The M7 2016 Kumamoto, Japan, Earthquake: Surface Strain in the Fault Damage Zone and Shallow Fault Slip Revealed with Near-Field Geodetic Imagery

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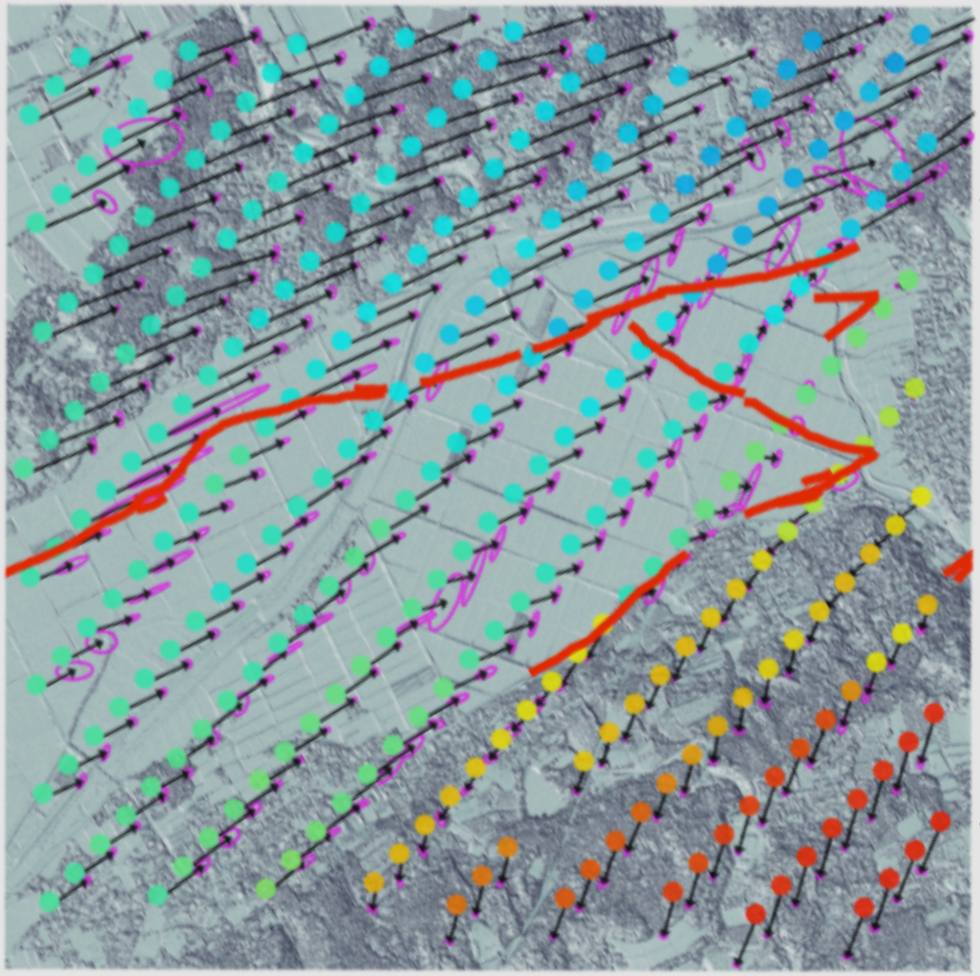
Motivation & Outline



3D coseismic displacements from the M7 Kumamoto Earthquake
Scott et al. (2018)

Upper fault zone behavior: How is slip transmitted to the surface?

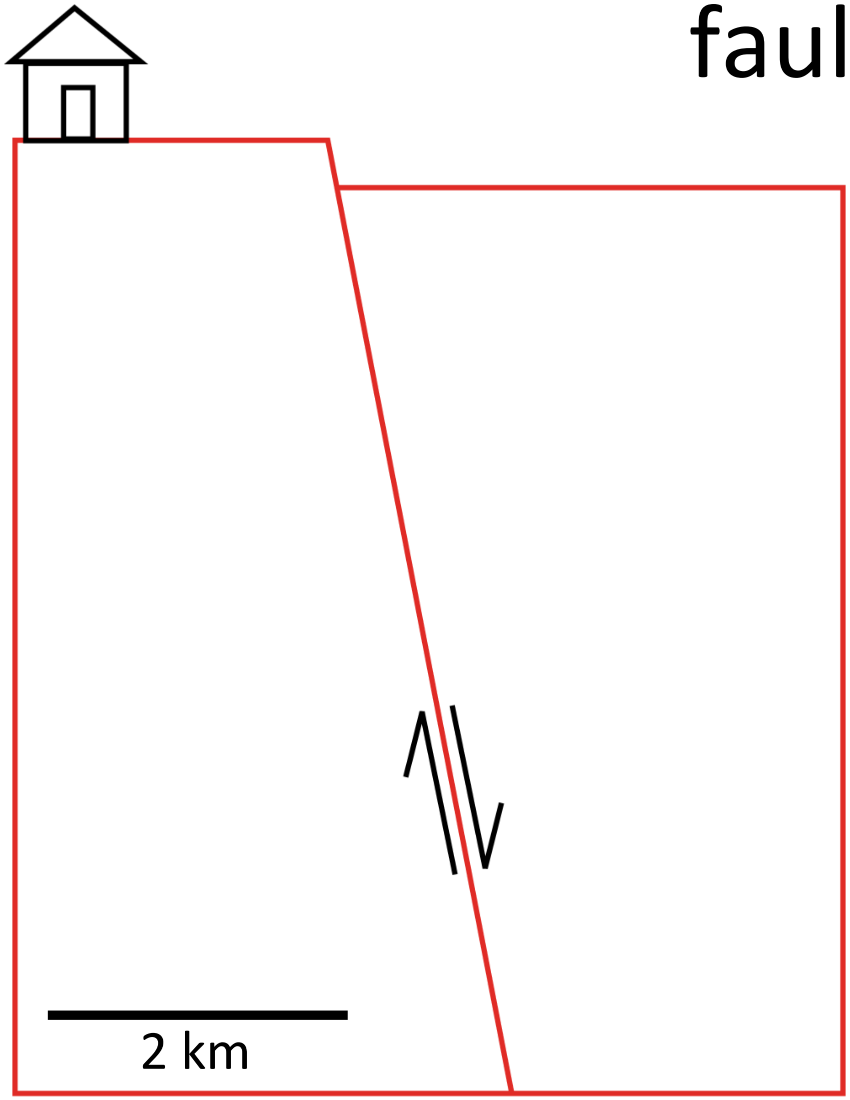
Differential topography fills near-fault data gap.

Inelastic failure of fault zone produces distributed deformation.

Fault slip inversion from topography, optical, and InSAR.

Broader impacts: Undergraduate lab; OpenTopography

What is the behavior of the upper fault zone?



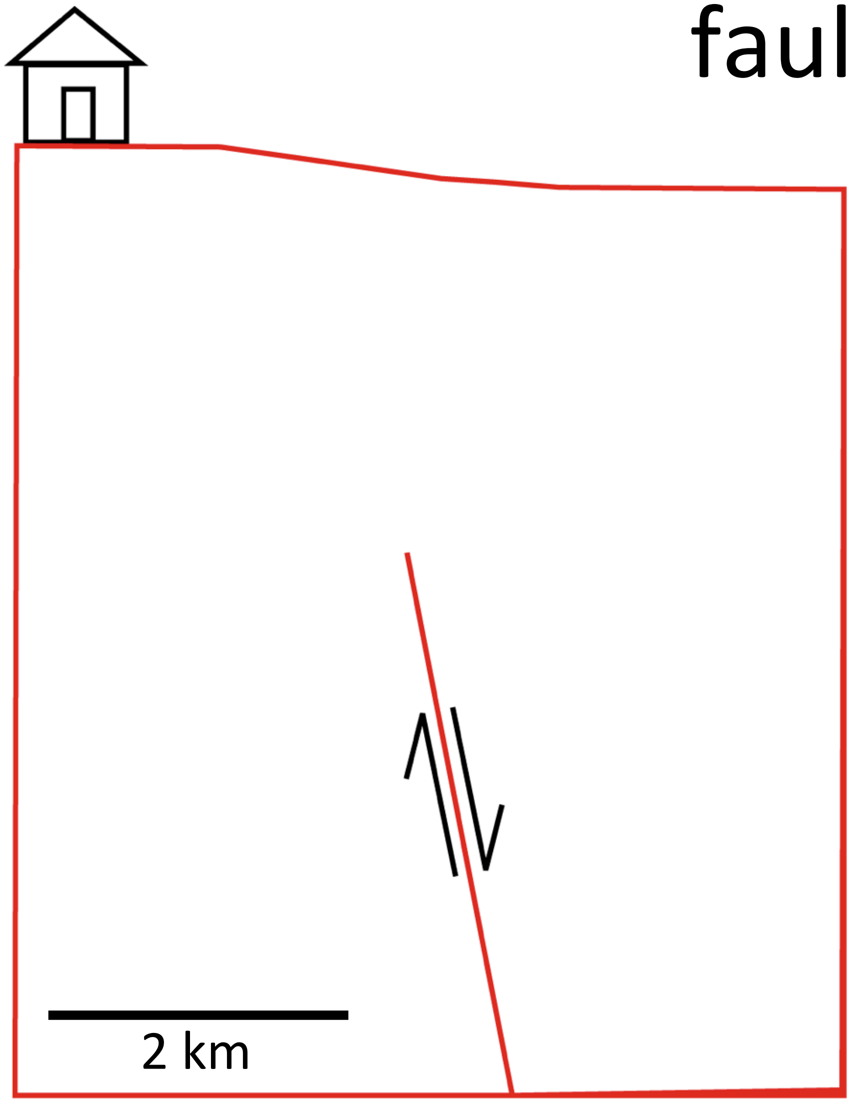
'Business as usual'

Does fault slip propagate through the velocity-strengthening portion of the crust?

Challenge: How to measure surface deformation with the fault zone?

Challenge: Is the upper crust best represented with an elastic rheology?

What is the behavior of the upper fault zone?



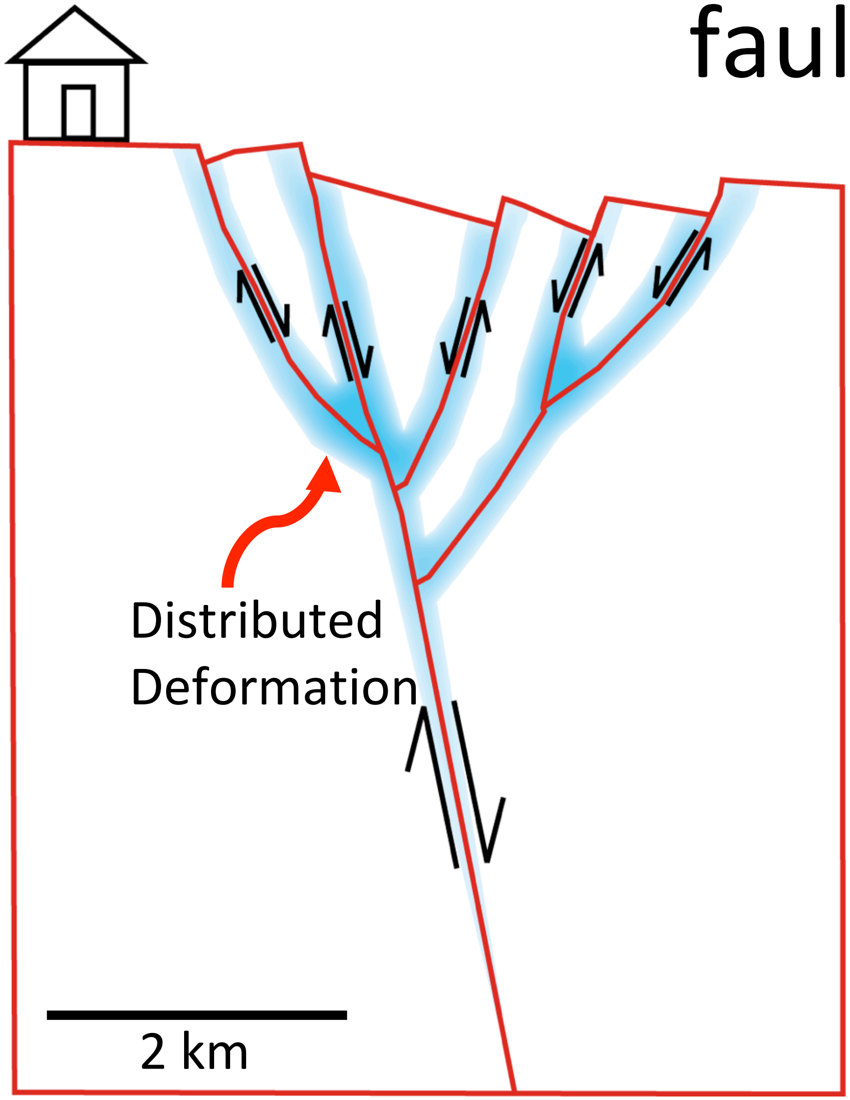
'No business'

Does fault slip propagate through the velocity-strengthening portion of the crust?

Challenge: How to measure surface deformation with the fault zone?

Challenge: Is the upper crust best represented with an elastic rheology?

What is the behavior of the upper fault zone?



