



Landslide Observations with SAR

Eric Fielding¹, Alexander Handwerger¹, Brent Delbridge², Roland Bürgmann², Pietro Milillo¹, Scott Hensley¹, William Schulz³

¹ Jet Propulsion Laboratory, California Institute of Technology,
Pasadena, California

² Department of Earth and Planetary Science, UC Berkeley, California

³ U.S. Geological Survey, Denver, Colorado, USA

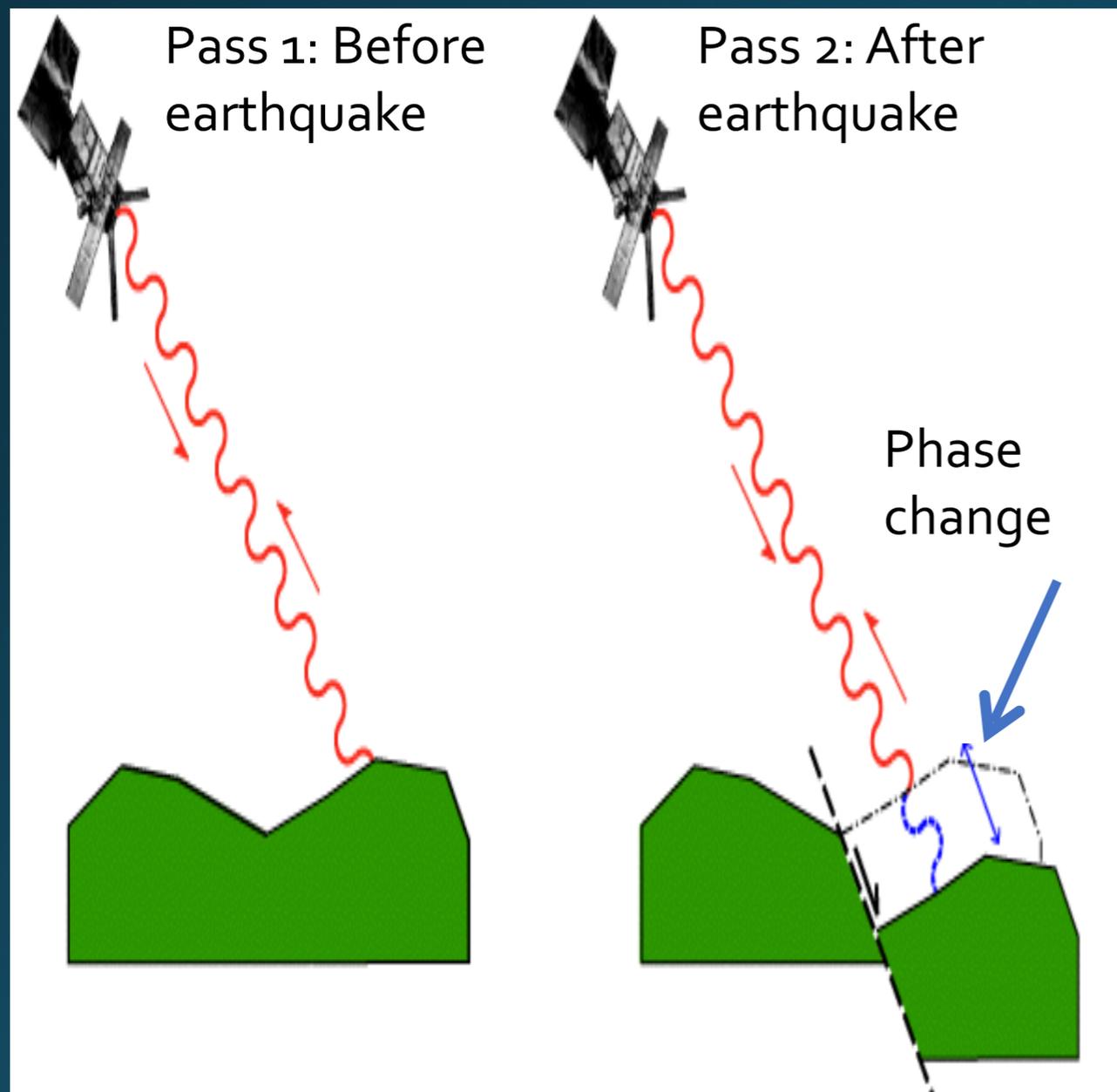
Acknowledgments

- JPL: N. Pinto, Y. Zheng, P. Agram, E. Gurrola, UAVSAR processing team
- NASA AFRC & JSC: J. McGrath, pilots and staff
- USGS: J. Coe
- U of Maryland: Mong-Han Huang
- NASA Earth Surface and Interior, Geodetic Imaging, NISAR Science Team programs

Methods

Interferometric Synthetic Aperture Radar (InSAR)

- Remotely measures surface deformation during a time period
- Deformation measured along the line-of-sight
- Interferogram represents the phase change between acquisitions



Advantages:

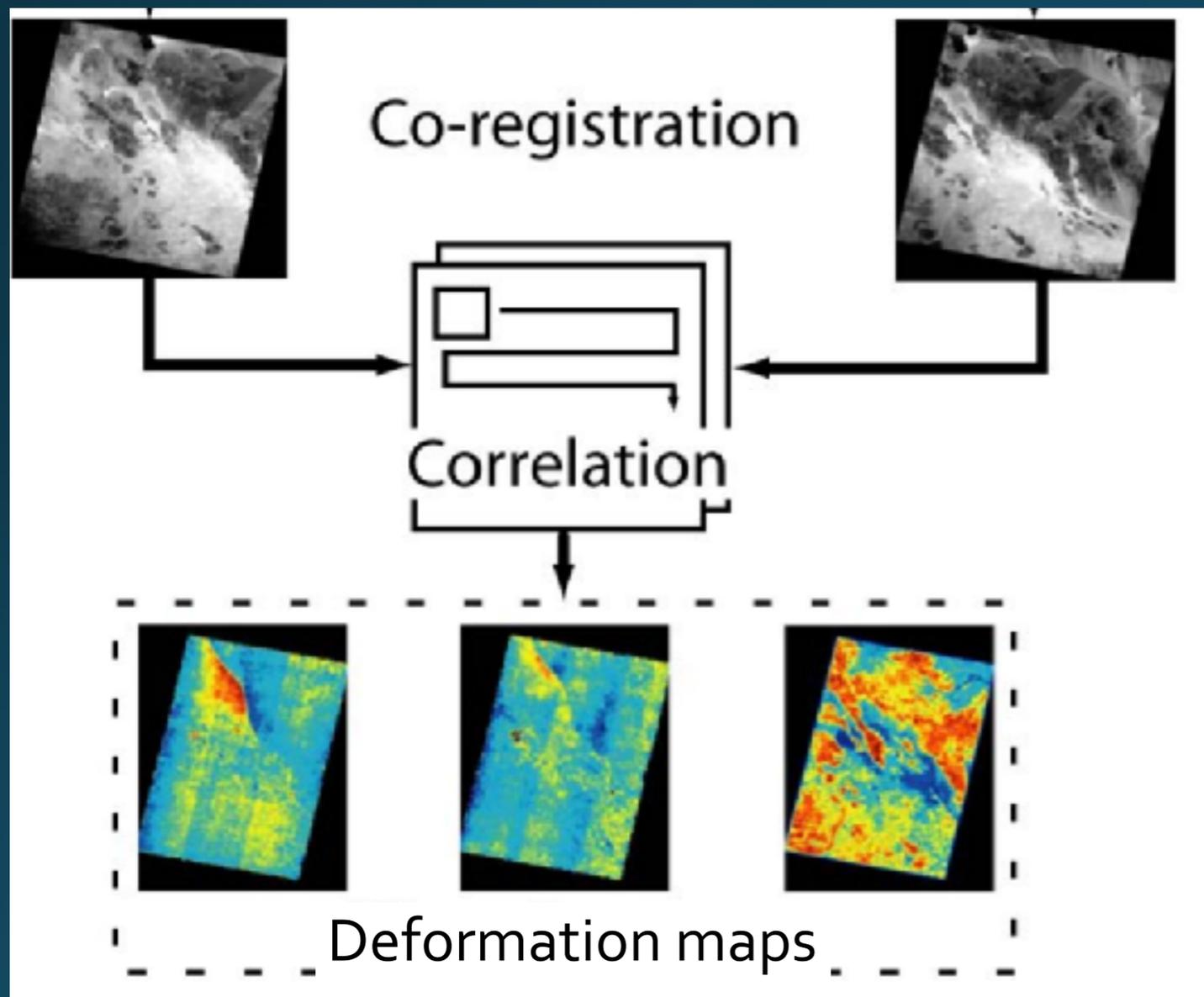
- Day and night data collection with regular time interval
- mm-scale line-of-sight sensitivity
- measures a continuous deformation field

Limitations:

- Deformation rate limit
- Atmospheric signals
- Vegetation
- Observational bias

Pixel Offset Tracking with SAR

- Remotely measures surface deformation during a time period
- 2D deformation measured along the line-of-sight and flight direction
- Cross correlates SAR amplitude images with subpixel precision to measure changes



Advantages:

- Provides 2D measurements
- No deformation rate limit
- measures a continuous deformation field

Limitations:

- **cm- to m-scale sensitivity**
- Vegetation
- Observational bias

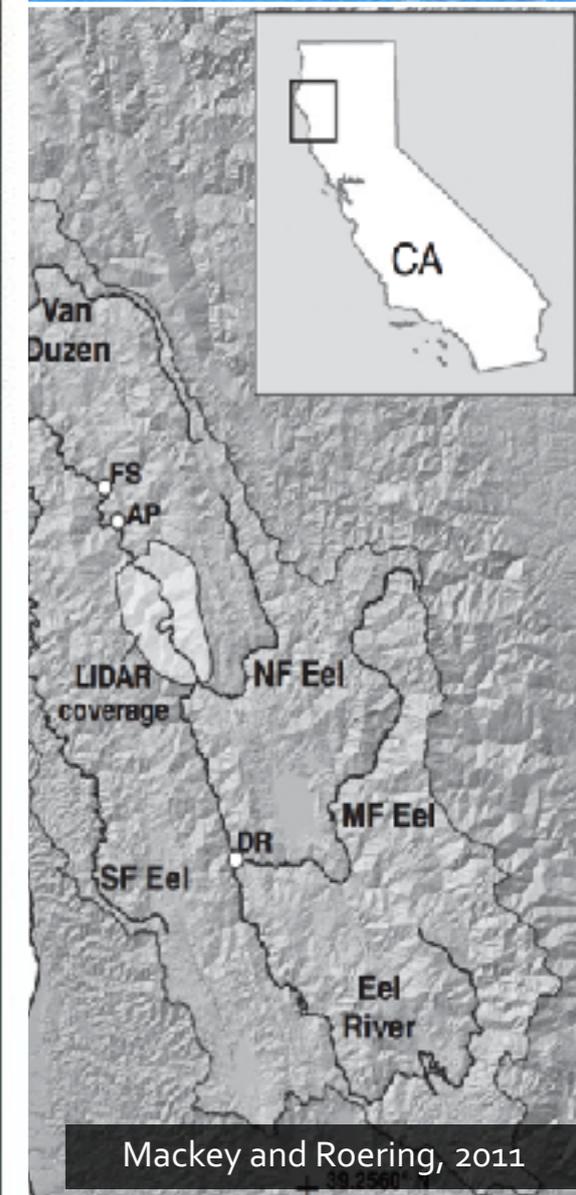
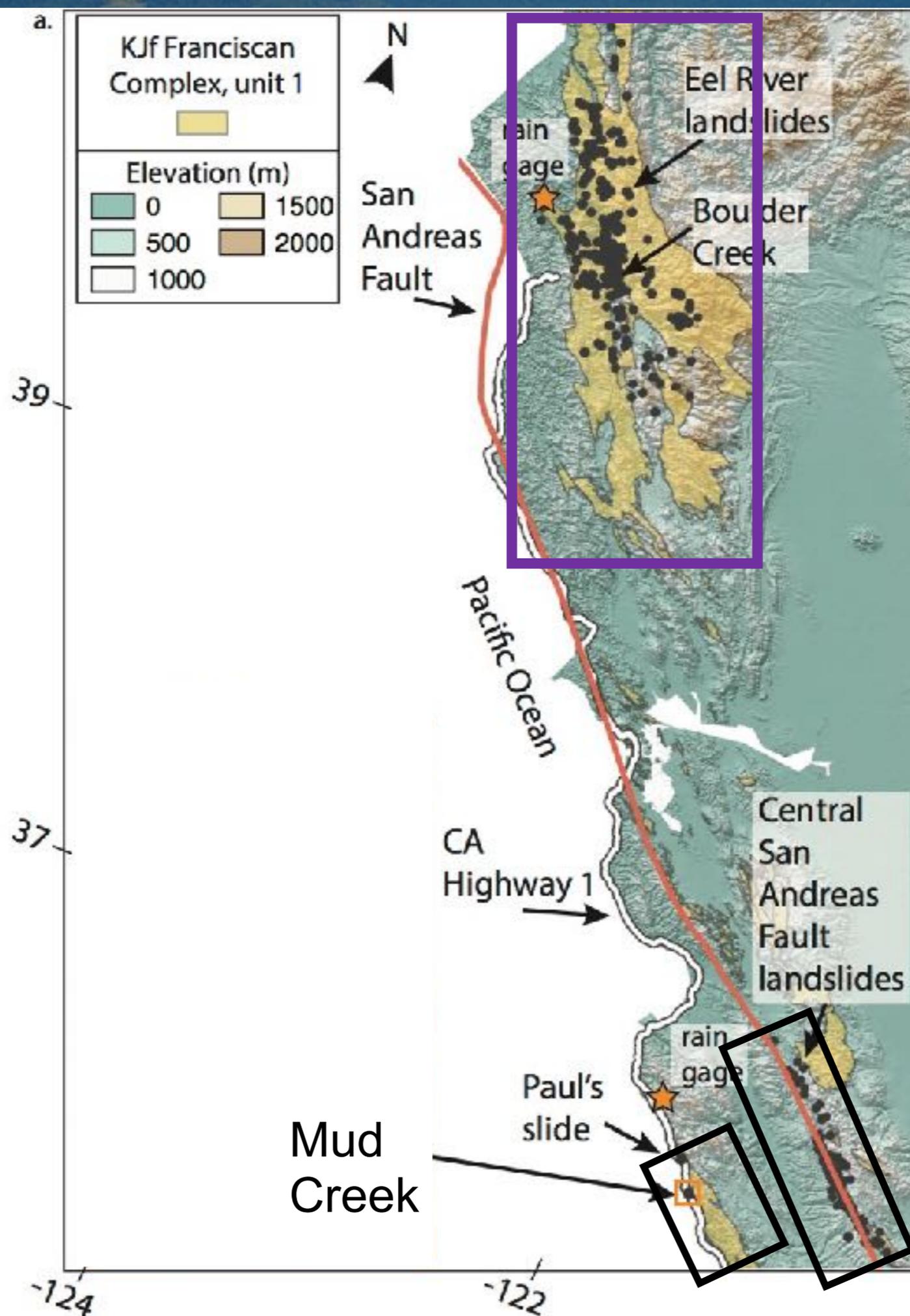
N



