# Recent crustal surface deformation of the Alpine region derived from geodetic observations

C. Völksen[1)], L. Sánchez [2)], A. Sokolov [1+2)], H. Arenz[2)] and F. Seitz[2)]

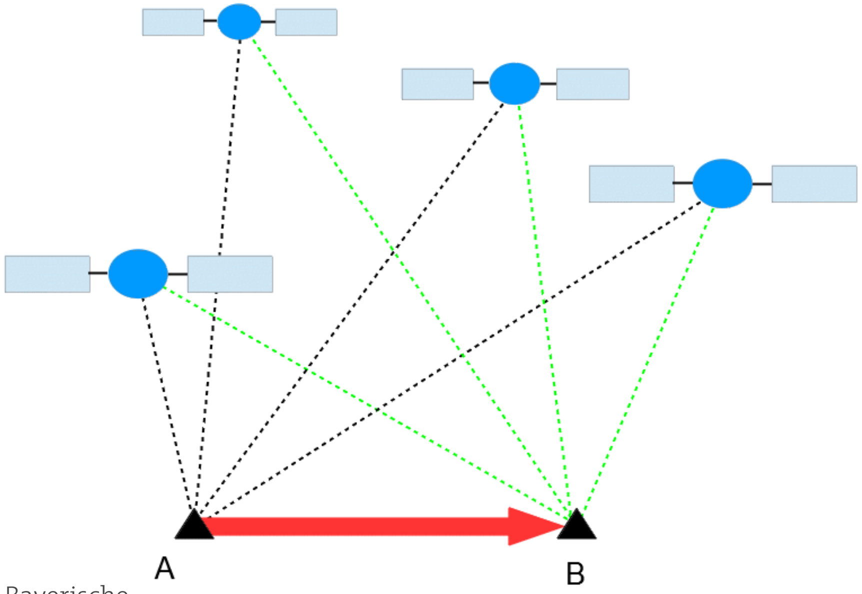
1) Bavarian Academy of Sciences and Humanities (BAdW)

2) Deutsches Geodätisches Forschungsinstitut of the TU München (DGFI-TUM)

Bayerische Akademie der Wissenschaften

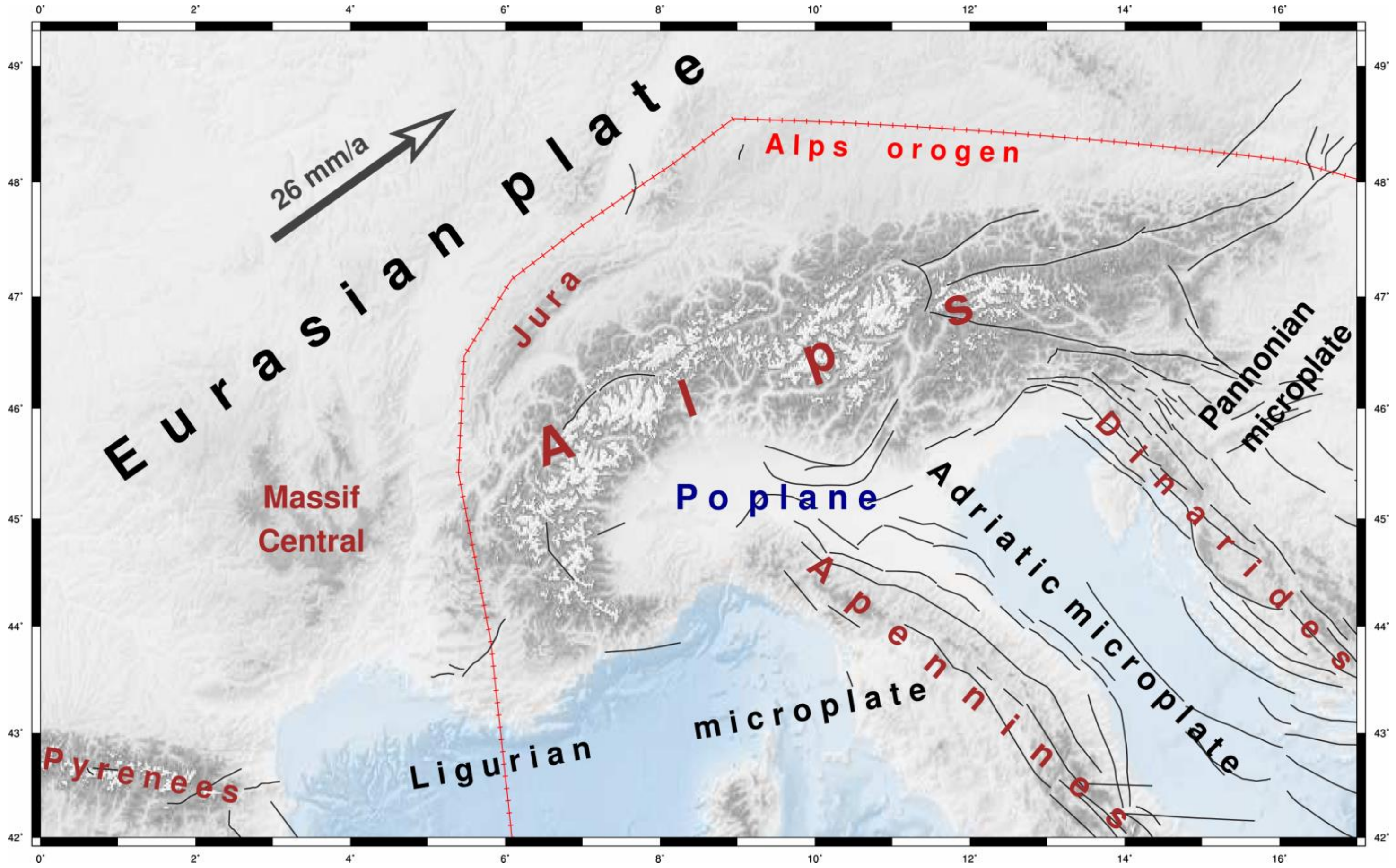
# Method

- Data of the Global Navigations Satellite Systems (GNSS) GPS and GLONASS have been used to derive precise positions in differential mode.
- Data were collected at each site continuously for years and files containing 24 h of data were processed for each day.
- Most of the continuously operation GNSS (CGNSS) stations were well connected to bedrock.