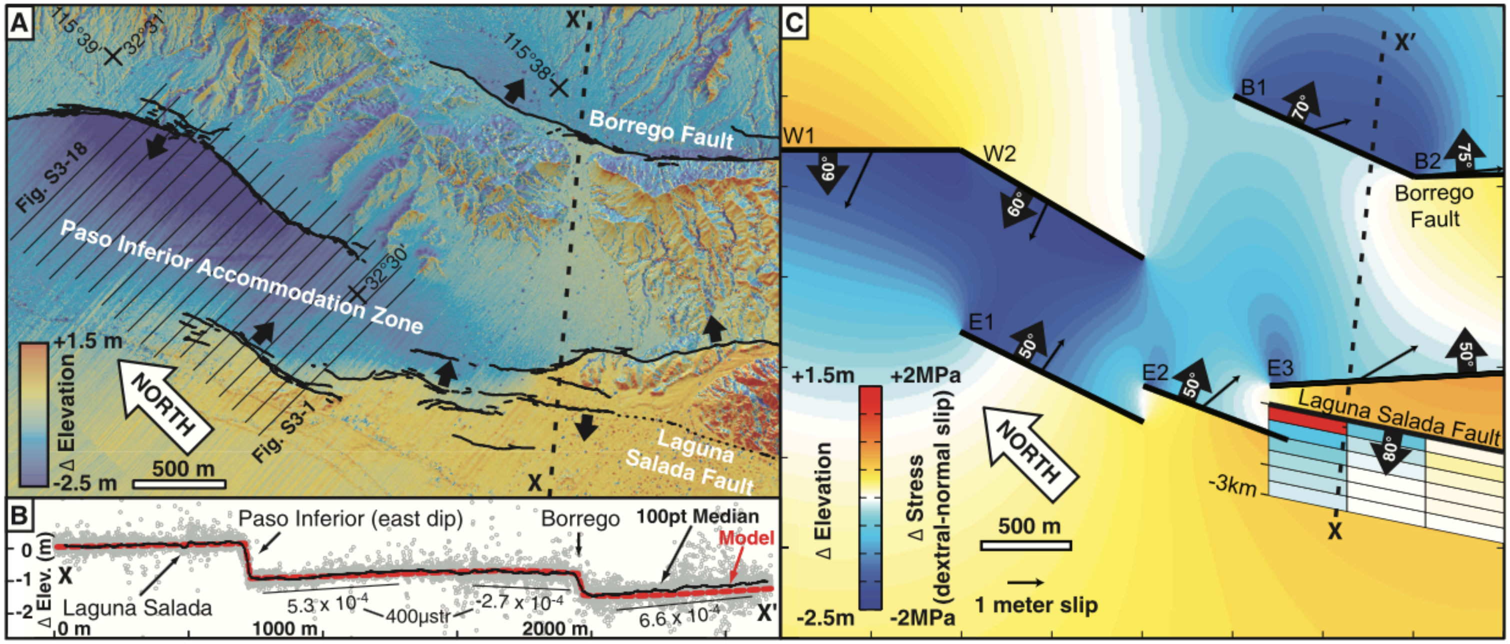
'Busy business'

Does fault slip propagate through the velocity-strengthening portion of the crust?

Challenge: How to measure surface deformation with the fault zone?

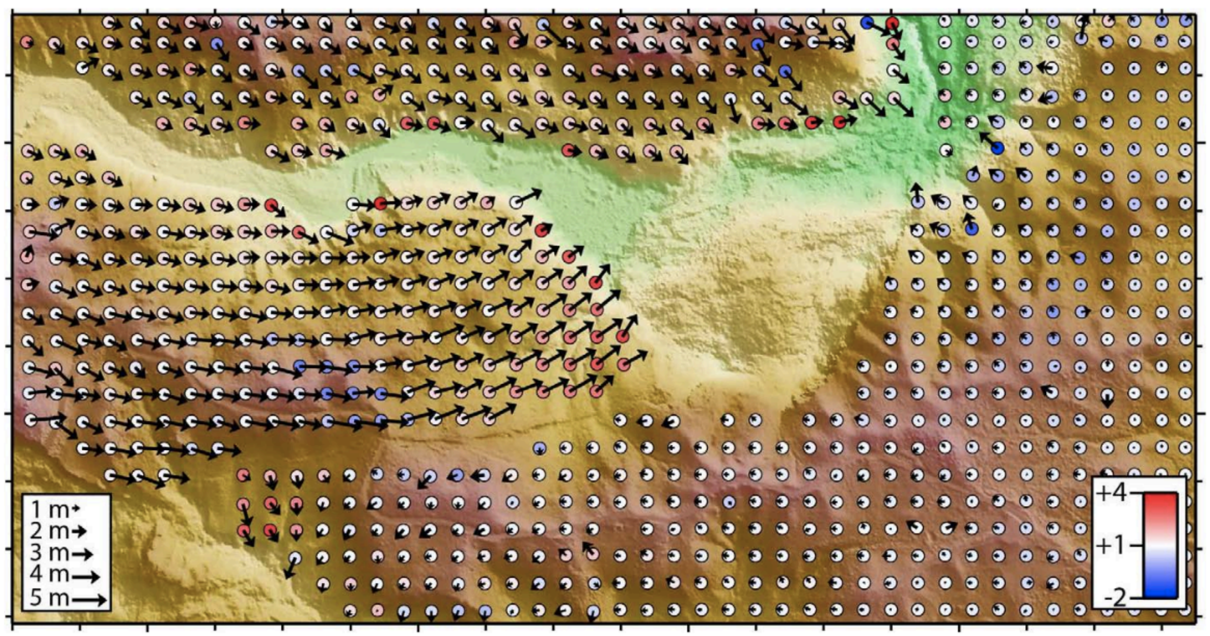
Challenge: Is the upper crust best represented with an elastic rheology?

Topographic differencing: Previous work



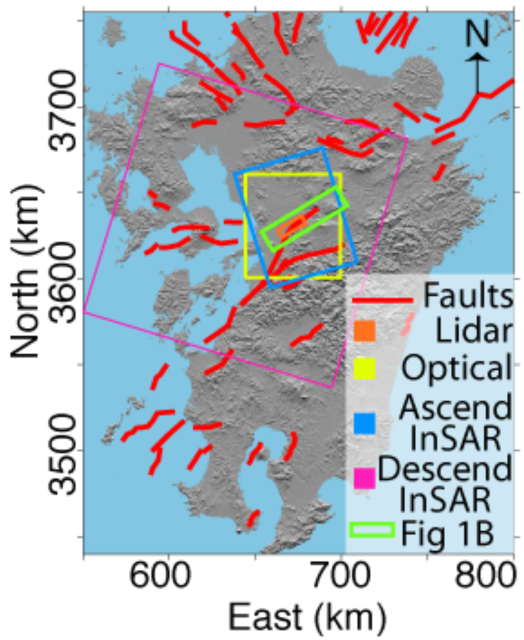
2010 M7.2 El Mayor-Cucupah Earthquake

Oskin et al. (2012)

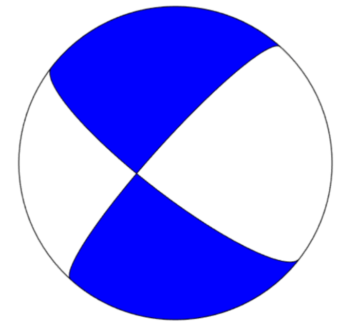


The 2008 Iwate-Miyagi earthquake (Mw 6.9), Japan

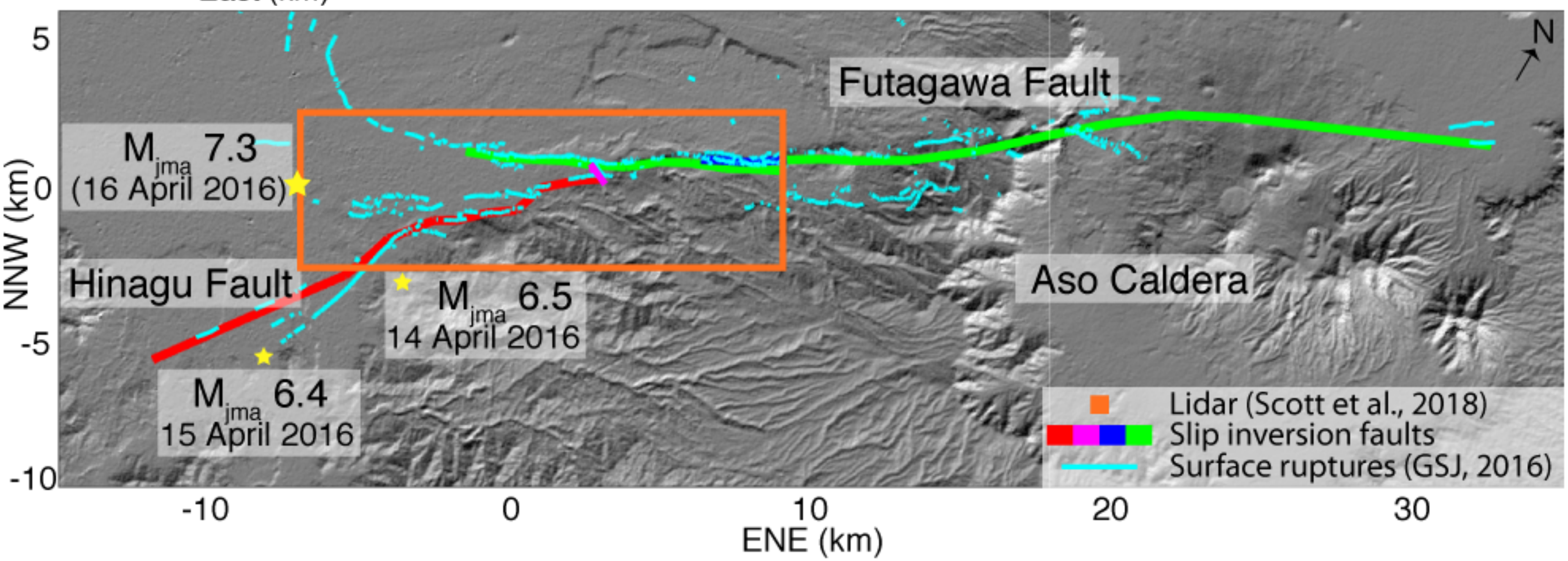
Nissen et al. (2014)



2016 M7.1 Kumamoto, Japan, Earthquake

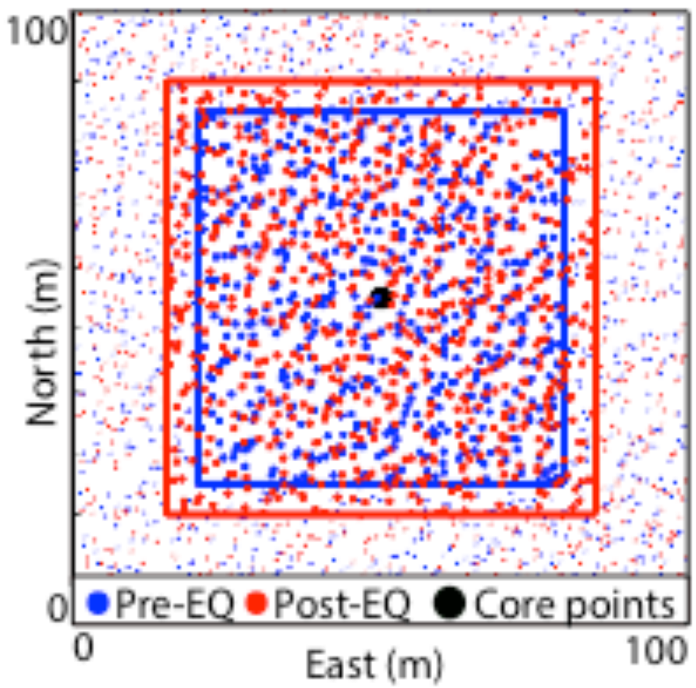


Airborne Lidar	Date	Shot density
Pre- EQ	15 April, 2016	2.5 pts/m^2
Post- EQ	23 April, 2016	3.5 pts/m^2

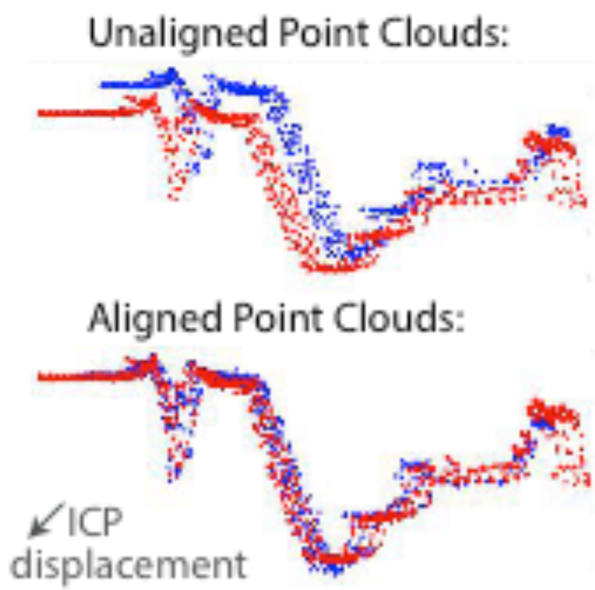


Scott et al. (2018): JGR; Scott et al. (2019): GRL;

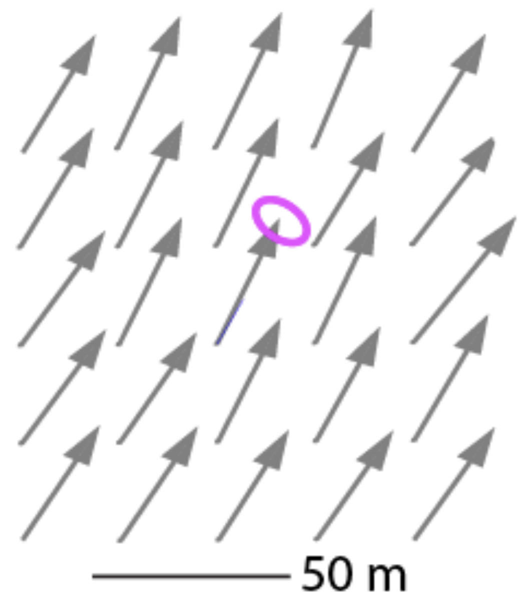
3D coseismic displacement:
Iterative **c**losest **p**oint (ICP)



