InSAR-Derived Surface Velocities: A Foundation for Machine Learning in Geohazards Monitoring

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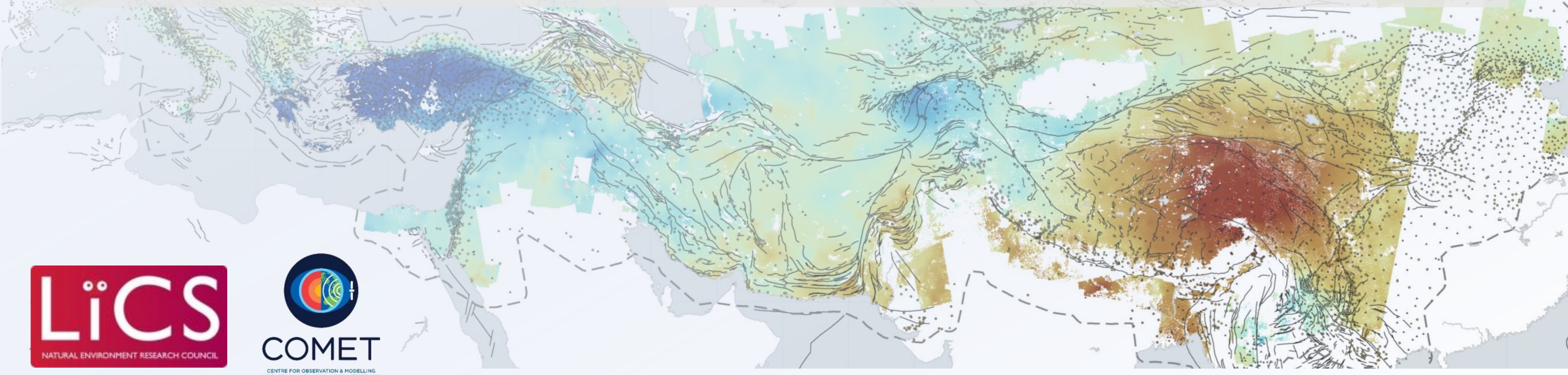

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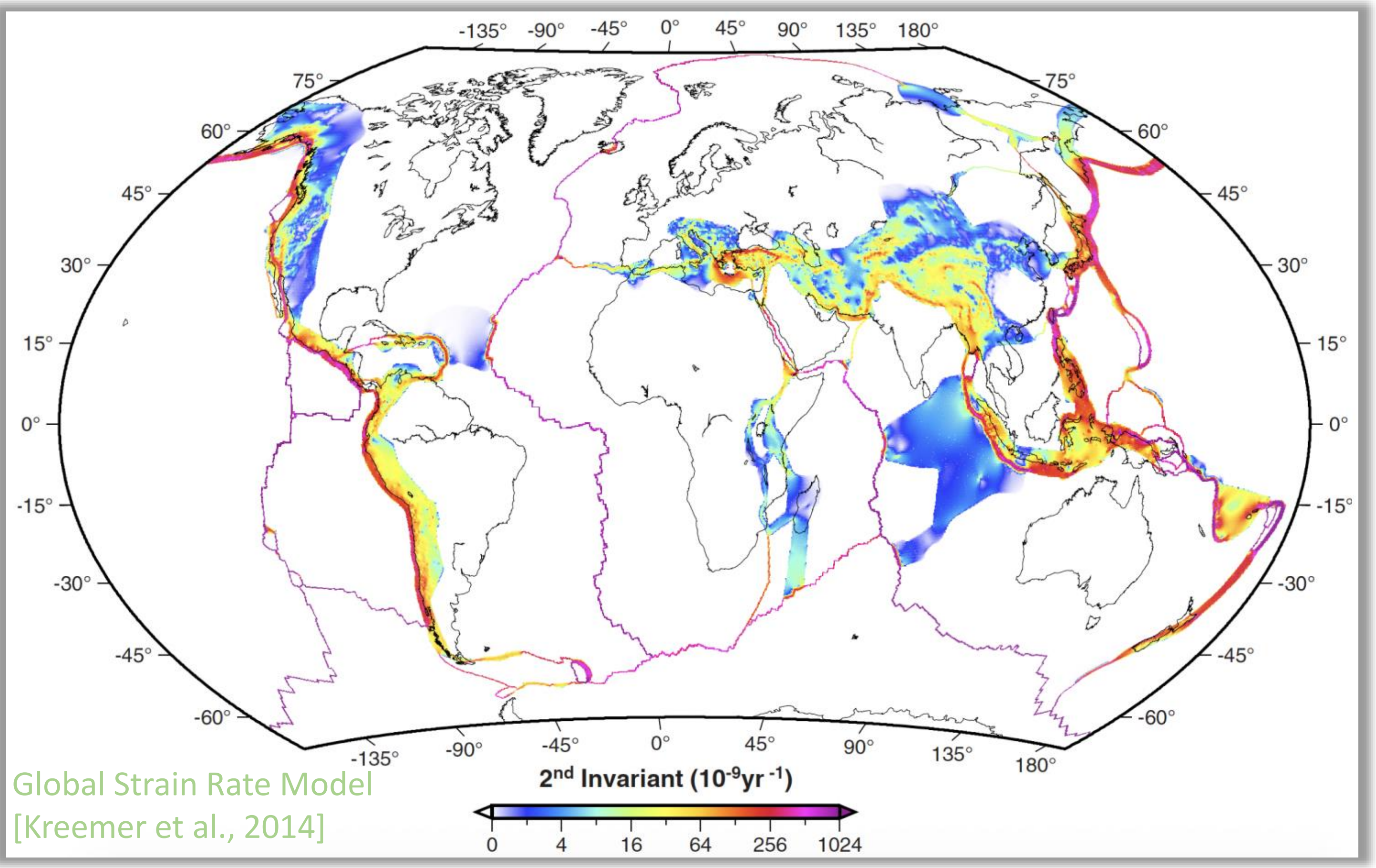
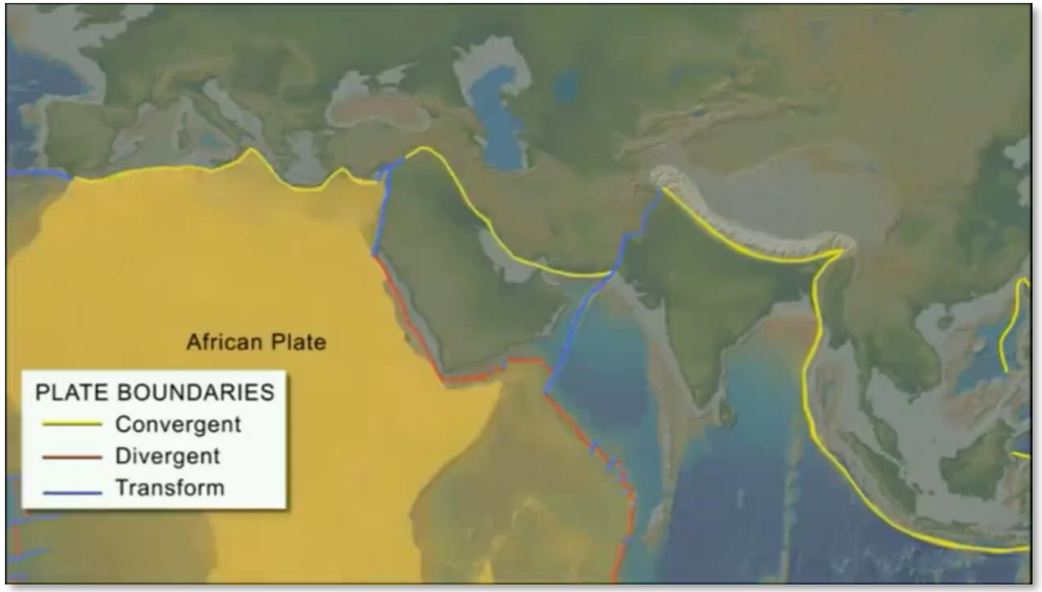
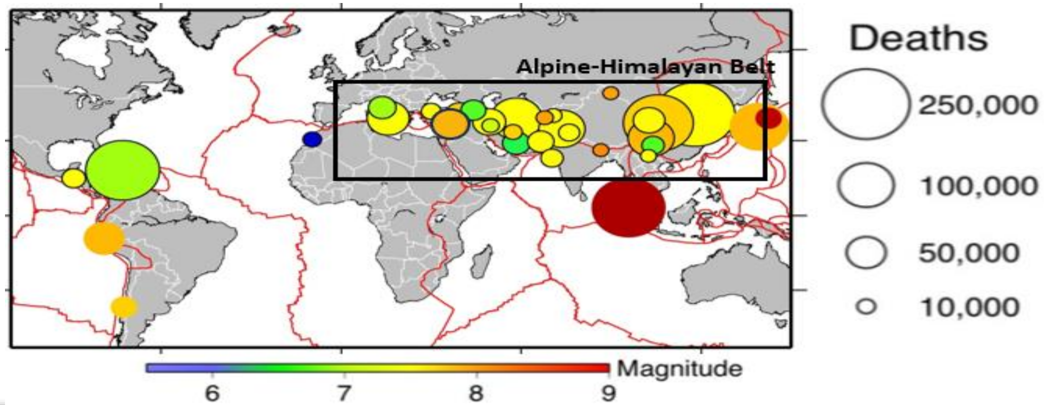
Motivation: Understanding how continents deform

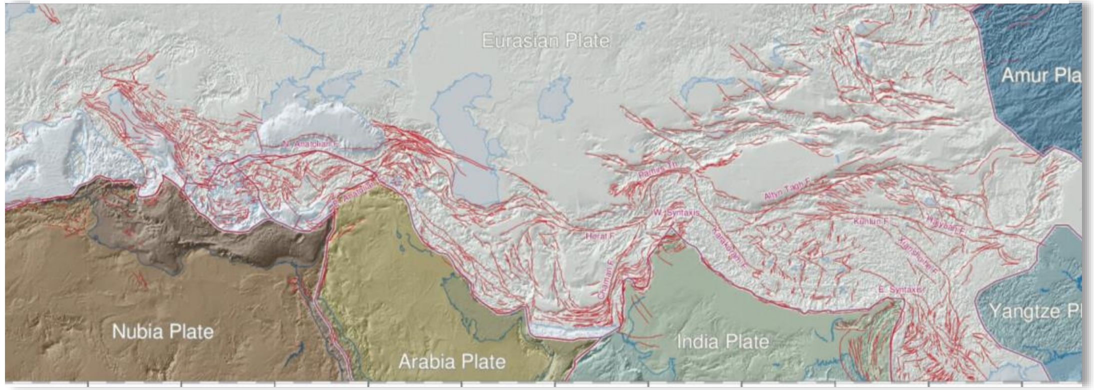
- Tracking the kinematics/dynamics of continental deformation
- Assessing the distribution of seismic hazard
- In AHB, the African, Arabian, and Indian Plates are colliding with the southern edge of the Eurasian plate
- 75% of earthquakes killing more than 10,000 people since 1900 have occurred in the AHB

