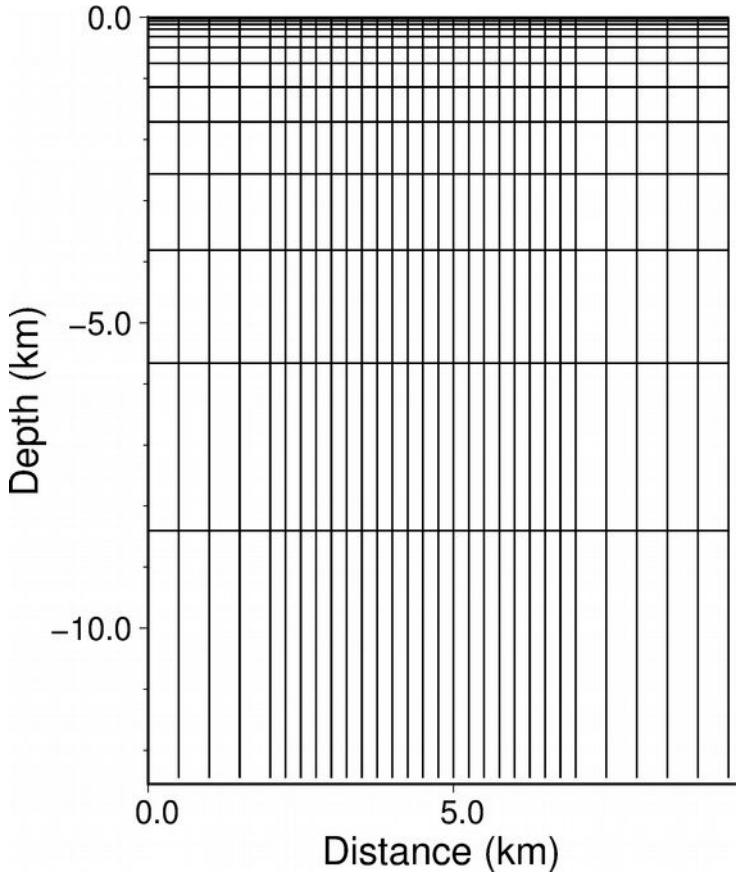
Strong heterogeneity between sites.

Only 3D imaging can allow to interpret such data sets.

3D inversion of MT data

Most available 3D inversion codes are based on model space inversion

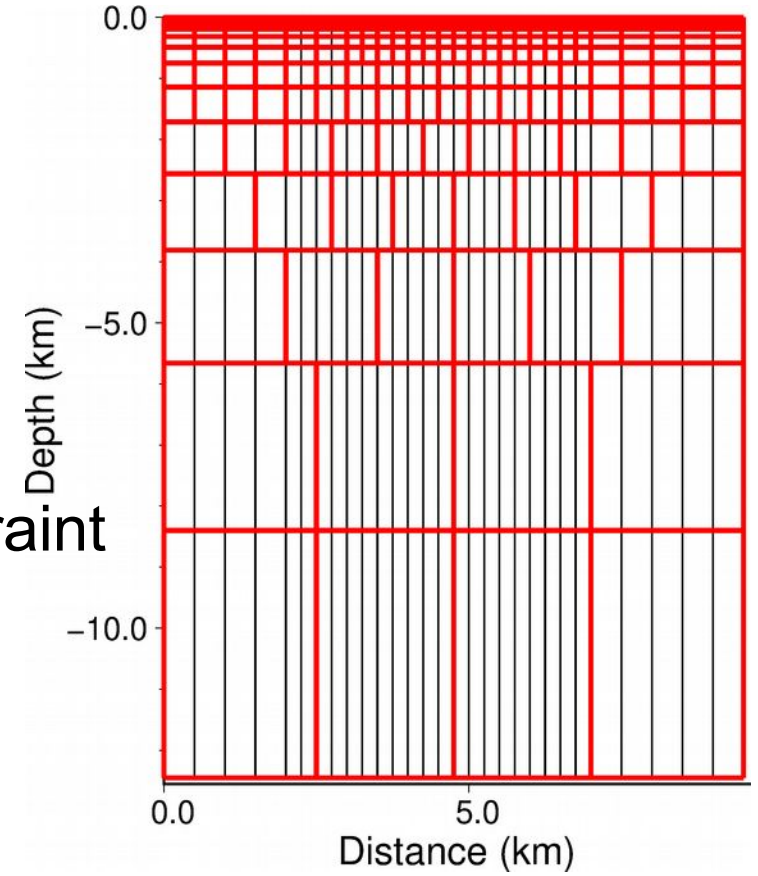
- Number of unknown (model parameters) >> number of data.
- The problem is solved with a strong smoothness constraint.



