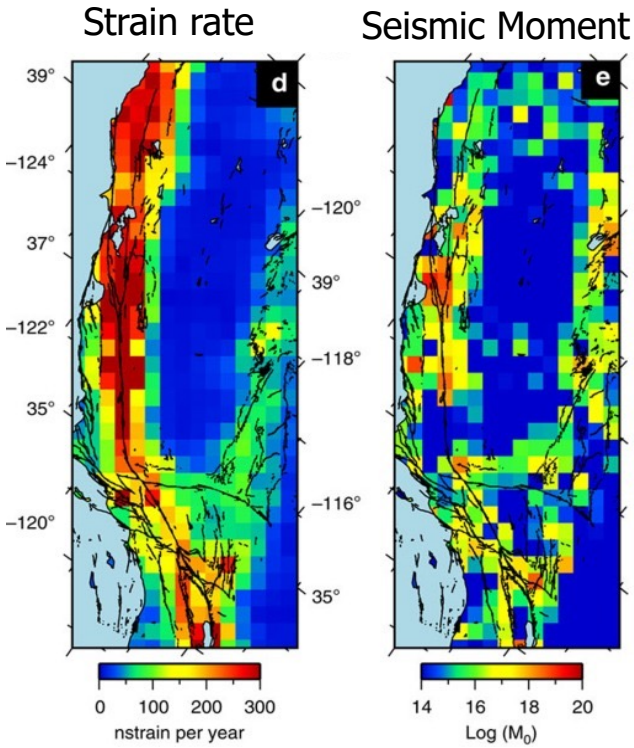
Large-scale, high-resolution maps of interseismic strain accumulation from Sentinel-1, and incorporation of along-track measurements

Andy Hooper[1], Pawan Piromthong[1], Tim J Wright[1], Jonathan Weiss[2], Milan Lazecky[1], Yasser Maghsoudi[1], Chris Rollins[1], Yu Morishita[3], John Elliott[1], and Barry Parsons[4]

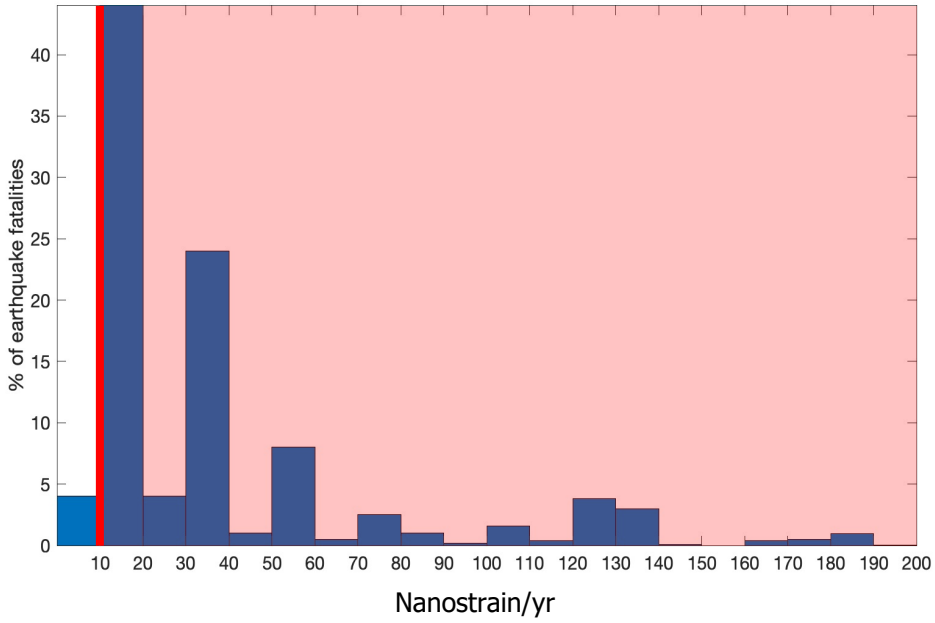
[1]COMET, University of Leeds, [2]University of Potsdam [3]GSI Japan [4]COMET, University of Oxford

COMET LiCS NATURAL ENVIRONMENT RESEARCH COUNCIL NERC SCIENCE OF THE ENVIRONMENT Earthquakes without Frontiers NATURAL ENVIRONMENT RESEARCH COUNCIL ECONOMIC & SOCIAL RESEARCH COUNCIL esa UNIVERSITY OF LEEDS

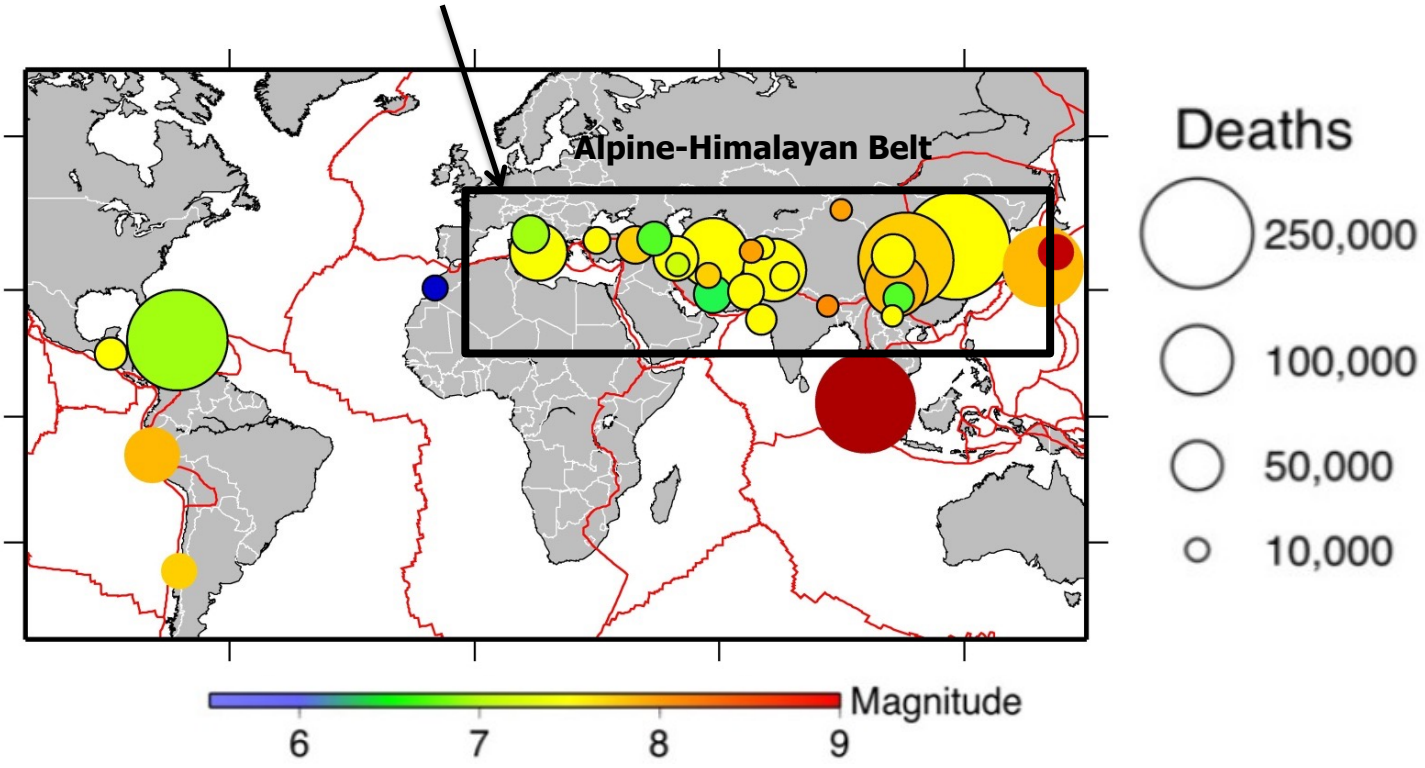
- Earthquakes generally occur where the surface is undergoing strain
- 96% of all earthquake deaths occur in regions straining more than 10 nanostrain/year



Elliott et al, 2016



75% of earthquakes killing more than 10,000 people since 1900 have occurred in the Alpine-Himalayan Seismic Belt

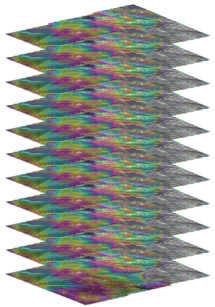


We can estimate strain rate from InSAR and GNSS and use this to constrain seismic hazard

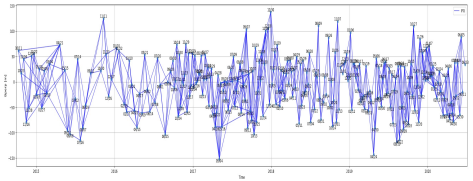
1. Make Interferograms



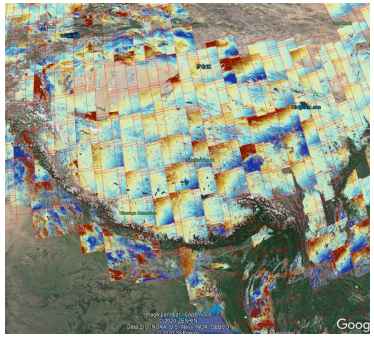
Sentinel-1 SLC data



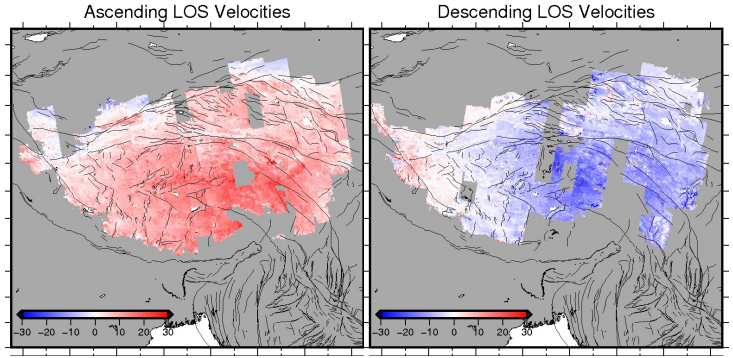
Interferogram Network



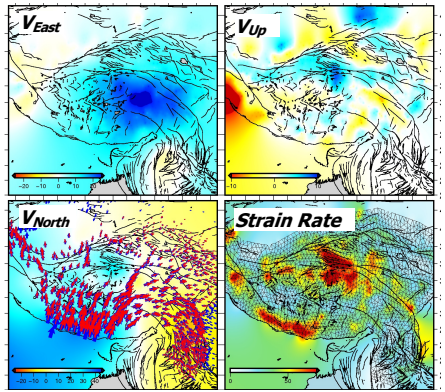
2. Invert for LOS Velocities (Frame by Frame)



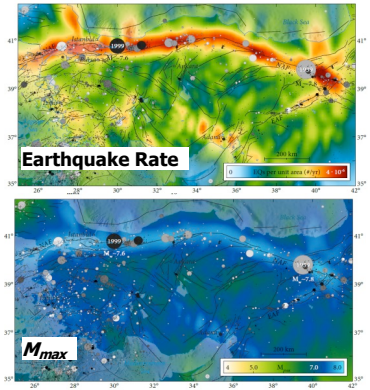
3. Reference InSAR Velocities to GNSS



4. Invert InSAR and GNSS data for 3D Velocity Field and Strain Rates



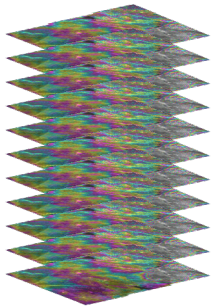
5. Combine Strain and Seismicity to Estimate Seismic Hazard



