

Towards unit-wise porosity mapping: MT investigations to image karstic reservoirs near Annecy (France)

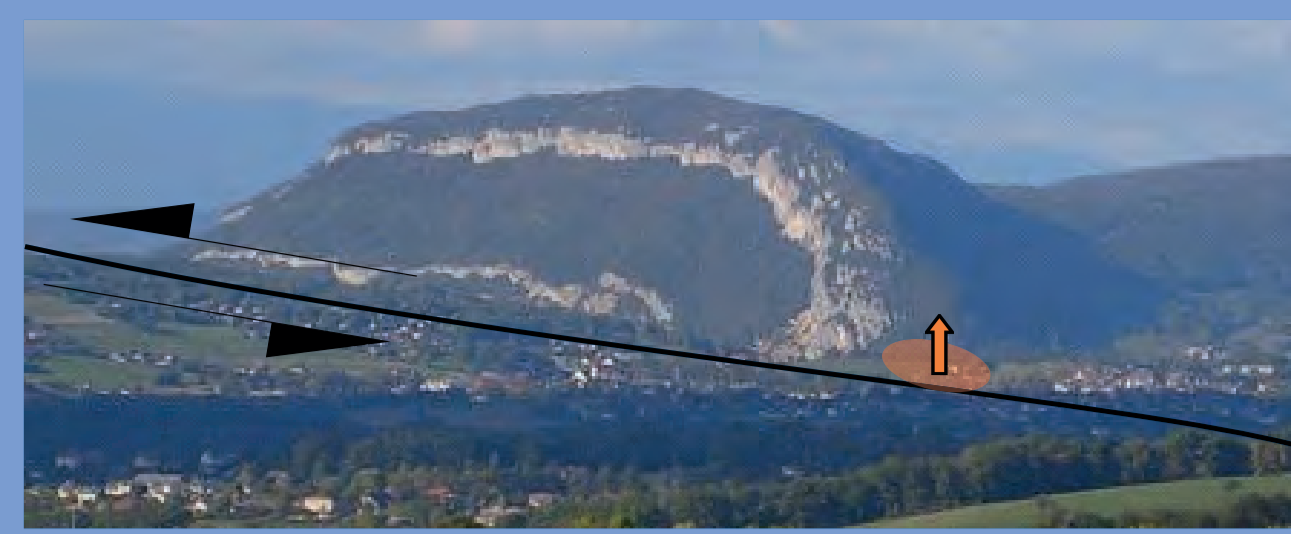


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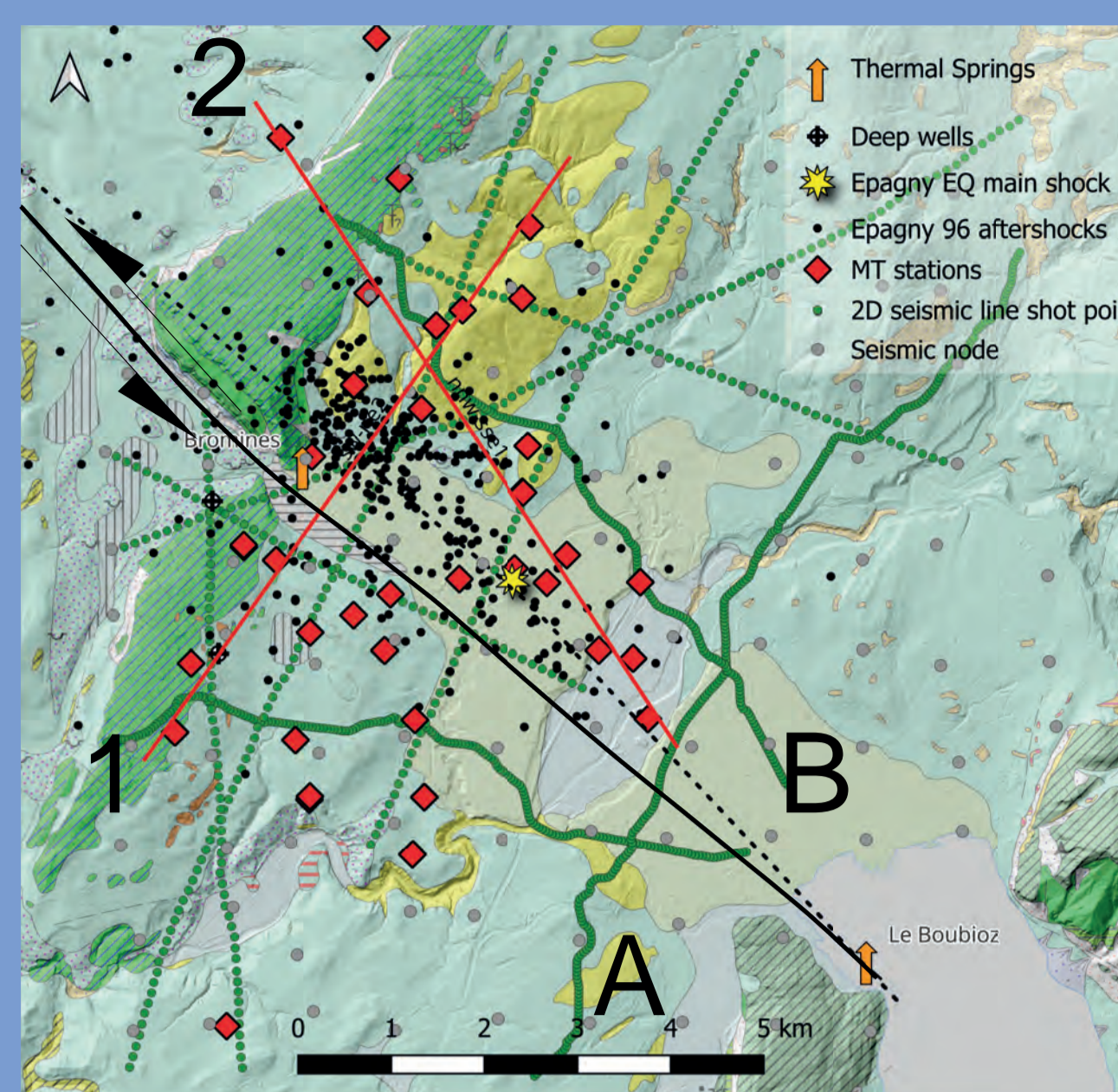
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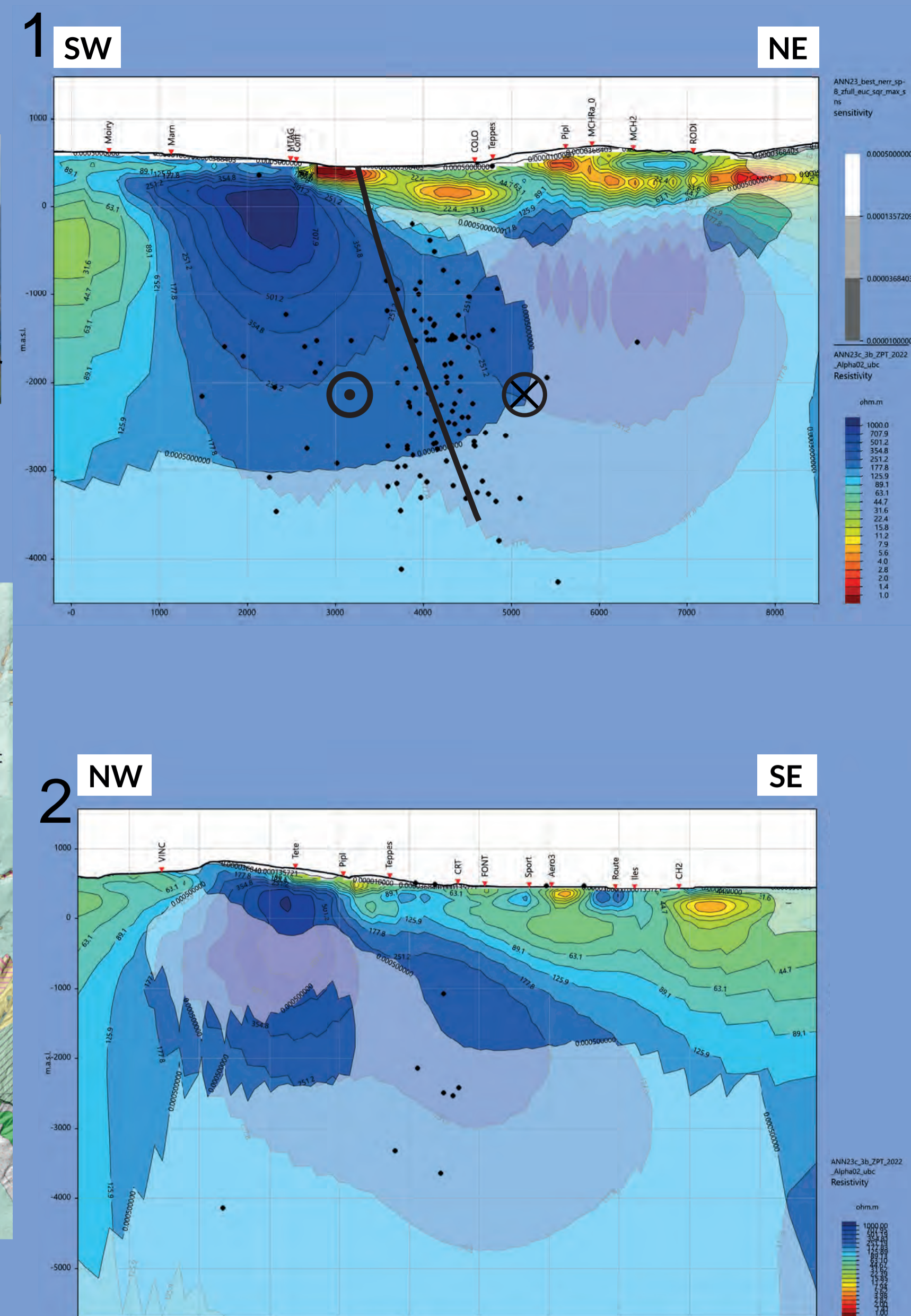
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Photograph of Mandallaz mountain intersection with Vuache fault and site of geothermal spring (orange)



Map of site investigated with MT stations (red), active seismic lines (green), profiles shown (red lines), aftershocks of Epagny 1996 EQ (black), mainshock hypocenter in yellow, seismic nodes in gray



Summary

A 3D geological model was built from 2D seismics, surface geology and well data to characterise potential karstic aquifers in the French alpine foreland

Goals: Produce MT inversions guided by the geological model's interfaces, where smoothing is suppressed.

➔ Evaluate unit-wise bulk resistivity, bulk porosity

➔ Assess geothermal potential and induced seismic risk.

