Geophysical integration of joint inverted models using principal component analysis : application to geothermal exploration

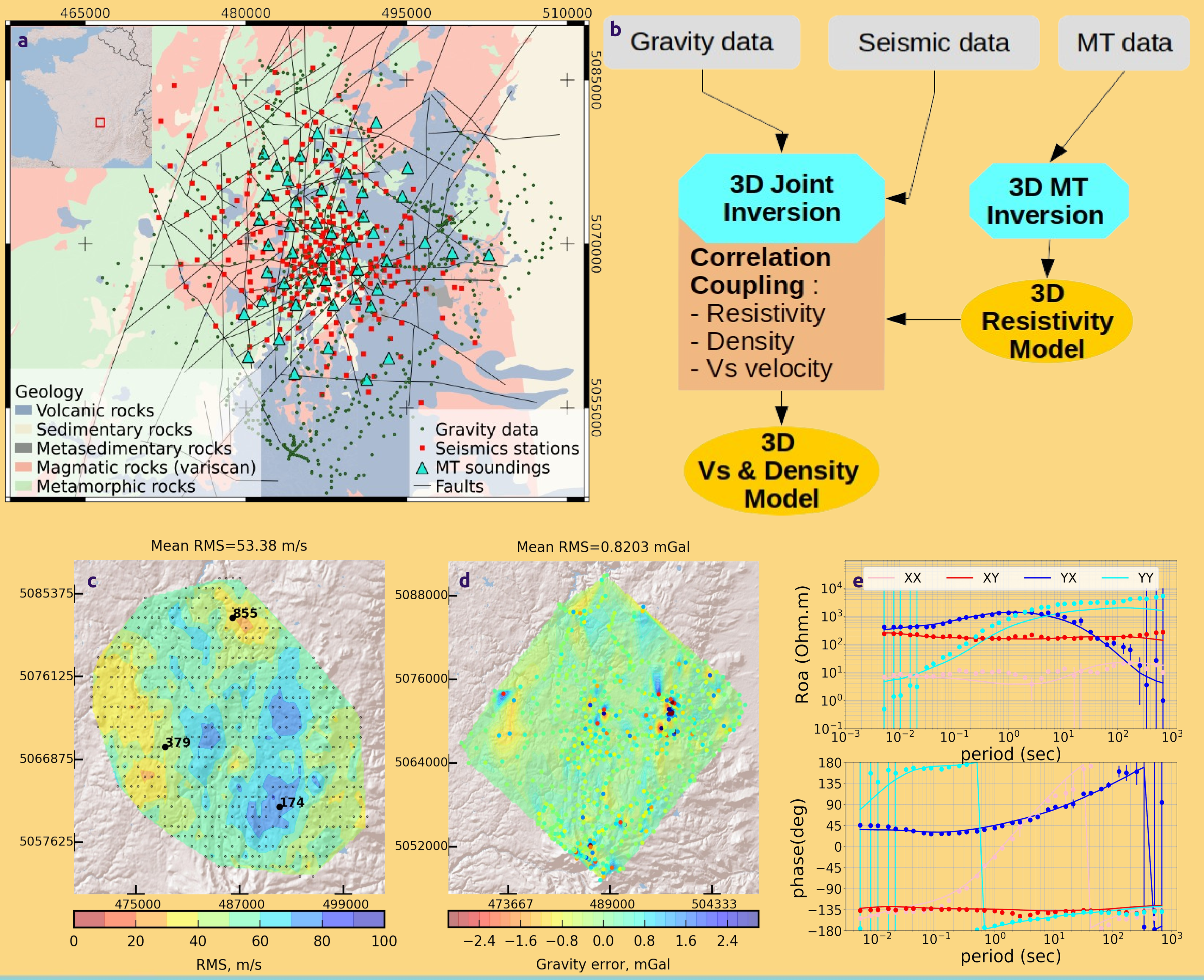
Jean-Michel Ars[1], Pascal Tarits[1,2], Sophie Hautot[2], Mathieu Bellanger[3], , Marcia Maïa[1]
Contact : jean-michel.ars@univ-brest.fr
(1) iuem (2) IMAGIR (3) TLS GEOTHERMICS

