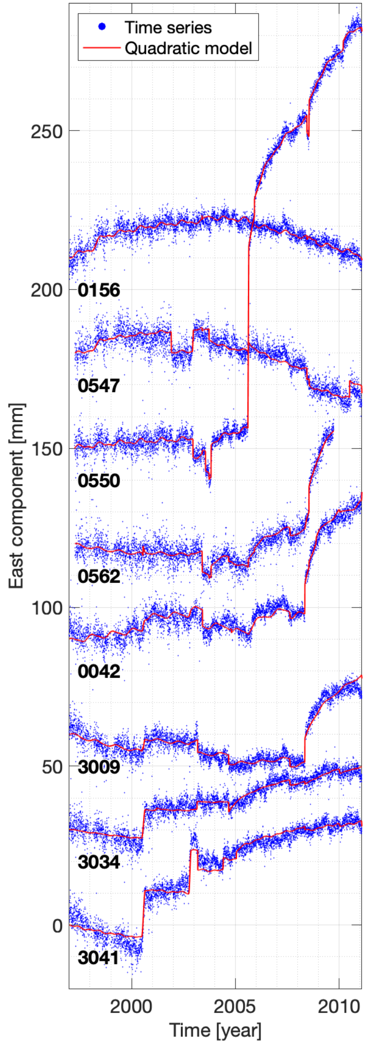
Analyzing GNSS time series to study the earthquake cycle



Anne Socquet

Corinth school on strain mapping
2024/10/22

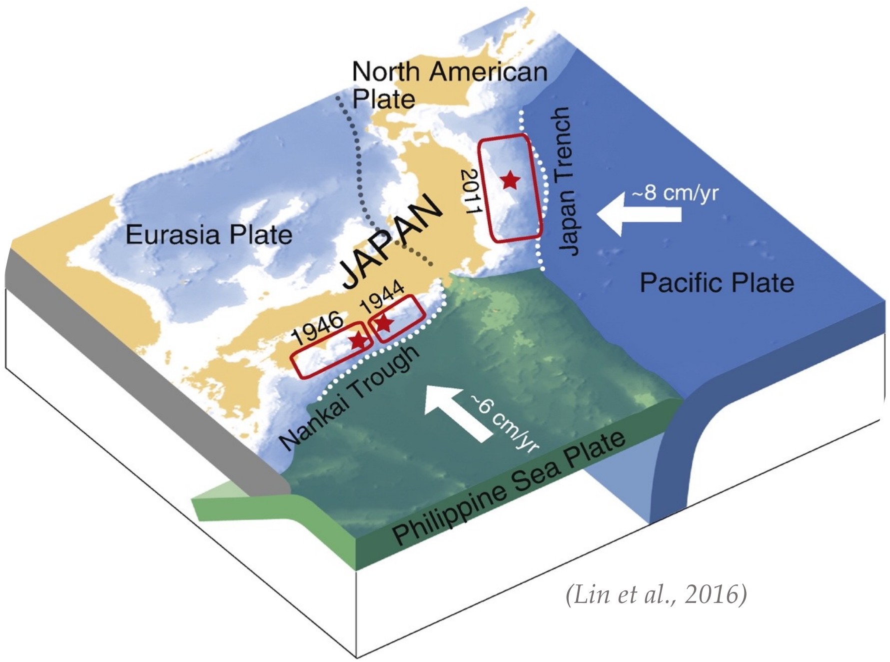
Geo-iNQUIRE

Université Grenoble Alpes

ISTerre
Institut des Sciences de la Terre

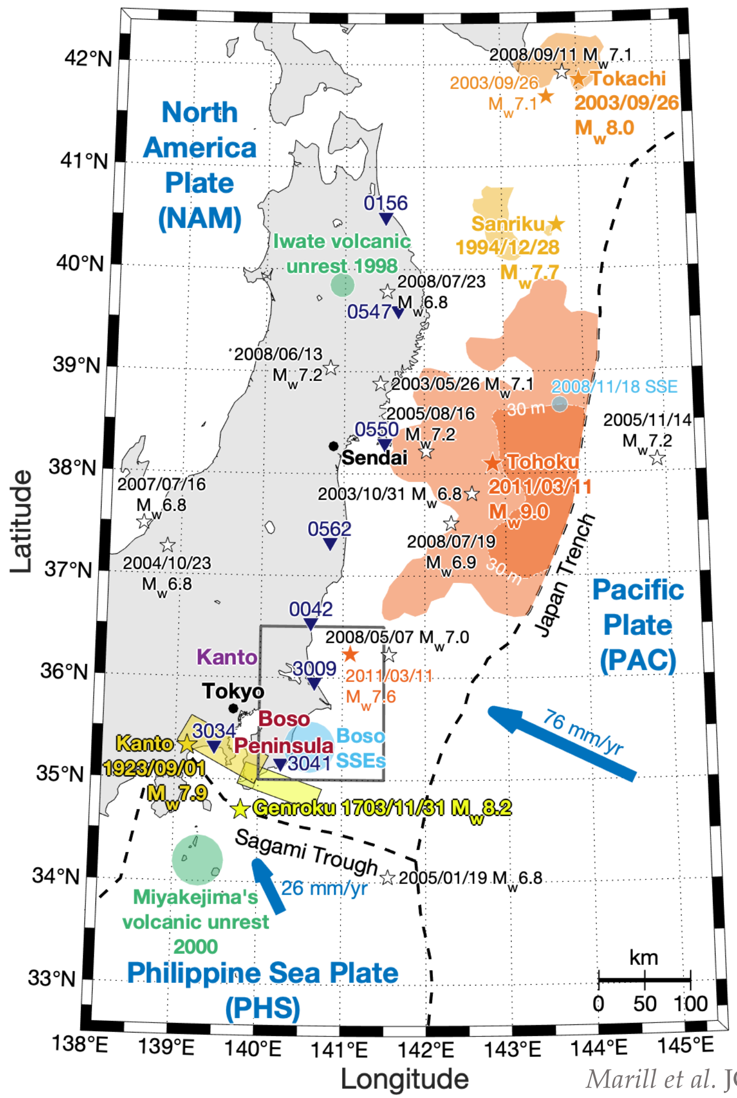
Seismic Cycle and Slow Slip Events

Illustrated on the Japan Trench



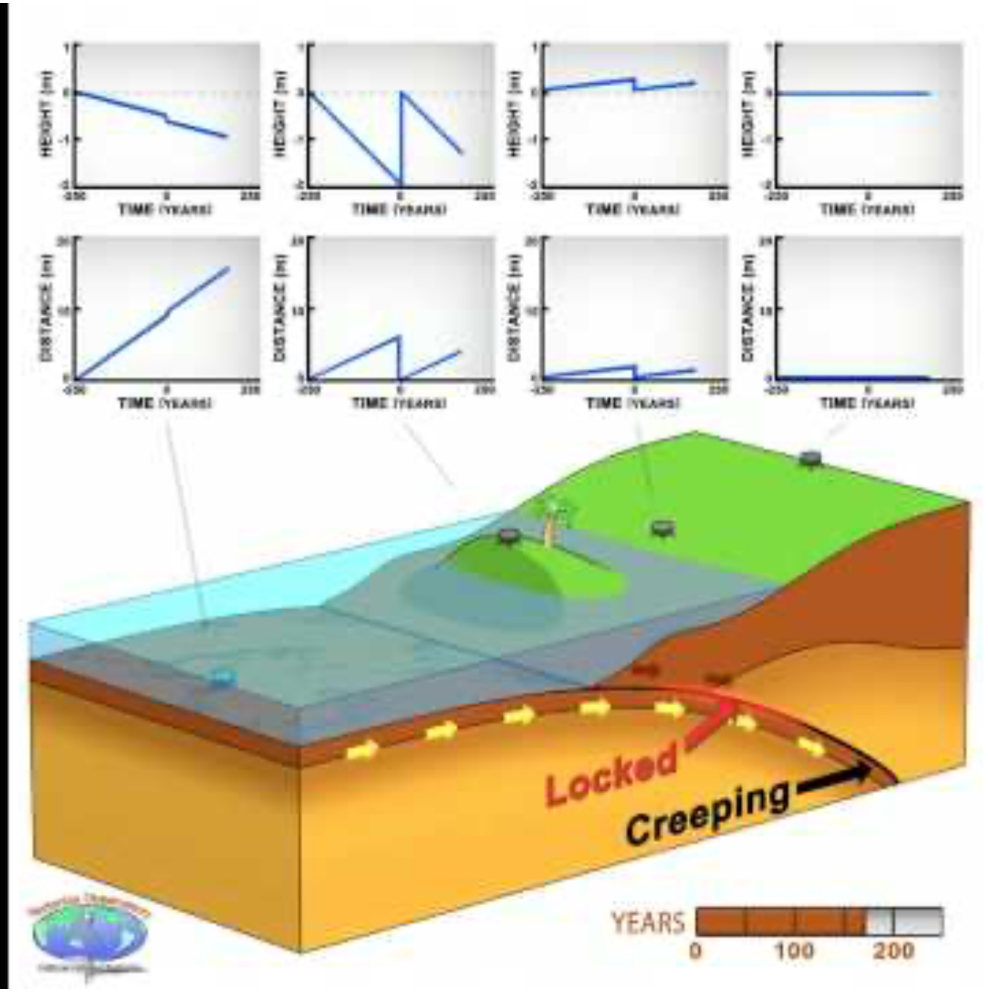
(Lin et al., 2016)

Honshu Tectonic Setting



Marill et al. JGR 2021

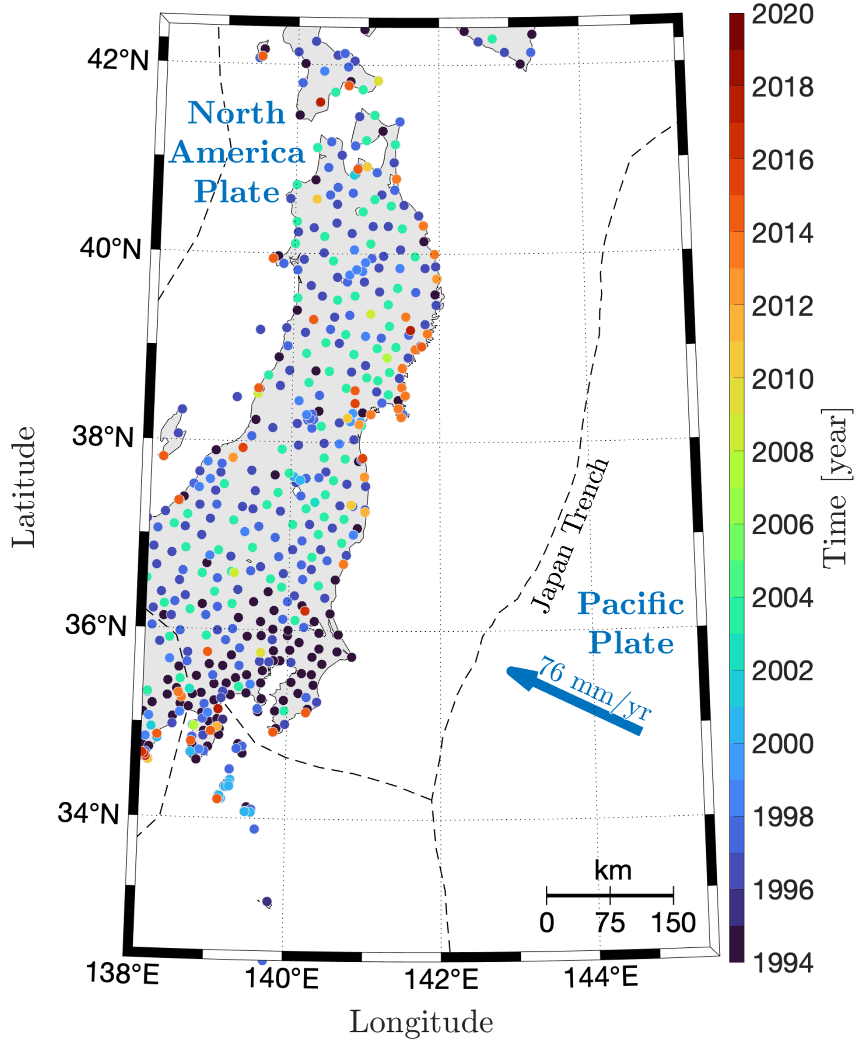
Seismic cycle



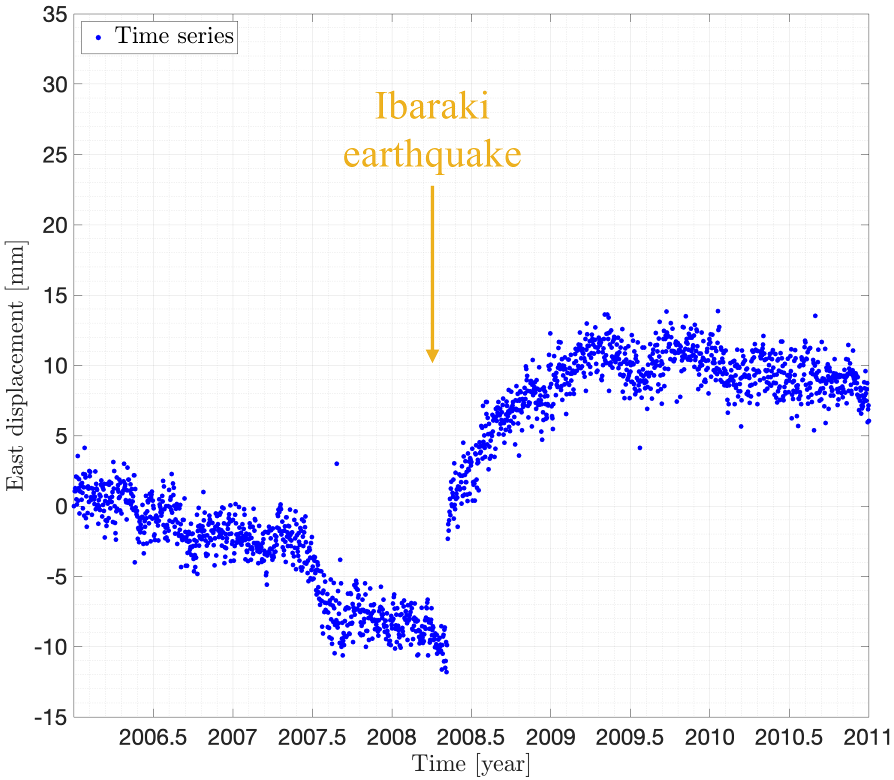
https://www.youtube.com/shorts/8u1xjWOIrE4

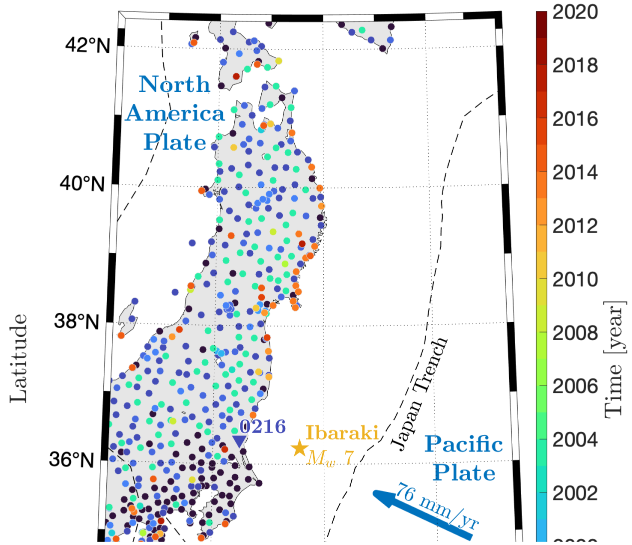
Seismic Cycle and Slow Slip Events

Illustrated on the Japan Trench



Seismic Cycle & Surface Deformation





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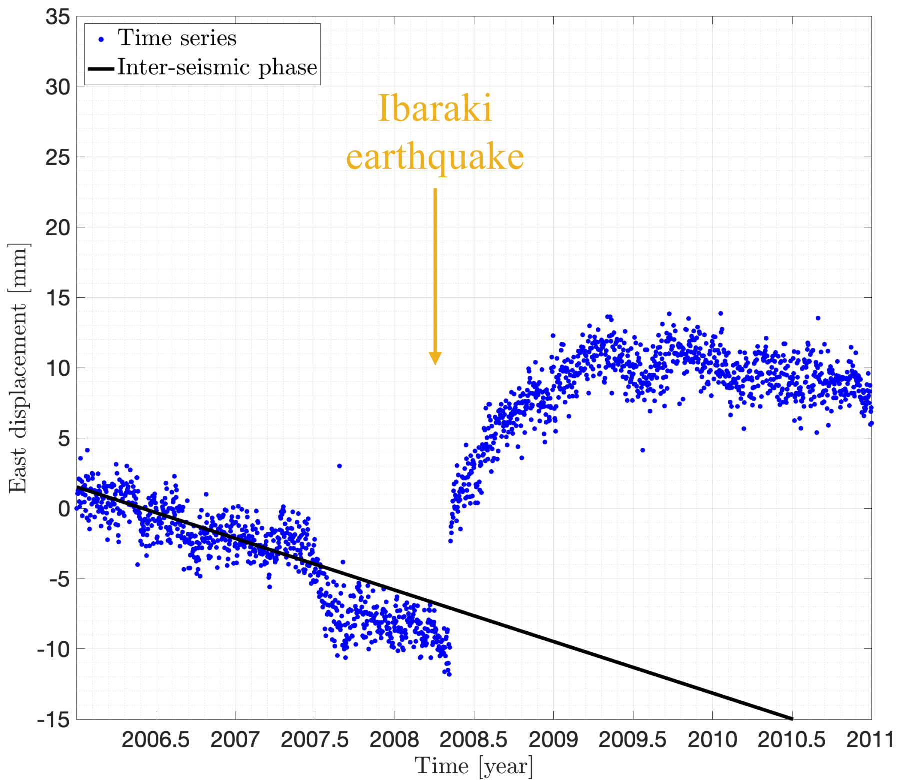
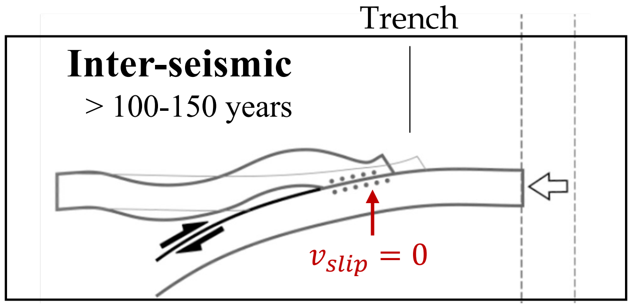
Seismic Cycle & Surface Deformation





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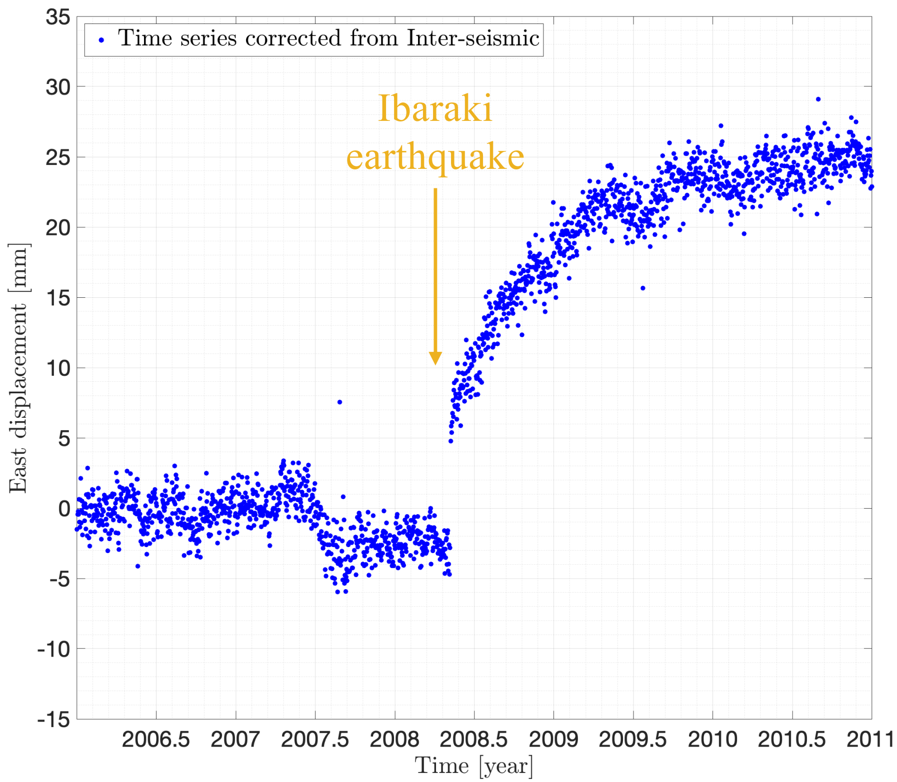
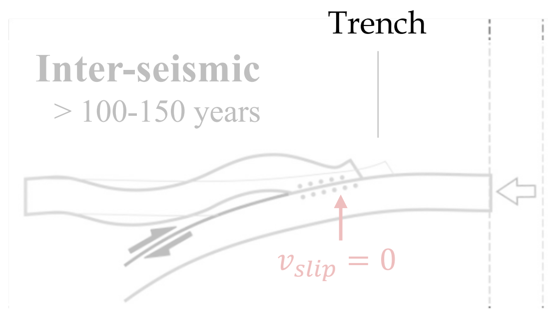
Seismic Cycle & Surface Deformation





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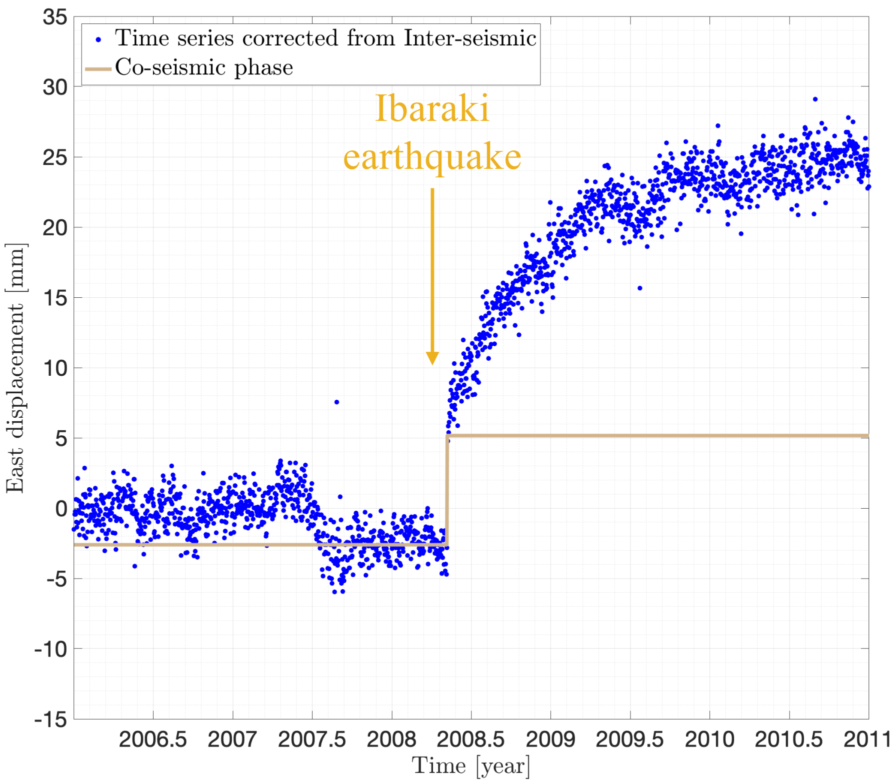
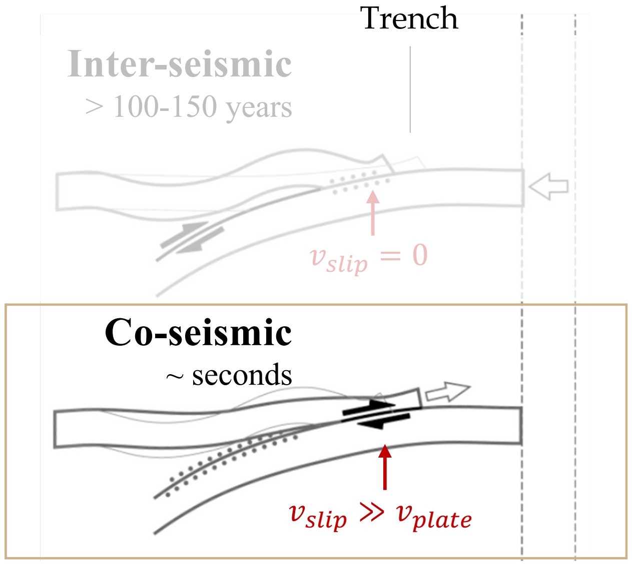
Seismic Cycle & Surface Deformation





