# Bayesian joint inversion of muographic and gravimetric data for the 3D imaging of volcanoes, case study of the Puy de Dôme

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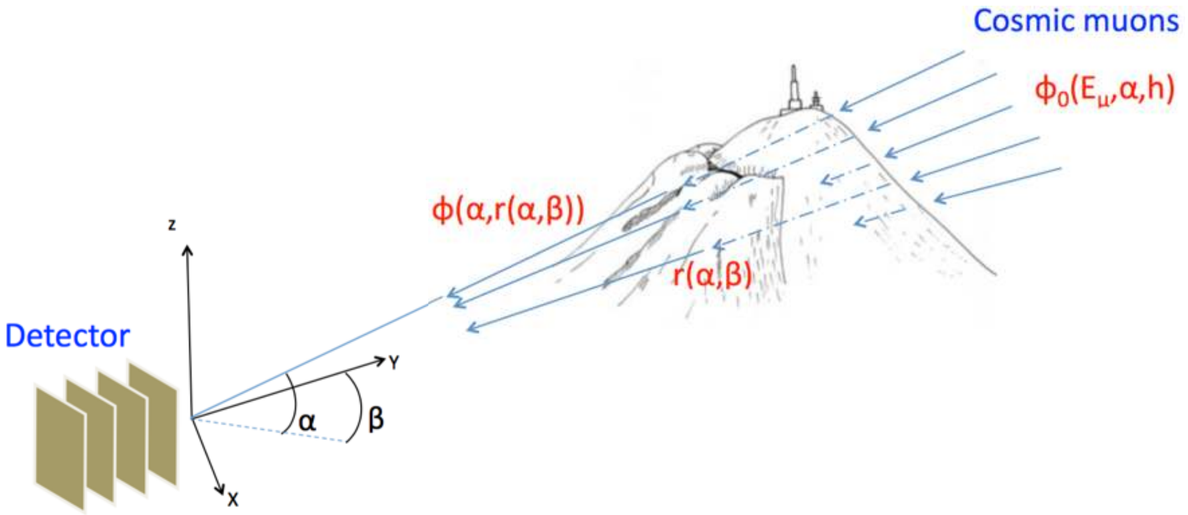
# Why jointly inverting muographic and gravimetric data?



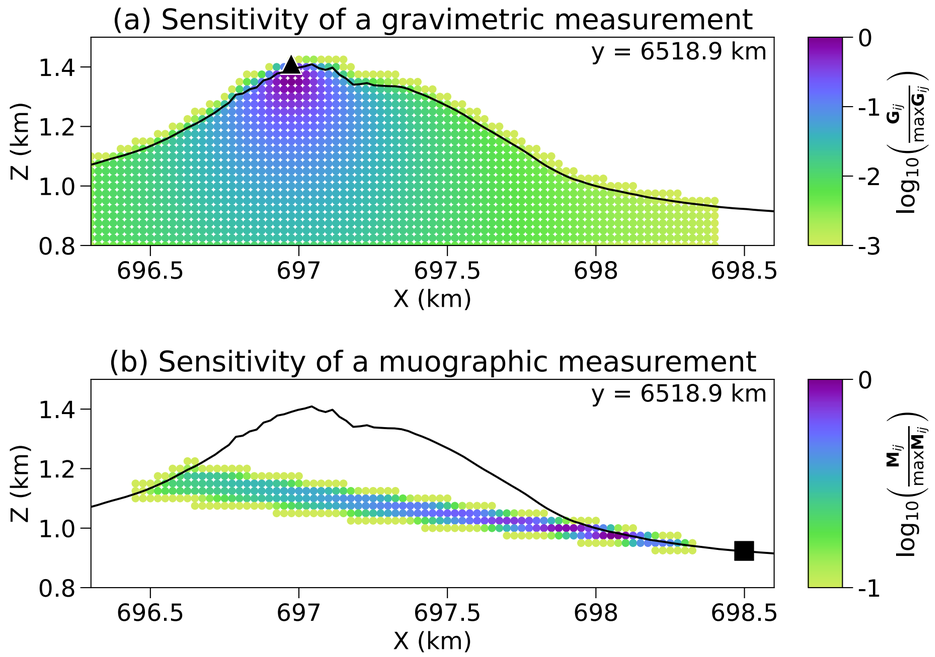

## What is muography?

Idea: **radiography with muons** -> 2D images of averaged density

## Muons

- come from the interaction of **cosmic rays** with the atmosphere (free!)
- similar to electron, 200 times heavier
- **interact with matter in a stochastic way** (depending on their energies and **density** of the medium)
- at high energy **cross several kms of matter** before decaying