Geophysical integration cover a wide range of approach from the visual interpretation of model presented side by side to a sophistical statistical analysis like automatic clustering. We present here a geophysical models integration based on principal component analysis (PCA). PCA allow to gain insight on a multivariable system with high level of interaction. PCA aim to reorganize the system by finding a new set of variables distributed along new orthogonal axis and keeping most of the variance from the data. Thus geophysical interaction are highlighted along components that can be interpreted in terms of patterns. We applied this integration method to gravity, ambient noise tomography and resistivity models obtained from joint inversion in the frame of unconventional geothermal exploration in Massif Central, France. PCA of the log-resistivity, the density contrast and the Vs velocity model tend to highlight 3 independent components. The first one (PC1) ,representing 69% of the total variance of the system, is highly influence by the parameters coupling enforced through the joint inversion process. PC1 allows to isolate geophysical anomalies that may be related to the geothermal system. The second component (PC2) represents 22% of the total variance and is strongly correlated to the resistivity. It seems to be interpretable as a fault marker. The third component (PC1: 9% of the total variance) is still reliable and seems to be related to the 3D geometry of the geological units. Such statistical approach allows geophysical interpretation into a reliable geothermal conceptual model identifying the target object of geophysical exploration.

GEOPHYSICAL DATA & JOINT INVERSION

Geothermal exploration based on **multi-physic imaging** methods along a major crustal fault zone on the edge of a granitic body (see figure below)

- **45 MT soundings**
  → Full impedance tensors, **3D inversion at all periods**
- **299 vertical geophones**
  → seismic data processed in **579 local dispersion curves**, using cross-correlation and FTAN analysis, **1D inversion**
- **627 gravity measurements**
  → Residual of the complete Bouguer anomaly 3D inversion



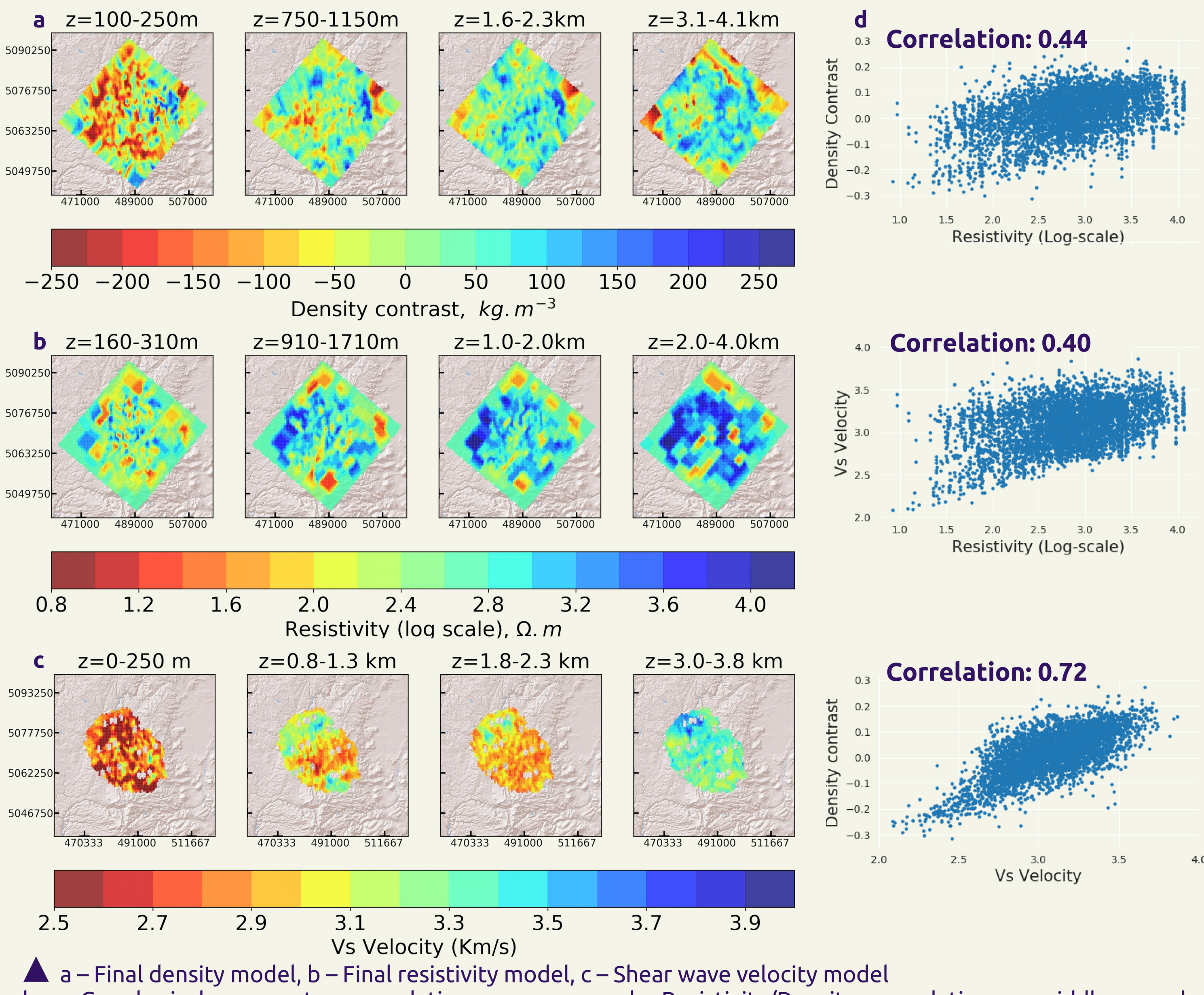
◀ a – Geophysical survey map overlaying pre-existing geological and fault models
b - Joint Inversion approach from Ars et al. (2019)
c – Final ambient noise tomography residual map by dispersion curves
d - Final gravity residual map
e – Example of 3D resistivity model response fit to the data on one typical MT impedance tensor.