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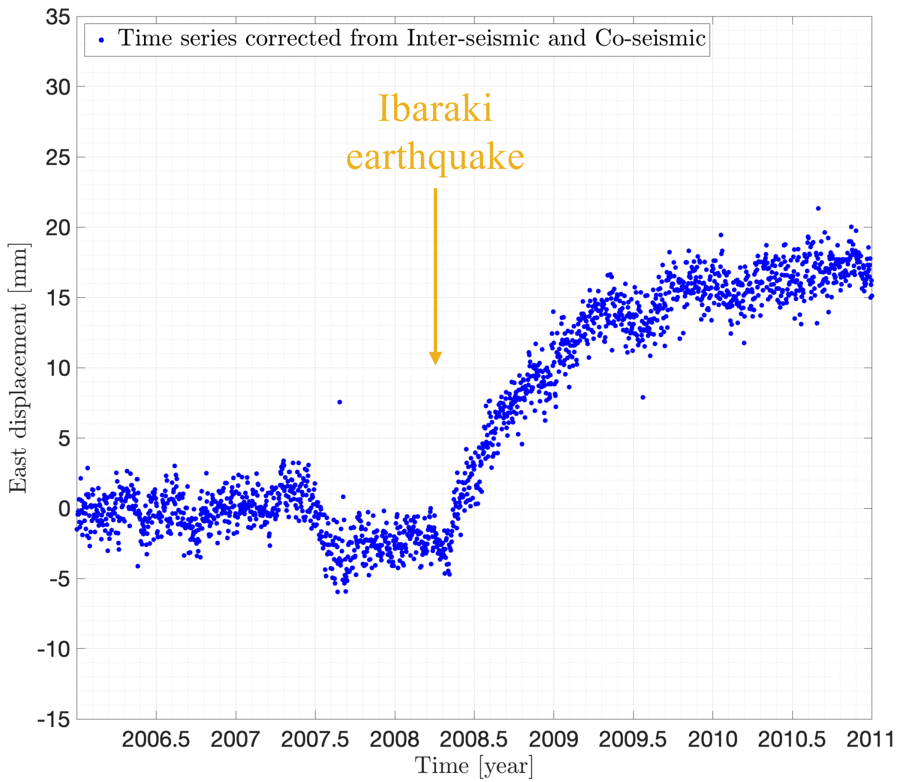
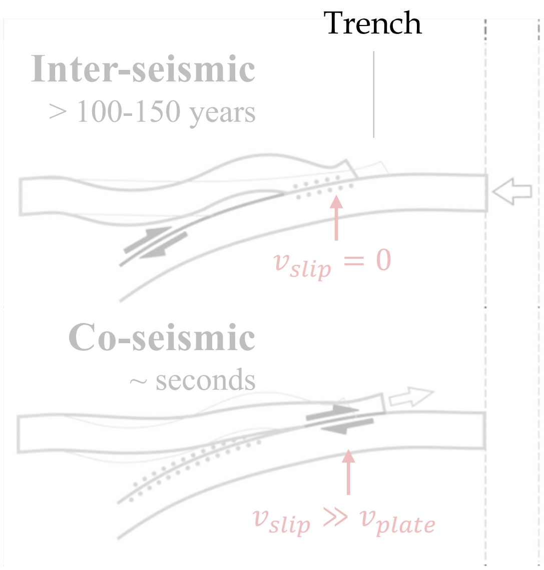
Seismic Cycle & Surface Deformation





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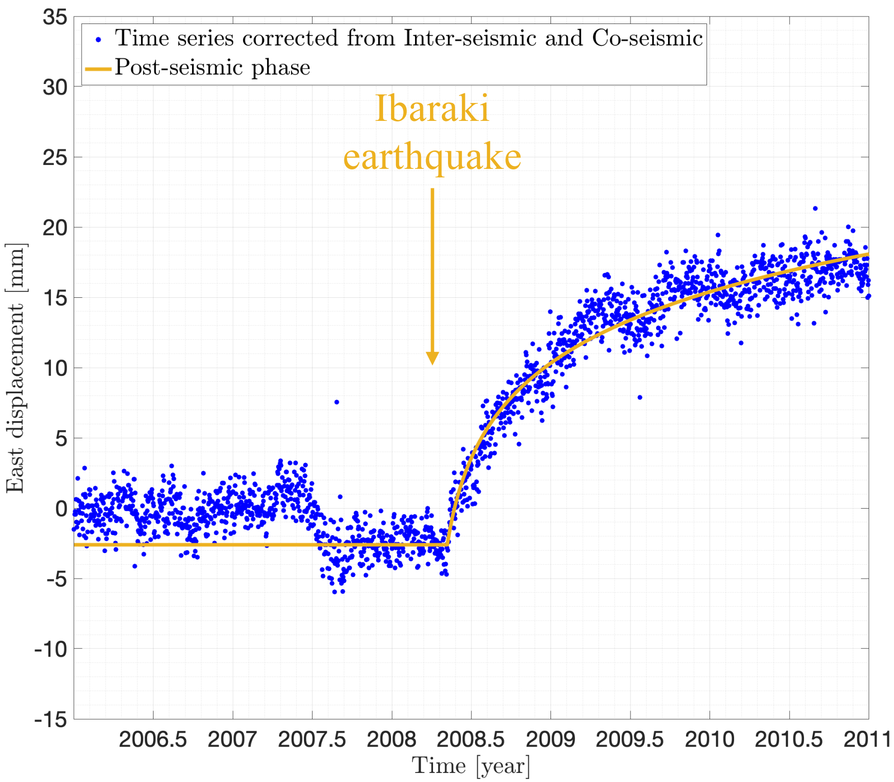
Seismic Cycle & Surface Deformation



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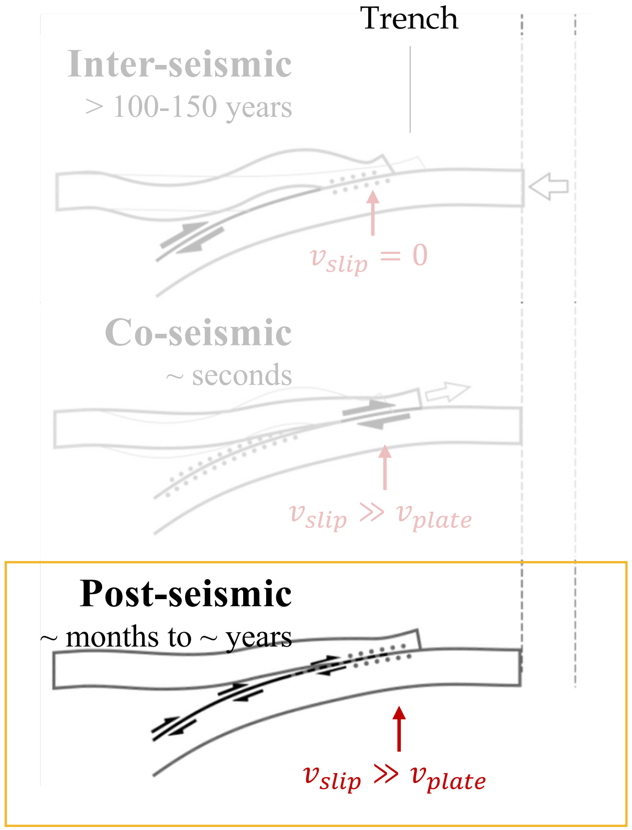
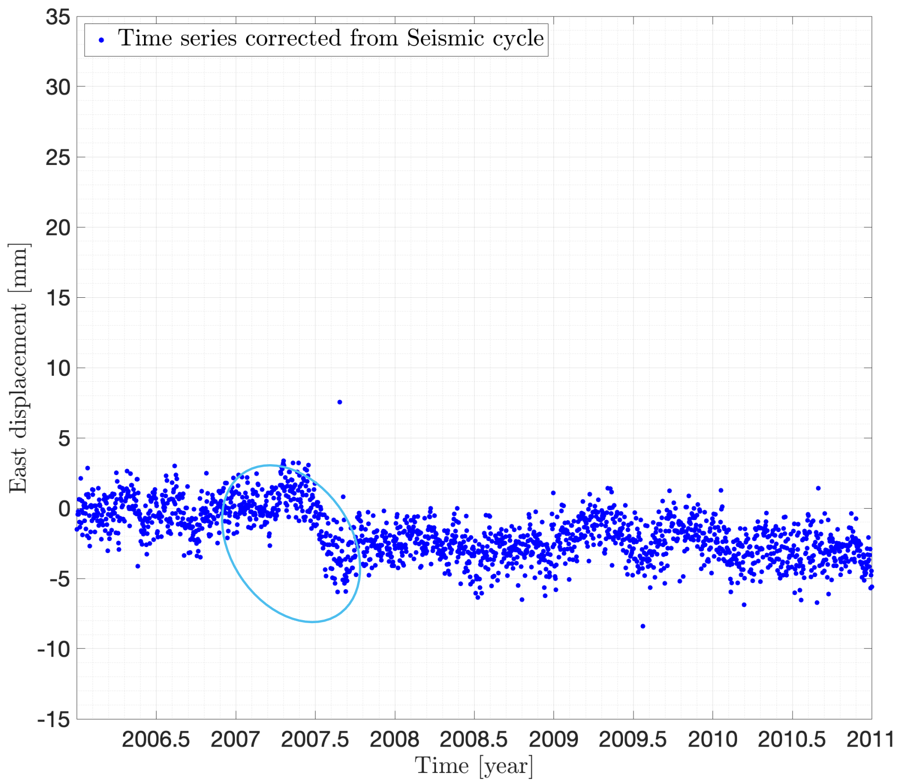
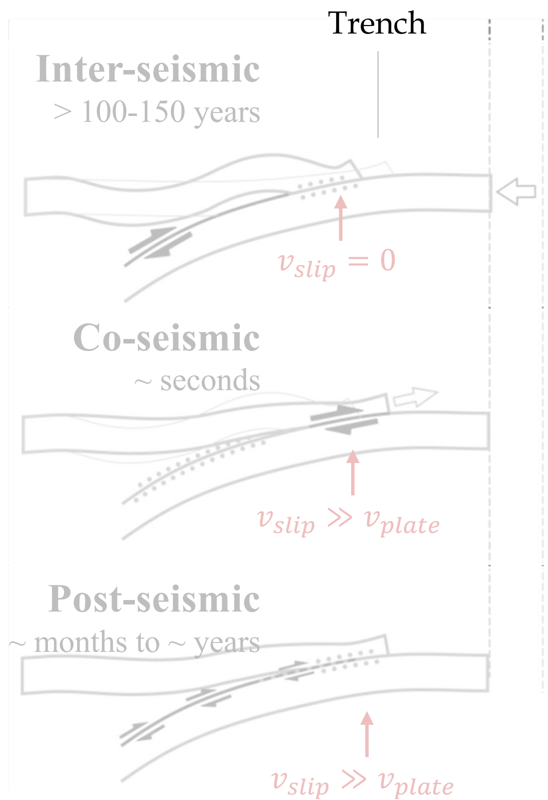


Seismic Cycle & Surface Deformation





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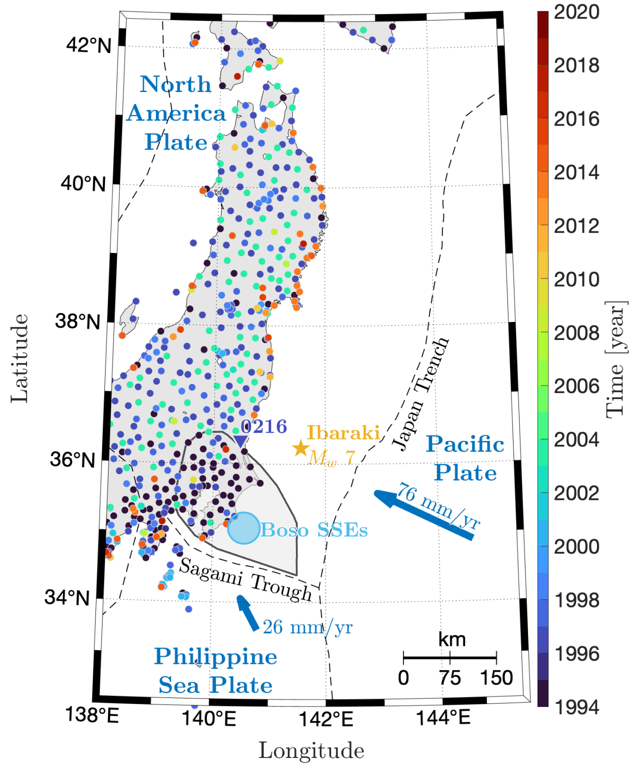
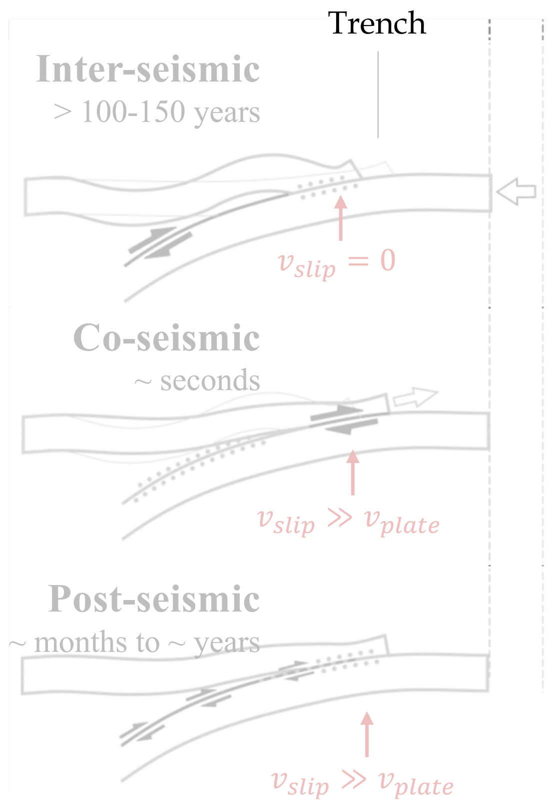
Seismic Cycle & Surface Deformation





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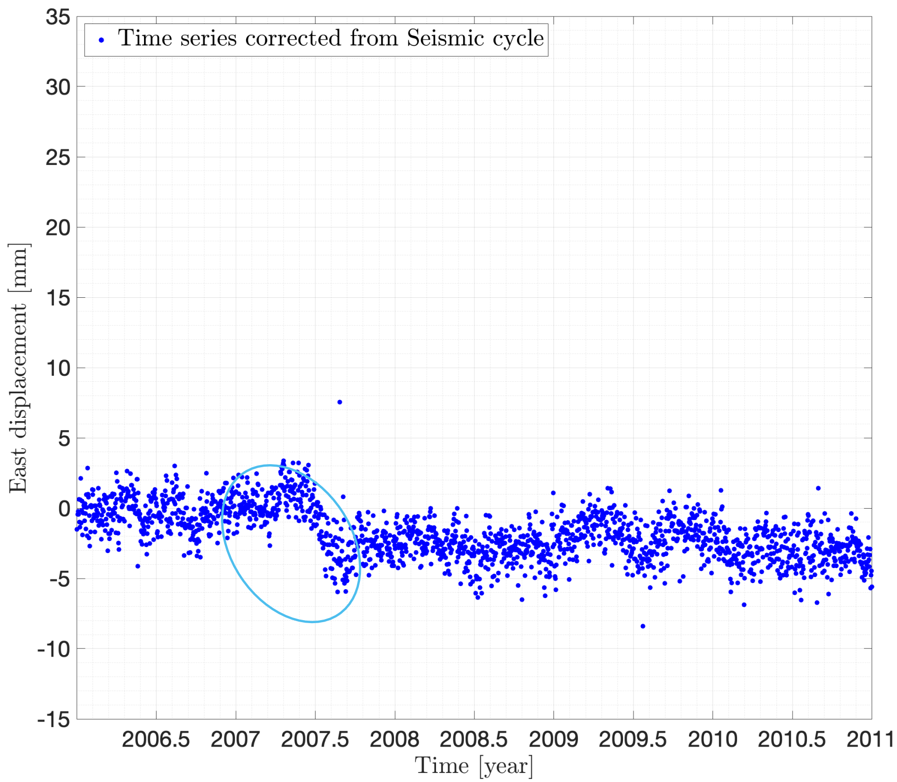
Seismic Cycle & Surface Deformation



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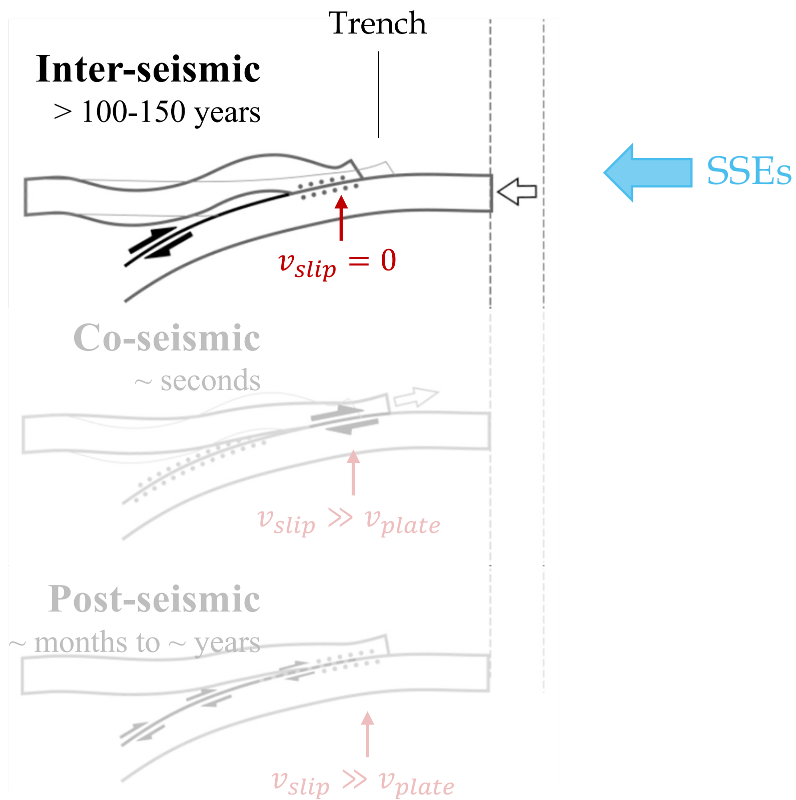
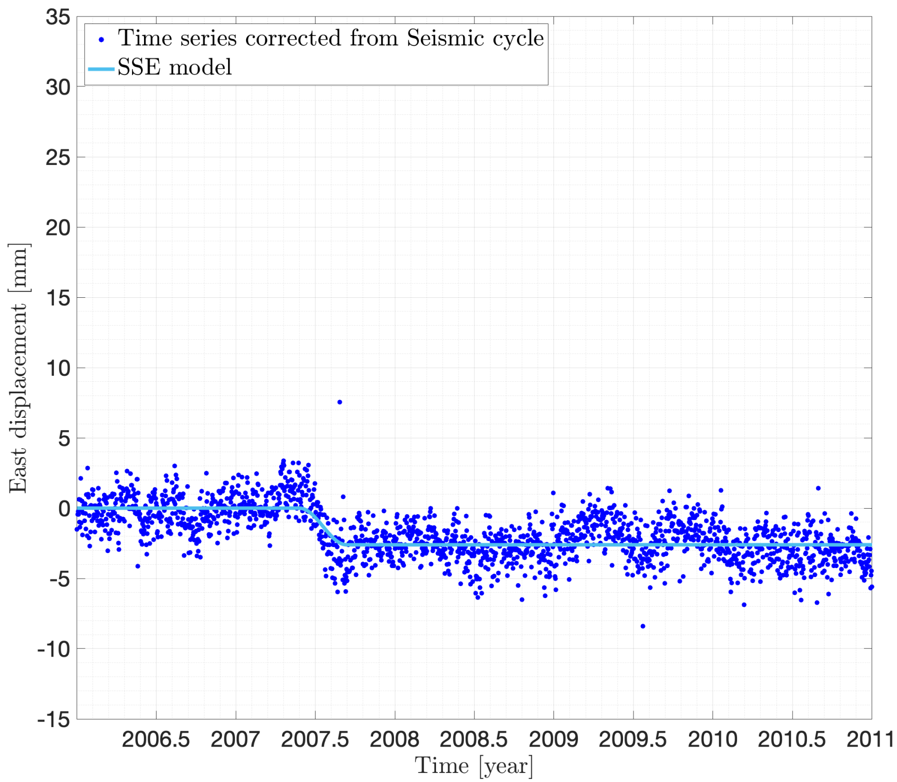
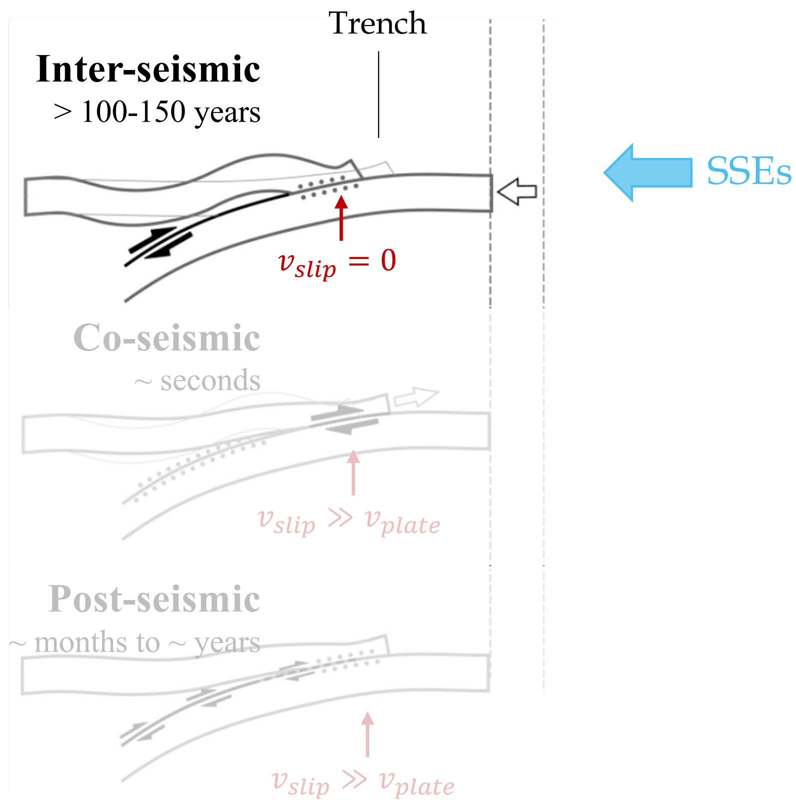