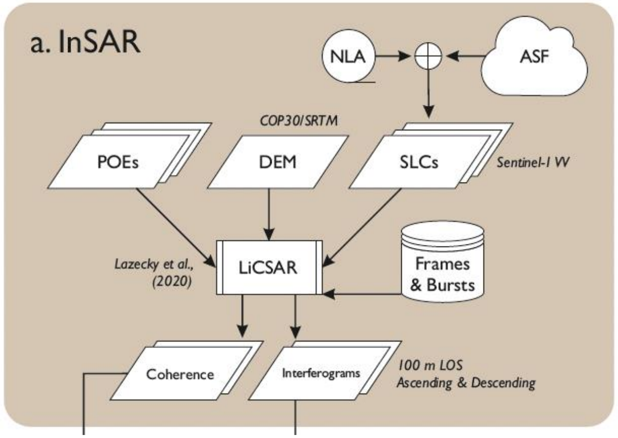


Global Strain Rate Model
[Kreemer et al., 2014]



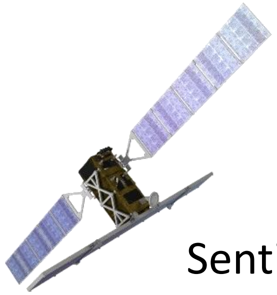






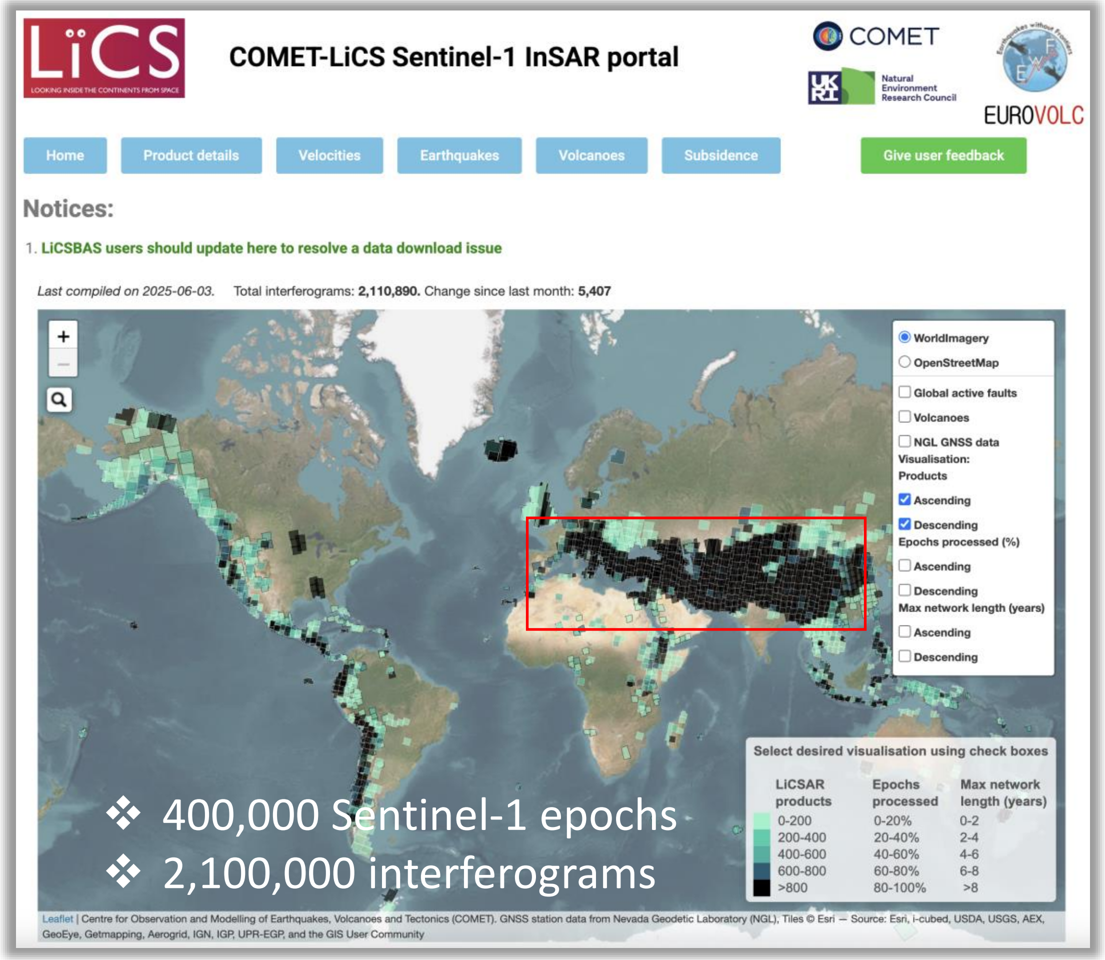
1) Interferometric SAR (InSAR) Processing

- All-weather, Day/Night imaging
- Systematic acquisitions every 6 or 12 days
- Designed for InSAR (boring acquisition strategy)



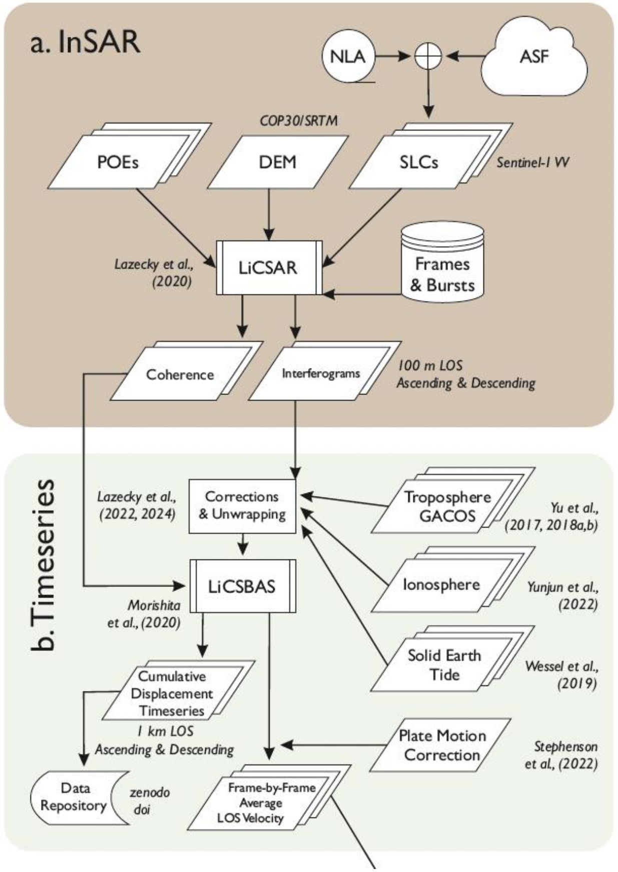
Sentinel-1

Lazecký et al. (2020)



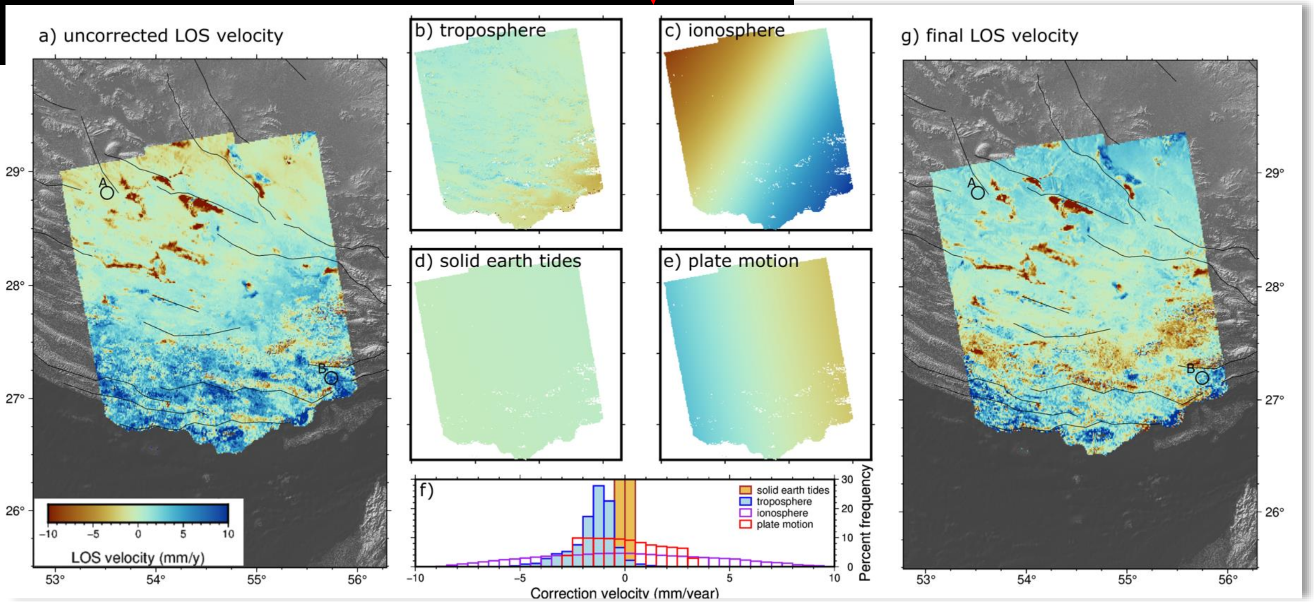
- ❖ 400,000 Sentinel-1 epochs
- ❖ 2,100,000 interferograms