GEOPHYSICAL MODELS

The joint inversion approach effectively increased **correlation between geophysical parameters** at model scale.
→ local correlated patterns between models

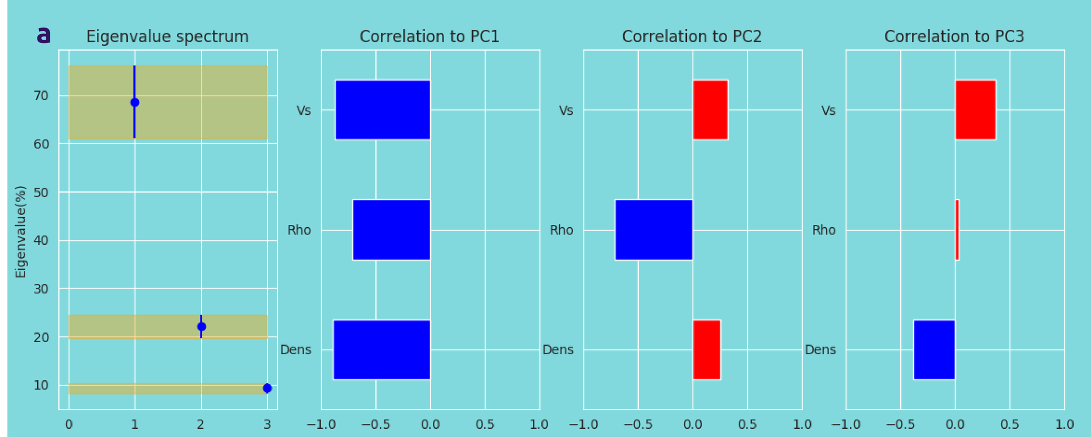
Nevertheless geological features such as faults or lithology are not easy to interpret from geophysical models. Indeed joint inversion does not completely overcome **inversion issues** and **coupling terms impose assumptions** on models. Moreover there are **complex interactions** between geophysical properties.

