Present-day surface deformation of the Alpine Region inferred from geodetic techniques

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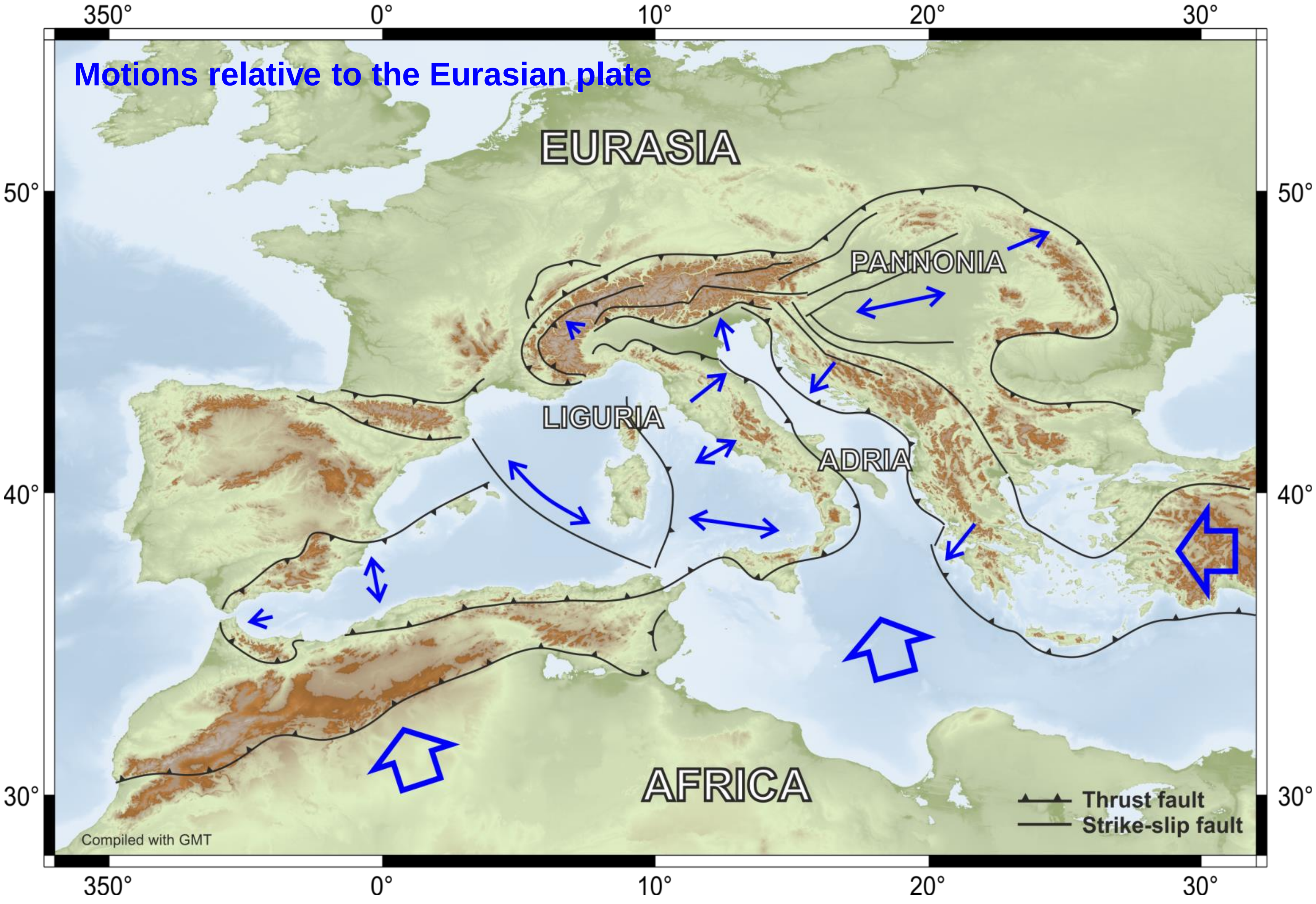
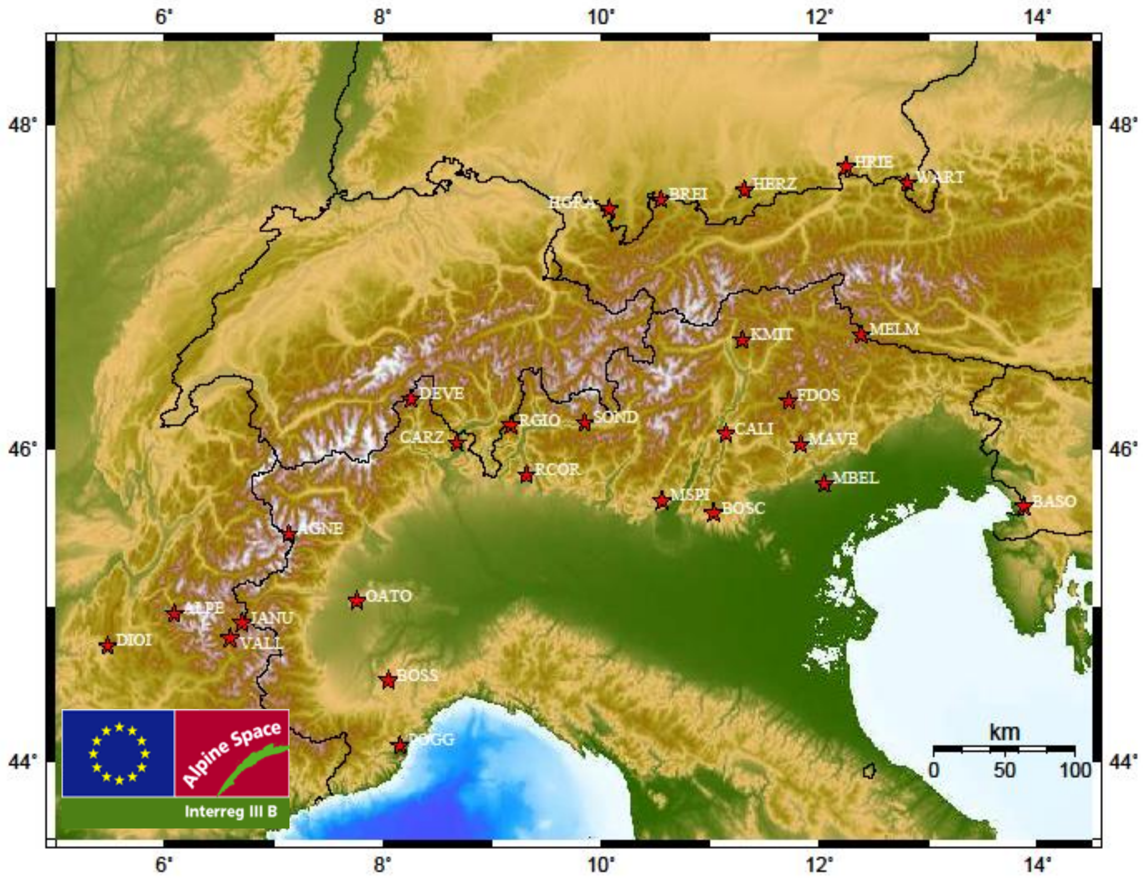
(Simplified) Tectonic framework in the Alps



Motivation

- The EU INTERREG III-B Alpine Space Programme established in 2004 the **project ALPS GPSQUAKENET** with the objective of installing the GPS array **GAIN** (**Geodetic Alpine Integrated Network**): duration **Jan 2004 to Mar 2007**, budget 2,424,638 €.
- ALPS GPSQUAKENET was supported by partners from
  - **France** (2): Institut Physique du Globe de Strasbourg and Laboratoire de Géophysique Interne et Tectonophysique (Grenoble)
  - **Italy** (7): Regional Authorities from Piedmont, Veneto, Bolzano, Liguria, Lombardy, Trento, and the Fondazione Montagna Sicura, Dipartimento di Scienze della Terra (UniversityTrieste)
  - **Germany** (2): Deutsches Geodätisches Forschungsinstitut (DGFI-TUM) and Bayerische Akademie der Wissenschaften (BAdW)
  - **Slovenia** (1): Environmental Agency of the Republic of Slovenia
  - **Switzerland** and **Austria** did not participate in the project.

GPS array GAIN: Geodetic Alpine Integrated Network



- About 30 continuously operating GNSS stations were installed between 2004 and 2006.
- The data collection still continues.
- Since 2007, DGFI-TUM and BAdW regularly computed positions and velocities of some stations of this network.
- The uncertainty of the results was larger than the deformation signals to be detected.
- Solution: A longer period of observations to become uncertainty values very much less that deformation signals.
- In 2016, it was possible to obtain a first suitable solution.