Windowed subset



3D rigid-body deformation

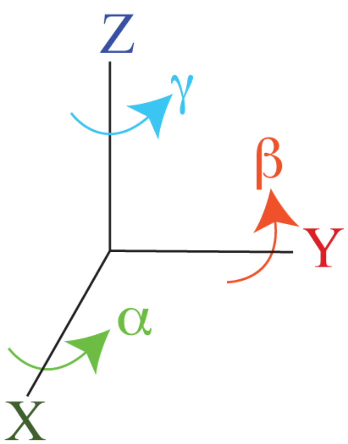


Uncertainty

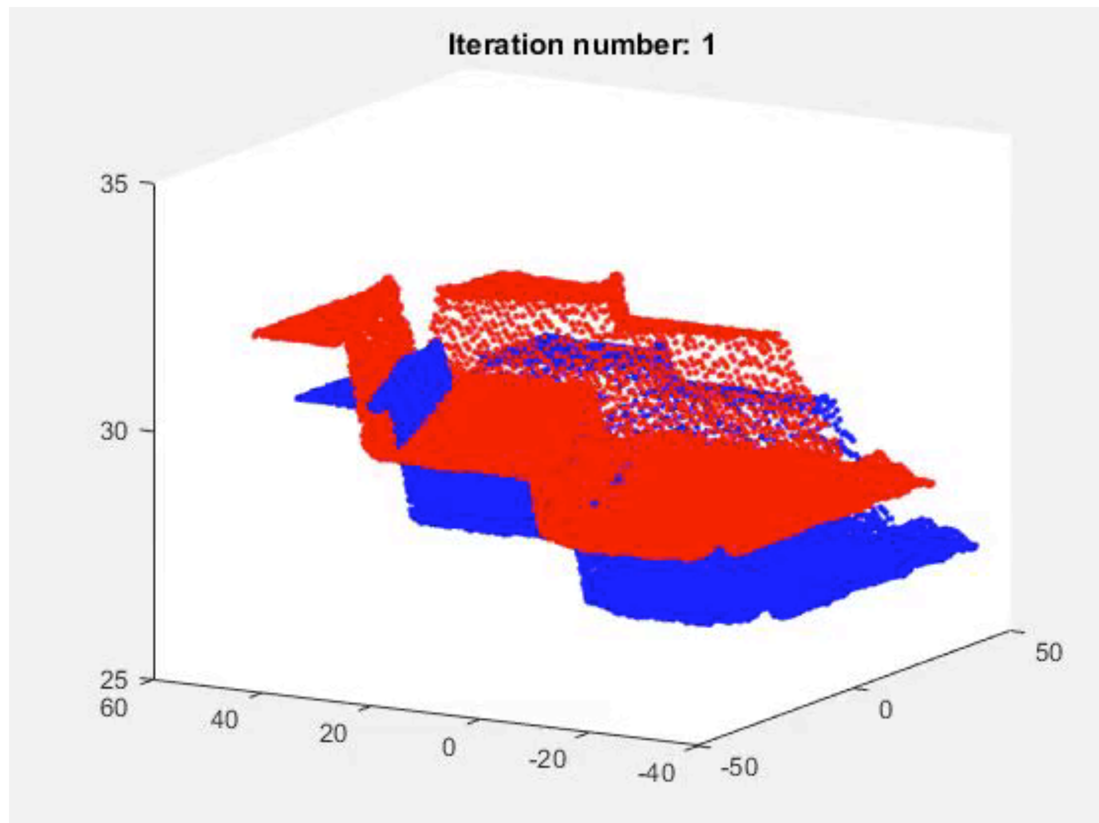
Besl and McKay (1992); Geiger et al. (2012); Nissen et al. (2012; 2014); Scott et al. (2018)

3D coseismic deformation

$$\text{Deformed point cloud} = \underbrace{\begin{bmatrix} 1 & -\gamma & \beta \\ \gamma & 1 & -\alpha \\ -\beta & \alpha & 1 \end{bmatrix}}_{\text{Rotation}} \begin{bmatrix} \text{Undeformed point cloud} \end{bmatrix} + \underbrace{\begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix}}_{\text{Translation}}$$



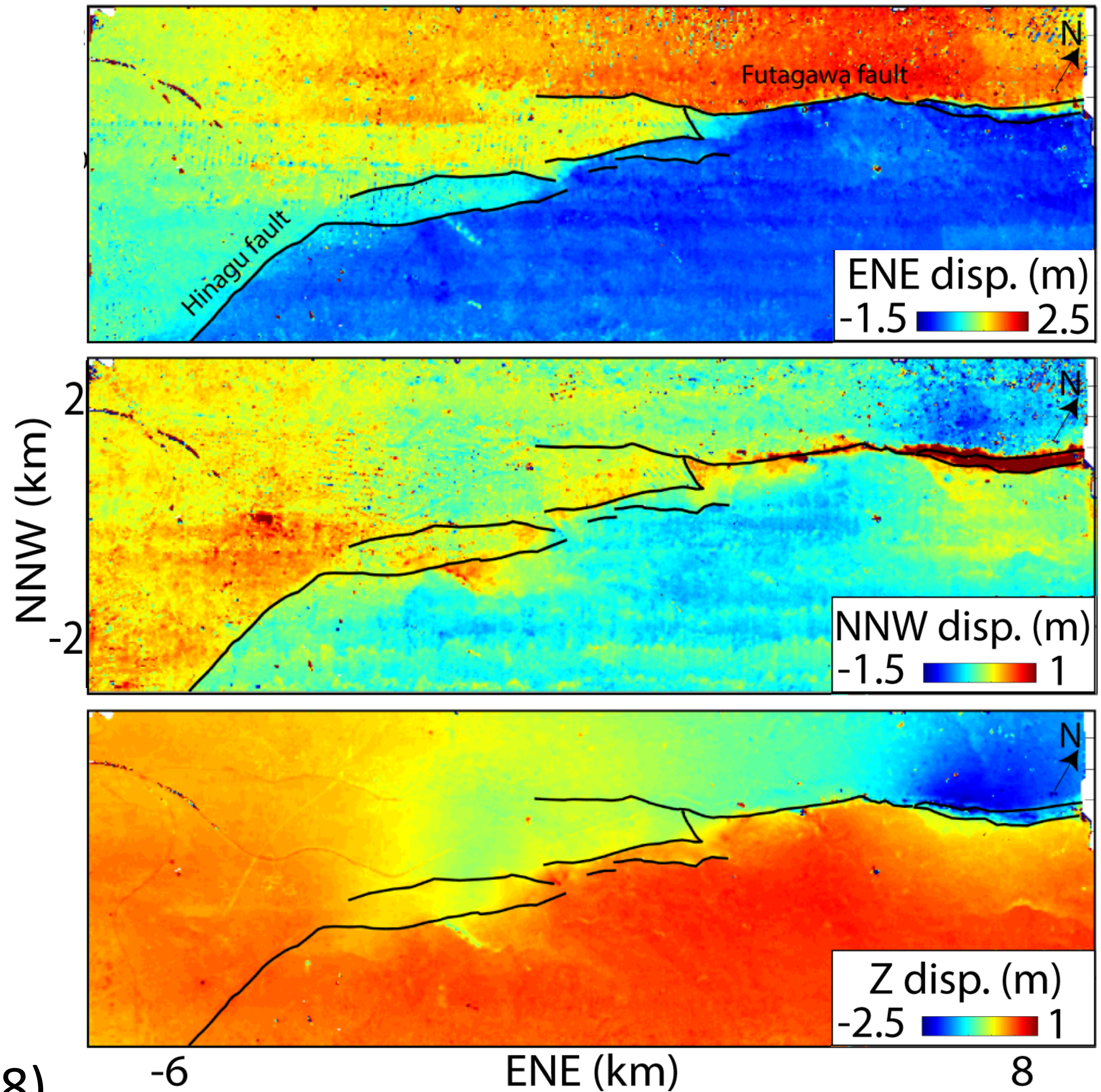
Coordinate system



Align pre- and post-earthquake point clouds

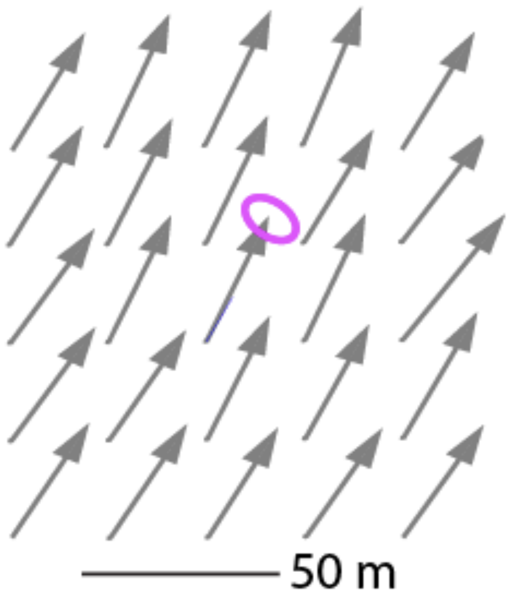
Scott et al. (2018)

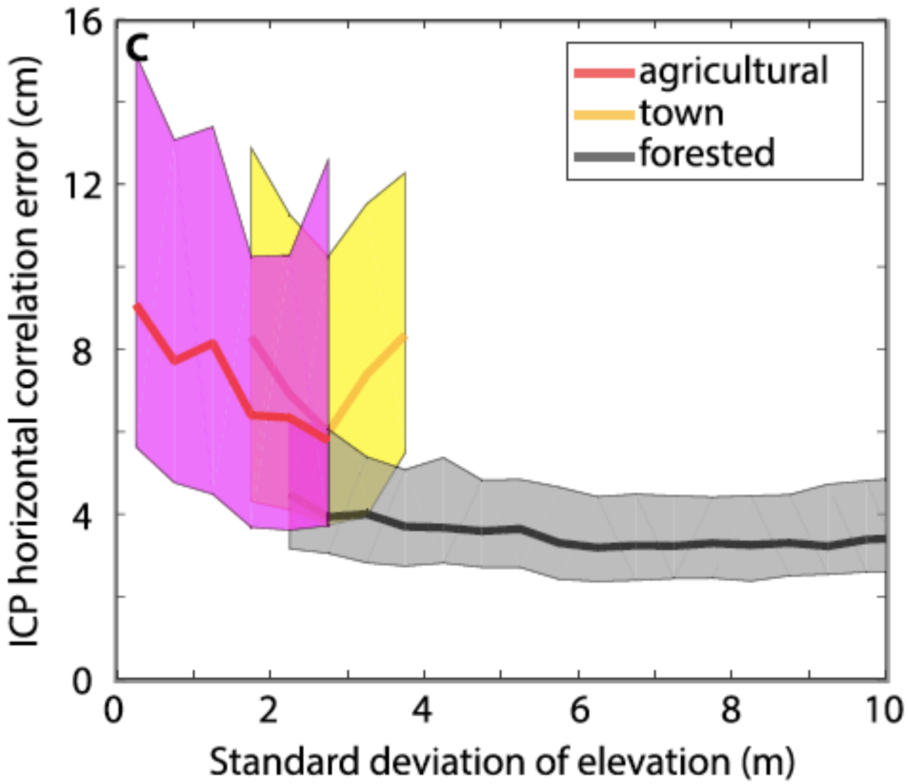
3D Displacement Fields

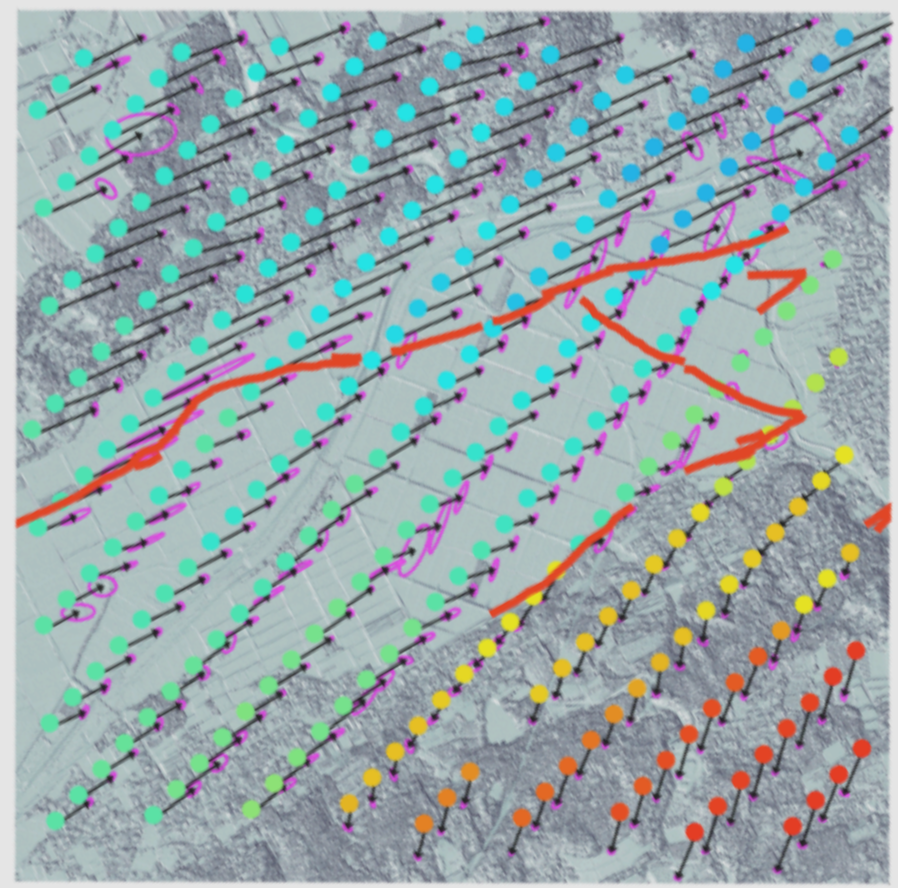


Scott et al. (2018)

Displacement uncertainty

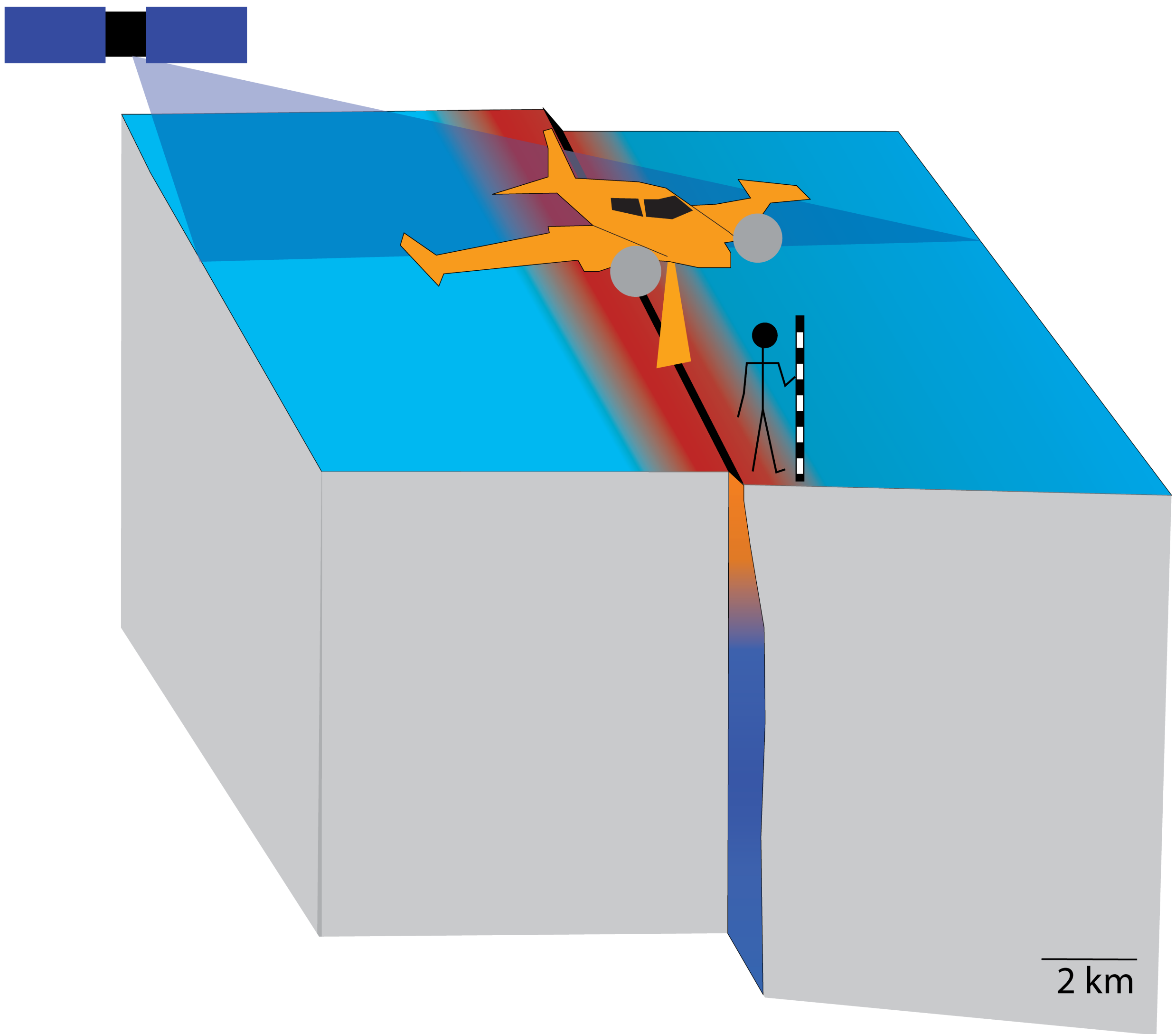






Scott et al. (2018)