Tectonics

- Mendocino Triple Junction
- Uplift rates ~ 1 mm/yr

(Lock et al., 2006)

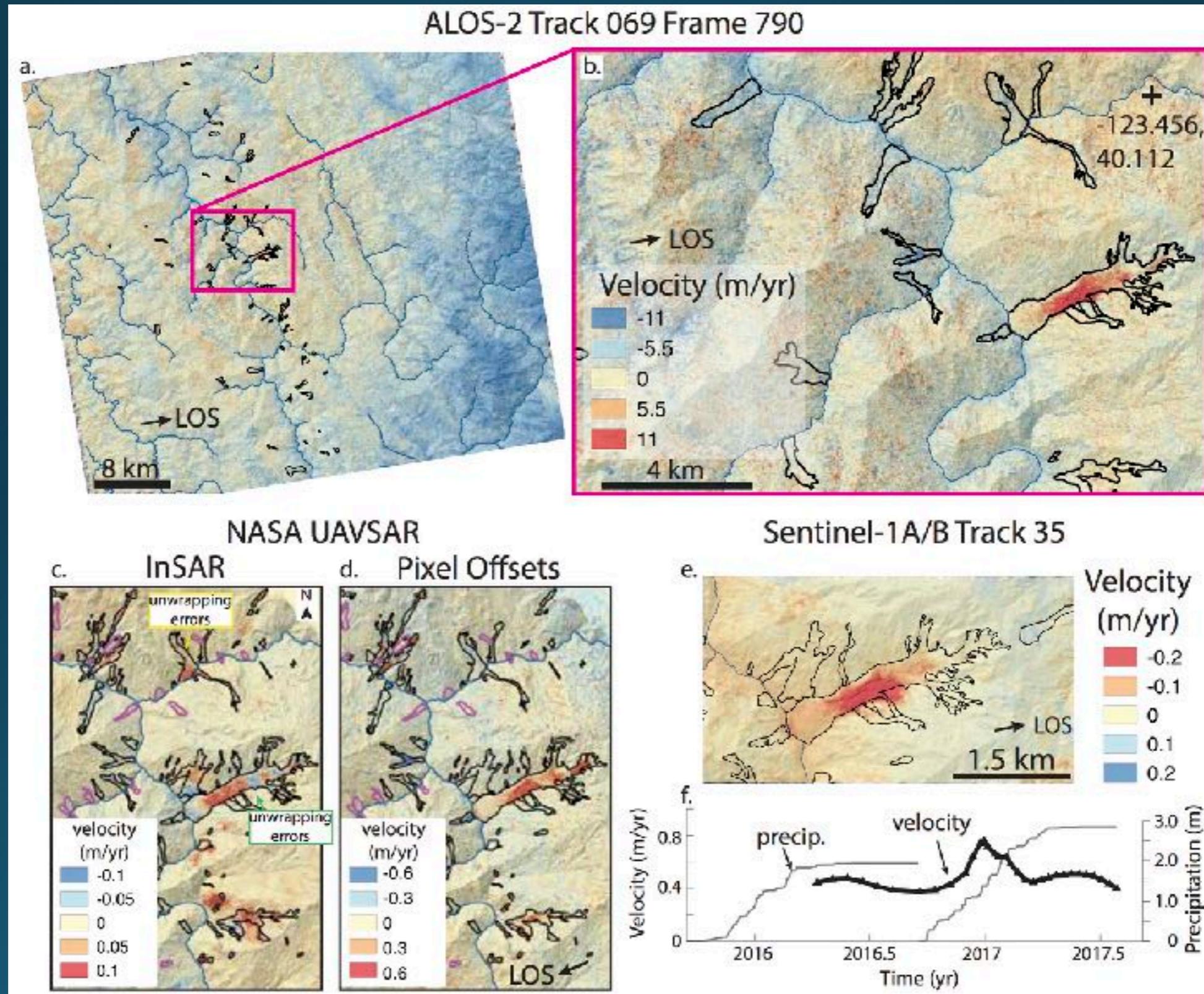


River Catchment

- Erosion rates ~ 0.9 mm/yr
- 1.5 m/year between Oct & May

(Croft and Summerfield, 2005)

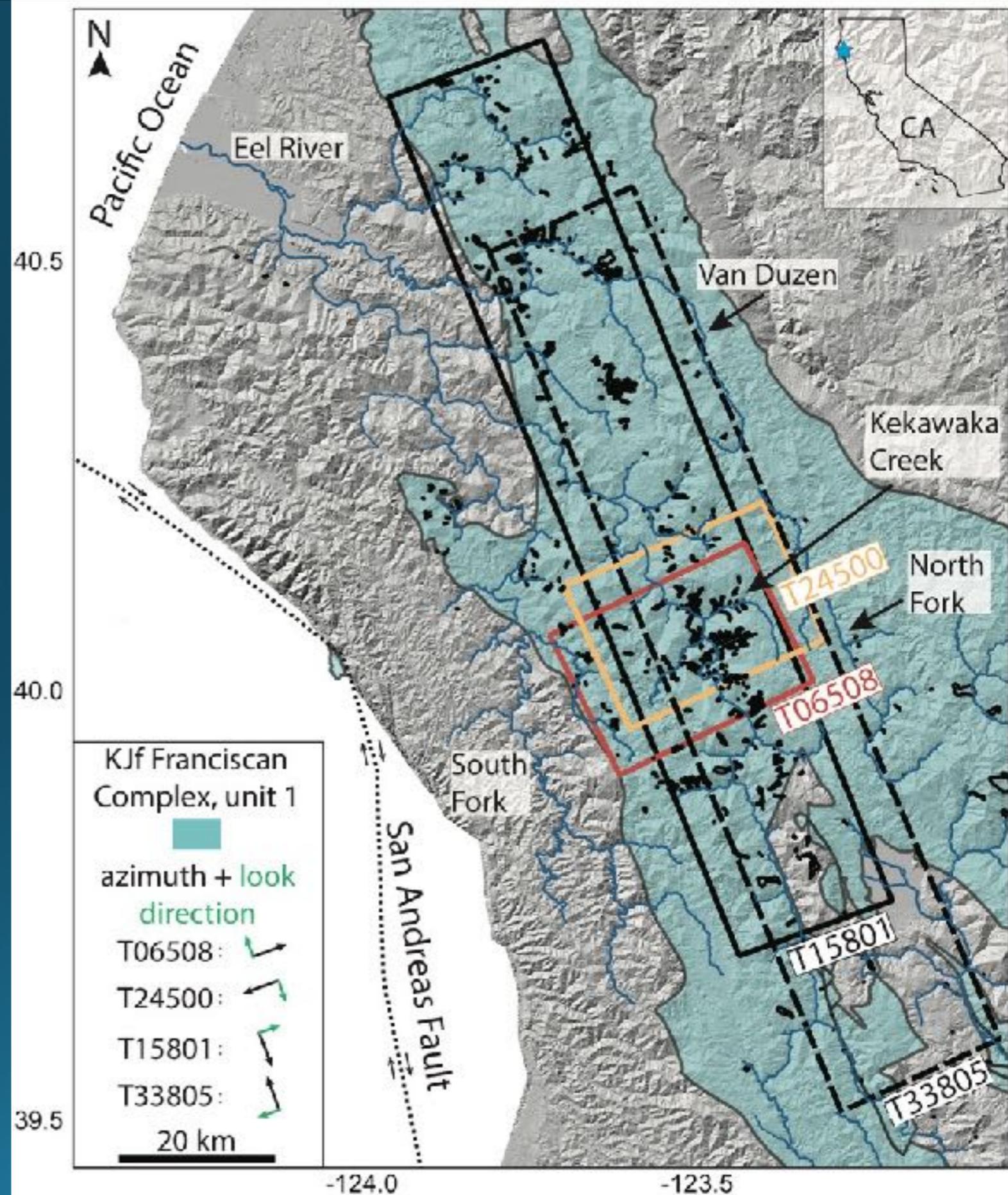
Eel River SAR analysis



InSAR and Pixel Offset Tracking

UAVSAR data

- 4 different flight paths
- 8 scenes collected between April 2016 and February 2018
- 112 InSAR pairs
- 112 Pixel offset pairs



The Slumgullion Natural Laboratory

- The active Slumgullion Landslide:
- Velocity: 1-2 cm/day
- Average Slope: 8 degrees
- Length: 3.9 km
- Width: ~300 m
- Depth: ~14 m
- Volume: 20×10^6 m

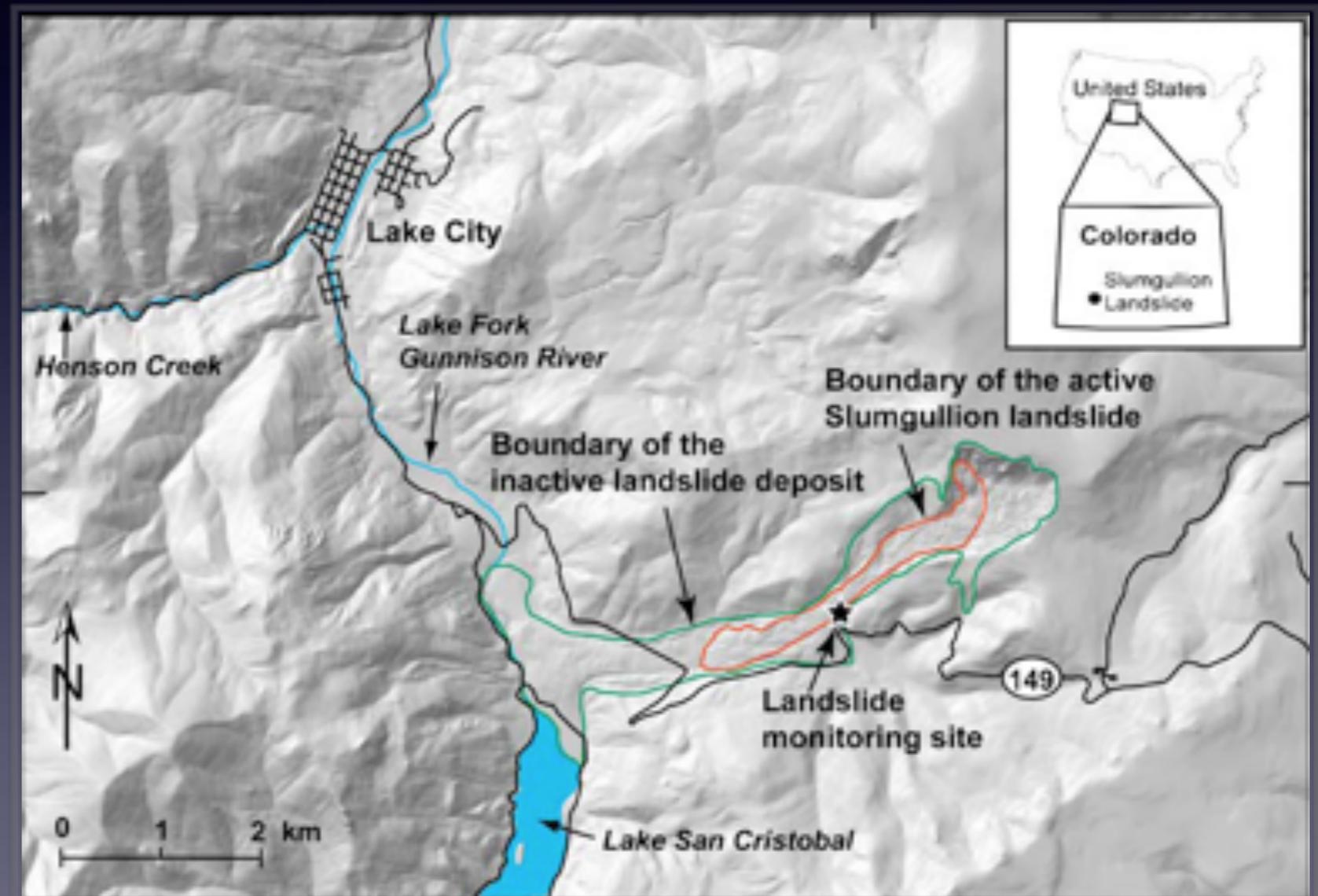
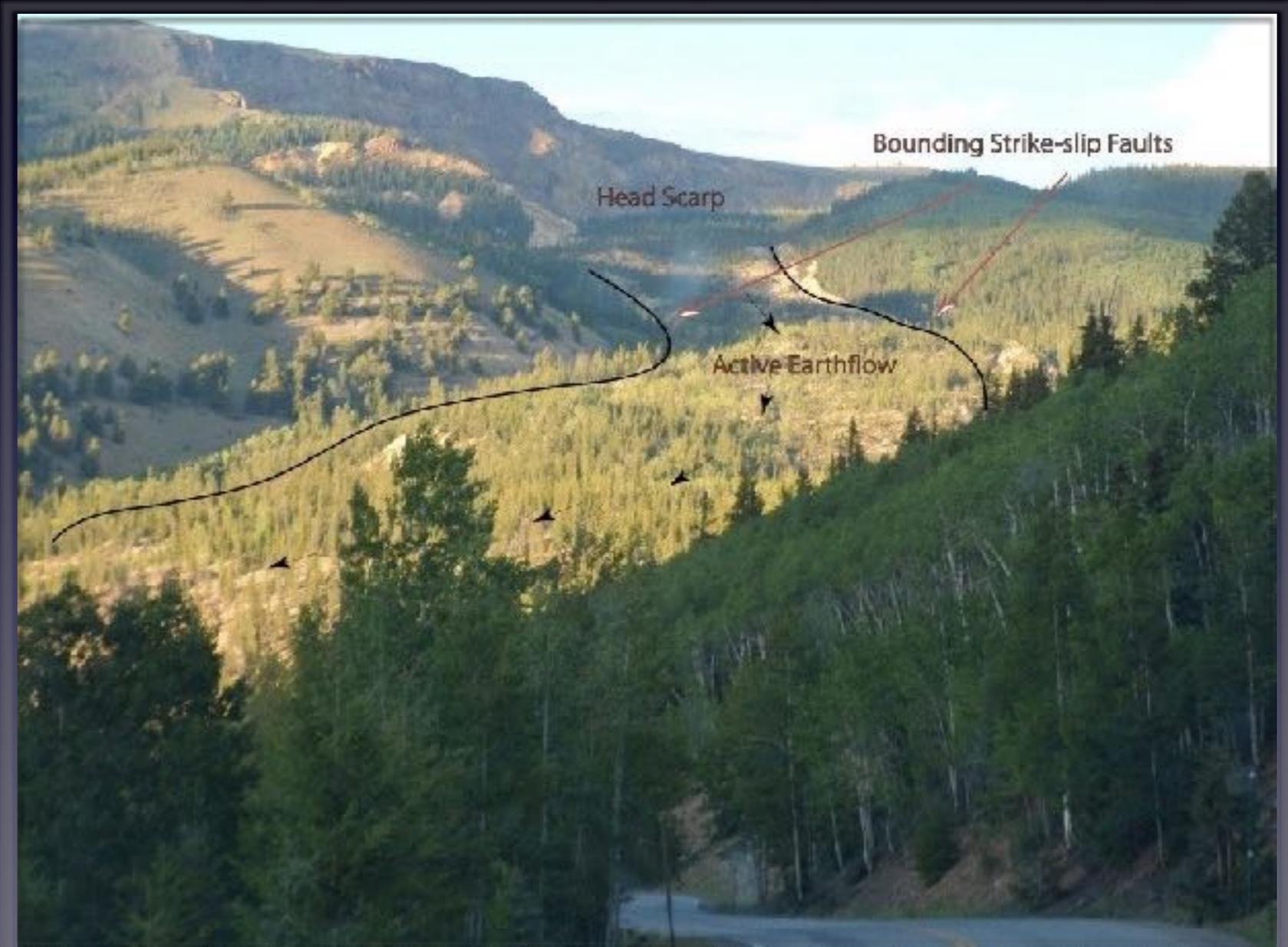