Seismic Cycle & Surface Deformation





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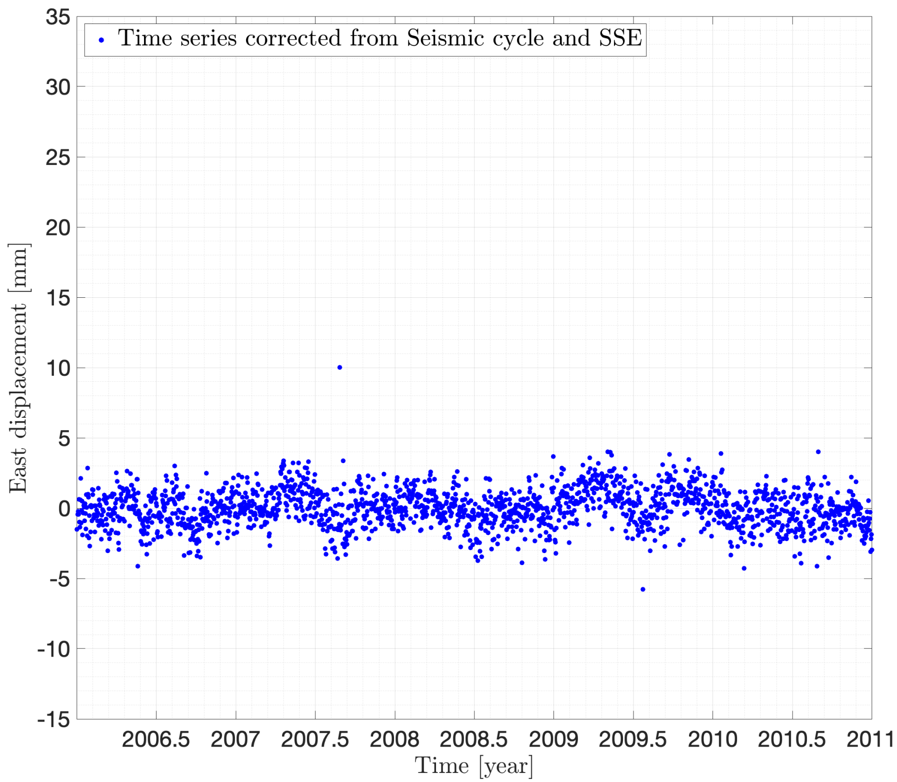
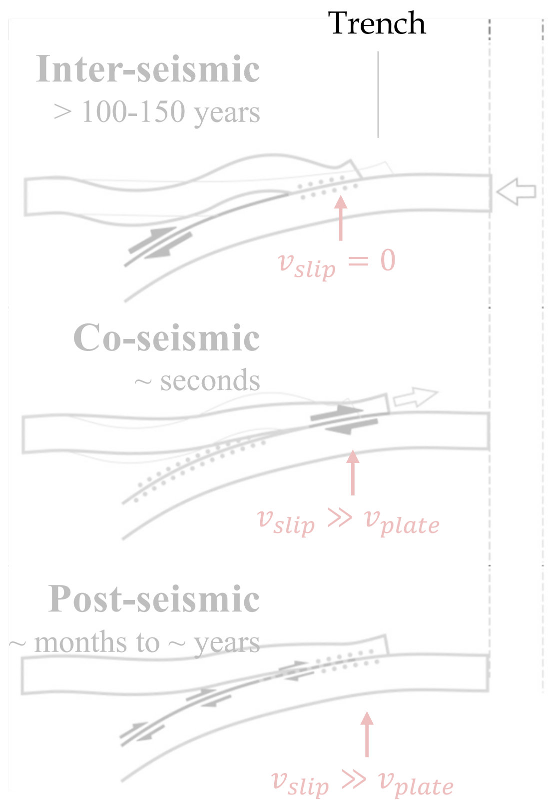
Seismic Cycle & Surface Deformation





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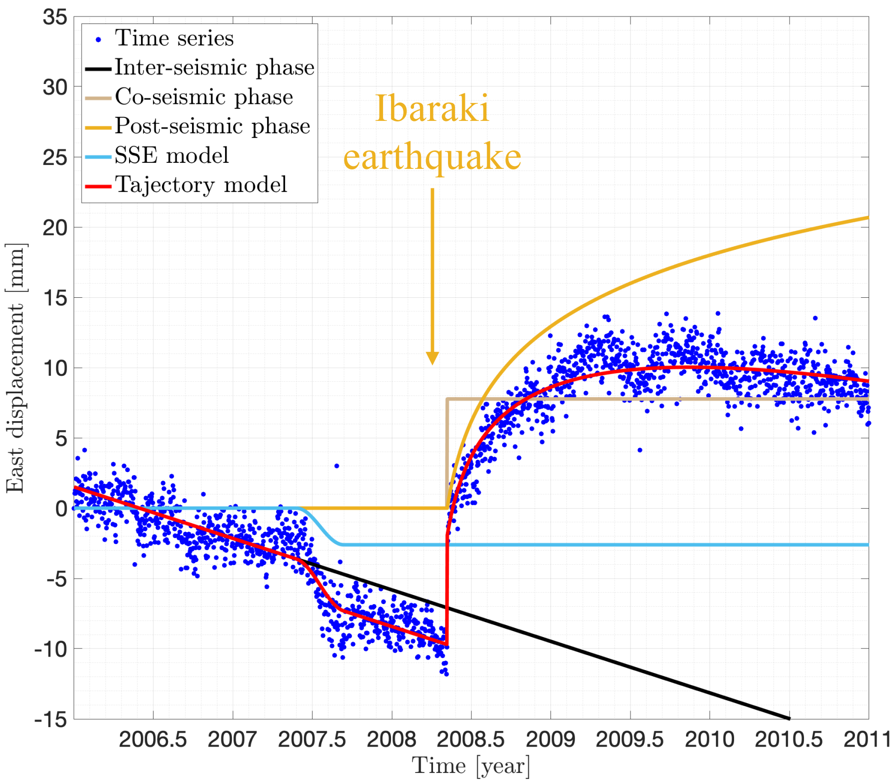
Trajectory Model



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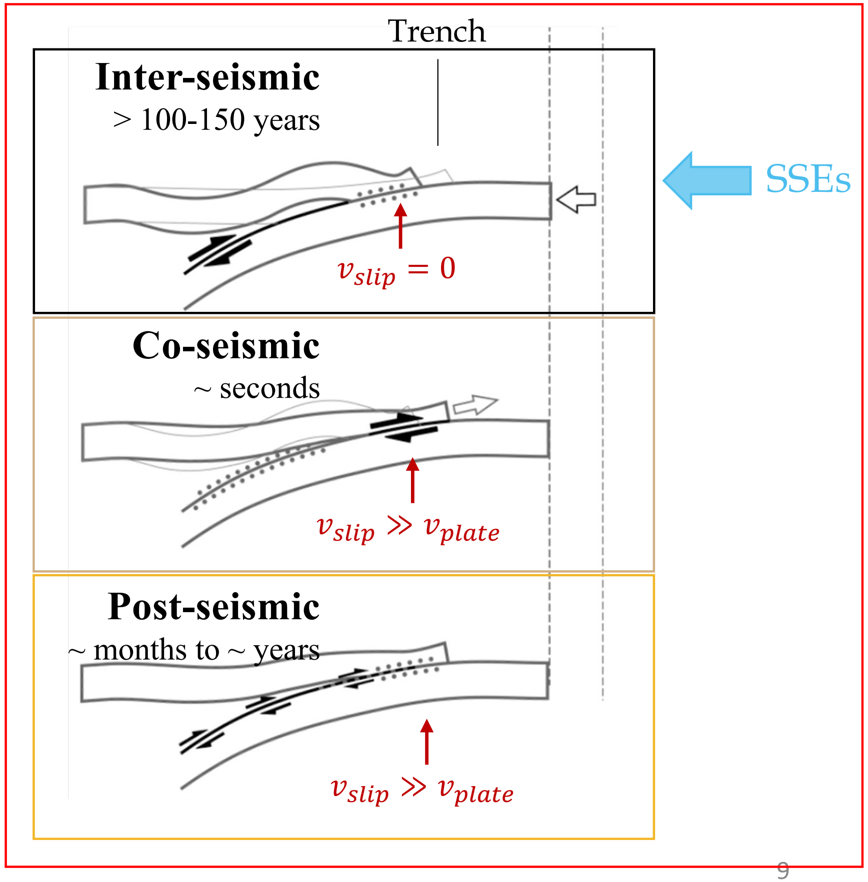
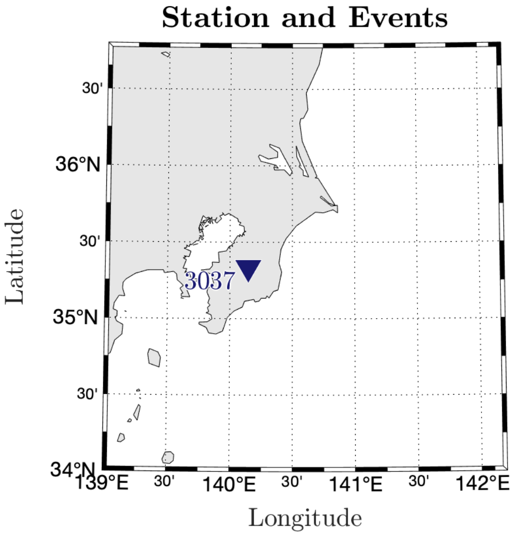


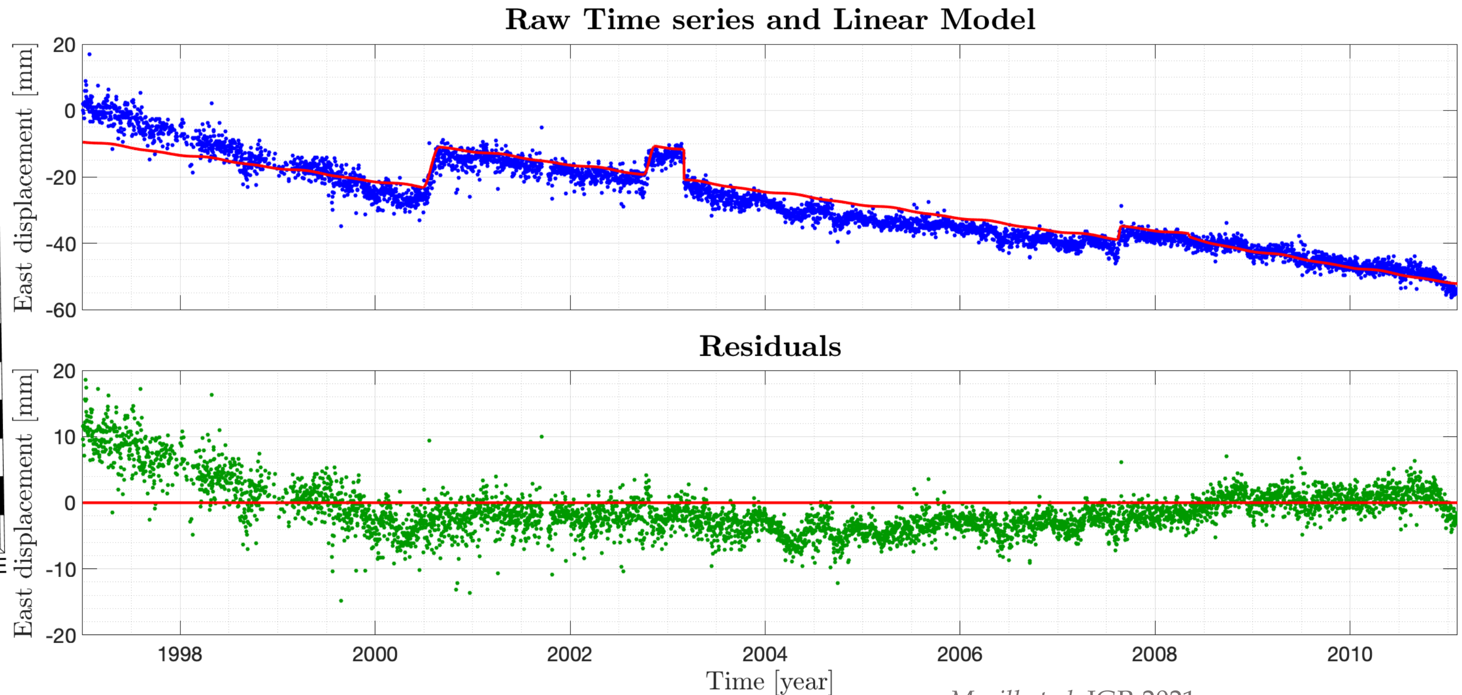
Linear Trajectory Model

Model   Inter-seismic   Seasonal variations

$$x(t) = x_R + v(t - t_R) + \sum_{k=1}^{2}\left[s_k \sin(2k\pi(t - t_R)) + c_k \cos(2k\pi(t - t_R))\right] + \sum_{j=1}^{n_J} b_j \mathrm{H}(t - t_j) + \sum_{s=1}^{n_S} d_s \mathrm{J}(t - t_s) + \sum_{i=1}^{n_i} a_i \log\left(1 + \frac{t - t_i}{100d}\right)$$

$$\mathrm{J}(t - t_s) = \mathrm{H}(t - t_s) \times \left(\frac{1}{2} - \frac{1}{2}\cos\left(\frac{t - t_s}{t_d}\pi\right)\right)$$





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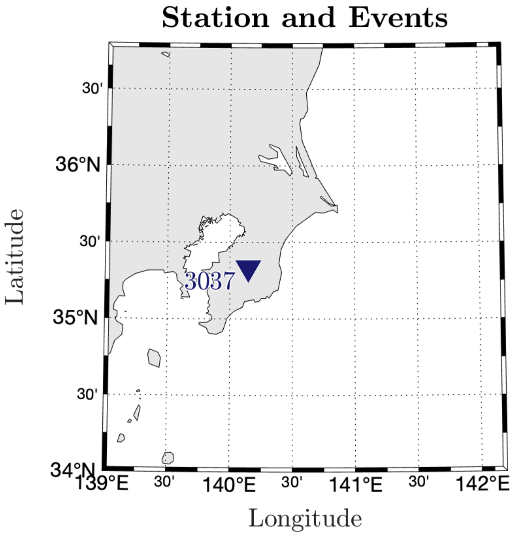
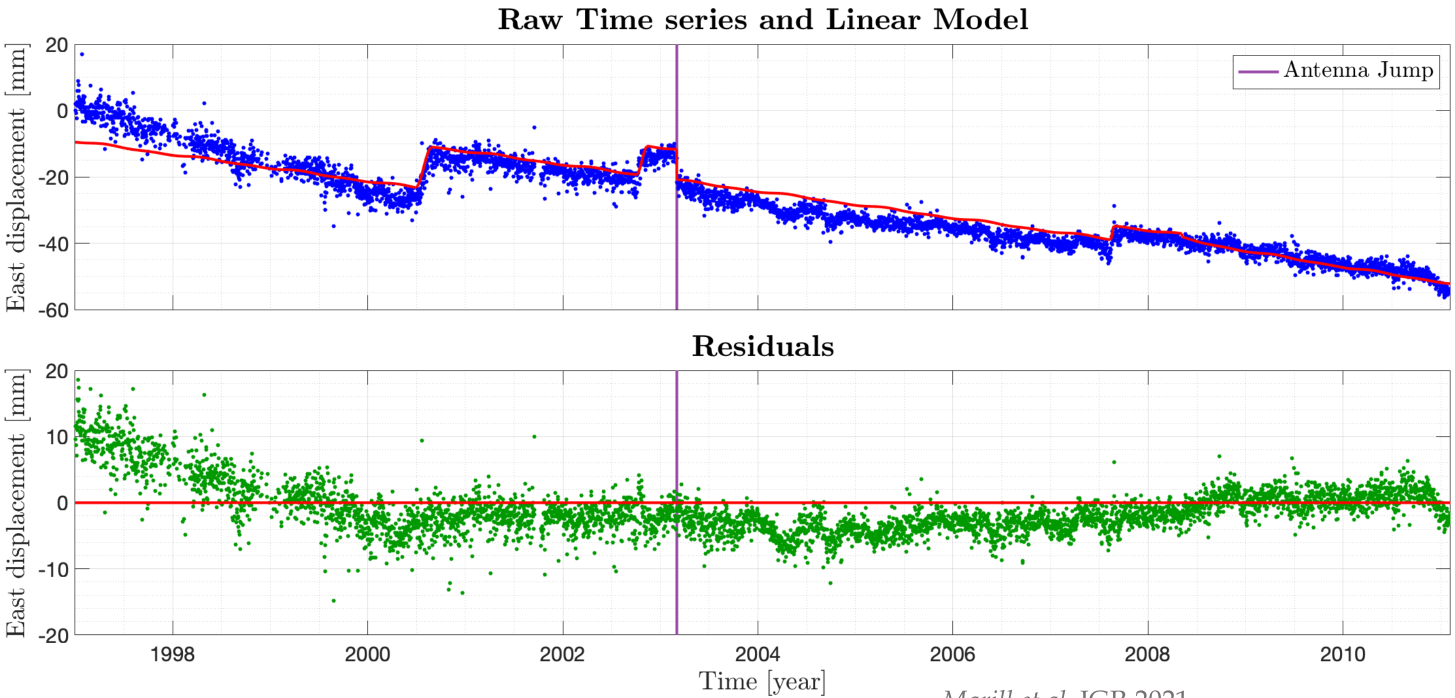
Linear Trajectory Model

Model — Inter-seismic — Seasonal variations — Antenna

$$x(t) = x_R + v(t - t_R) + \sum_{k=1}^{2} [s_k \sin(2k\pi(t - t_R)) + c_k \cos(2k\pi(t - t_R))] + \sum_{j=1}^{n_J} b_j \mathrm{H}(t - t_j) + \sum_{s=1}^{n_S} d_s \mathrm{J}(t - t_s) + \sum_{i=1}^{n_i} a_i \log\left(1 + \frac{t - t_i}{100d}\right)$$

$$\mathrm{J}(t - t_s) = \mathrm{H}(t - t_s) \times \left(\frac{1}{2} - \frac{1}{2}\cos\left(\frac{t - t_s}{t_d}\pi\right)\right)$$





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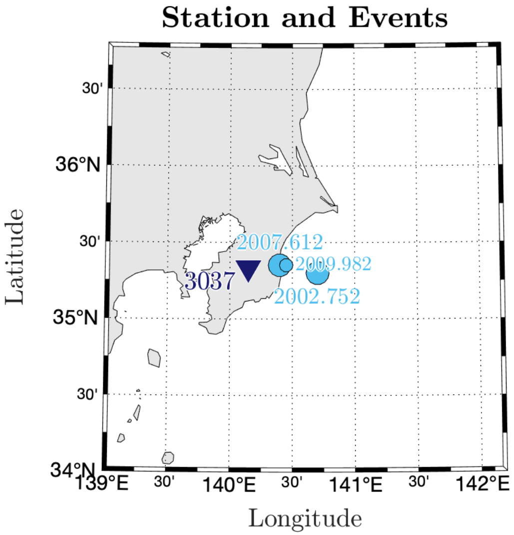
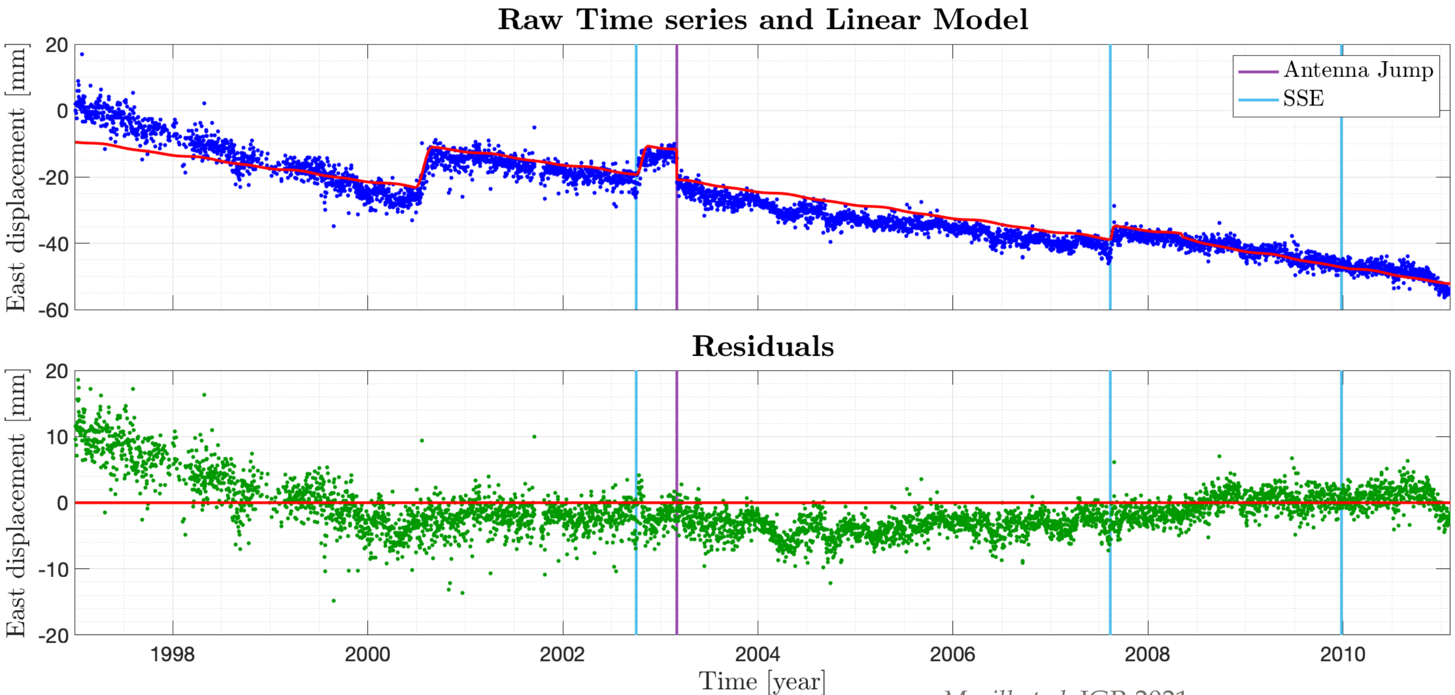
Linear Trajectory Model

Model Inter-seismic Seasonal variations Antenna SSE

$$x(t) = x_R + v(t - t_R) + \sum_{k=1}^{2}[s_k \sin(2k\pi(t - t_R)) + c_k \cos(2k\pi(t - t_R))] + \sum_{j=1}^{n_J} b_j \mathrm{H}(t - t_j) + \sum_{s=1}^{n_S} d_s \mathrm{J}(t - t_s) + \sum_{i=1}^{n_i} a_i \log\left(1 + \frac{t - t_i}{100d}\right)$$

$$\mathrm{J}(t - t_s) = \mathrm{H}(t - t_s) \times \left(\frac{1}{2} - \frac{1}{2}\cos\left(\frac{t - t_s}{t_d}\pi\right)\right)$$