Download from http://comet.nerc.ac.uk/COMET-LiCS-portal



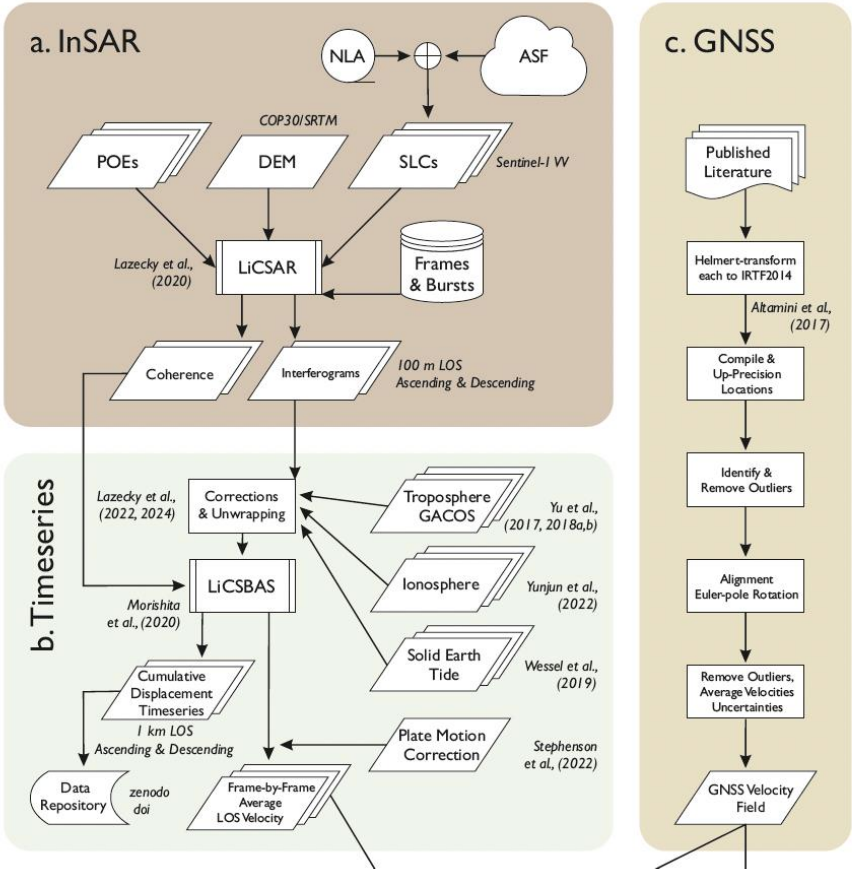
Morishita et al. (2020)

2) InSAR Time-series Analysis

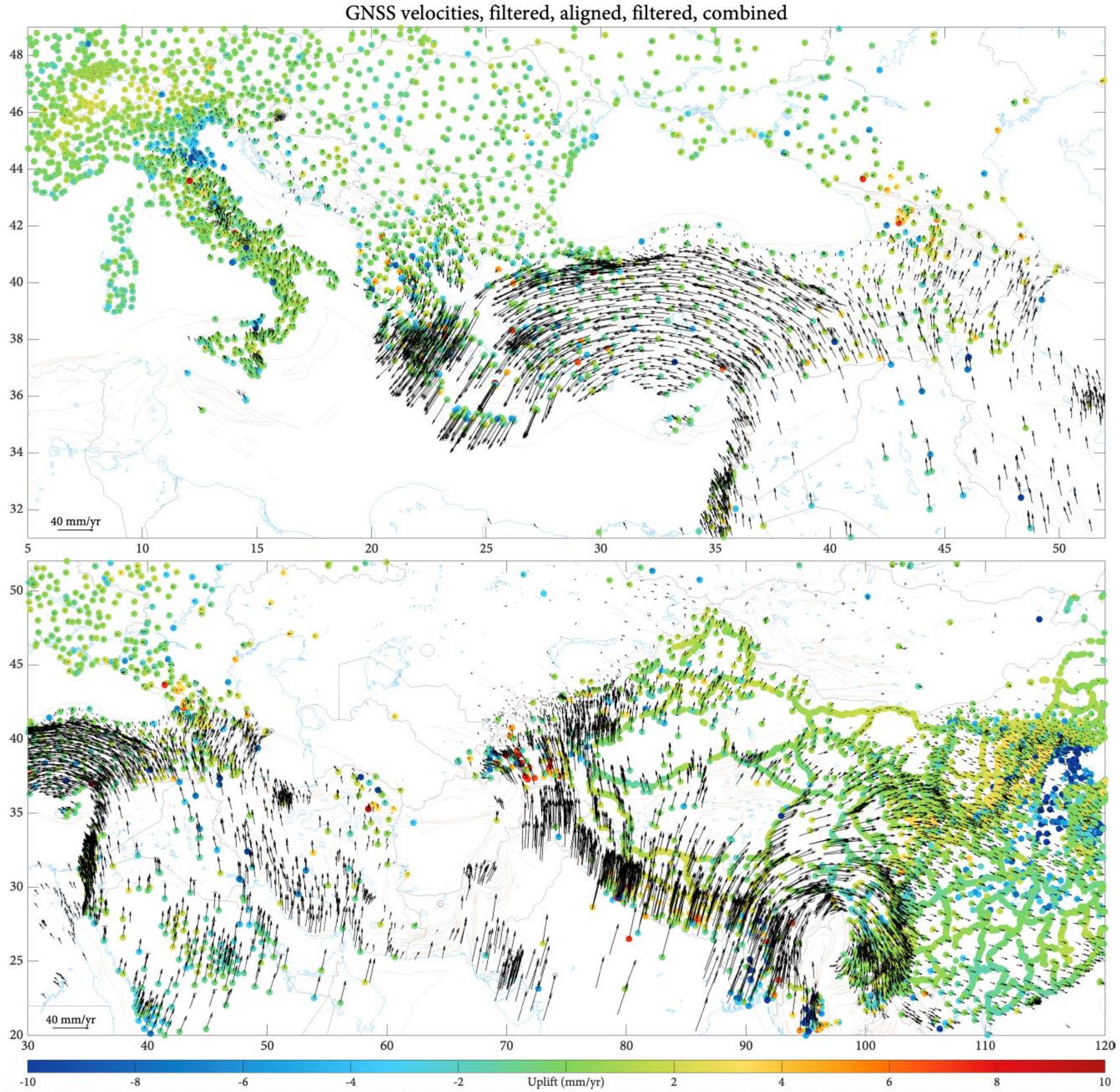


To study slow deformations (e.g land subsidence and tectonic movements) with millimetric precision.

Through some inversion techniques, we derive time-series displacements, and surface velocities.