Figure From Schulz et al 2009

The Slumgullion Natural Laboratory

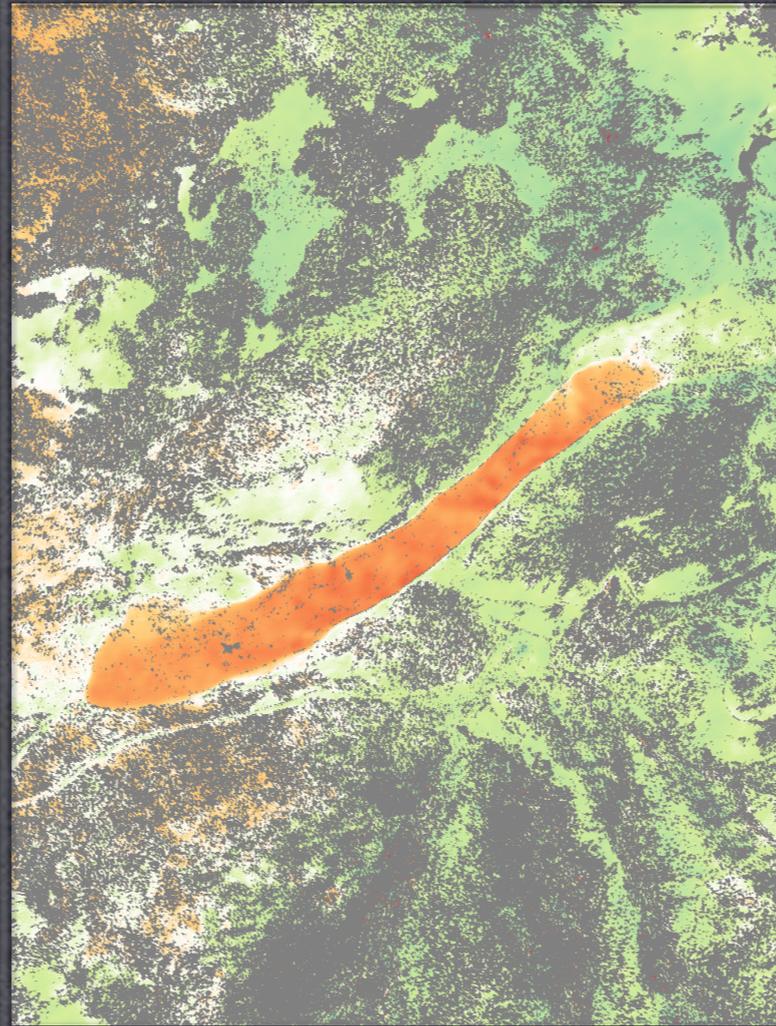
- Rapid deformation rate allows us to observe the deformation on the timescale of days
- Large spatial extent of the slide allows to explore complex interactions between distinct kinematic units
- Slide's continuous motion allows us to observe its response to environmental forcing



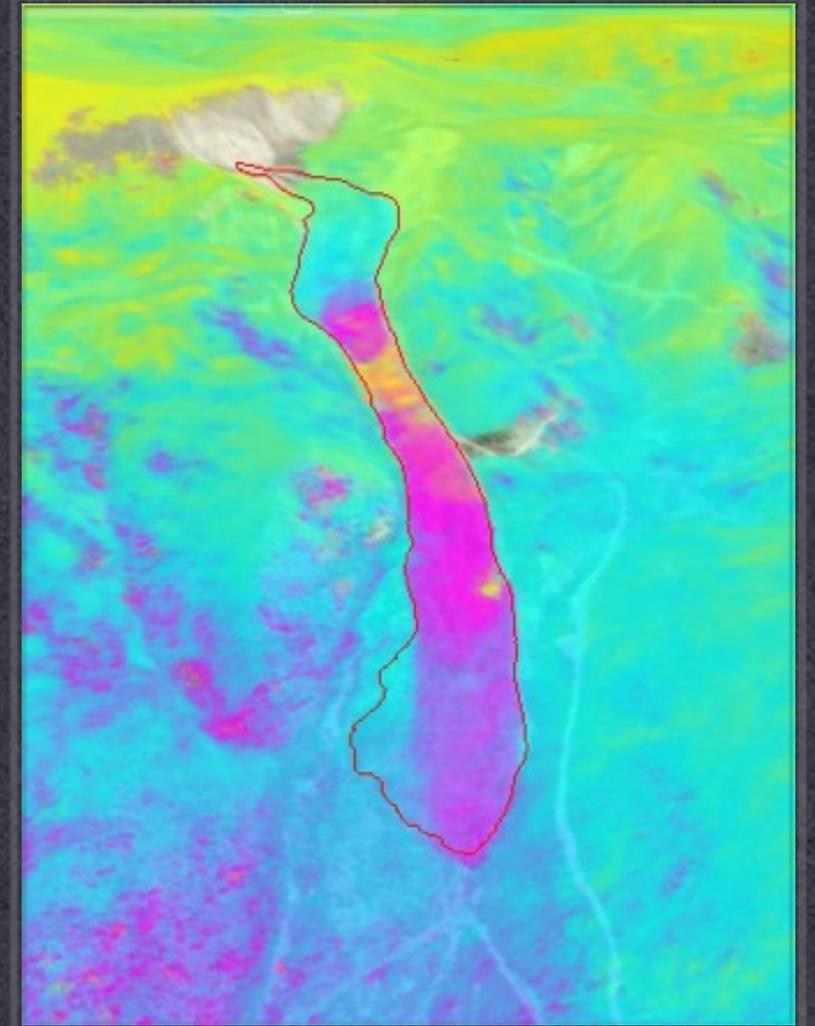
GPS



COSMO-SKYMED

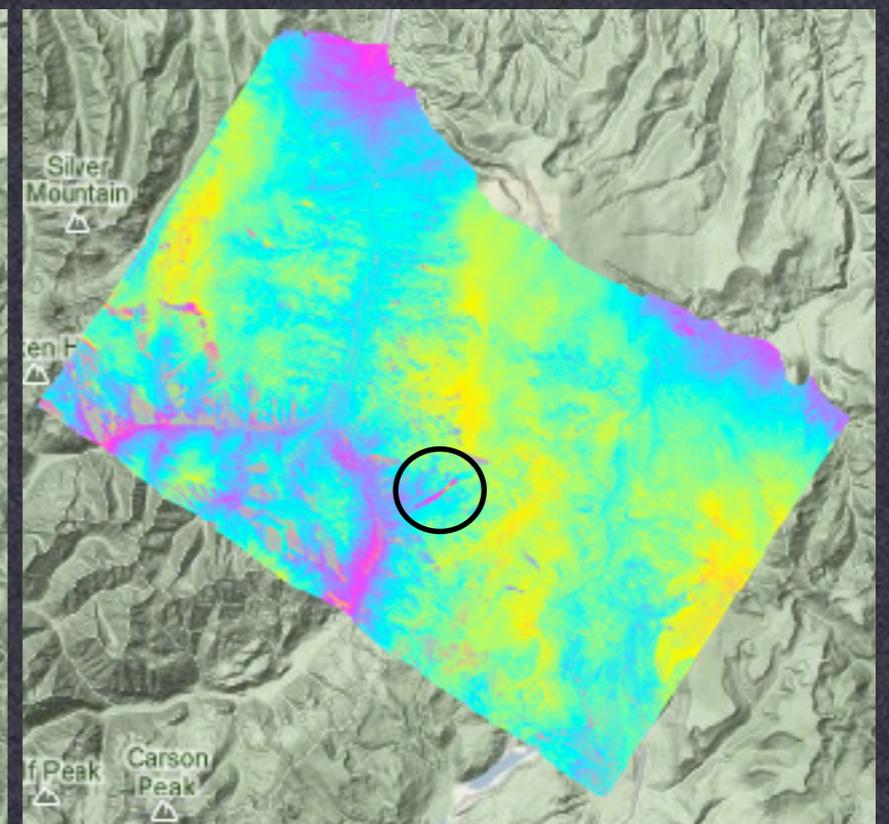
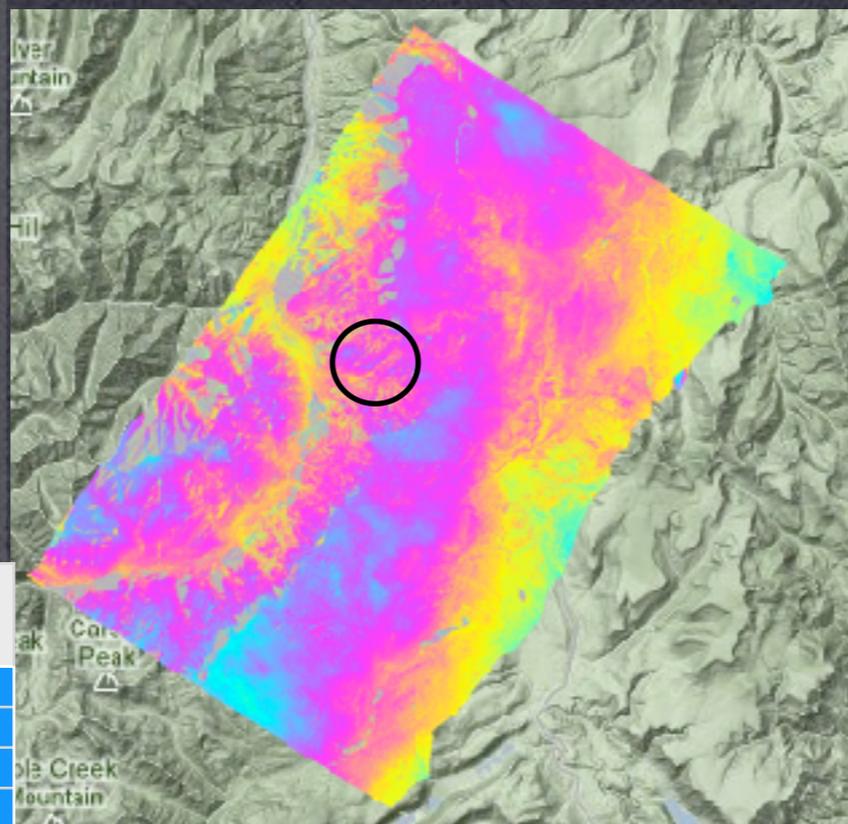
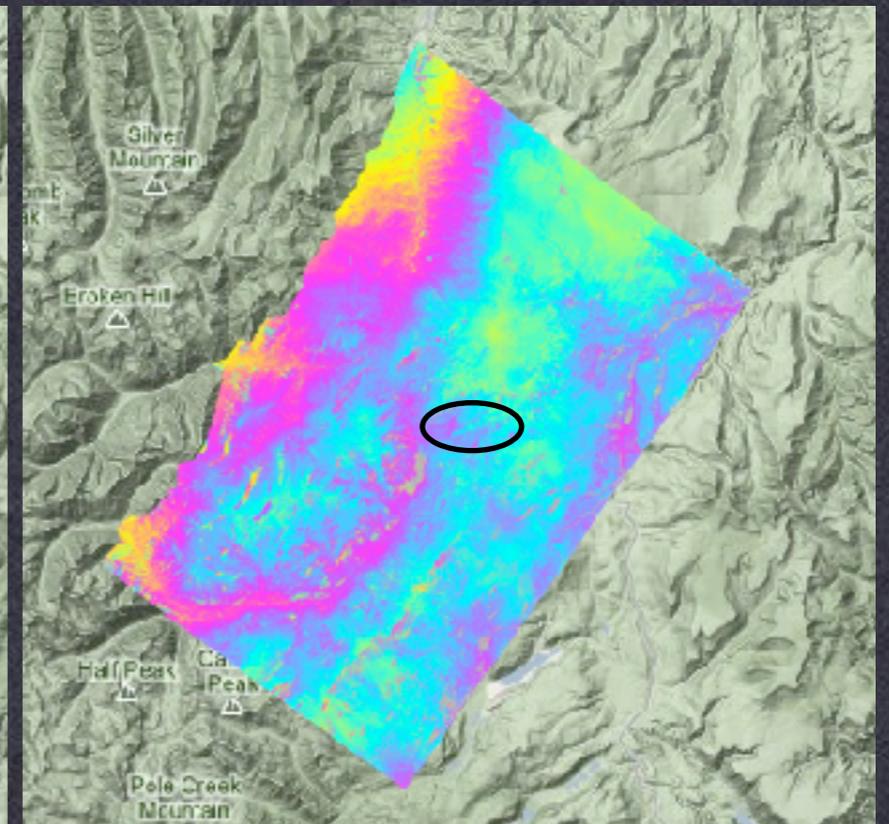
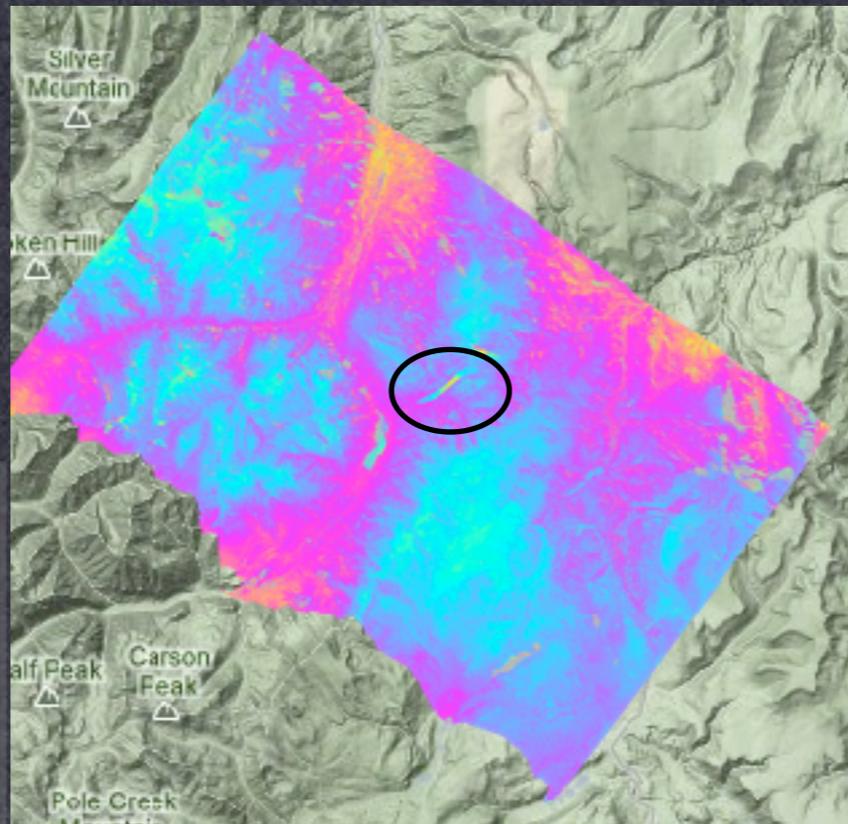
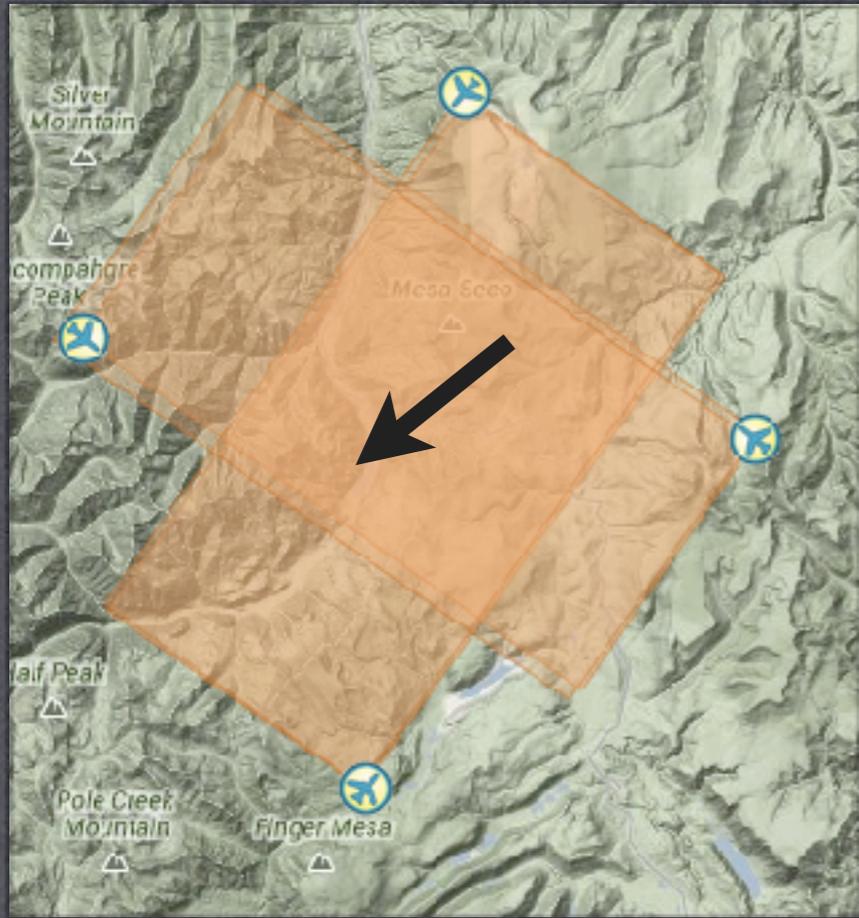