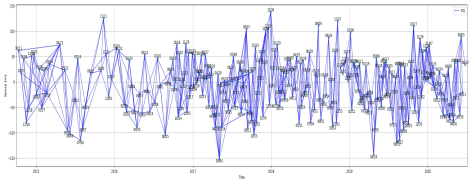
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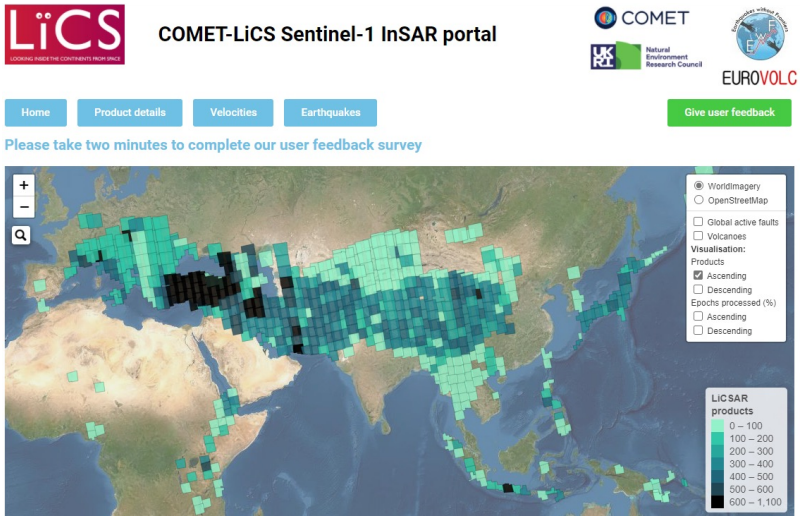
Sentinel-1
SLC data



Interferogram
Network

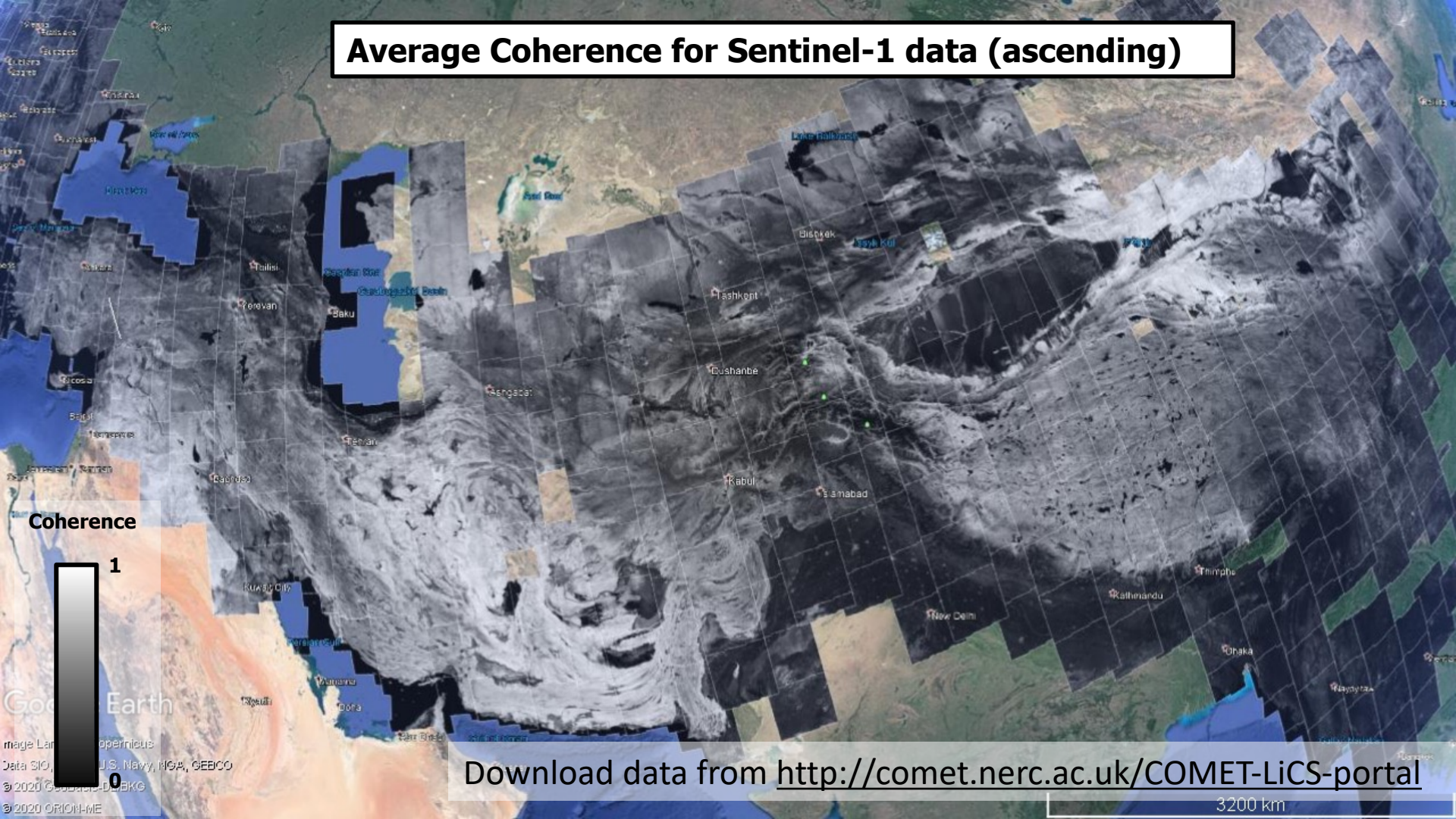


- We make interferograms automatically for 250 x 250 km frames, using LiCSAR. For details of approach see
  - Lazecky et al. **Remote Sensing 2020**, doi:10.3390/rs12152430
  - See also Lazecky et al. EGU21-2929
- We form interferograms with 4 closest previous acquisitions (plus additional pairs to improve the network as needed)
- 350,000+ interferograms are available for download from COMET-LICSAR portal (223,000 in the Alpine-Himalayan Belt)



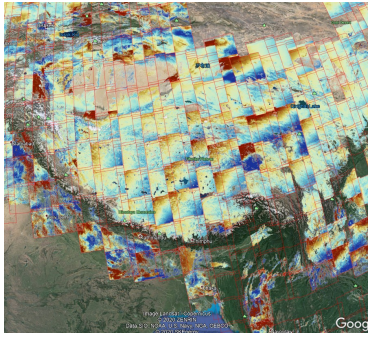
Download data from http://comet.nerc.ac.uk/COMET-LiCS-portal

Average Coherence for Sentinel-1 data (ascending)

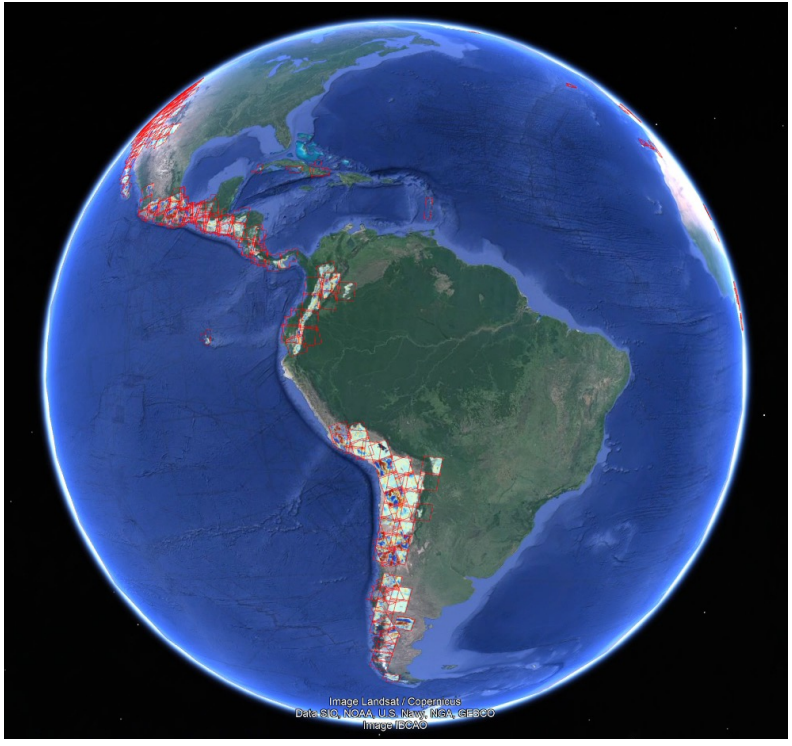


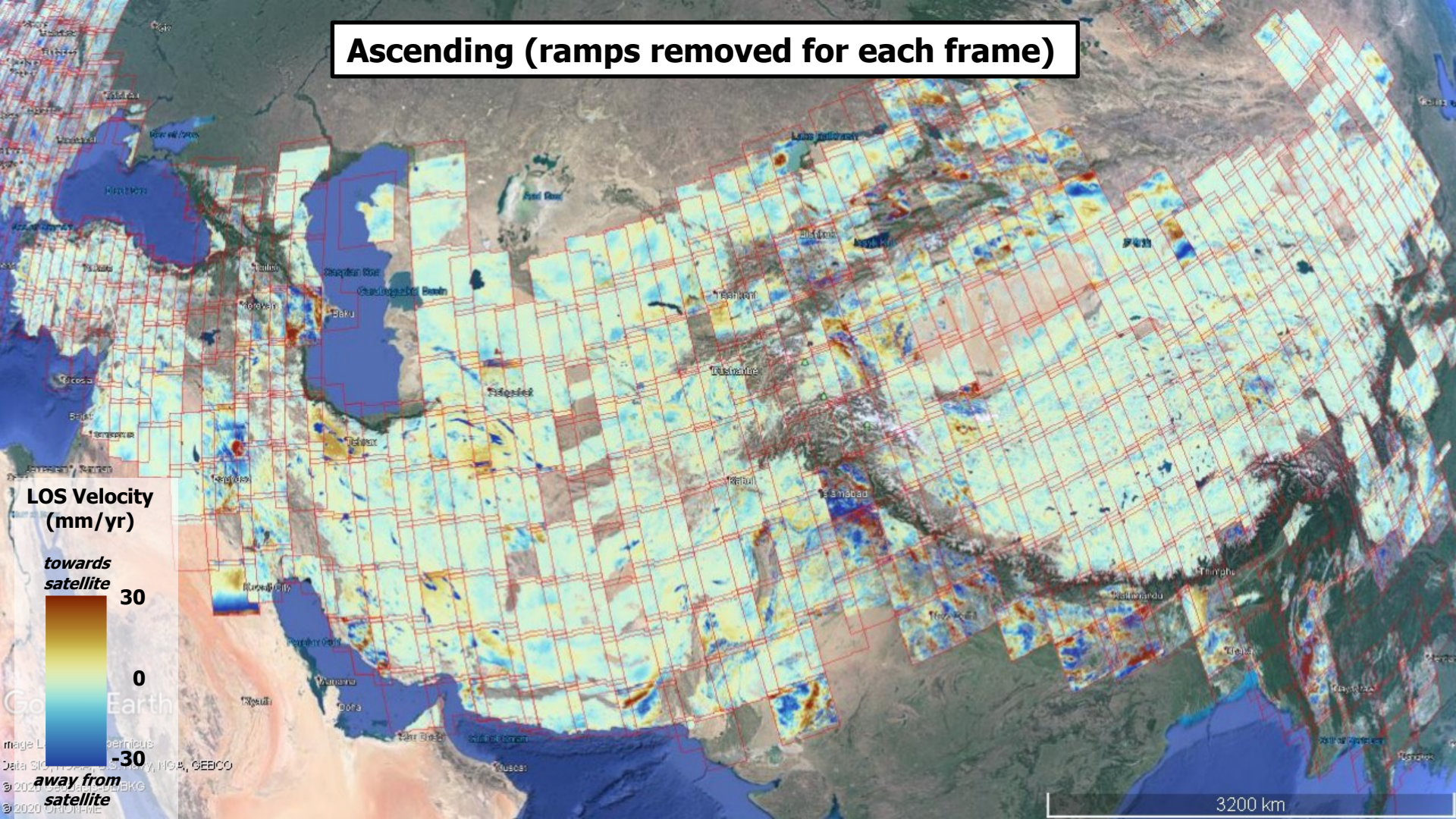
Download data from http://comet.nerc.ac.uk/COMET-LiCS-portal

