Topographic differencing: 1983 M6.9 Borah Peak, Idaho, and 2016 M7.0 Kumamoto, Japan, earthquakes and the creep San Andreas Fault

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Introduction

Topographic differencing measures spatially dense & high amplitude vertical and 3D deformation surrounding faults.

2016 M7 Kumamoto earthquake: 3D deformation & inelastic strain

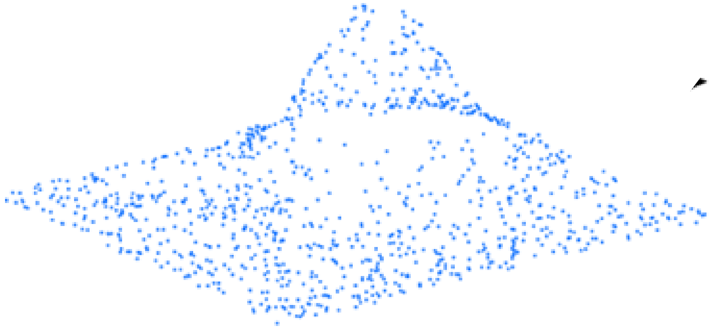
1983 M6.9 Borah Peak earthquake: Very old pre-data, field vs. remote sensing displacements

Central San Andreas Fault creep: First creep measured with differencing, rates and active fault

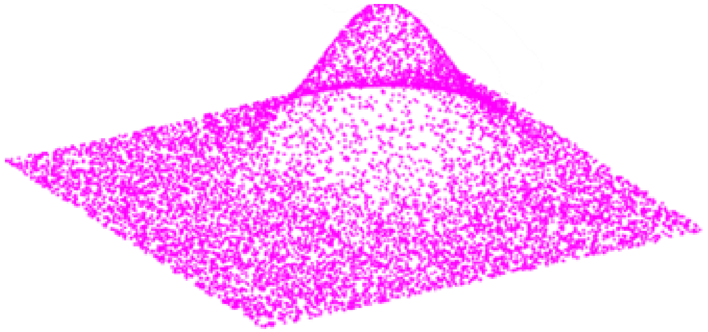
Vertical Topographic Differencing

Topographic data

Before the earthquake:

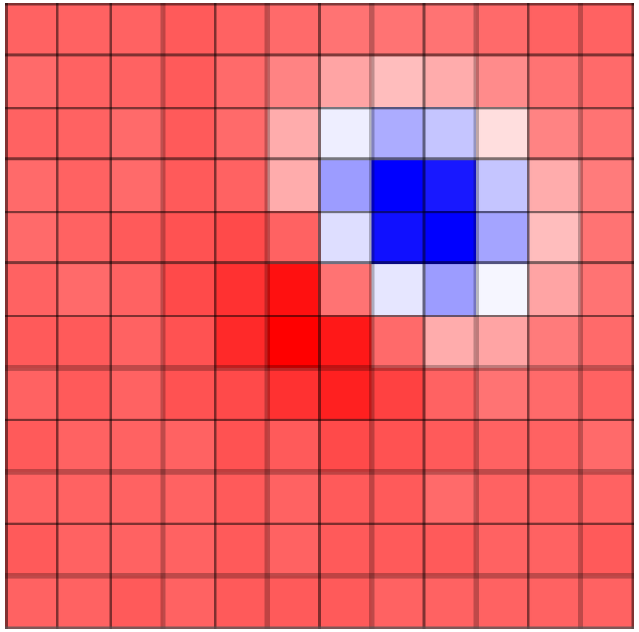


After the earthquake:

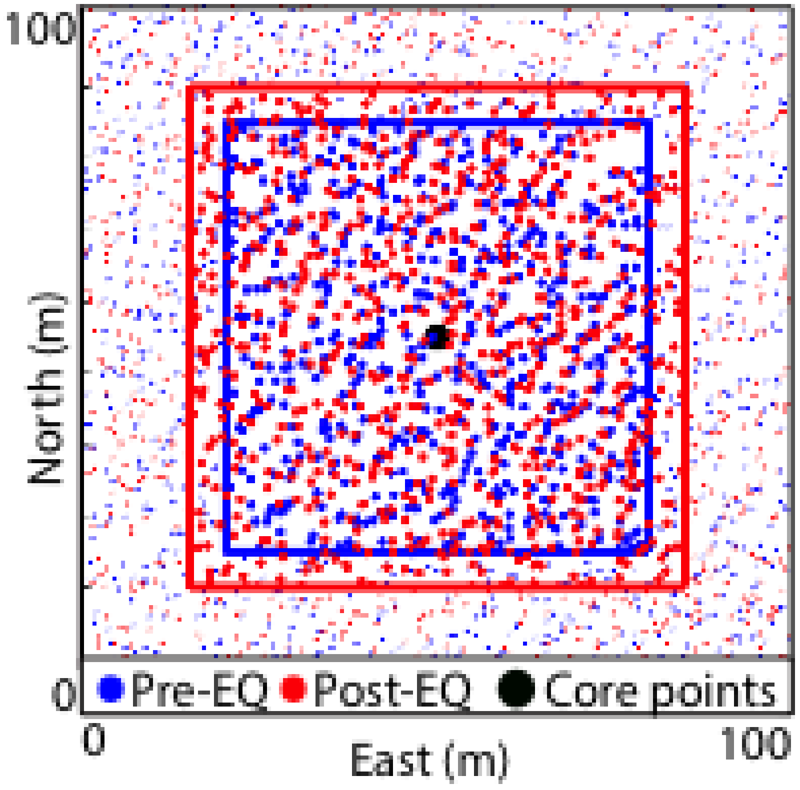


Difference = After- before

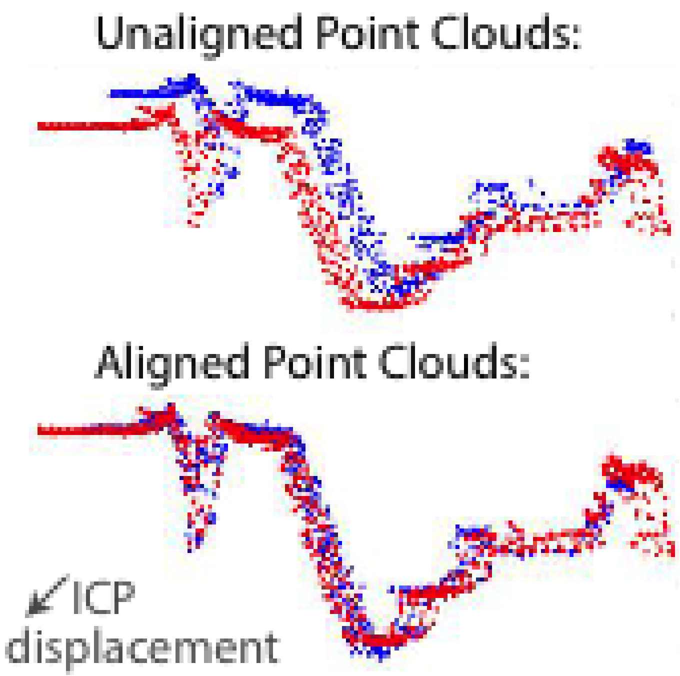
Down Up



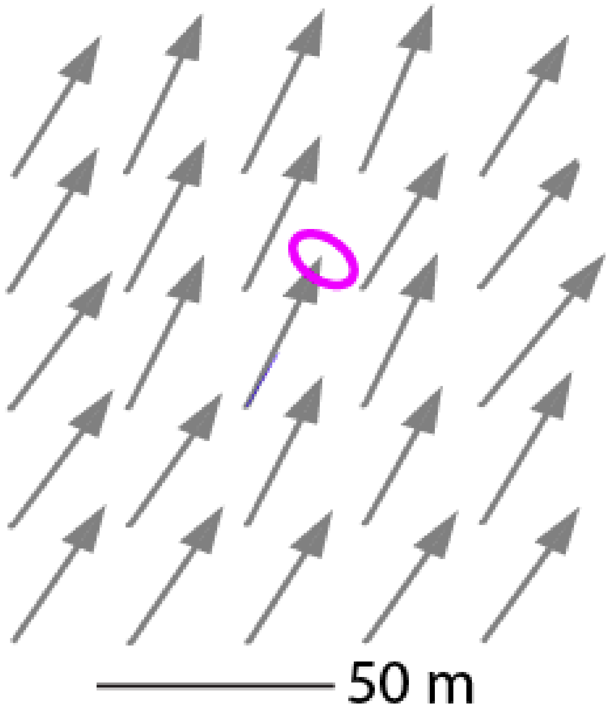
3D Topographic Differencing: Iterative Closest Point