3D inversion of MT data

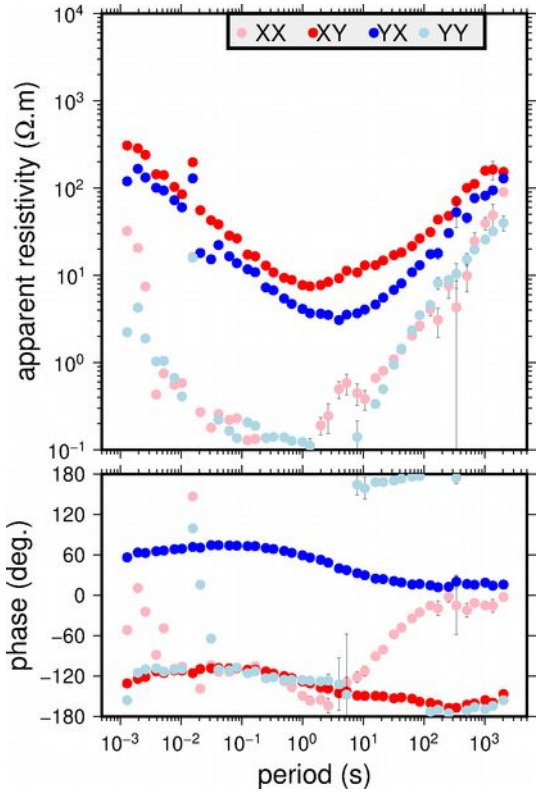
We propose a different approach :

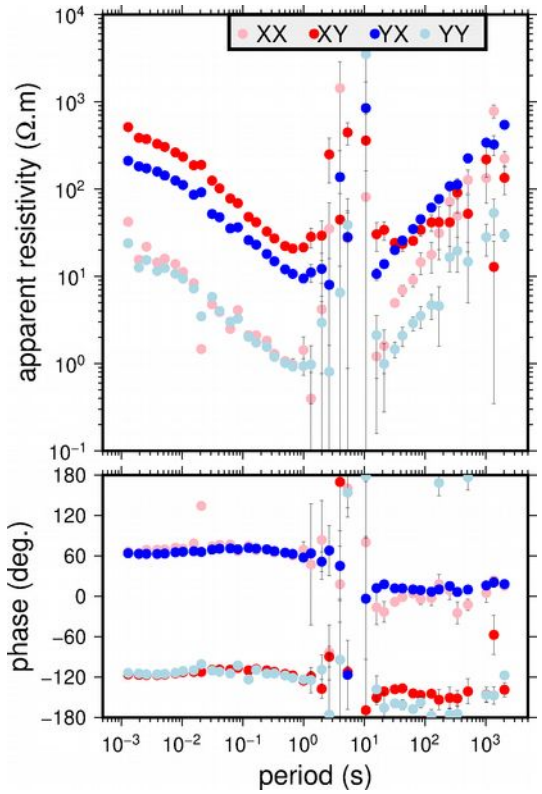
- Data driven inversion
- Number of data >> Model parameters
- Block parametrisation adjusted to the resolution of data
- Result is more « blocky » but no strong smoothness constraint
- Allows to image strong resistivity contrasts, even at depth
- The full tensor is always inverted

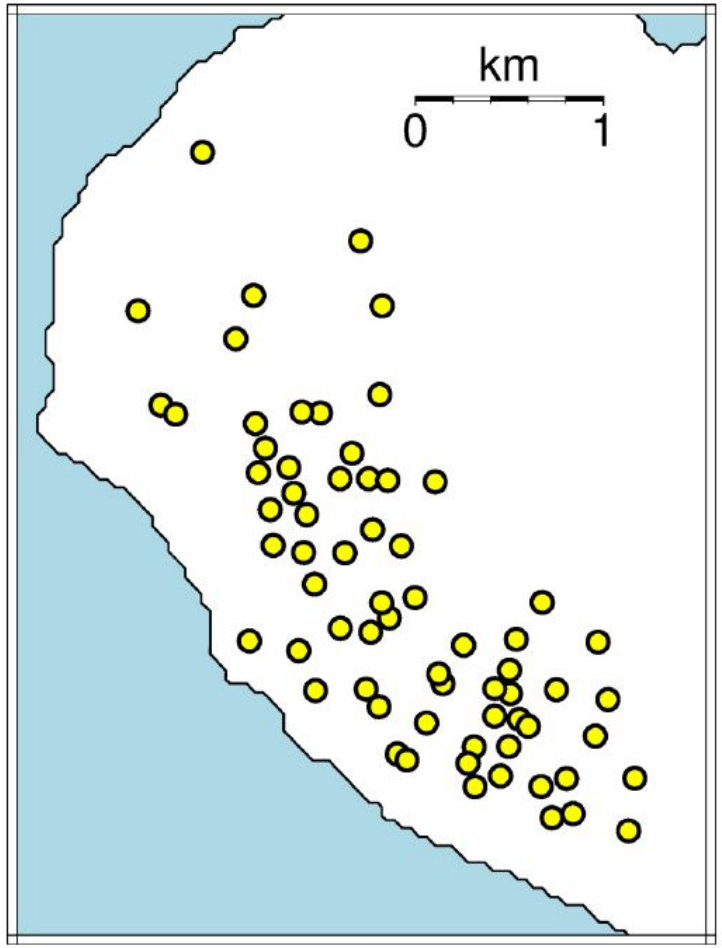


Case Study 1: 3D MT imaging of a conventional system (Carribean Sea)

- Project with Teranov
- Acquisition of 68 MT sites
- Irregular distribution and quality (low energy, anthropic noise)