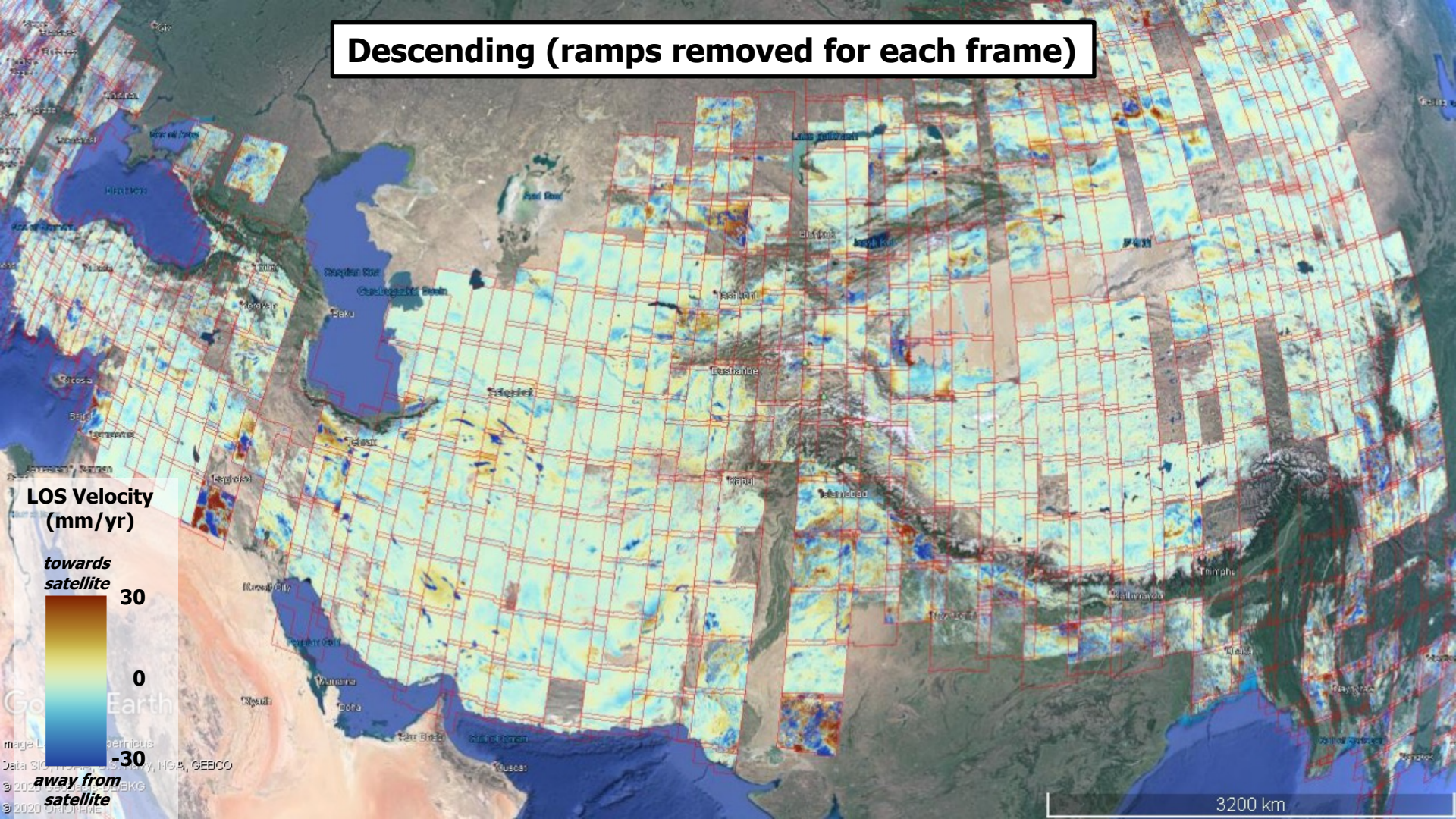
2. Invert for LOS Velocities (Frame by Frame)



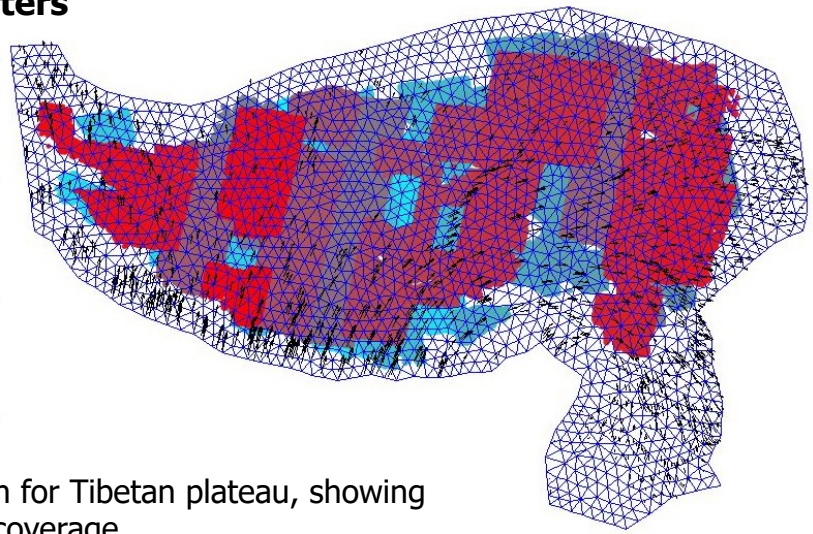
- We create average line-of-sight velocities using LiCSBAS, an open source time series code based on a modified NSBAS approach. See
  - *Morishita et al.* **Remote Sensing 2020**, doi:10.3390/rs12030424
- We generate velocities for every frame where we have LiCSAR data (about 1400 250x250 km frames, covering ~90 million km^2 at 1 km resolution)




Ascending (ramps removed for each frame)
LOS Velocity (mm/yr)
towards satellite
30
0
-30
away from satellite
3200 km

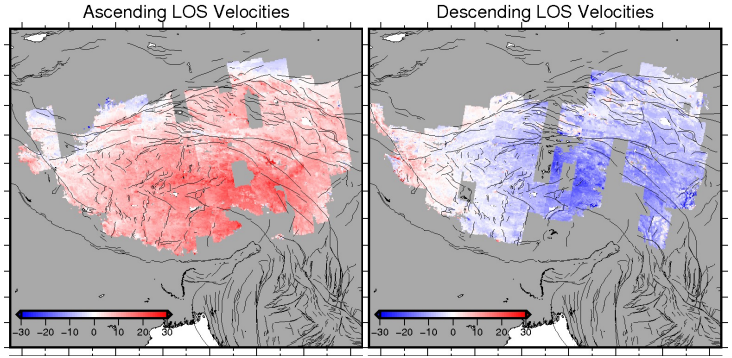

Descending (ramps removed for each frame)
LOS Velocity (mm/yr)
towards satellite
30
0
-30
away from satellite
3200 km

- We **jointly** invert GNSS and InSAR LOS velocities using the Velmap approach (Wang and Wright, GRL 2012).
  - ➢ See also Rollins et al. EGU21-630
- This solves for **velocities of the nodes** in a mesh of spherical triangles AND the **reference frame adjustment parameters**

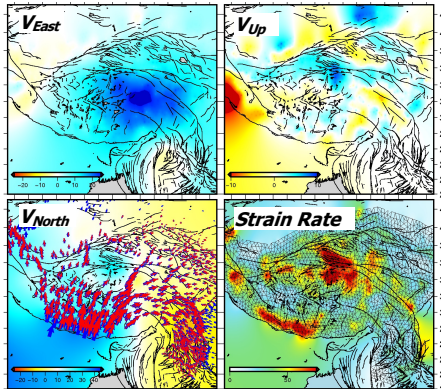


Velmap Mesh for Tibetan plateau, showing InSAR data coverage
(GNSS from Wang and Shen, 2020)