Interpretation of multi-physic approach into a **conceptual model requires integration**
→ Integration method based on PRINCIPAL COMPONENT ANALYSIS



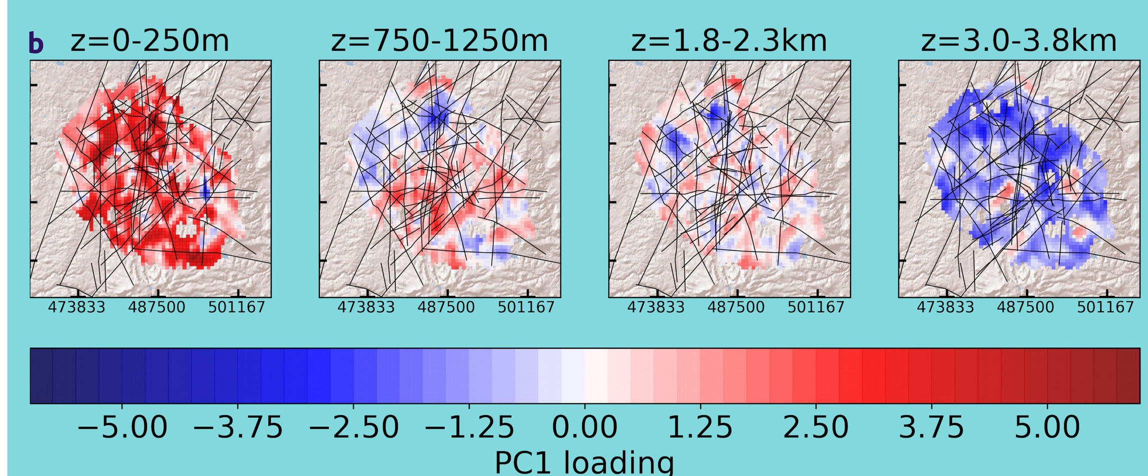
▲ a – Final density model, b – Final resistivity model, c – Shear wave velocity model
d – Geophysical parameter correlation, upper panel: Resistivity/Density correlation, middle panel: Resistivity/Velocity Correlation, lower panel: Velocity/Density correlation.

PRINCIPAL COMPONENT ANALYSIS

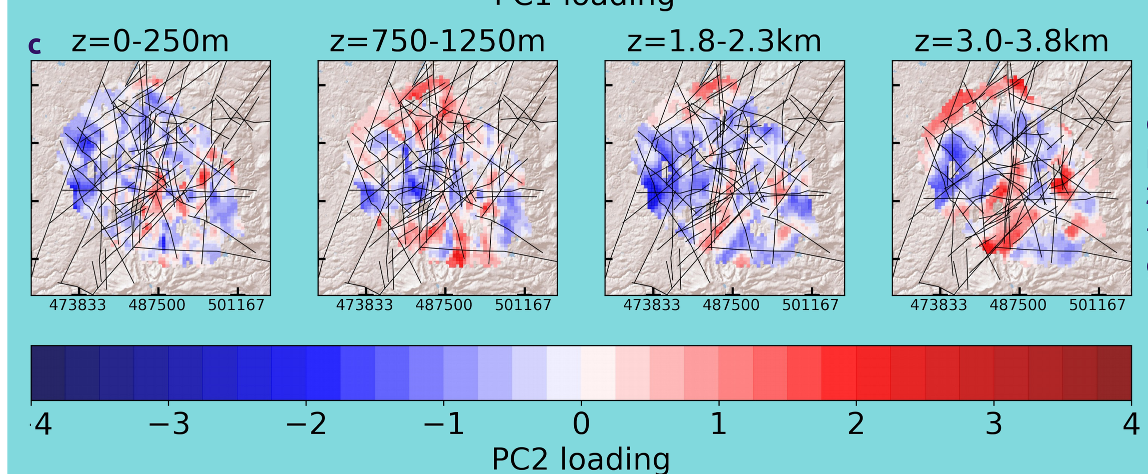


Principal Component Analysis (PCA) or Empirical Orthogonal Function (EOF) « aims at finding a new set of variables that **capture most of the observed variance** from the data » (Hannachi et al, 2007) along new **orthogonal components**.