Surface displacement at increasing aperture



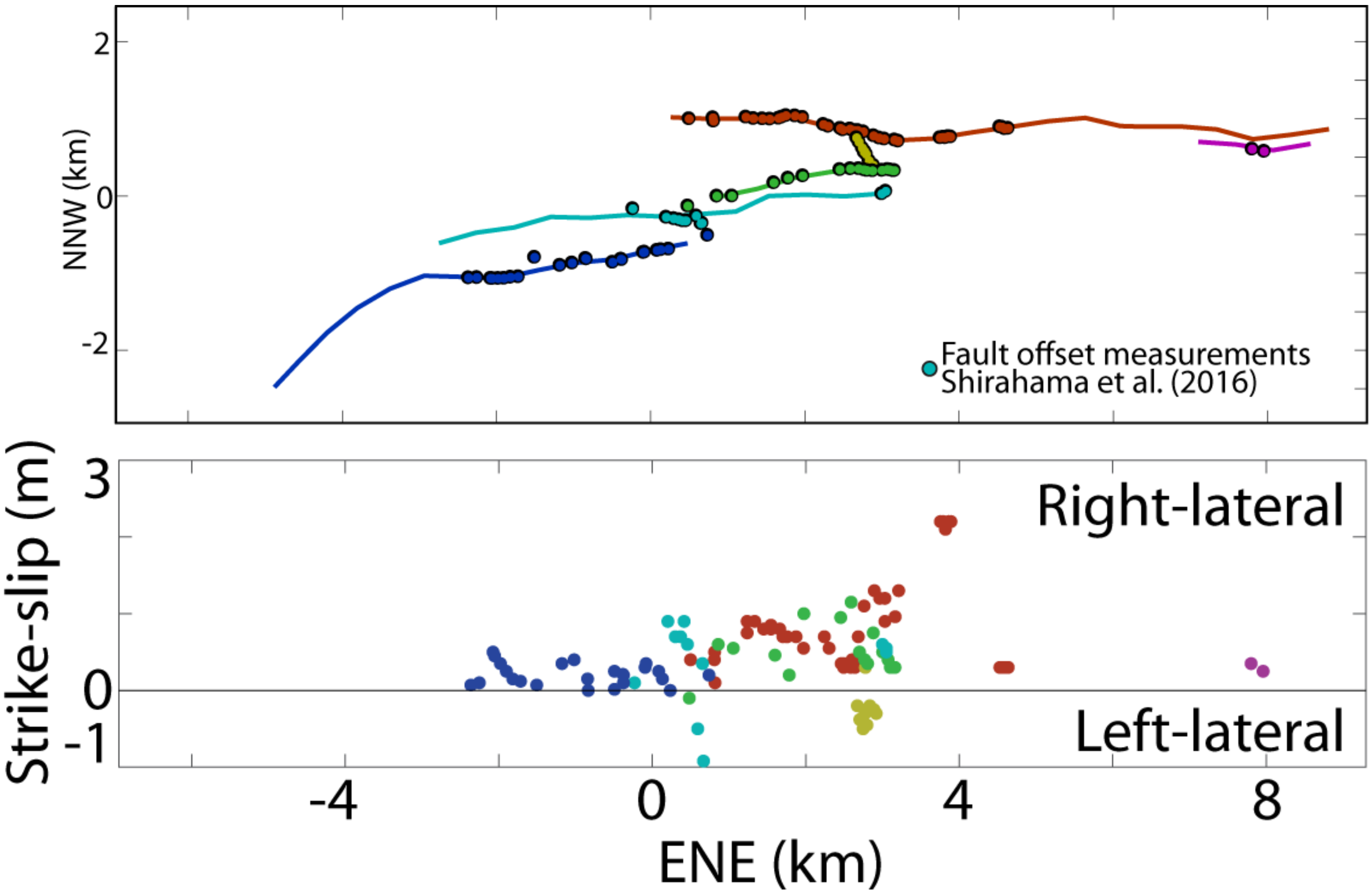
Surface:
Field data

Tens of meters depth: Displacement discontinuity

To the depth of the seismogenic zone:
Joint lidar- optical correlation- InSAR slip inversion

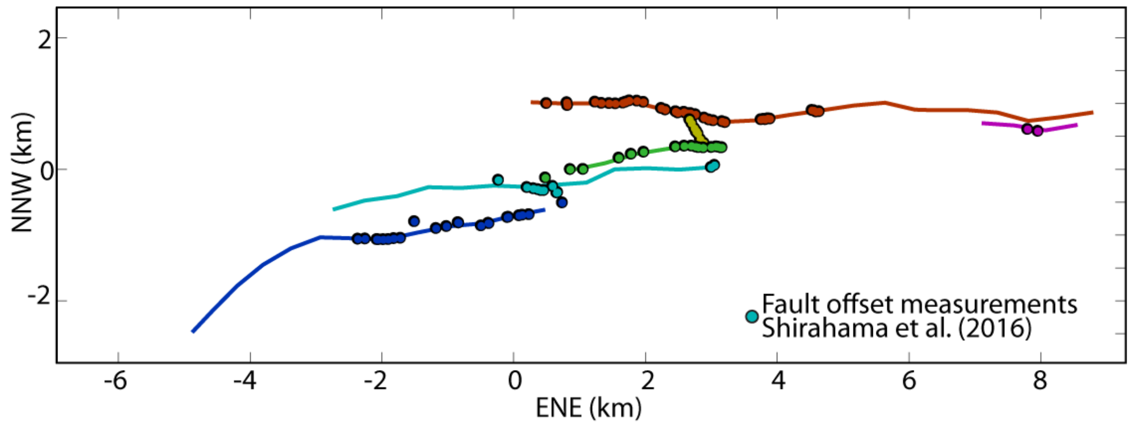
Scott et al. (2018)

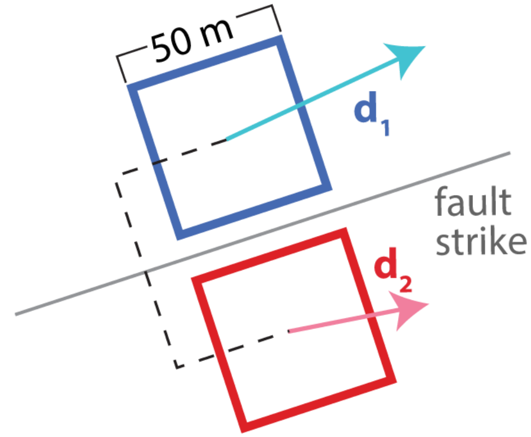
Surface offset measurements

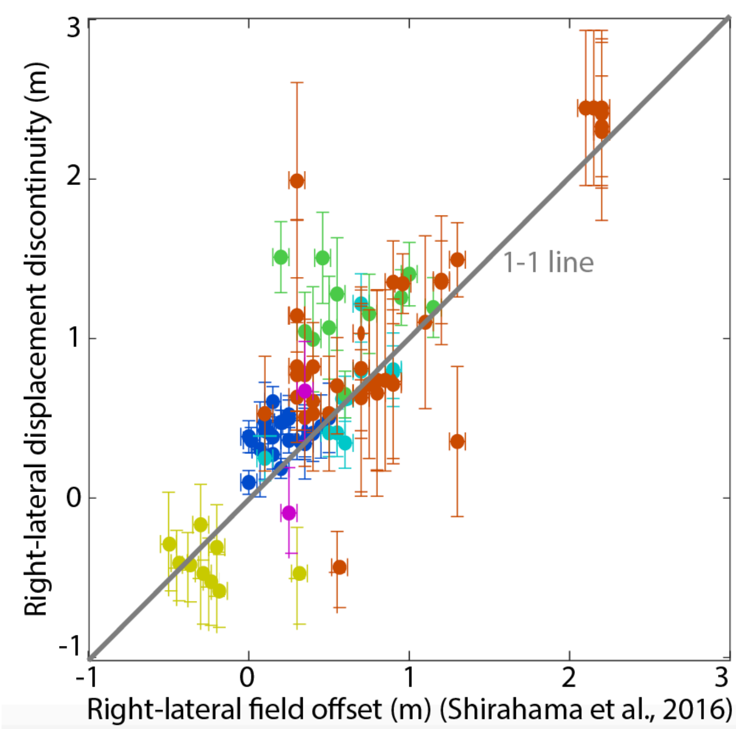


From Shirahama et al. (2016)