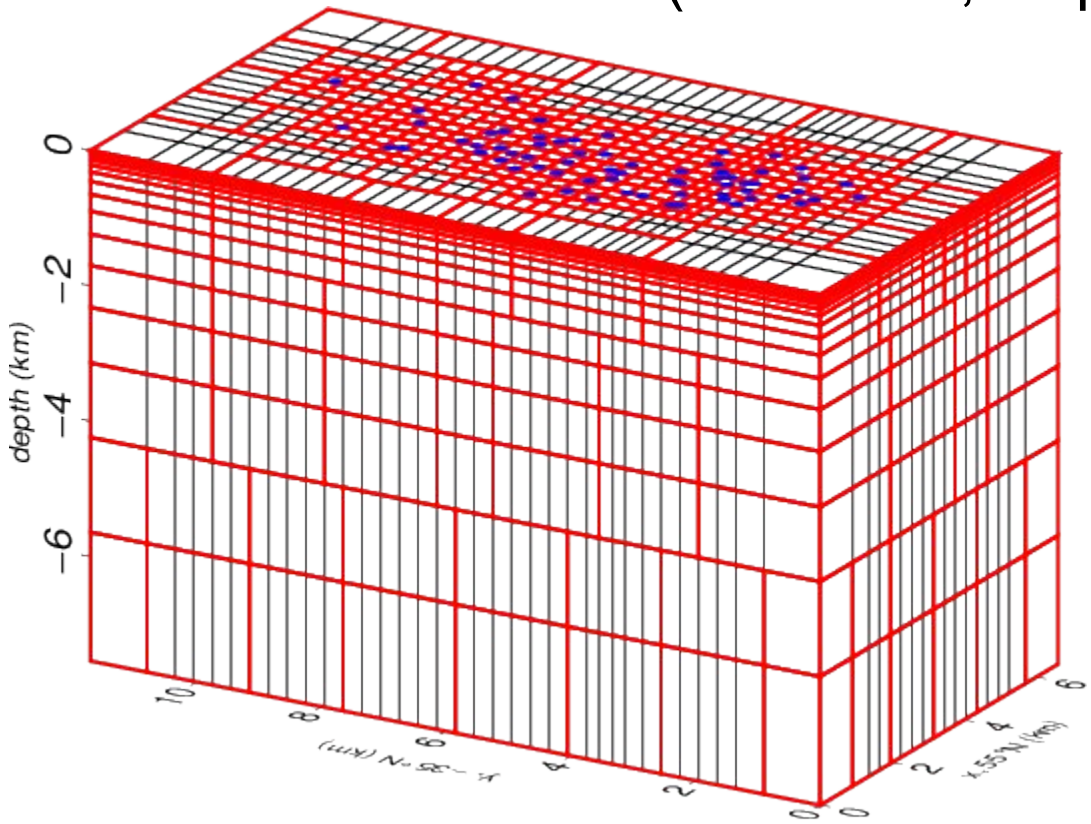


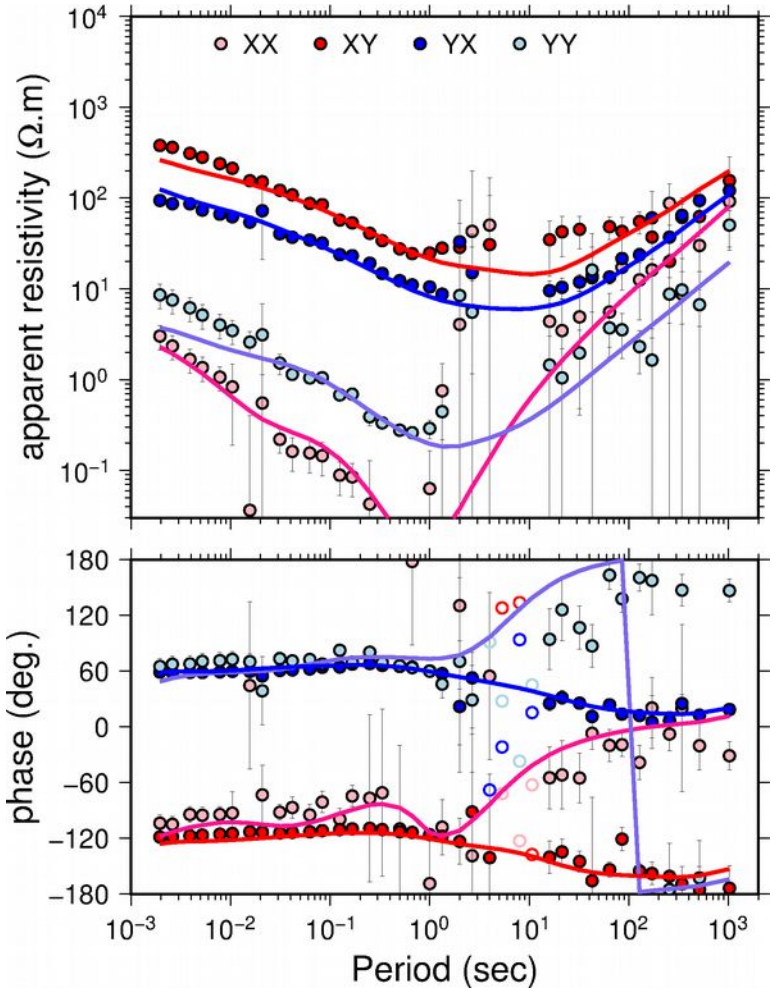


Case Study 1: 3D MT imaging of a conventional system (Carribean Sea)