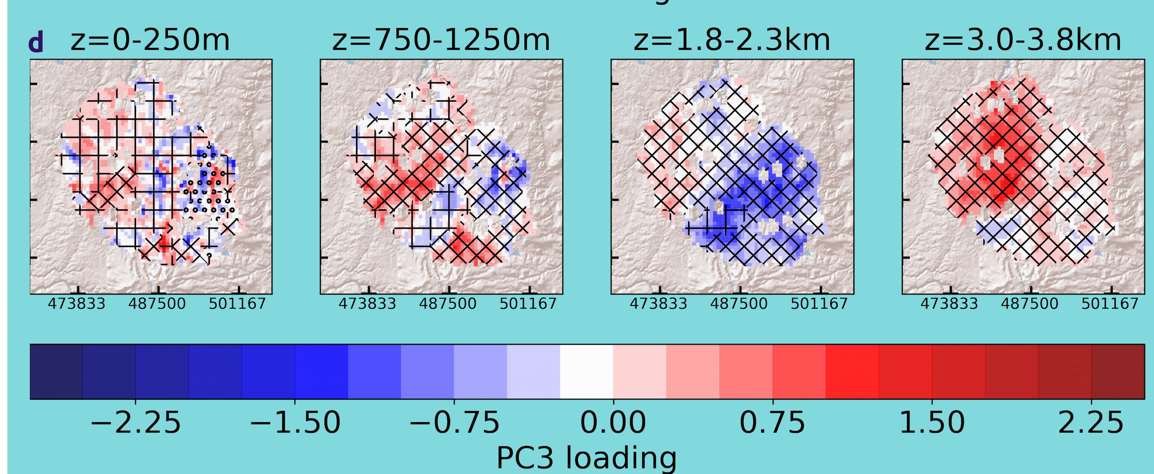
PCA can be used for **dimensionality reduction** or **pattern extraction**. Widely used in climate science, oceanography, social science…



PC1 represents 69 % of variance, equally correlated to every geophysical parameter. PC1 highlight parameters correlation enforced by the coupling term of the joint inversion.
High positive PC1 anomalies at fault intersection (in depth) reveal strong correlation of low resistivity, low density, low velocity
→ PC1 may be related to alteration process



PC2 represents 22 % of variance, anti-correlated to resistivity. Negative PC2 features superimpose with high density fault zone from pre-existing model
→ PC2 as a mean to constrain faults geometry with depth