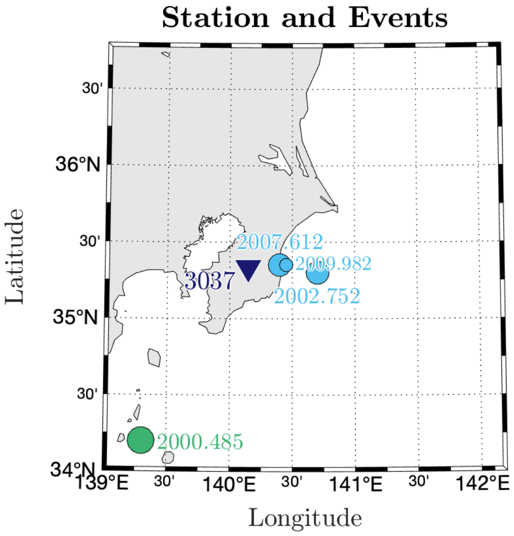
Marill et al. JGR 2021

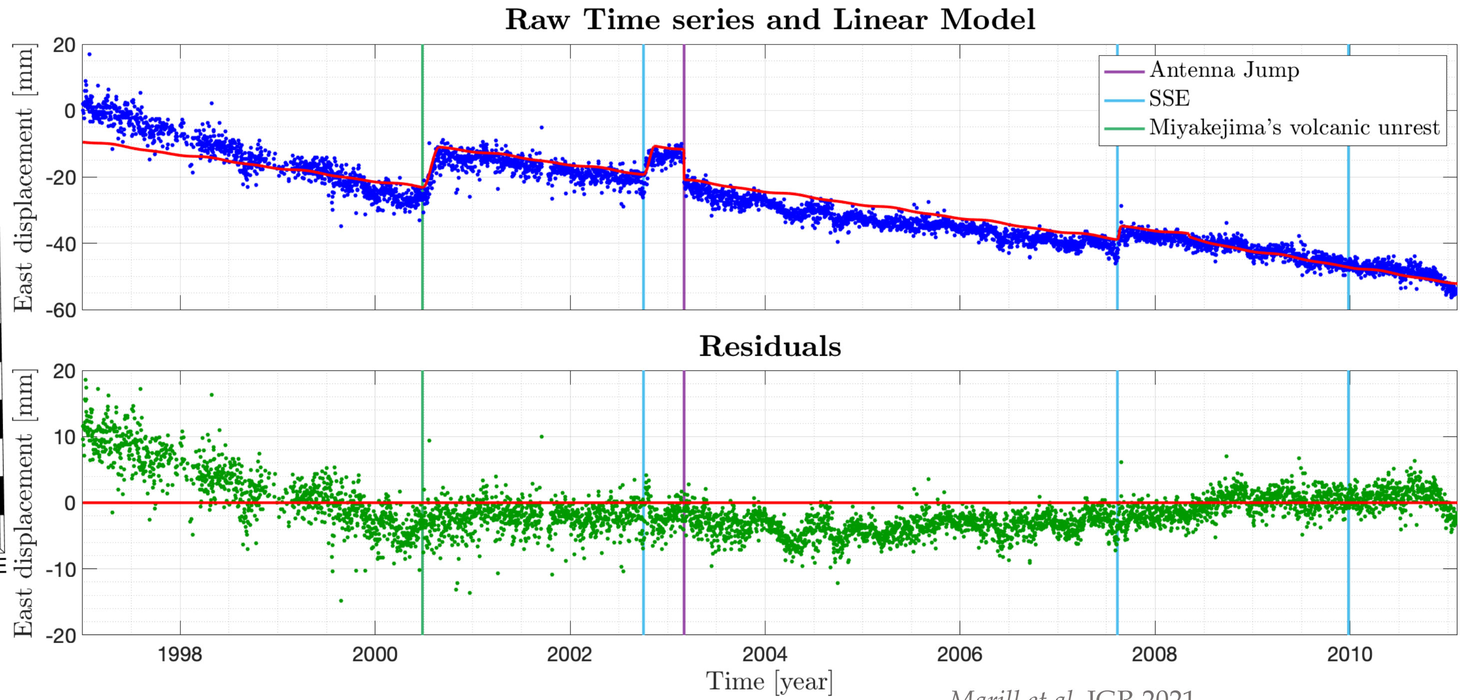
Linear Trajectory Model

Model · Inter-seismic · Seasonal variations · Antenna · SSE & Swarm

$$x(t) = x_R + v(t - t_R) + \sum_{k=1}^{2}\left[s_k \sin(2k\pi(t - t_R)) + c_k \cos(2k\pi(t - t_R))\right] + \sum_{j=1}^{n_J} b_j \mathrm{H}(t - t_j) + \sum_{s=1}^{n_S} d_s \mathrm{J}(t - t_s) + \sum_{i=1}^{n_i} a_i \log\left(1 + \frac{t - t_i}{100d}\right)$$

$$\mathrm{J}(t - t_s) = \mathrm{H}(t - t_s) \times \left(\frac{1}{2} - \frac{1}{2}\cos\left(\frac{t - t_s}{t_d}\pi\right)\right)$$





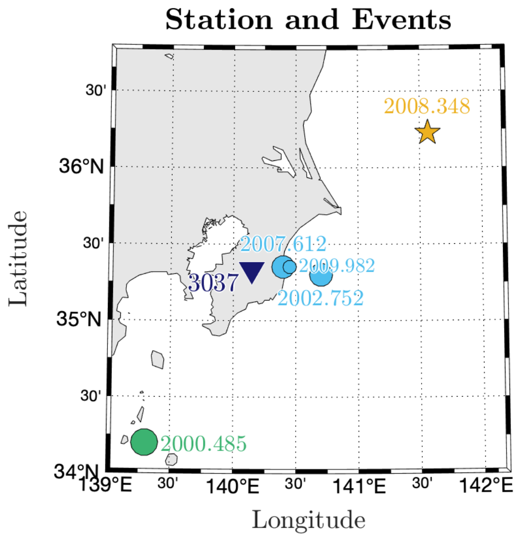
Marill et al. JGR 2021

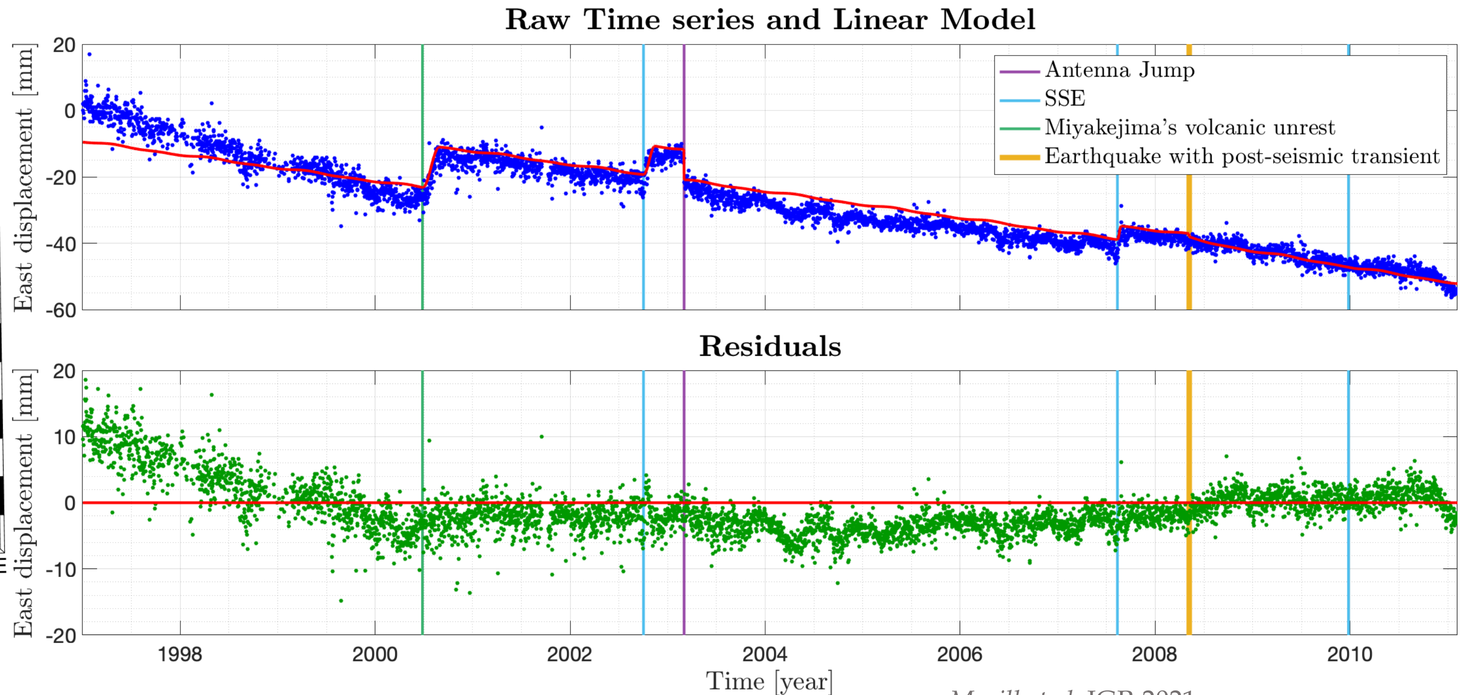
Linear Trajectory Model

Model — Inter-seismic — Seasonal variations — Antenna & Co-seismic — SSE & Swarm — Post-seismic

$$x(t) = x_R + v(t - t_R) + \sum_{k=1}^{2}\left[s_k \sin(2k\pi(t - t_R)) + c_k \cos(2k\pi(t - t_R))\right] + \sum_{j=1}^{n_J} b_j \mathrm{H}(t - t_j) + \sum_{s=1}^{n_S} d_s \mathrm{J}(t - t_s) + \sum_{i=1}^{n_i} a_i \log\left(1 + \frac{t - t_i}{100d}\right)$$

$$\mathrm{J}(t - t_s) = \mathrm{H}(t - t_s) \times \left(\frac{1}{2} - \frac{1}{2}\cos\left(\frac{t - t_s}{t_d}\pi\right)\right)$$





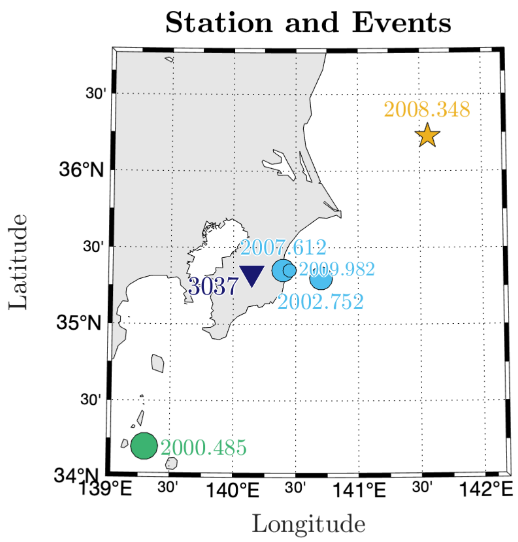
Marill et al. JGR 2021

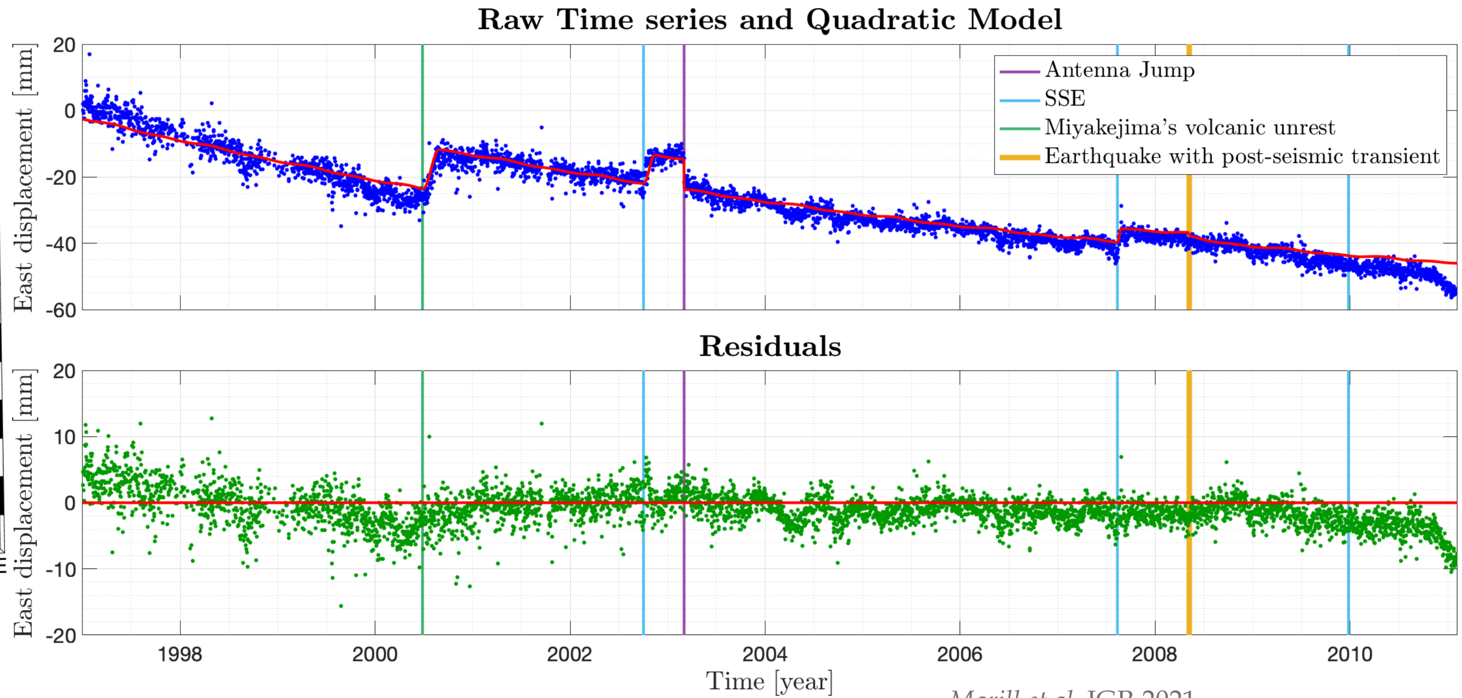
Quadratic Trajectory Model

Model | Inter-seismic | Acceleration | Seasonal variations | Antenna & Co-seismic | SSE & Swarm | Post-seismic

$$x(t) = x_R + v(t - t_R) + \frac{1}{2}a(t - t_R)^2 + \sum_{k=1}^{2}[s_k \sin(2k\pi(t - t_R)) + c_k \cos(2k\pi(t - t_R))] + \sum_{j=1}^{n_J} b_j \mathrm{H}(t - t_j) + \sum_{s=1}^{n_S} d_s \mathrm{J}(t - t_s) + \sum_{i=1}^{n_i} a_i \log\left(1 + \frac{t - t_i}{100d}\right)$$

$$\mathrm{J}(t - t_s) = \mathrm{H}(t - t_s) \times \left(\frac{1}{2} - \frac{1}{2}\cos\left(\frac{t - t_s}{t_d}\pi\right)\right)$$





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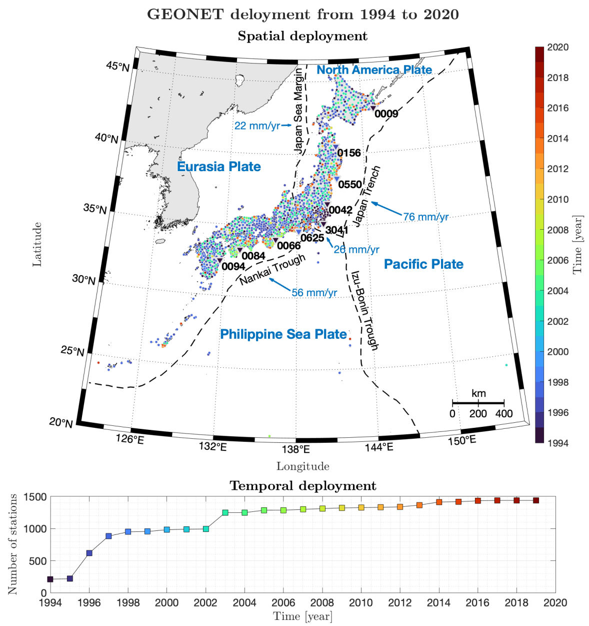
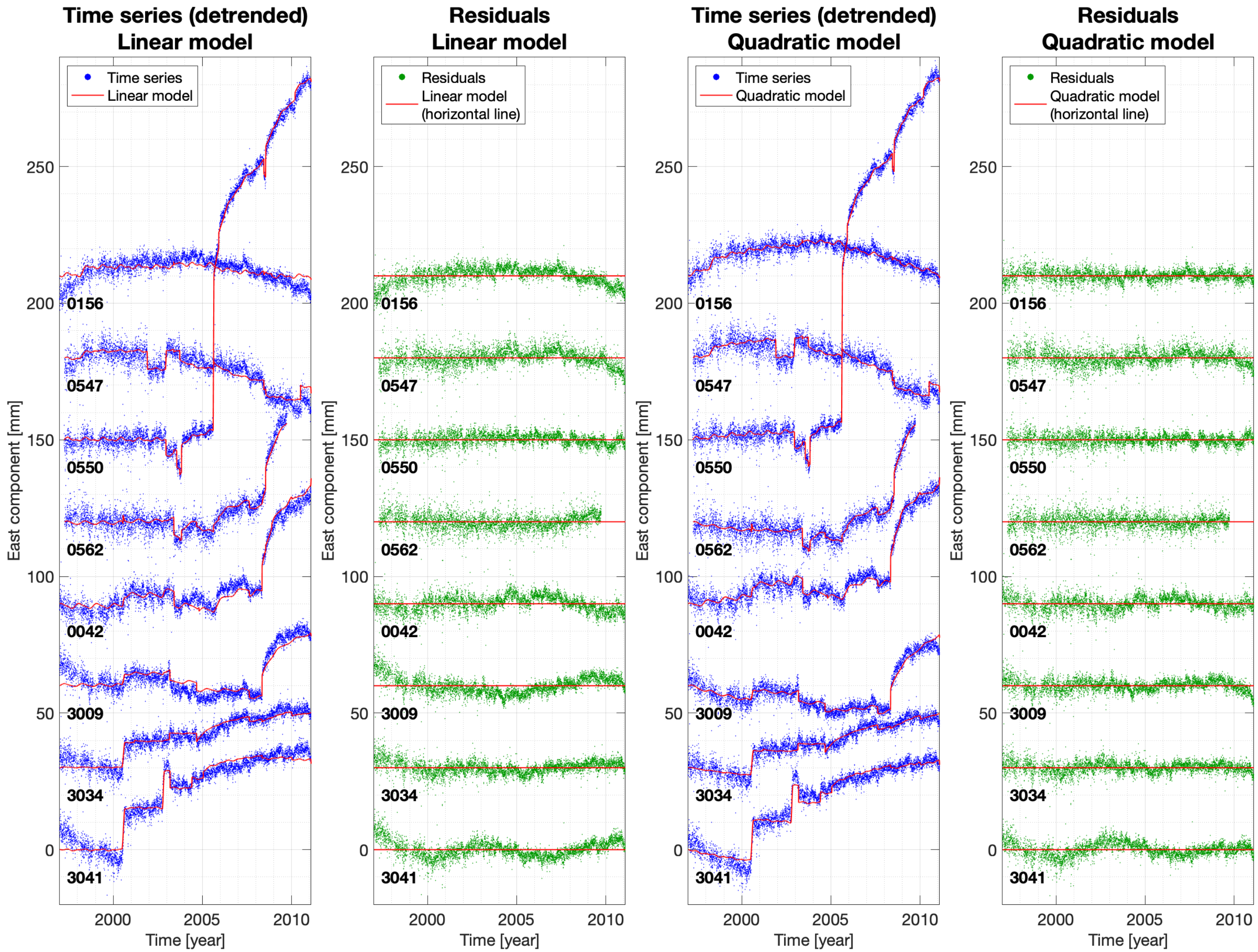
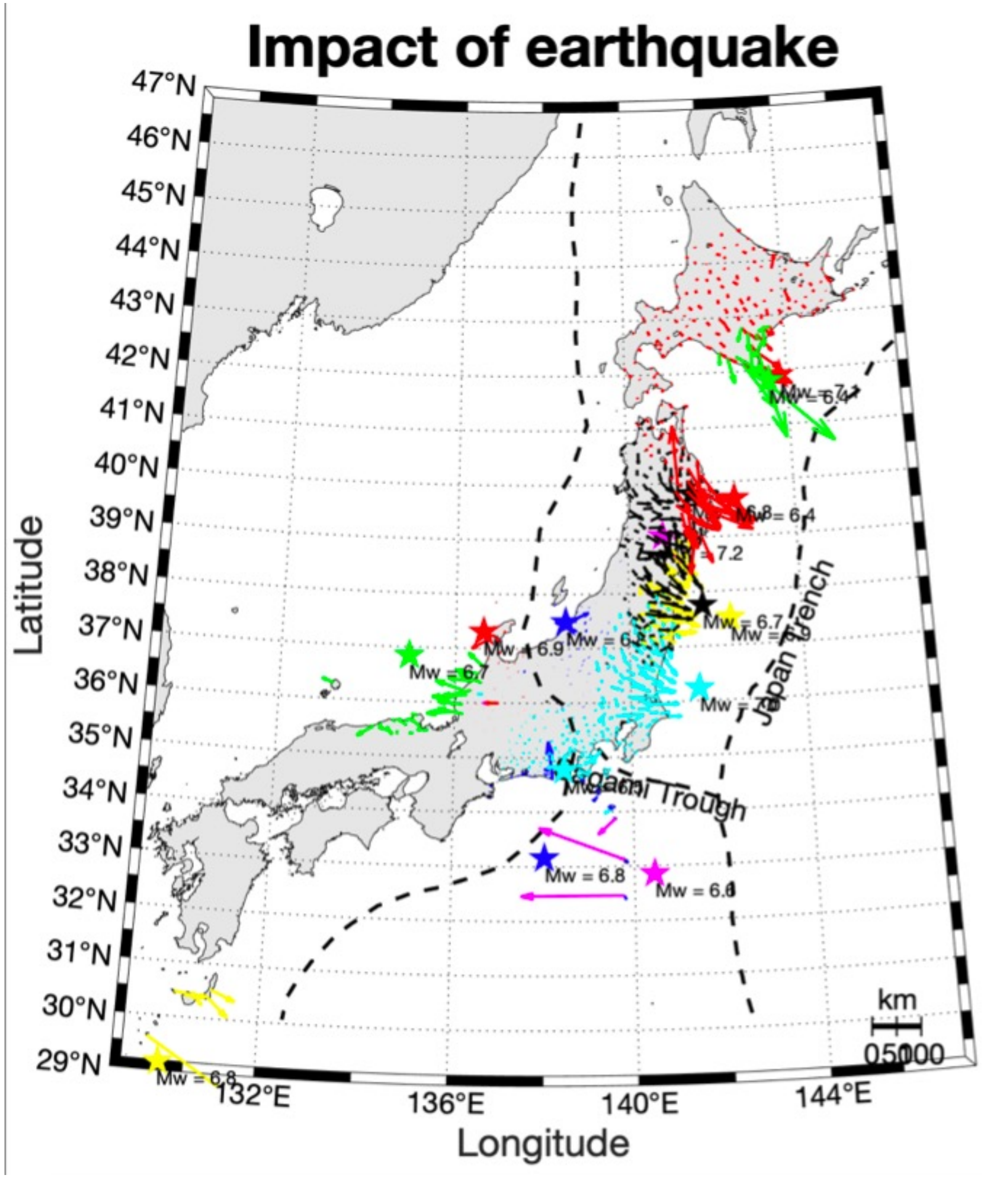
Linear and quadratic trajectory models for 8 stations, from 1997 to 2011, for the East component