Displacement discontinuity: 10's m aperture





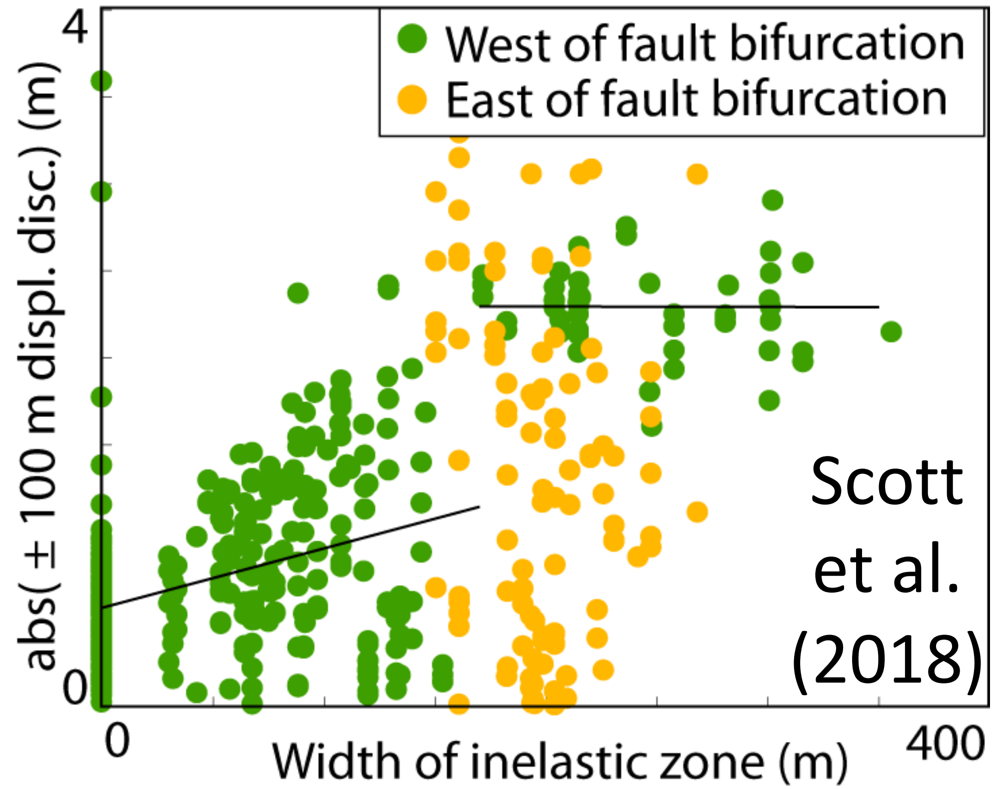


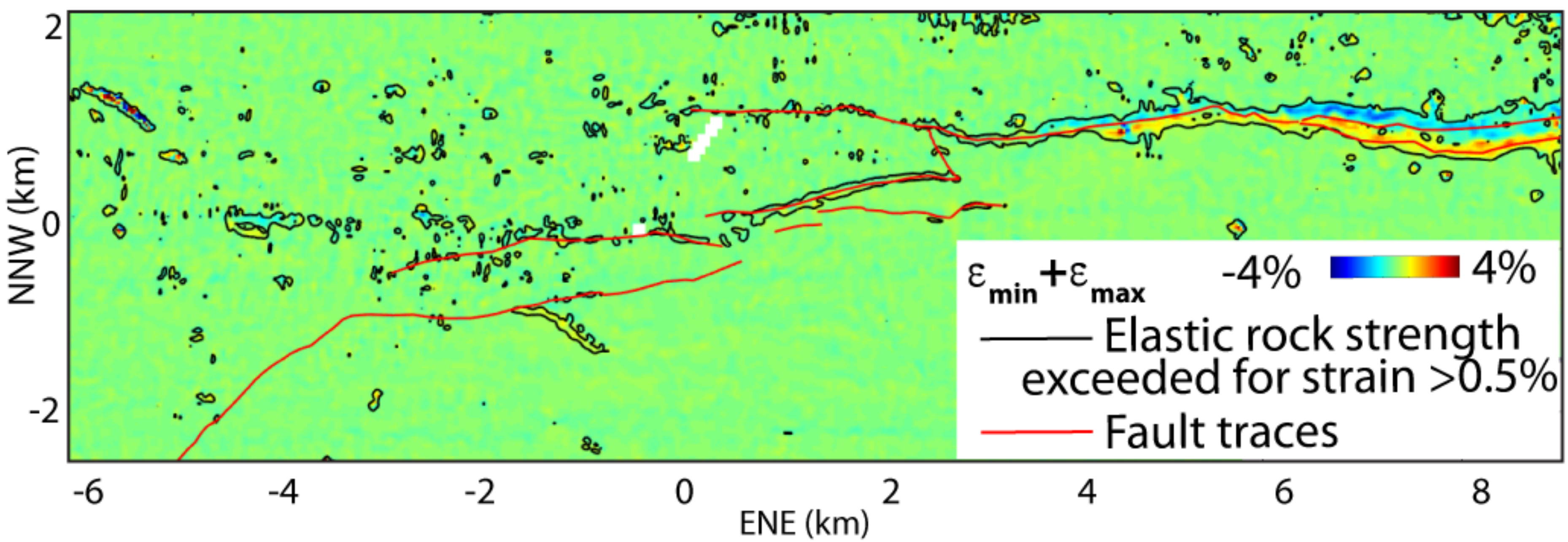
Coseismic strain

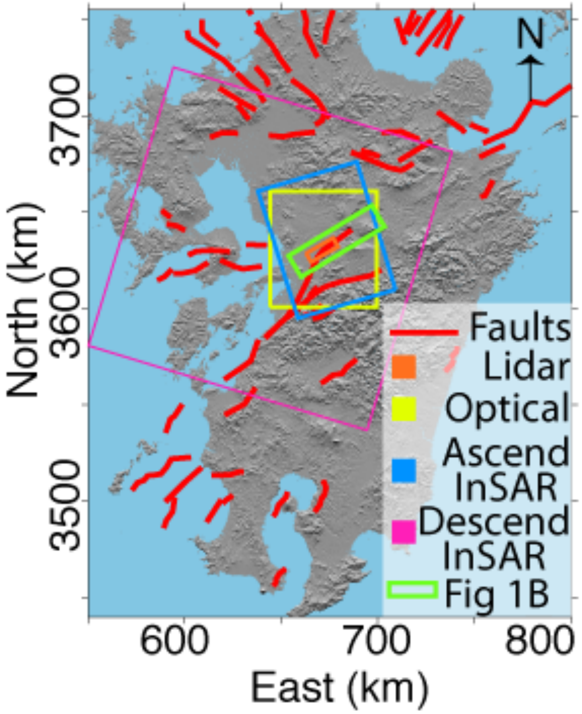
First invariant of 2D strain tensor (area change)

Elastic strain limit:

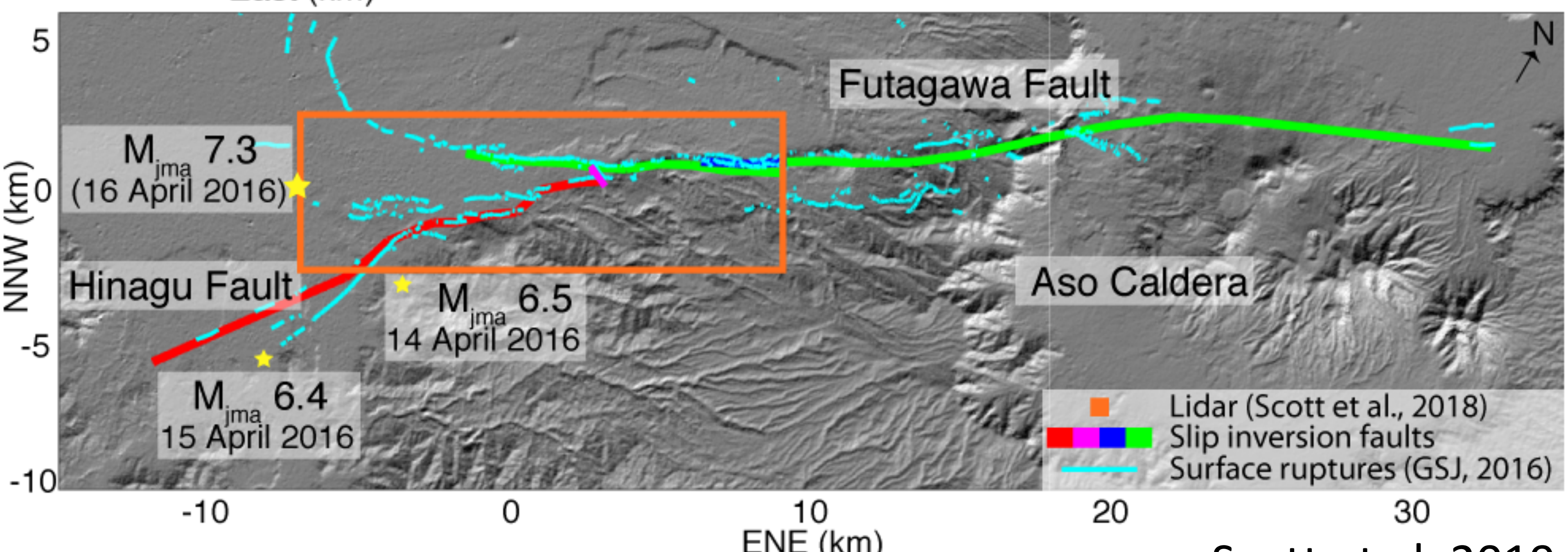
$$\varepsilon_{yield} = \sigma_{yield} / E \approx 0.5\%$$





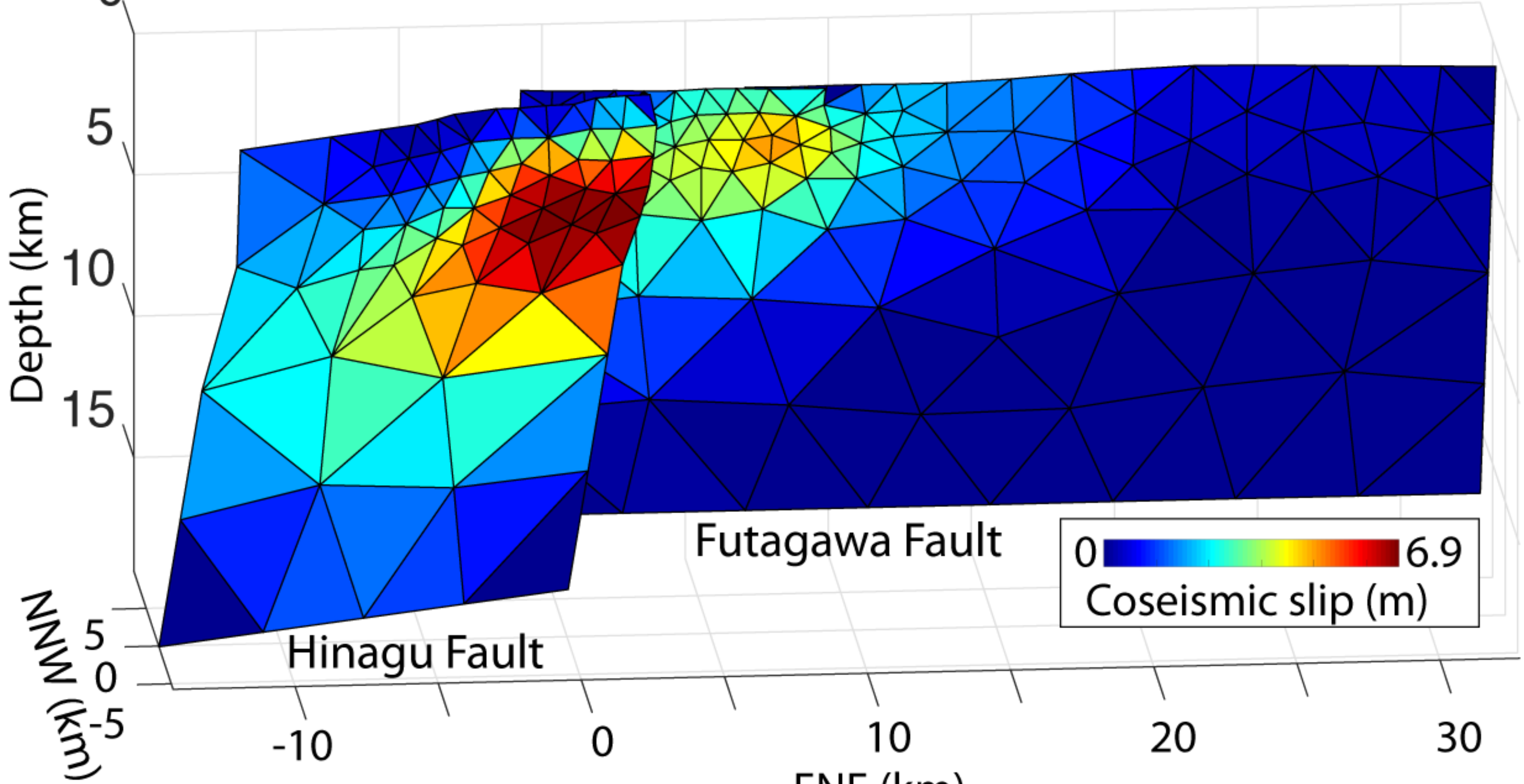


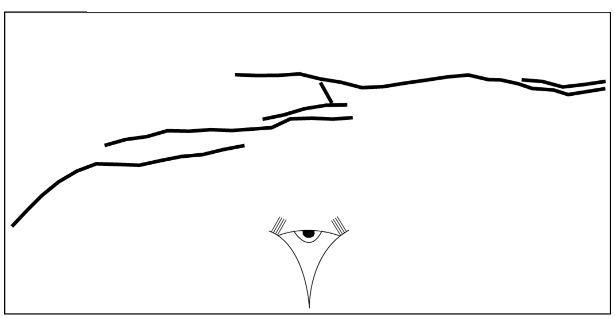
Joint differential lidar topography- optical correlation- InSAR earthquake source inversion