The inversion grid is adapted to the data resolution and distribution :

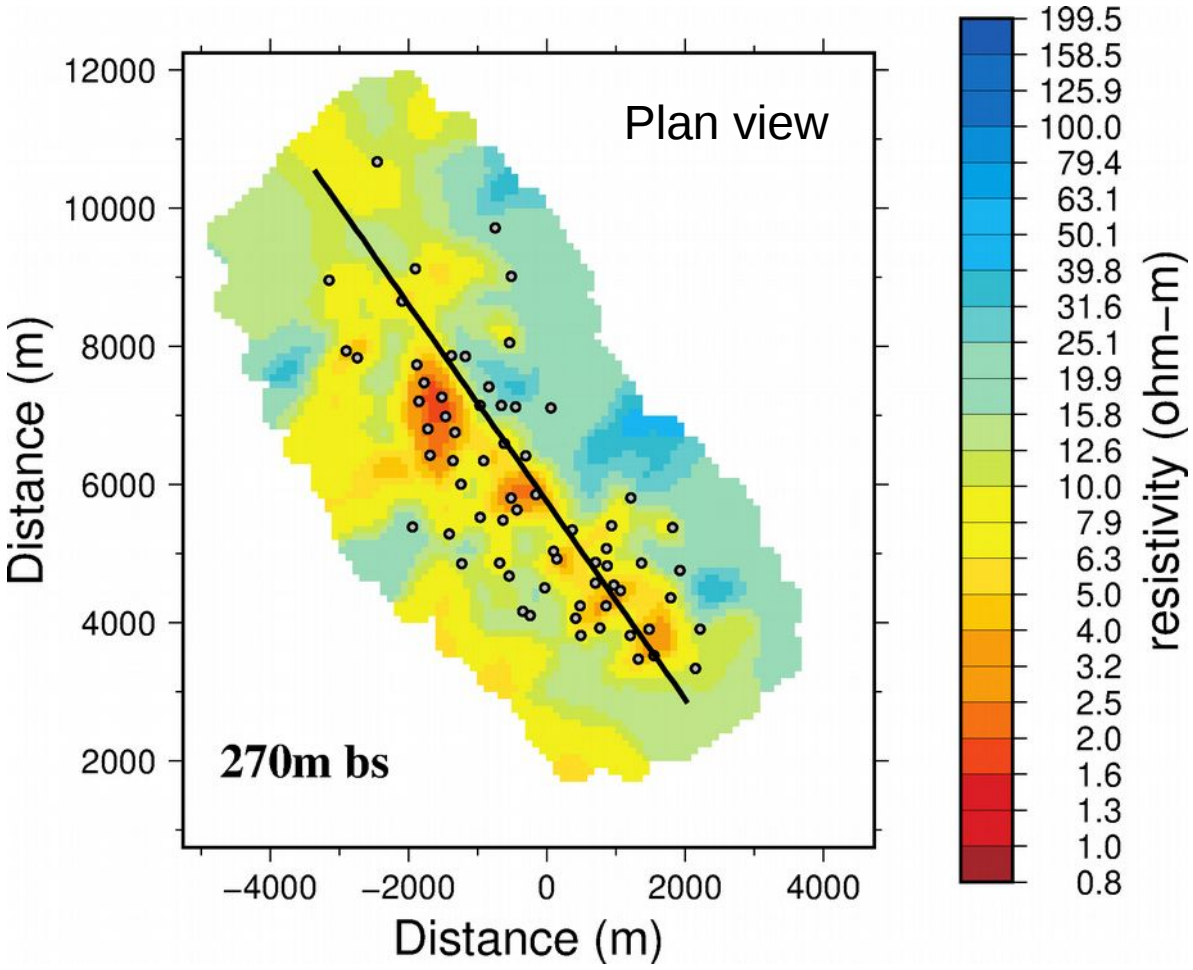
2931 unknown for 17390 data (full tensor, all periods).