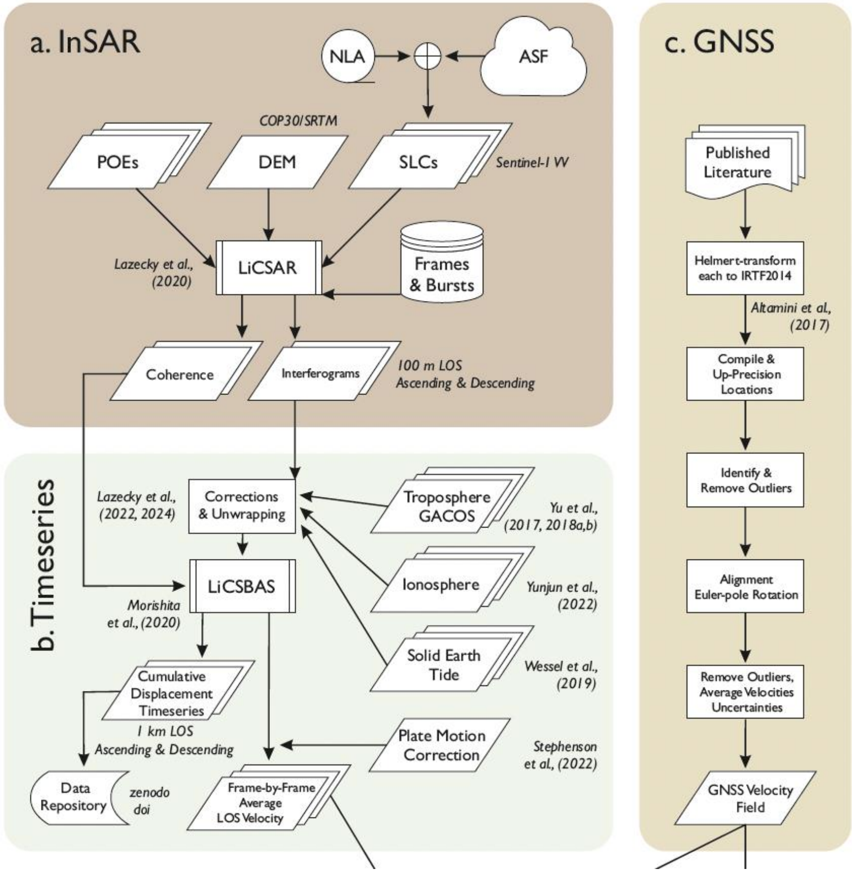


3) Referencing InSAR Velocities to GNSS



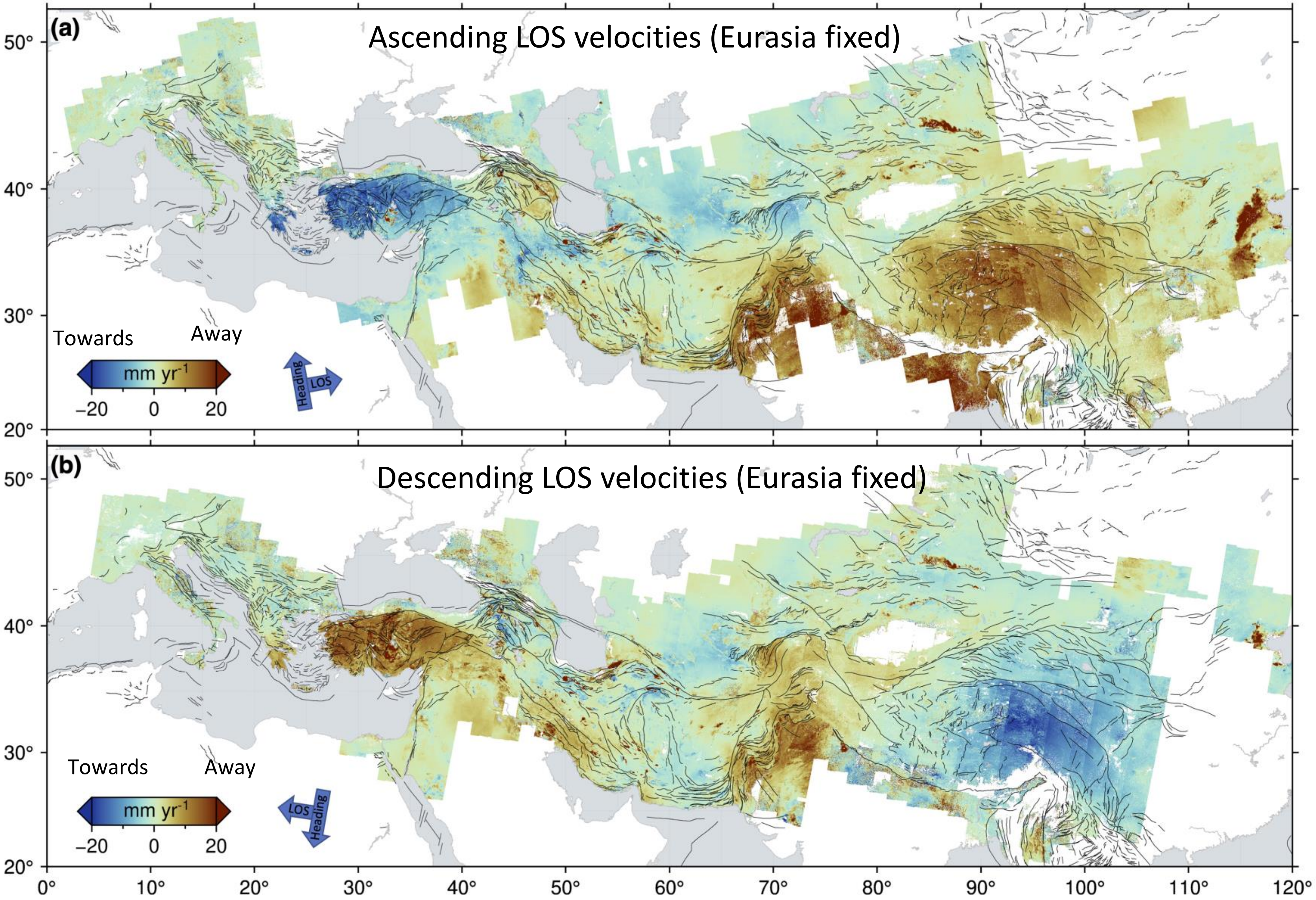
- To underpin the InSAR velocities and tie them to a unified reference frame
- 58,970 point velocities from 150 studies and datasets
  - 49,608 GNSS velocities
  - 9,258 levelling rates
  - ….

GNSS velocity vectors in the western and eastern AHB. Arrows show horizontal motions with respect to the ITRF2014 Eurasia-fixed reference frame



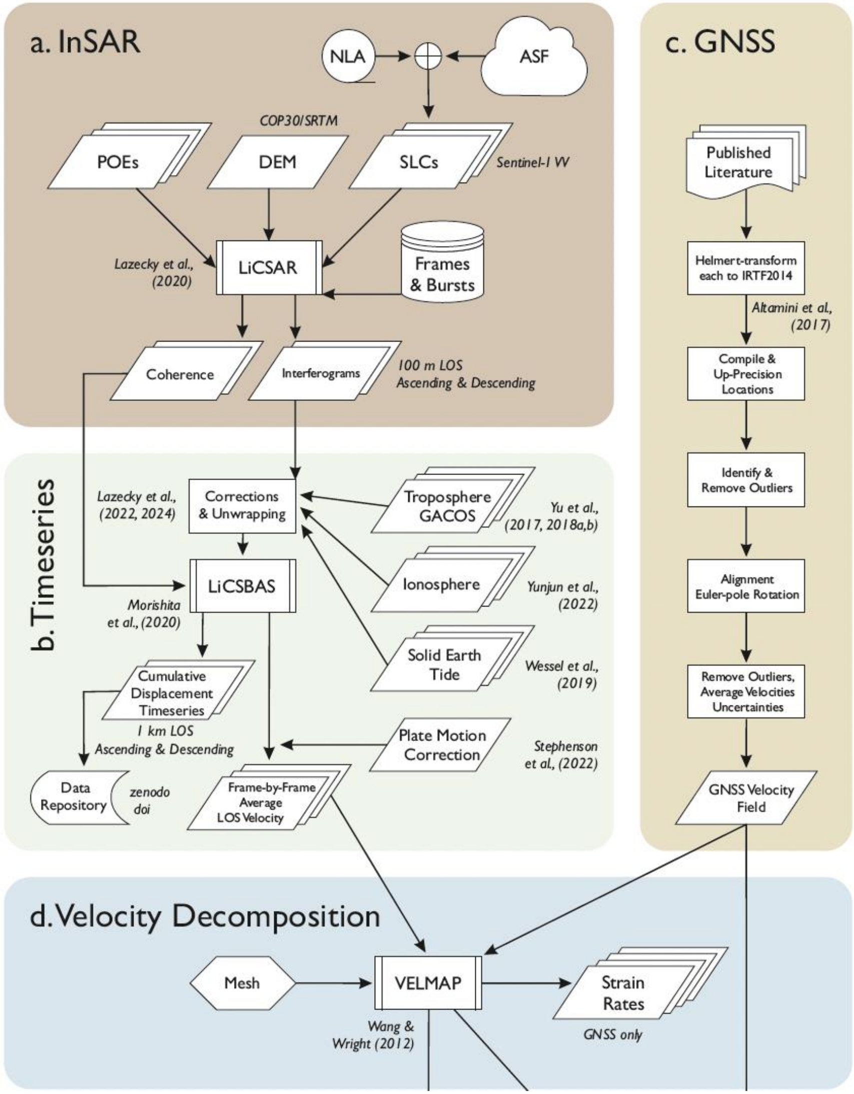
3) Referencing InSAR Velocities to GNSS

InSAR LOS velocities in a Eurasian reference frame



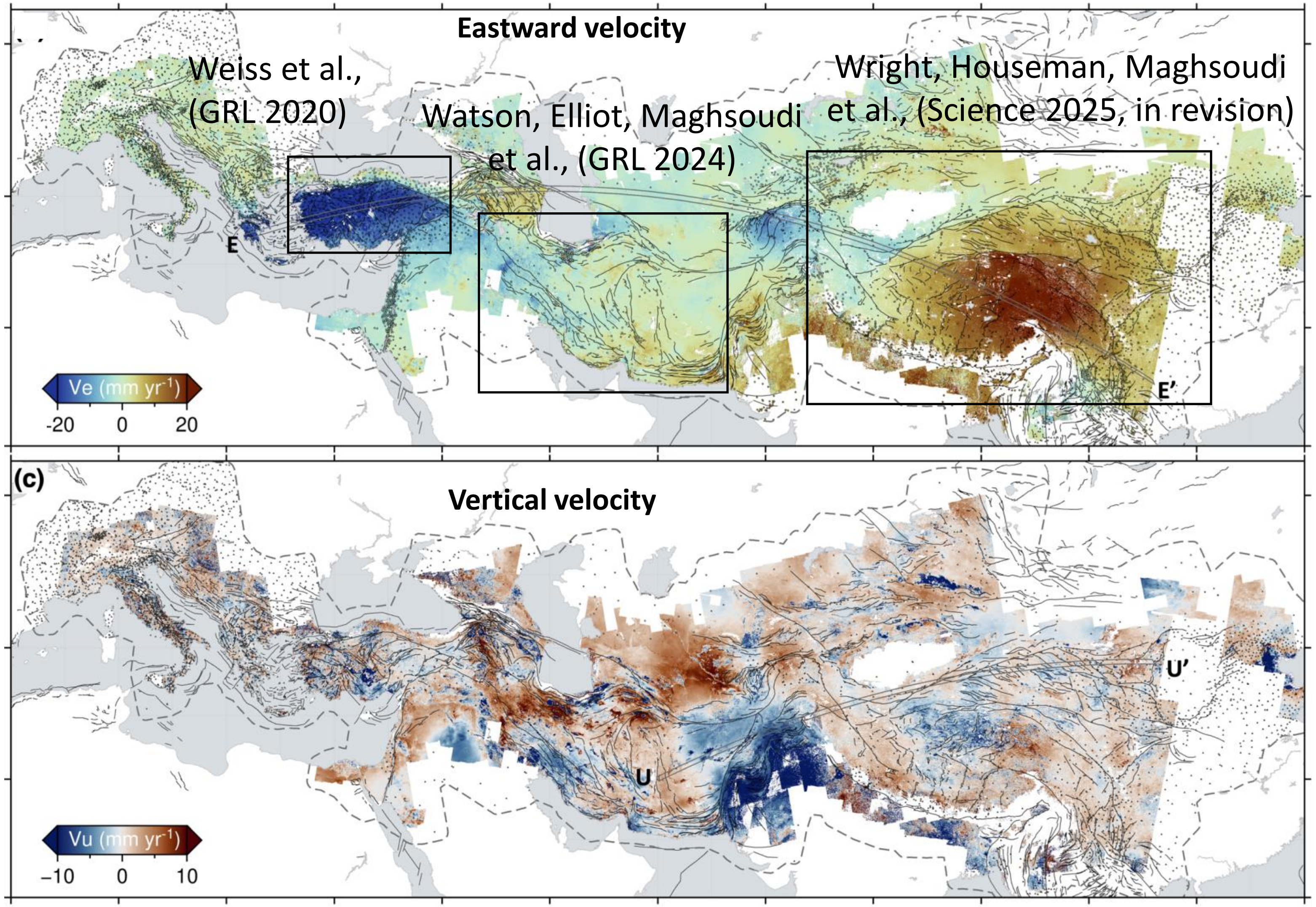
Jointly inversion of the GNSS data and the InSAR velocities.