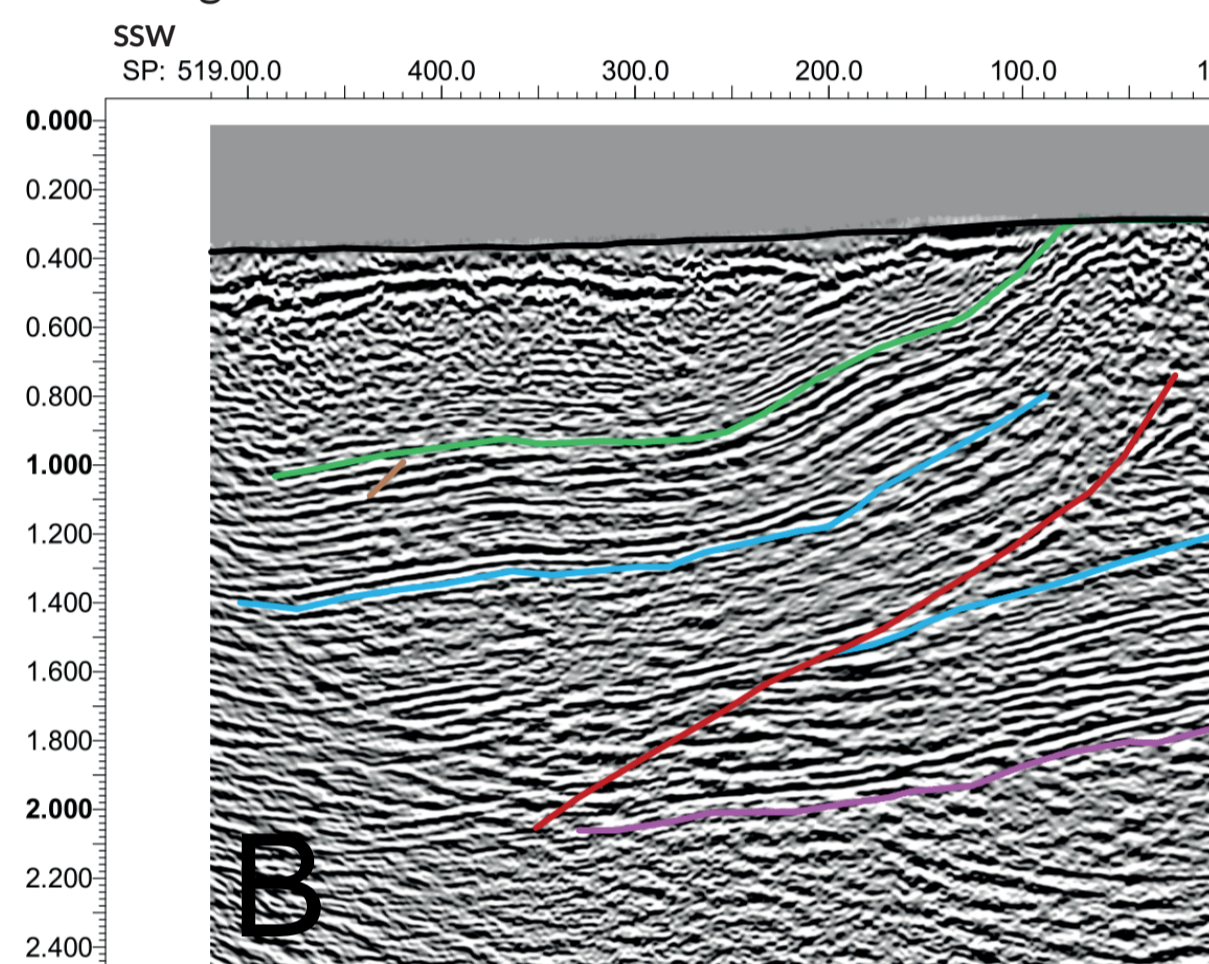
➔ Post-inversion, investigate the solution space to quantify uncertainty

BACKGROUND: The exploitation of deep geothermal energy for district heating applications requires that the risk of drilling unproductive wells – and that of generating induced seismic activity – be small. This requires sound knowledge of the nature, quality and boundaries of the targeted reservoir.

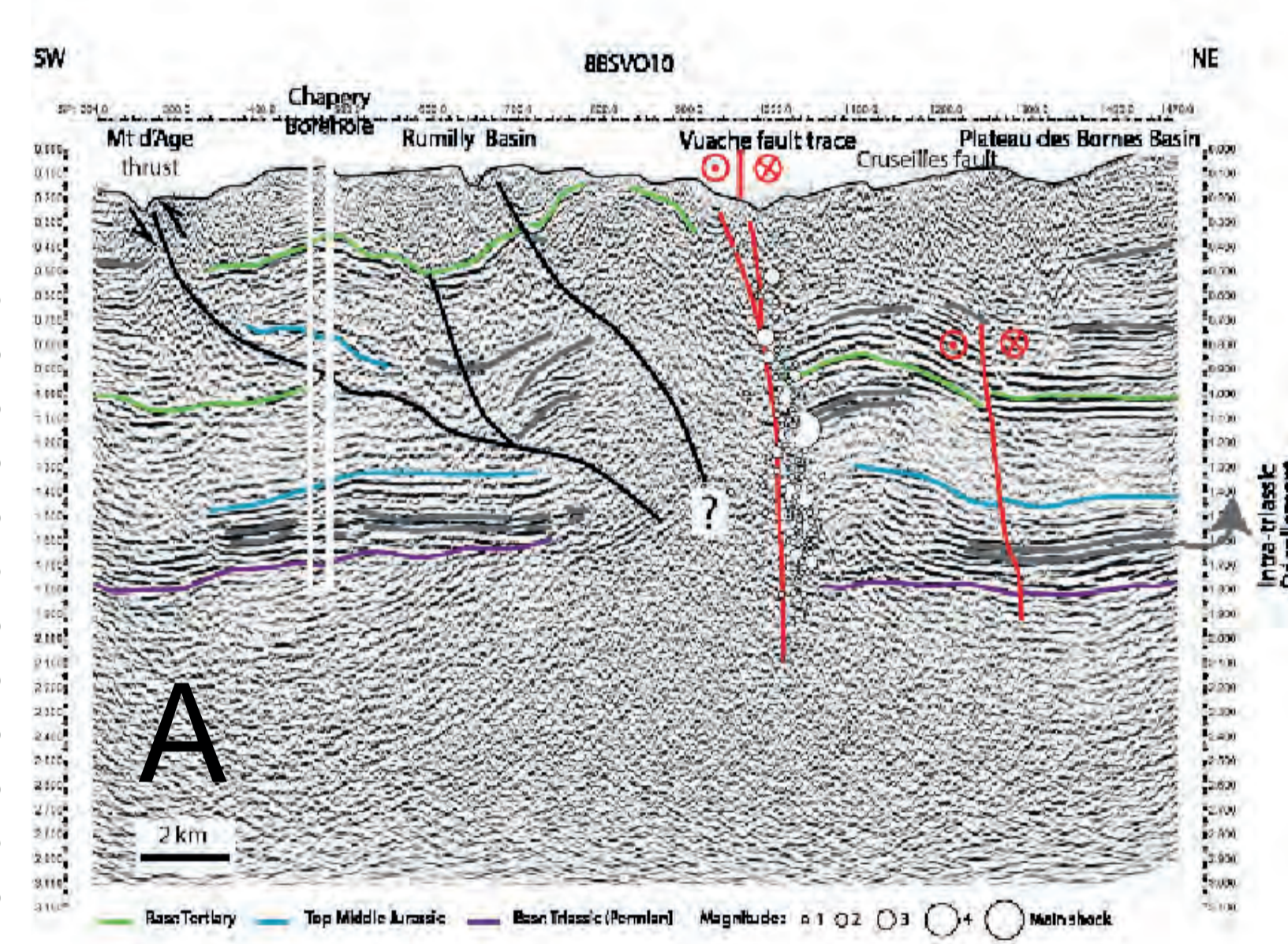
We use **broadband magnetotelluric (MT)** data to investigate a low enthalpy karstic geothermal aquifer in the pre-alpine Molasse Basin at depths up to ~2km in the region of Annecy, France. Thrust faults offset different compartments of the target geological units, also intersected by the **Vuache fault**, an active strike-slip fault which caused a M_L5.3 earthquake in 1996 around Epagny