Geodetic surface deformation modelling

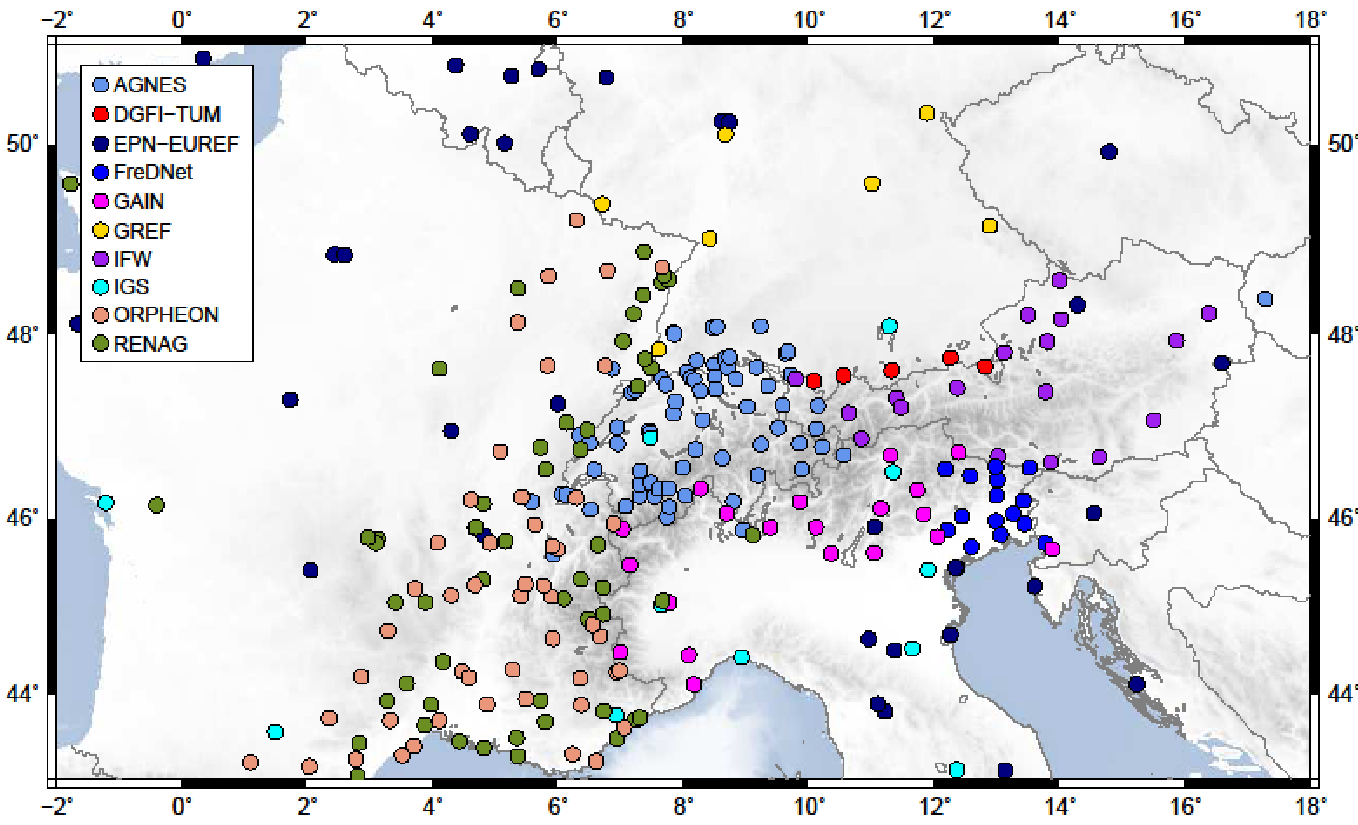
1) High-level data processing of GNSS observations collected over 12 years along the Alpine Region → **Precise station positions and velocities**

2) Removal of the Eurasia plate motion from the (observed) station velocities → **Deformation vectors**

3) Interpolation of the deformation vectors to a regular grid using a geodetic Least Squares Collocation approach (LSC) → **Deformation model**

4) Estimation of deformation gradients and computation of strain components → **Strain field** (Horizontal projection of the surface deformation)

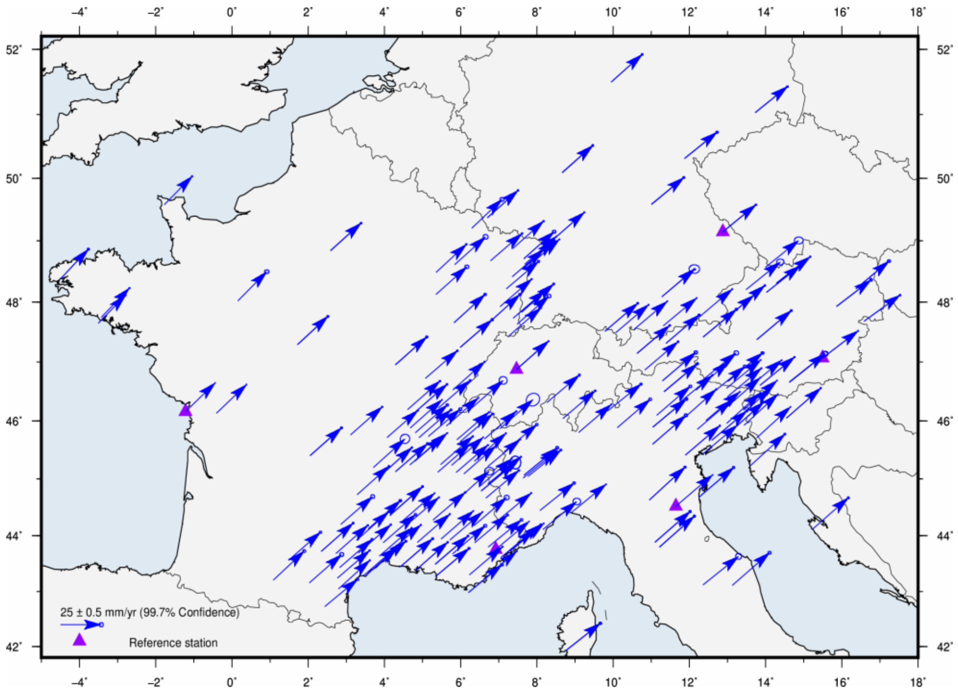
GNSS stations processed for the estimation of the surface deformation in the Alps

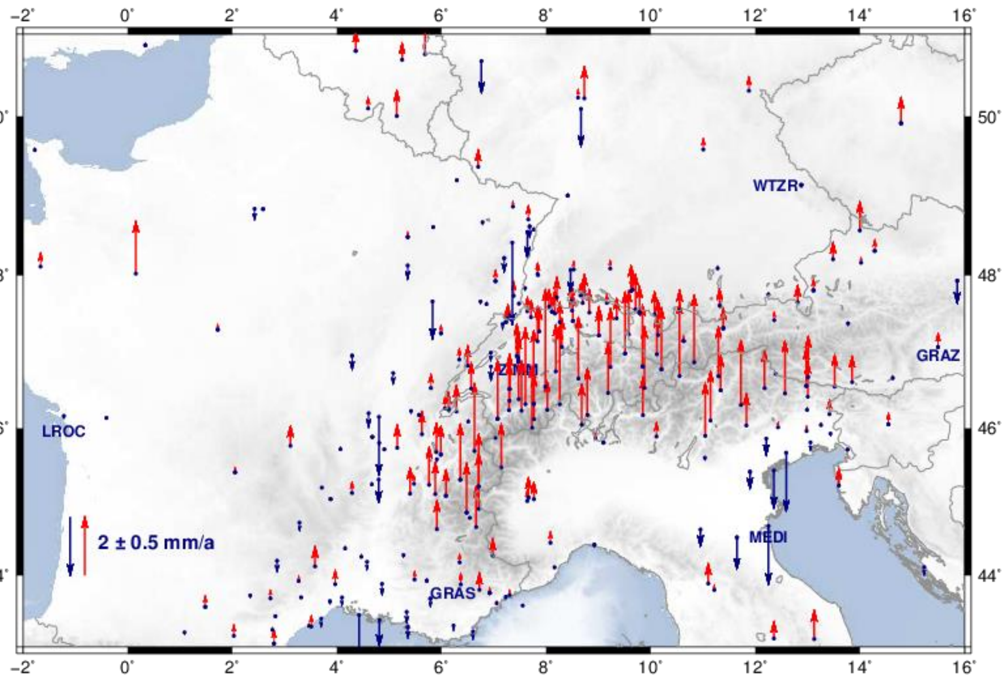


GAIN stations plus stations provided by

- International GNSS Service – **IGS**
- Reference Frame Sub-Commission for Europe of the International Association of Geodesy – **EUREF**
- Federal Agency for Cartography and Geodesy of Germany (BKG) – **Germany**
- Space Research Institute of the Austrian Academy of Sciences – **Austria**
- Centro Ricerche Sismologiche (CRS) of the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS) – **Italy**
- Réseau National GPS – **France**
- Orpheon network – **France**
- Automated GNSS Network for **Switzerland** – AGNES (coordinate solution from **swisstopo**)