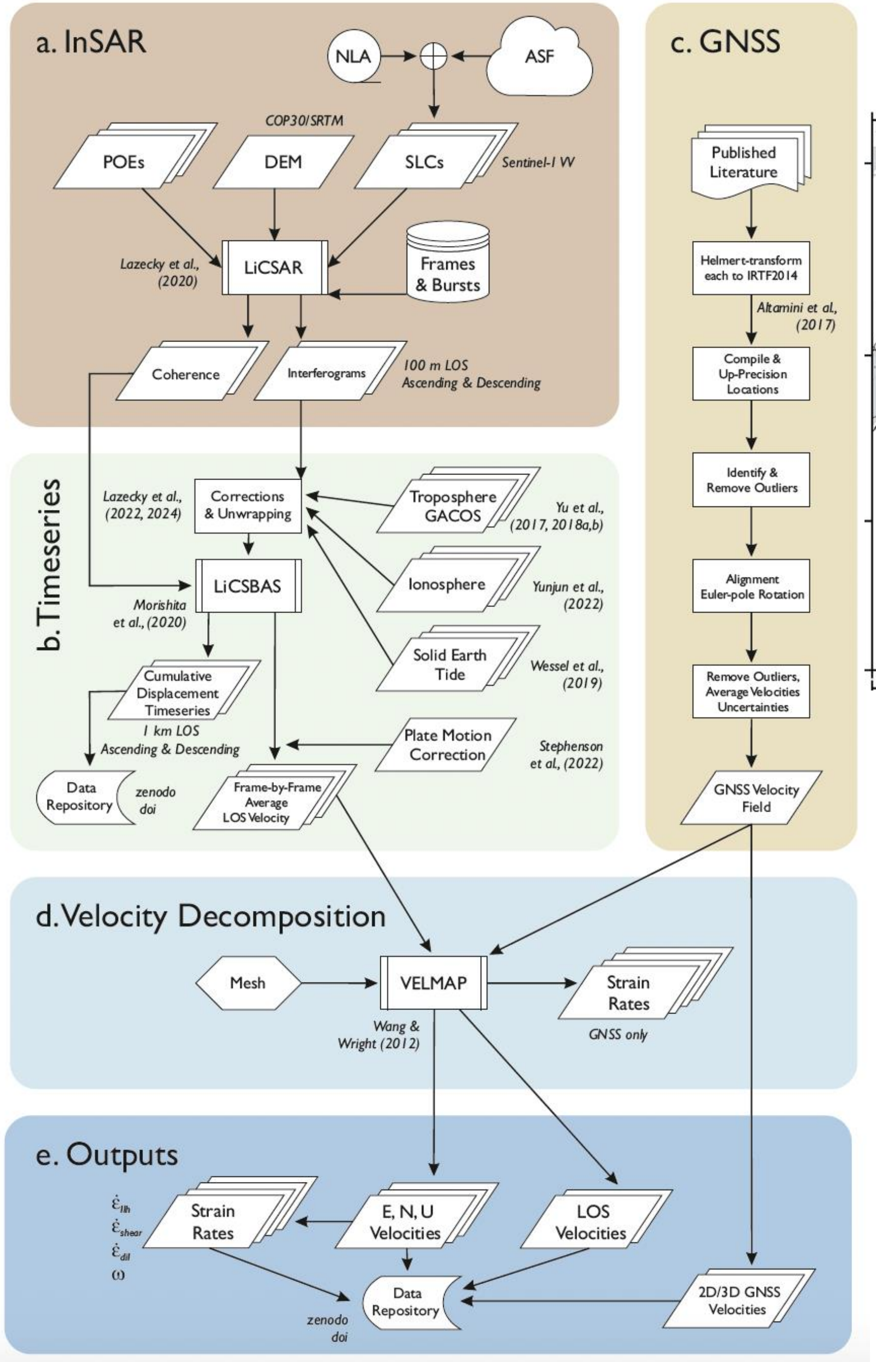
4) Velocity Decomposition



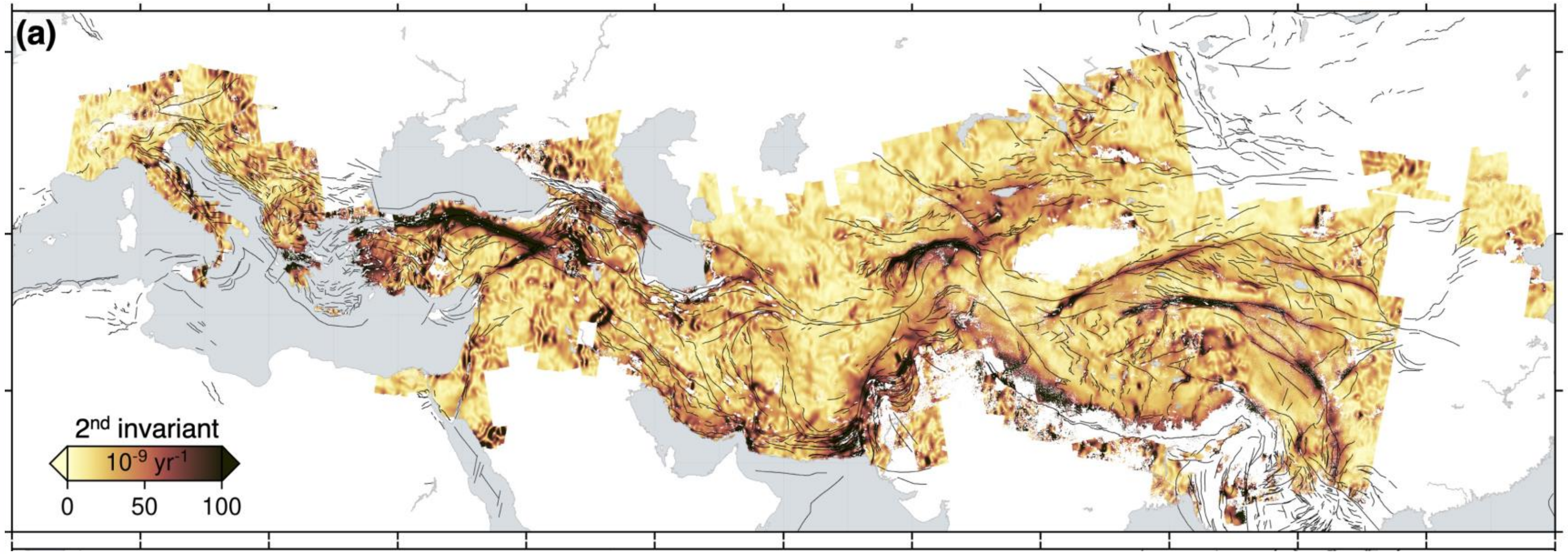
Decompose the referenced LOS velocities into the East west and vertical velocities.

Westward movement of the Anatolian plate with reference to the Eurasian plate





4) Strain Rates



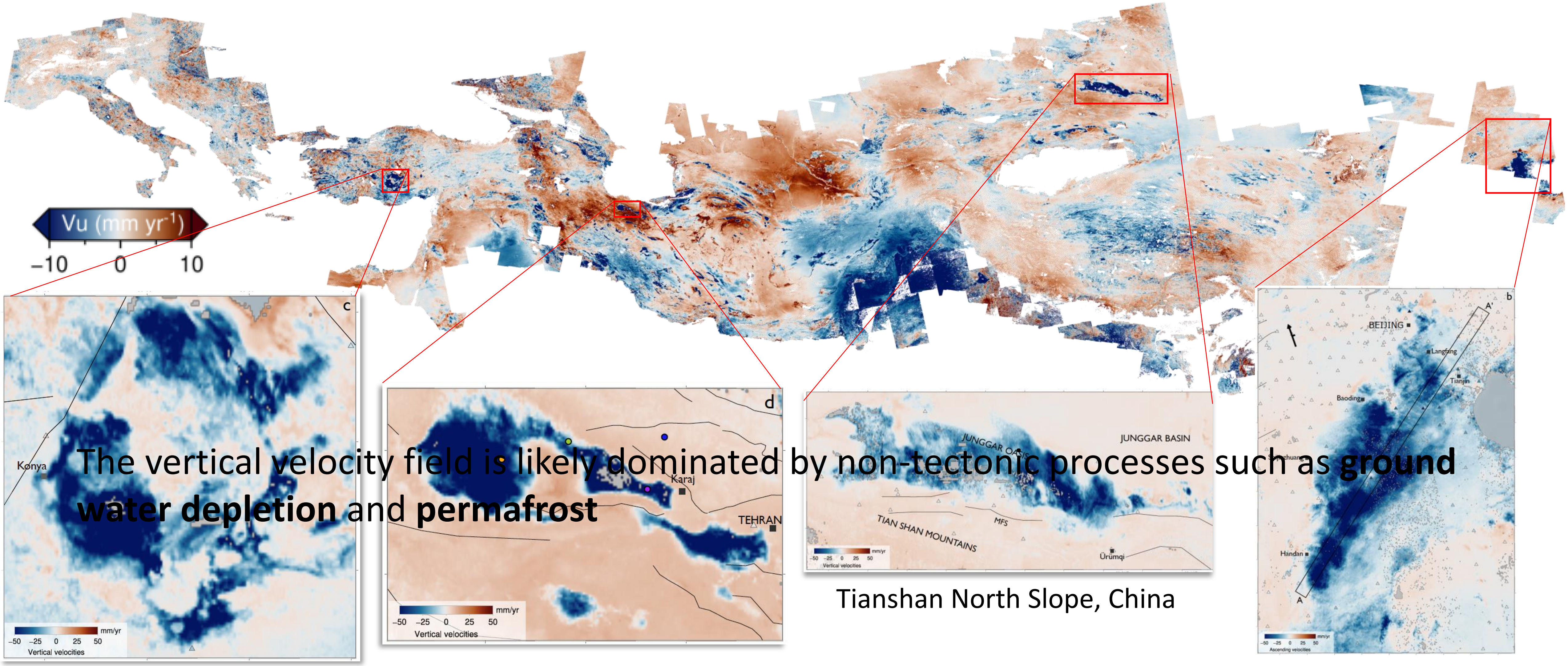
As the tectonic plates move, strain is accumulated along the fault.

Derived from gradients of the velocity field.

This allows us to pinpoint areas of high strain accumulation with very high spatial resolution, by combining InSAR and GNSS data.