UAVSAR



This project focuses on improving the understanding of the physical mechanisms controlling landslide motion by studying the landslide-wide kinematics of the Slumgullion landslide in southwestern Colorado using interferometric synthetic aperture radar (InSAR) and GPS.

RELEASED REPEAT PASS INTERFEROGRAM (RPI) PRODUCTS

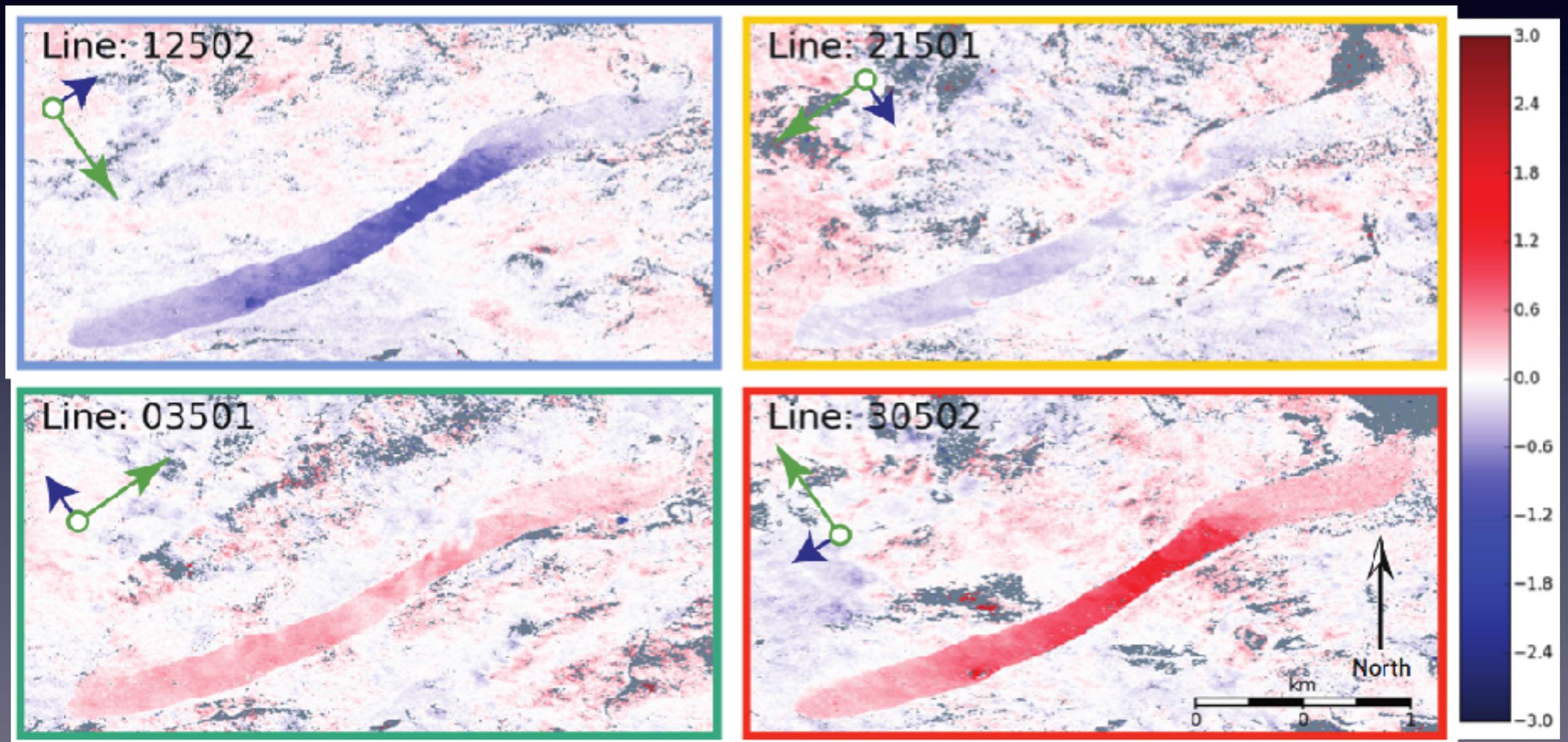


Flight Line ID:	Peg Heading:	Flight Direction:	Look Direction:	Deformation Sensitivity:
3501	35.0	Toe to Head	NW Across	Perpendicular
12502	124.9	SE Across	From Toe Upslope	Slope Parallel
21501	-145.0	Head to Toe	SE Across	Perpendicular
30502	-54.9	NW Across	From Head Downslope	Slope Parallel

LINE-OF-SIGHT(LOS)