3D MODEL BUILDING (AFTER DUFOUR, 2019)

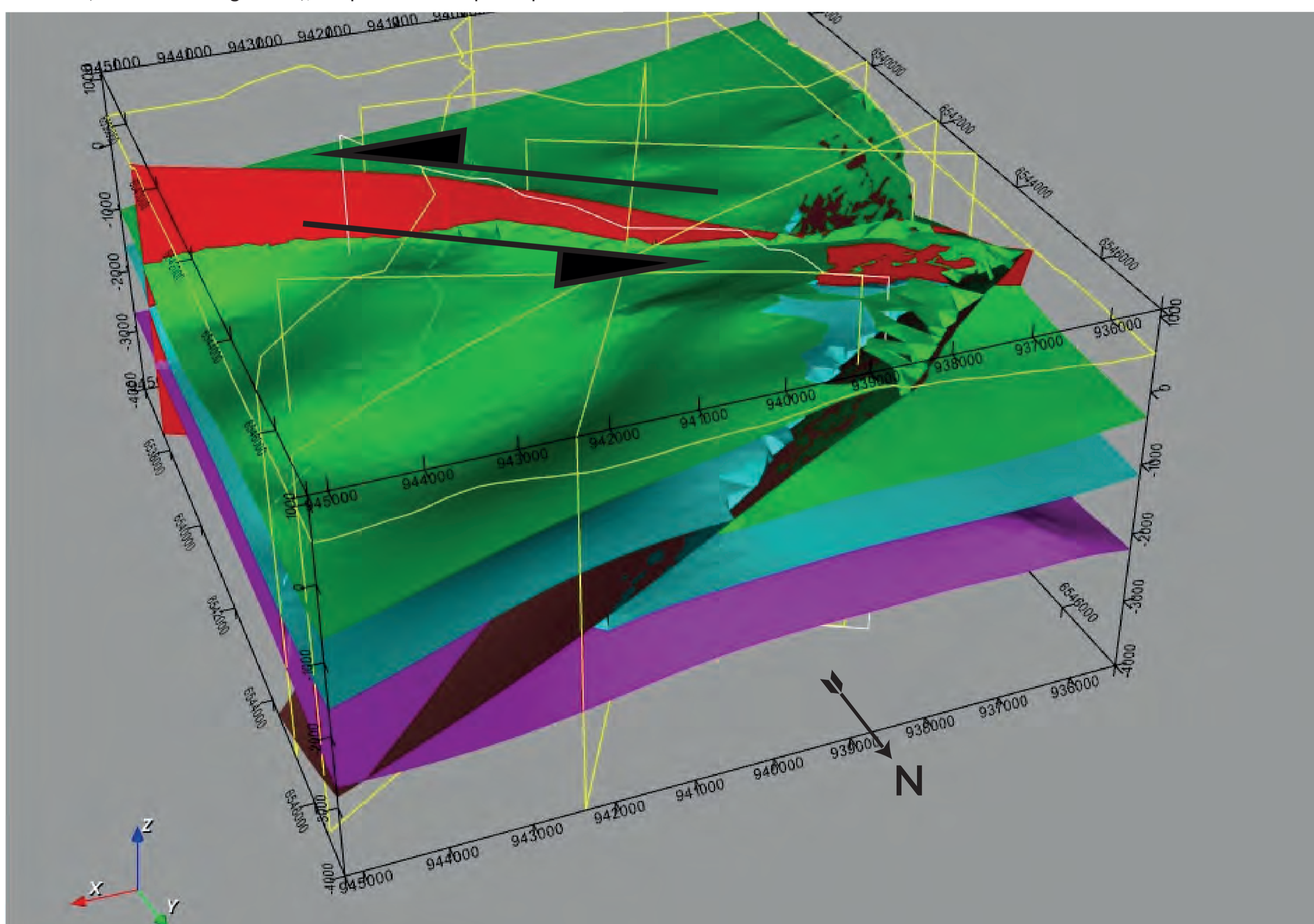
- 2D seismic lines interpretation
- Well ties (stratigraphy)
- Geological field reconnaissance