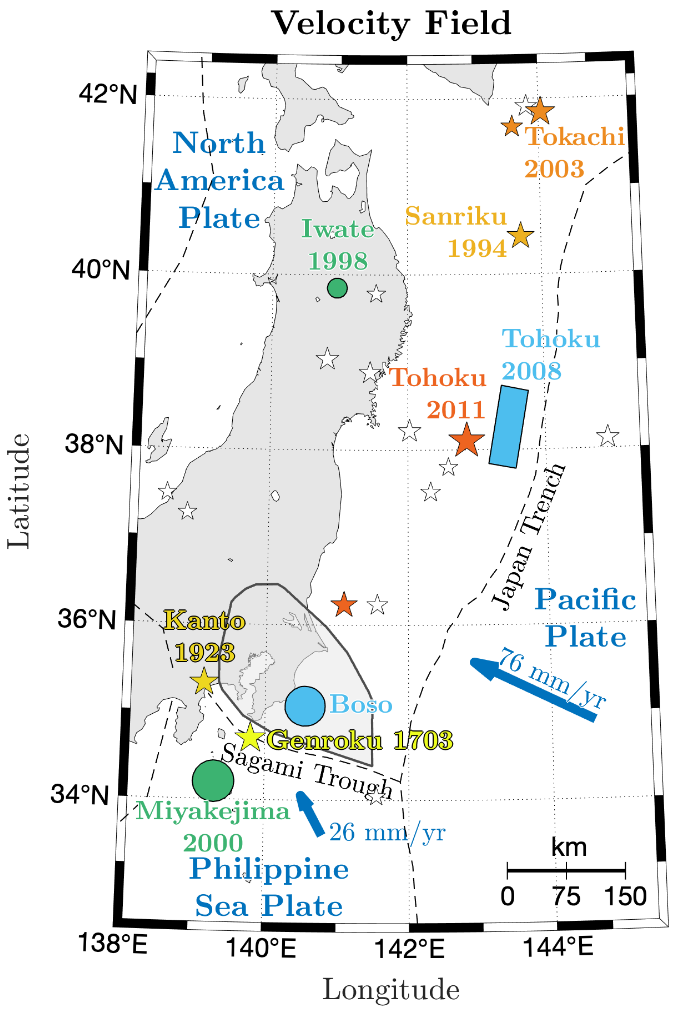


Marill et al. JGR 2021



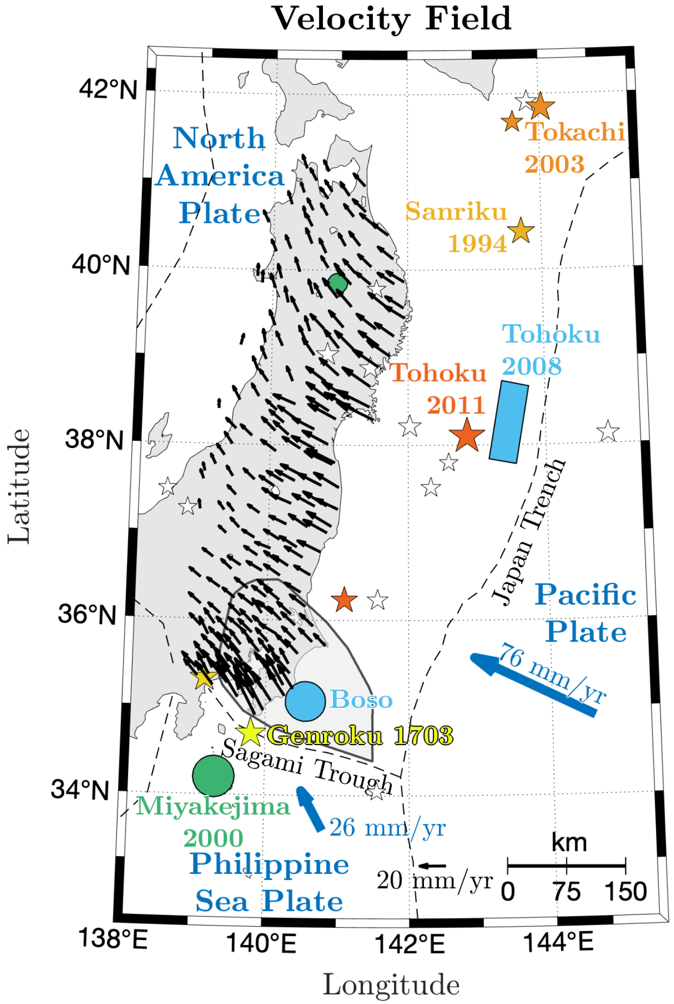
Coseismic displacements computed by the trajectory model

Corrected Events



- Megathrust earthquake and main aftershocks
- $M_w \geq 6.8$ earthquake
- SSE area
- Volcanic unrest area

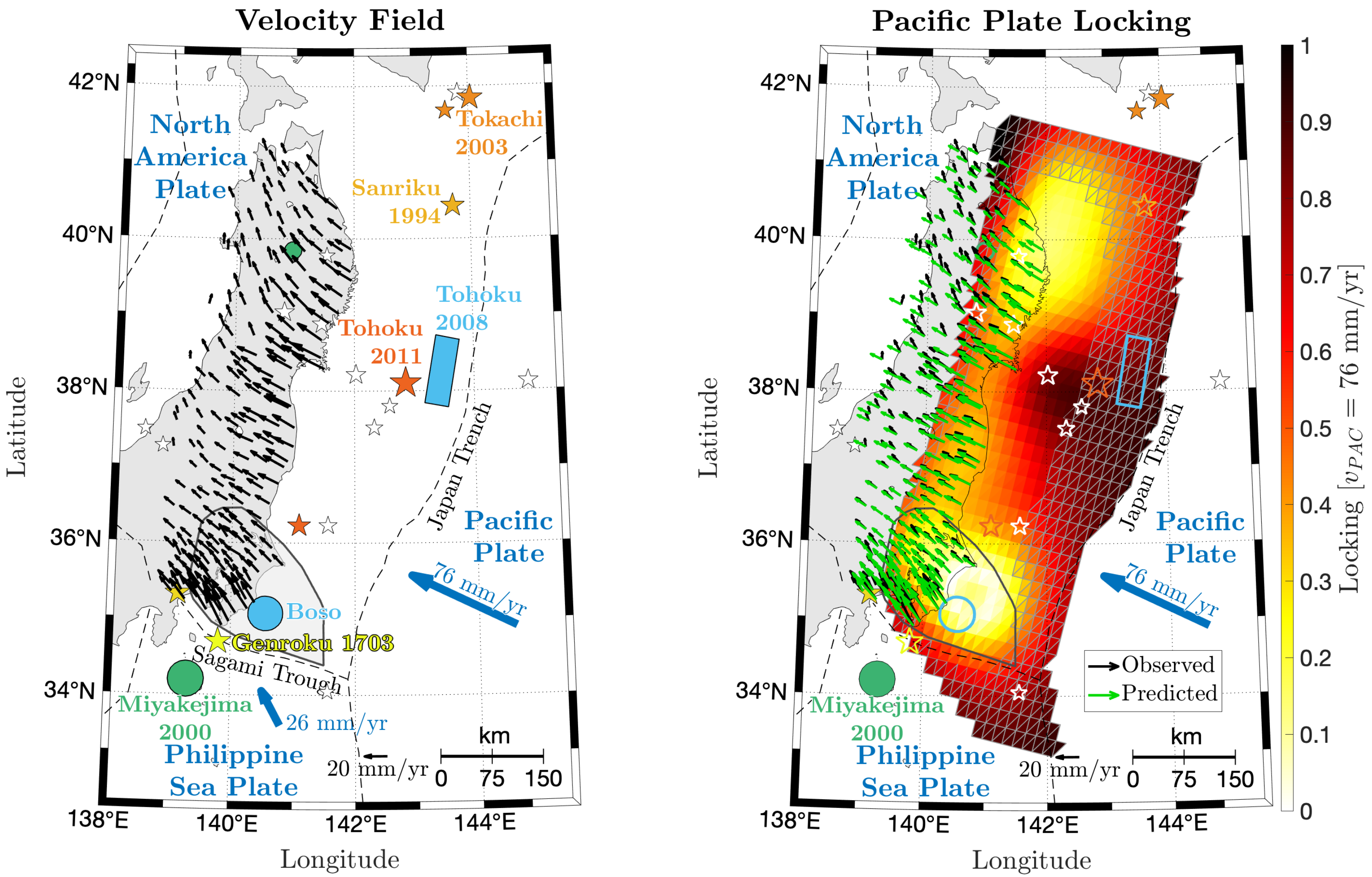
Average Velocity Field



- Megathrust earthquake and main aftershocks
- $M_w \geq 6.8$ earthquake
- SSE area
- Volcanic unrest area

Average Velocity Field and inverted interseismic coupling

- ★ Megathrust earthquake and main aftershocks
- ☆ $M_w \geq 6.8$ earthquake
- ● SSE area
- ● Volcanic unrest area



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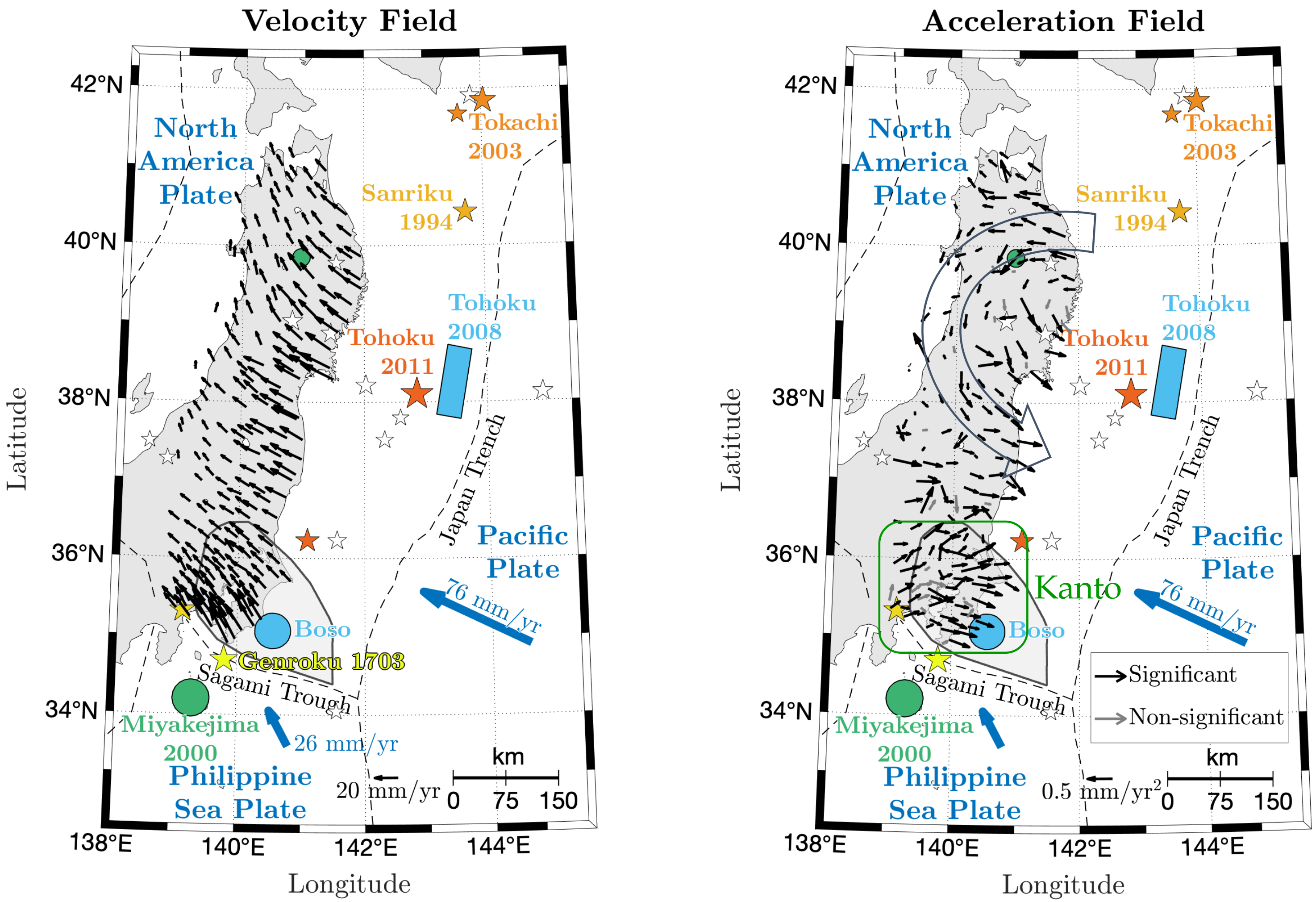
Average Velocity Field and Acceleration Field



Megathrust earthquake and main aftershocks

$M_w \geq 6.8$ earthquake

SSE area

Volcanic unrest area

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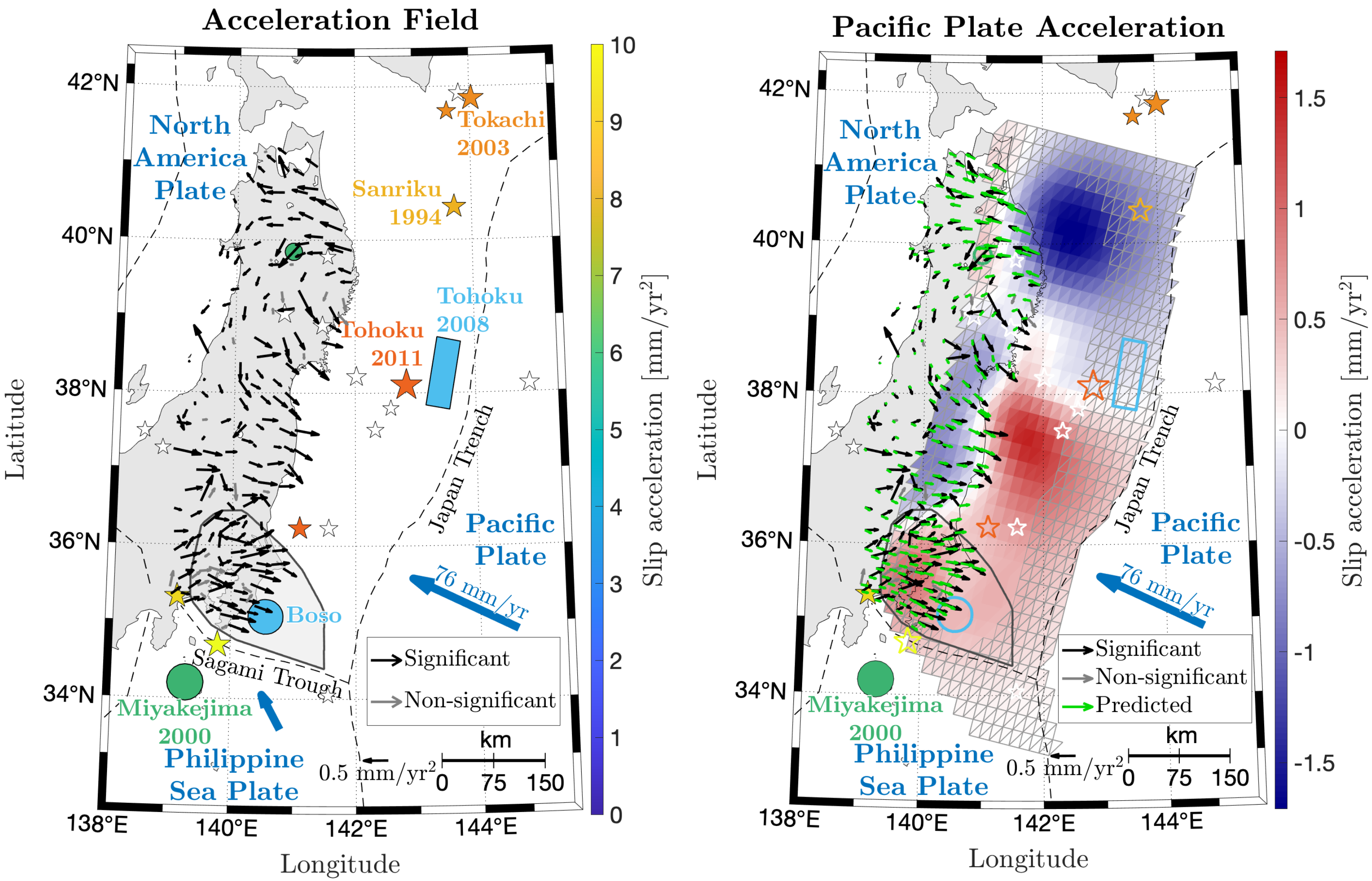
Accelerated slip before Tohoku earthquake

- Megathrust earthquake and main aftershocks
- $M_w \geq 6.8$ earthquake
- SSE area
- Volcanic unrest area



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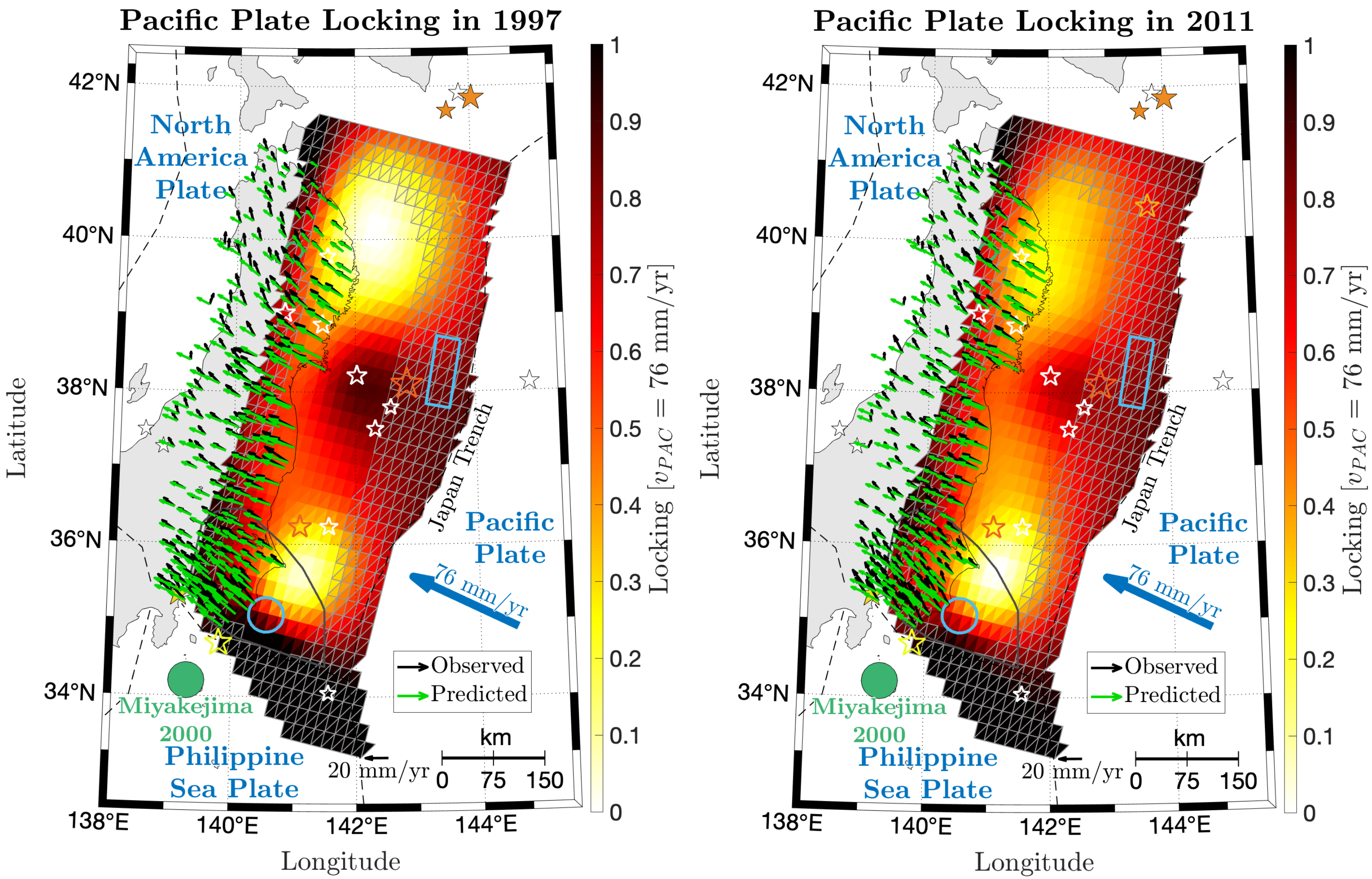
Changes in Velocity Field and interseismic coupling

Megathrust earthquake and main aftershocks

$M_w \geq 6.8$ earthquake

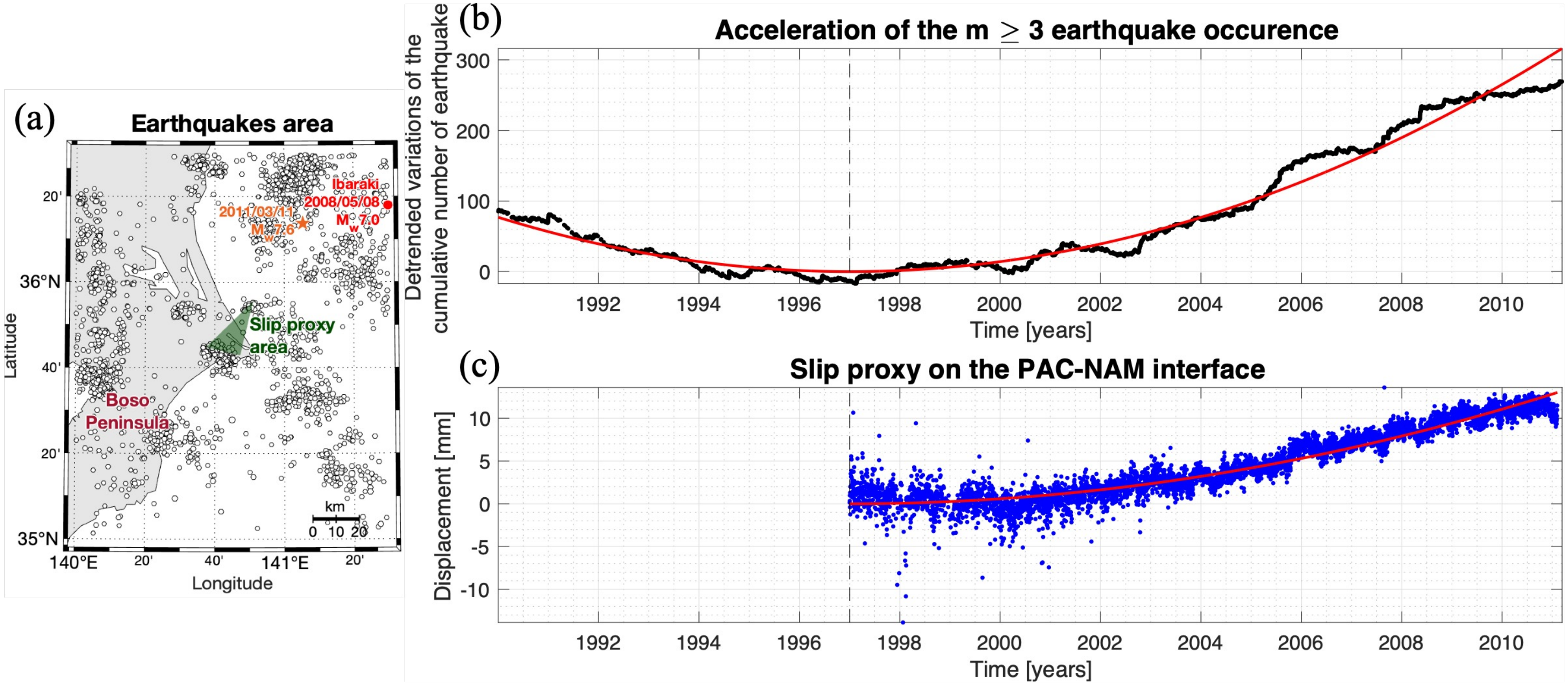
SSE area

Volcanic unrest area



Marill et al. JGR 2021

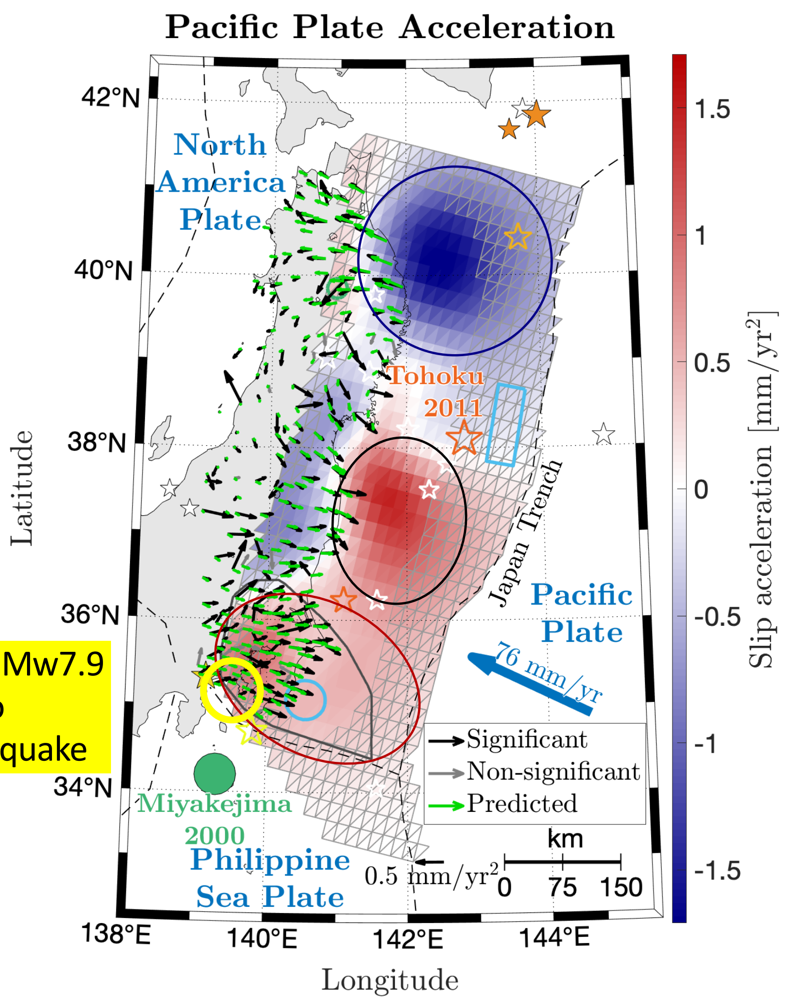
Acceleration of $m \geq 3$ earthquakes and slip proxy (weighted stack) on the PAC-NAM interface



Marill et al. JGR 2021

14-yearAcceleration Along the Japan Trench

1923 Mw7.9 Kanto earthquake



Deceleration North of 39°N

- Heki et al. (1997): related to 1994 Sanriku earthquake ?
  - → Does not explain acceleration up to 2011
- Heki & Mitsui (2013): related to 2003 Tokachi earthquake ?
  - → Visco-elastic relaxation ?