4 UNWRAPPED INTERFEROGRAMS IN LOS FROM APRIL 16TH TO 23RD, 2012

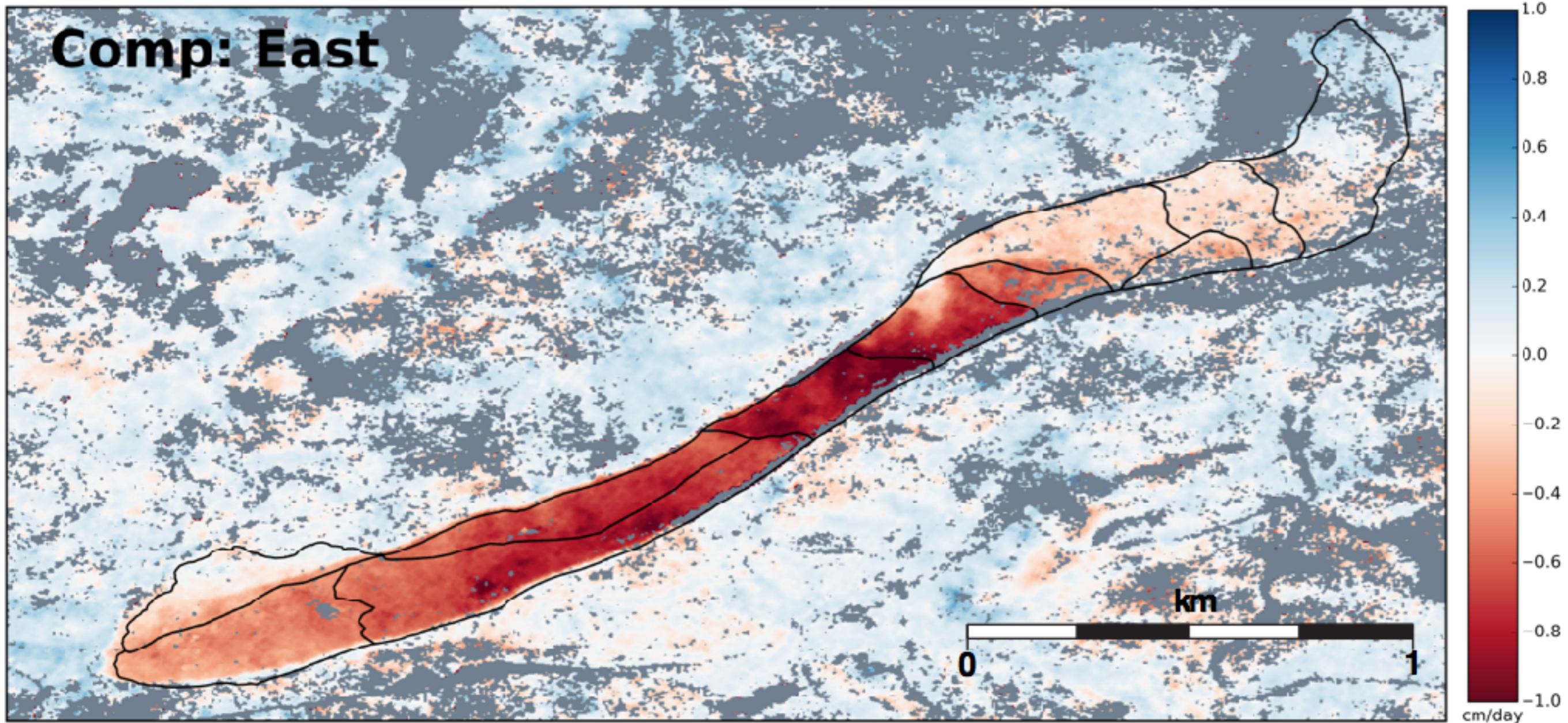
UAVSAR 7-Day Interferograms



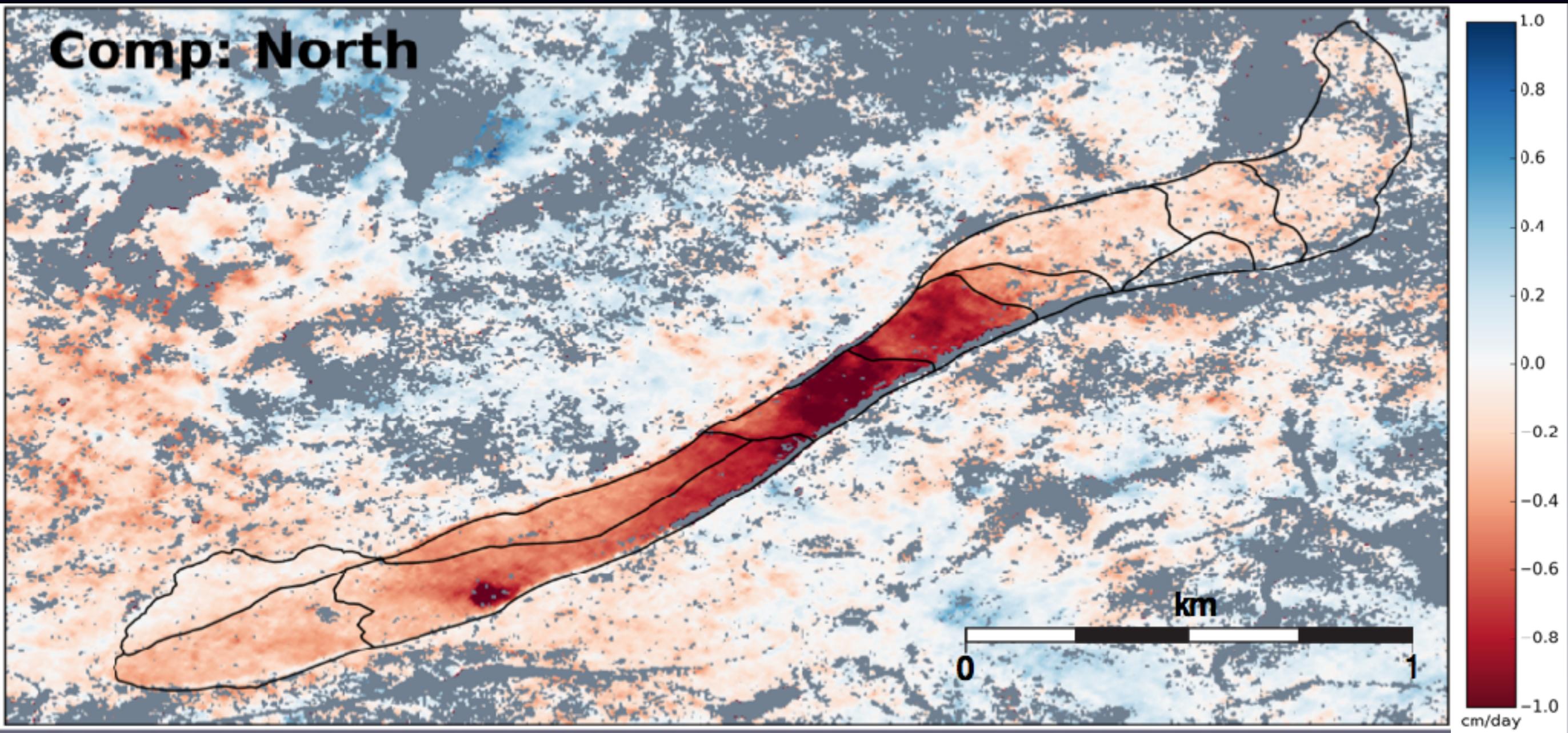
B. Delbridge corrected unwrapping

Results of the Three Dimensional Vector Inversion

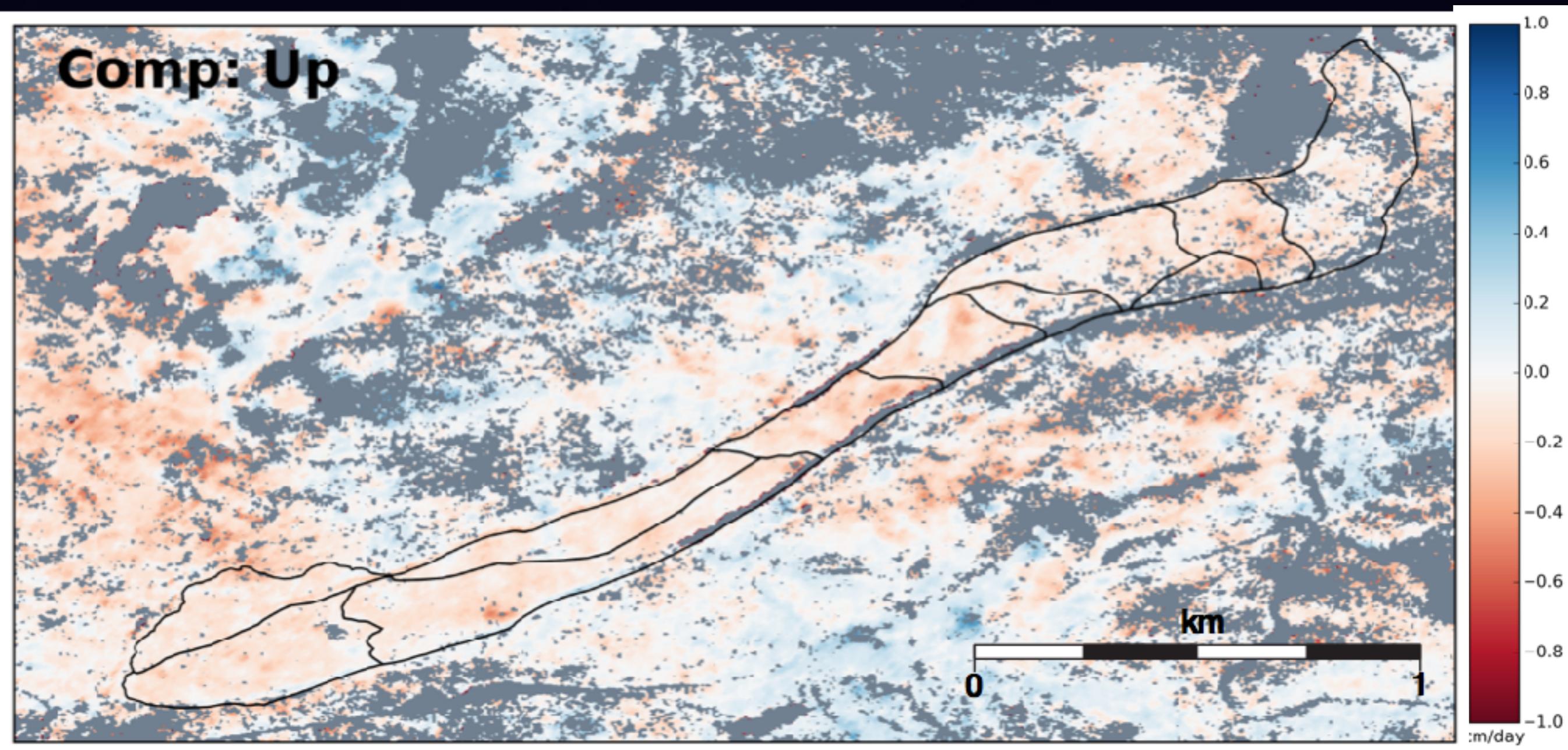
Comp: East



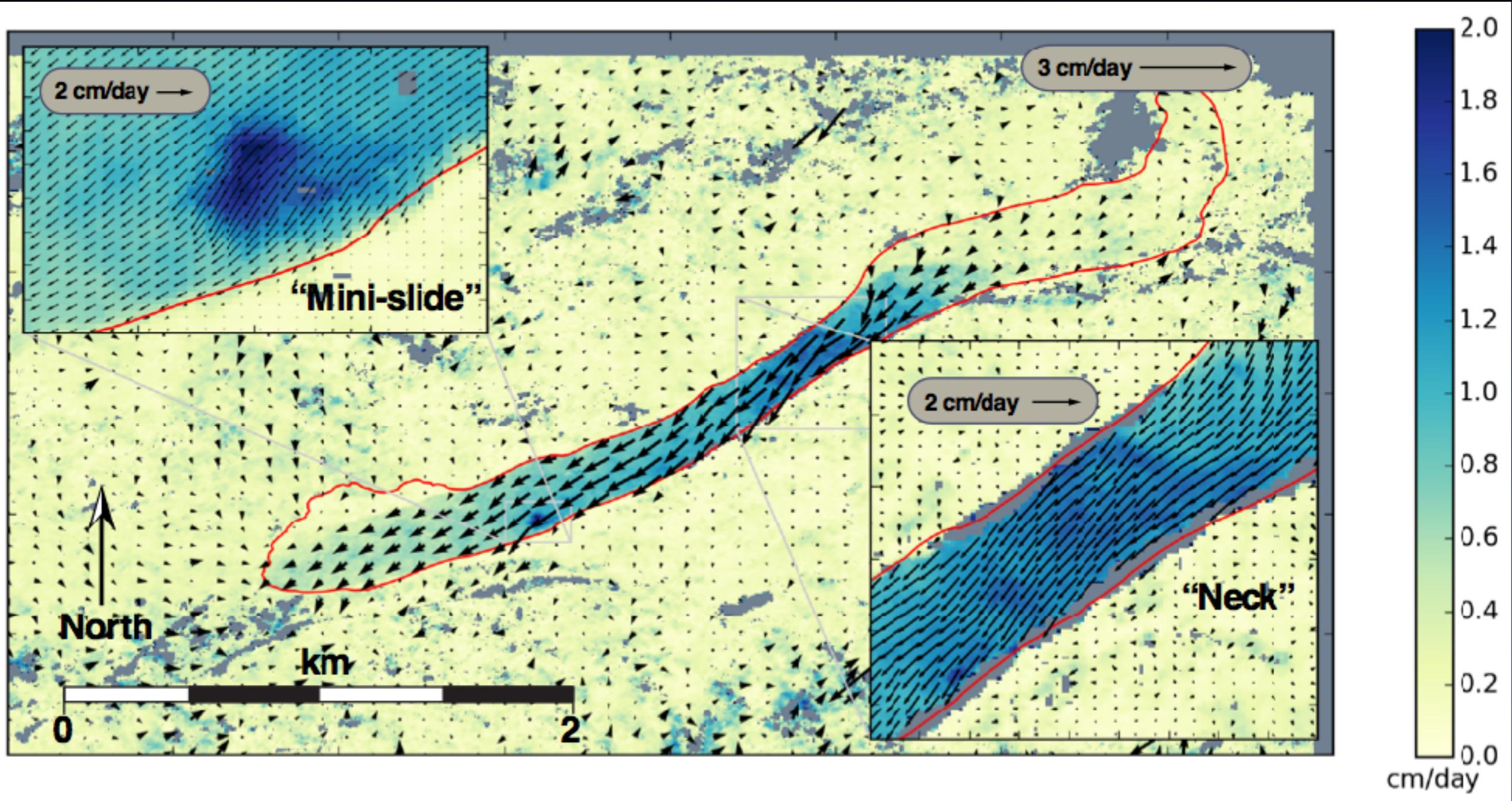
Results of the Three Dimensional Vector Inversion



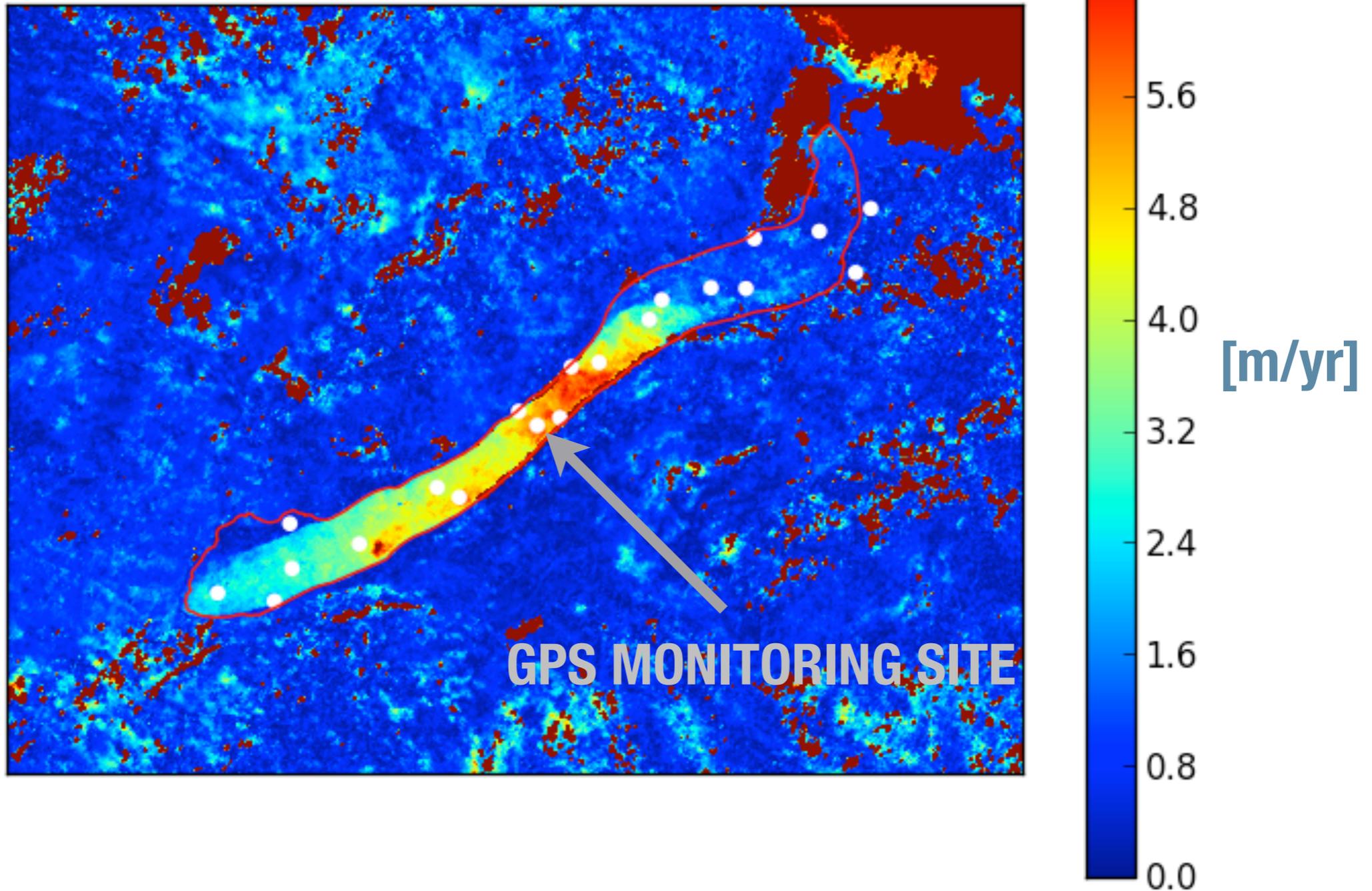
Results of the Three Dimensional Vector Inversion