Interpretation of seismic line 88SVO-005 (SSE-NNW along thrust), see point B on map at top



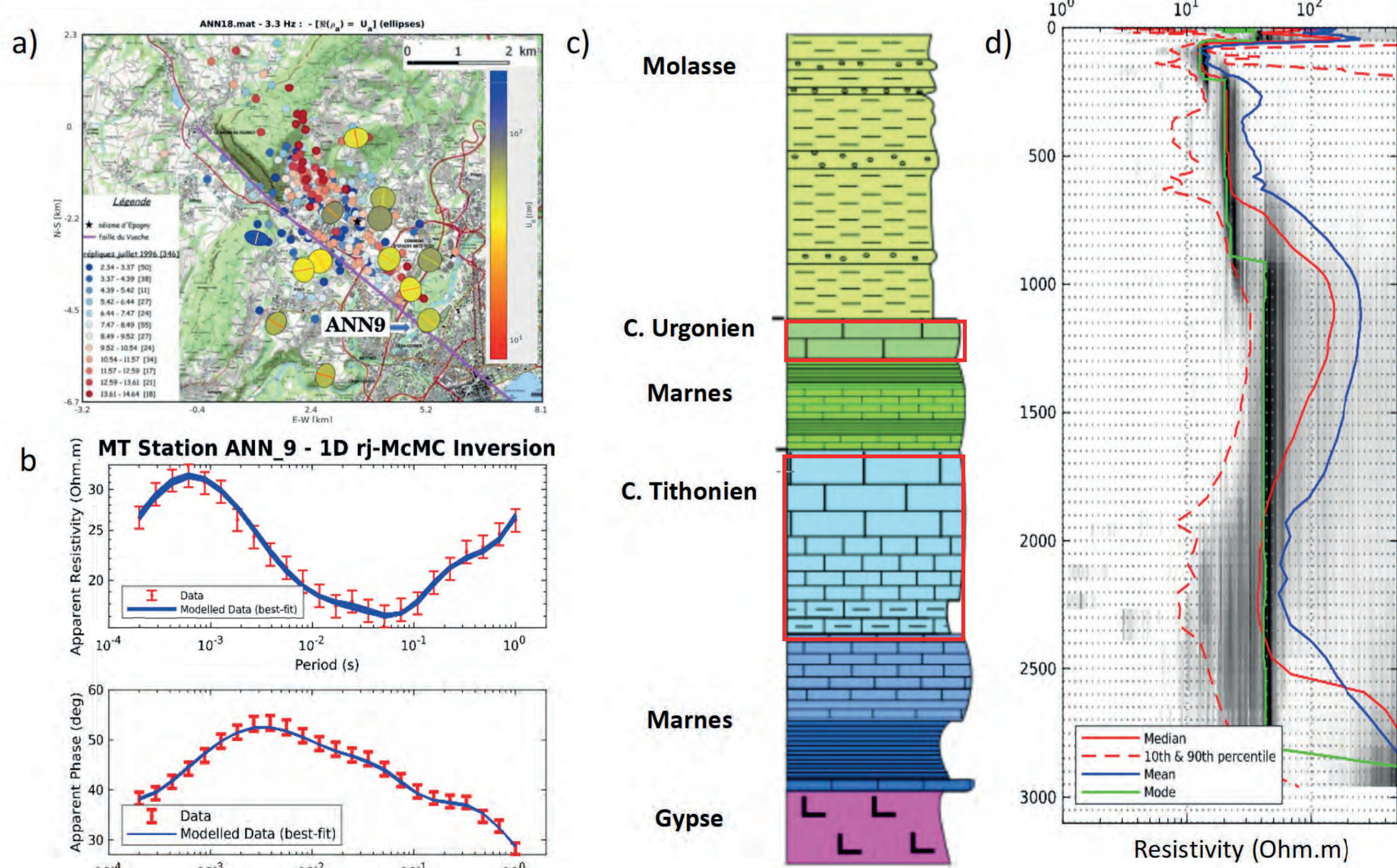
Interpretation of seismic line 88SVO-010 (SW-NE through Annecy), see point A on map at top



3D Geological model built on the basis of surface seismic surveys, well data, the geological map and surface reconnaissance after Dufour, 2019

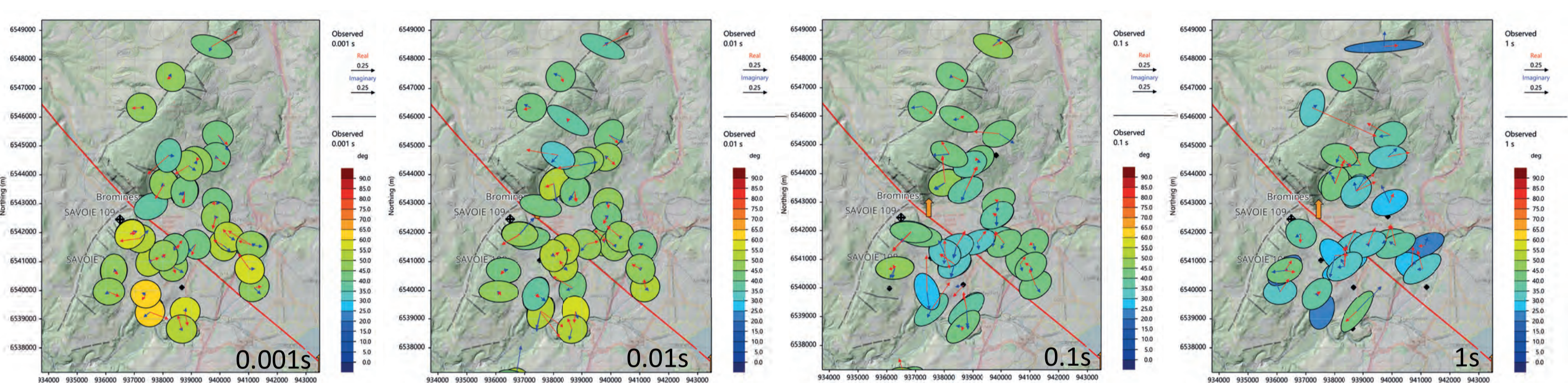
MT SURVEY WORK (2019-2024)