## Sensitivity of gravimetric and muographic data to the density

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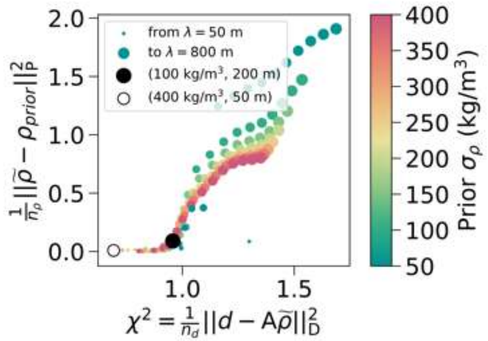
> **Bayesian joint inversion** of muographic and gravimetric data

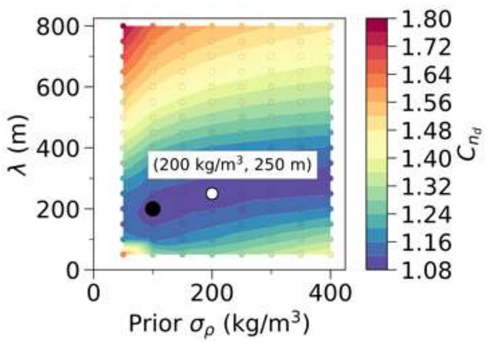
# Determination of the inversion regularization parameters

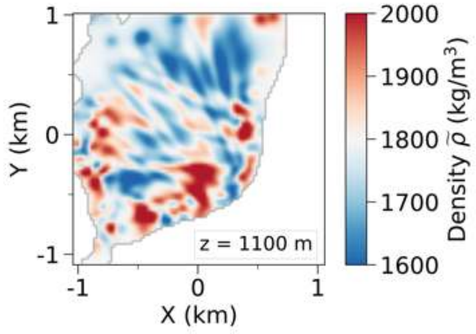
- Systematic determination of the regularization parameters
  - ***a priori* density standard deviation**
  - **spatial correlation length**