Horizontal Motion



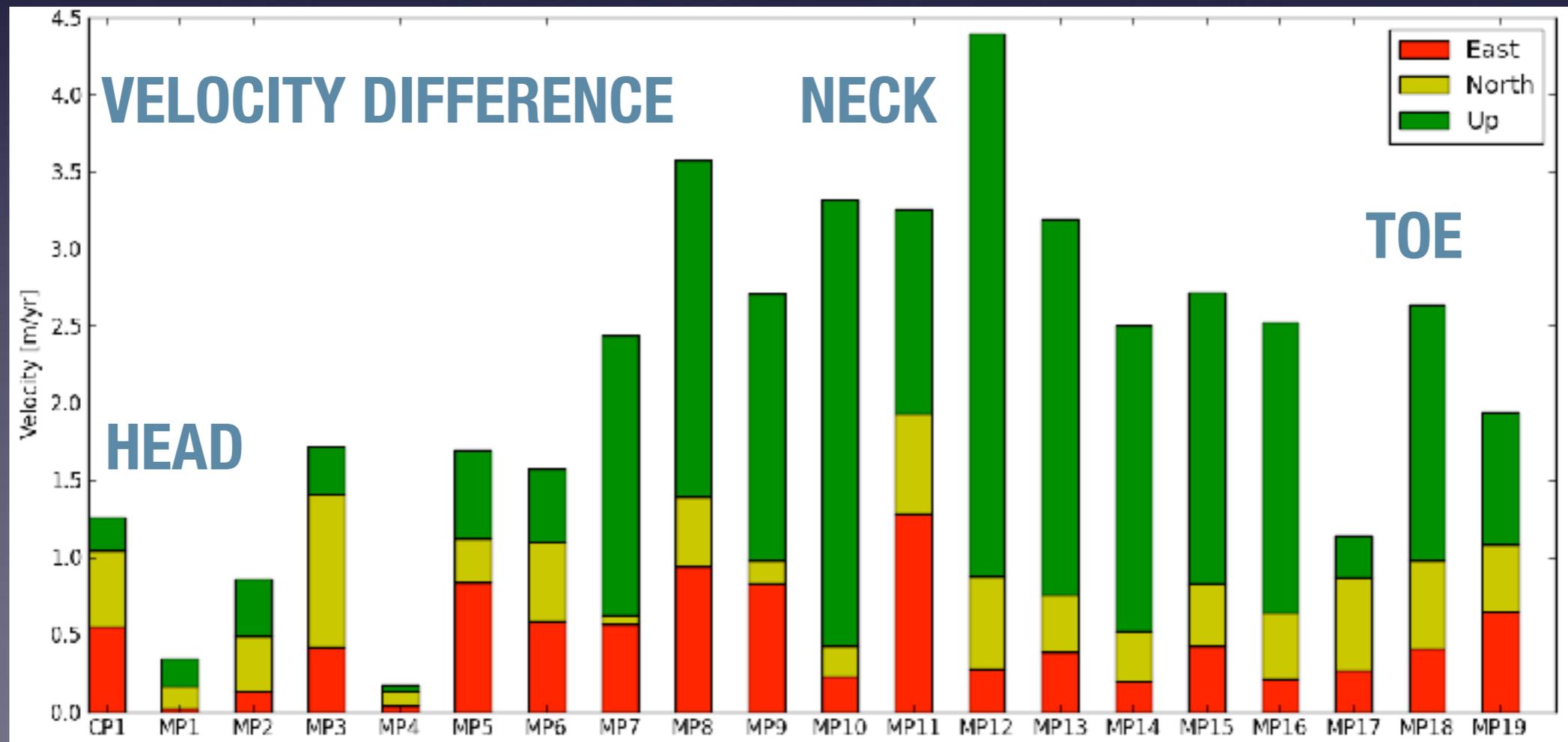
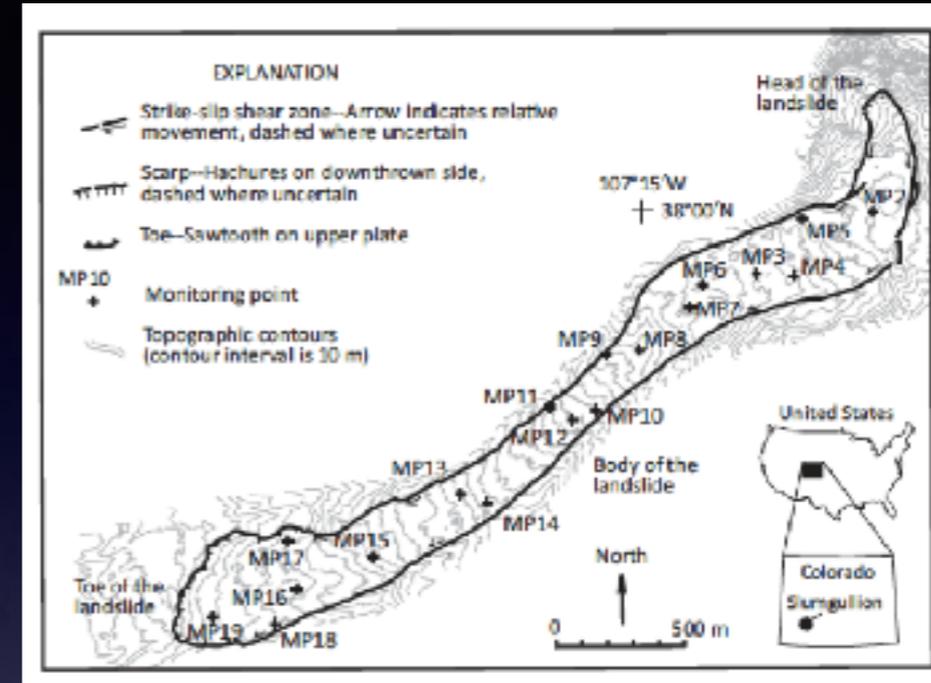
FULL VELOCITY MAGNITUDE