- 34 sites acquired over long periods (2-10 days) to obtain low frequency coverage to ~1-10s.
- High level of anthropic noise required careful bivariate processing (FFMT) making use of remote measurements acquired at Wittstock, Germany by GFZ (Ritter et al, 2015).
- 1D inversions indicate a possible link between the deep tithonian (Malm) aquifer and low resistivities



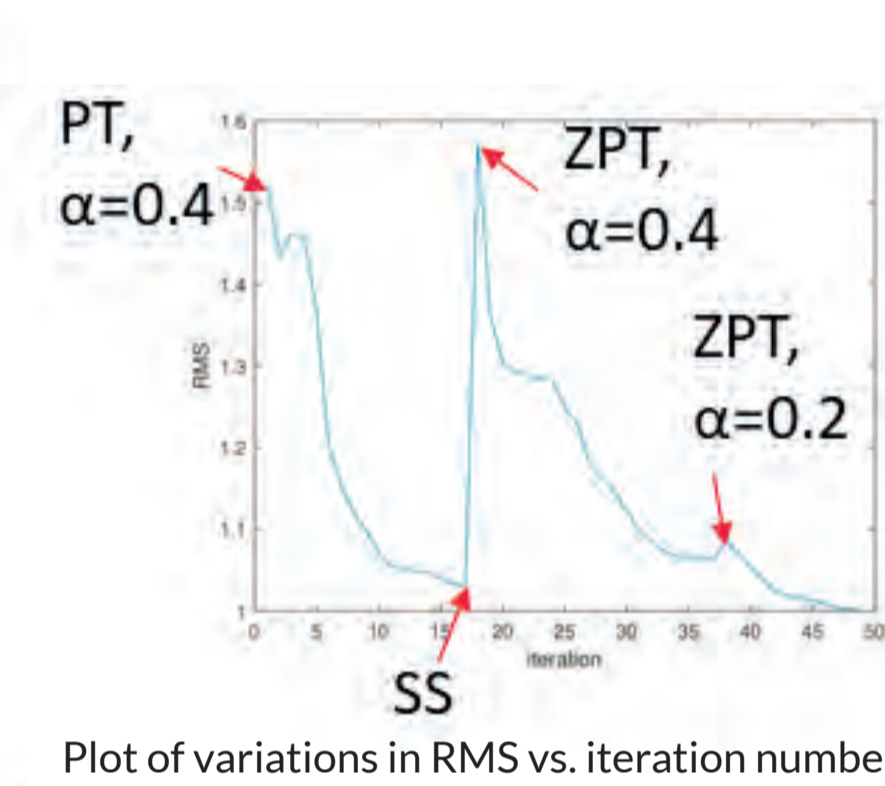
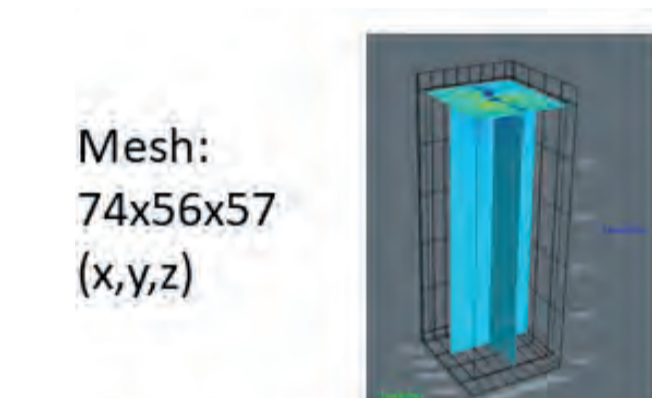
1D inversion with rjmcmt (Brodie and Jiang (2018))