Windowed subset of lidar topography



3D rigid-body deformation



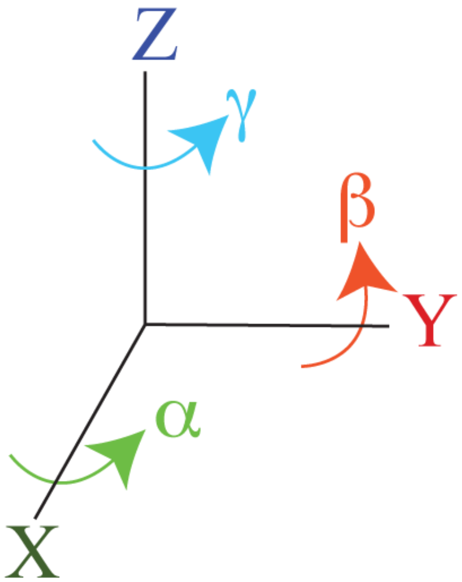
Uncertainty

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

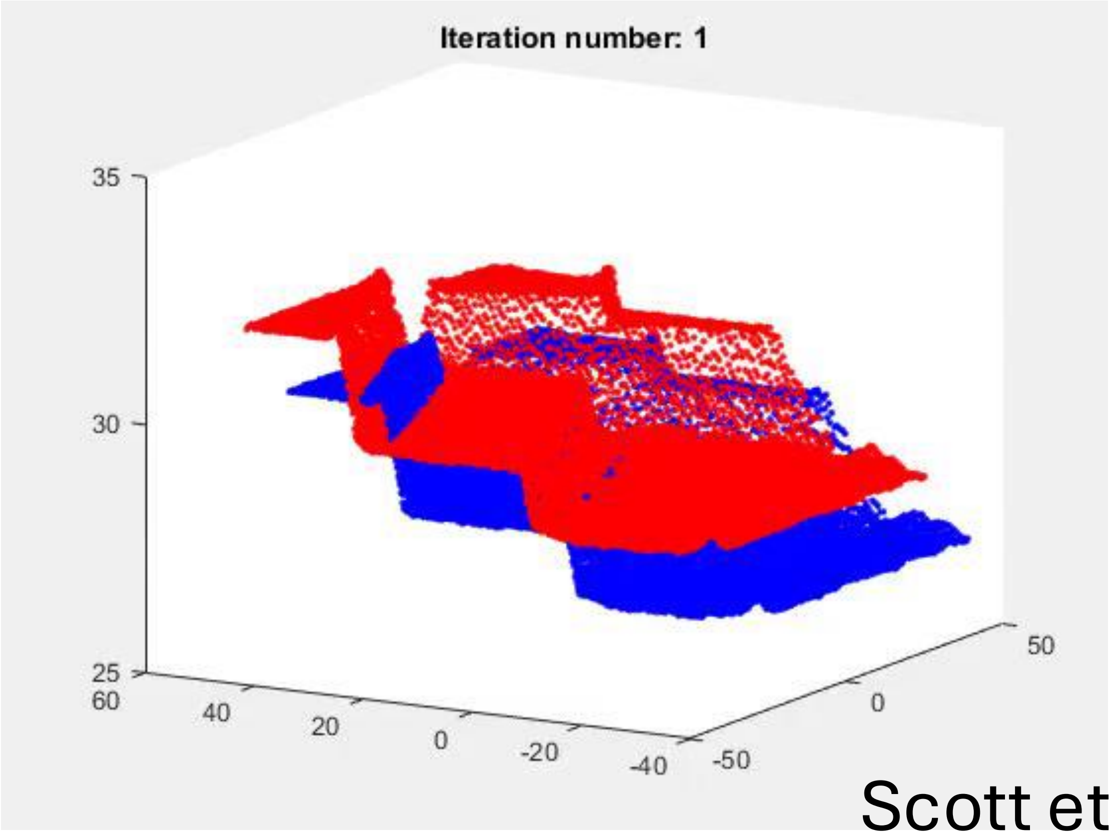
3D coseismic deformation

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