Acceleration area at 37°–38°N

- Hasegawa & Yoshida (2015): Might have contributed to 2011 Tohoku earthquake failure

New acceleration area South of 36°N

- From acceleration field: slip acceleration on the Pacific Plate
- Far from 2011 Tohoku rupture ➔ remains to be explained

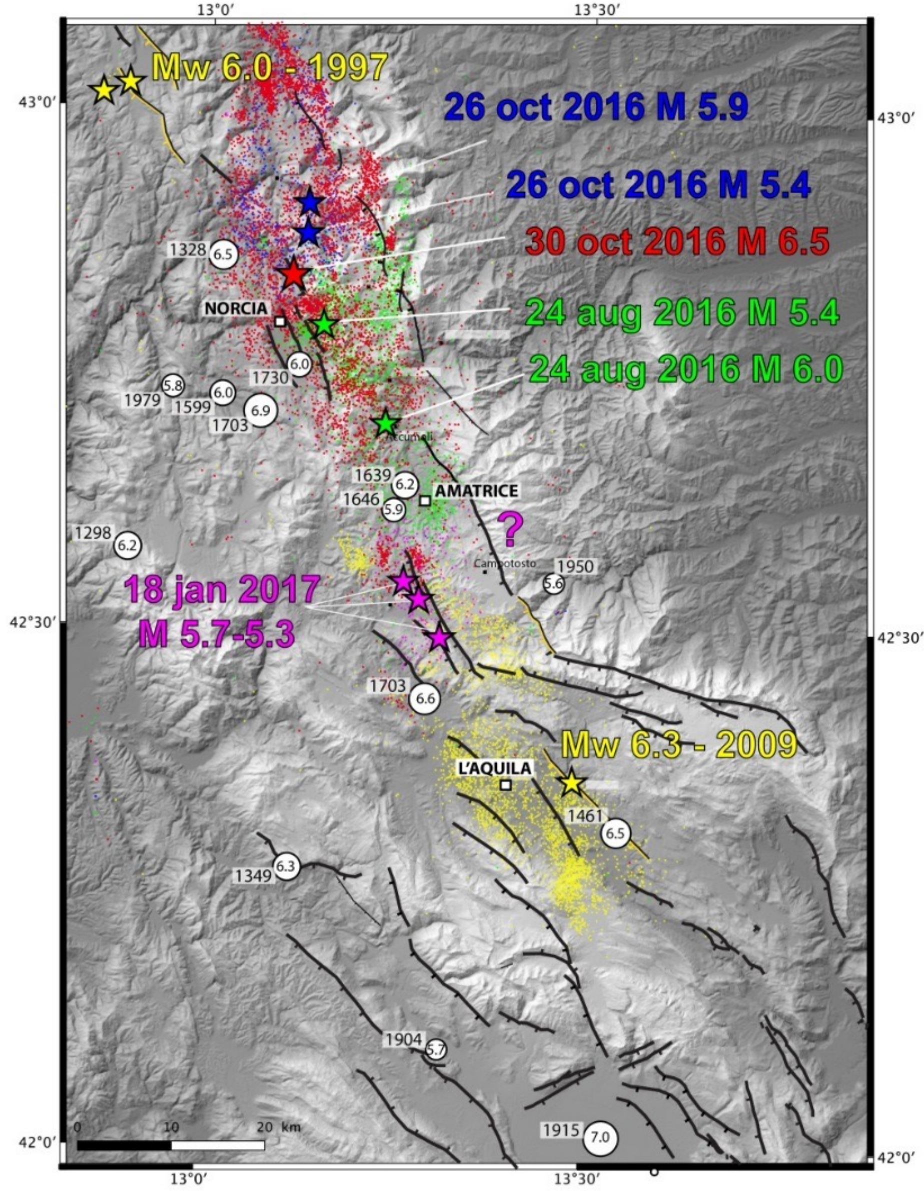
Marill et al. JGR 2021

The 2016 Italian seismic sequence

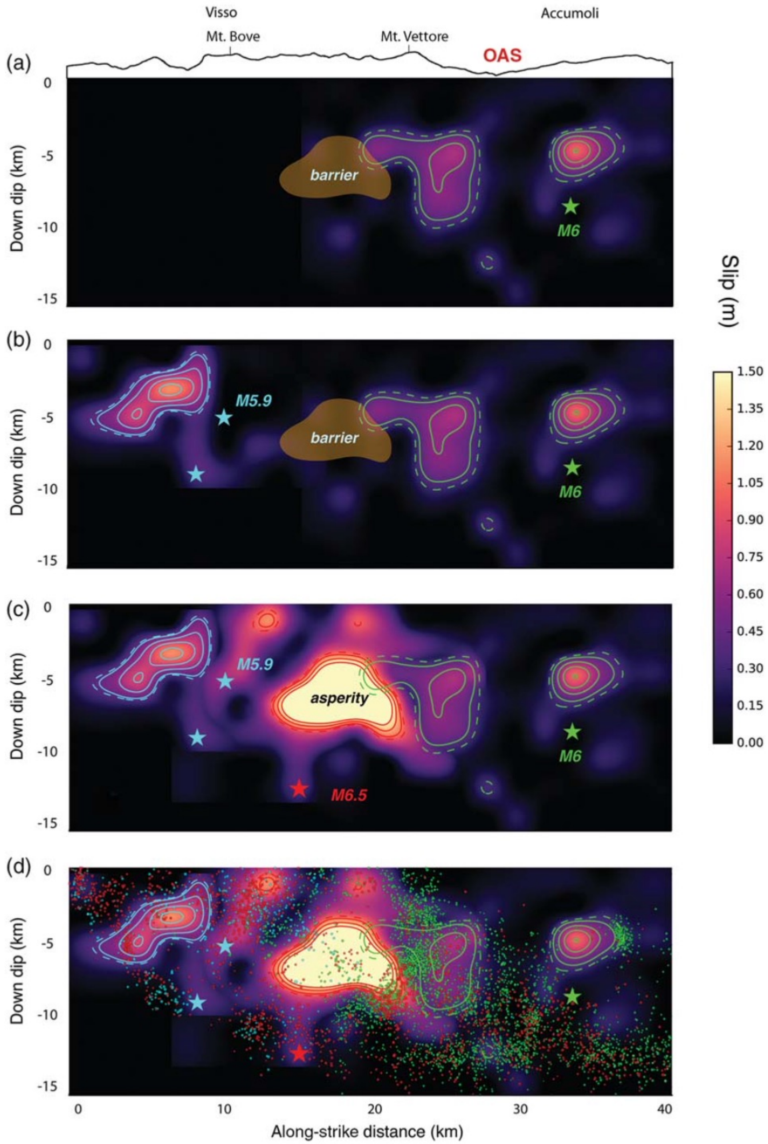
A practical example of how
EPOS GNSS products & Geo-Inquire services
can be useful together with time series analysis

Seismic sequence

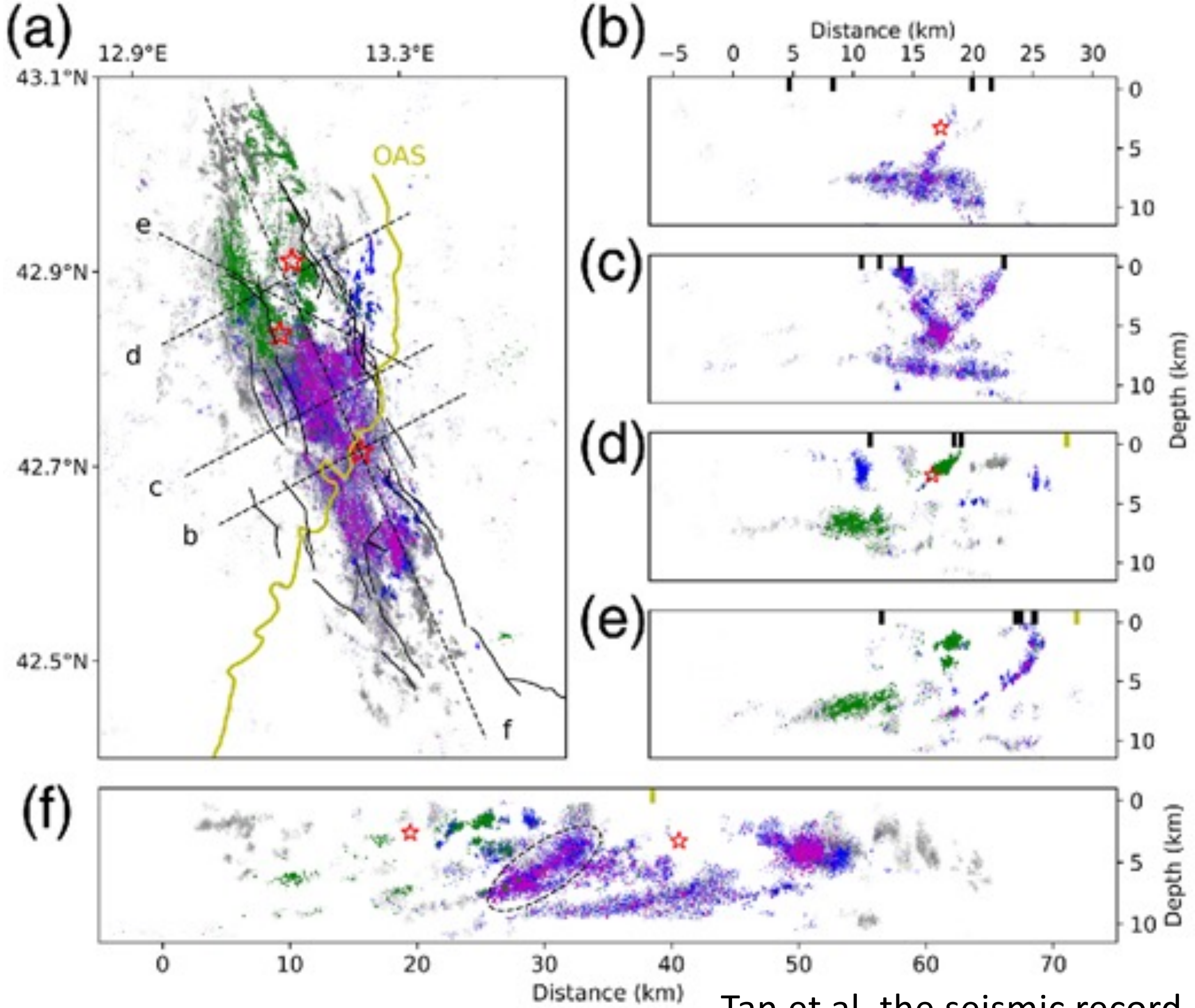
- Aquila : Mw 6.1 – 09/04/2009
- Amatrice Mw 6.1 24/08/2016
- Visso Mw 5.9 – 26/10/2016
- Norcia Mw 6.6 – 30/10/2016
- Campotosto Mw 5.7 – 18/01/2017