MT PHASE TENSORS

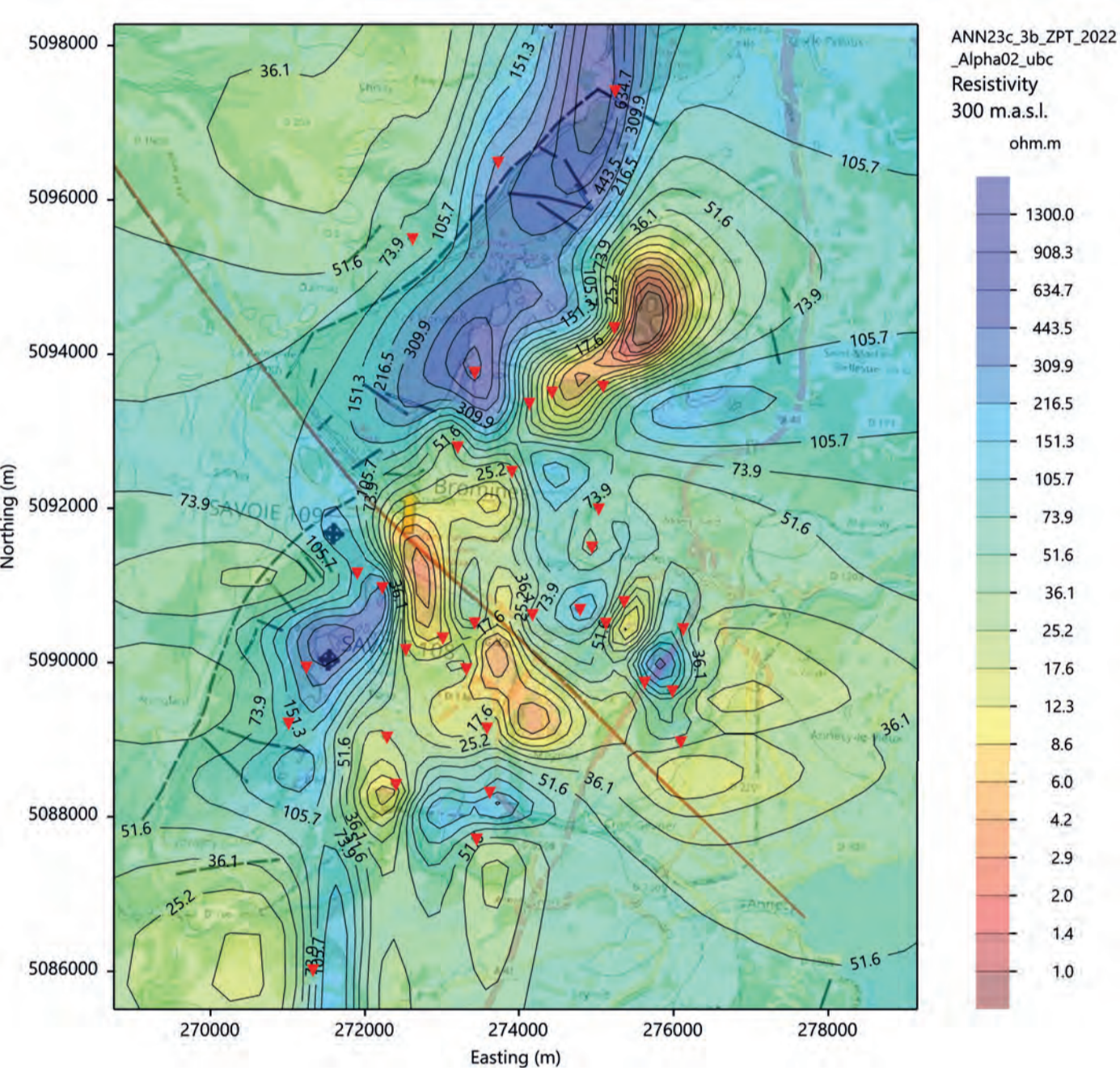


- Resistivity structure close to 1D to 0.01s (except on the ramp)
- Complex resistivity structure, including at depth
- Strike (long ellipse axis) at 1s approximately perpendicular to thrust axis

MT 3D INVERSION SCHEME WITH MODEM (KELBERT ET AL 2014)



1. 17 inversions of PT based on prior at 100 ohm.m, $\alpha = 0.4$
2. Static shift corrections
3. 20 inversions of Z,PT with $\alpha = 0.4$
4. 7 inversions of Z,PT with $\alpha = 0.2$

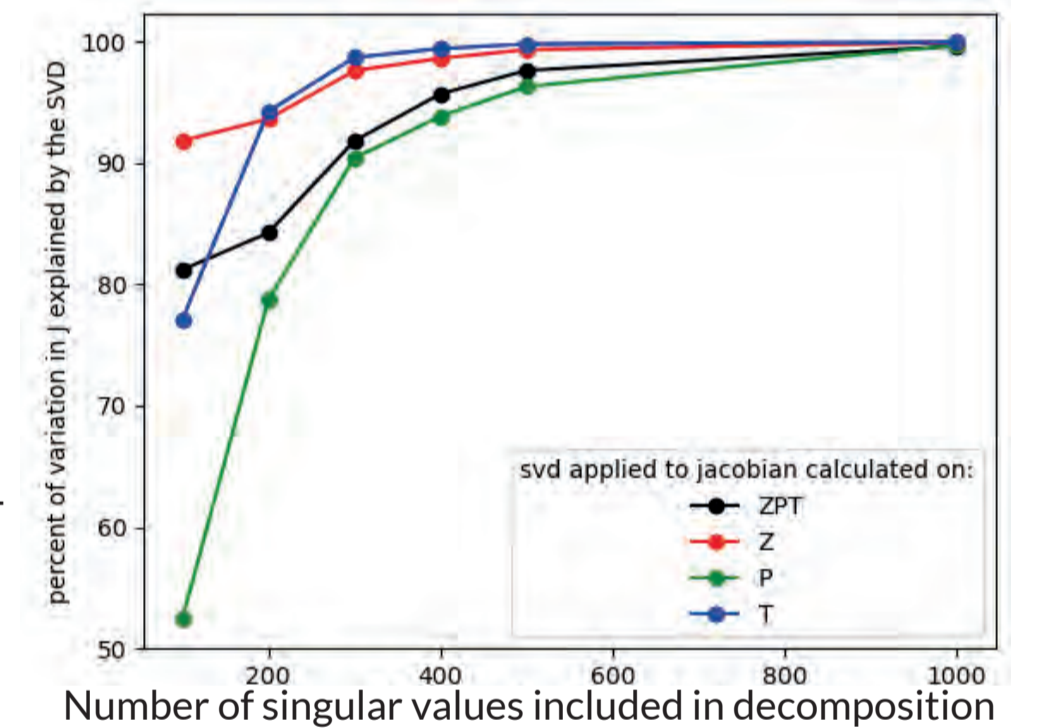


SENSITIVITY ANALYSIS (JacoPyAn, Rath 2024)