Rotation Translation



Coordinate system



Rigid body deformation to align pre- and post- earthquake point clouds

Scott et al., (2018)

2016 M7 Kumamoto Earthquake

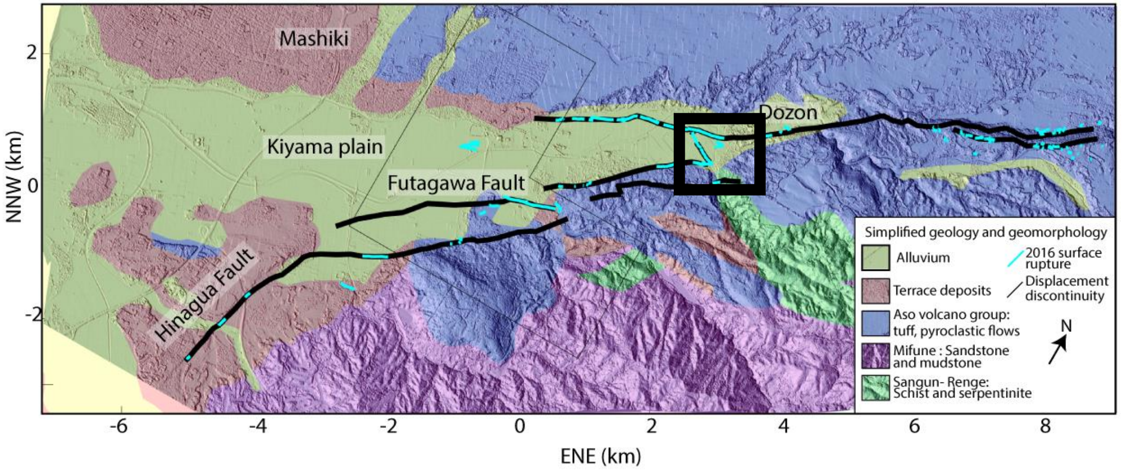
Lidar	Date
Pre (1 day)	15 April, ’16
Post	23 April, ‘16