Station positions and velocities



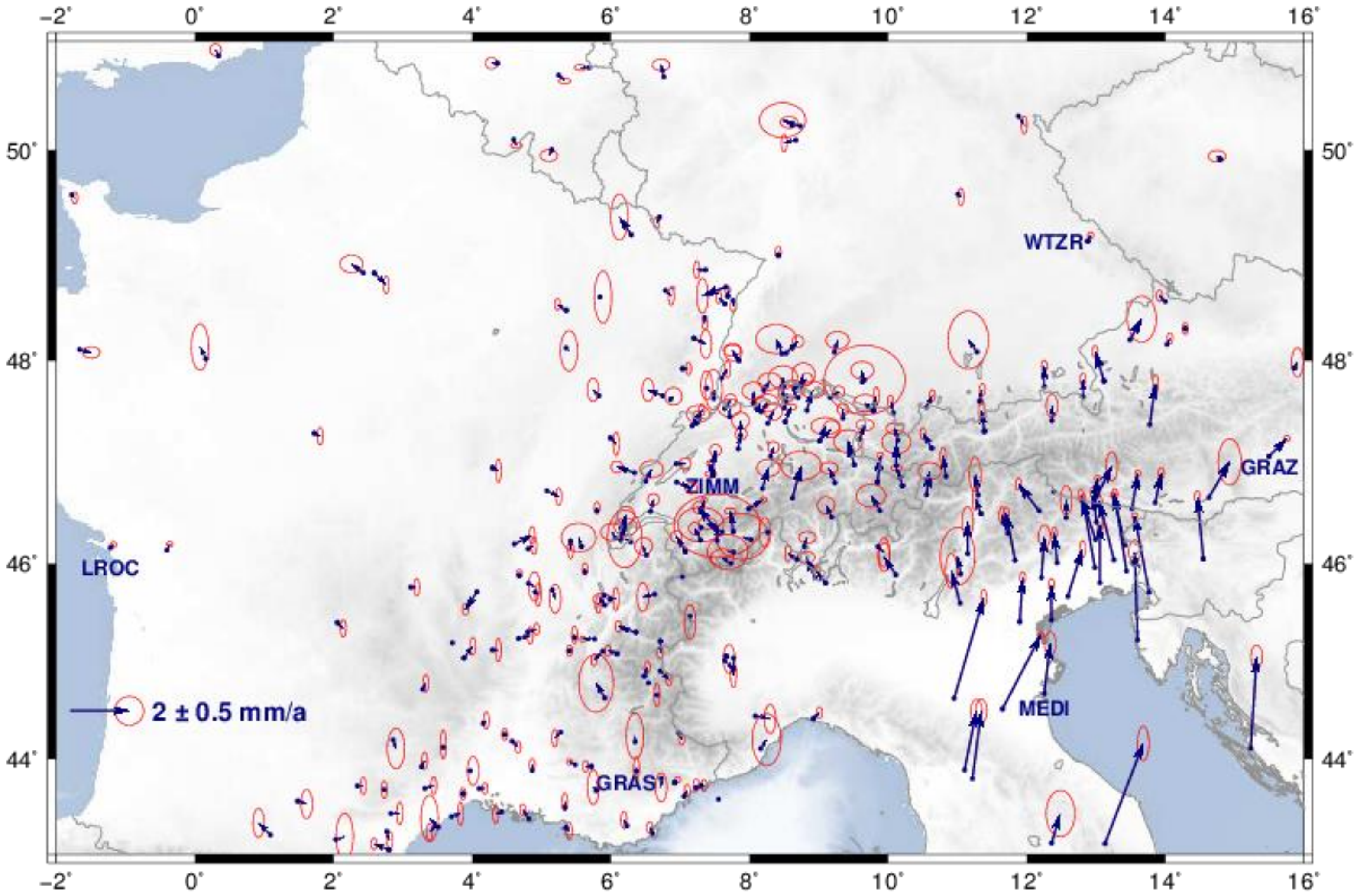


- Time span: 2004-01-01 to 2016-05-30
- Bernese GNSS Software V.5.2 (Dach et al. 2015)
- GPS + GLONASS
- Reference frame IGS08/IGb08
- Reference epoch 2010.0
- 306 occupations

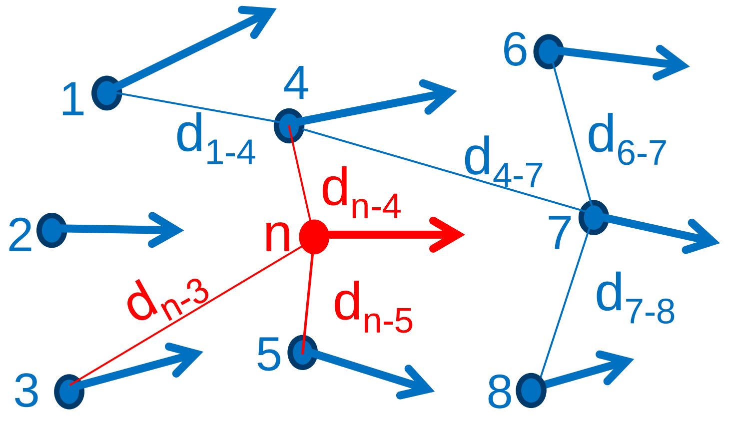
- Mean precision of station positions at the reference epoch
  N – E = ±1.1 mm ; h = ±2.3 mm
- Mean precision of the station velocities
  $V_N – V_E$ = ±0.2 mm/a ; V_h = ±0.4 mm/a

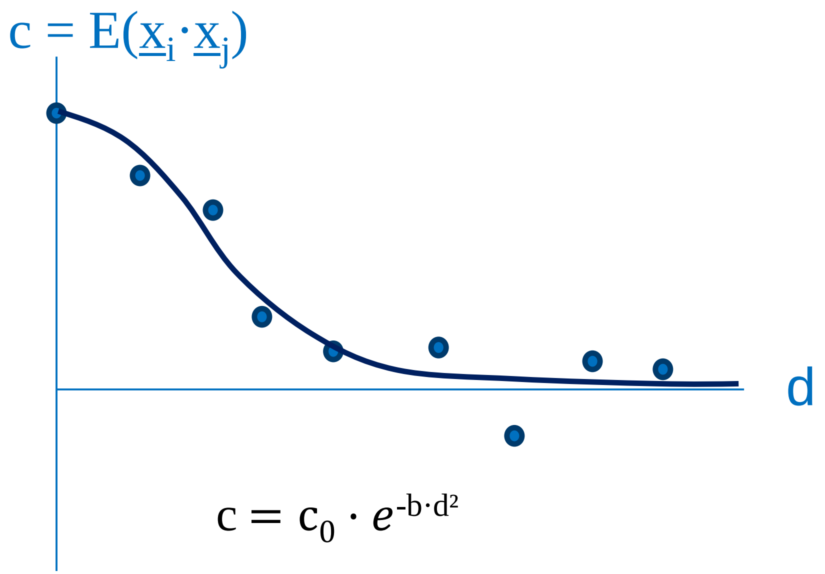
Horizontal deformation vectors

after removing the Eurasian plate motion from the station velocities



Modelling of deformations based on the geodetic Least Squares Collocation approach (LSC)





Vector prediction:

$$\mathbf{v}_{pred} = \mathbf{C}_{new}^{T} \left(\mathbf{C}_{obs} + \mathbf{C}_{nn} \right)^{-1} \mathbf{v}_{obs}$$

$\mathbf{v}_{\mathrm{pred}}$ = predicted velocities in a regular grid

$\mathbf{v}_{\mathrm{obs}}$ = (observed) velocities in geodetic stations

$\mathbf{C}_{\mathrm{new}}$= correlation matrix between predicted and observed vectors

$\mathbf{C}_{\mathrm{obs}}$= correlation matrix between observed vectors

$\mathbf{C}_{\mathrm{nn}}$= noise covariance matrix (uncertainty of the station velocities)

$\mathbf{C}_{\mathrm{obs}}$ and $\mathbf{C}_{\mathrm{new}}$ are built from empirical isotropic, stationary covariance functions

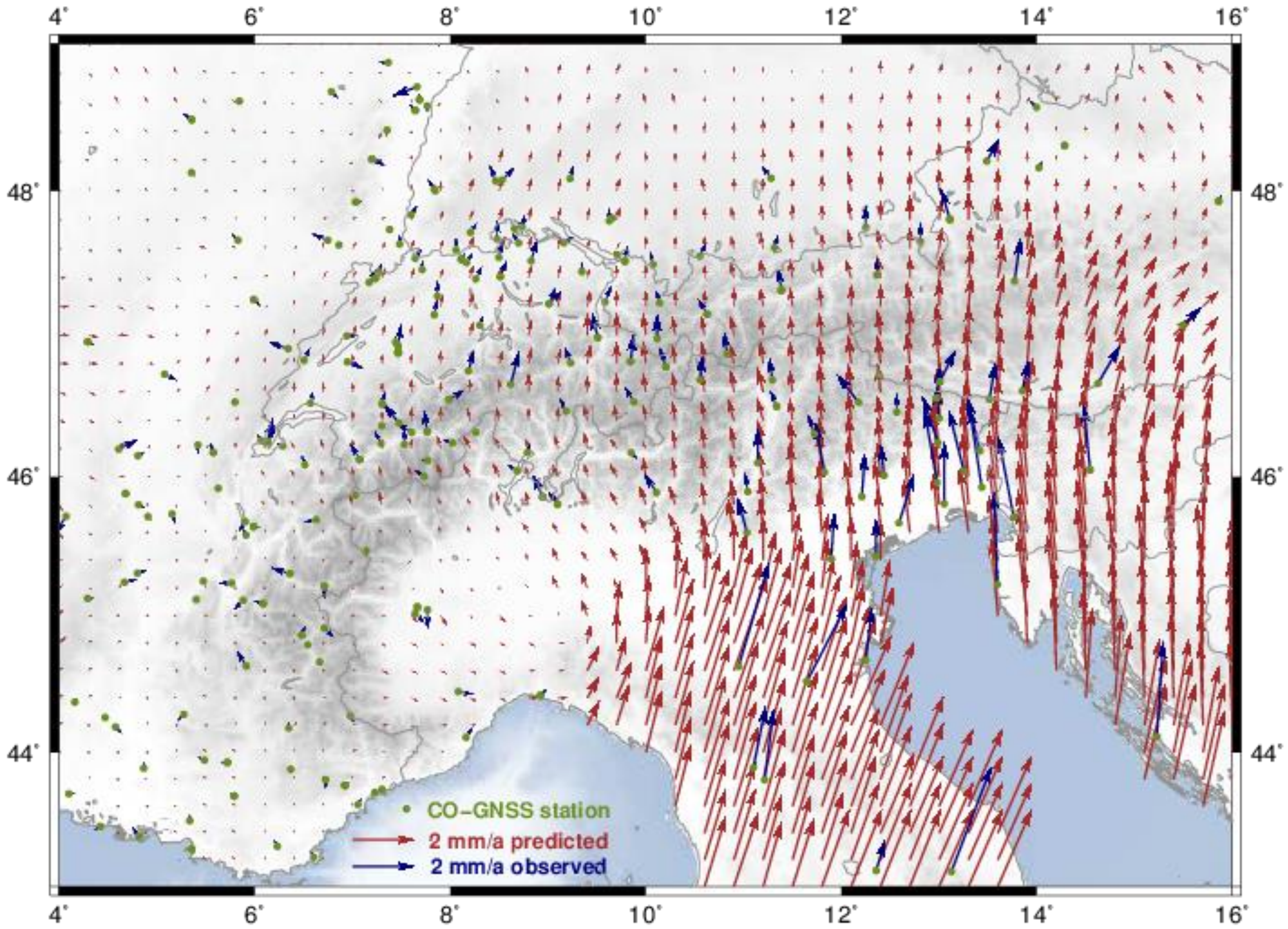
d = maximum correlation distance:

d ≤ 100 km for the horizontal deformation model

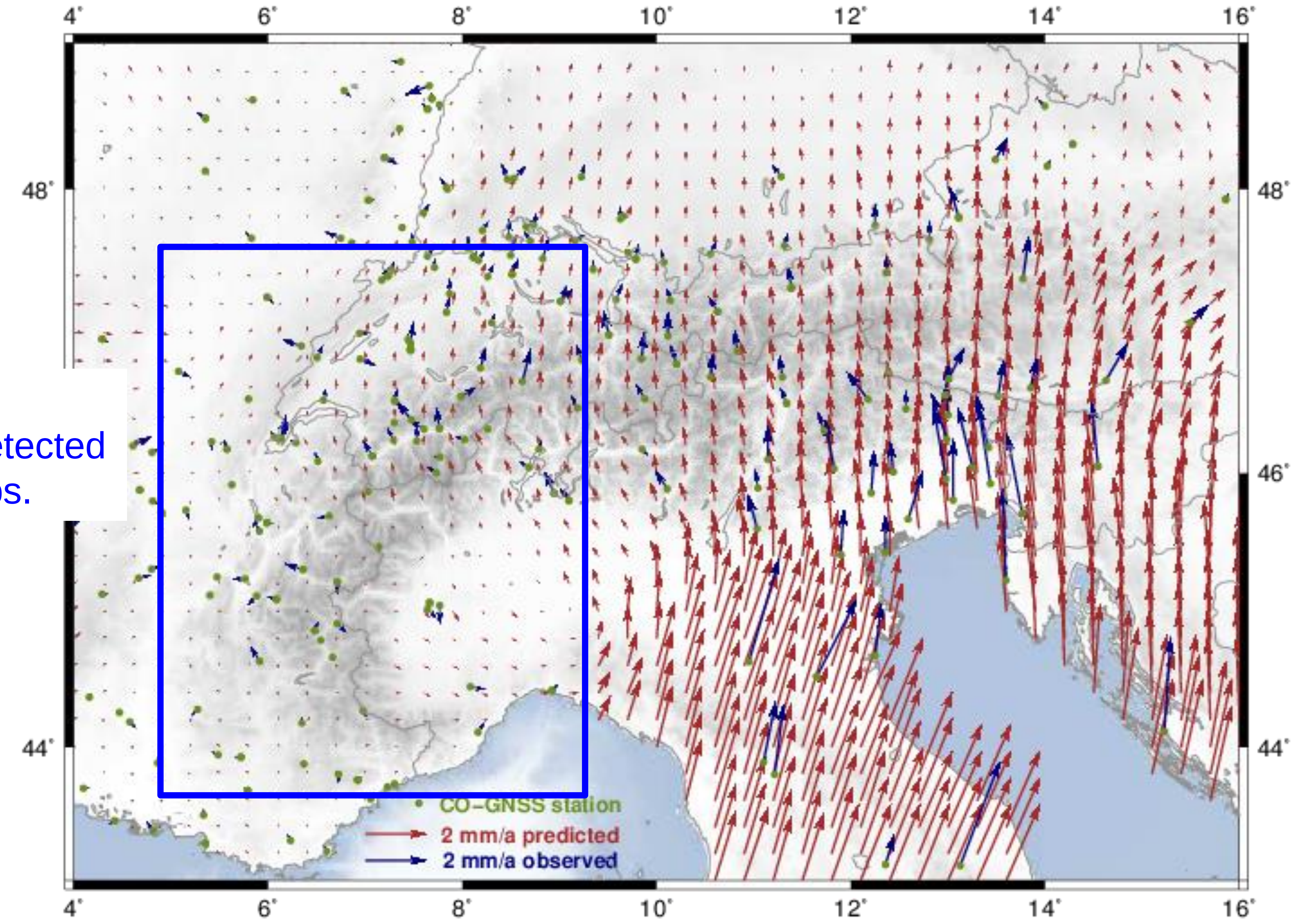
d ≤ 300 km for the vertical deformation model

Horizontal deformation model

after predicting the point-wise deformation vectors into a regular grid (25 km x 25 km)