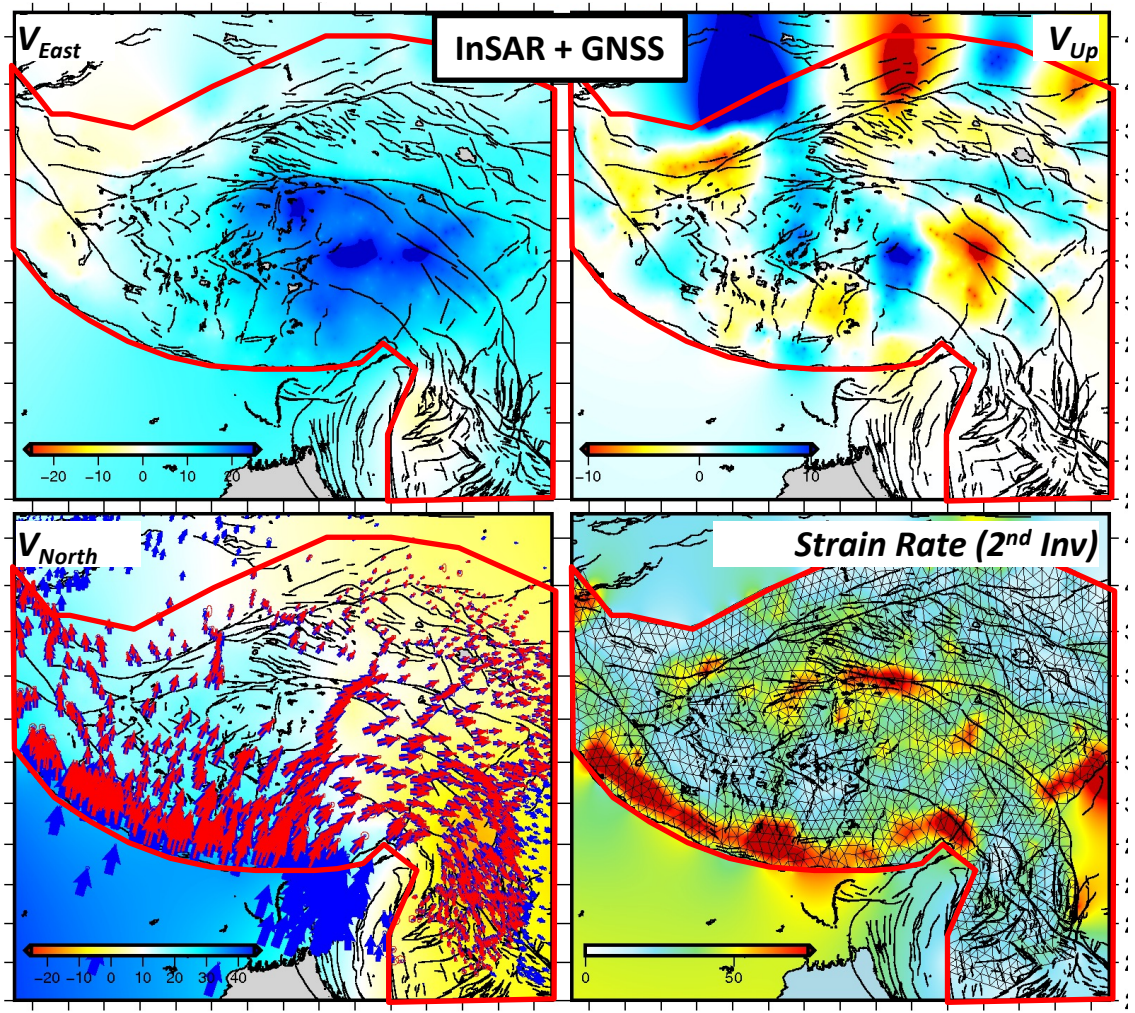
3. Reference InSAR Velocities to GNSS



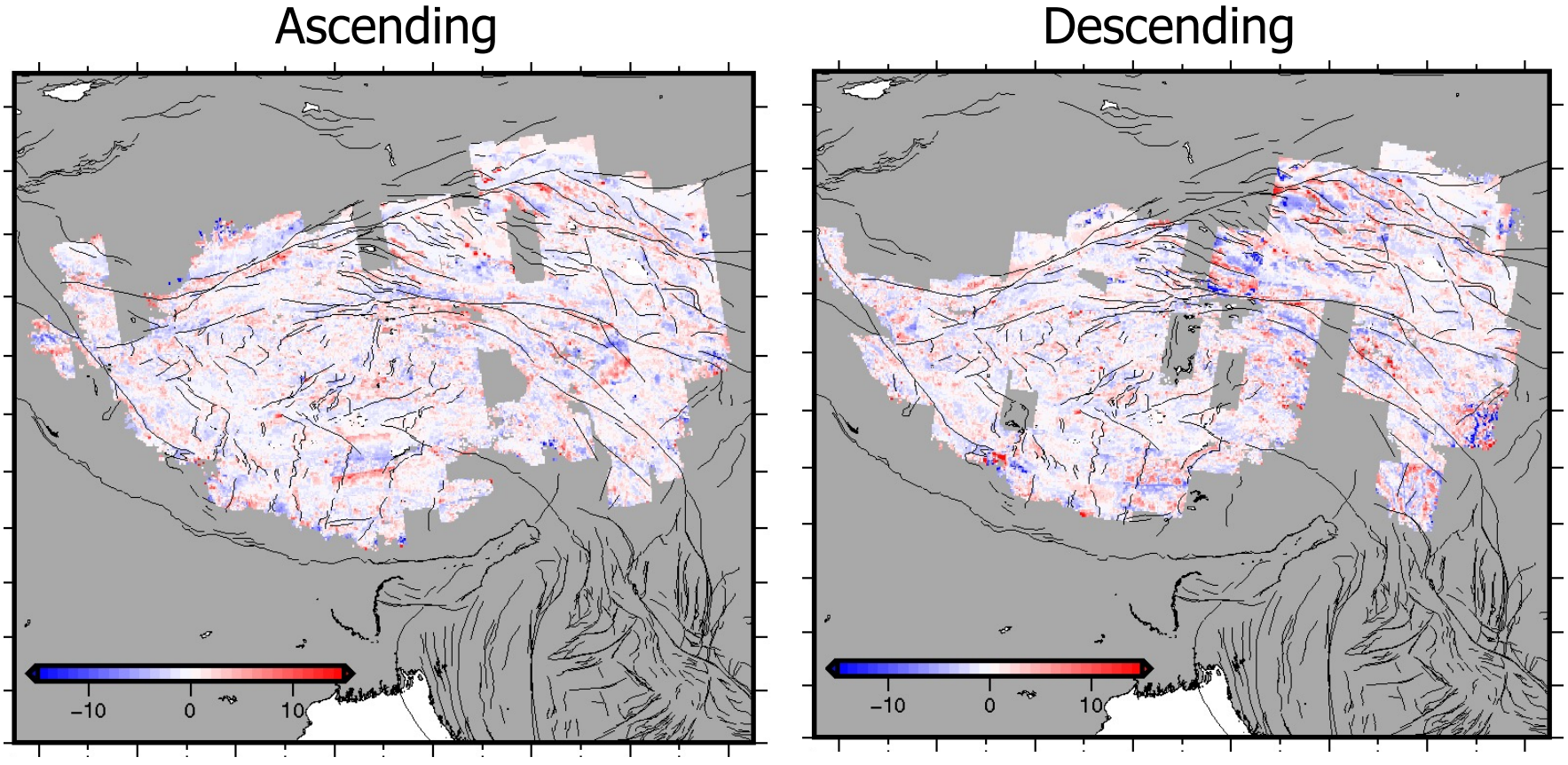
4. Invert InSAR and GNSS data for 3D Velocity Field and Strain Rates



3D Velocity field for the Tibetan Plateau from InSAR and GNSS
(preliminary)

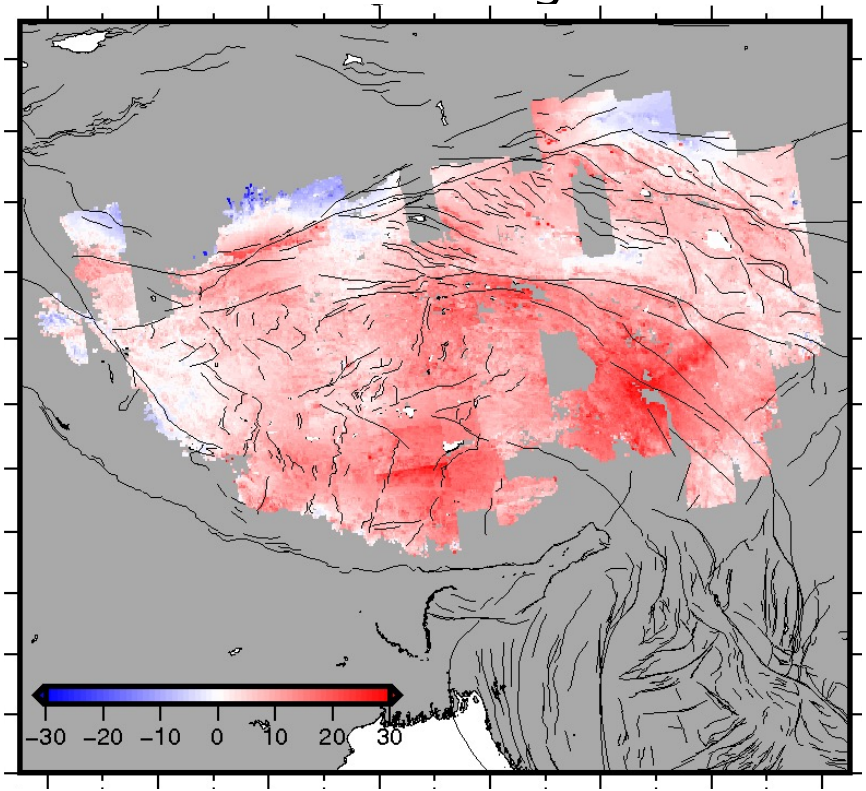


Mosaic of LOS Velocities for Tibet in InSAR Reference Frame (ramps removed)