Bayerische Akademie der Wissenschaften

# Tectonic Setting

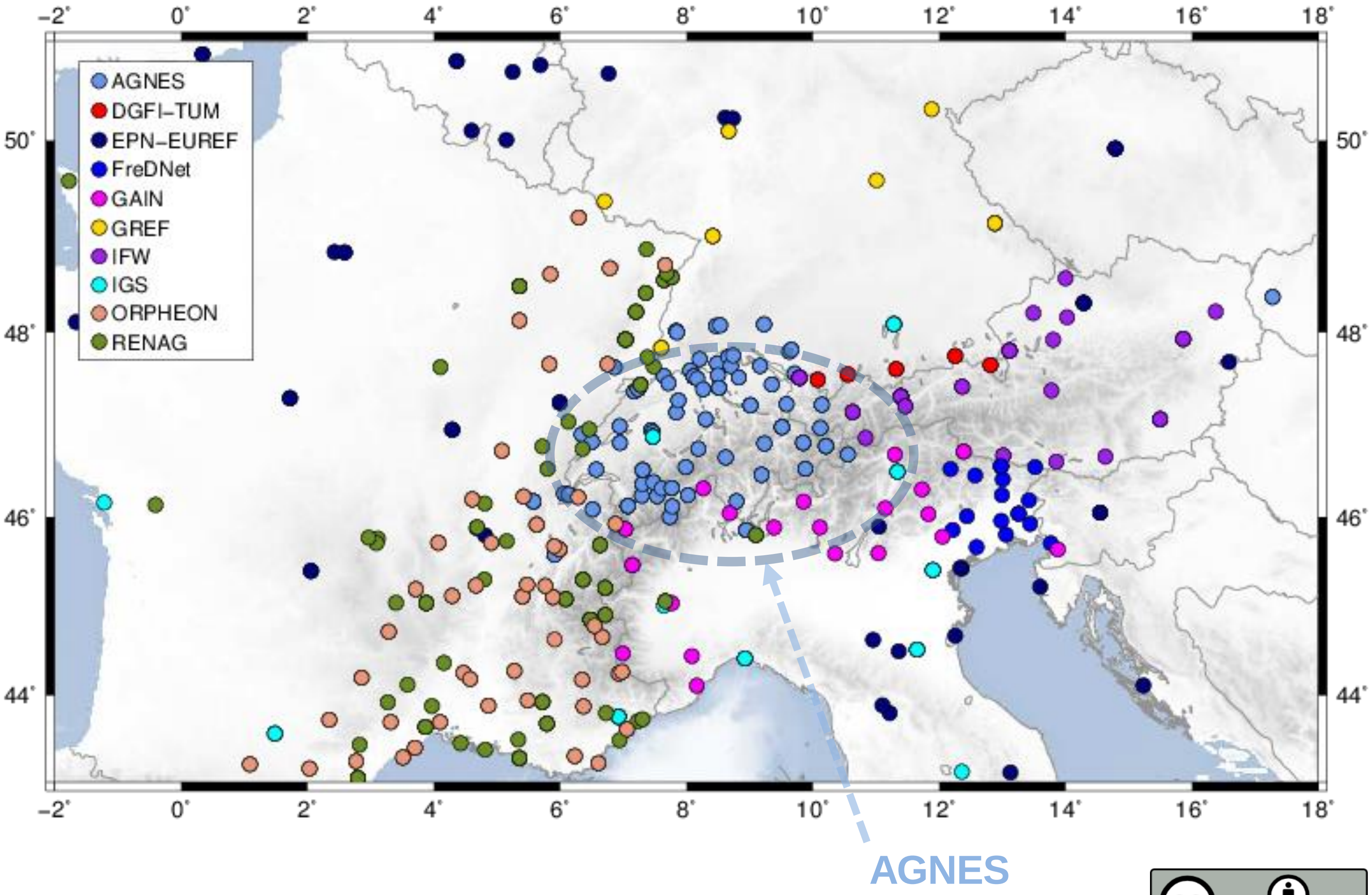



Tectonics of the Alpen region with their plates (i.e. Eurasian, Pannonian, Adriatic and Liguria).
The red line represents the Alpen orogen (Bird, 2003). Black lines are the tectonic faults (Source: http://diss.rm.ingv.it/share-edsf/).
The topography is taken from the ETOPO1 model (Amante and Eakins, 2009.
Source: https://www.ngdc.noaa.gov/mgg/global/global.html).

Bayerische Akademie der Wissenschaften

# CGNSS Stations with freely available Data

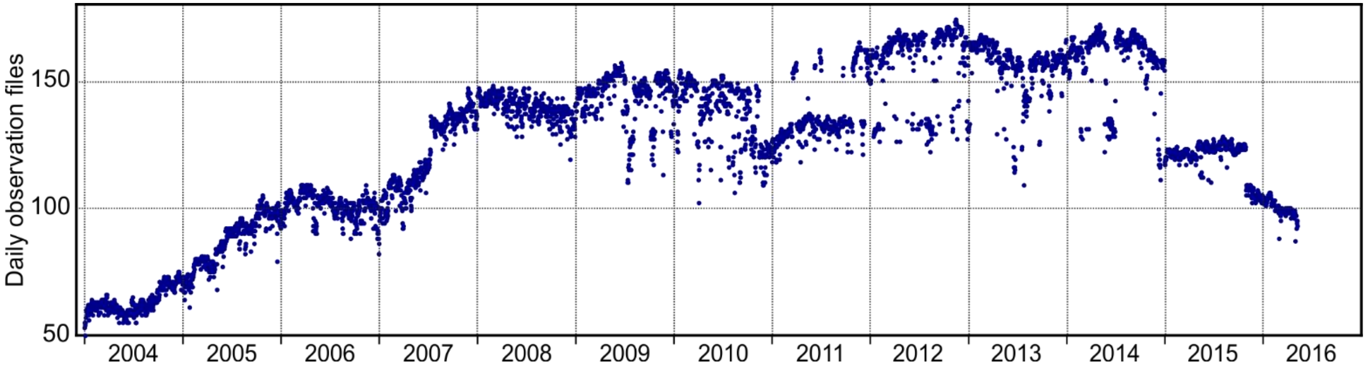
- Data from Continuously operating GNSS Stations (CGNSS) were free for downloading from many different agencies.
- The situation was different for region of Switzerland, because not many GNSS data were available.
- But **positions** and **velocities** were provided directly by *swisstopo* for their **30** CGNSS stations (Elmar Brockmann).
- The Federal Office of Topography (*swisstopo*) maintains the AGNES network, which covers Switzerland.