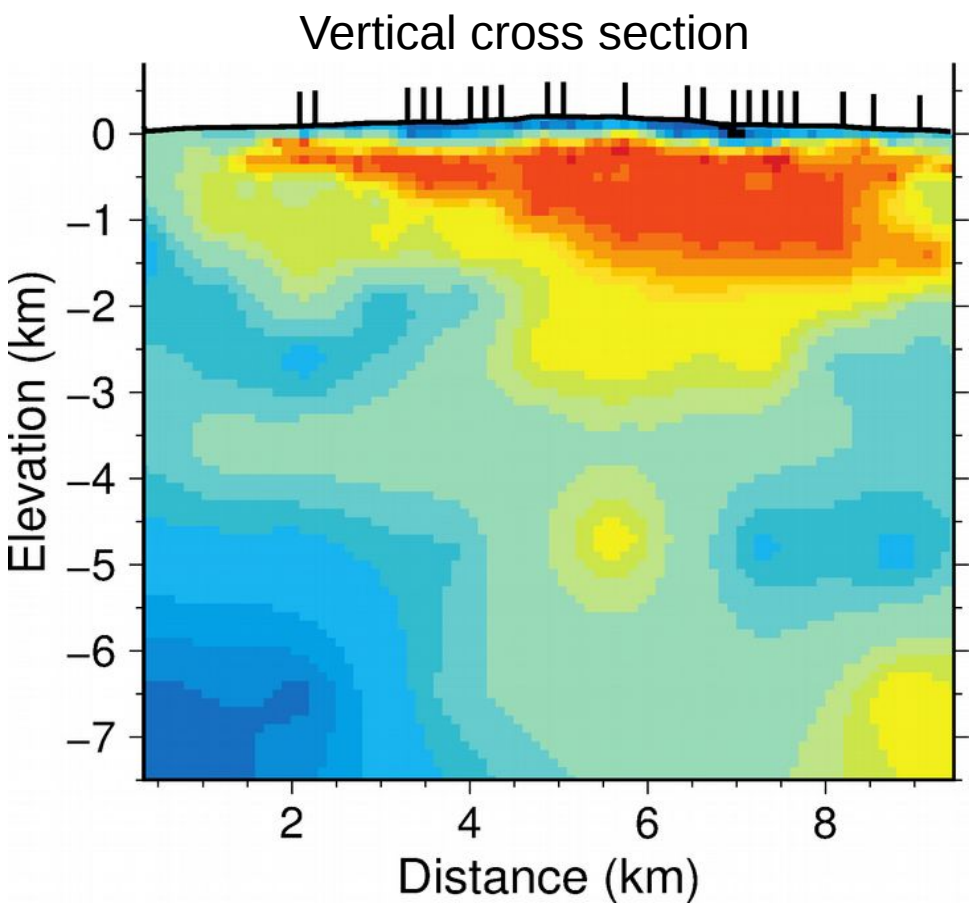




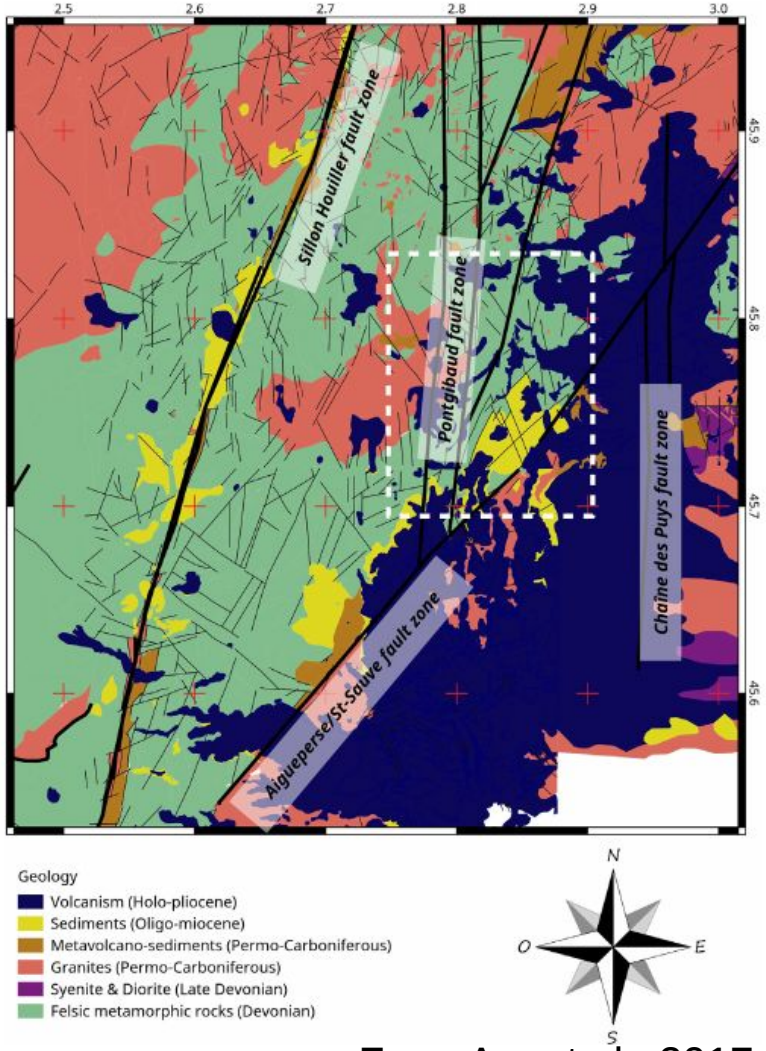
Case Study 1: 3D MT imaging of a conventional system (Carribean Sea)

Results : Image of the « clay cap » and structures at depth





Case Study 2: 3D MT imaging of a unconventional system (Massif Central, France)