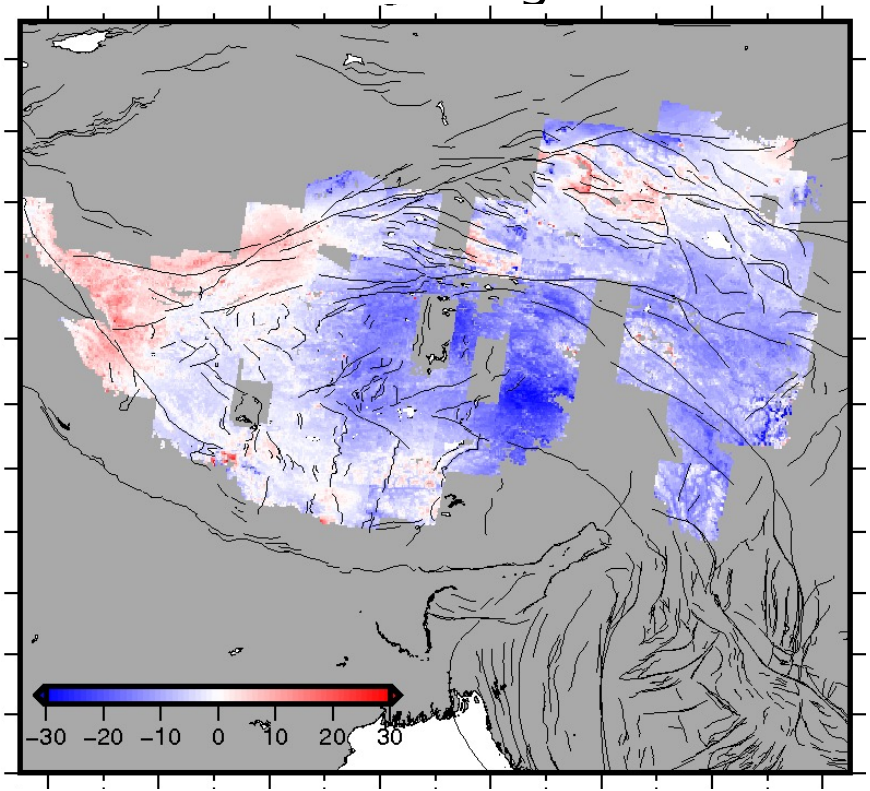


Mosaic of LOS Velocities for Tibet in Eurasia Reference Frame

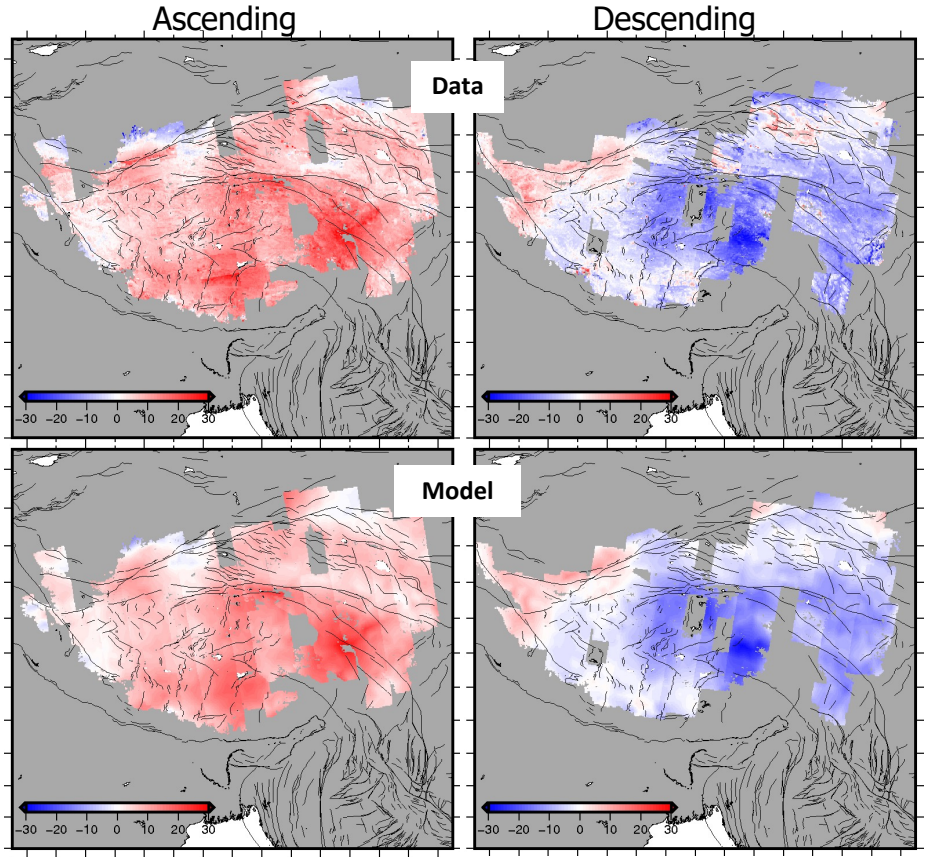
Ascending



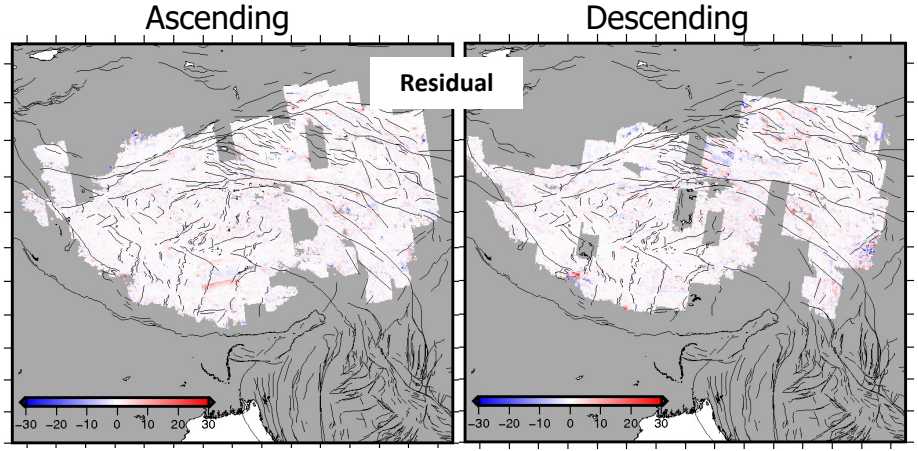
Descending

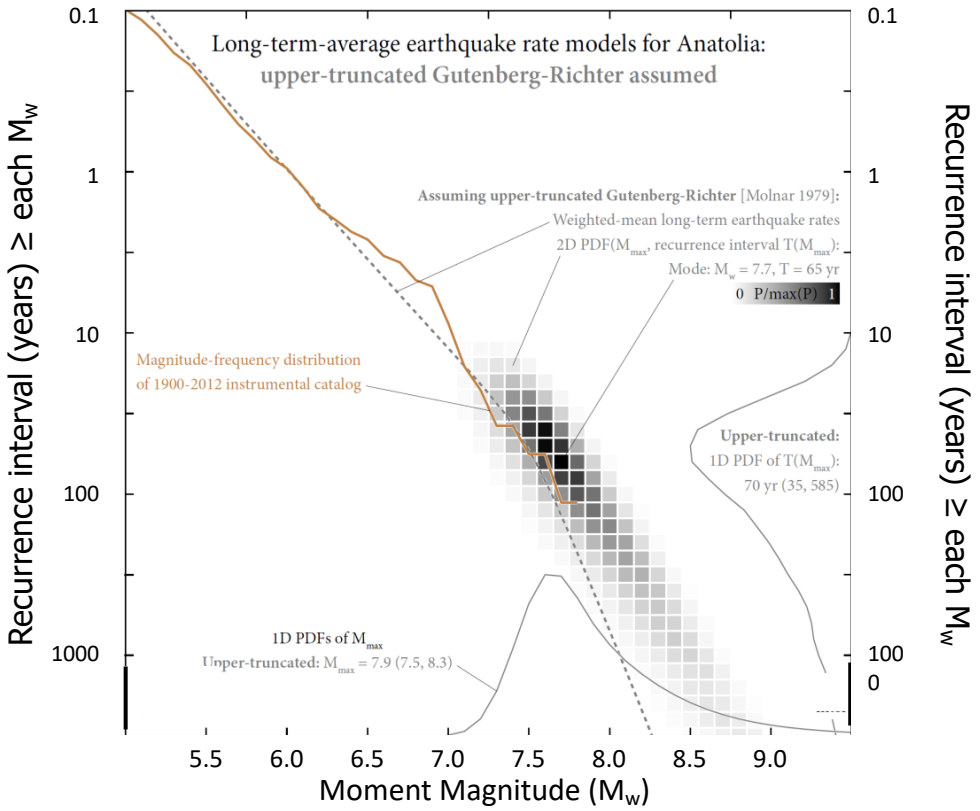


Mosaic of LOS Velocities for Tibet in Eurasia Reference Frame



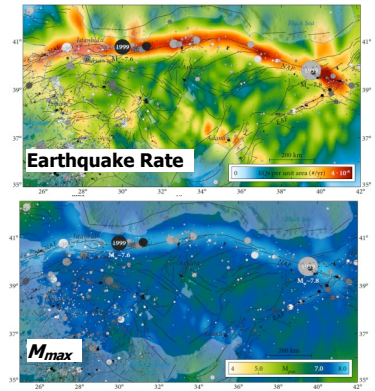
- In general, solving jointly for velocities and InSAR reference frame adjustments frame by frame works well.
- Jointly inverted velocity field provides a good fit to the InSAR and GNSS data:
  - InSAR RMS Residual = 2.3 mm/yr
  - GNSS RMS Residual = 1.2 mm/yr





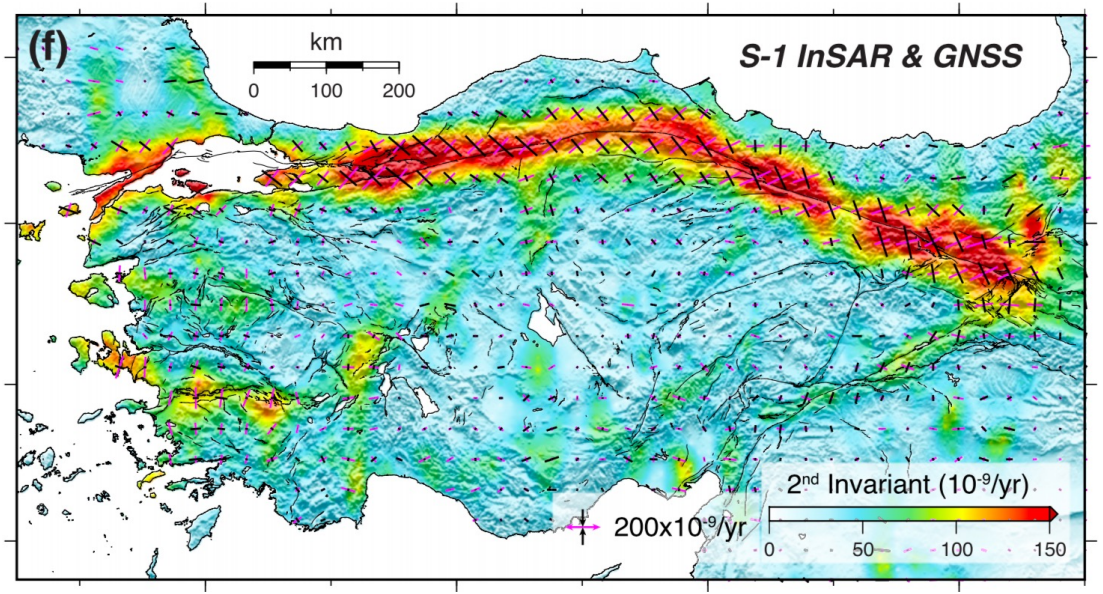
- Combining geodetic strain and seismicity data allows you to constrain earthquake recurrence and maximum magnitudes.
  - For more details see Chris Rollins DeTect talk (http://www.ipgp.fr/~klinger/web_Yann/Detect_page/detect.html)

5. Combine Strain and Seismicity to Estimate Seismic Hazard



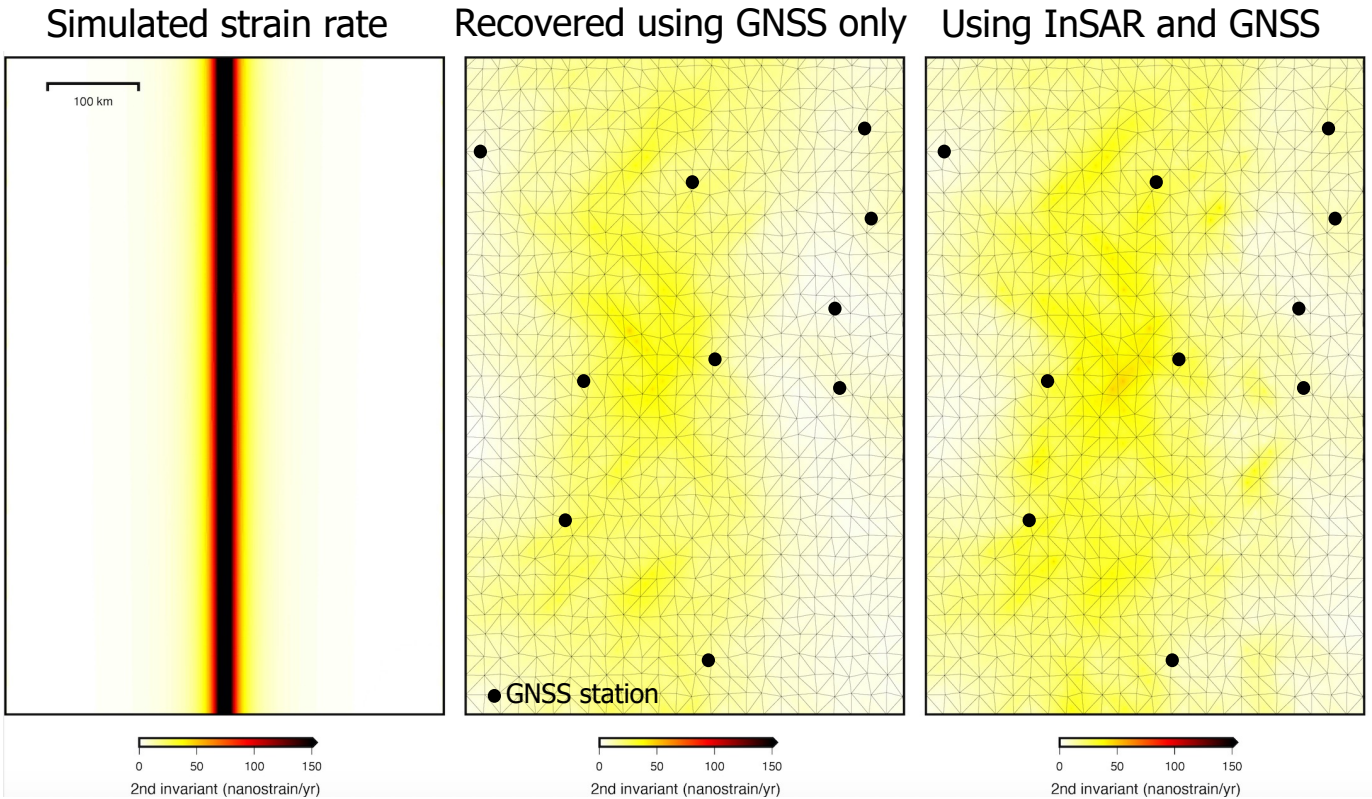
- However, InSAR gives good constraint only on E-W component of horizontal motion
- Constrains strain rate well for E-W shear zones, with N-S motion from GNSS





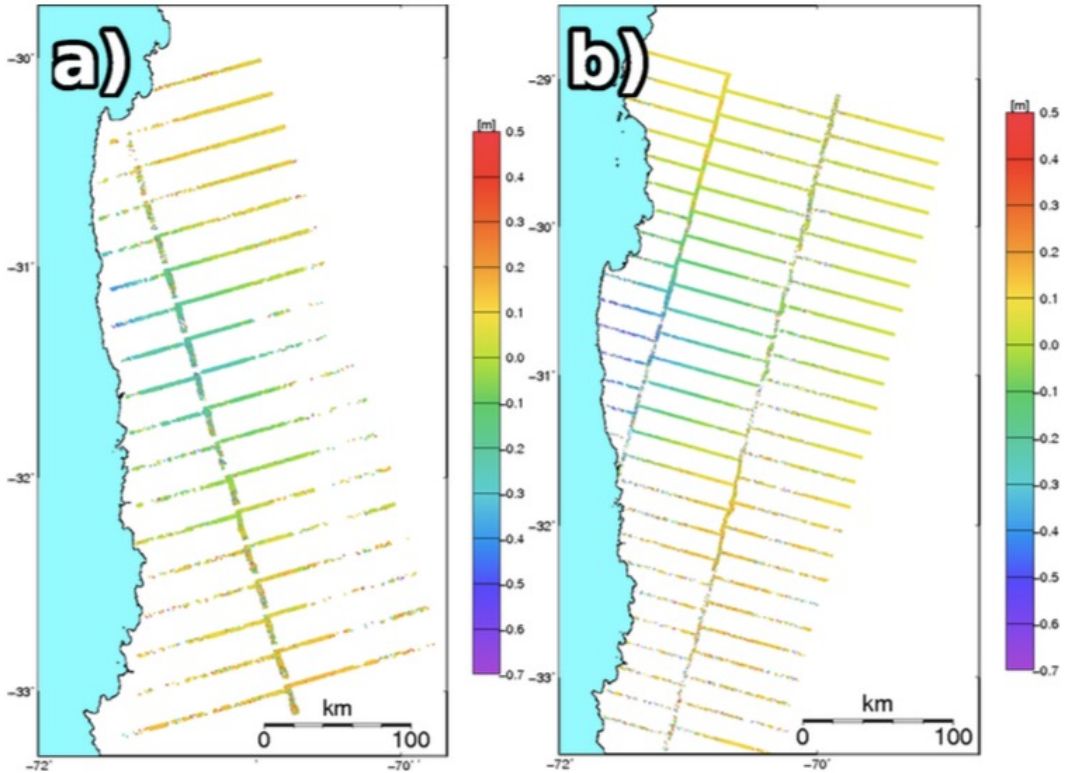
Strain rate for Anatolia from Sentinel-1
(Weiss et al, 2020)

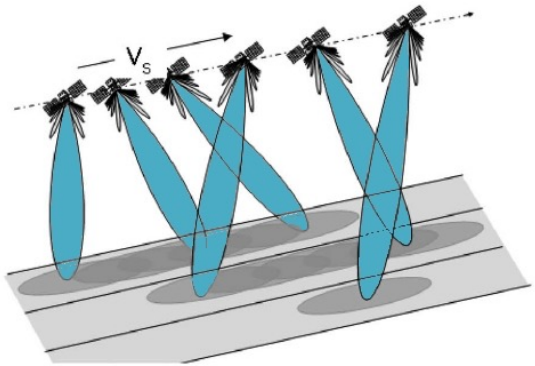
- InSAR does not constrain strain rate well for N-S shear zones