These maps are being used by our impact partner global earthquake model (GEM) in a new generation of seismic hazard models

Non-Tectonic Vertical Signals: Groundwater Depletion



The vertical velocity field is likely dominated by non-tectonic processes such as **ground water depletion** and **permafrost**

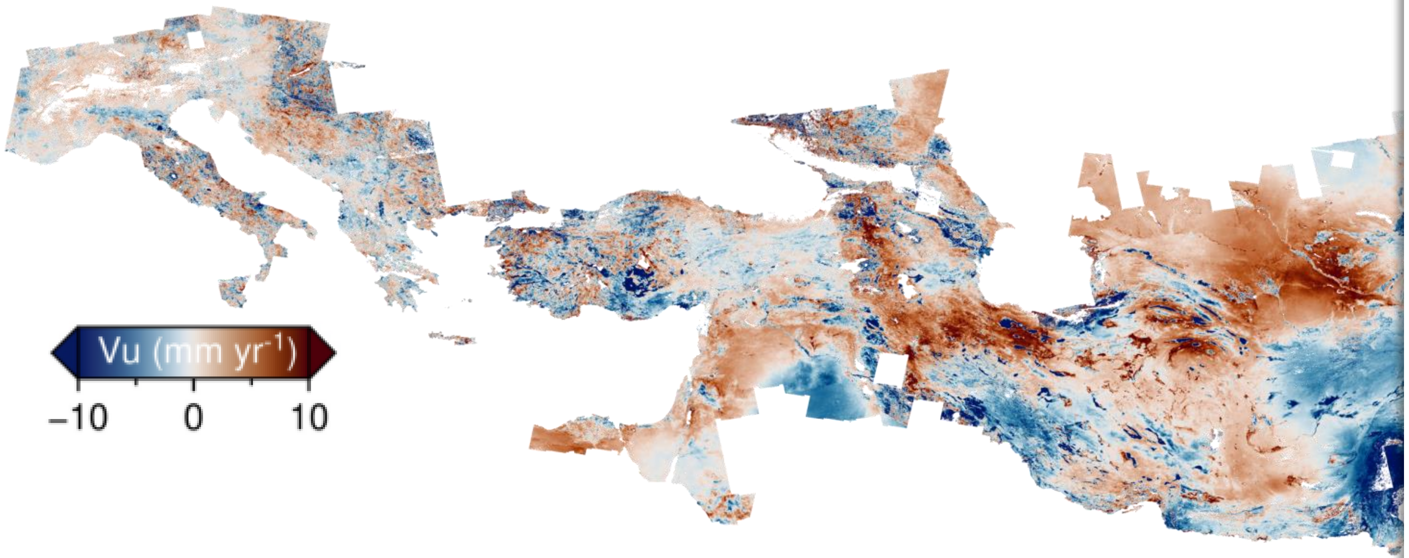
Konya Basin, Turkiye

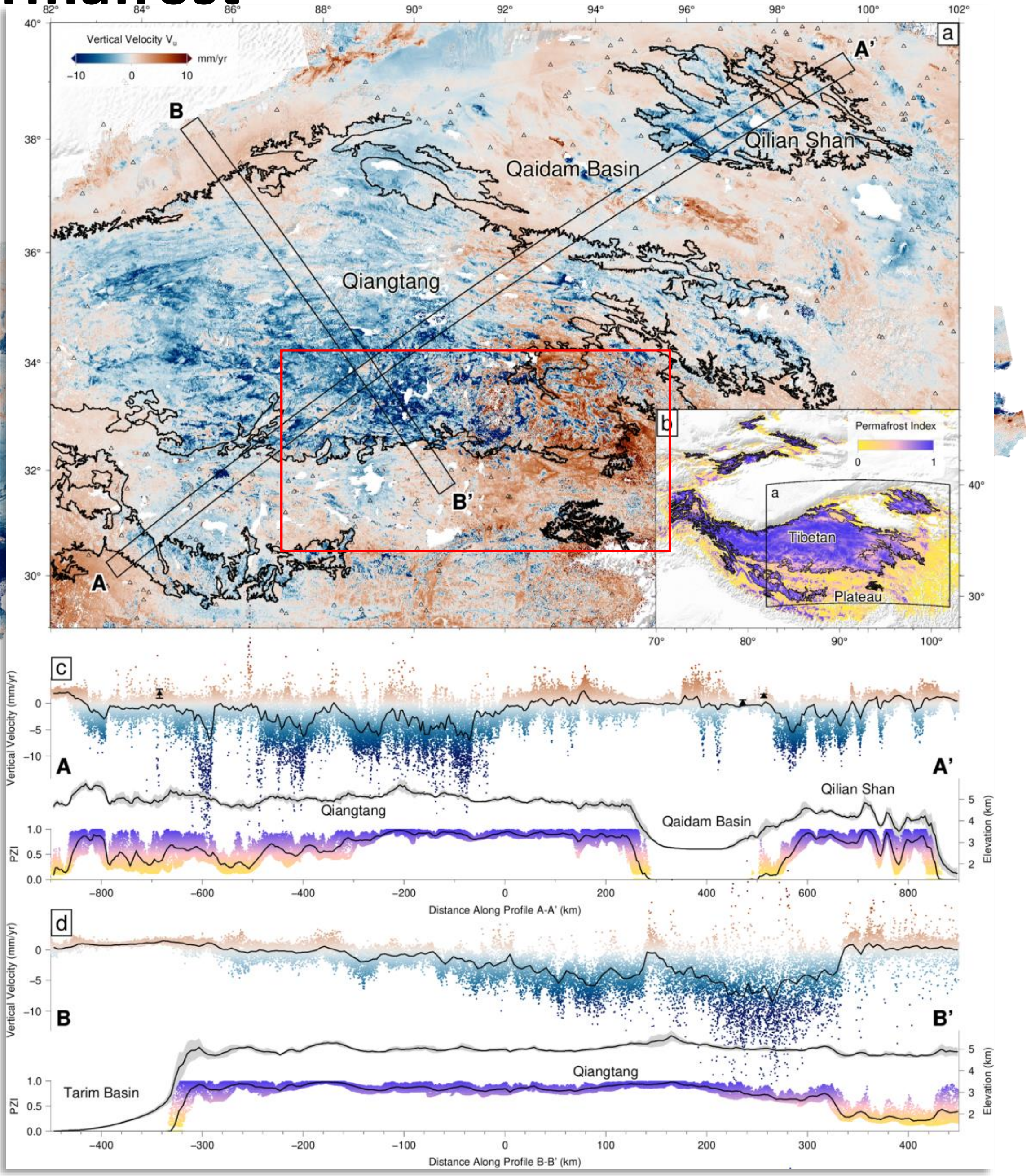
Tehran and Karaj, Iran

Tianshan North Slope, China

Eastern China

Non-Tectonic Vertical Signals: Permafrost

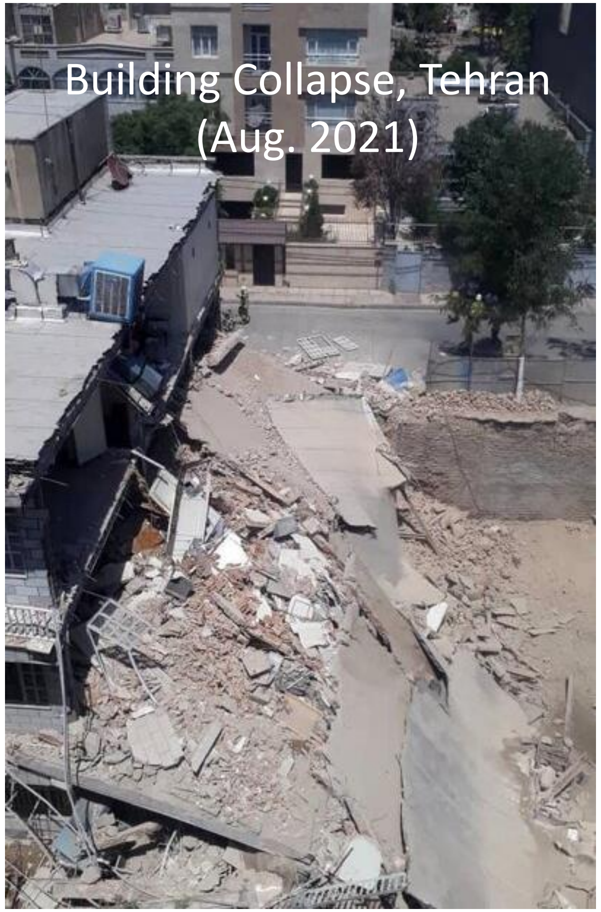


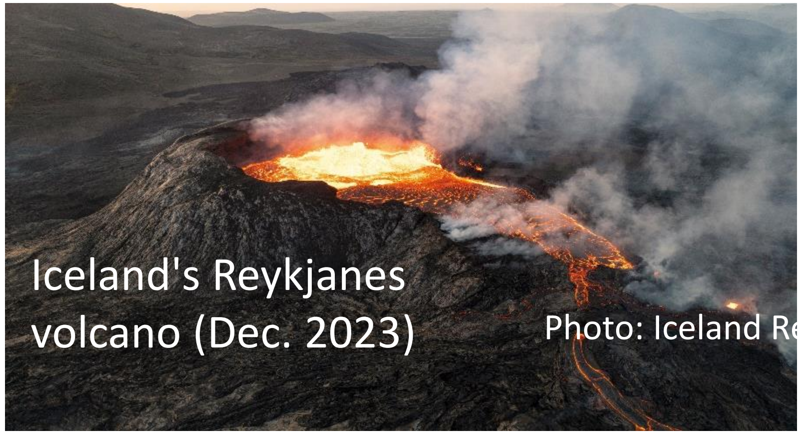


- Another process that causes land subsidence is the thawing of permafrost under a warming climate.
- Clear spatial correlation between zones of subsidence and areas with permafrost zonation index (PZI) above 0.5 (e.g. in Qilian Shan and the Qiangtang regions)
- Subsidence is strongly associated with permafrost degradation
- InSAR for climate-induced ground instability

Geohazard Monitoring with InSAR and Machine learning

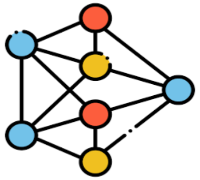
- These InSAR measurements open up many opportunities for monitoring various geohazards with machine learning.
- InSAR's dense spatial and temporal coverage makes it ideal anomaly detection and pattern recognition