Bayerische
Akademie der Wissenschaften

# Amount of Processed Data

Daily RINEX FILES



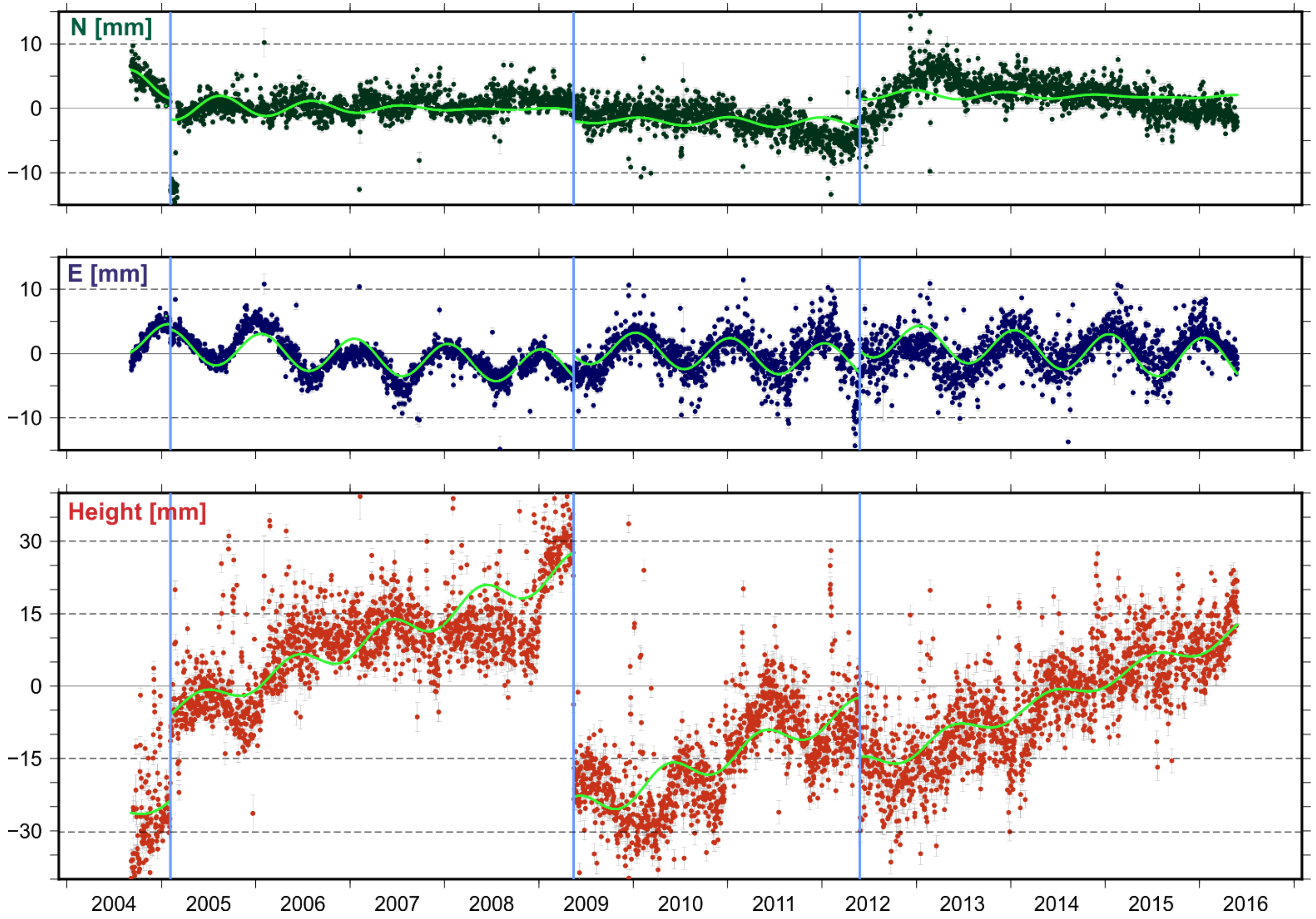

- Data analysis spans the period between 1.1.2004 until 30.5.2016 (>12 years)
- In total 194 CGNSS sites were included in the network
- 570.000 daily RINEX observation files were processed
- Significant increase of CGNSS sites between 2004 and 2008
- Between 2012 and 2015 data (RINEX) of almost 180 CGNSS sites were processed for each day

Bayerische Akademie der Wissenschaften

# Analysis of the GNSS Data

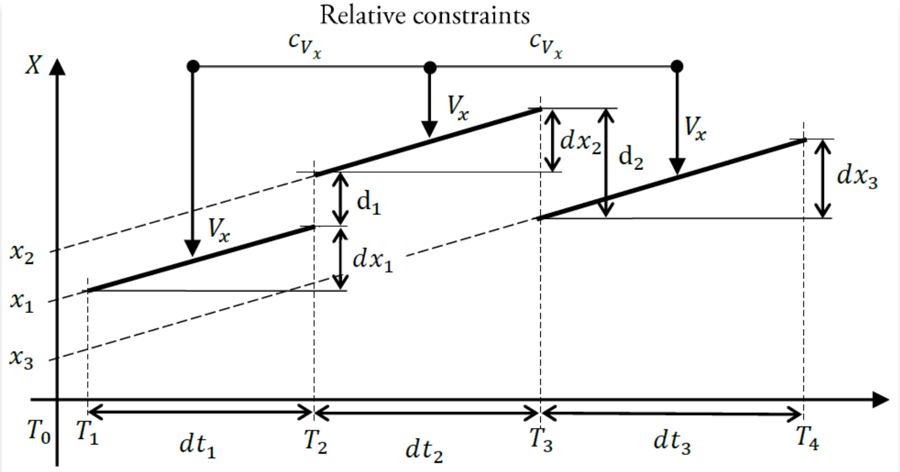
- Data from the systems GPS and GLONASS have been processed
- Implementation of the same global terrestrial reference frame (IGb08) for the entire time span
- Determination of station positions and velocities based on selected IGS reference sites surrounding the Alps
  - Selected IGS Sites: Wettzell(D), Zimmerwald (CH), Grasse (F), Graz (AU), Medicina (I), La Rochelle (F))
  - Positions and Velocities of these station are well known and are used for constraining the network
- The data were processed with BERNESE GNSS Software
  - Type mean antenna calibrations models were (igs08.atx) used
  - CODE final orbits: reprocessed (2004-2013) & final/operational (2014-1016))
  - Linear velocity estimation using ADDNEQ2 (at least 3 years of data have to be available)
  - Analysis of the position time series for the detection of outliers and sudden jumps