Scott et al. 2019

Distributed slip inversion: Mw 7.09↓−0.05↑+0.03

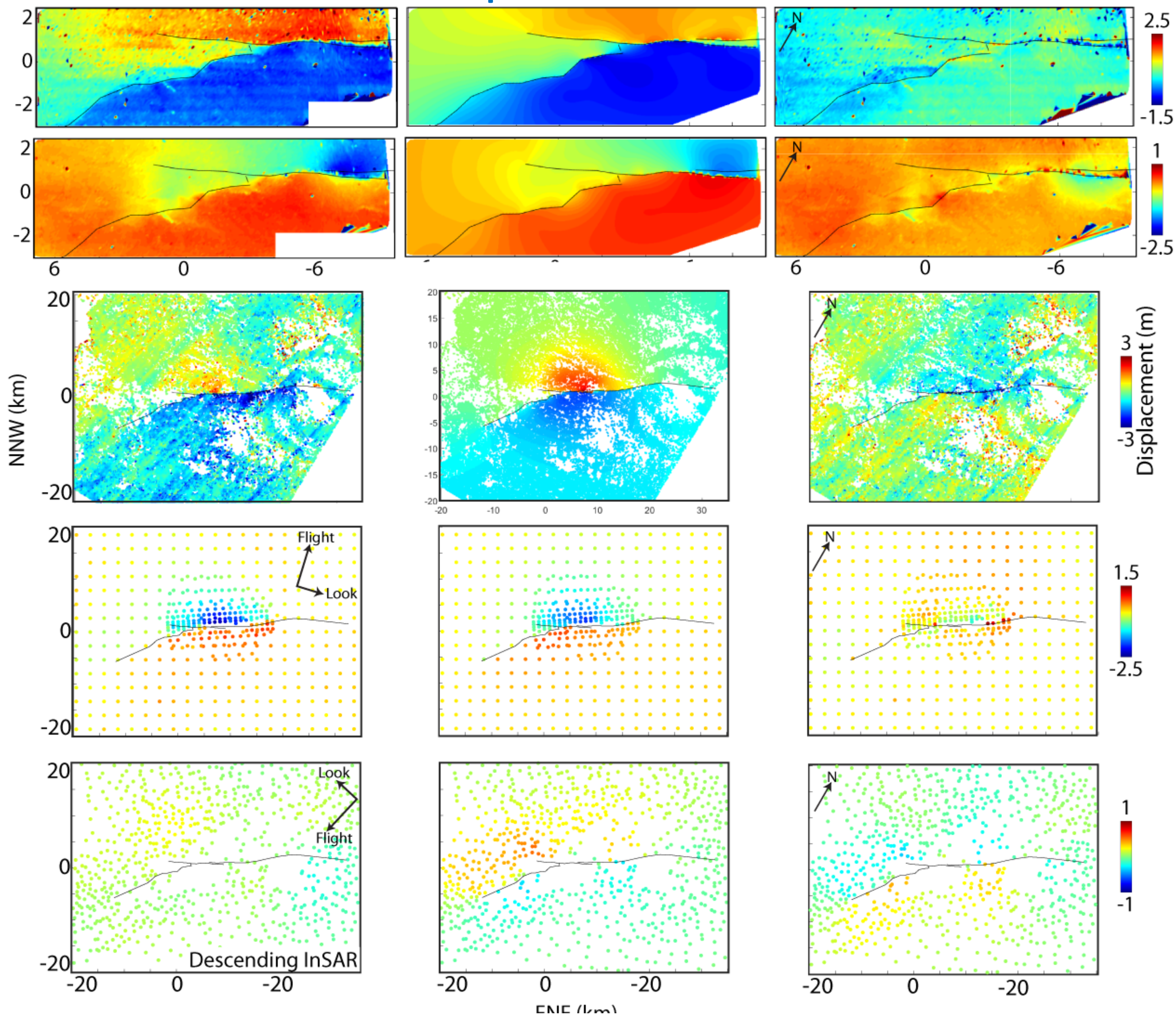




Datasets: Topographic differencing, optical correlation, InSAR

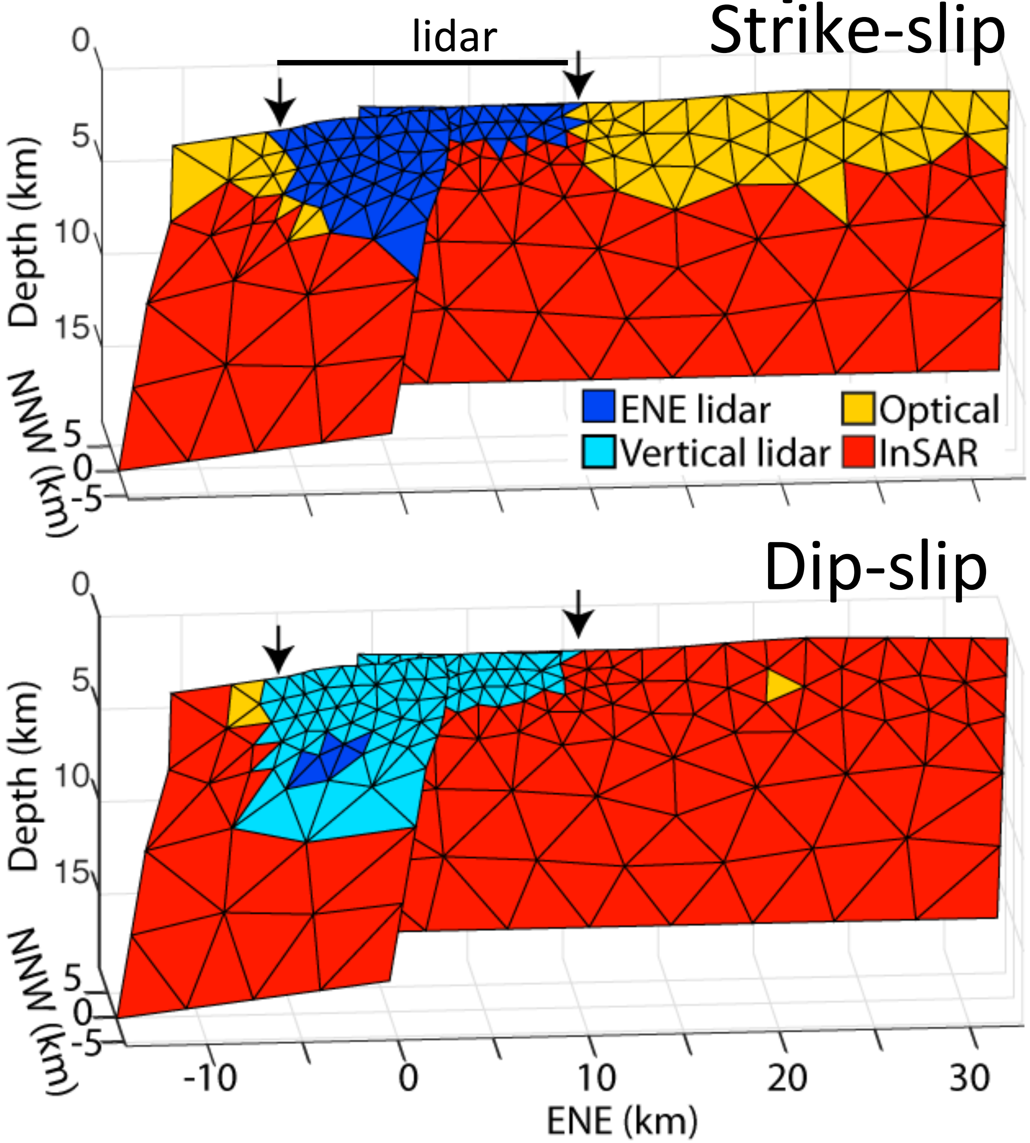
Scott et al. 2019

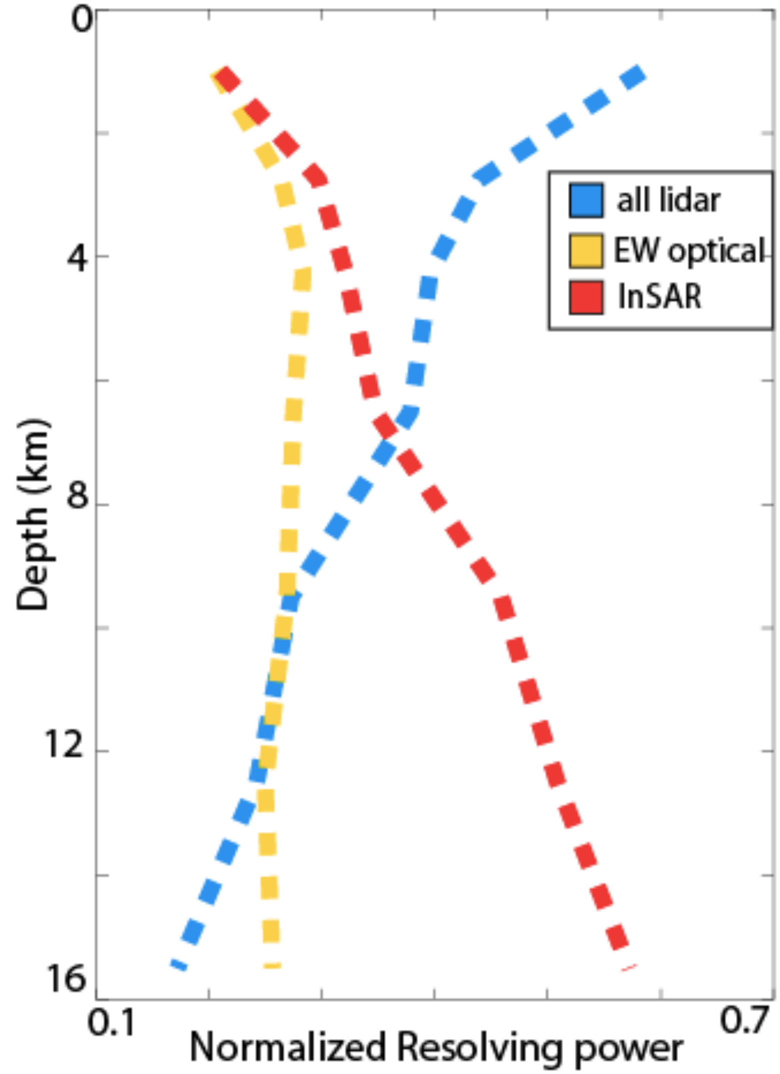
	Displacement	Slip model Displacement	Residual
Lidar			
Optical			
InSAR			



Scott et al. 2019

Fault slip constraints

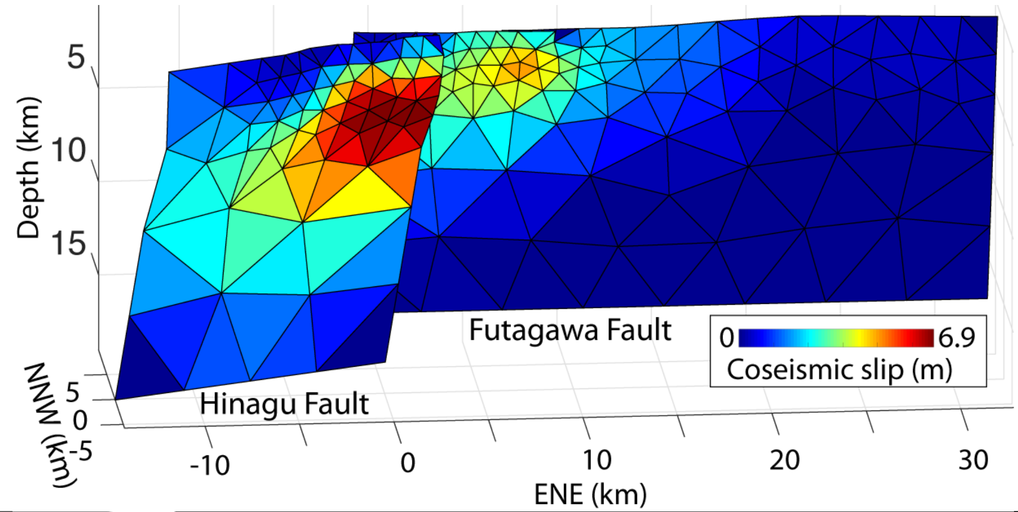


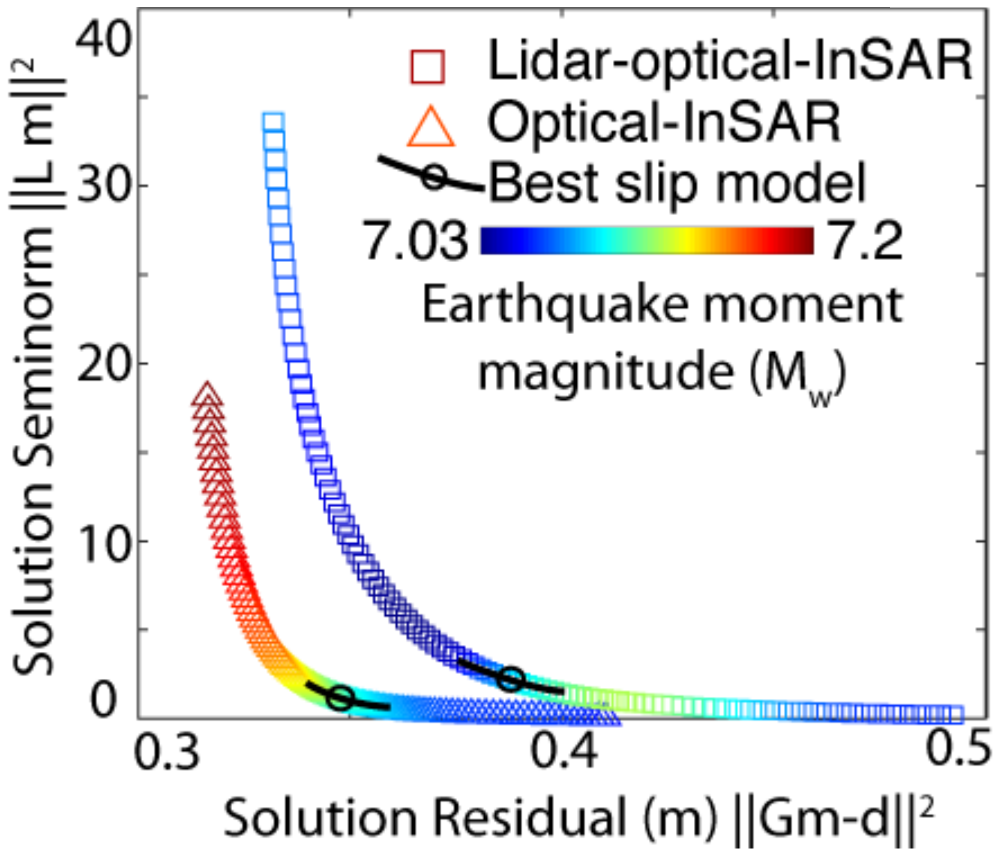


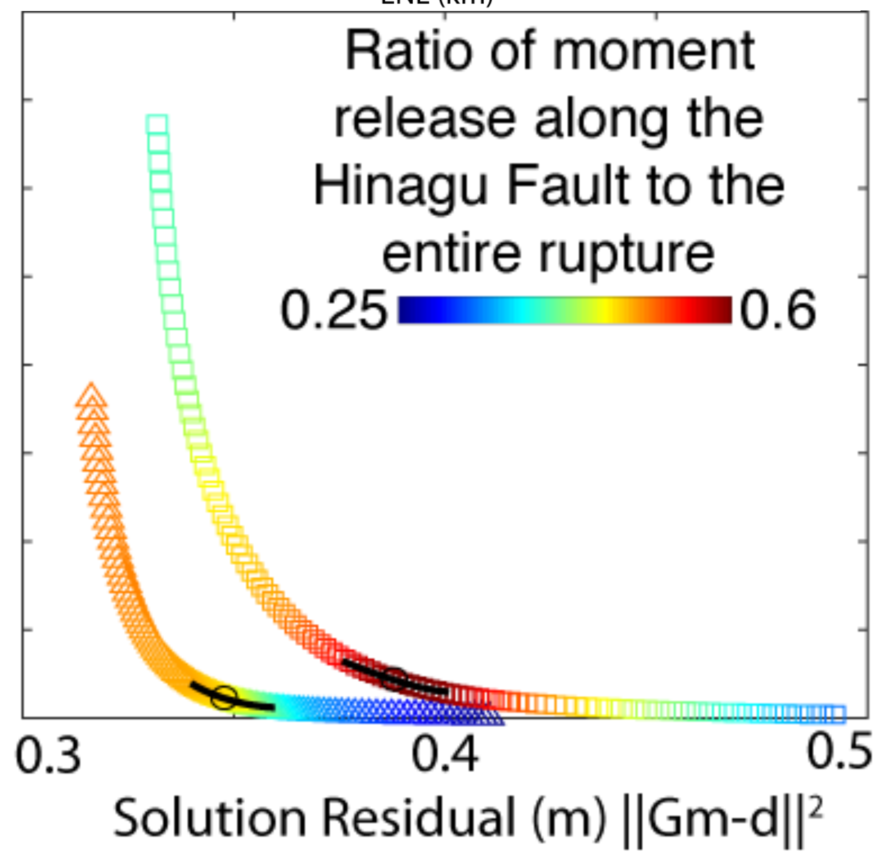
Grand Challenges in Geodesy:
The need to better express data constraints