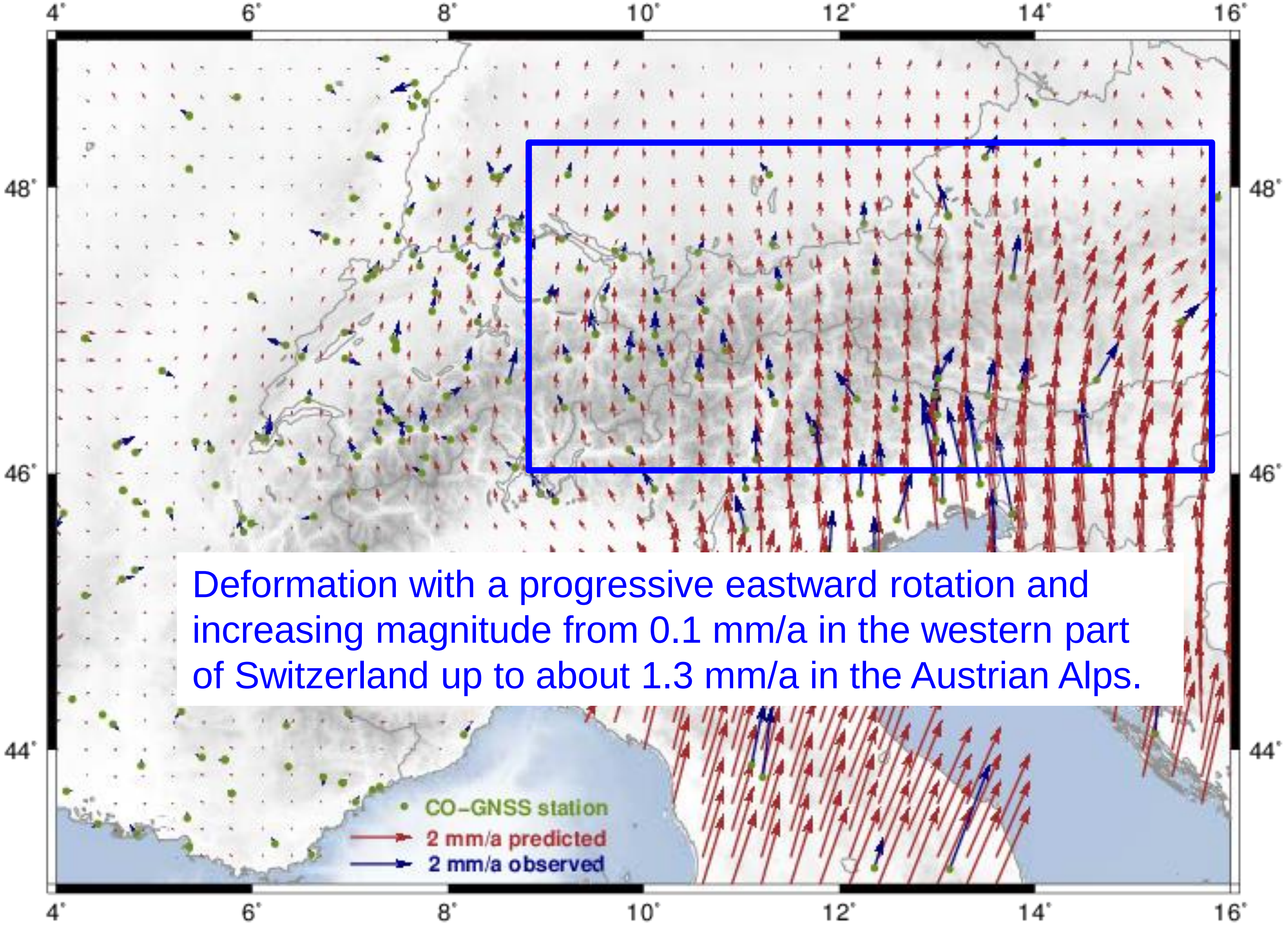


Horizontal deformation model

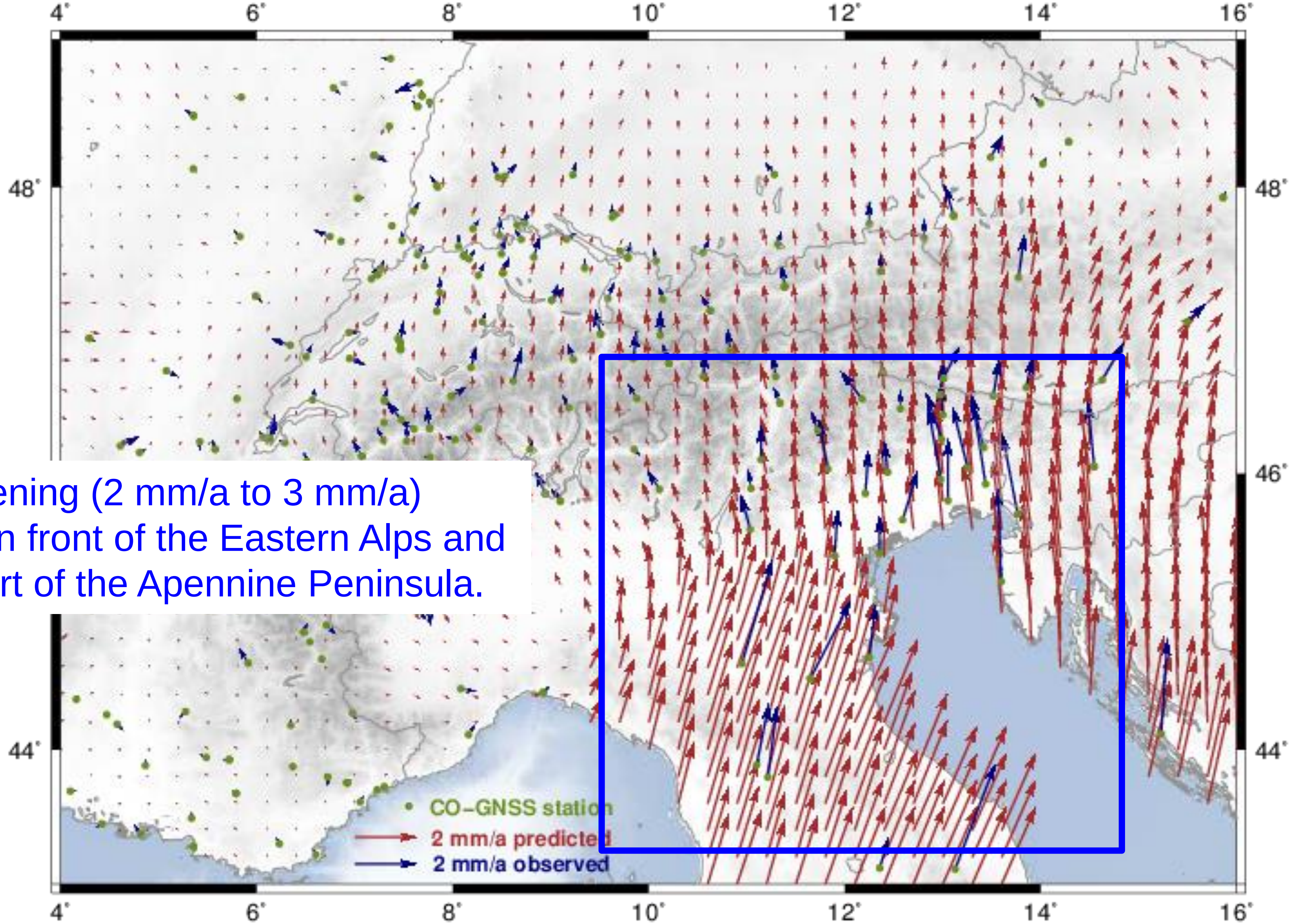


No significant deformation detected in the West Alps.