# Analysis of Position Time Series (Bologna)



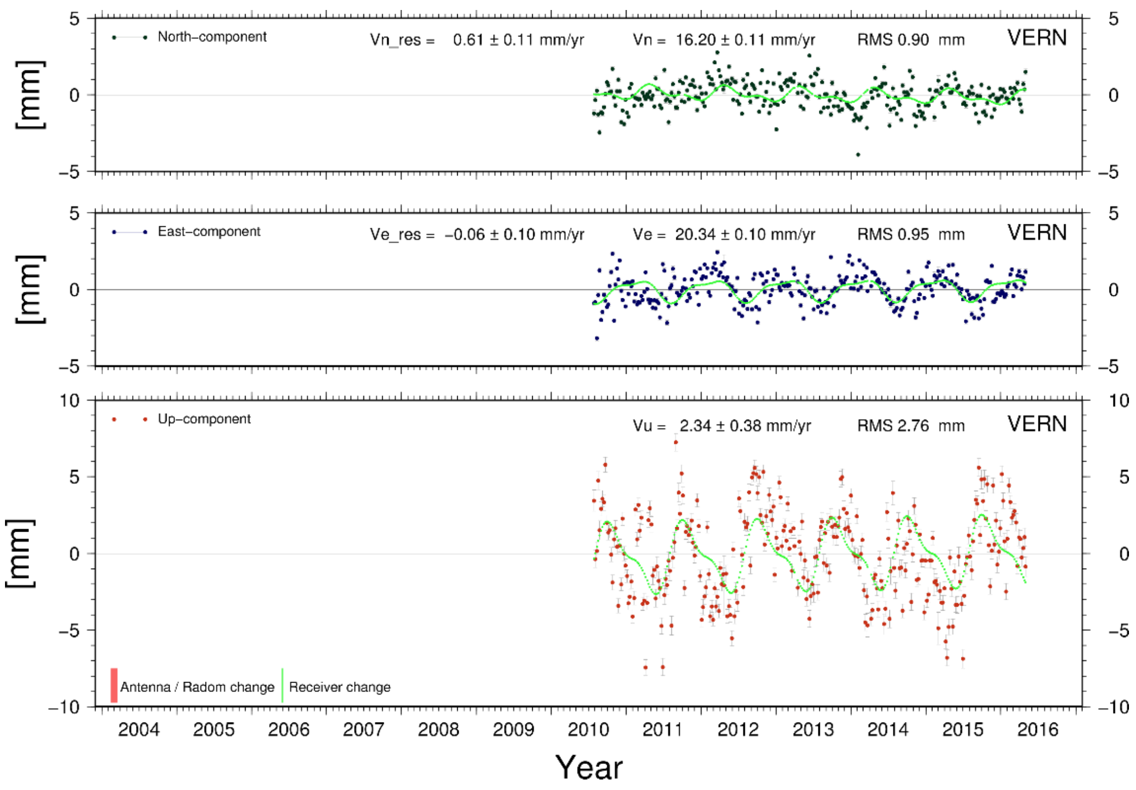

Time Series of a CGNSS site for the North, East and Up components (bad example):

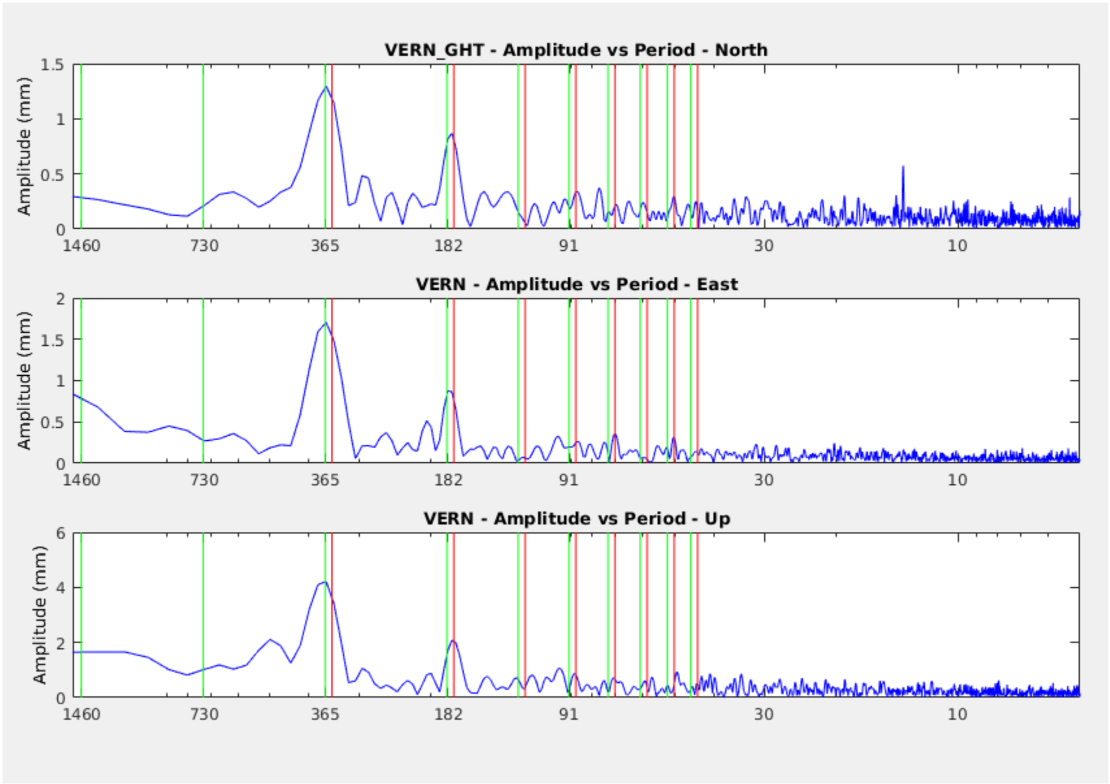
- Annual and semi-annual signals are typical
- Offsets caused by equipment change (e.g. antennas) or man made.
- Main task is to identify and determine those offsets $\mathbf{d_i}$
- Assumption: the velocity is constant during the entire observation time.