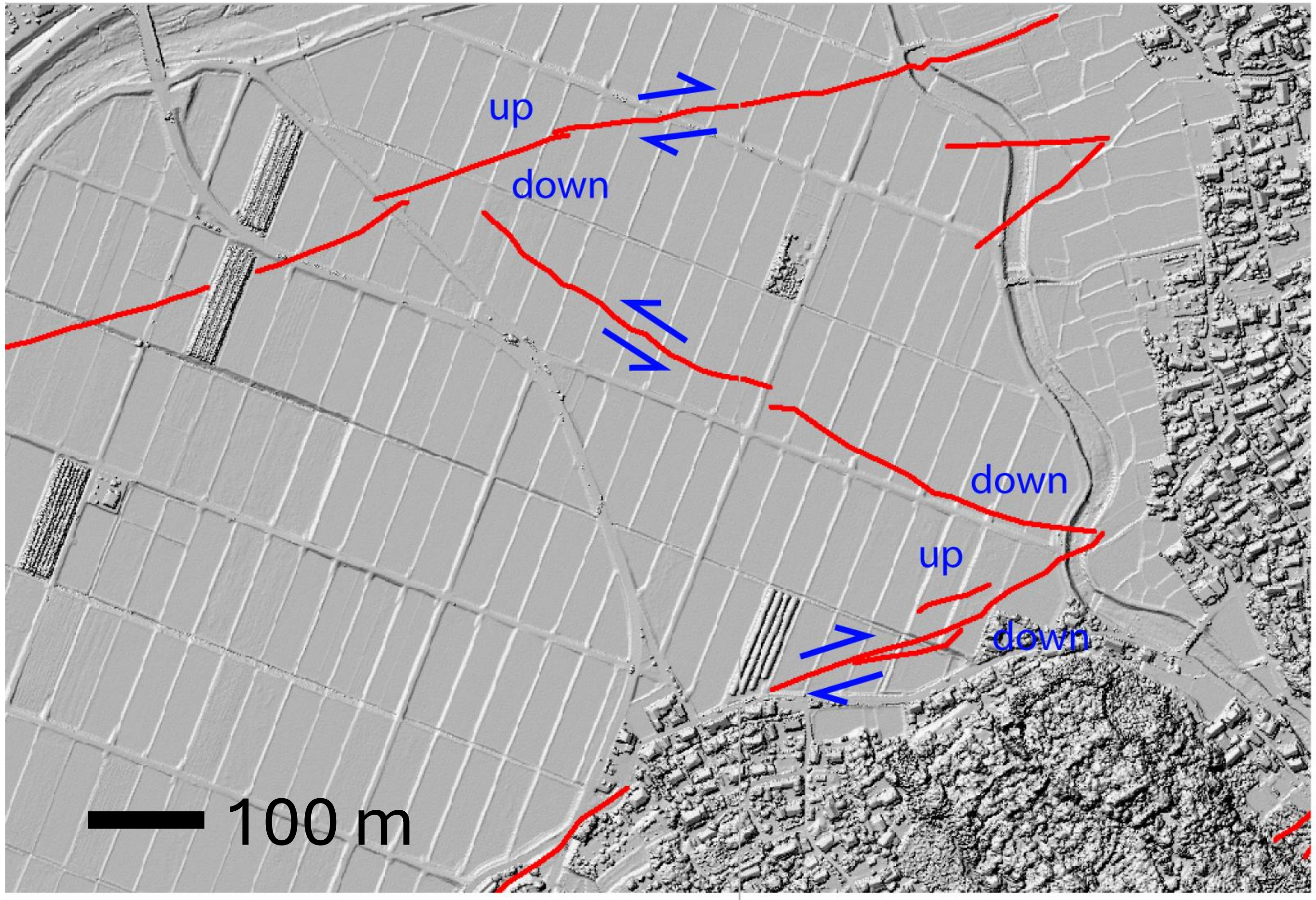
AGU100 ADVANCING EARTH AND SPACE SCIENCE
JGR
Journal of Geophysical Research: Solid Earth
RESEARCH ARTICLE
10.1029/2018JB015581

Key Points:
- Three-dimensional coseismic displacements constrained from differential lidar topography reveal complexity in the on- and off-fault

The *M*7 2016 Kumamoto, Japan, Earthquake: 3-D Deformation Along the Fault and Within the Damage Zone Constrained From Differential Lidar Topography