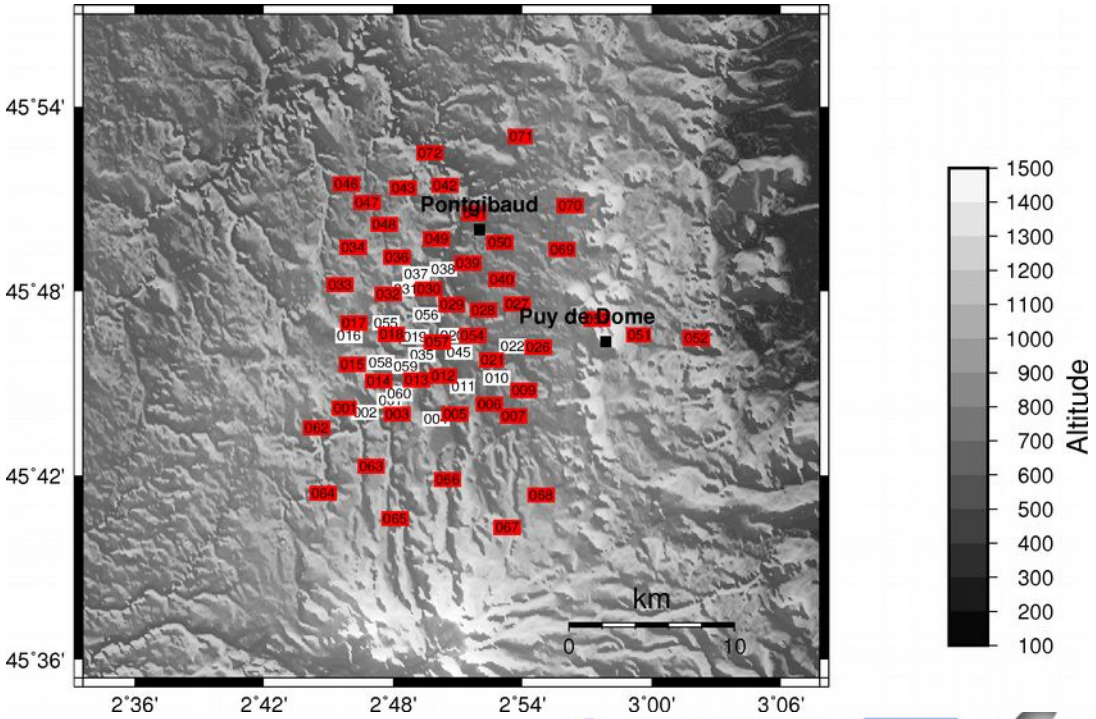


From Ars et al., 2017

Project with TLS Geothermics

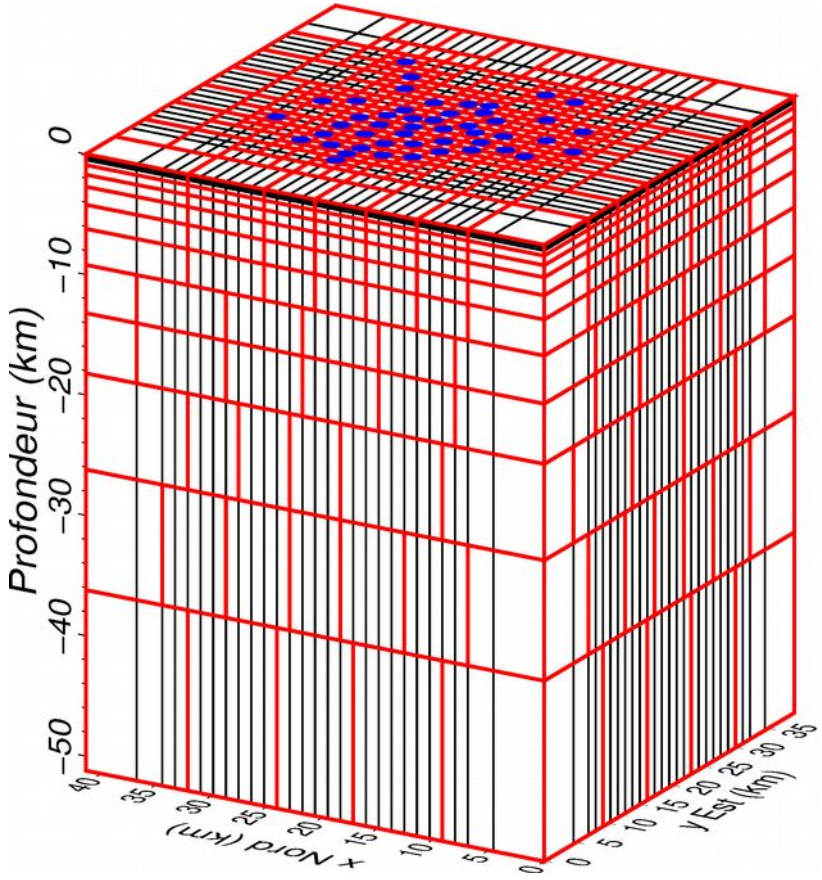
Complex geological context. The geothermal targets are deep crustal faults within a cristalline and volcanic region