BAdW

# Spectral Analysis of Position Time Series (Vernagt)

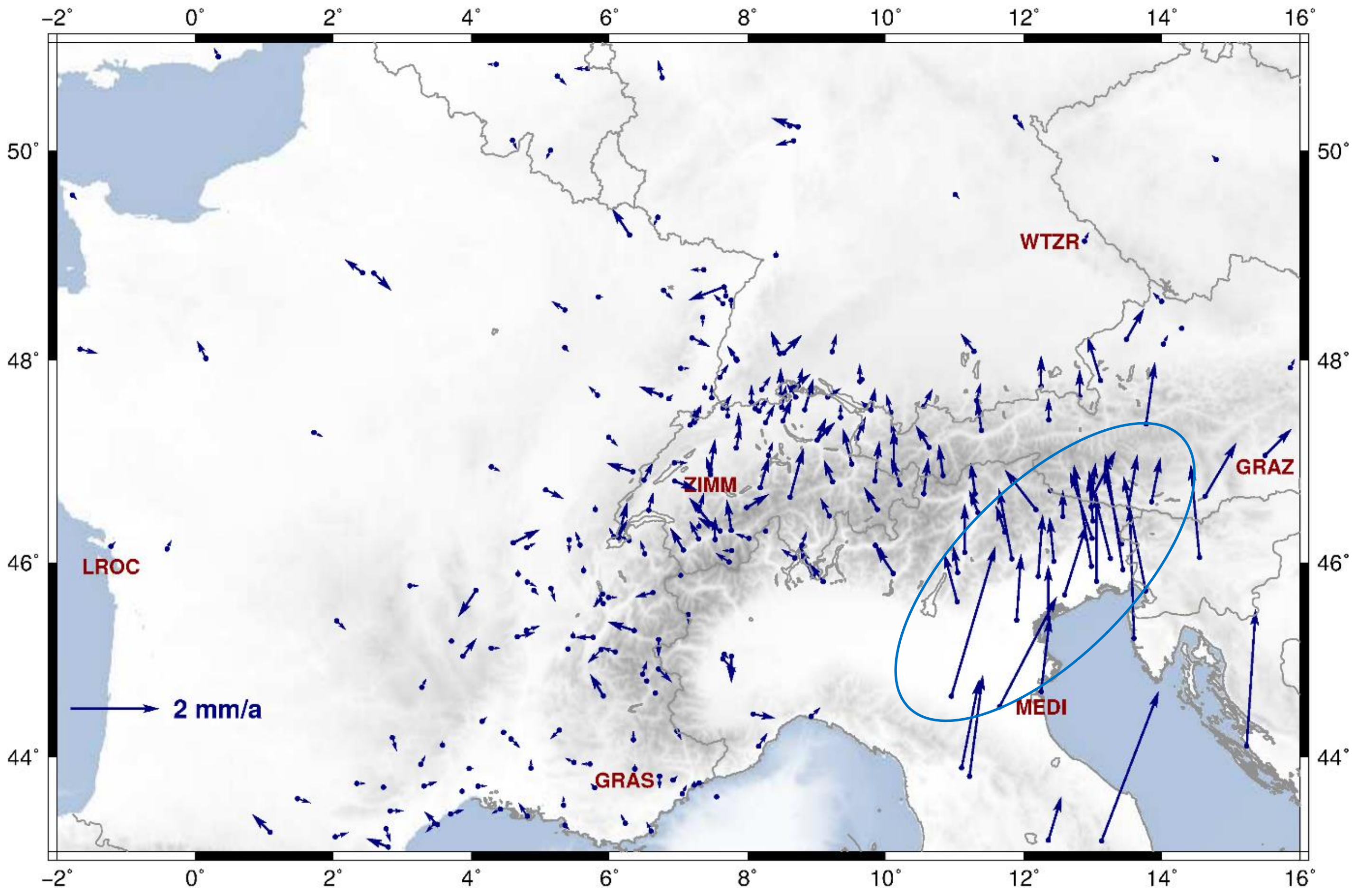



| Velocities Station: VERN | $V_{North}$ | $V_{East}$ | $V_{Height}$ | $S_{north}$ | $S_{east}$ | $S_{height}$ |
|---|---|---|---|---|---|---|
| | [mm/a] | | | [mm] | | |
| Linear | 16.06 | 20.38 | 2.25 | 2.39 | 2.20 | 5.85 |
| Linear+annual and semianual Signal | 16.04 | 20.37 | 2.29 | 2.01 | 1.67 | 5.03 |