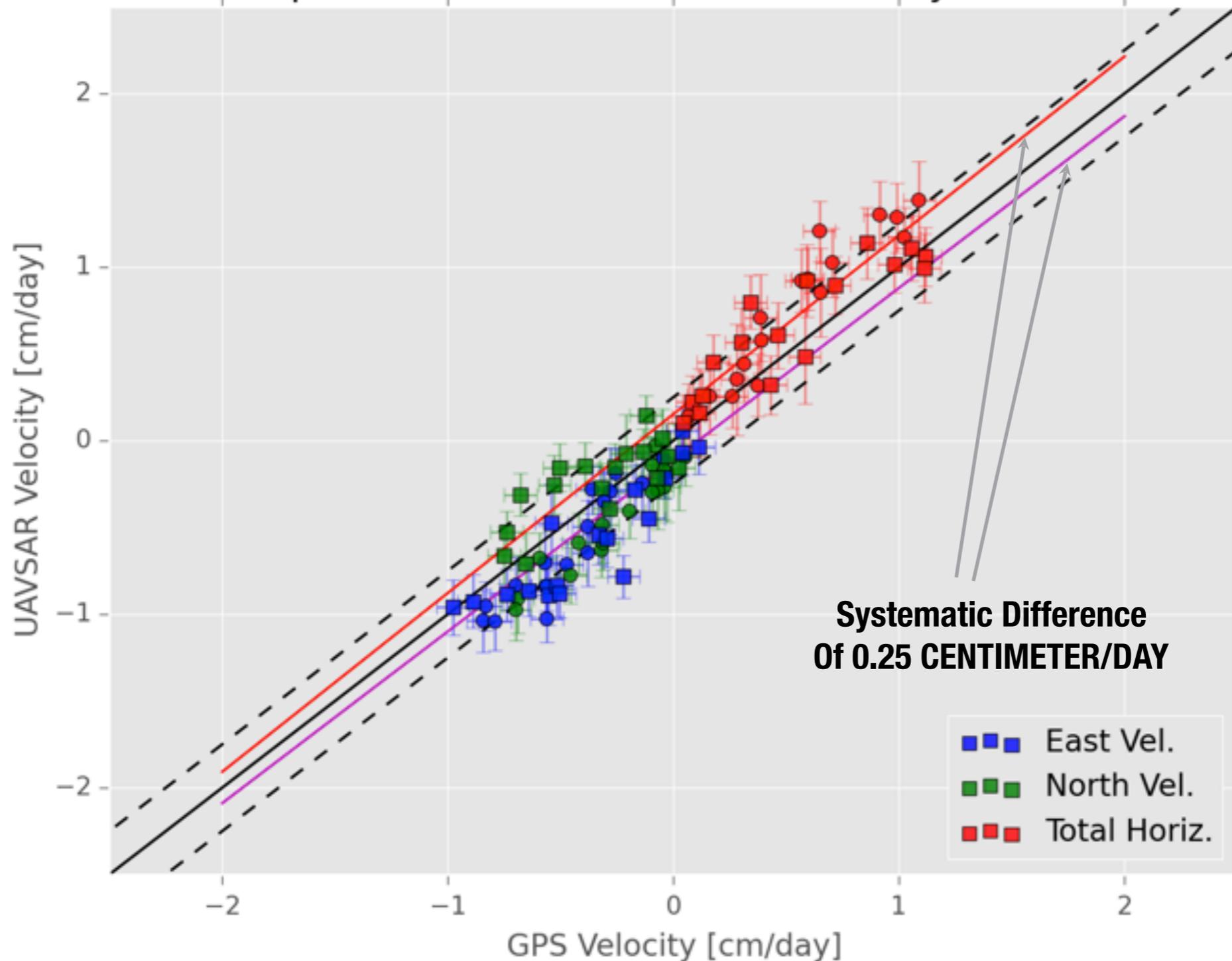
COMPARISON WITH CONCURRENT GPS DATA

Velocity Comparison

Biggest difference between UAVSAR and GPS is in the vertical component

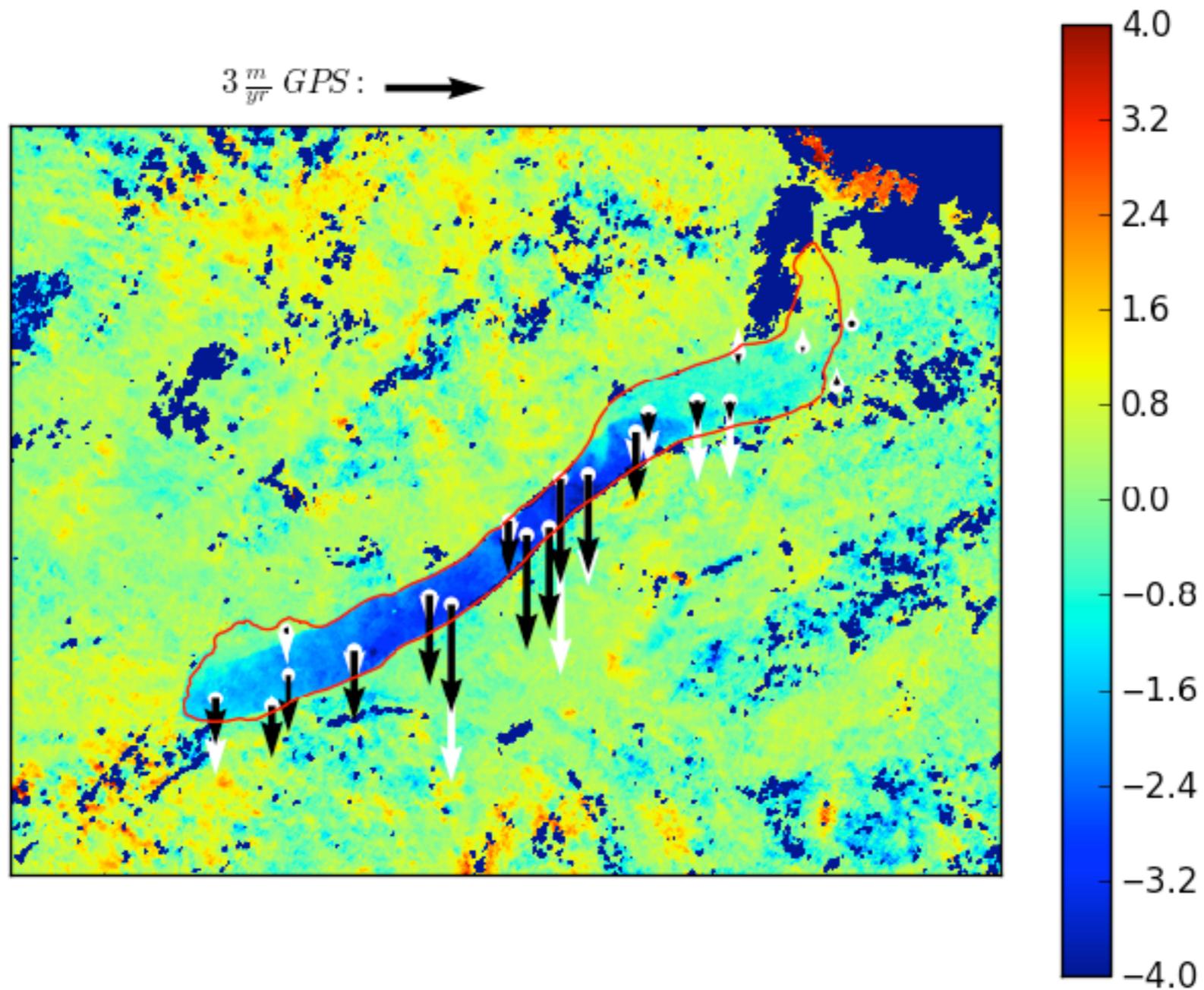


Comparison of GPS and UAVSAR velocity estimates



Horizontal Motion

Comparison with concurrent campaign GPS data

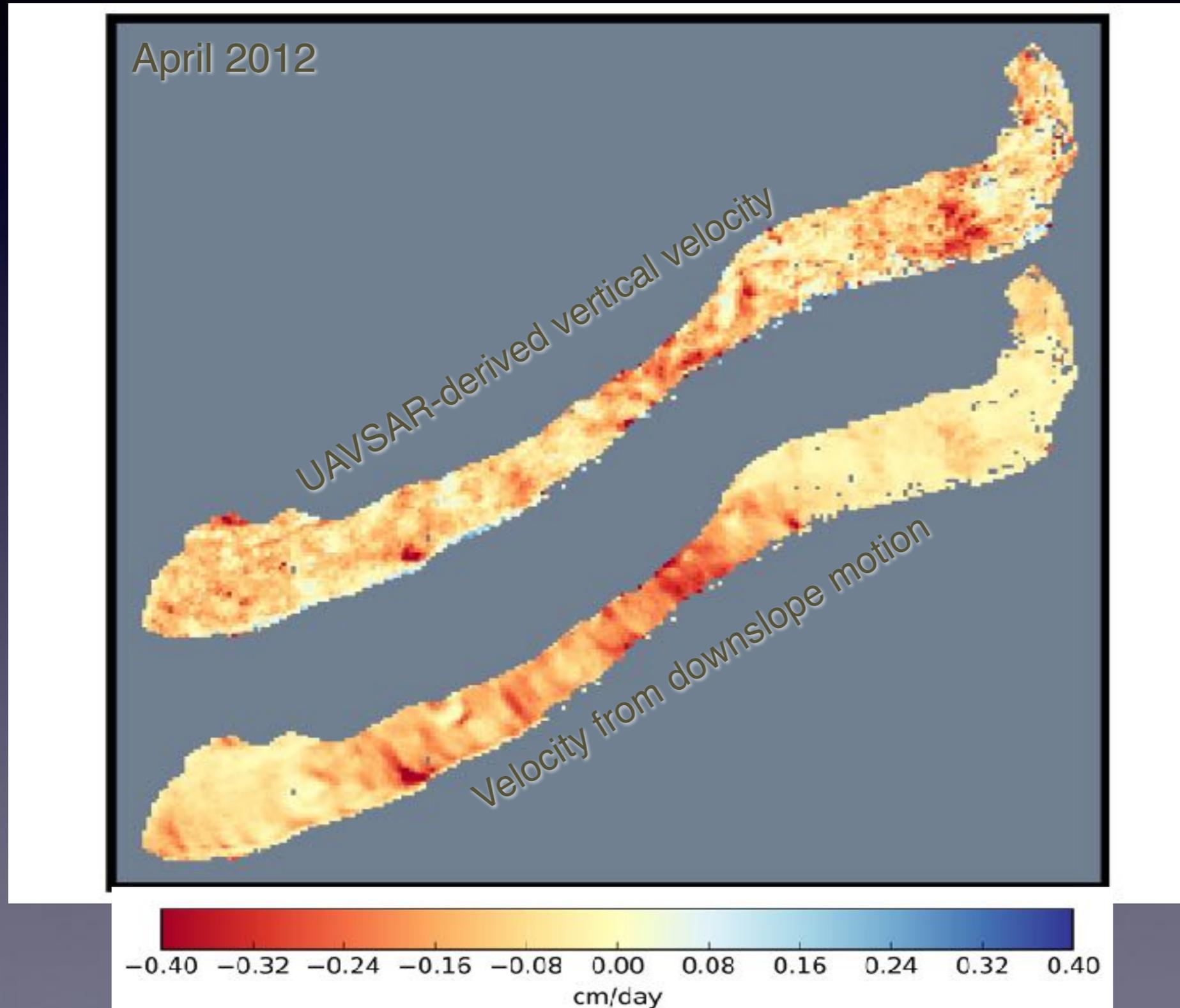


Vertical Motion

Comparison With concurrent GPS Data

Vertical Motion

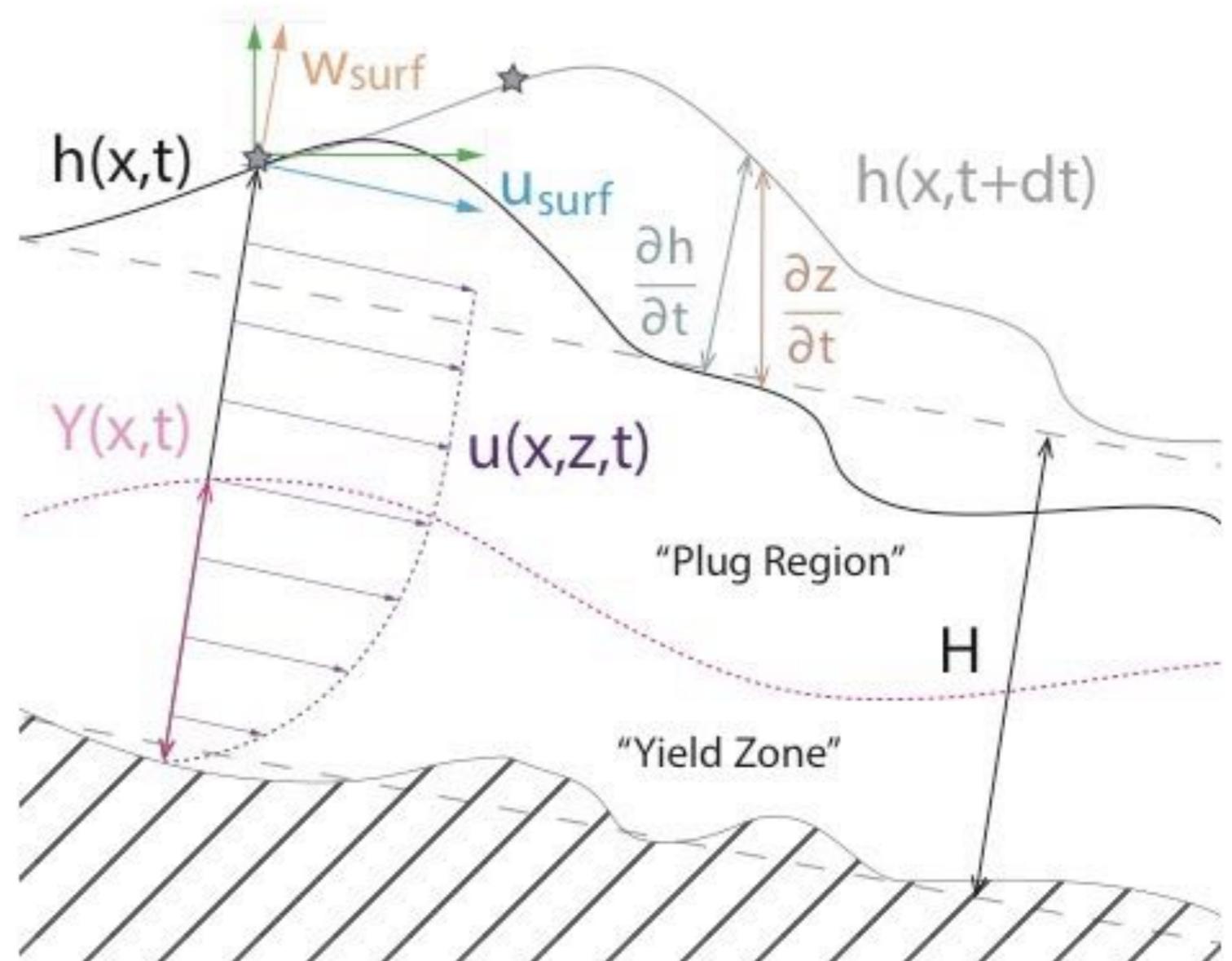
Comparison of measured vertical velocity versus predicted vertical deformation from horizontal velocity and slope



ENABLED APPLICATIONS: MECHANICAL MODELING, RHEOLOGY, TIME SERIES ANALYSIS, DEPTH INVERSION ETC.

The "landslide-wide" coverage of the UAVSAR-derived velocity field allows us to overcome the limitations of point measurements and estimate the thickness across the entire landslide.

The 3D surface deformation enables inversion of the depth and orientation of the landslide basal plane using conservation of mass and a free-surface kinematic boundary conditions.

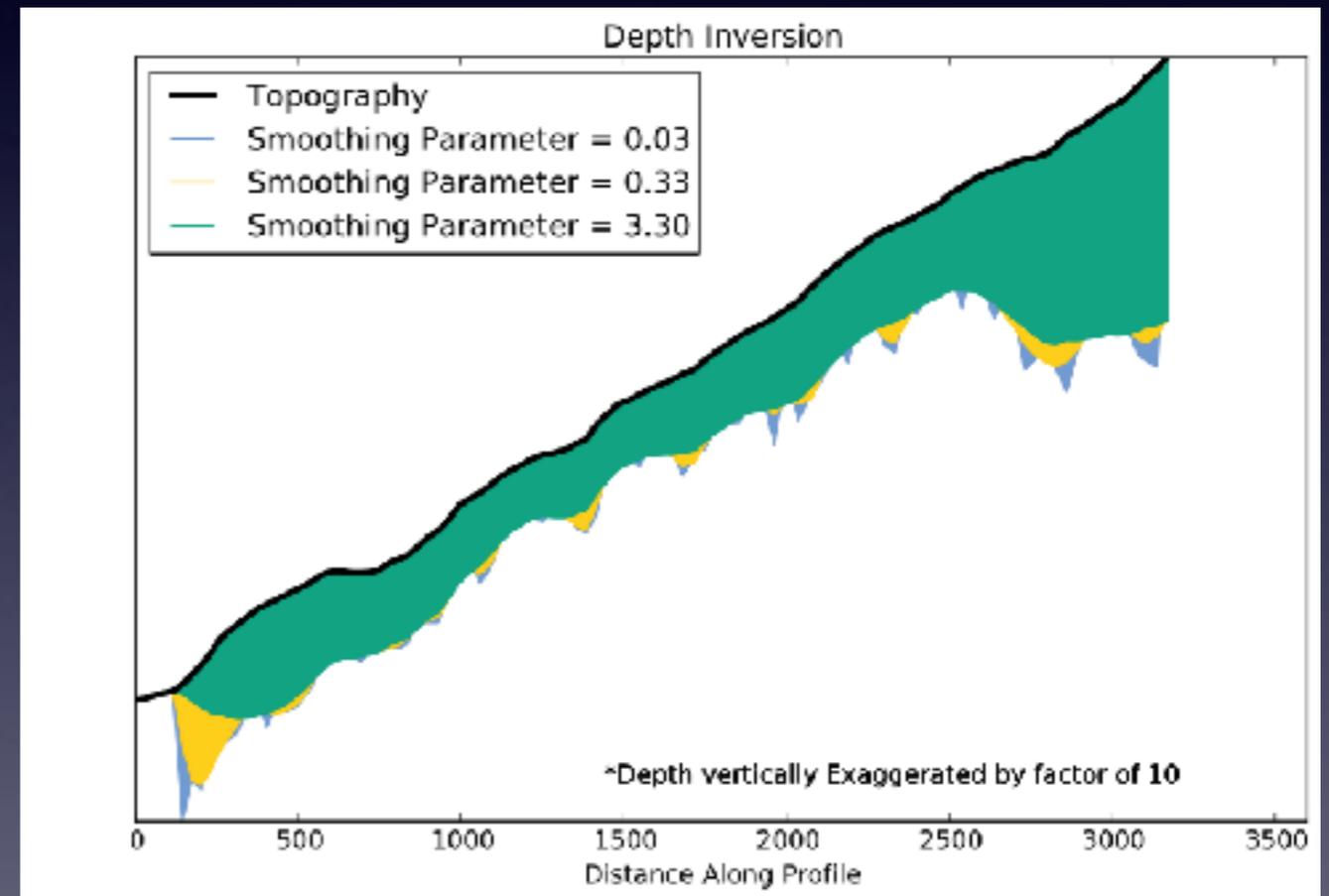
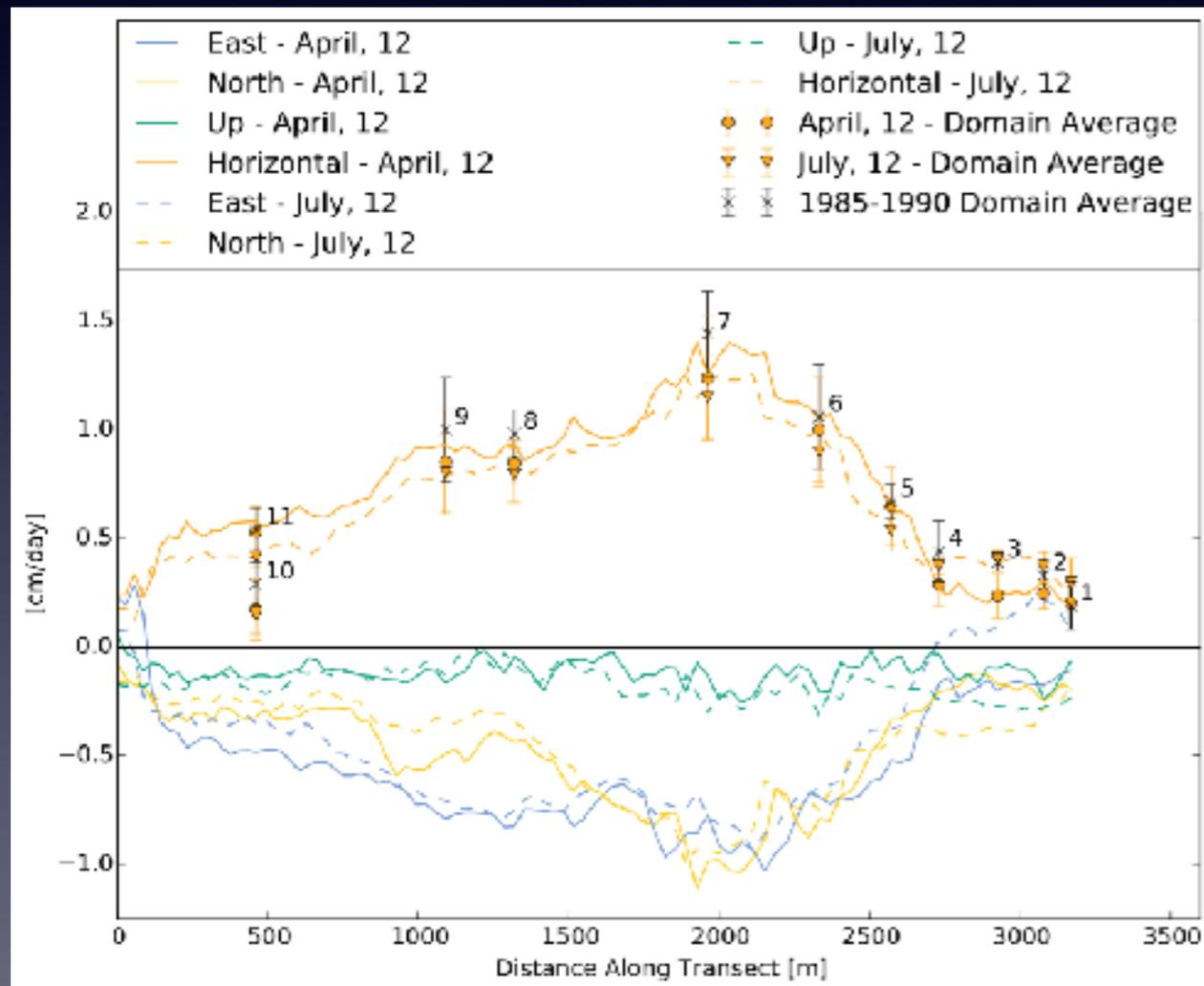


$$w_{surf} = -\nabla_H \cdot (h\bar{\mathbf{u}}) + \mathbf{u}_{surf} \cdot \nabla_H h_{surf}$$