Velmap inversion with 10mm/yr slip rate and 10 km locking depth

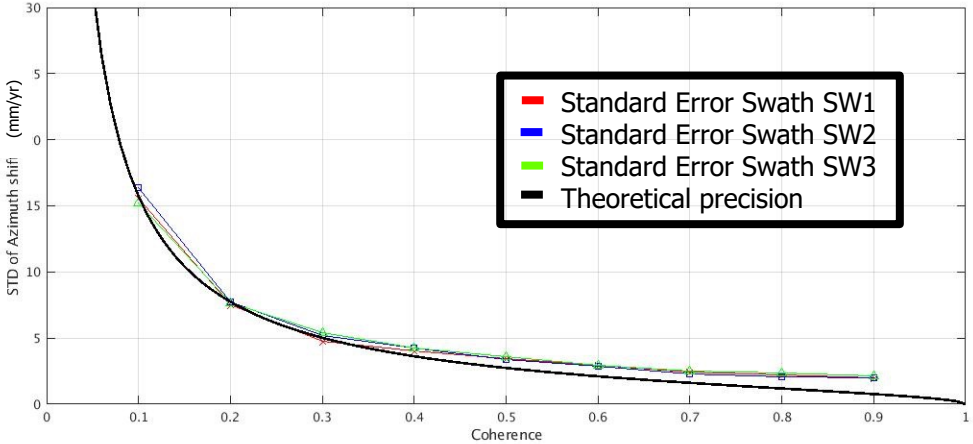
- Along track measurement is however possible with Sentinel-1 at burst overlaps

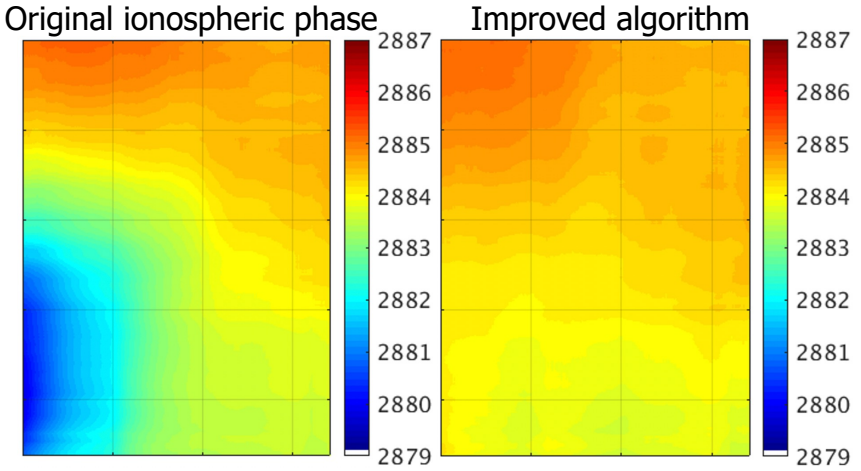




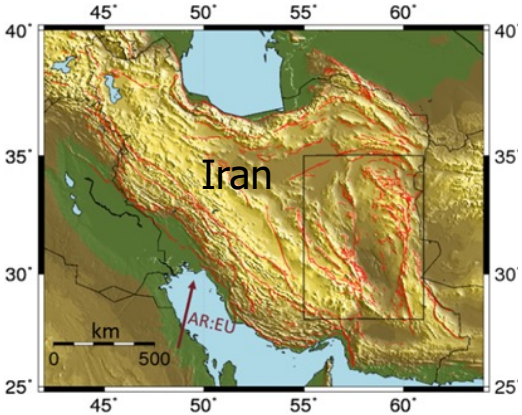
2015 Illapel Earthquake, Chile, up to ~60 cm motion (Spaans PhD thesis, 2016)

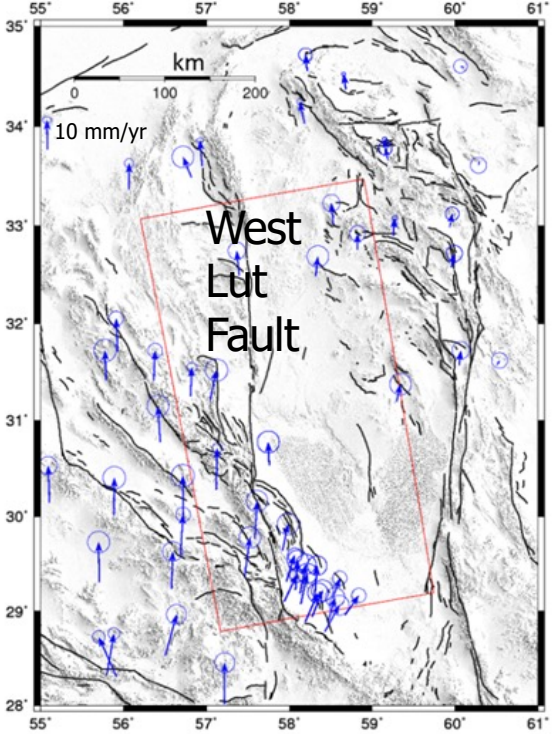
- We have developed a time series approach to estimate along-track velocities
- We incorporate a time series approach to ionospheric correction



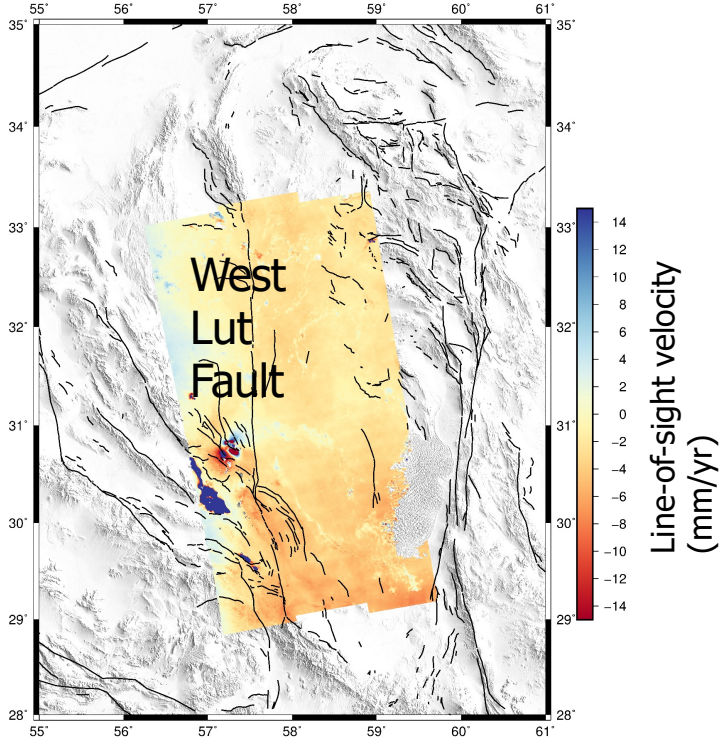


- Case study: West Lut Fault, located in eastern Iran
- InSAR results not sensitive to the velocity gradient across the fault



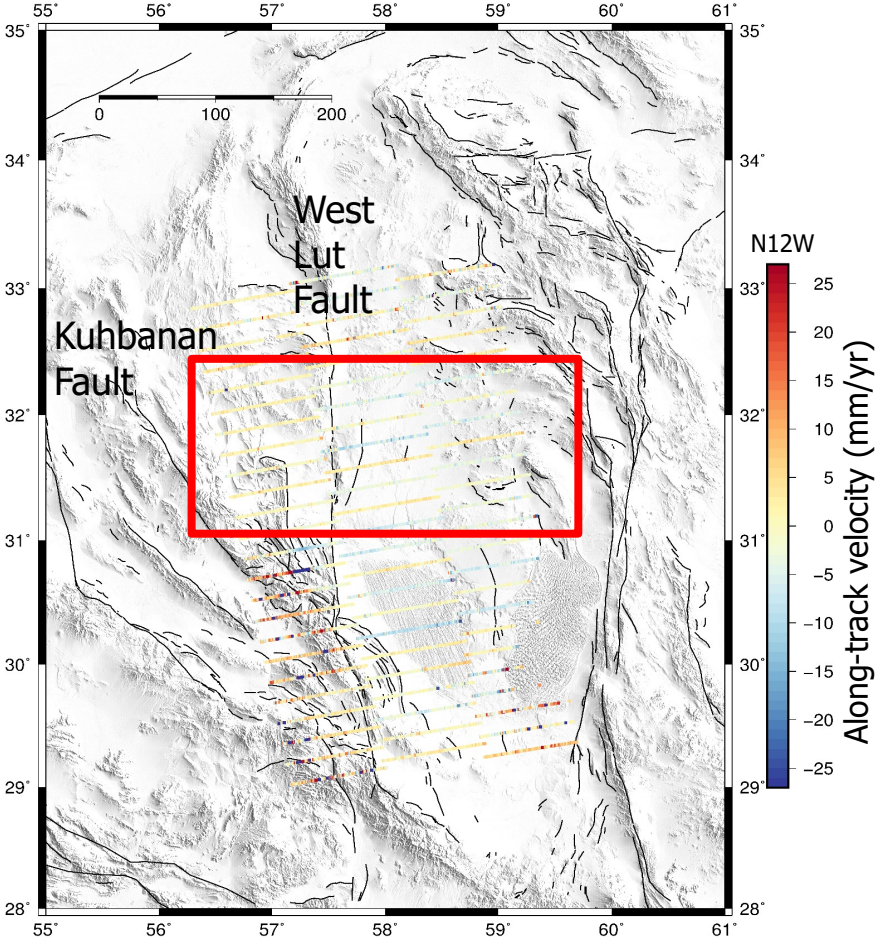


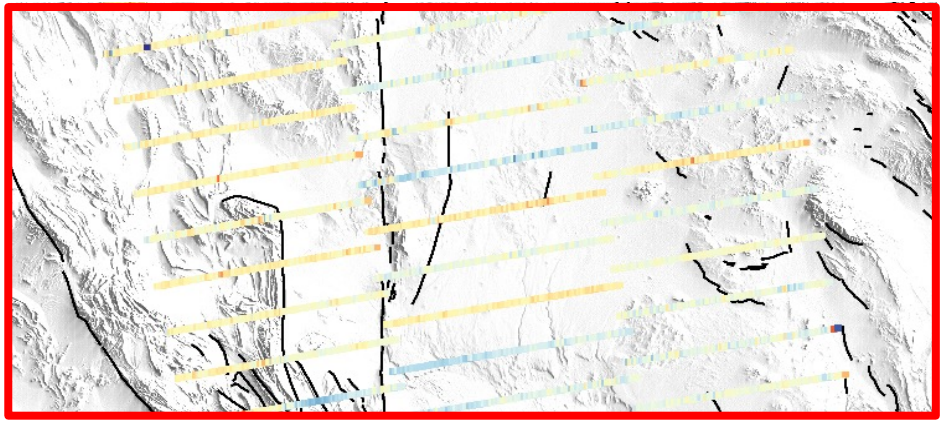
GNSS (Walpersdorf et al, 2014)