Bayerische Akademie der Wissenschaften

# Horizontal Velocities Relative to the Eurasian Plate

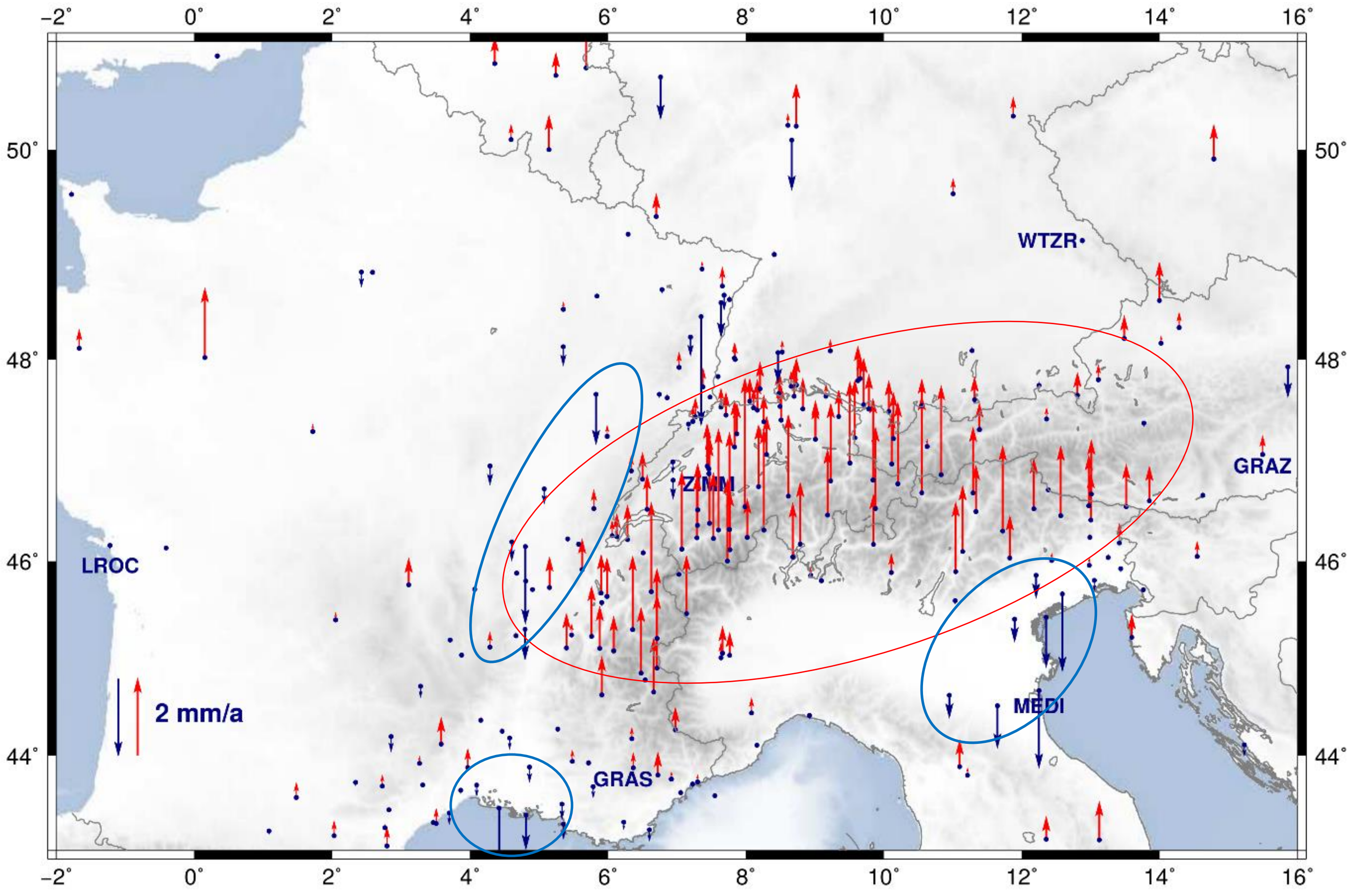



- The motion of the Eurasian plate is removed.
- Vectors show a significant movement of more than 2 mm/a in the northern Area of the of the Venetian-Friuli Basin.
- Area is also known for high seismic activity.

Standard deviation of the horizontal components: ~ 0.2 mm/a

Bayerische Akademie der Wissenschaften

# Vertical Velocities




Uplift

Subsidence

Uplift region:

- Alps

Subsidence region:

- Rhine Graben
- Rhône-Bresse Graben
- Venetion-Friuli-Po Basin

Standard deviation of the vertical components: ~ 0.4 mm/a

BAdW

# Verification of our Results

## Velocity Comparison with other Groups

| Project | Common Sites | MEAN_N [mm/a] | SDEV_N [mm/a] | MEAN_E [mm/a] | SDEV_E [mm/a] | MEAN_U [mm/a] | SDEV_H [mm/a] |
|---|---|---|---|---|---|---|---|
| AlpArray Init. (alp08) | 114 | -0.15 | 0.20 | -0.37 | 0.18 | -0.47 | 0.58 |
| EPN Densification (epnd14) | 108 | 0.05 | 0.20 | -0.05 | 0.28 | 0.39 | 0.66 |
| CEGRIN 14 (cgn14) | 78 | -0.08 | 0.21 | -0.01 | 0.33 | -0.14 | 0.73 |
| Swisstopo 16 (ch16) | 50 | -0.05 | 0.14 | -0.16 | 0.19 | -0.17 | 0.41 |
| EPN14 | 47 | -0.02 | 0.19 | -0.07 | 0.19 | 0.20 | 0.41 |
| ITRF14 | 18 | 0.04 | 0.24 | 0.02 | 0.14 | 0.38 | 0.37 |

- The table shows comparisons between our network and selected networks. The MEAN values represent the deviation between the two velocities fields.
- All velocity components of each networks are estimated independently from each other.
- The standard deviations of this table agree with our estimates for the velocity estimates.