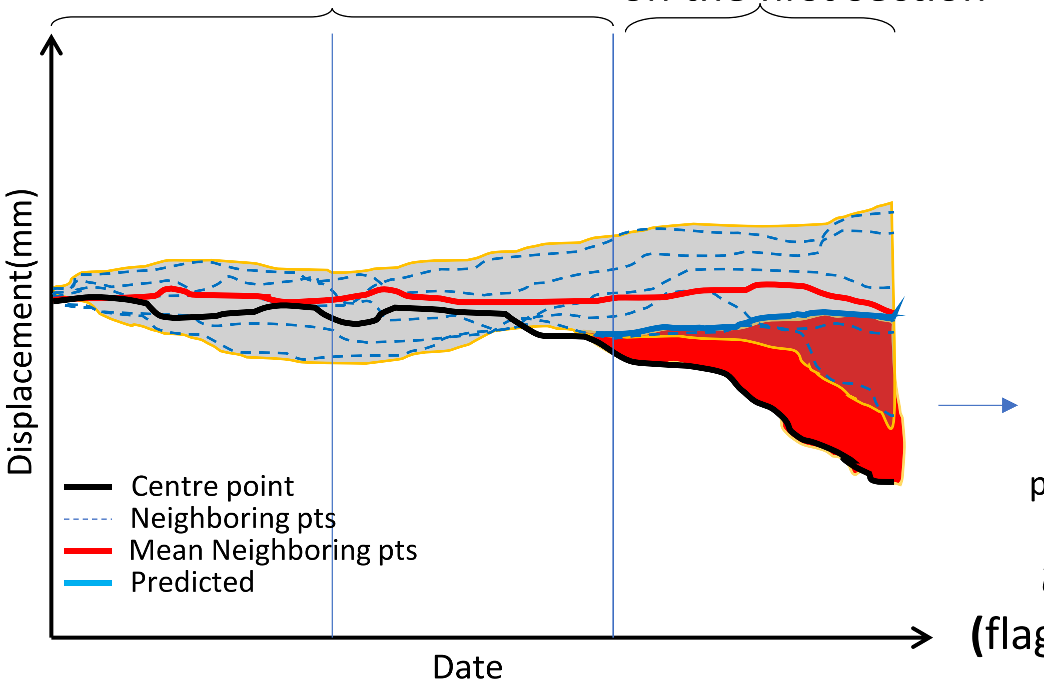




Collapse Monitoring with InSAR and Machine learning

- To identify precursory signals before building collapses using InSAR time-series data and ML.
- To detect anomalous points that may indicate structural failure

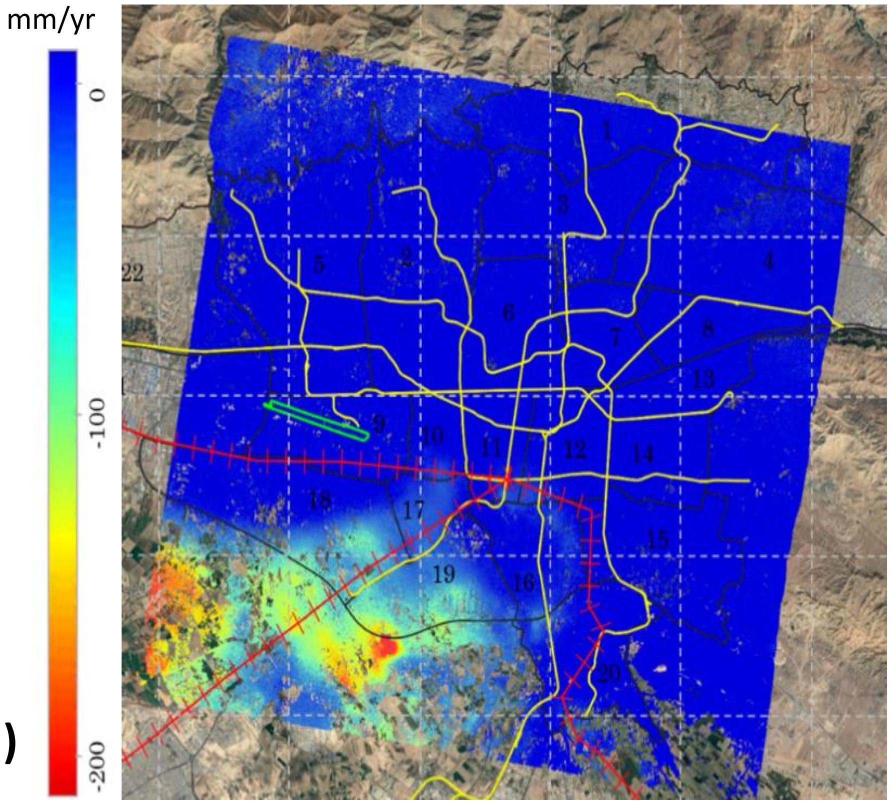




Δ: Difference between predicted TS and the actual TS

$$\boldsymbol{if\ \Delta > \tau\ \Rightarrow alaram}$$

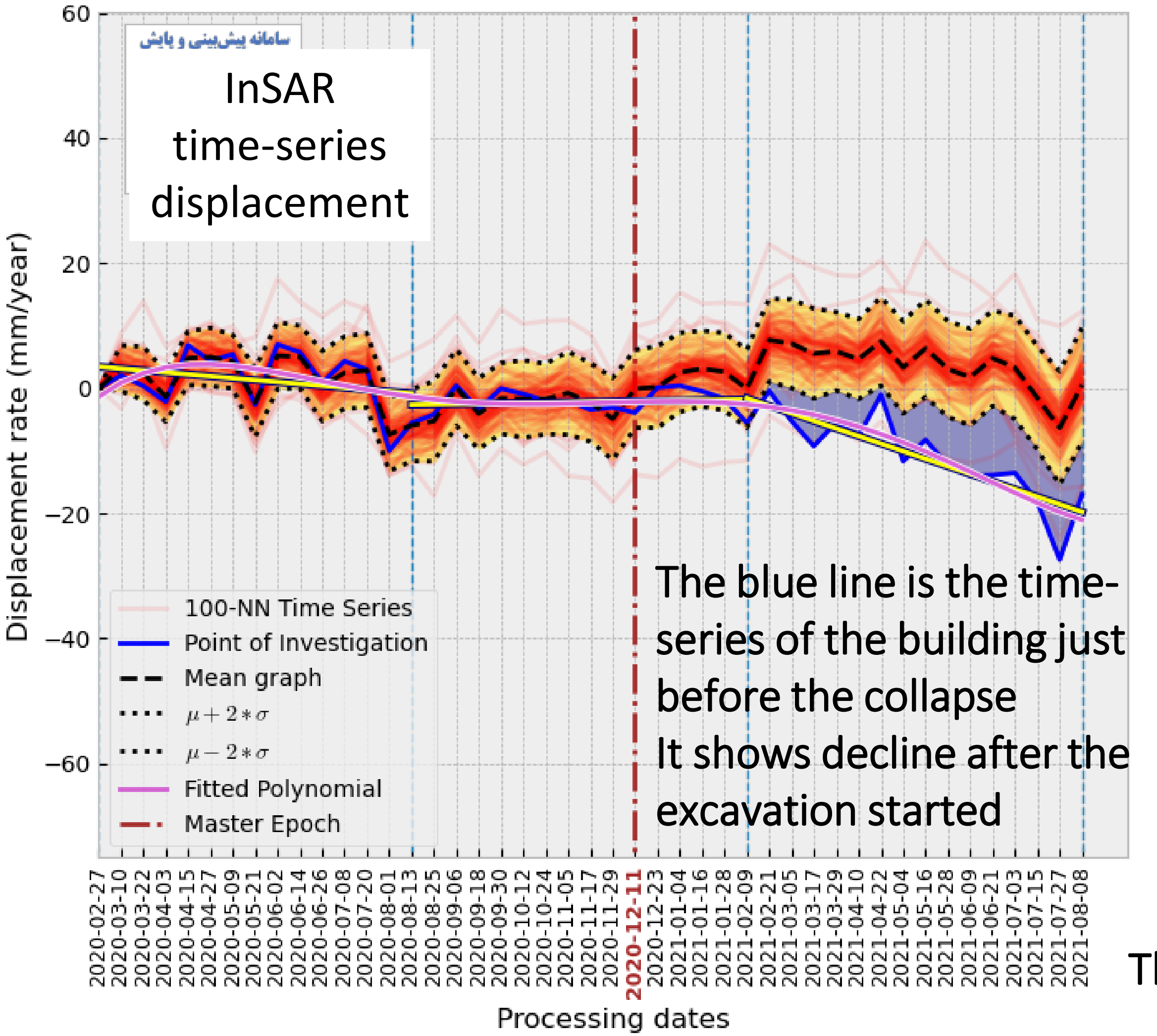
(flagged as potential hazard)



Land subsidence map in Tehran with ~ 2 million pts

Alizadeh, N.; Maghsoudi, Y.; Managhebi, T.; Azadnejad, S. Collapse Hotspot Detection in Urban Area Using Sentinel-1 and TerraSAR-X Dataset with SBAS and PSI Techniques. *Land* **2024**, *13*, 2237.

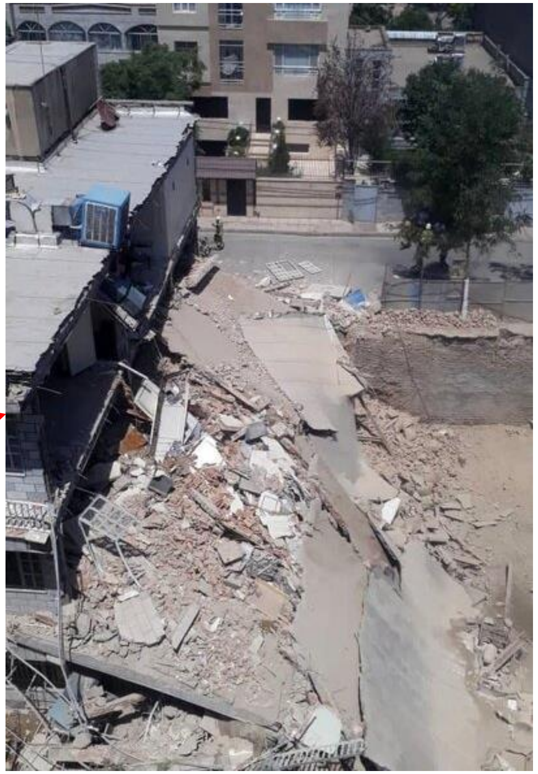
Collapse Monitoring with InSAR and Machine learning



InSAR time-series displacement

The blue line is the time-series of the building just before the collapse
It shows decline after the excavation started