DEPTH INVERSION

ALONG SLIDE VELOCITY
PROFILES

RESULTING BASAL
GEOMETRY

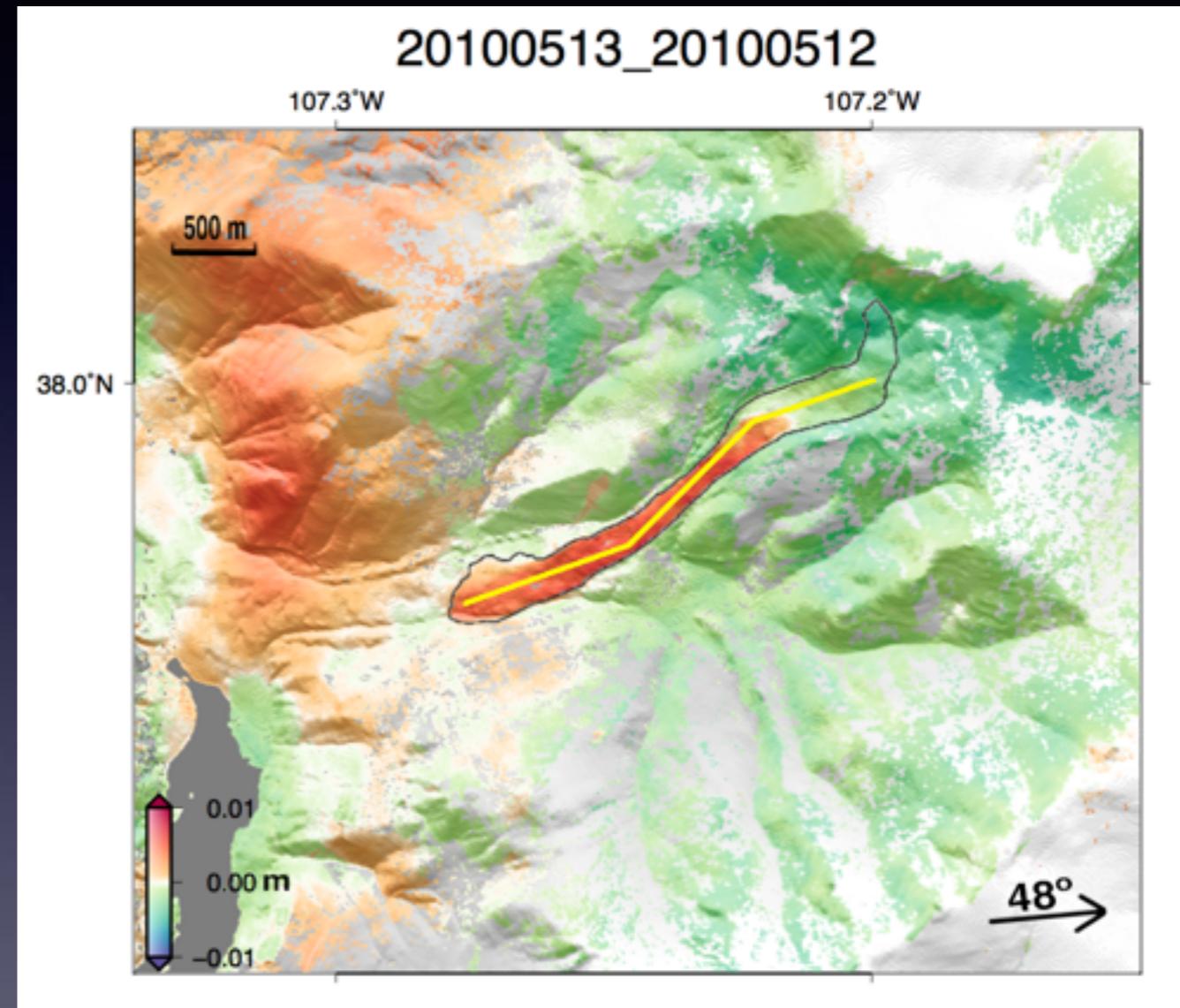


Conclusions

- We overcome spatial and temporal limitations of traditional space-based InSAR and ground-based displacement measurements using the unique capabilities of the UAVSAR airborne repeat-pass interferometry system.
- A comparison with GPS measurements validates this method and shows that it provides reliable and accurate 3D surface motion measurements.
- UAVSAR provides more accurate measurements of the vertical motion than campaign GPS.
- High-resolution 3D kinematics can constrain inversions for landslide thickness and more advanced models of landslide mechanics and rheology.
- This data acquisition and processing scheme can be used to measure 3D surface deformation of any kind with applications to glaciers, hydrology, seismology, and volcanology.
- The complex kinematics of Slumgullion are likely related to bedrock configuration beneath landslide

COSMO-SkyMed

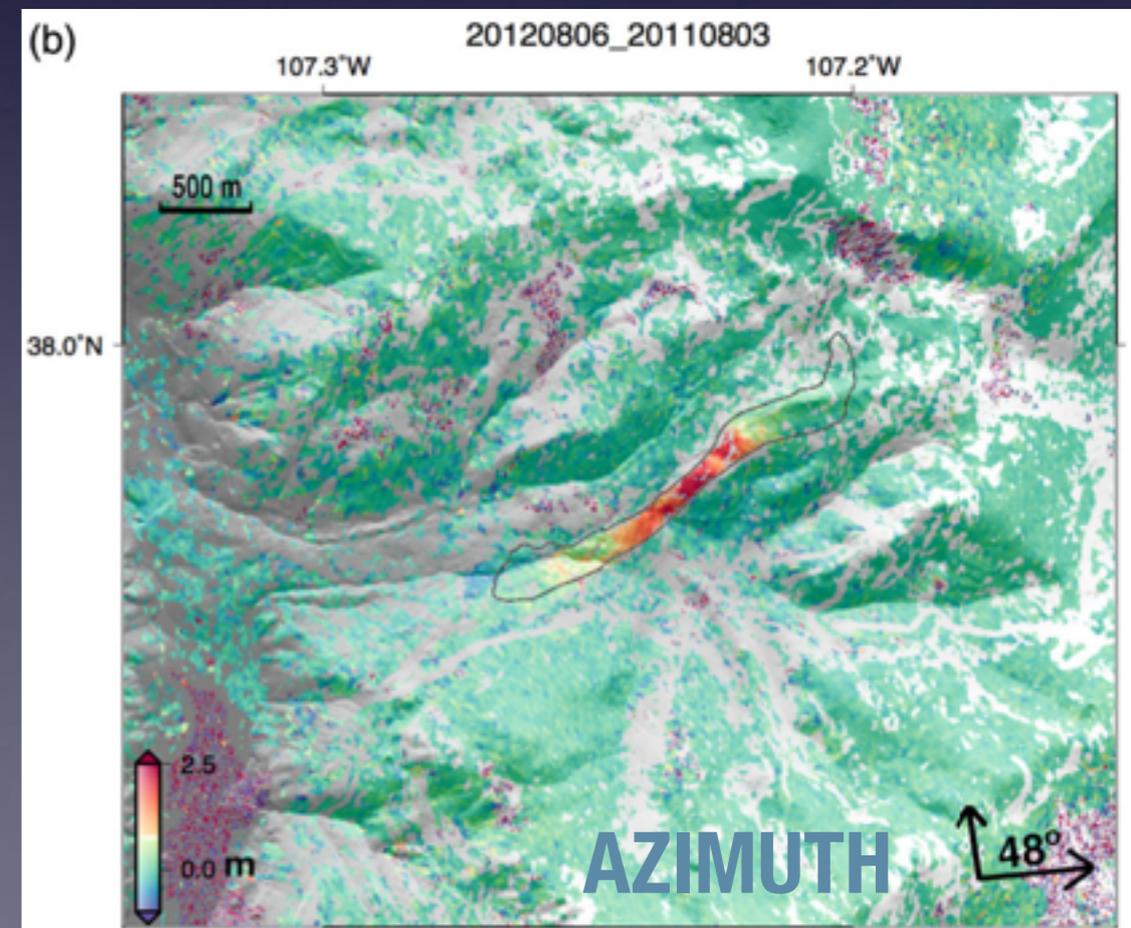
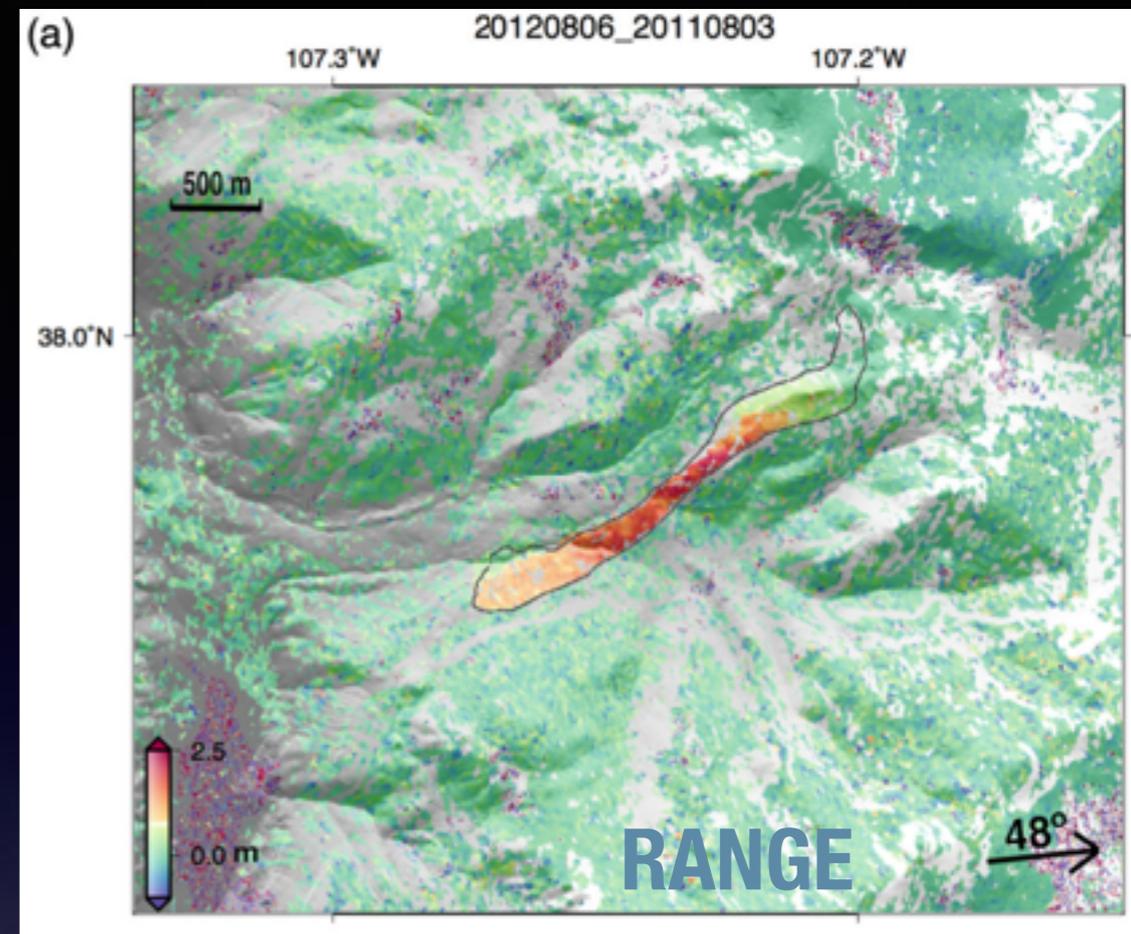
- CSK spotlight mode
- 1-day interferogram from May 2010
- 4 x 4 looks
- processed with ISCE
- preliminary results published in Milillo, et al. (2014)



Milillo, P., E. J. Fielding, W. H. Schulz, B. Delbridge, and R. Burgmann (2014), COSMO-SkyMed Spotlight Interferometry Over Rural Areas: The Slumgullion Landslide in Colorado, USA, IEEE JSTARS, 7(7), 2919-2926, doi:10.1109/jstars.2014.2345664.

COSMO-SkyMed pixel offsets

- CSK spotlight mode
- pixel size 0.5 x 0.7 m
- 1-year pixel offsets from August 2011–August 2012
- processed with ISCE



UAVSAR pixel offsets

- UAVSAR SLC stack (ongoing acquisitions)
- pixel size 0.6 m (azimuth) x 1.2 m (range)
- processed by Teng Wang (SMU), being updated by Xie Hu (Berkeley)
- up to 8 m/year of motion