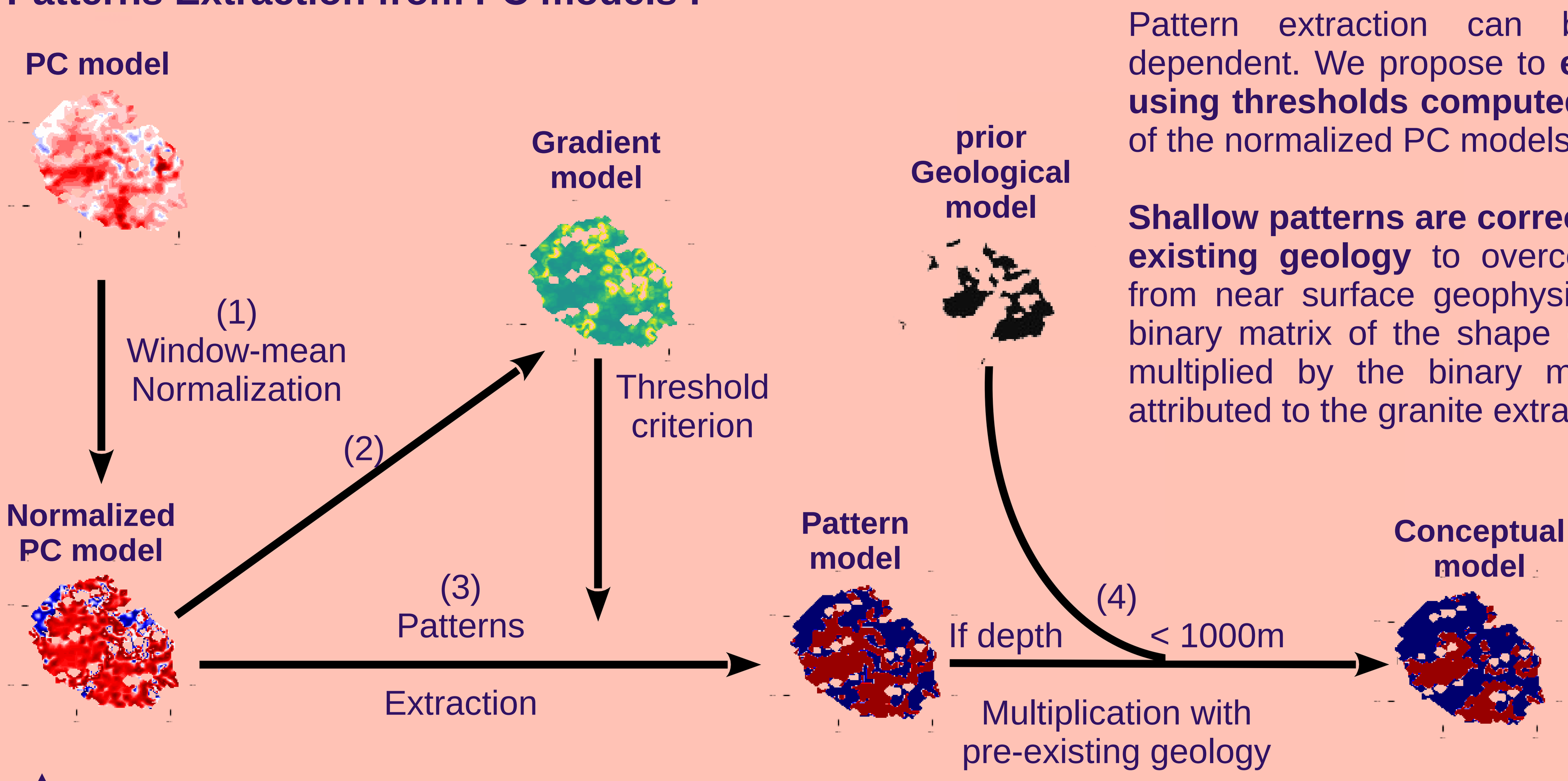
PC3 represents 9 % of variance and is correlated to Vs velocity and anti-correlated to density. Shallow positive PC3 features are in accordance with the pre-existing geological model down to 1km

→PC3 may constrain the geometry of the lithology in depth

▲ a - Covariance matrix spectrum and PC correlation to geophysical parameter
b - PC1 loading model with prior fault model
c – PC2 loading model with prior fault model
d – PC3 loading model with pre-existing geological model (tilted hatches : granitic, vertical hatches : metamorphic, dots : volcanic)

GEOPHYSICAL INTEGRATION

Patterns Extraction from PC models :