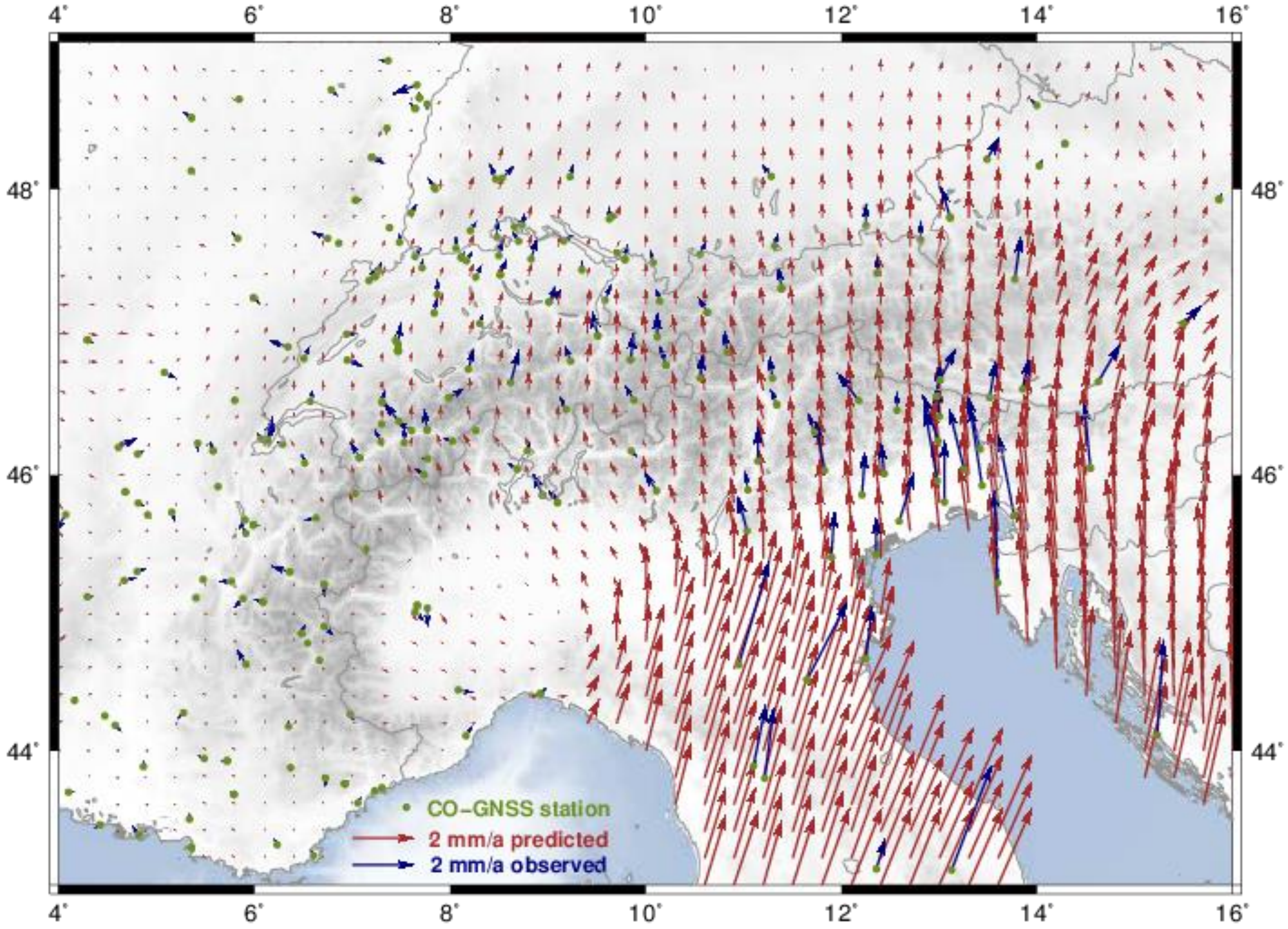
Source: EUREF Working Group on European Dense Velocities
http://pnac.swisstopo.admin.ch/divers/dens_vel/index.html

Bayerische Akademie der Wissenschaften

# Deformation Models

- Separation between horizontal and vertical movements in two models
- Mean standard deviation for horizontal velocities 0.2 mm/a and 0.4 mm/a for vertical movement respectively
- Velocity components are derived for a grid (25 km x 25 km) via least-squares collocation (LSC)
  - Grid width corresponds to average station distance
  - Correlation length d ~ 100 km
- Separation of the trend (horizontal plate movement) required in advance
- Deviations in the velocity of a single station of more than 0.5 mm/a from surrounding stations were interpreted as local effects and were removed in the collocation