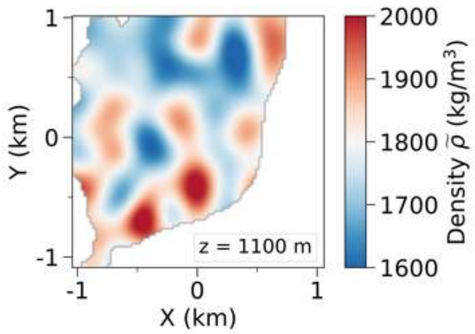
**L-curve**



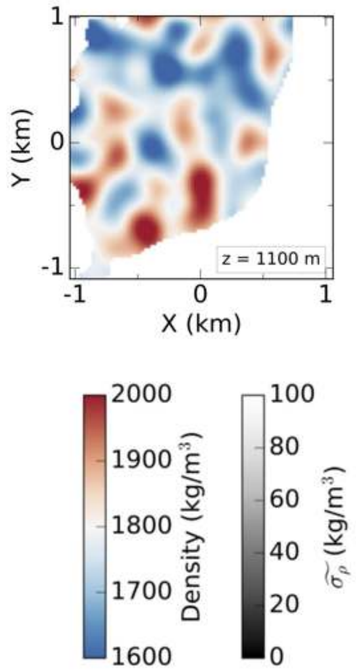

**Leave One Out**



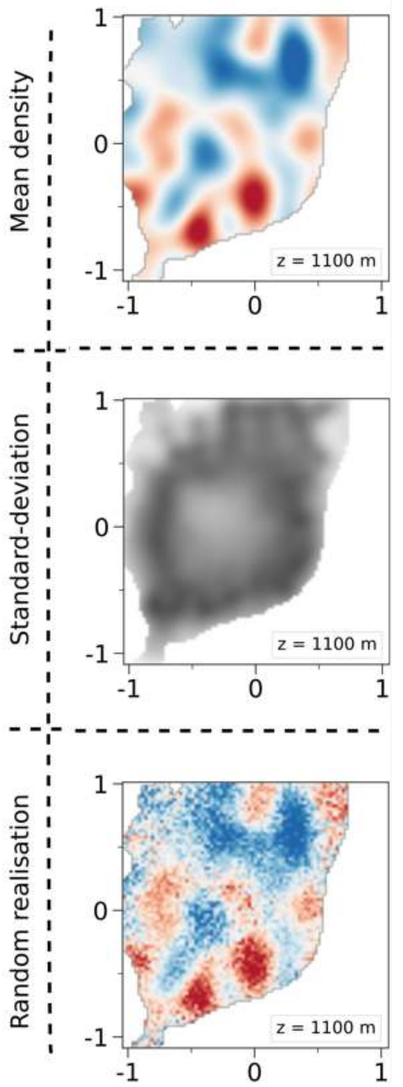




**Synthetic model**




**Inversion result**

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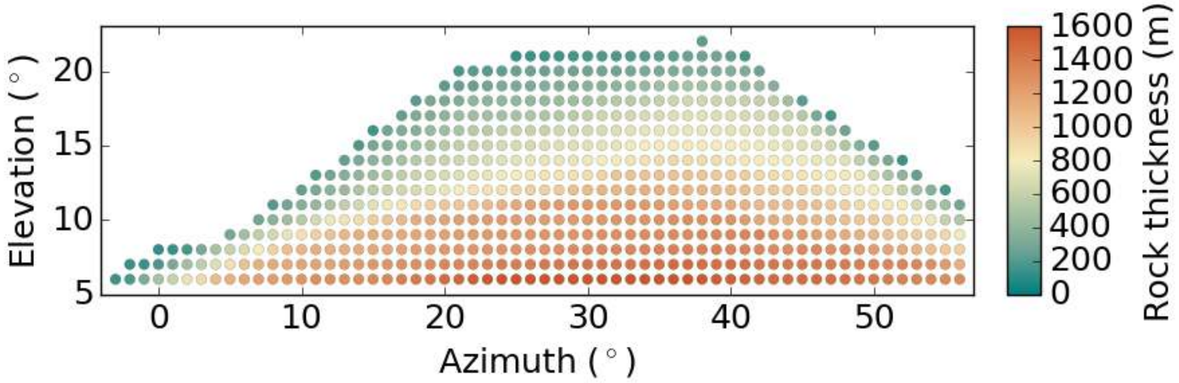
> **Leave One Out** criterion to determine the two regularization parameters

# Data from the Puy de Dôme volcano (France)


Rock thickness crossed by muons detected at the Col de Ceyssat (CDC)