- Sensitivity matrix is reordered for analysis, reconstructed and visualised overlaid on resistivity contours (cross sections 1 and 2 in center)
- The jacobian (or sensitivity) matrix linking data d and

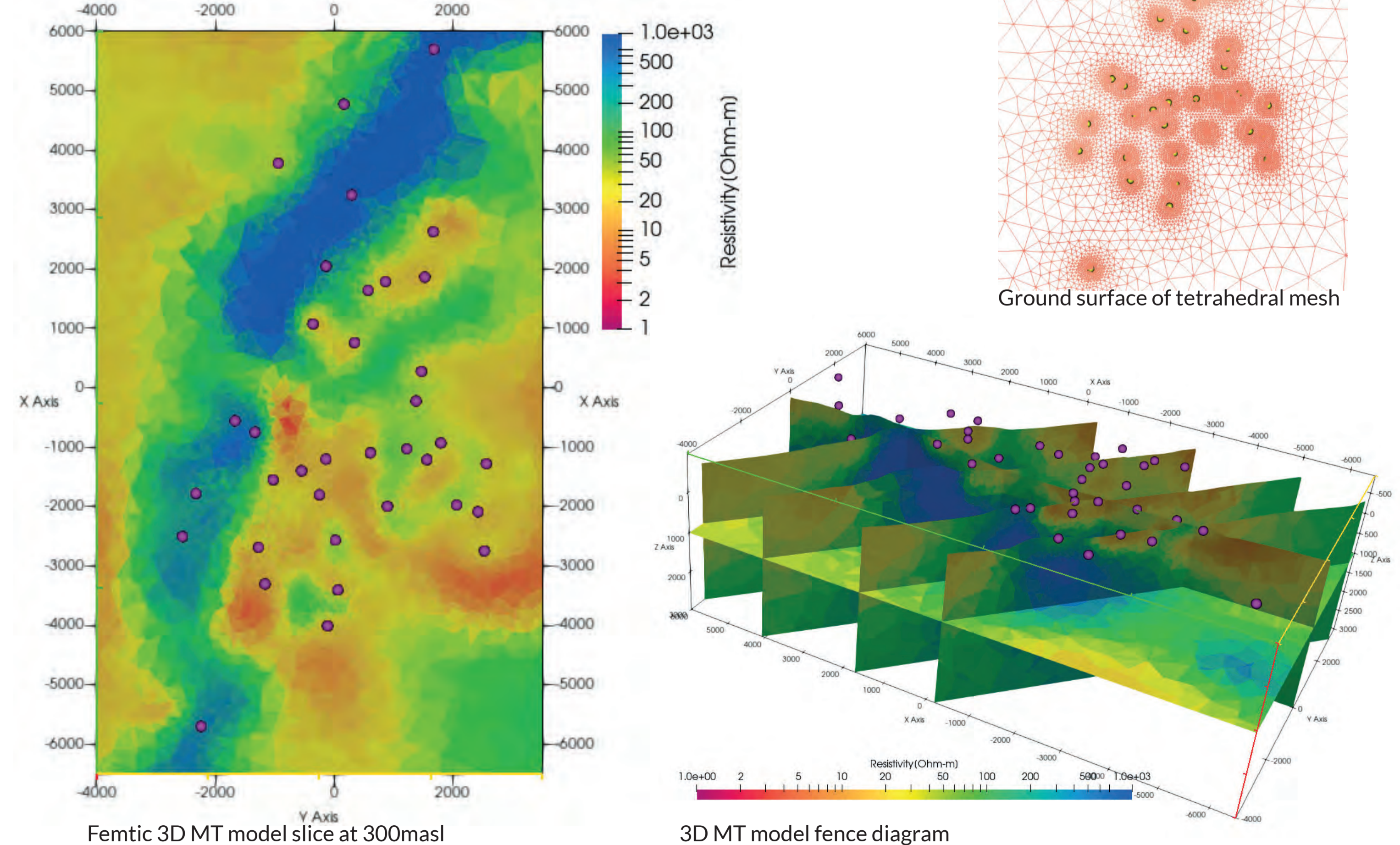
$$\text{parameter } m \text{ is defined as } J_{ij} = \frac{\delta d_i}{\delta m_j}$$

- We calculate it as s_j where: $s_j^2 = \sum_{i=1}^n |J_{ij}|^2 = \text{diag}(J^T J)$ and normalize it against its maximum value.
- The singular value decomposition of J informs on the complexity of the problem, and the relative sensitivity of each inverted parameter



MT 3D INVERSIONS USING FEMTIC: TETRAHEDRAL ADAPTIVE MESH AND RESULTING MODEL

- We have used a finite element MT inversion code (Femtic, Usui 2015) on a tetrahedral mesh based on the same dataset, with 2 stations added (36 in total)
- 400,000 elements
- 7 iterations of full tensor and tipper with trade-off parameter of 3, then 1 inversion with a trade-off parameter of 1.
- resulting RMS = 2.3
- Results coherent with ModEM inversion results, further improvement in RMS value requires reducing error floors and inverting for galvanic distortion.



PLANS

- Using the current best inverted model, forward modelling the karstic units with a range of resistivities to test the detectability of resistivity changes within them.
- Turning off smoothing at geological interfaces before running new inversions.
- Applying the nullspace shuttles (Muñoz and Rath, 2006) technique to test the compatibility of forward-modelled hypotheses with the inversion result.
- Reduce the size of the problem to test Monte-Carlo simulations with defined probability density functions for input variables
- Inferring porosities within the karstic units on the basis of inversion results by applying empirical relationships such as Archie's law.

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