# Horizontal Deformation Model of the Alps

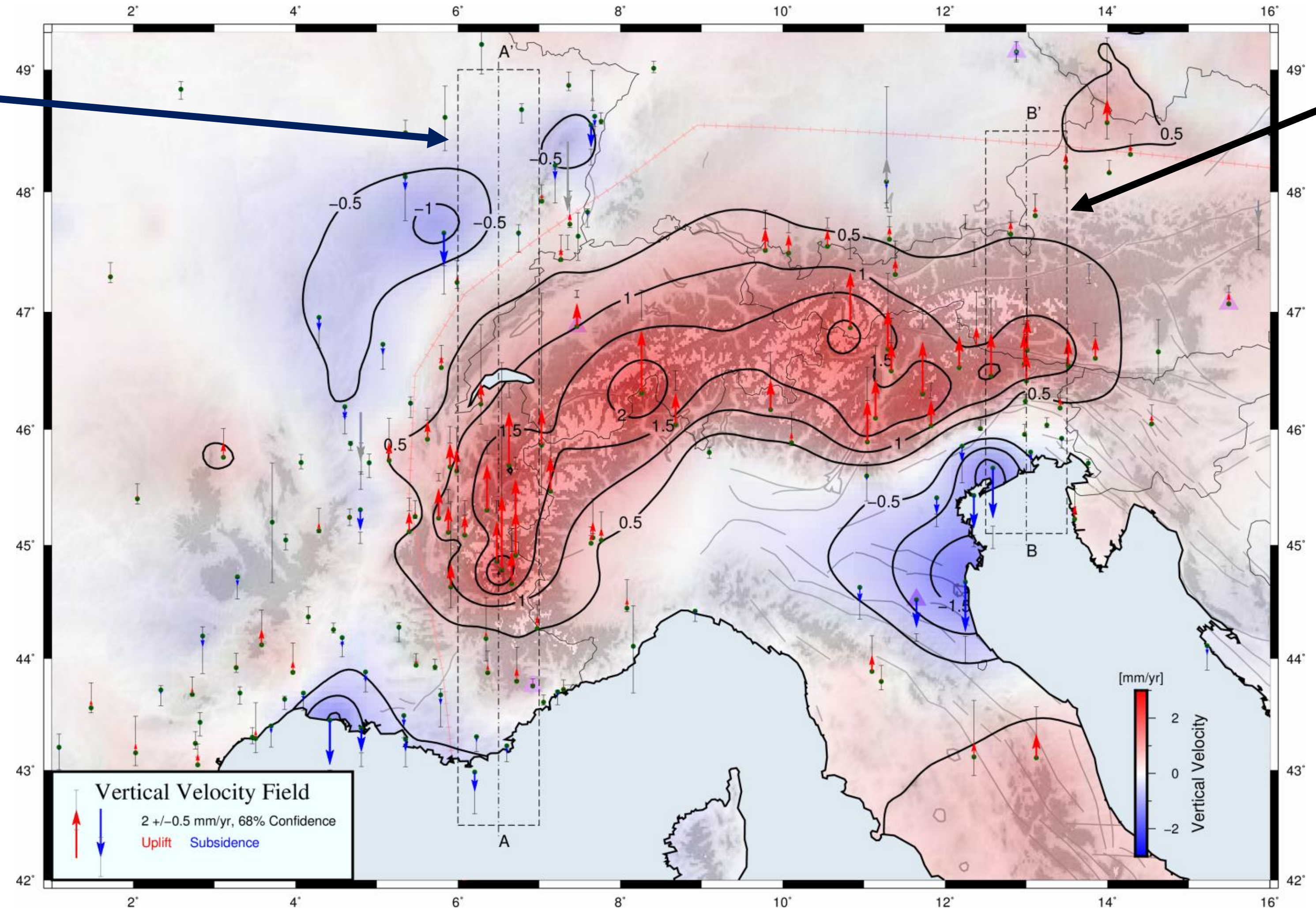



Bayerische Akademie der Wissenschaften

# Vertical Deformation Model of the Alps

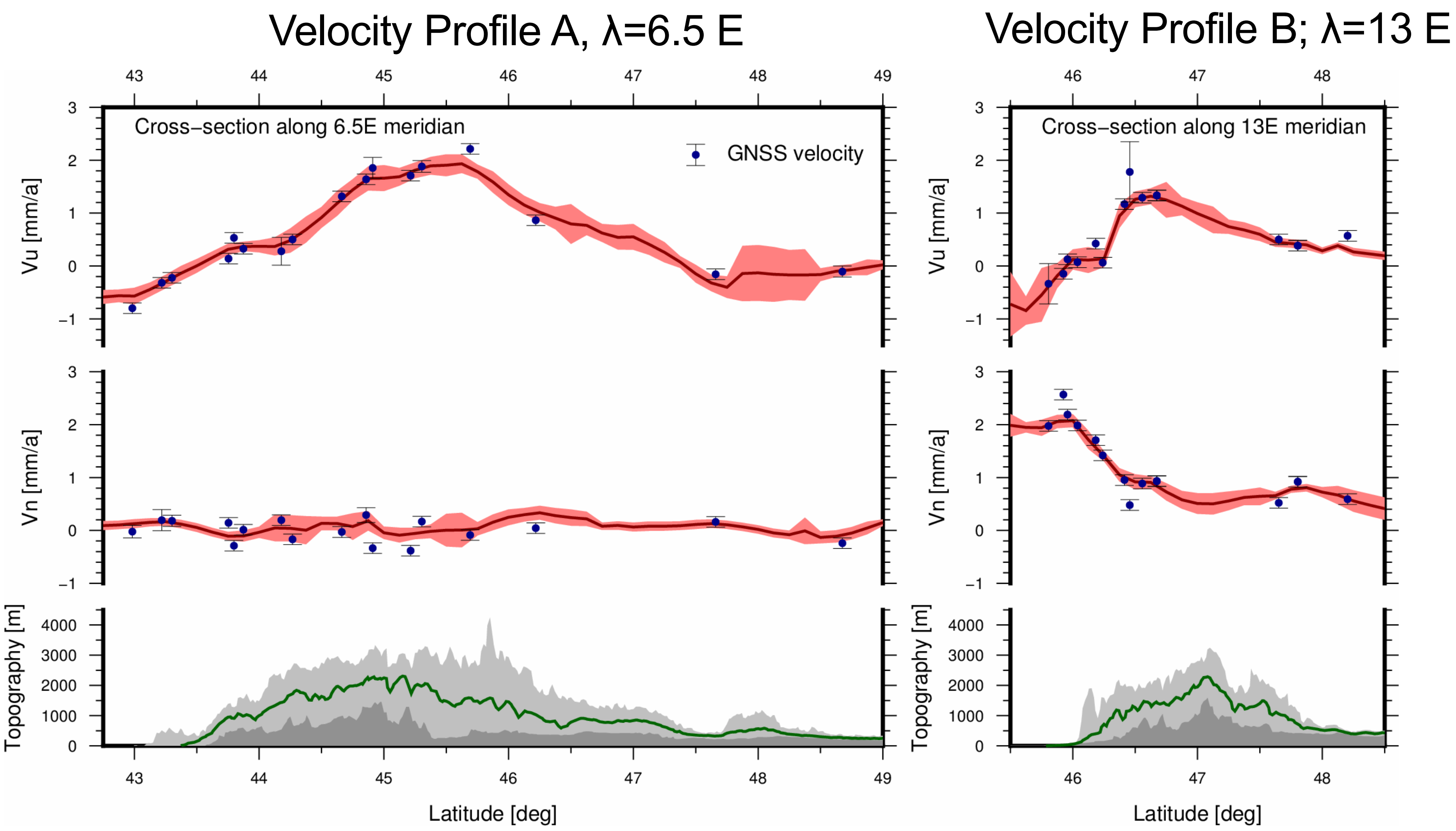
Velocity Profile A

Velocity Profile B




Bayerische Akademie der Wissenschaften

# Velocity Profiles for the North and Up Component



# Summary

- The mean uplift rate of the Alps is 1.8 mm/a, with largest rates of 2.5 mm/a in the central area of the Western and the Southern Alps
- Subsidence can be found in the Upper Rhine Graben, the Bresse Graben and the Venetian-Friuli Basin
- 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
- Numerical results are available through the World Data Center *Pangaea*
  - https://doi.pangaea.de/10.1594/PANGAEA.886889