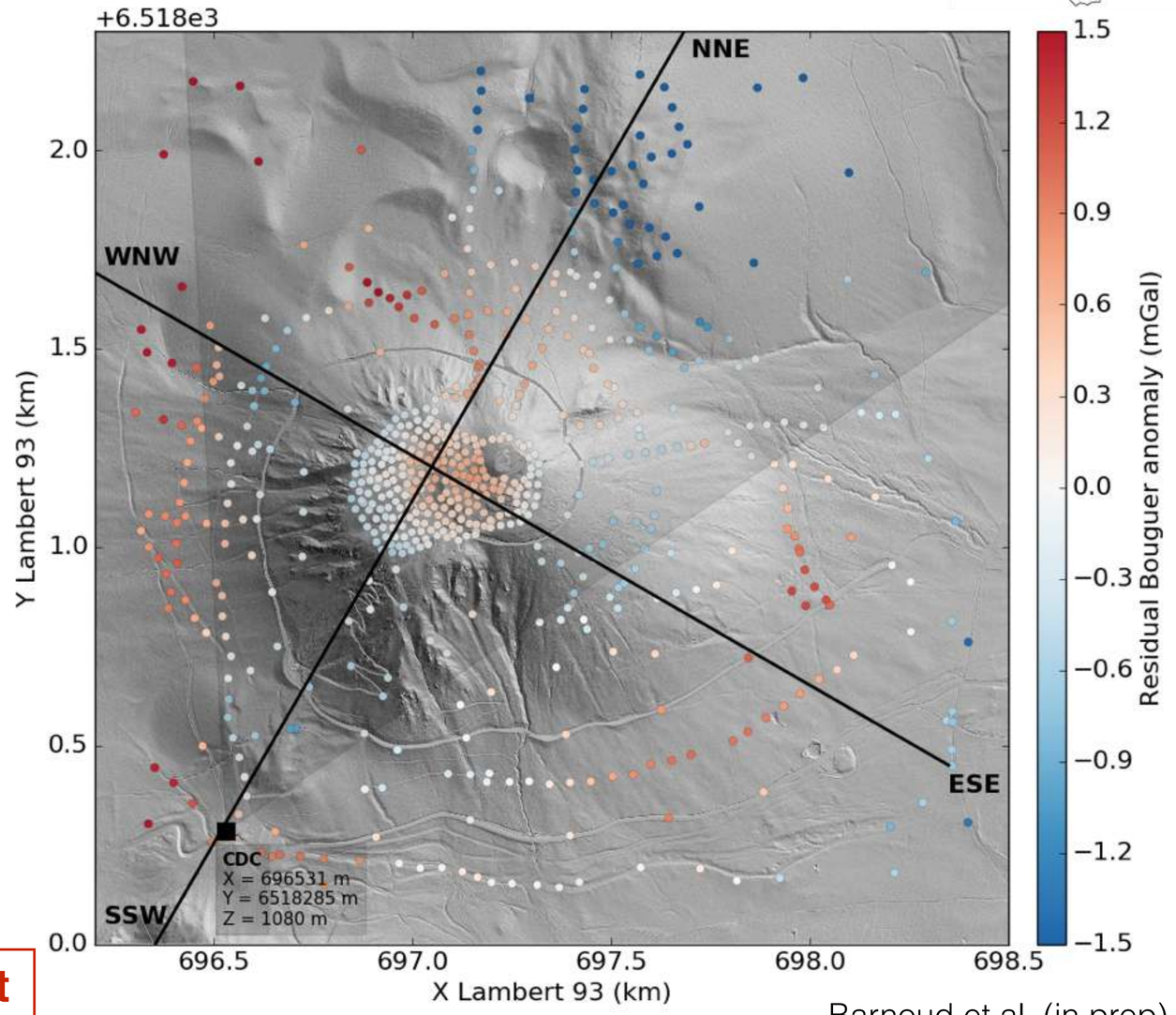



Estimation of average density

- from gravimetric data: **~1890 kg/m³** (Nettleton/Parasnis methods)
- from muographic data: **~1660 kg/m³** (weighted by rock thickness)

- from dry rock samples: ~1839 kg/m³
- from saturated rock samples: ~2044 kg/m³

> Least-square determination of a **constant density offset**

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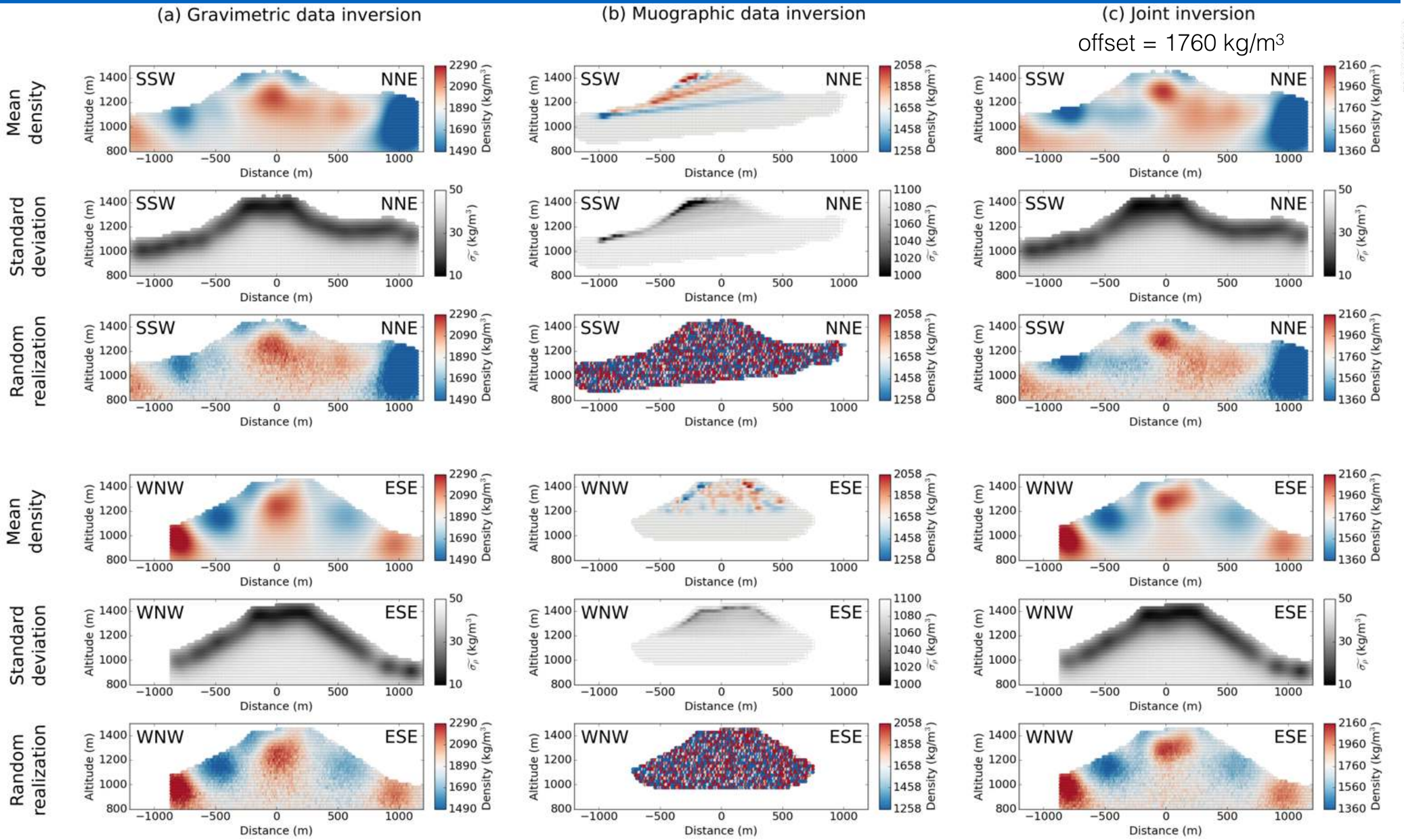
# Slices from the 3D independent and joint inversion results