Horizontal deformation model

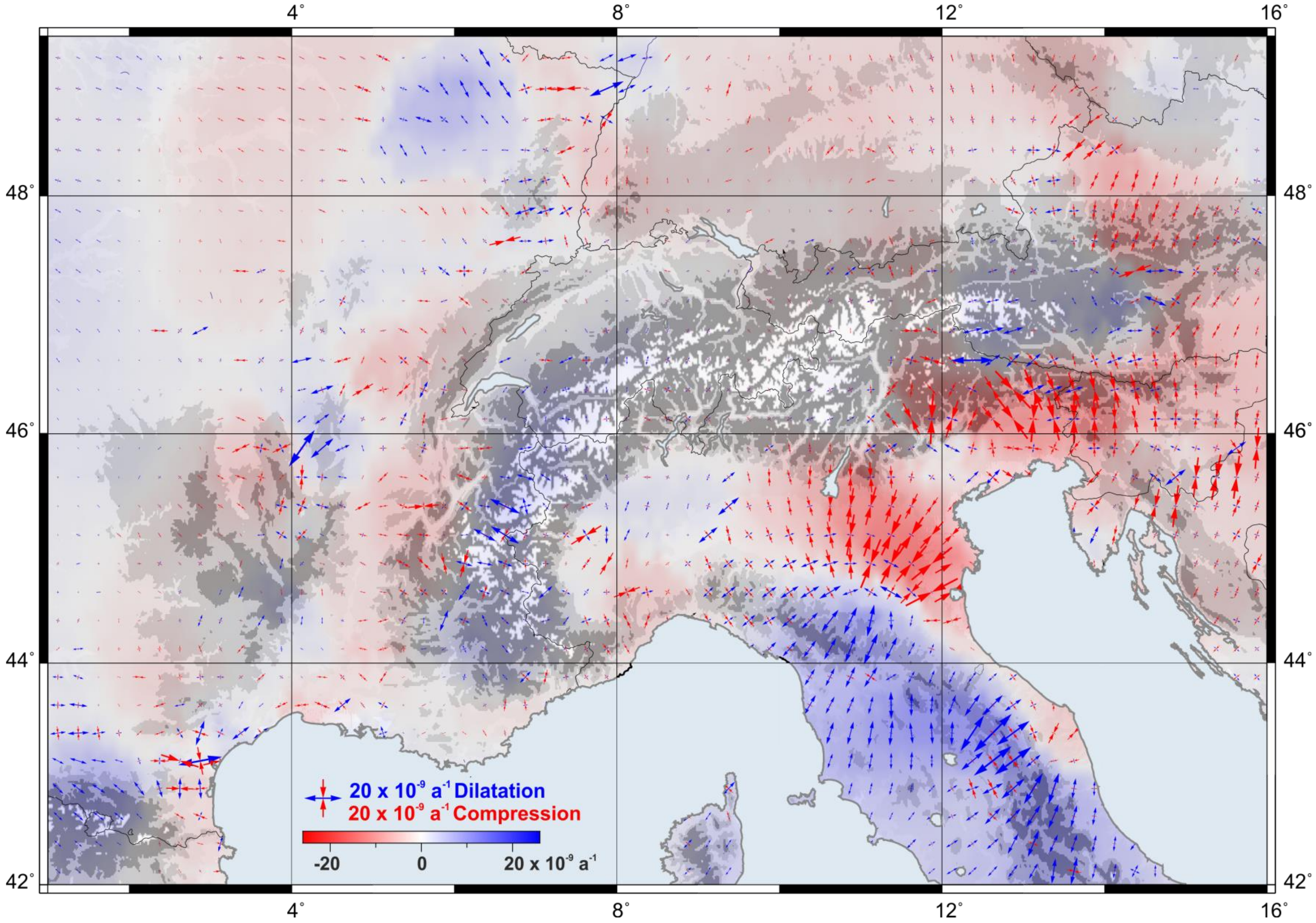


Horizontal deformation model

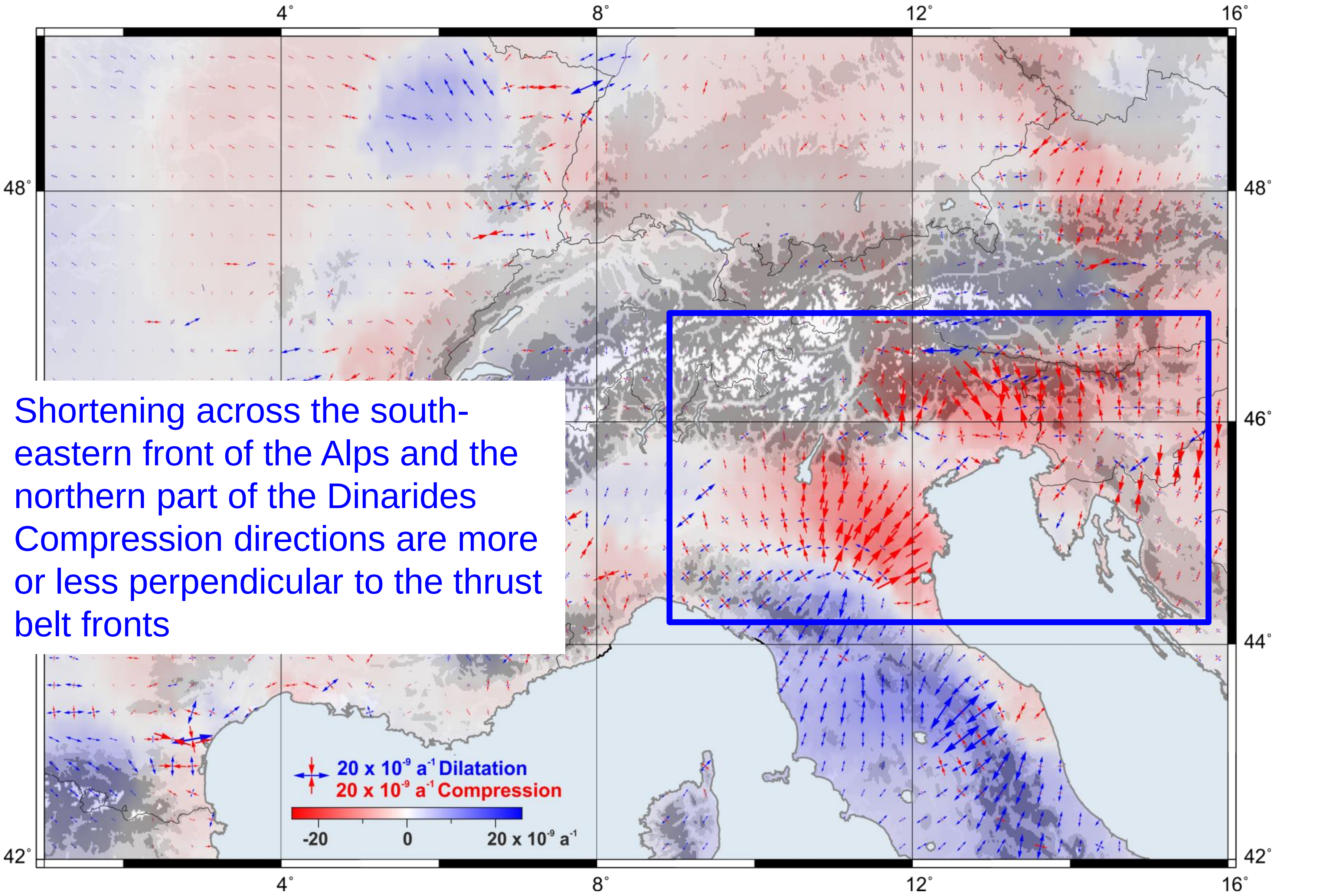


The largest shortening (2 mm/a to 3 mm/a) along the southern front of the Eastern Alps and in the northern part of the Apennine Peninsula.

Strain field
inferred from the horizontal deformation model

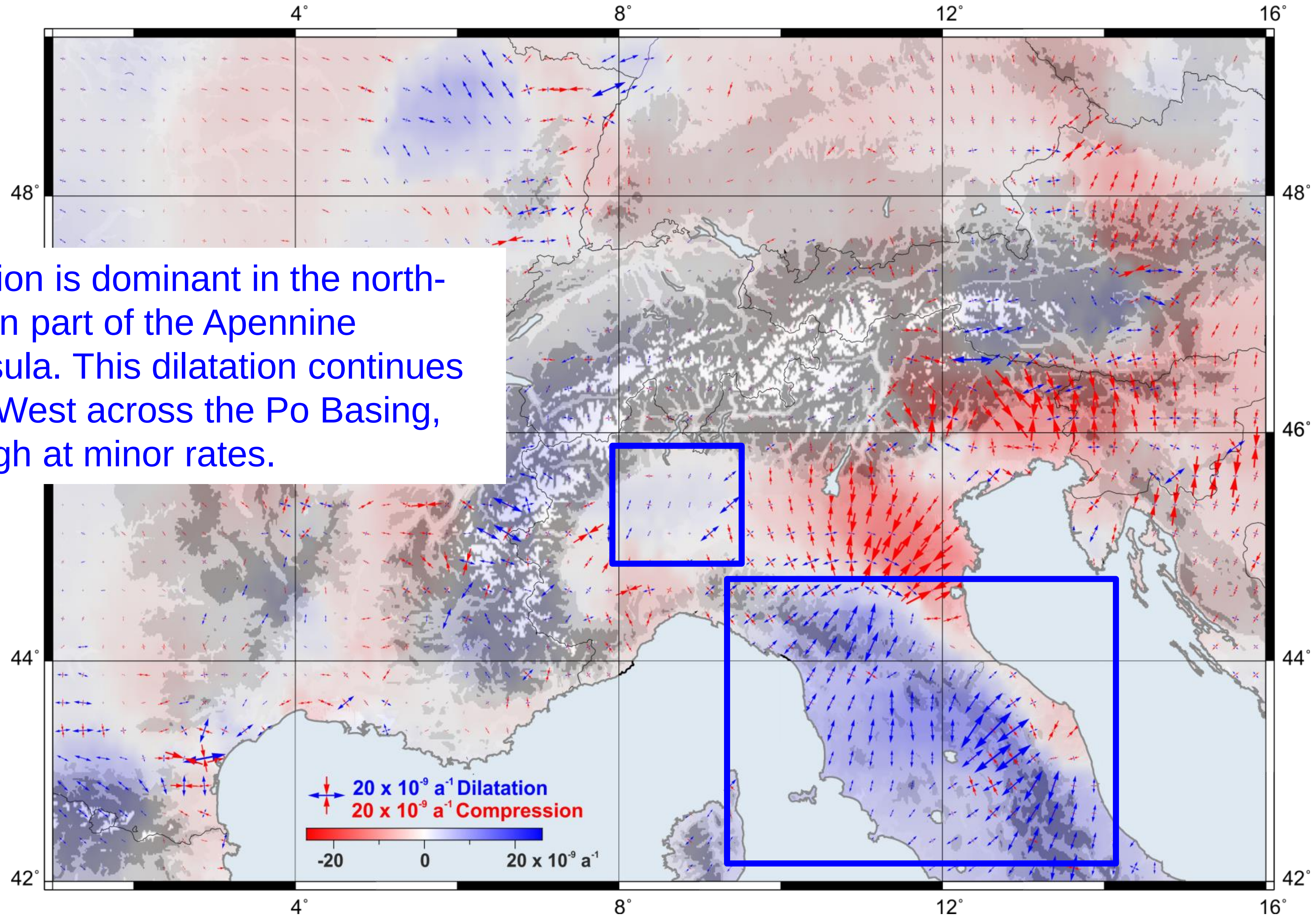


Strain field



- Shortening across the south-eastern front of the Alps and the northern part of the Dinarides
- Compression directions are more or less perpendicular to the thrust belt fronts