A building collapsed in August 2021 due to nearby excavation



The point was identified as a hazard two months prior to the collapse

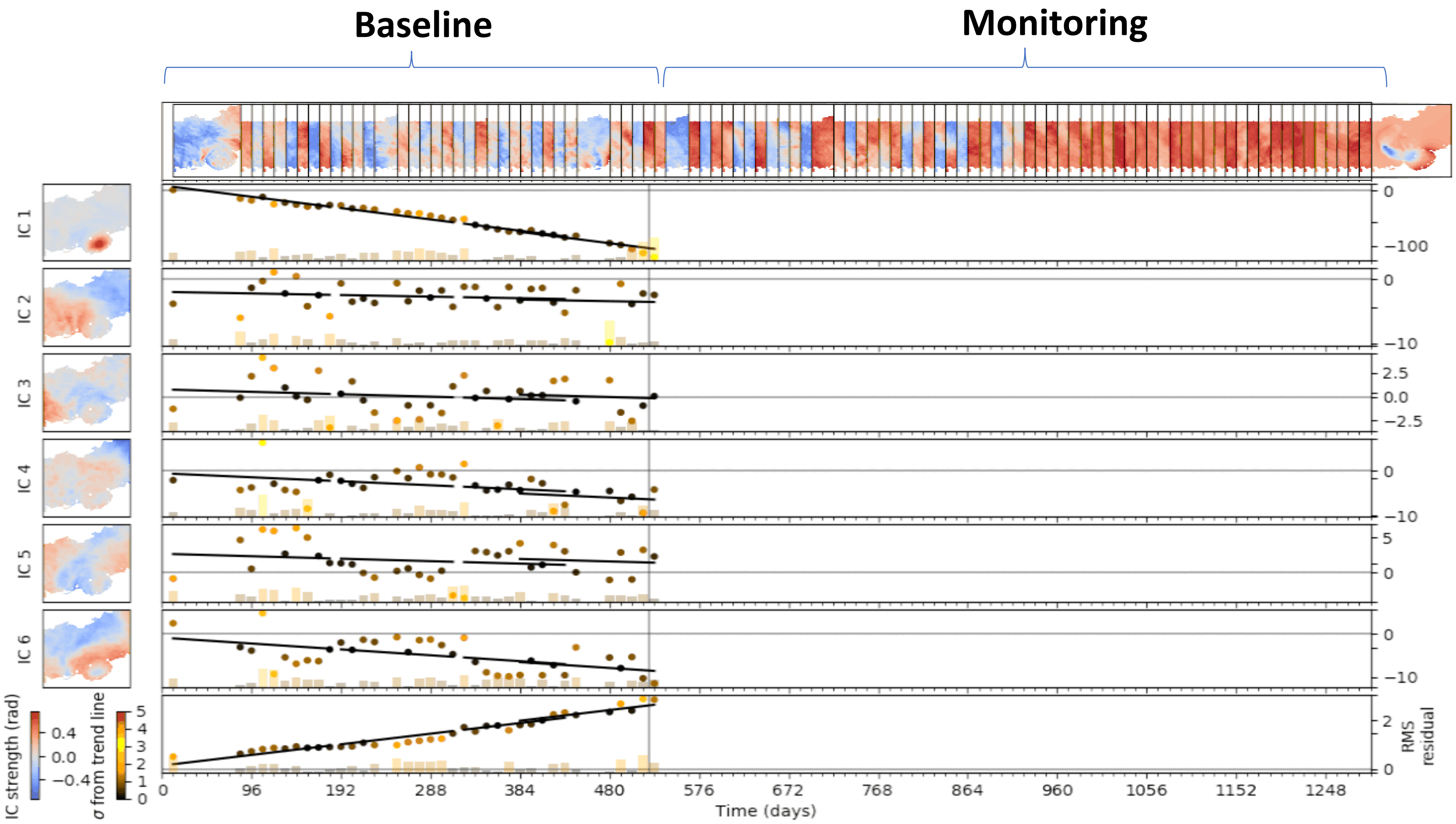
Alizadeh, N.; Maghsoudi, Y.; Managhebi, T.; Azadnejad, S. Collapse Hotspot Detection in Urban Area Using Sentinel-1 and TerraSAR-X Dataset with SBAS and PSI Techniques. *Land* **2024**, *13*, 2237.

LiCSAlert – Automated Detection of Volcanic Unrest (Gaddes et al., 2019)

1) Split the Time Series to baseline (1-2 year, no unrest, for training), and monitoring (the remainder)

2) Apply ICA to baseline ifgs, separate deformation signals from noise (usually atmosphere)

3) Fit each baseline interferogram as a linear combination of spatial sources (learn temporal coefficients that explain the data)



The main objective of this method is to detect early signs of deformation that could signal unrest at volcanoes, before it becomes visually apparent

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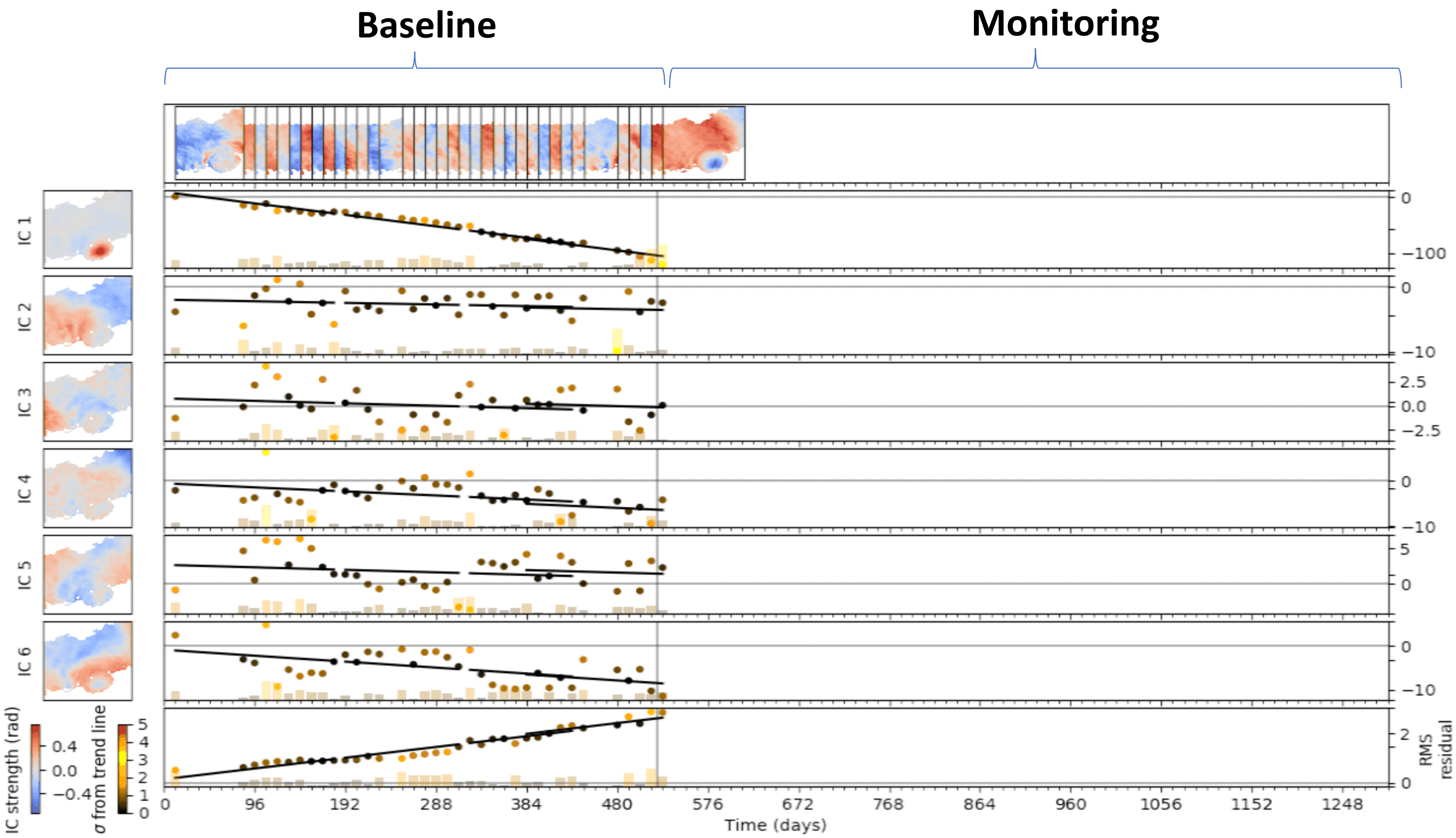
2) Apply ICA to baseline ifgs, separate deformation signals from noise (usually atmosphere)

3) Fit each baseline interferogram as a linear combination of spatial sources (learn temporal coefficients that explain the data)

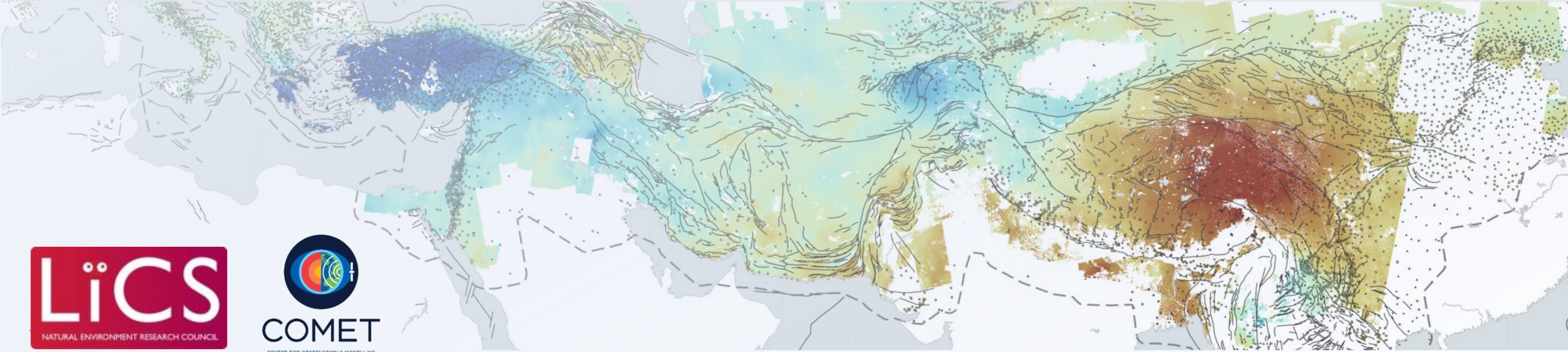
4) Run monitoring (apply same spatial sources to new interferograms and compute new temporal coefficients and residuals)



Flags the volcano as having potentially entered a period of unrest: if the residuals between predicted and actual data grow large

Conclusions

- First trans-continental scale three-component velocity field of the Alpine-Himalayan Belt derived from the archive of Sentinel-1 satellite radar observations
- Horizontal deformation is dominated by tectonics, vertical by other surface processes such as fast and persistent subsidence due to water extraction from aquifers
- There is a great potential in using InSAR time-series displacements with machine learning for geohazard monitoring



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