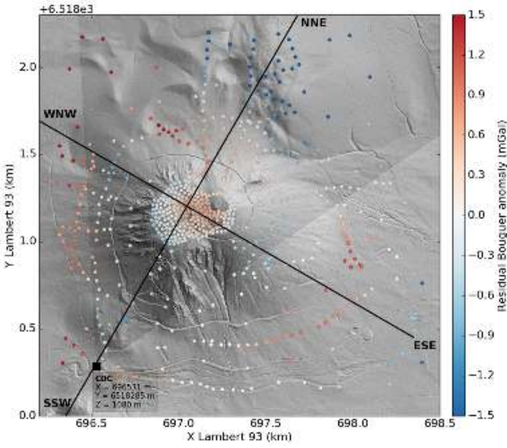
(a) Gravimetric data inversion

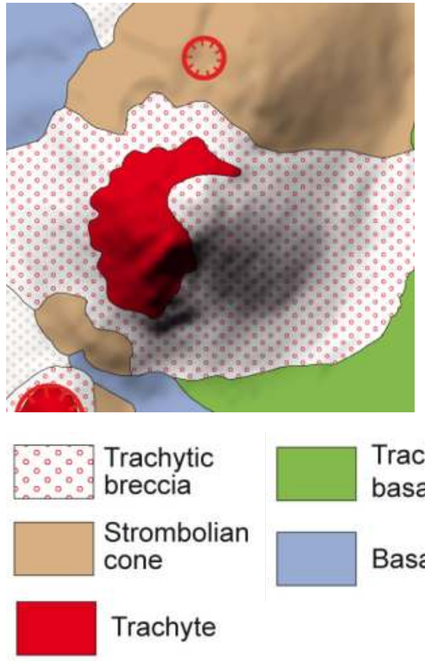
(b) Muographic data inversion

(c) Joint inversion

offset = 1760 kg/m$^3$

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# Conclusions and references

## Conclusions

- Robust method validated on synthetic and real data
  - Bayesian inversion with estimation of resolution parameters
  - Leave One Out criterion to determine the two regularization parameters
  - Least-square automatic determination of a constant density offset between the two datasets
- 3D density imaging of the Puy de Dôme
  - The muographic data help better delineating the trachytic core of the dome.
  - The recovered densities are in accordance with a dry and permeable dome.

## References


- Barnoud A., Cayol V., Lelièvre P. G., Portal A., Labazuy P., Boivin P., Gailler L. Robust Bayesian joint inversion of gravimetric and muographic data for the density imaging of the Puy de Dôme volcano (France), *to be submitted*.
- Barnoud A., Cayol V., Niess V., Cârloganu C., Lelièvre P., Labazuy P., Le Ménédeu E., 2019. Bayesian joint muographic and gravimetric inversion applied to volcanoes, *Geophysical Journal International* 218 (3), 2179-2194. doi:10.1093/gji/ggz300.
- Lelièvre P. G., Barnoud A., Niess V., Cârloganu C., Cayol V., Farquharson C. G., 2019. Joint inversion methods with relative density offset correction for muon tomography and gravity data, with application to volcano imaging, *Geophysical Journal International* 218 (3), 1685-1701. doi:10.1093/gji/ggz251.