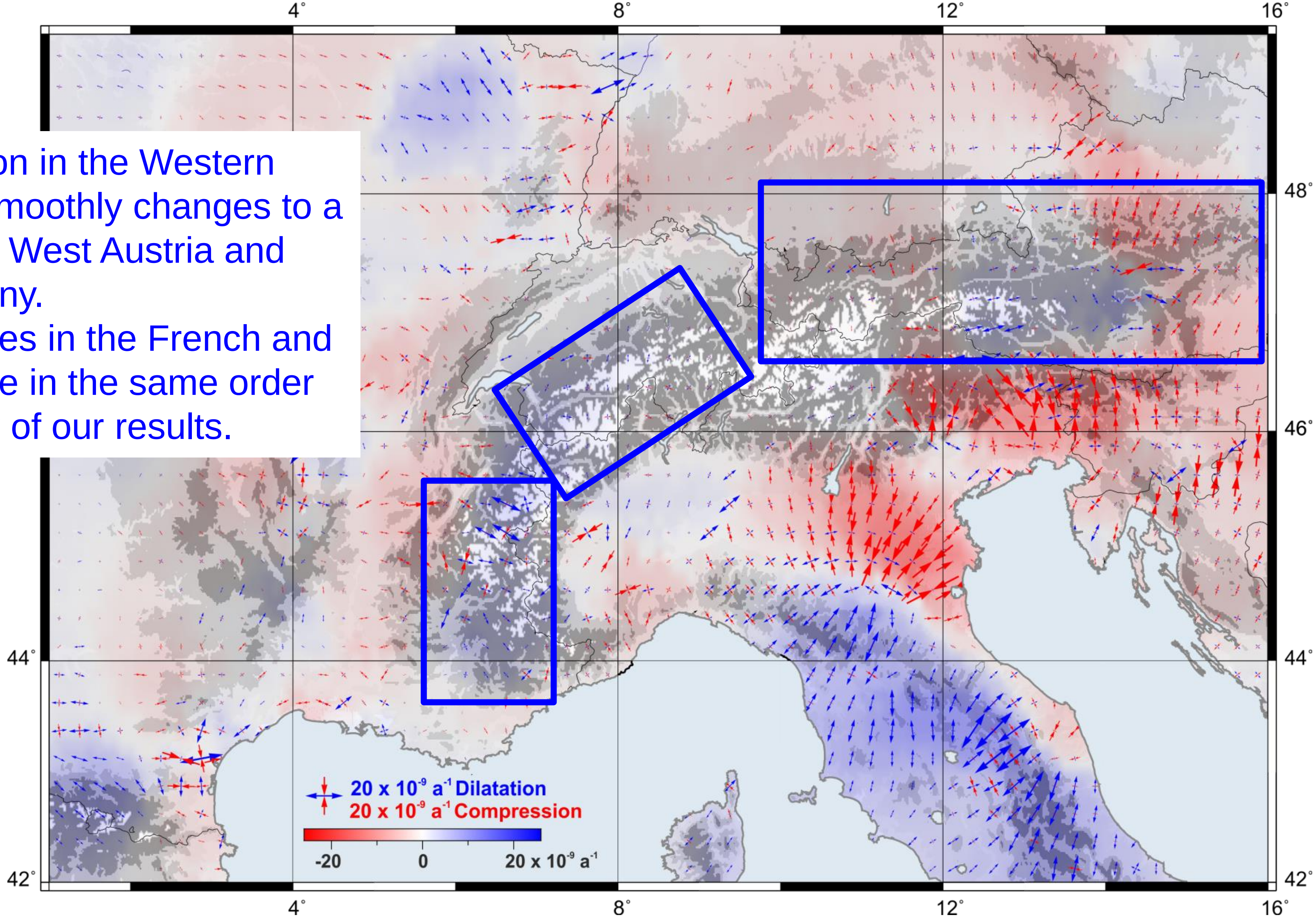
Strain field



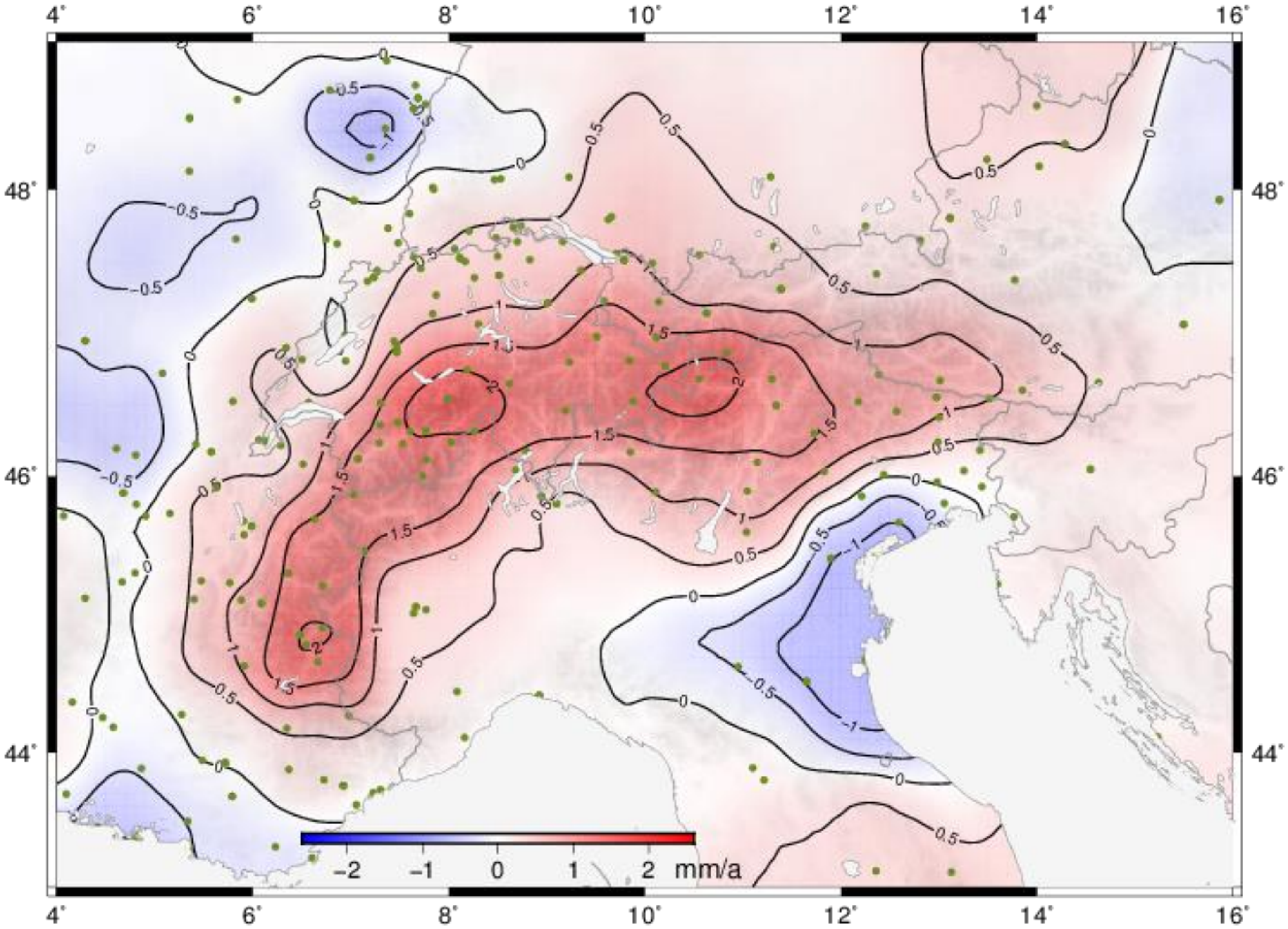
Dilatation is dominant in the north-western part of the Apennine Peninsula. This dilatation continues to the West across the Po Basing, although at minor rates.

Strain field

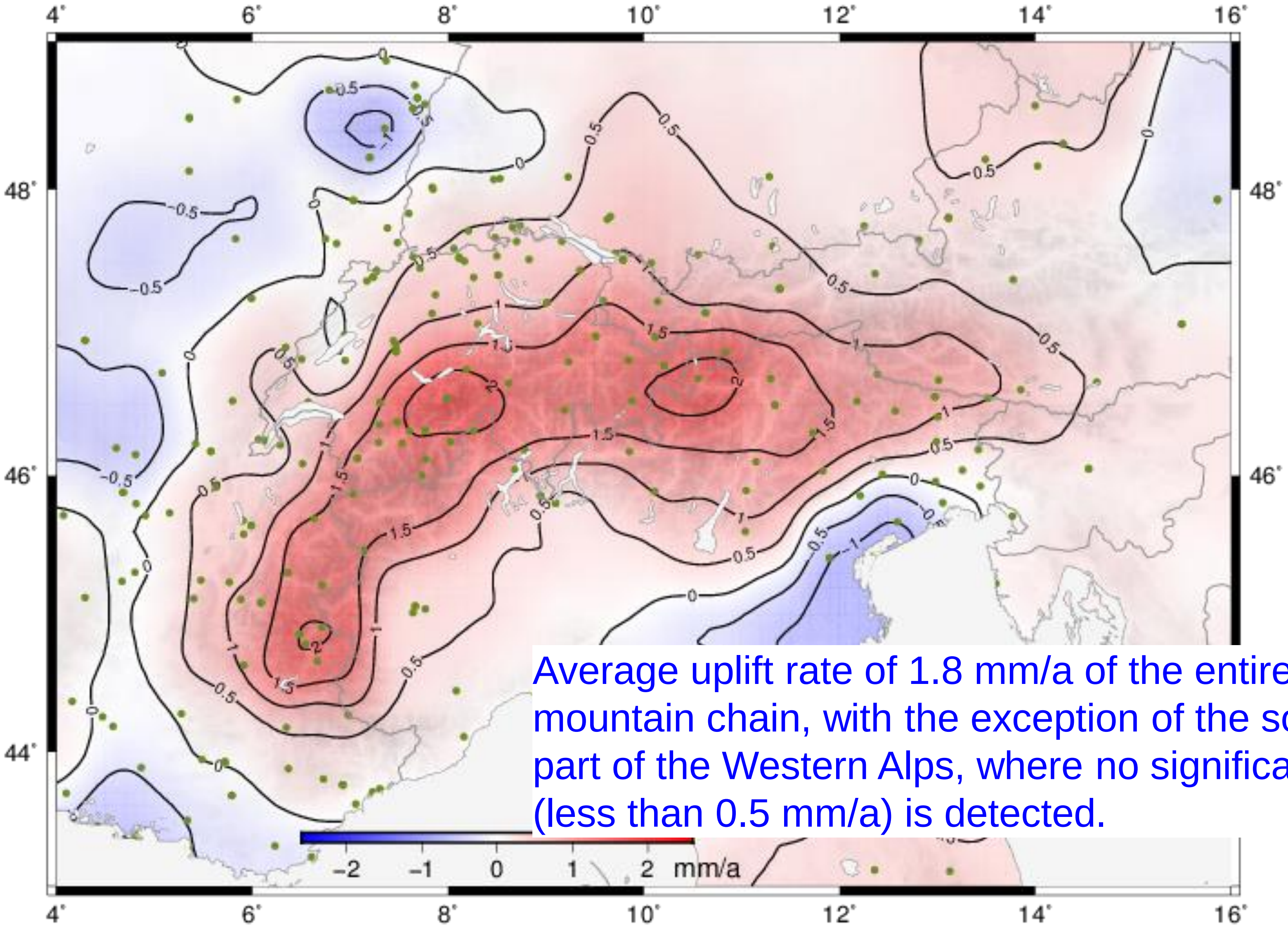
- Slight dilatation in the Western Alps, which smoothly changes to a contraction in West Austria and South Germany.
- The strain-rates in the French and Swiss Alps are in the same order of uncertainty of our results.