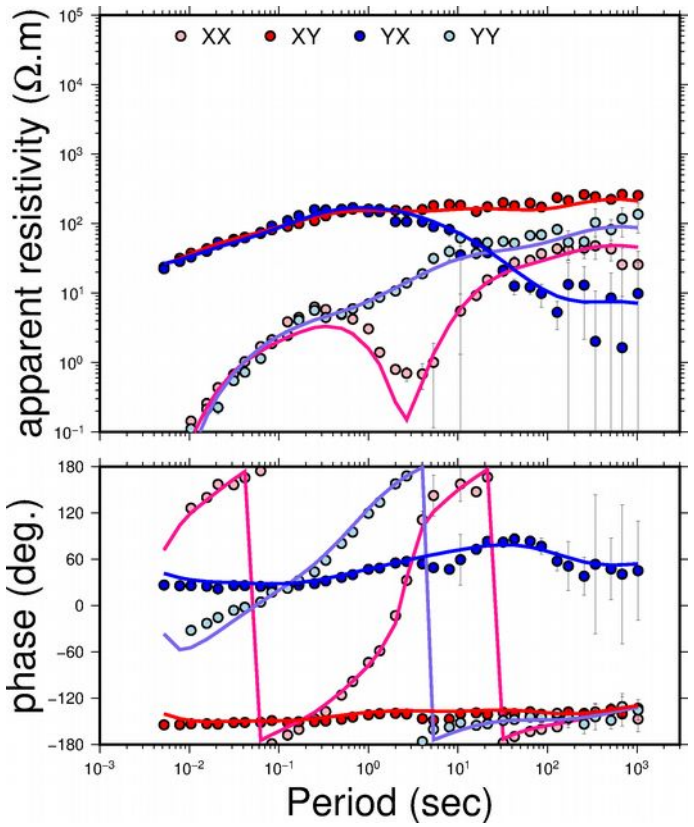
MT survey (48 sites)

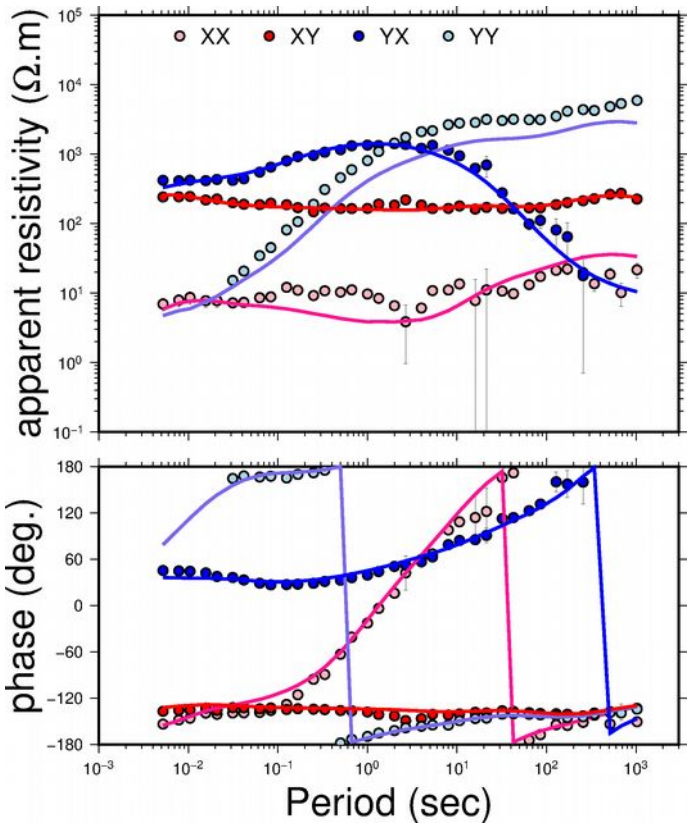


Case Study 2: 3D MT imaging of a unconventional system (Massif Central, France)

The adapted grid allows to model very heterogeneous data : Large diagonal terms, out of quadrant phases (Zyx),..