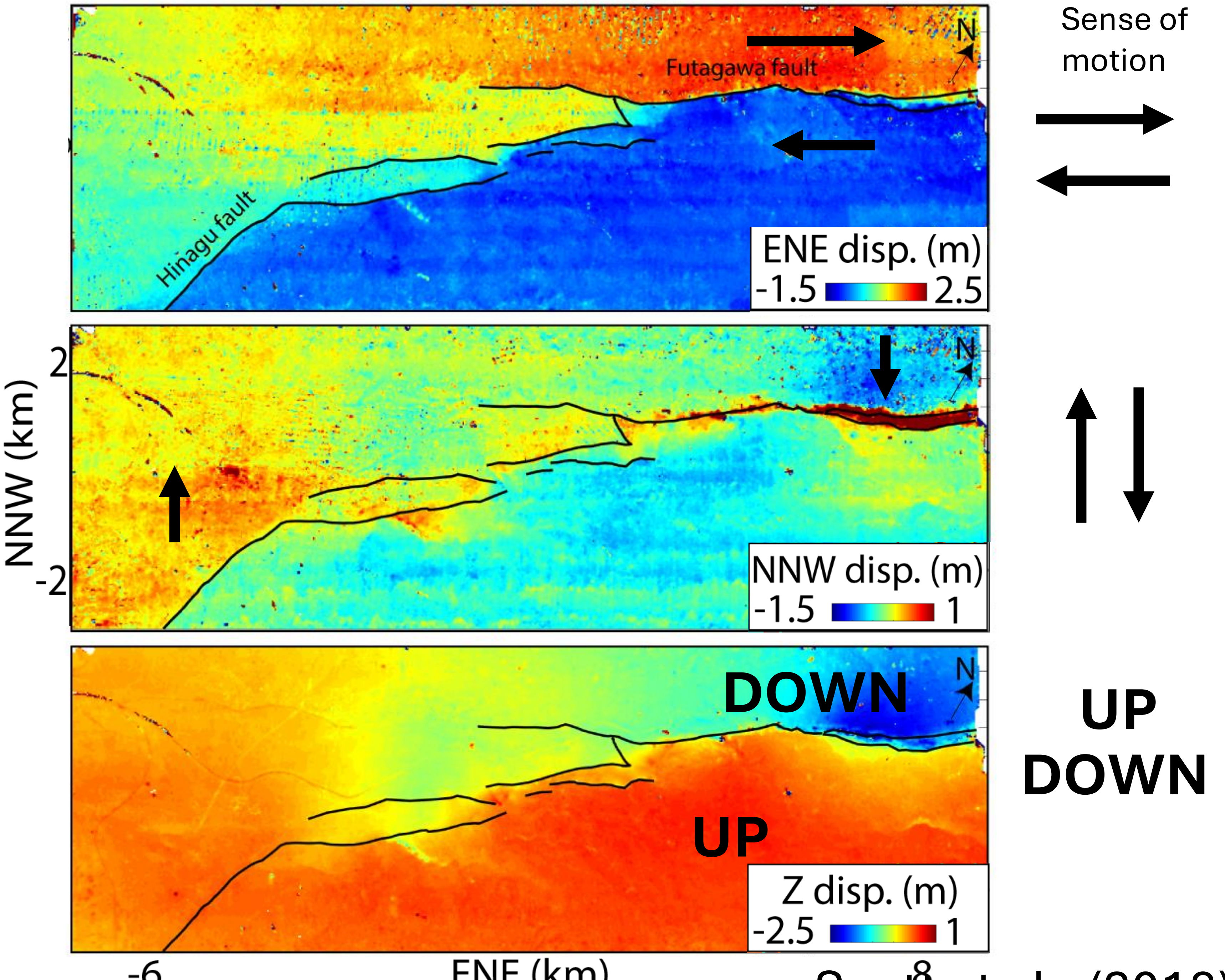
Chelsea P. Scott[1], J Ramon Arrowsmith[1], Edwin Nissen[2], Lia Lajoie[3], Tadashi Maruyama[4], and Tatsuro Chiba[5]





Scott et al., (2018)

3D Displacement Fields

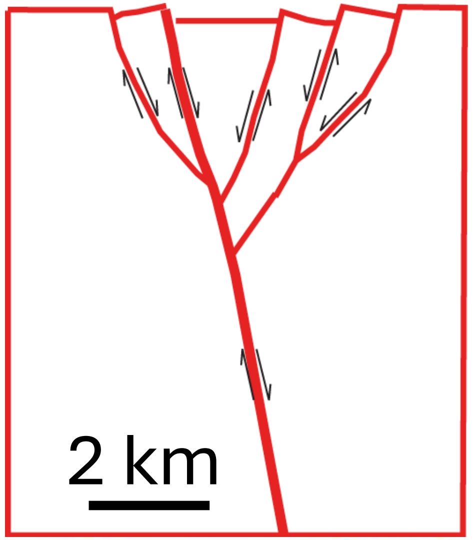


Scott et al., (2018)