Scott et al. 2019

Slip Inversion Regularization





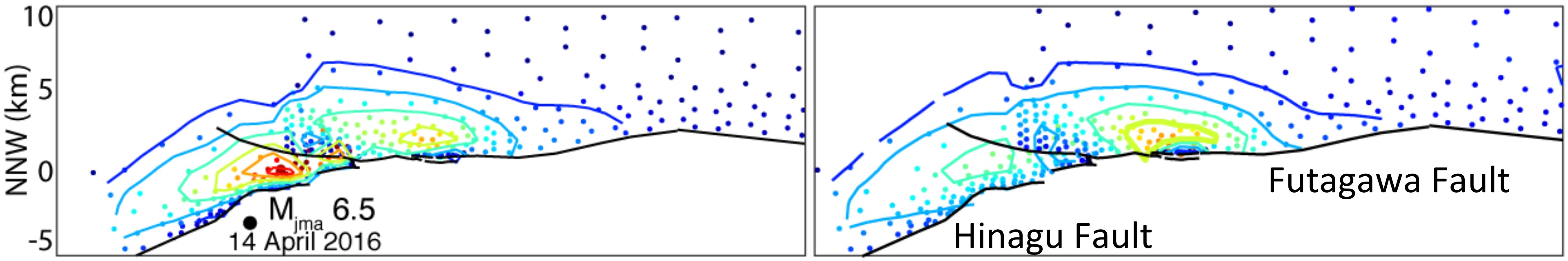


Scott et al. 2019

Compare slip inversions

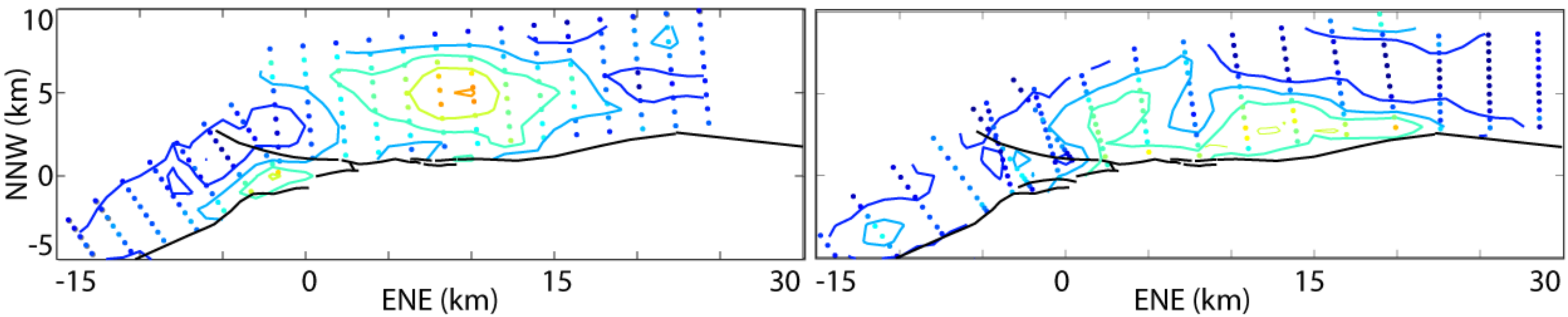
Topography, optical, InSAR

Optical, InSAR



Asano & Iwata (2016):
Strong motion seismic

Kobayashi et al. (2017):
Strong motion seismic,
teleseismic, GNSS

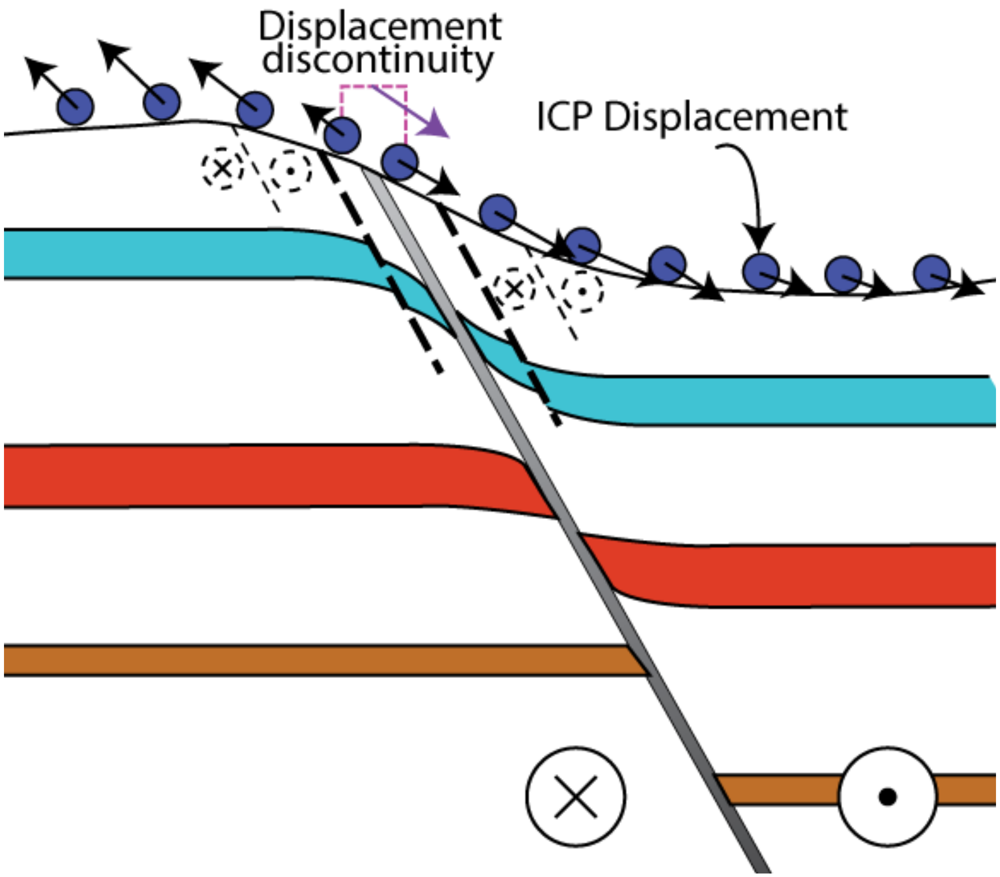


Scott et al. 2019

Science Conclusions

We examine surface deformation and coseismic fault slip from differential topography, optical correlation, and InSAR imagery.

The inelastic failure of damaged fault zone rocks caused by the high strains produces a distributed deformation signal.



The apparent on-fault slip depletion is likely accommodated as off-fault inelastic deformation.

Future earthquakes will likely be recorded with hybrid datasets. New opportunity to learn about shallow fault slip.

Next: Broader impacts

Undergrad differencing lab

Grand Challenges in Geodesy:

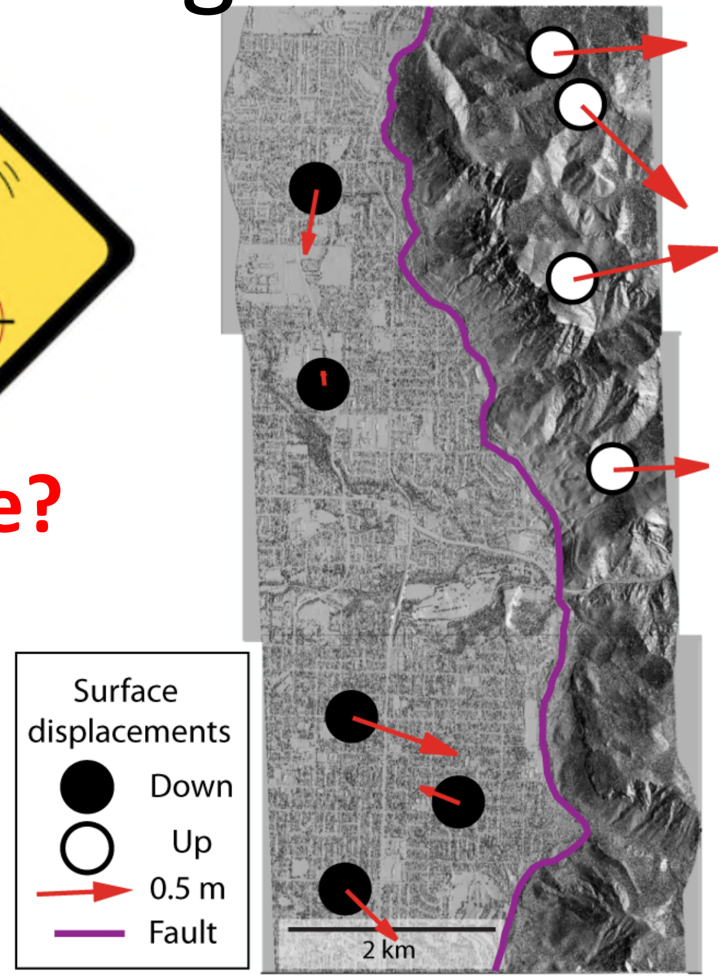
Frequent mention of education

Integration of geodesy and data science

Where?

Size?

Fault type?



Students pretend to work for the Utah GS following a hypothetical EQ:

(1) Visualize how earthquakes deform landscapes.

(2) Relate fault slip, surface displacement, and earthquake magnitude.

(3) Interpret quantitative geospatial datasets with uncertainty.

www.opentopography.org/learn/ugrad_differencing

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Undergraduate Topographic Differencing Exercise

After a big earthquake people ask, 'Where did the earthquake occur? How big was it? What type of fault was activated.' We design an undergraduate laboratory exercise where students learn how geologists use airborne lidar data to answer these questions for a synthetic earthquake along the Wasatch Fault in Salt Lake City, Utah. Students use remote sensing data to measure how much and in what direction the ground moves during an earthquake. They explore classical faulting relationships by estimating the earthquake magnitude and determining the type of fault activated (e.g., normal, reverse, strike-slip). In addition, students learn about the hazard and scientific response required for large surface rupturing earthquakes and are exposed to cutting-edge technology for working with topography data.

Pre-earthquake topography:

Post-earthquake topography:

Material includes:

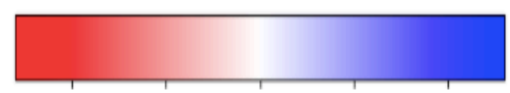
- Pre-laboratory lecture
- Lab handout
- Student video
- Pre- and post- earthquake topographic datasets
- By request to cpscott1@asu.edu:
- Solutions video

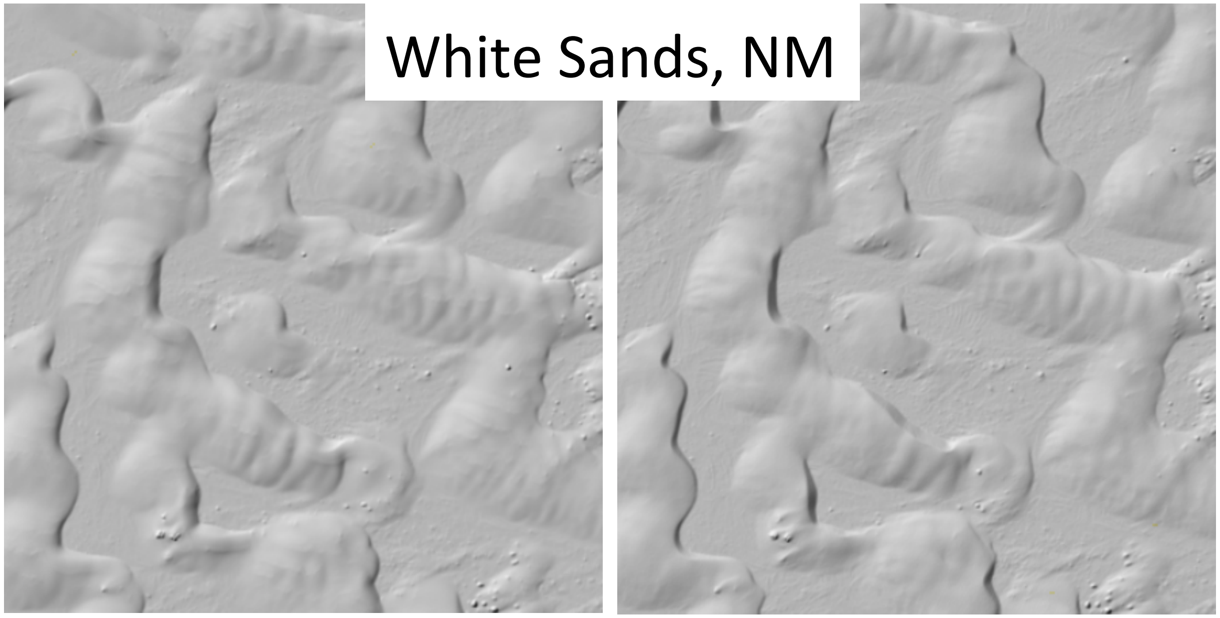
OpenTopography

On-demand Topographic differencing

Infrastructure damage during the 2016 M7 Kumamoto earthquake

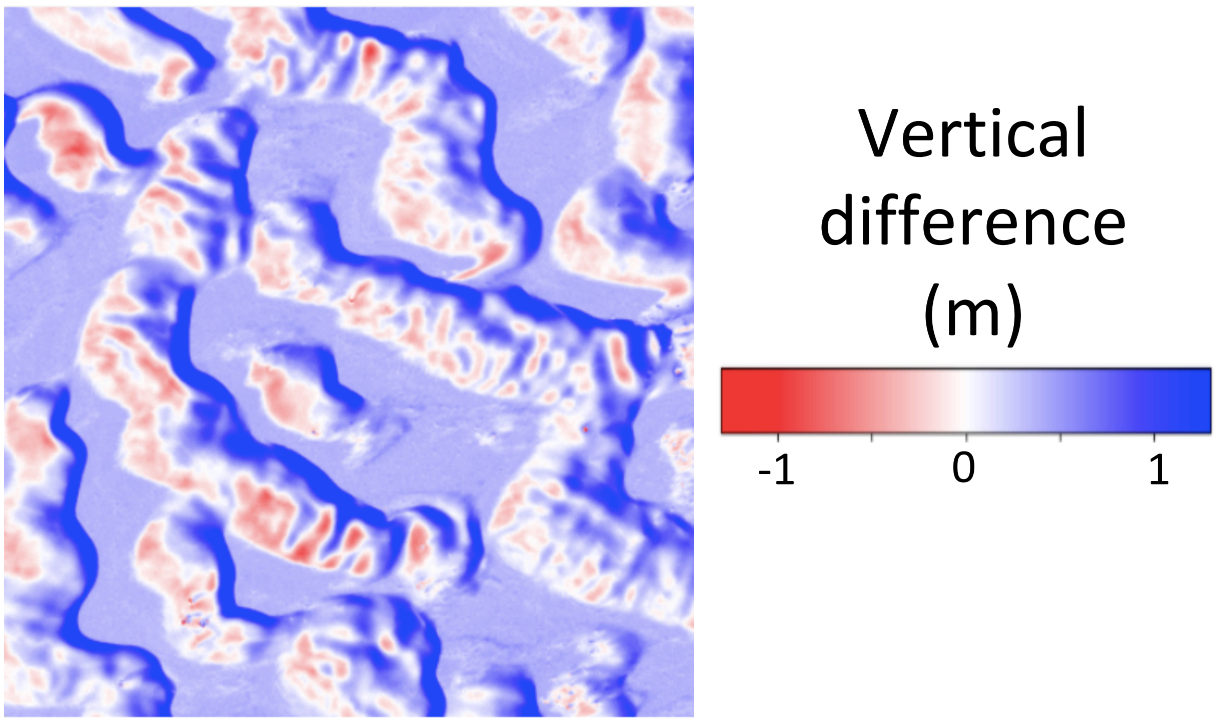
Vertical difference (m)