Vertical deformation model (Uplift model)

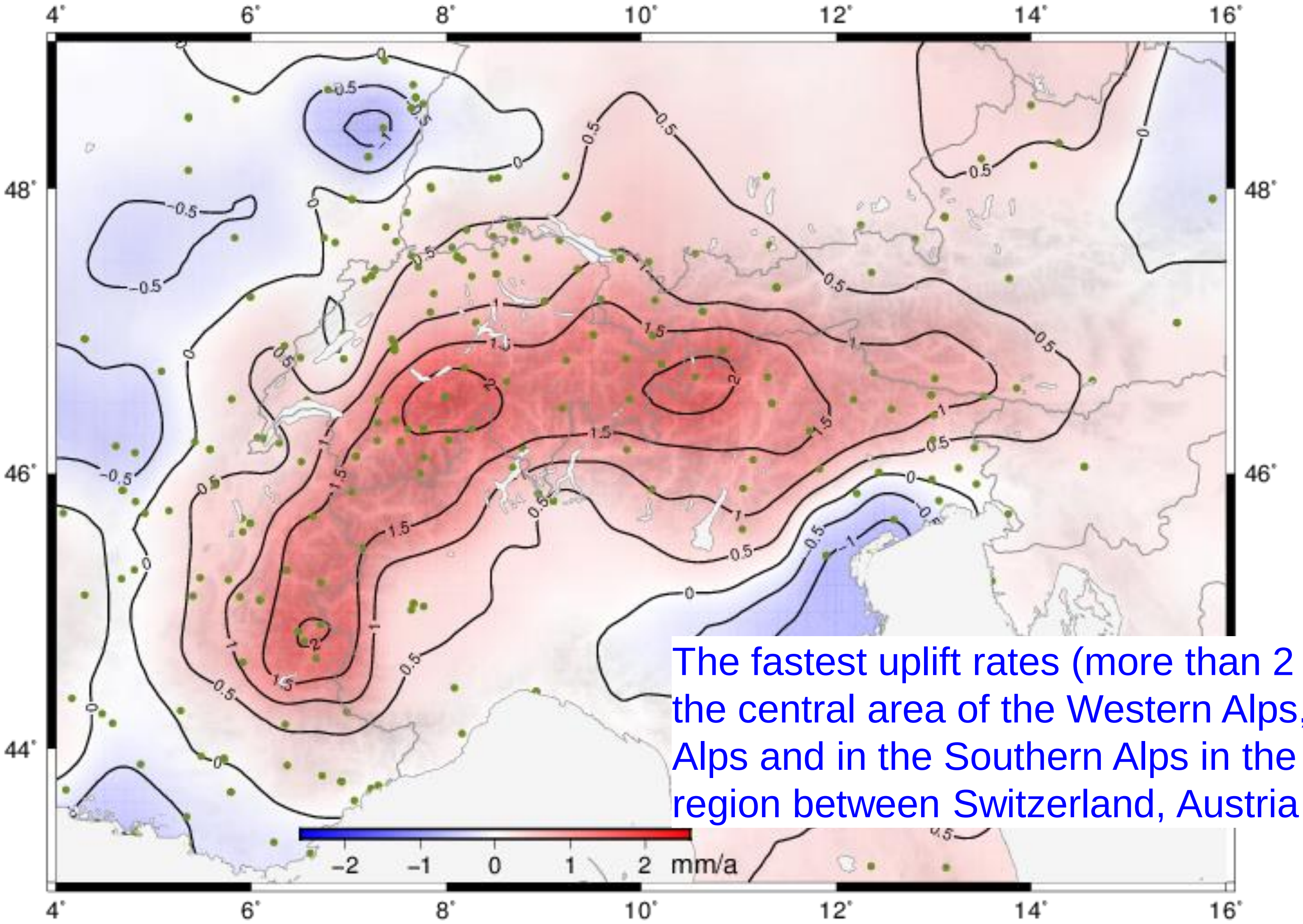


Vertical deformation model (Uplift model)



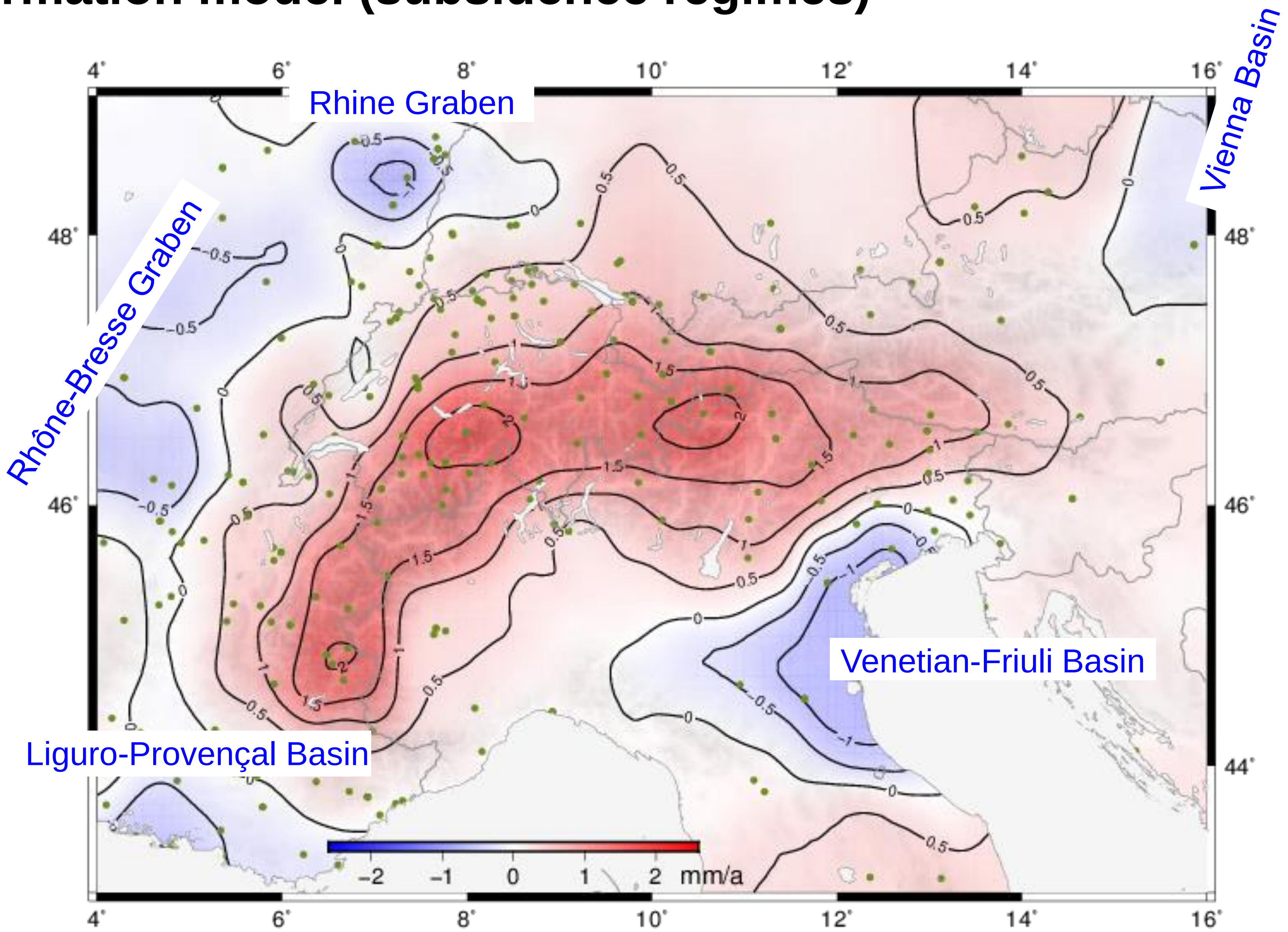
Average uplift rate of 1.8 mm/a of the entire mountain chain, with the exception of the southern part of the Western Alps, where no significant uplift (less than 0.5 mm/a) is detected.

Vertical deformation model (Uplift model)



The fastest uplift rates (more than 2 mm/a) occur in the central area of the Western Alps, in the Swiss Alps and in the Southern Alps in the boundary region between Switzerland, Austria and Italy.

Vertical deformation model (subsidence regimes)



Closing remarks

- Computations were performed in the IGS08/IGb08 reference frame. To extend the time span of the GNSS station position time series, a reprocessing based on the IGS14 reference frame is necessary.
- A larger number of GNSS stations along the Po Basin should be considered to improve the resolution of the deformation model in the southern margin of the Alps.
- Methods and results are published in Earth System Science Data ESSD:

  Sánchez, L., Völksen, C., Sokolov, A., Arenz, H., and Seitz, F .: Present-day surface deformation of the Alpine region inferred from geodetic techniques, Earth Syst. Sci. Data, 10, 1503-1526, https://doi.org/10.5194/essd-10-1503-2018, 2018

- Station coordinates, deformation models, and strain rate field are available at the long-term data repository Pangaea

  https://doi.pangaea.de/10.1594/PANGAEA.886889