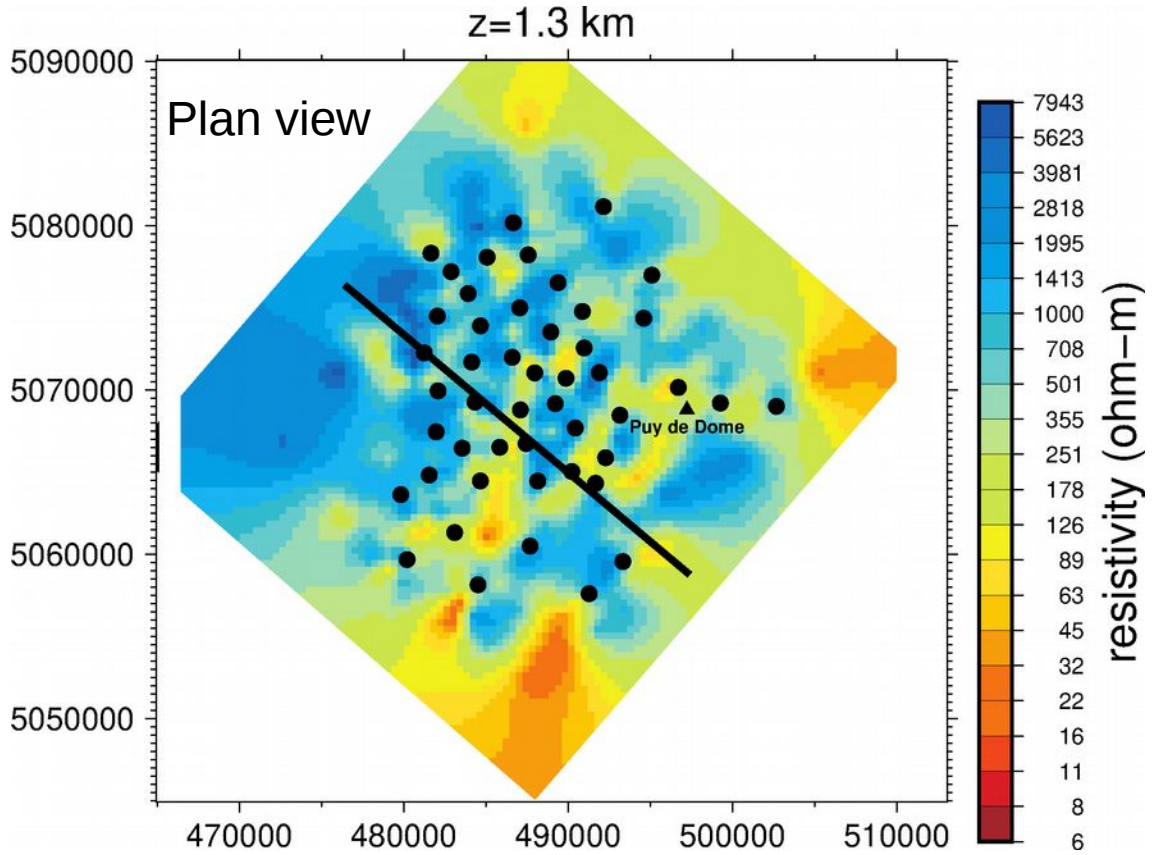


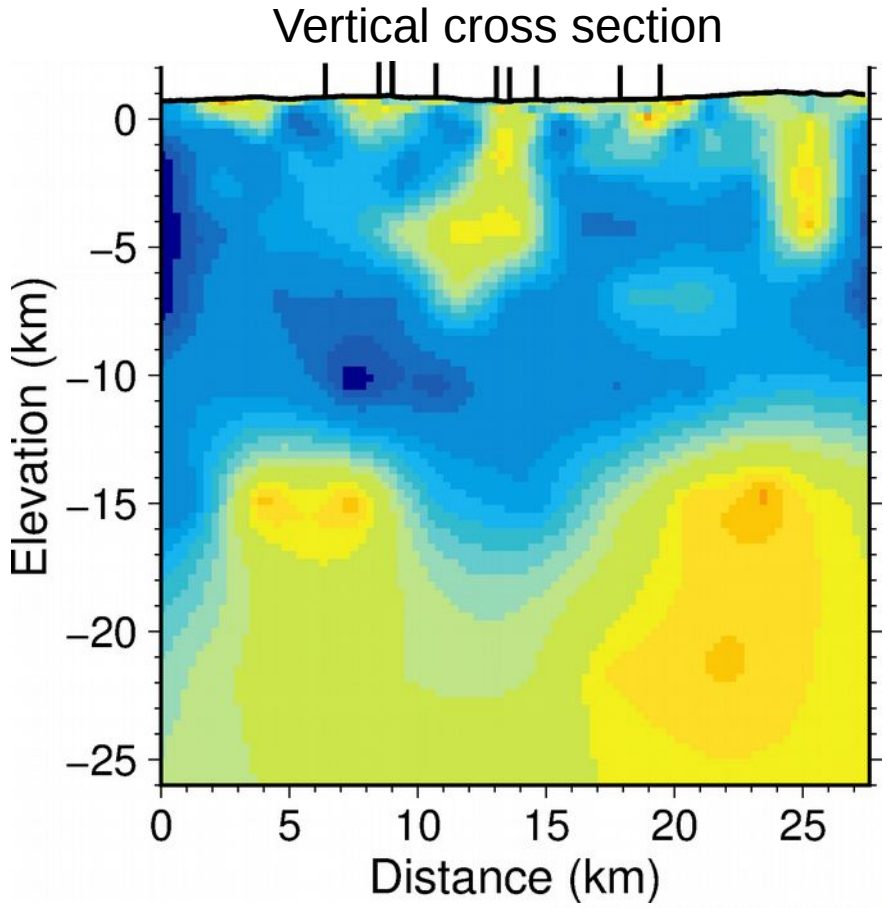




Case Study 2: 3D MT imaging of a unconventional system (Massif Central, France)

Results show the extension of faults at depth and crustal heterogeneities





Conclusion

- Progress in equipment, processing and inversion tools allow to obtain more and more trustable images of geothermal systems
- With MT alone, there is still some ambiguity in the interpretation of the features imaged.
- For example, a low resistivity cannot always be only explained in term of clay cap
- Integration with other geophysical methods and joint inversion are the way forward to better characterise geothermal systems
- Promising results with joint inversion :
  - Case study 1 : Joint MT/Gravity (Tarits et al., 2017)
  - Case study 2 : Joint MT/Gravity/Ambient Noise (Ars et al., 2017)

Merci ! Contact : sophie.hautot@imagir.eu