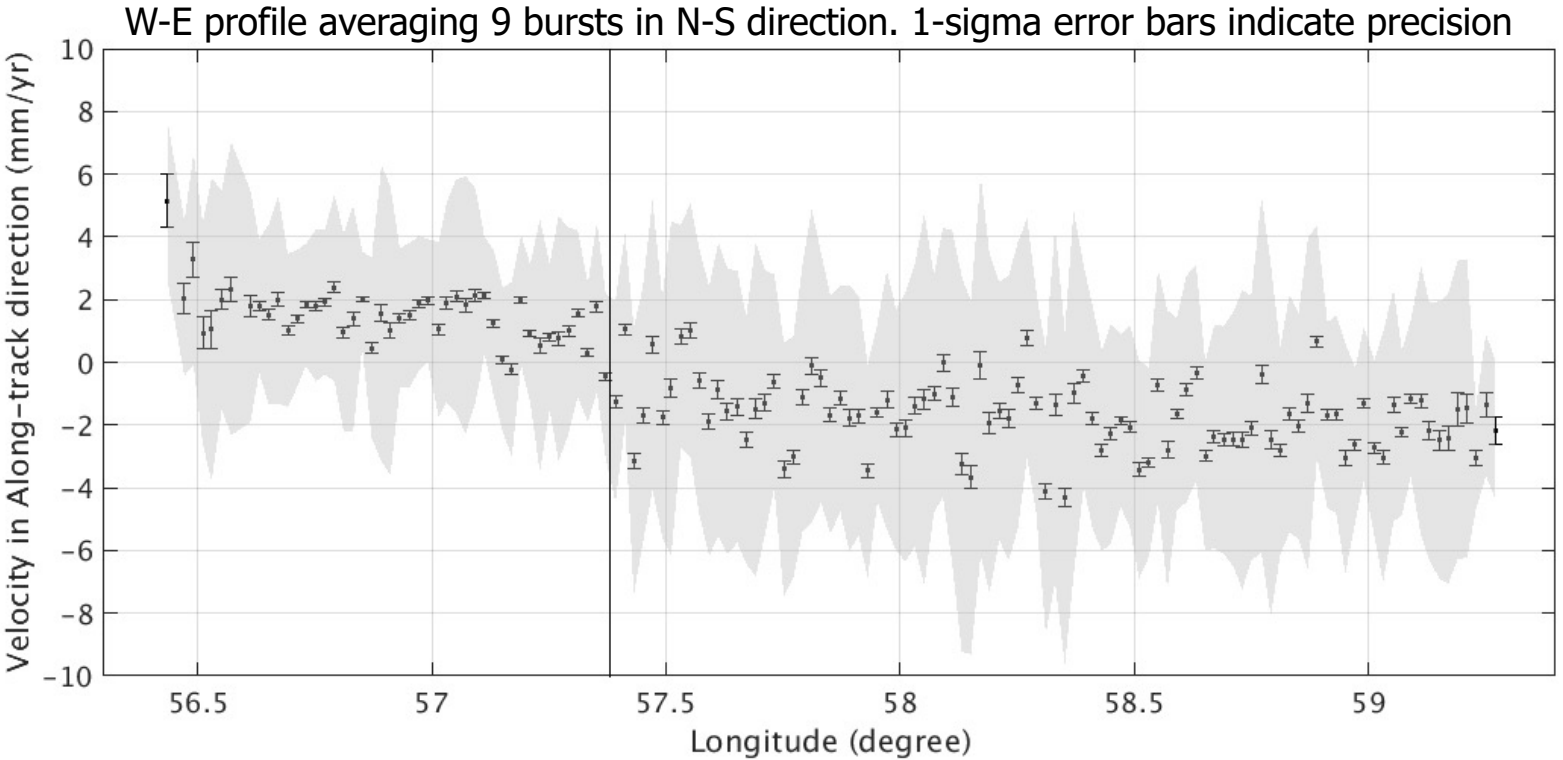
InSAR results

- Residual ionospheric signal adds significant spatially-correlated noise
- However, there is a significant trend of decreasing velocity across fault



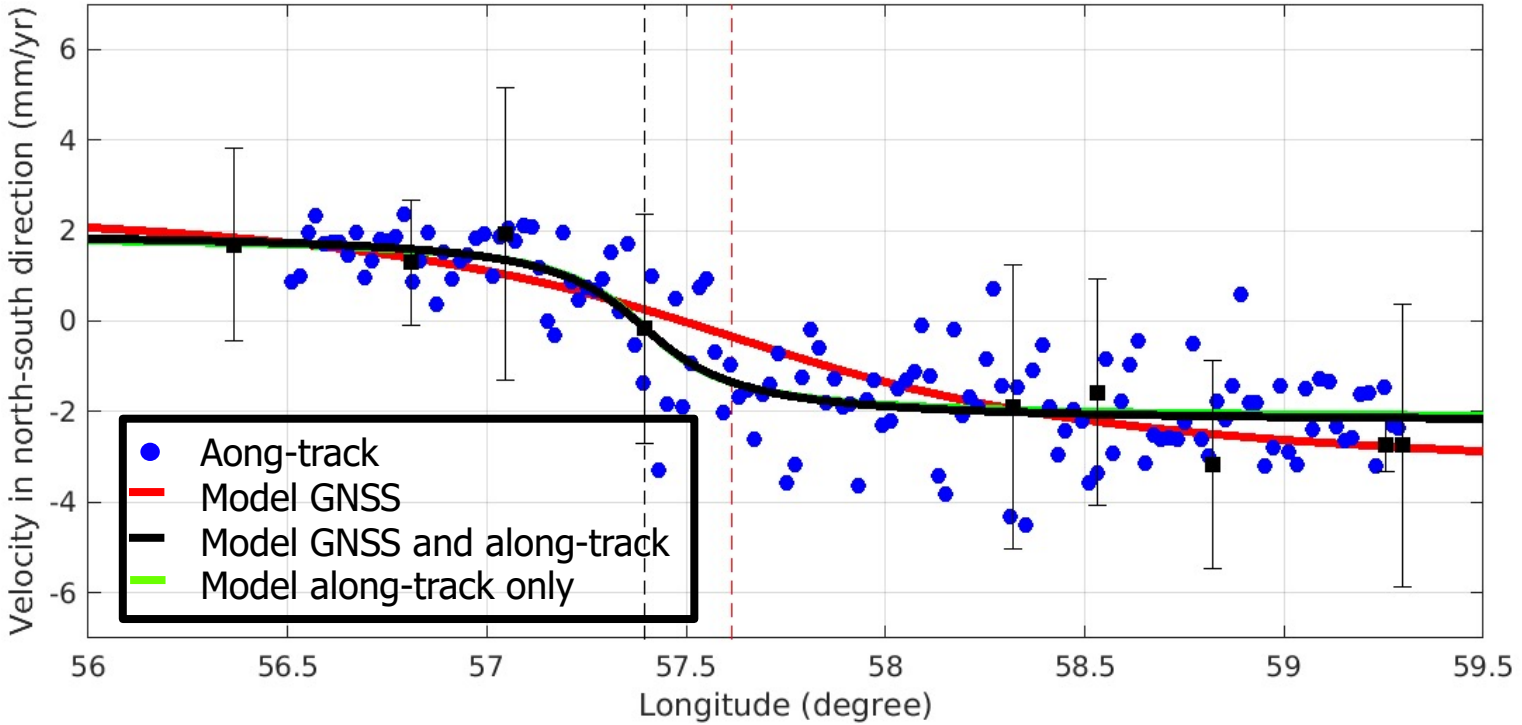


- Averaging over 9 bursts in N-S clearly shows change in velocity across fault

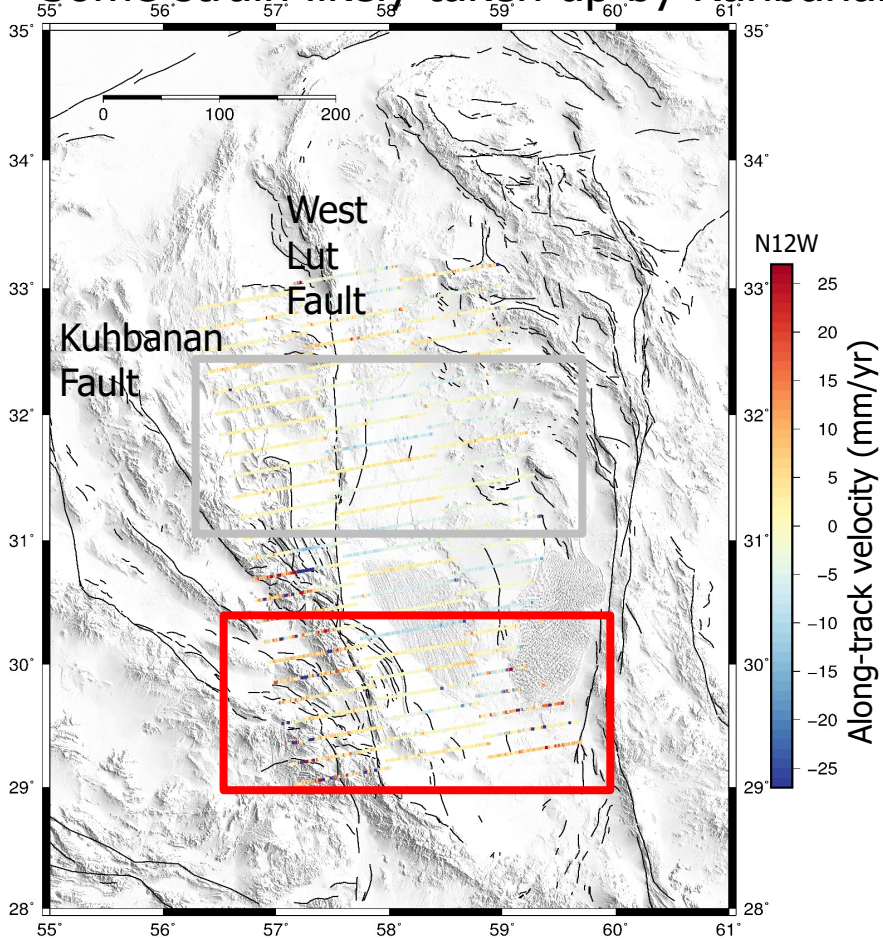


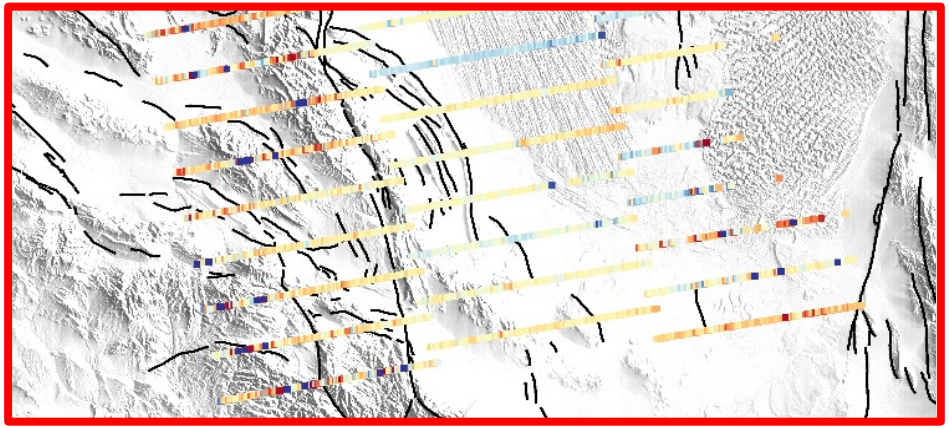
- Excellent agreement with GNSS
- Higher resolution of InSAR allows constraint of locking depth (GNSS not even needed)