Central Italy sequence



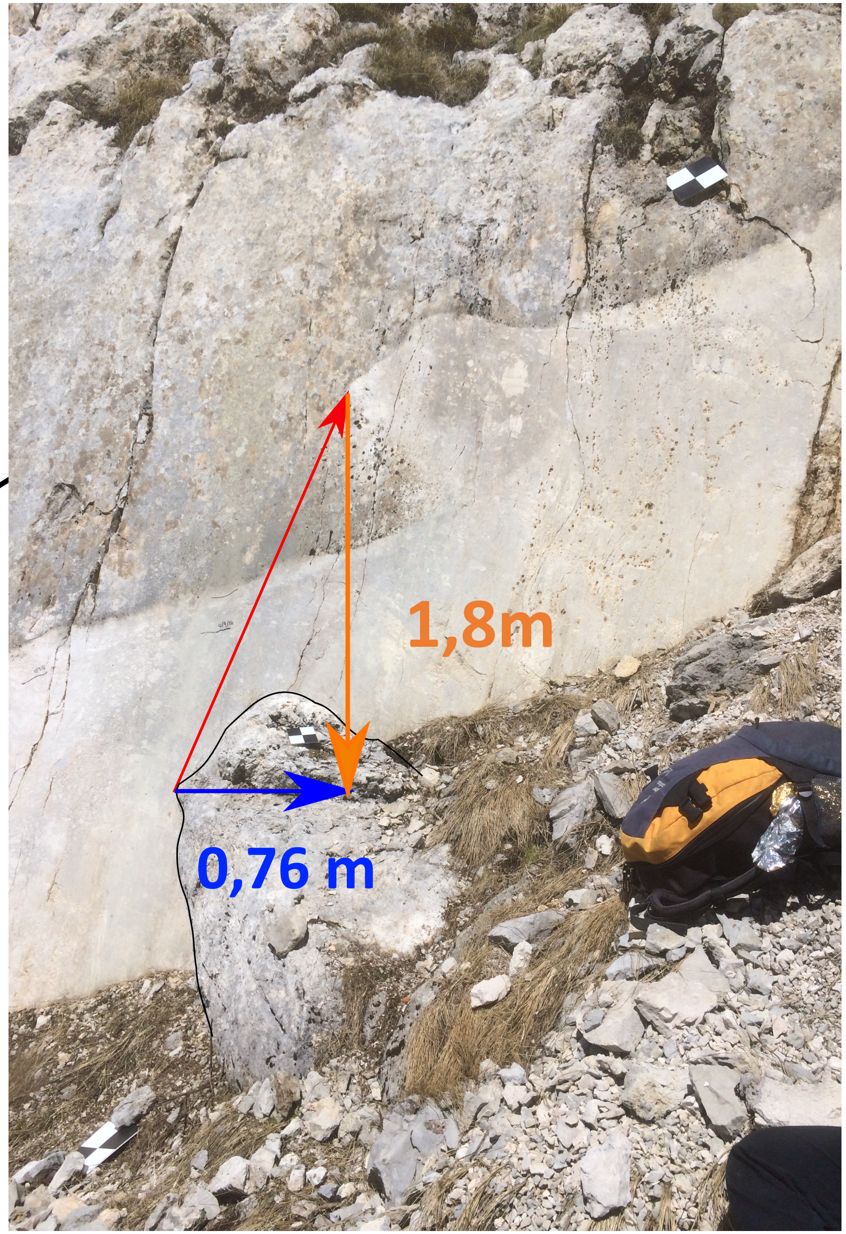
Chiaralucce et al., SRL 2017



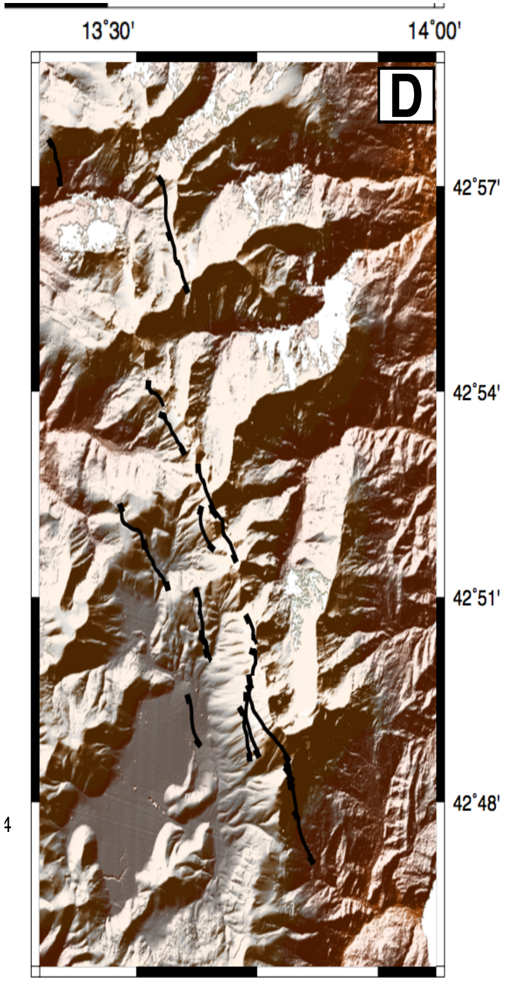
Tan et al, the seismic record, 2021

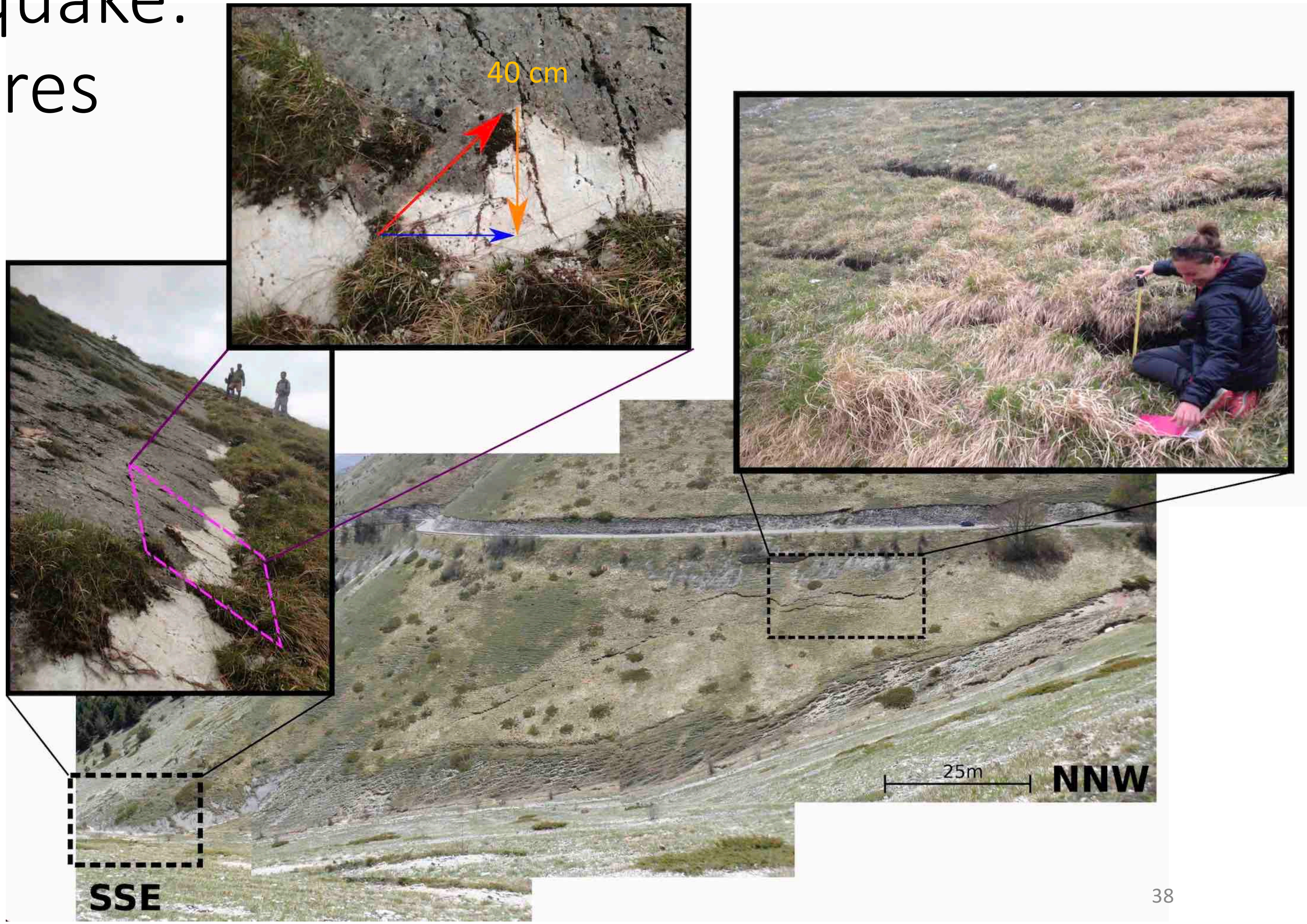
Norcia earthquake: surface ruptures

- Monte Vettore Fault System

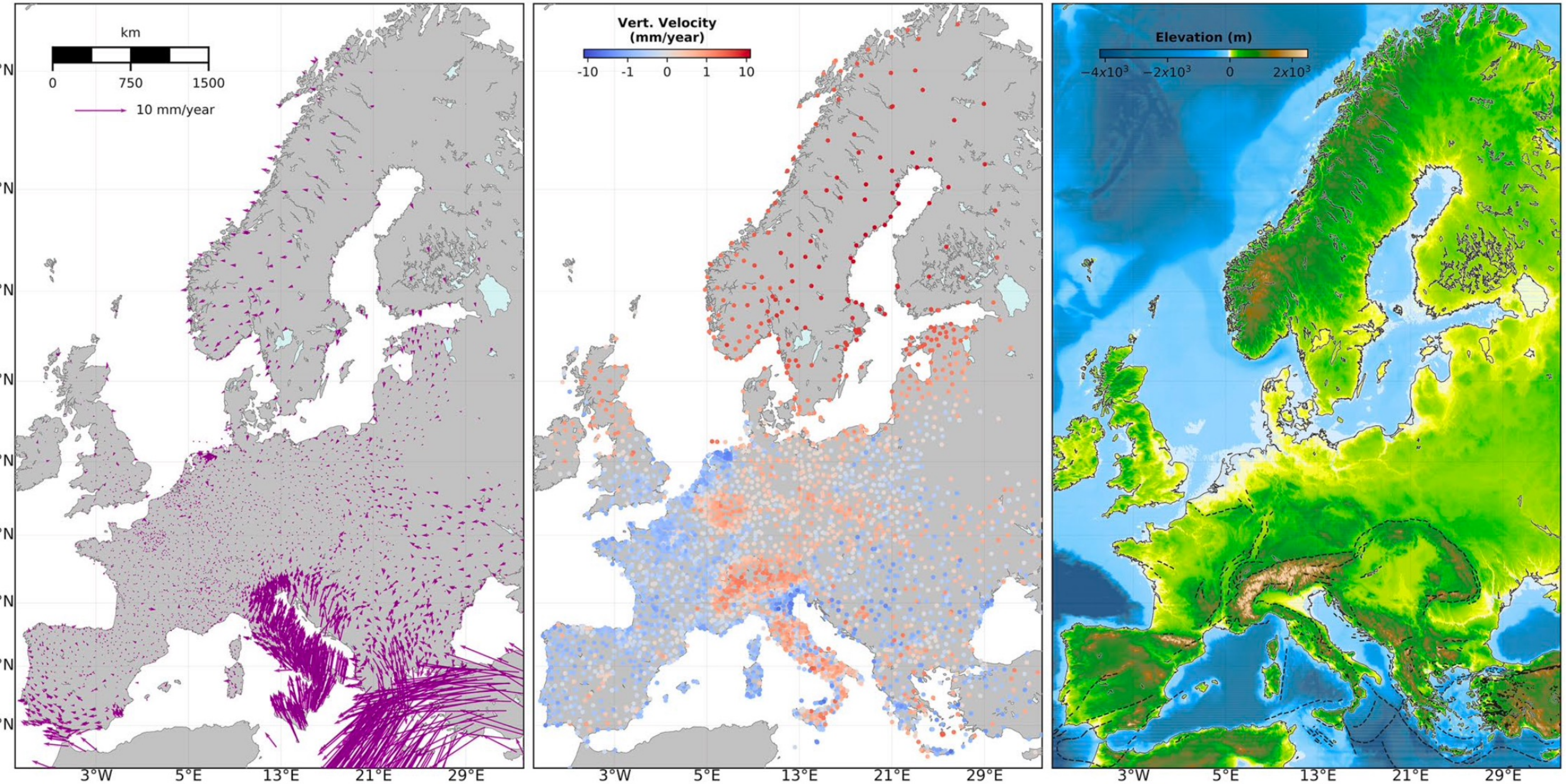


Norcia earthquake: surface ruptures



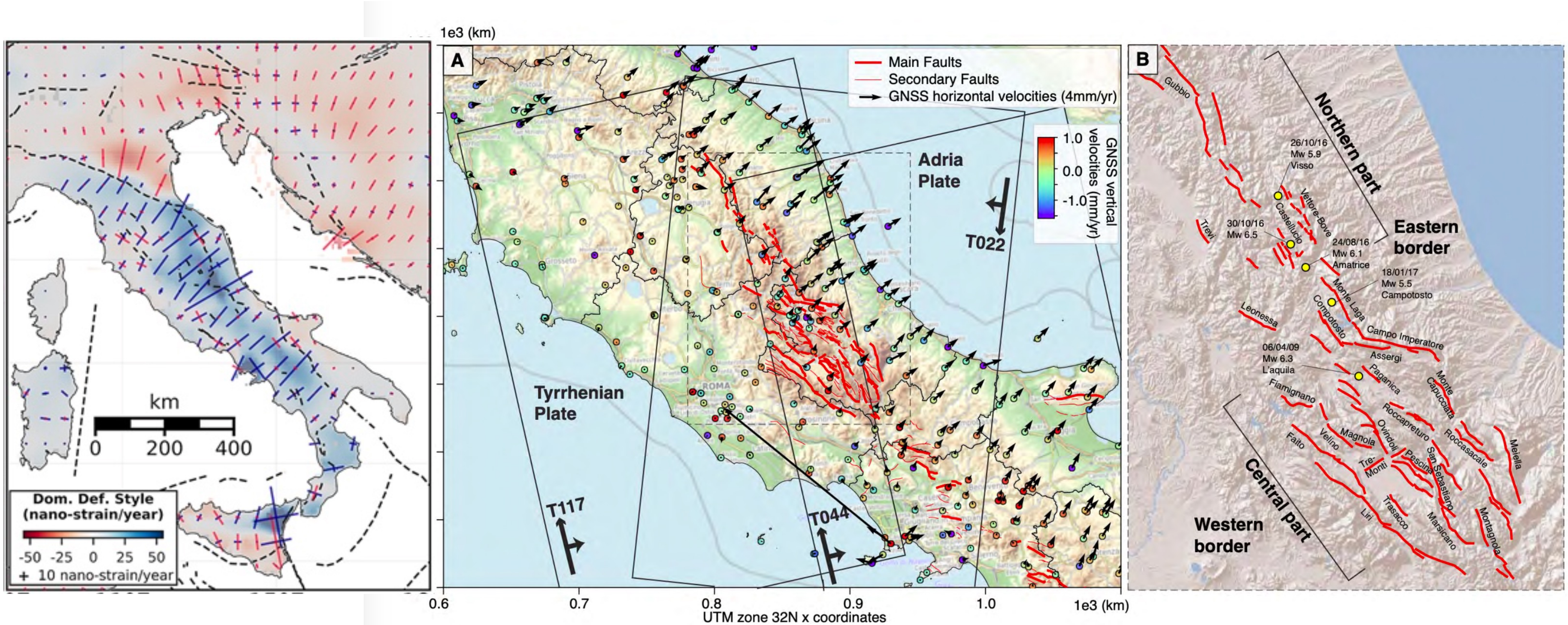


3D GNSS velocity field in Europe



Piña Valdes et al., JGR 2022

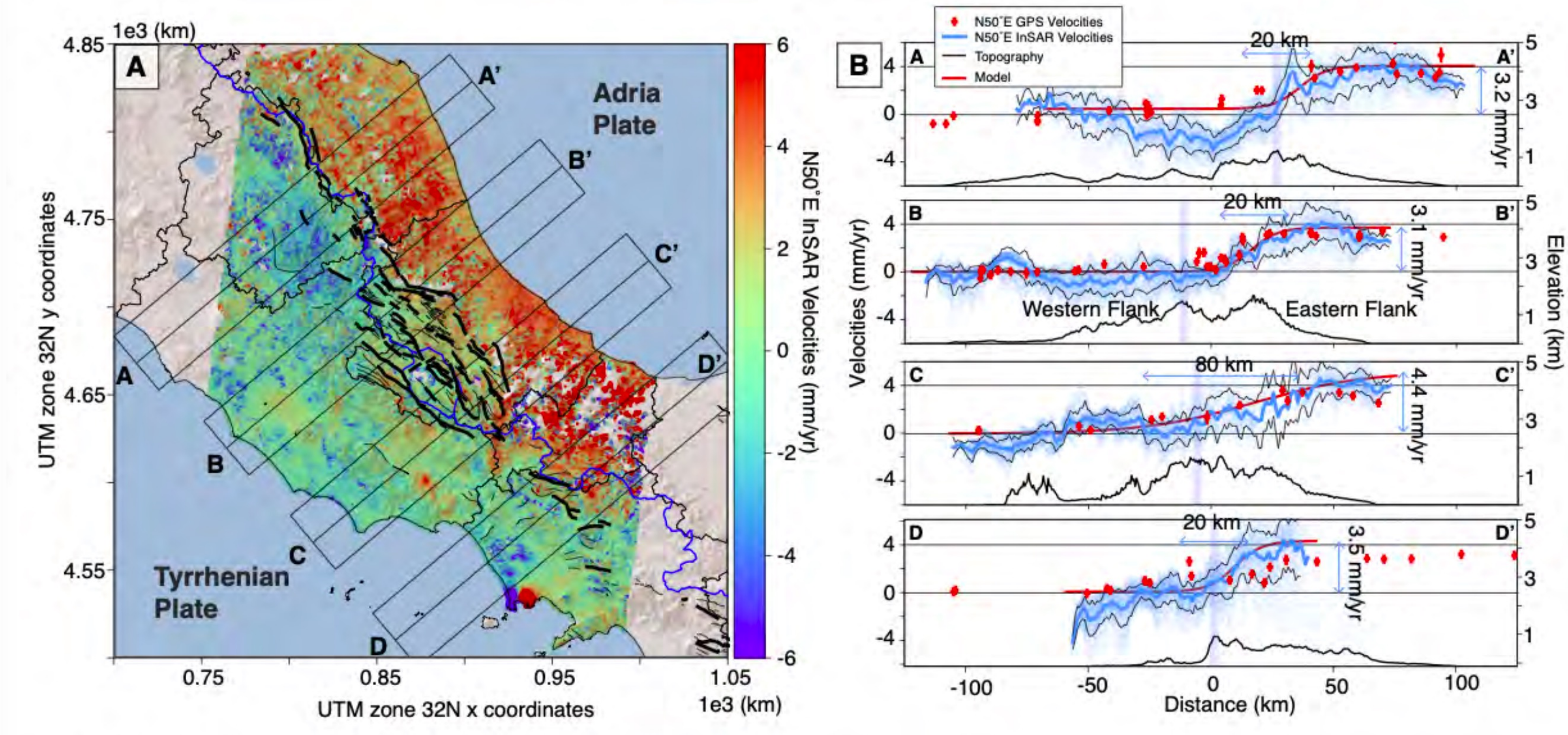
Interseismic extension across the Appenines seen by GNSS



Piña Valdes et al., JGR 2022

Daout et al., Tectonophysics 2023

Interseismic extension : comparison GPS INSAR

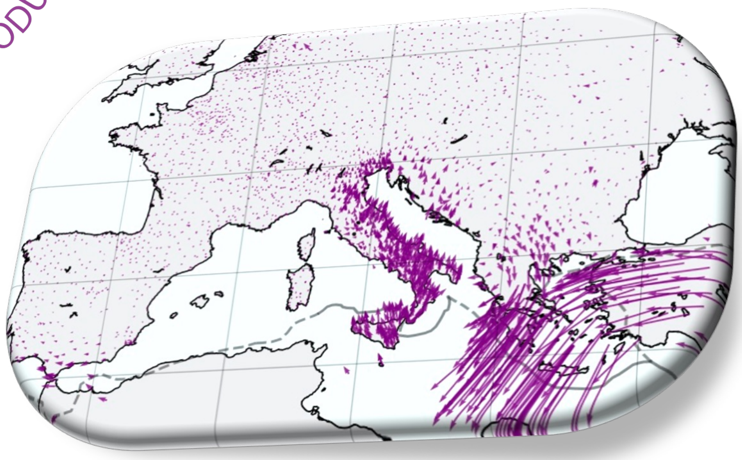


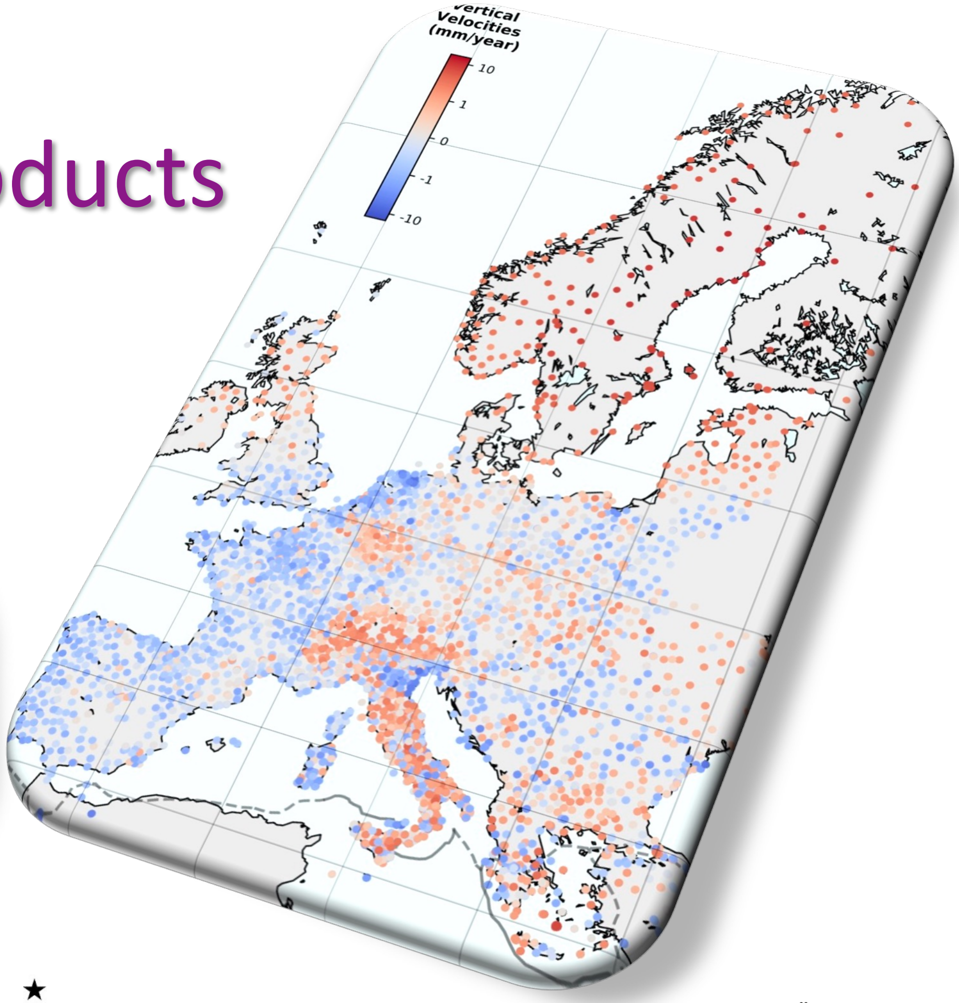
Daout et al., Tectonophysics 2023

What about co-seismic GNSS displacements ?

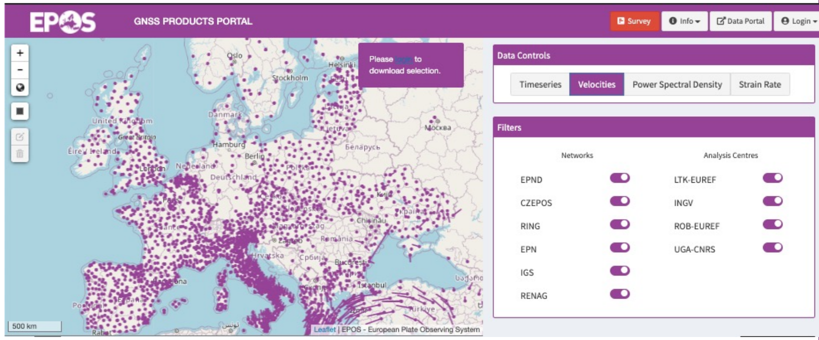
→ One possibility is to use the EPOS-GNSS products

EPOS GNSS Products

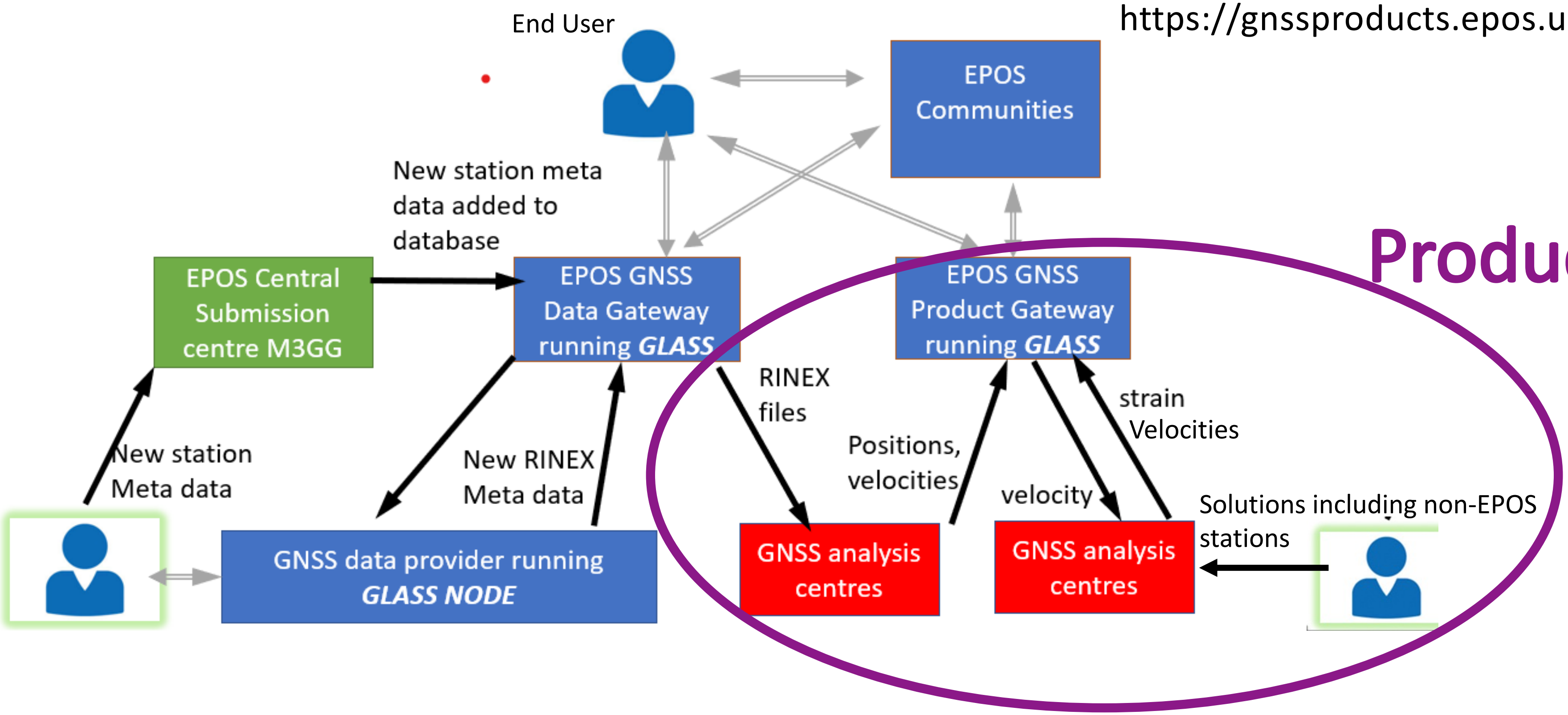




EPOS GNSS work flow



https://gnssproducts.epos.ubi.pt/



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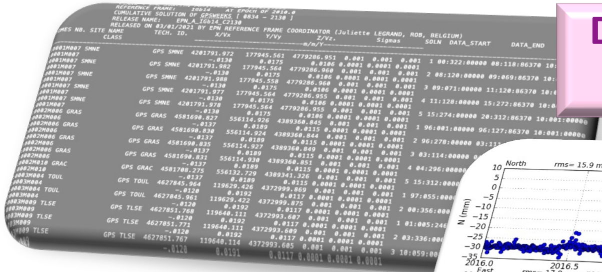
GNSS DATA AND PRODUCTS

What are the GNSS products?

Université Grenoble Alpes

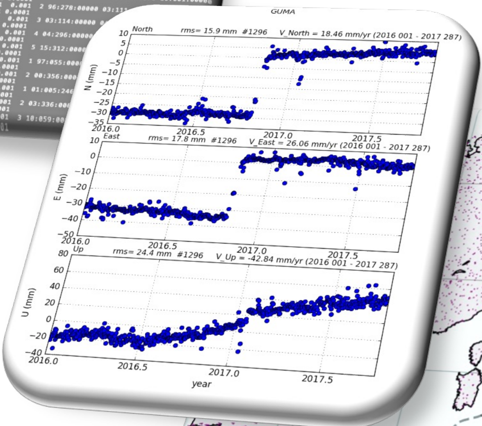
Processing phase observable
& invert for positions