Compare: 2009

Reference: 2010



Workflow

Overlapping data

Identical grids

Raster subtraction

Error threshold

Challenges

Legacy data
- Invaluable
- Quality control

Hybrid data
- point cloud and raster
- TLS, SfM, global raster

Cyber-infrastructure

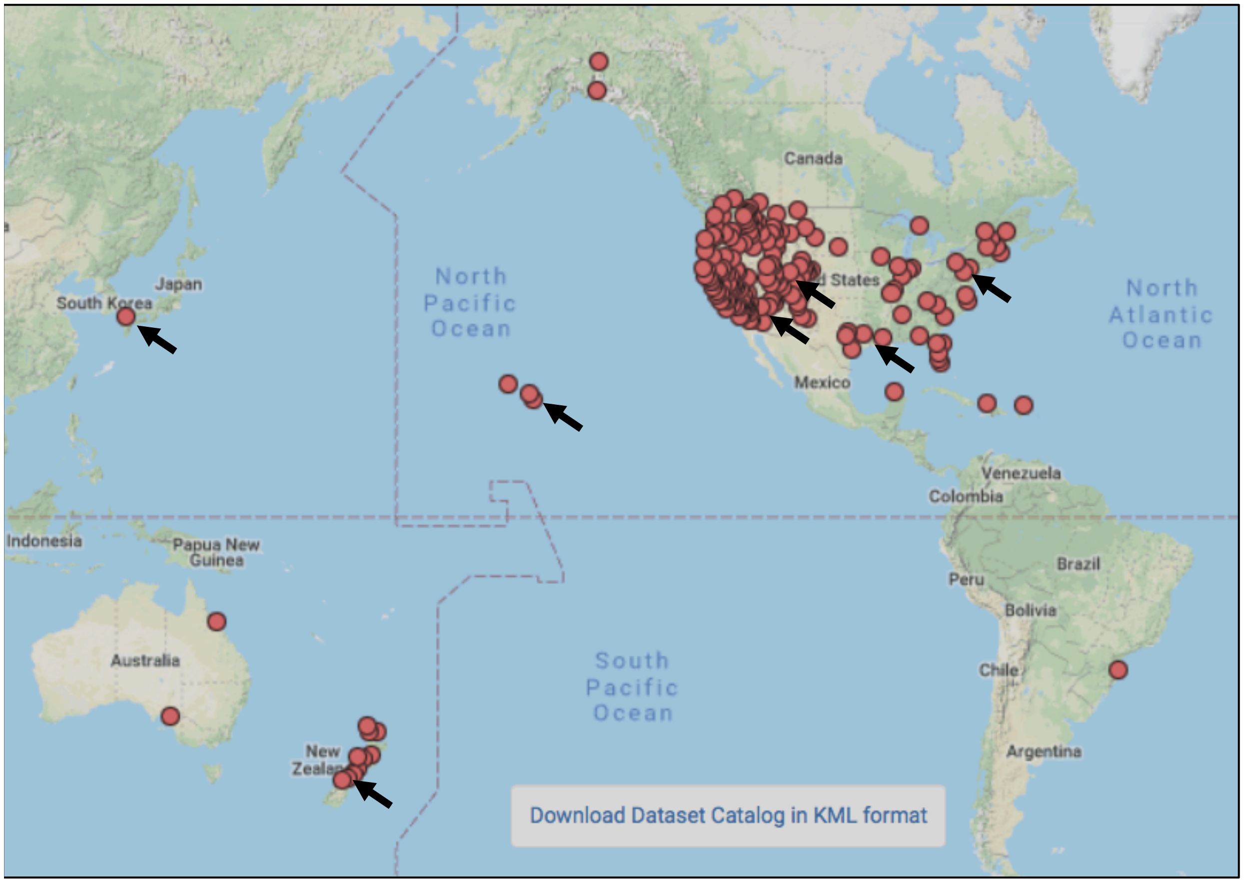
3D differencing: Coming soon

Scott et al. In Review

Where can I perform differencing?

www.opentopography.org

Change Detection



~40 dataset pairs

Critical Zones

Earthquakes

Volcanic eruptions

Rockfalls

Fluvial Processes

Landslides

Urban growth

Many geomorphic and active tectonic processes

Thank you!

Acknowledgements

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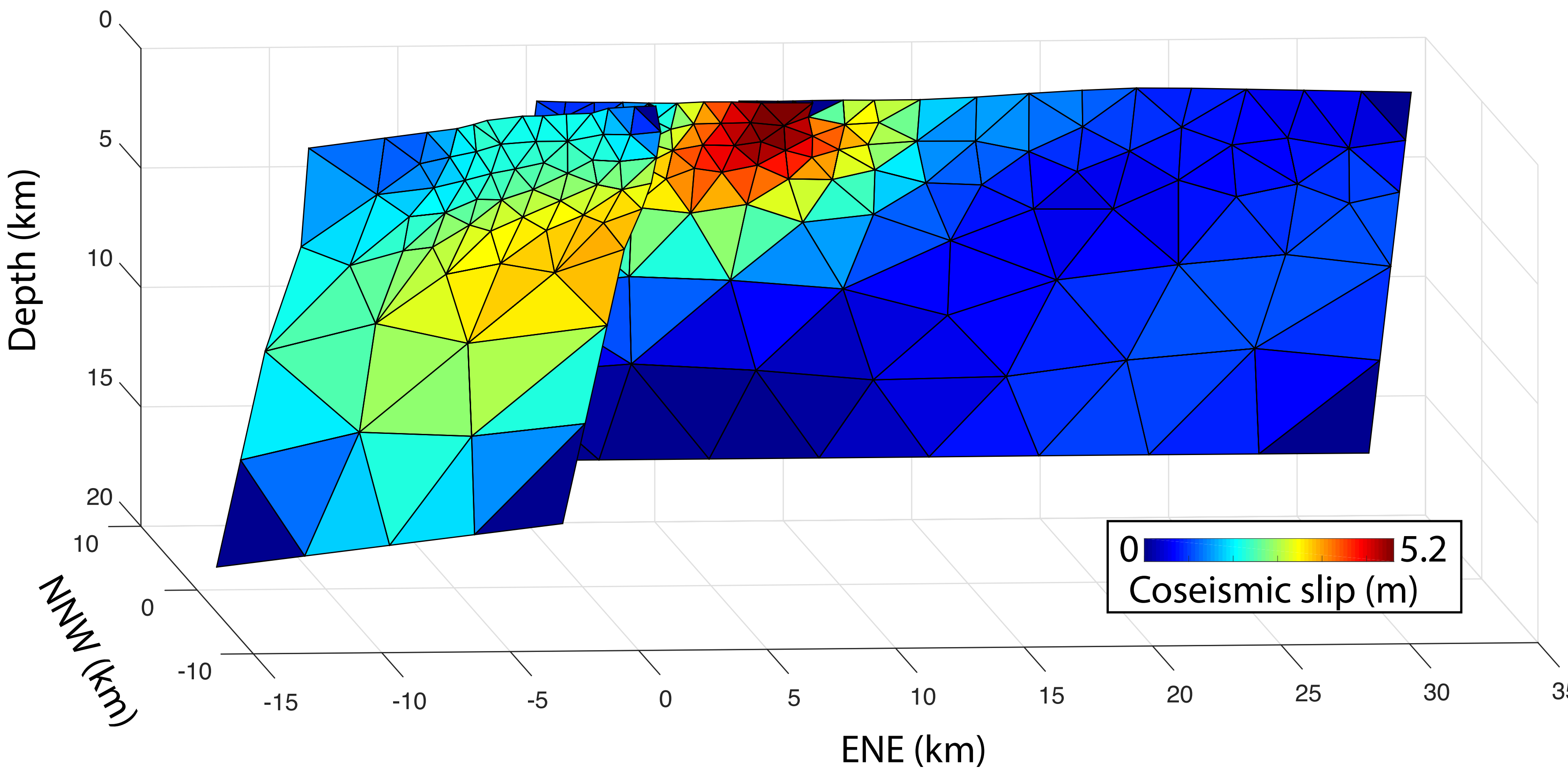
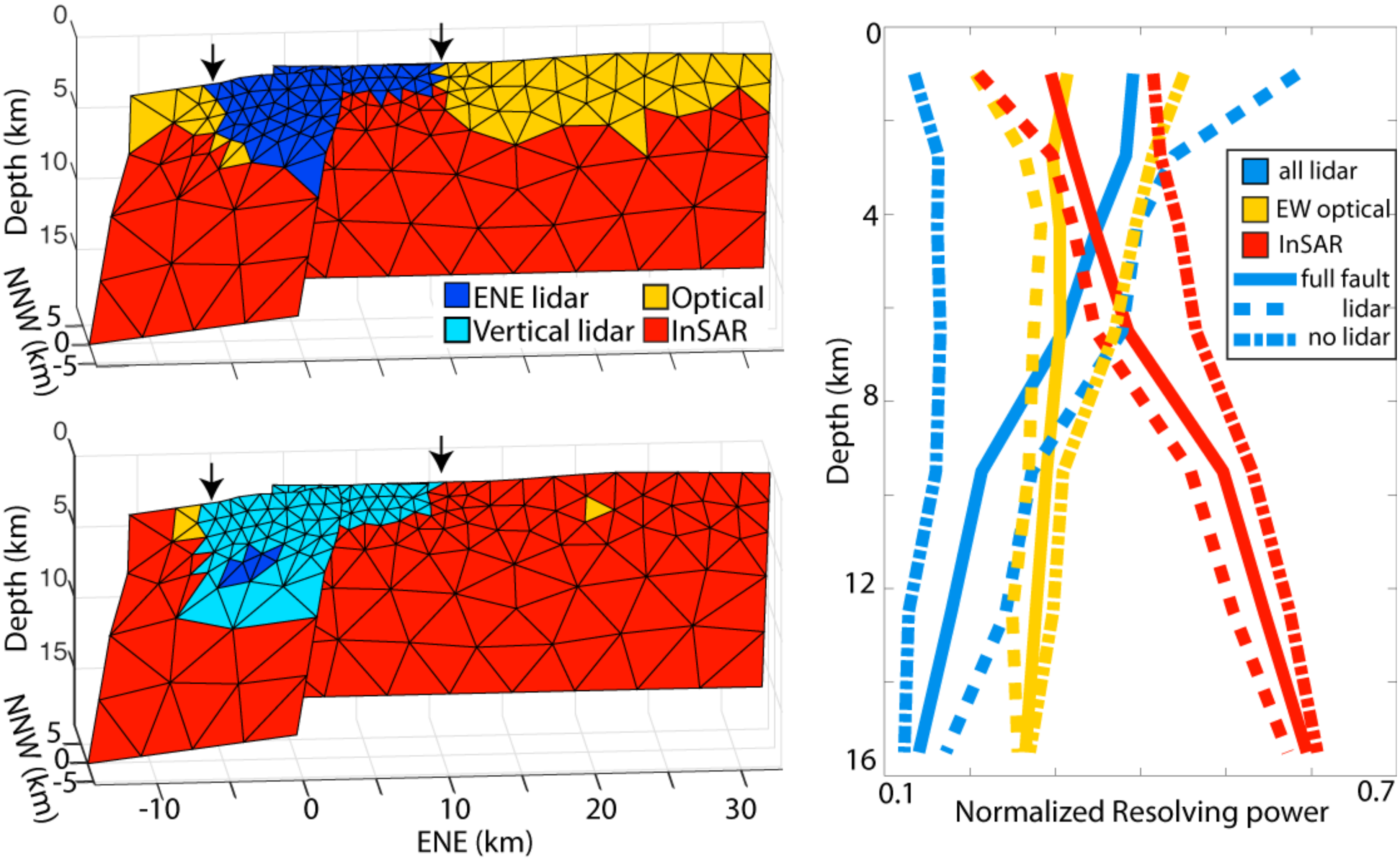
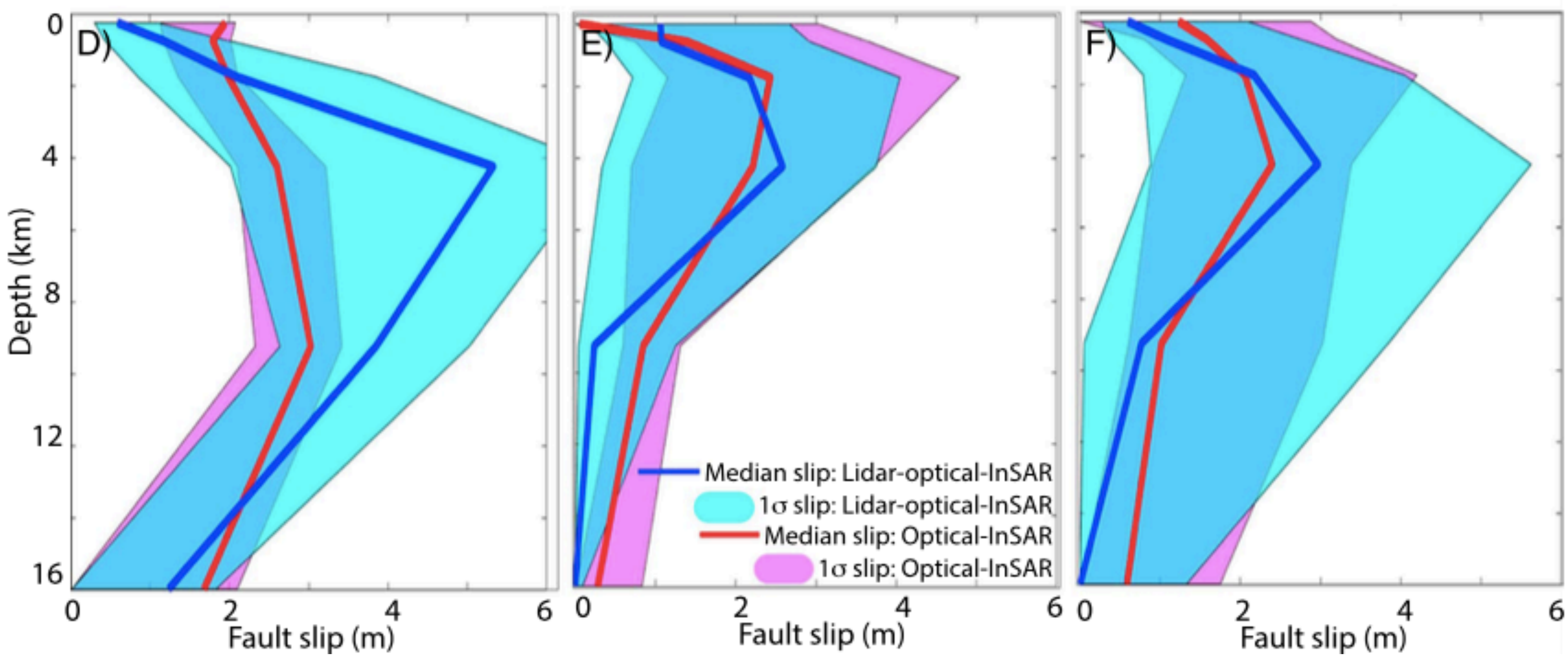
Optical Correlation-InSAR





Depth (km)
NNW (km)
ENE lidar
Vertical lidar
Optical
InSAR
ENE (km)
all lidar
EW optical
InSAR
full fault
lidar
no lidar
Normalized Resolving power
0.1
0.7



Hinagu Fault Futagawa Fault Entire Earthquake