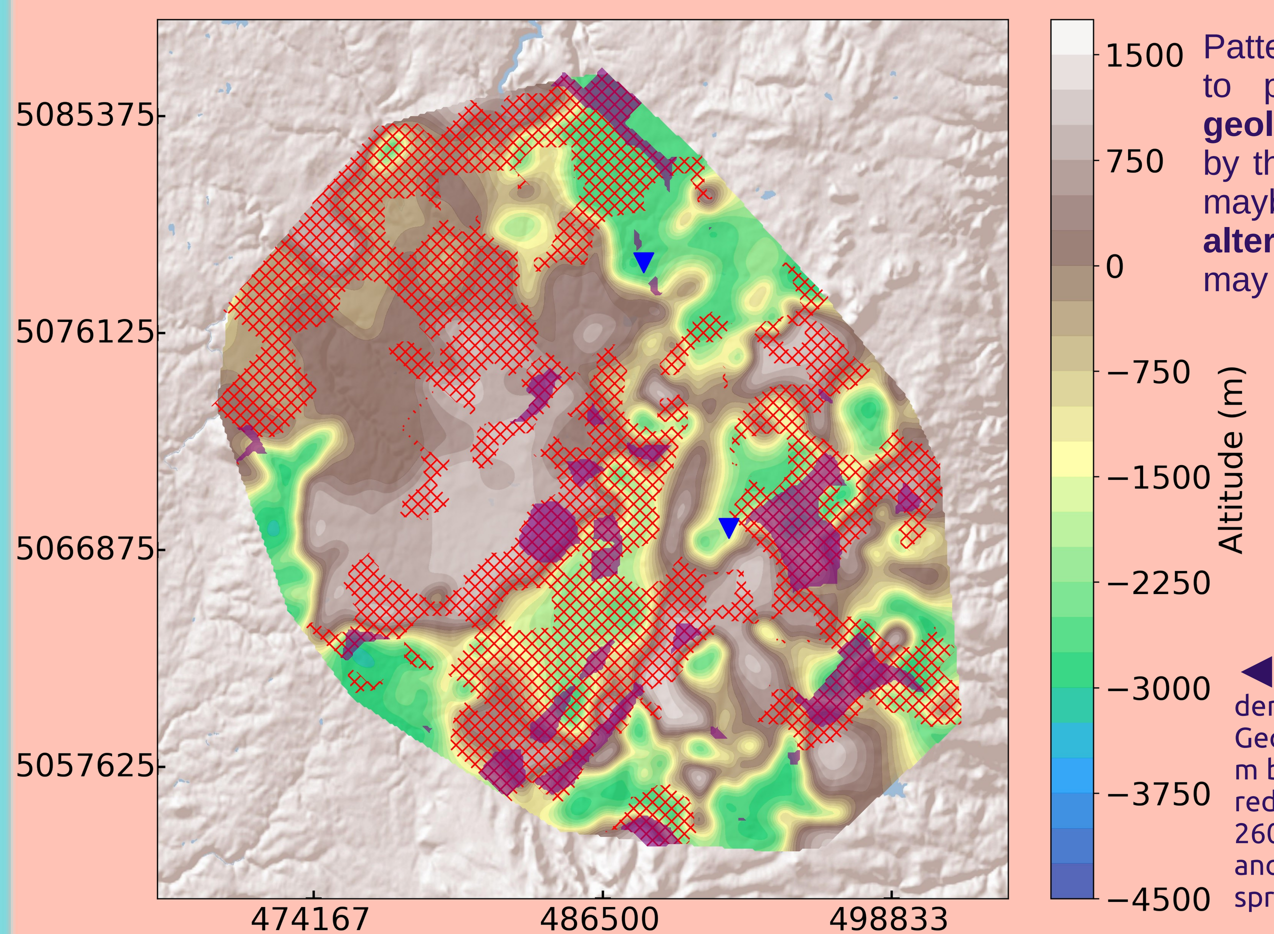


Pattern extraction can be very user-dependent. We propose to **extract patterns using thresholds computed from gradient** of the normalized PC models.

Shallow patterns are corrected by the pre-existing geology to overcome instabilities from near surface geophysical models. Ex: binary matrix of the shape of the granite is multiplied by the binary matrix of pattern attributed to the granite extracted from PC3.

▲ (1) Running absolute mean-normalization (Normalize by the absolute mean of a window scanning the model). (2) Gradient computation. (3) Extract pattern from normalized model depending on a threshold based on gradient model. (4) Correct pattern model with the pre-existing geological model for shallow layers (<1000m depth)

Conceptual Model :



Pattern extraction from PC models allow to propose a **3D geometry of the geological model constrained in depth** by the geophysical models. Moreover we maybe able to define **potential zone of alteration** within the fault network that may be related to geothermal activities.

◀ 3D Geometry of the top of the granite derived from PC3 colored with depth. Geometry of the main conductive faults at 2600 m below surface derived from PC2 colored with red hatches. Potential alteration zones at 2600m below surface derived from PC1 anomalies colored in purple. Thermo-mineral springs represented with blue triangles

Ars, J. M., Tarits, P., Hautot, S., Bellanger, M., Coutant, O., & Maia, M. (2019). Joint inversion of gravity and surface wave data constrained by magnetotelluric: application to deep geothermal exploration of crustal fault zone in felsic basement. Geothermics, 80, 56-68.

Hannachi, A., Jolliffe, I. T., & Stephenson, D. B. (2007). Empirical orthogonal functions and related techniques in atmospheric science: A review. International Journal of Climatology: A Journal of the Royal Meteorological Society, 27(9), 1119-1152.