Daily / Weekly Positions



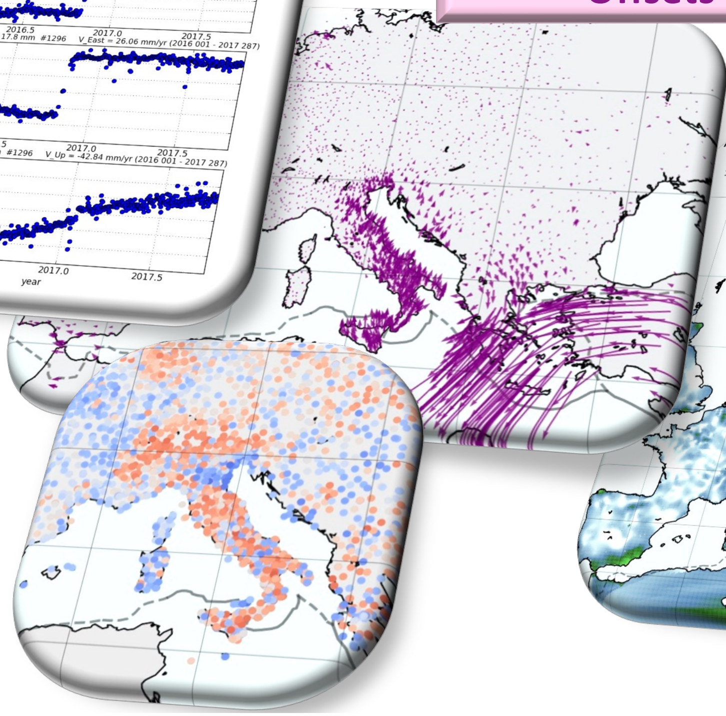
Combining and referencing

Daily / Weekly Position Time Series



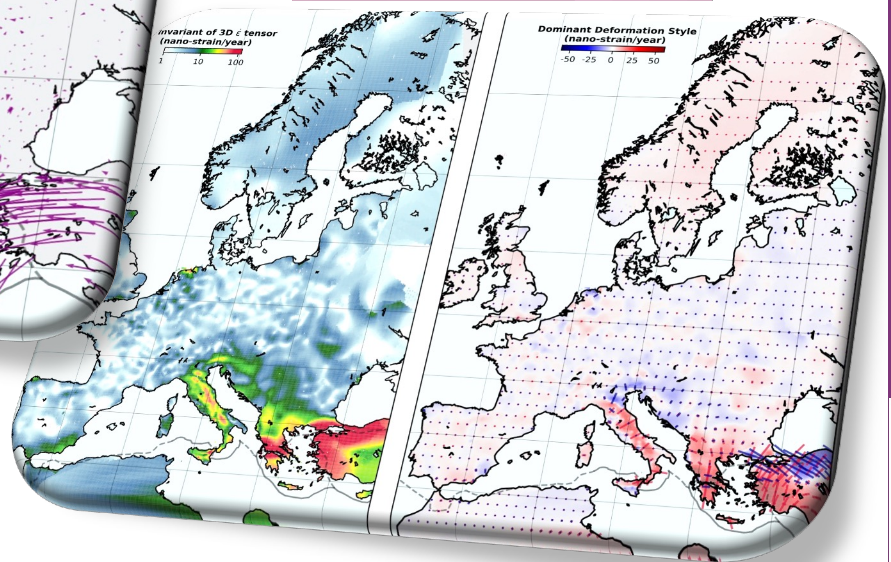
Time series analysis

Secular velocities Offsets



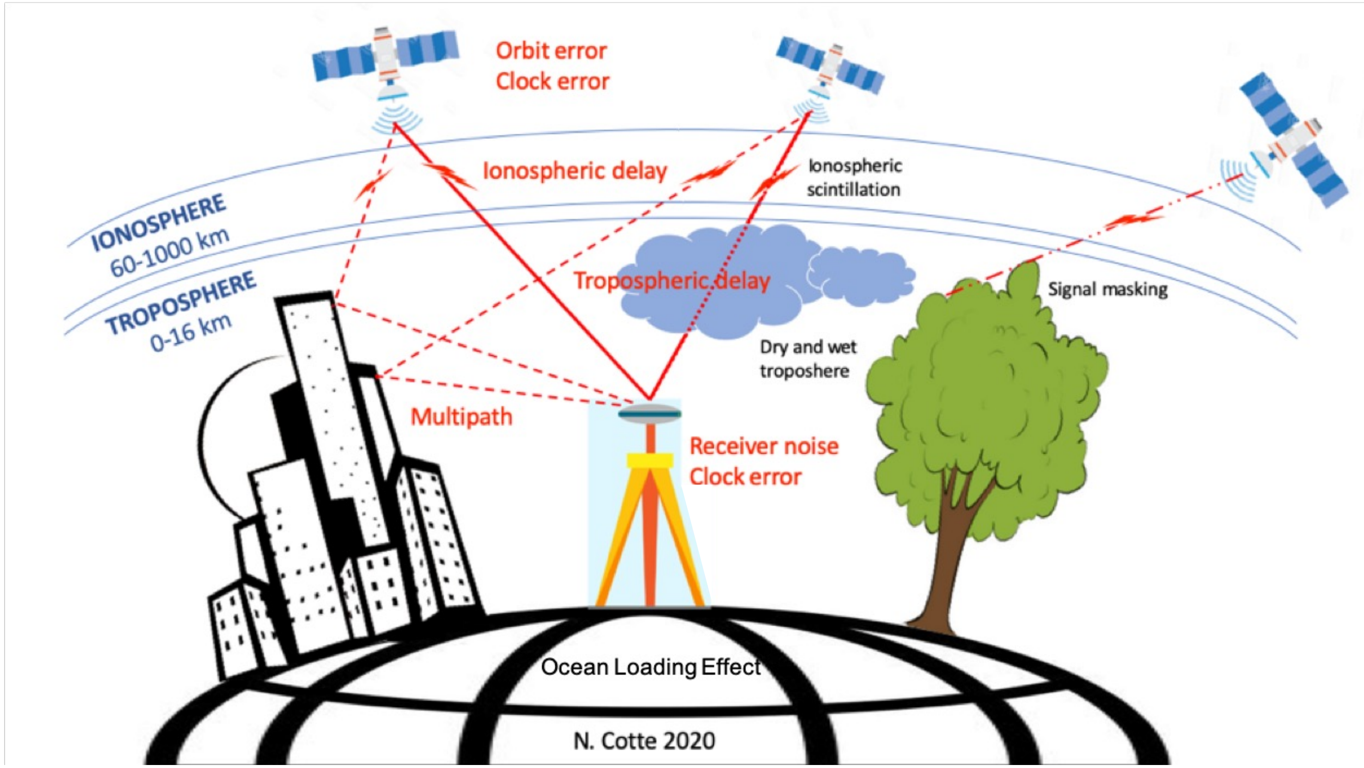
Spatial derivative of
displacements /velocity fields

Strain rate maps

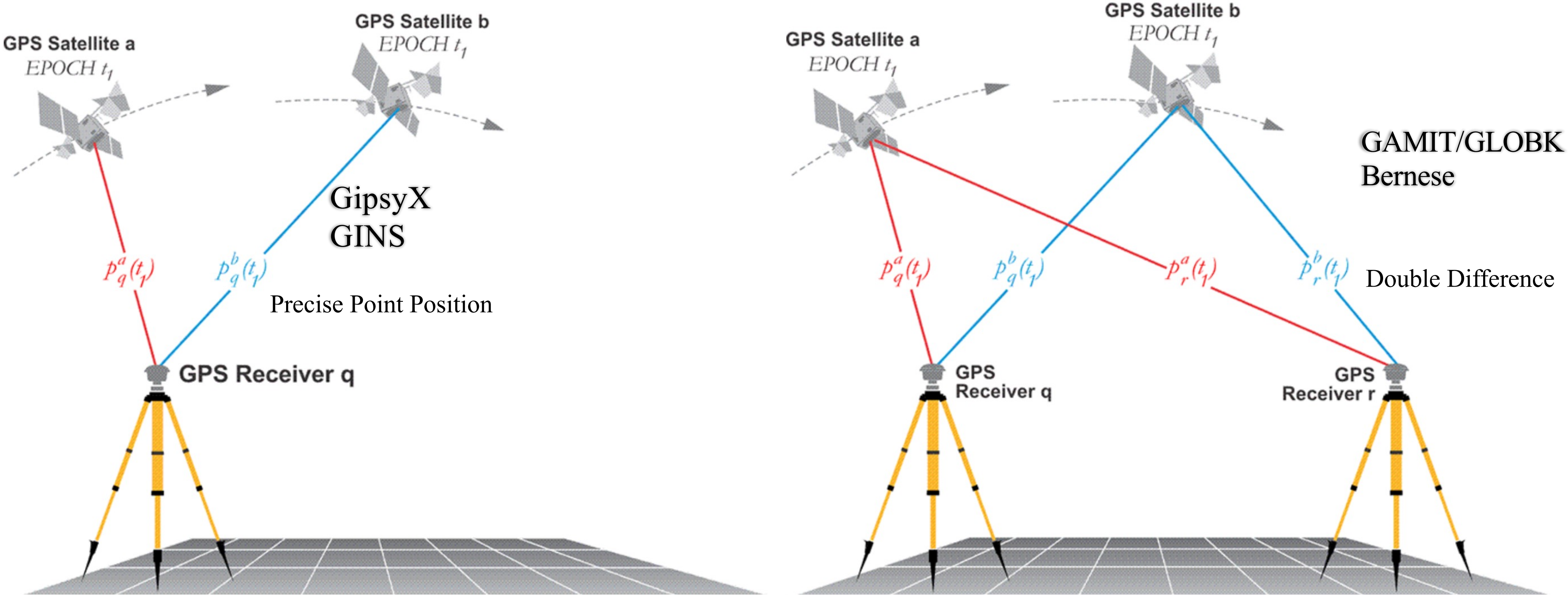


GNSS DATA AND PRODUCTS

GNSS Positioning & Errors



GNSS Positioning Methods



(https://www.e-education.psu.edu/geog862/node/1727)

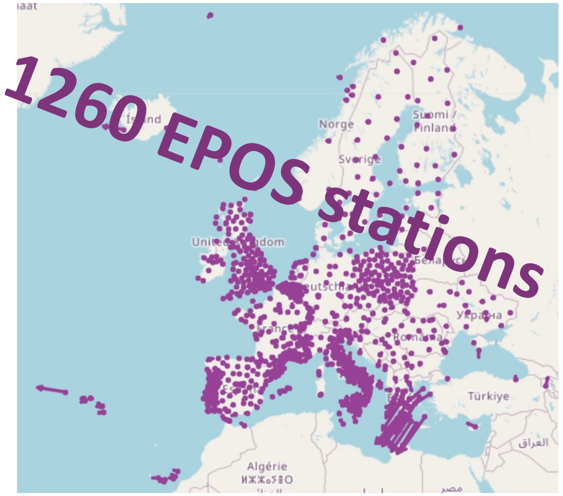
What are the different products labels? What are their specificities?

EPOS, EUREF, EPOS-EUREF

Two product solutions developed specifically for EPOS

Principles:

- **Open science, reproducible**
  - **All data available:** RInEx from EPOS-GNSS Data Gateway, metadata available & verified
  - **Fully documented** processing strategies using **open-source softwares**
- **Specifically designed for geophysical studies** (including for slow movements)
  - Each solution is internally-consistent, generated @ a single Pan-European processing center with one strategy



Daily positions & Multi-year solutions @ 2 Pan-European EPOS Analysis Centers

2 x
- Positions
- Time Series
- Velocities
- Offsets

Quality Check

- ➢ Two independent daily solutions :
  - generated @ 2 independent processing centers
  - with 2 independent processing Strategies & Softwares :

Double difference GAMIT/GLOBK/ITSA Automatic updates @ D-2 & D-25	PPP GIPSY-OASIS-II Regular Updates

- ➢ Automated outlier rejection, introduction of discontinuities in time series
- ➢ Velocities Computed with MIDAS, station classification based on uncertainty

Independent cross-comparison and validation @ Pan-European Analysis Combination Center

- ➢ Comparison of Positions Time Series using CATREF
- ➢ Identification of outlier and inconsistencies
- ➢ Validation or feedback to the EPOS Analysis Centers

LECHNER TUDÁSKÖZPONT

GNSS DATA AND PRODUCTS

What are the different products labels? What are their specificities?

EPOS, EUREF, EPOS-EUREF

Original EUREF product made available through the EPOS GNSS Product Gateway

Principles:

- **Open data :** RInEx available from EPN data centers, metadata available & verified
- **Specifically designed for geodesy and reference frame studies :**
  - Geodetic-class stations from the EUREF Permanent Network (EPN)
  - Densifies ITRF over Europe and provides access to European Terrestrial Reference Frame (ETRF/ETRS89)

Regional daily position solution @ 16 EPN Analysis Centers →

- each station processed by at least 3 ACs to insure redundancy and increase reliability
- 3 softwares: Bernese, Gamit, Gipsy

Daily and Weekly Combined Positions @ EPN Analysis Combination Center →

Positions

- Pan-European combinations with Bernese
- Each AC solution is compared to the combined solution to identify and reject outliers
- Aligned to IGS14 using no-net-translation

Multi-year Solution @ EPN Reference Frame Analysis Center

Positions **Time Series** **Velocities**

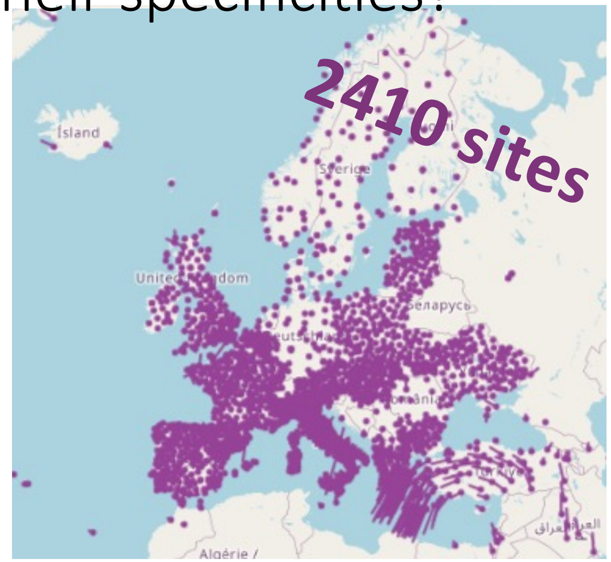
- Updated each 15 weeks
- Using CATREF
- Outlier rejection by visual inspection of time series, introduction of position and velocity discontinuities, station classification based on velocity uncertainties from Hector and velocity variability

ROYAL OBSERVATORY OF BELGIUM

GNSS DATA AND PRODUCTS

What are the different products labels? What are their specificities?

EPOS, EUREF, EPOS-EUREF



Densification Product from EUREF and EPOS

Principles:

- **Provide a densified velocity field,** including non-EPOS stations that do not release raw data (yet?)

Regional daily position solution @ 30 EPND & EPOS Analysis Centers

- ➢ 3 softwares: Bernese, Gamit, Gipsy

→

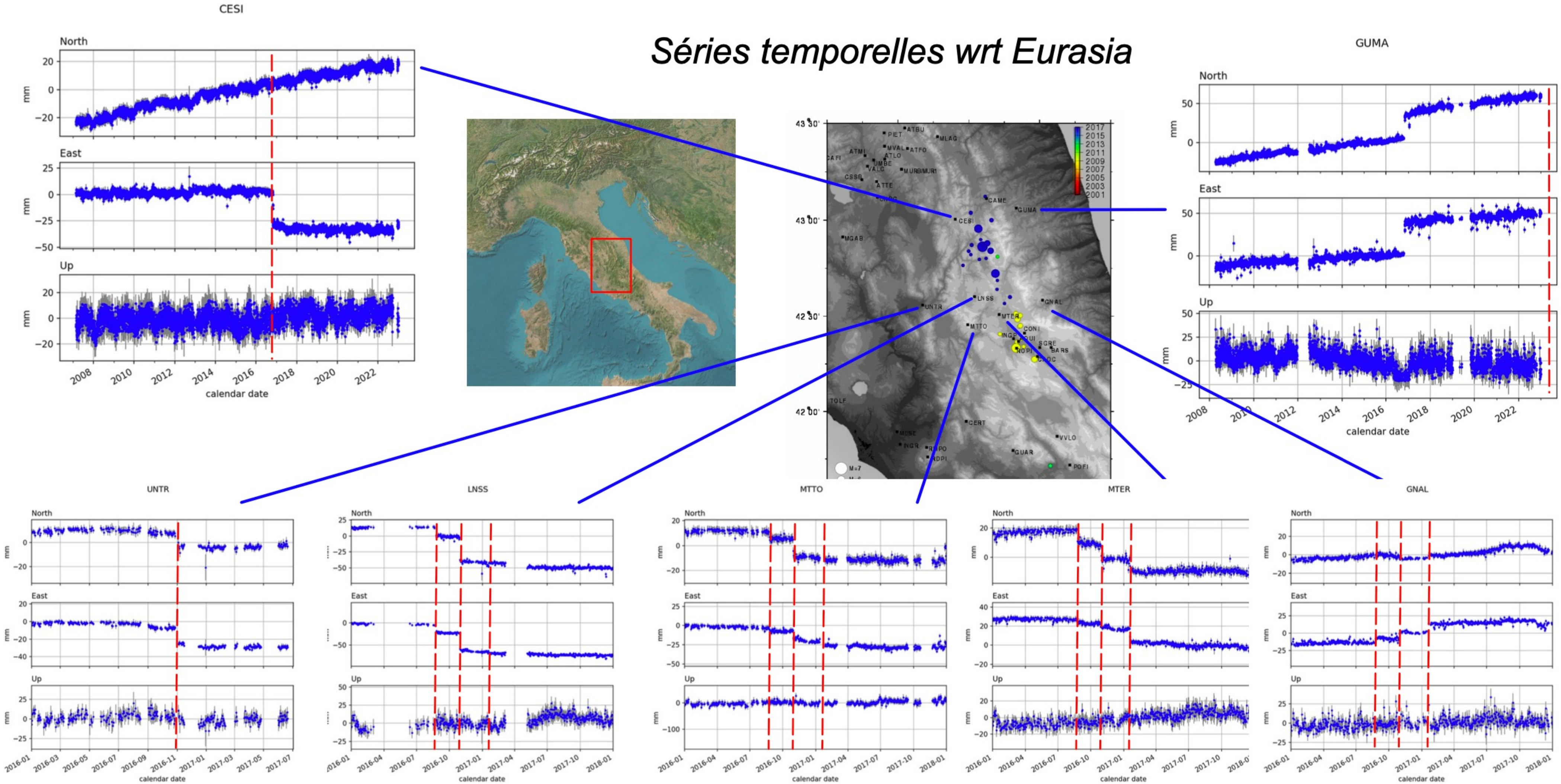
Multi-year Combined Solution @ EPOS-EUREF Combination Center

Positions | **Time Series** | **Velocities**

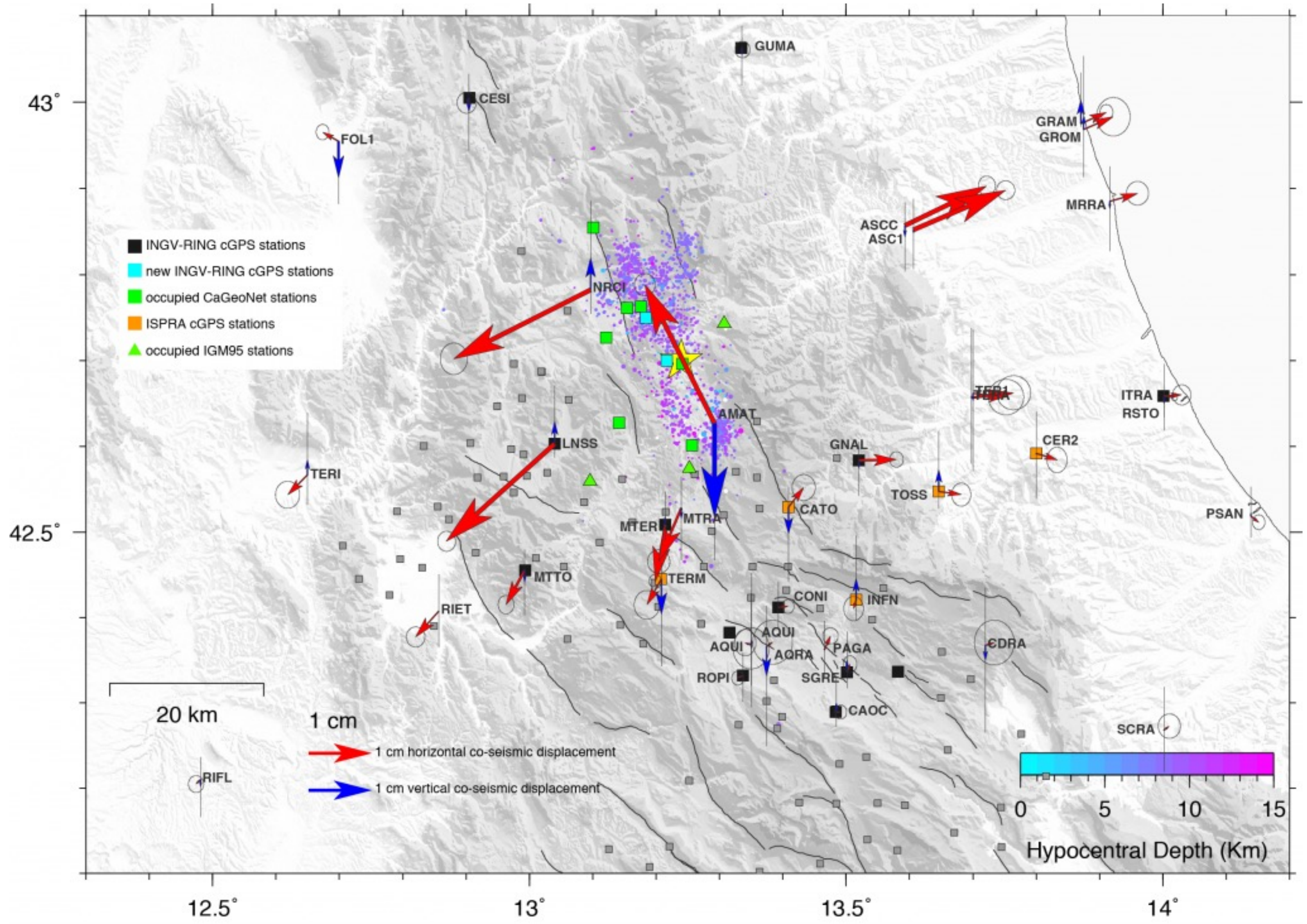
- ➢ Weekly Combined Positions Time Series using CATREF
- ➢ Velocities using CATREF, MIDAS, HECTOR
- ➢ Station metadata harmonization
- ➢ Outlier rejection by automated and visual inspection of time series, introduction of position and velocity discontinuities, velocity filtering, removal of non-representative stations (data quality or monumentation)

GNSS DATA AND PRODUCTS

2016 Mw6.2 Amatrice & Mw6.1 Norcia, & 2017 Mw5.7 Campotosto



Co-seismic displacements for the August 24, 2016 ml6, Amatrice (central Italy) earthquake estimated from continuous GPS stations



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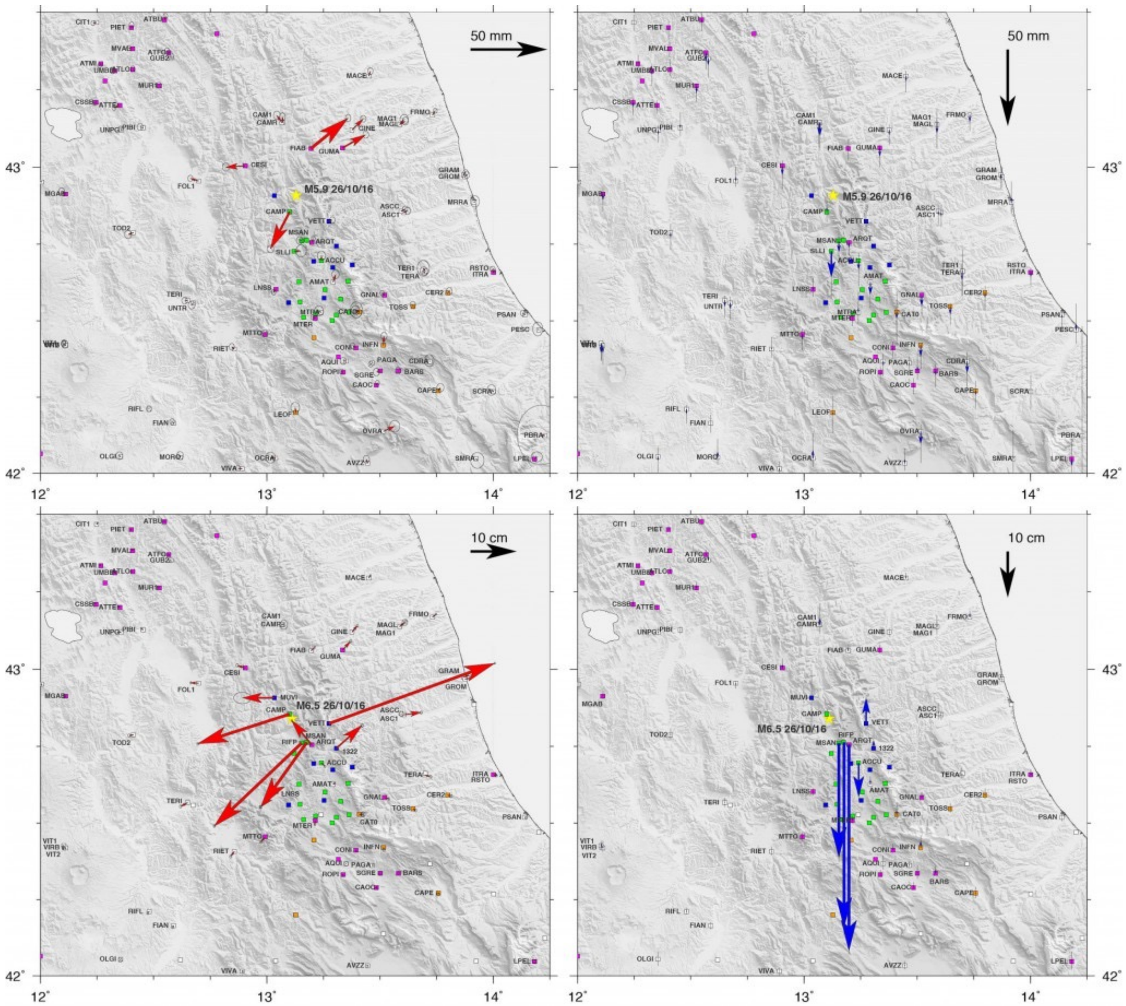
Co-seismic Displacements For The October 26 (Mw5.9) And October 30 (Mw6.5) Central Italy Earthquakes From The Analysis Of GPS Stations



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