Same W-E profile. Slip rate=4.3±0.5 mm/yr, locking depth =17.9 ± 9.7 km

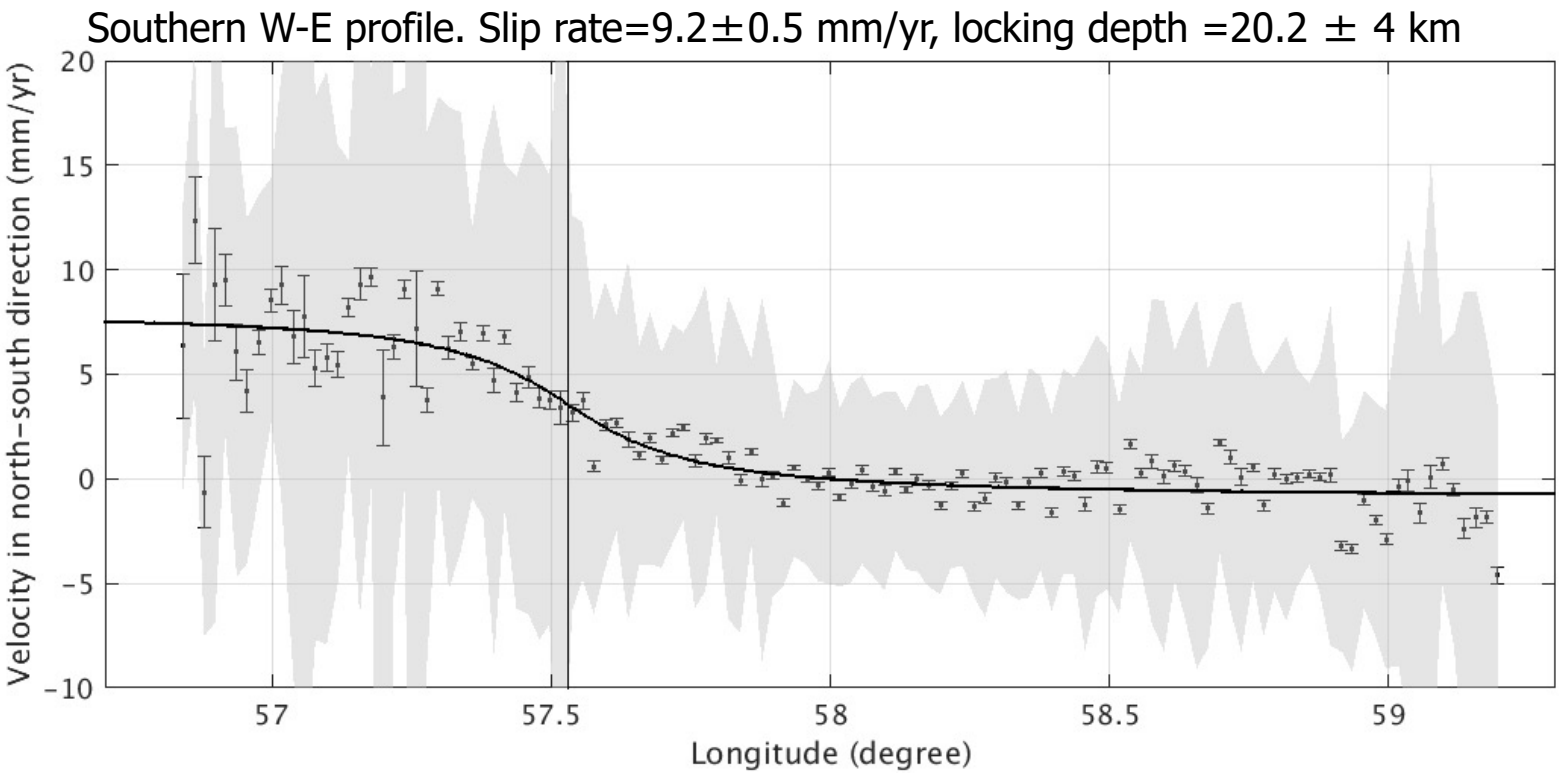


- Velocity difference across southern segment is higher
- Some strain likely taken up by Kuhbanan Fault in the North

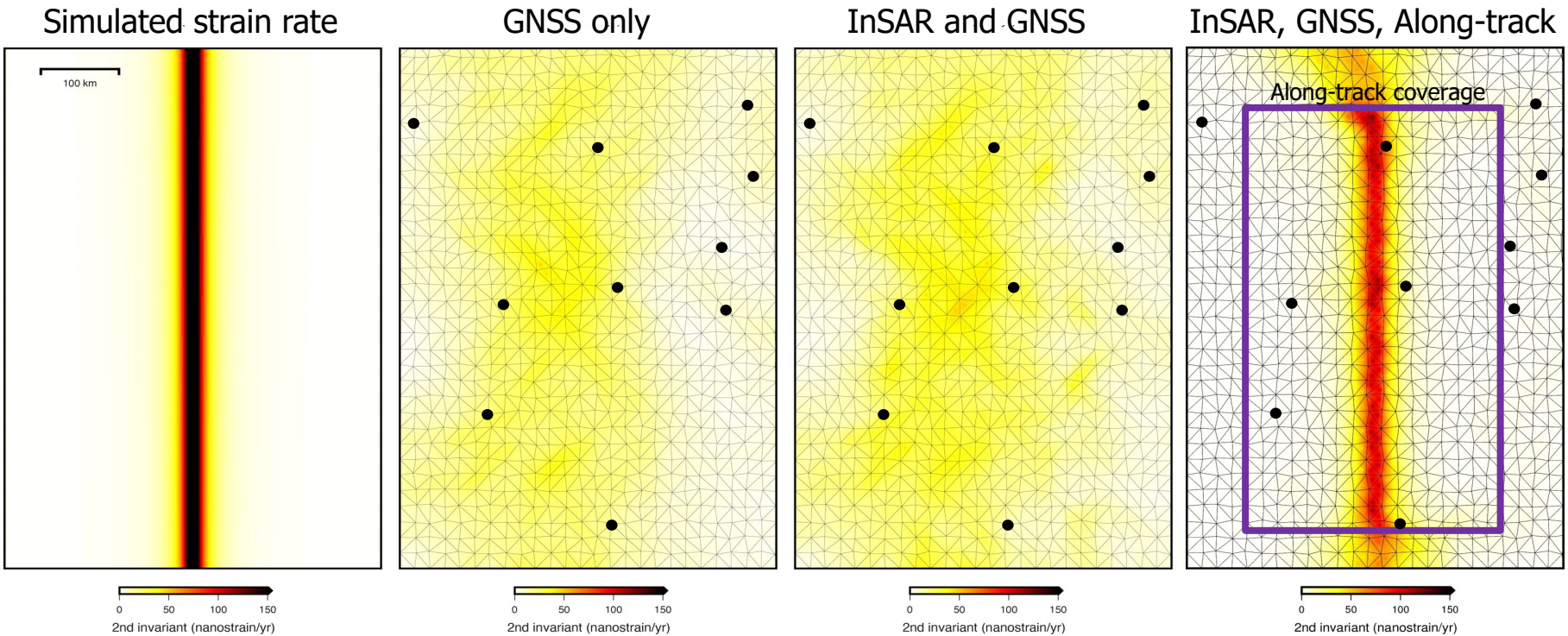




- Slip rate in south is approximately double that in the north

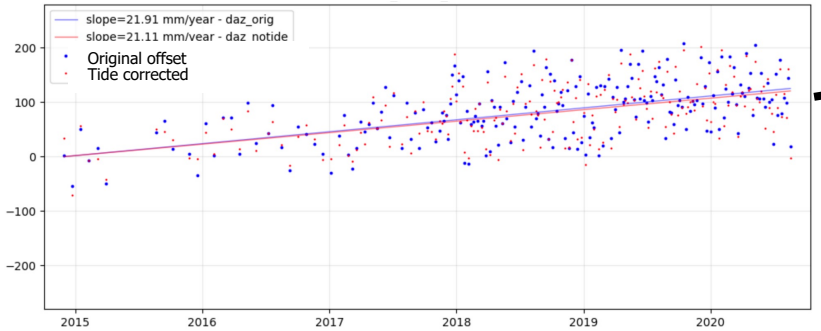


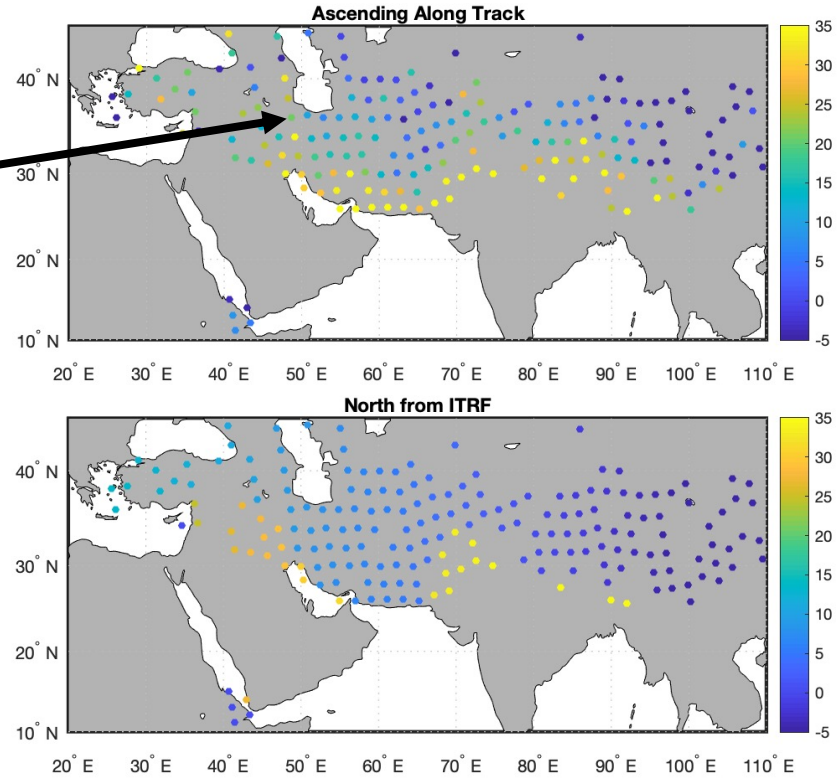
- Addition of along-track velocities resolves localization of strain rate for N-S shear zone



Magnitude of strain rate underestimated due to coarseness of mesh

- Along-track velocities are not relative, like InSAR, but in a global reference frame
- Compares well with ITRF no-net-rotation, away from plate boundaries





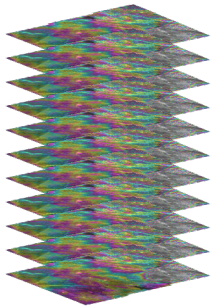
- Mean velocity calculate for whole frames
- Corrected for tides
- No ionospheric correction yet

REVISED WORKFLOW incorporating along-track velocities

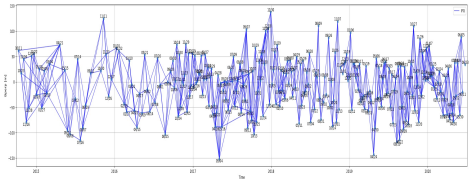
1. Make Interferograms



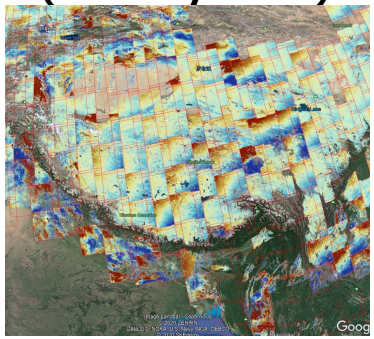
Sentinel-1 SLC data



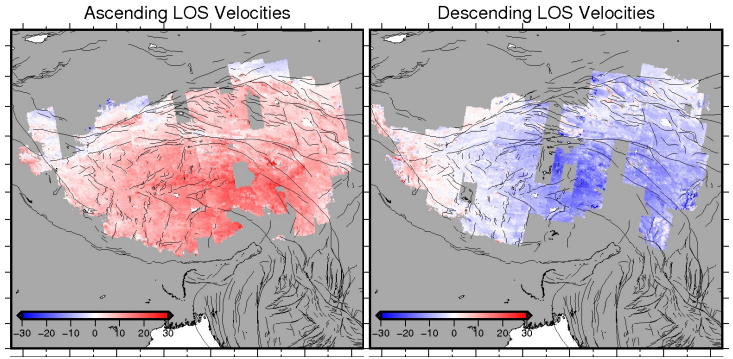
Interferogram Network



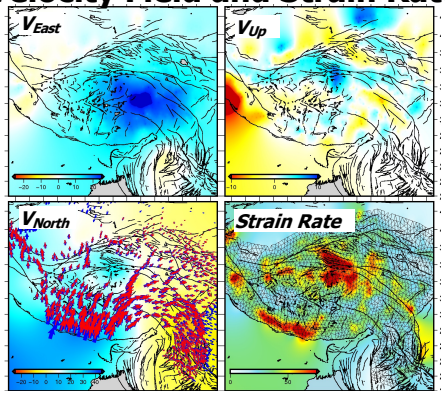
2. Invert for LOS and along-track Velocities (Frame by Frame)



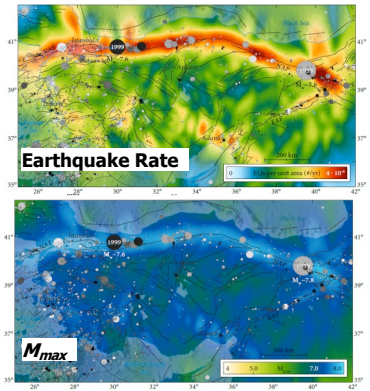
3. Reference InSAR Velocities to GNSS



4. Invert InSAR, GNSS data and along-track velocities for 3D Velocity Field and Strain Rates



5. Combine Strain and Seismicity to Estimate Seismic Hazard



In conclusion,

- Automatic processing of Sentinel-1 enables us to produce large scale velocity fields and strain-rate maps
- Along-track measurements from Sentinel-1 burst overlaps vastly improve our resolution of long-term strain rates for N-S shear zones