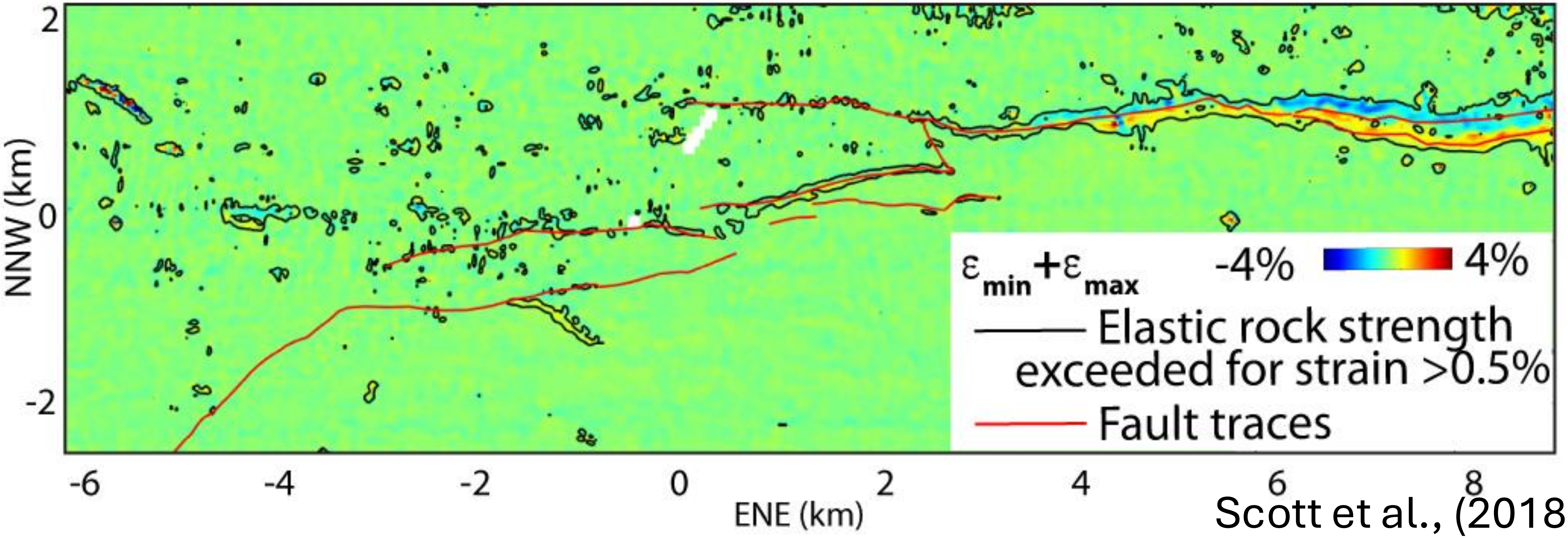
Coseismic strain

First invariant of the 2D strain tensor (area change)

Elastic strain limit:
$\varepsilon_{yield} = \sigma_{yield} / E \square 0.5\%$



500 m wide zone of extension (red)/ contraction (blue), broader than shear strain
Inelastic begins where displacement >50 cm



Scott et al., (2018)

1983 M6.9 Borah Peak, Idaho, earthquake

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Geophysical Research Letters

RESEARCH LETTER
10.1029/2025GL115882

Unveiling Coseismic Deformation From Differenced Legacy Aerial Photography and Modern Lidar Topography: The 1983 M6.9 Borah Peak Earthquake, Idaho, USA

Chelsea P. Scott[1], Nadine G. Reitman[2], and Simone Bello[3,4,5]

Key Points:

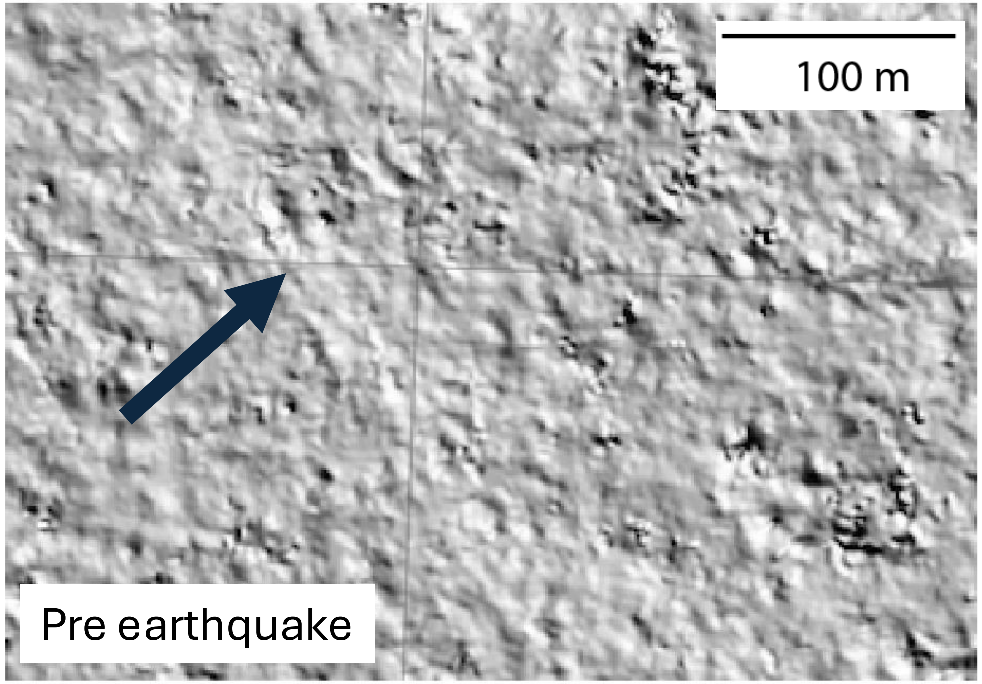
- We measured the 1983 M6.9 Borah Peak earthquake's vertical change by differencing 1966 aerial imagery with

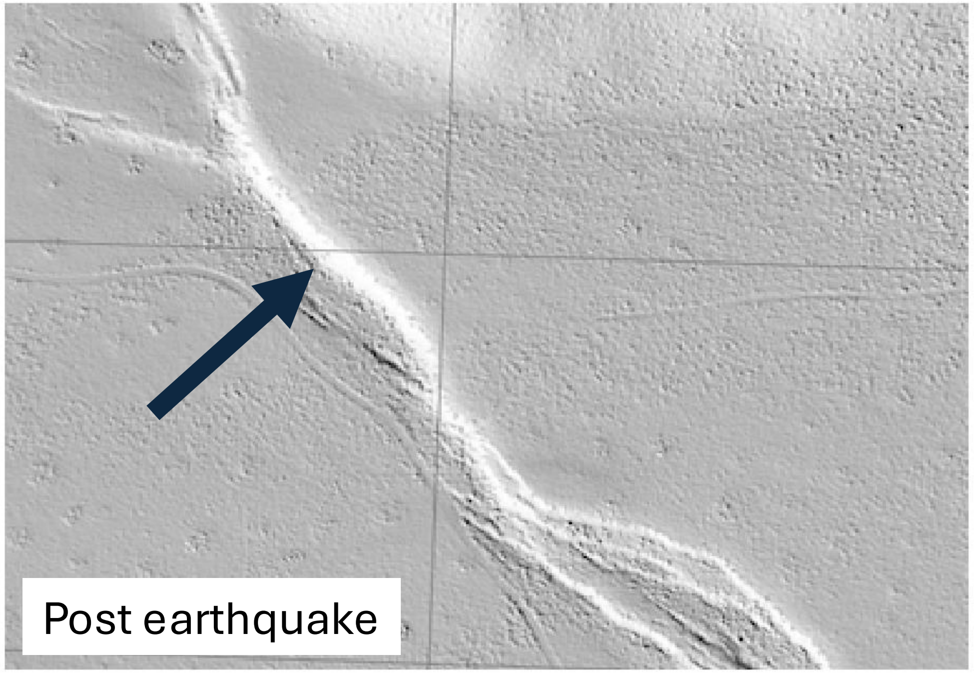
Differencing of the 1983 Borah Peak, Idaho, Earthquake

	Pre	Post
Year	1966	2019
Type	234 scanned aerial images	USGS 3DEP lidar
Point cloud	0.4 points/m^2	20 points/m^2
Accuracy	Meters- to 10-m scale, 18 benchmarks	10 cm

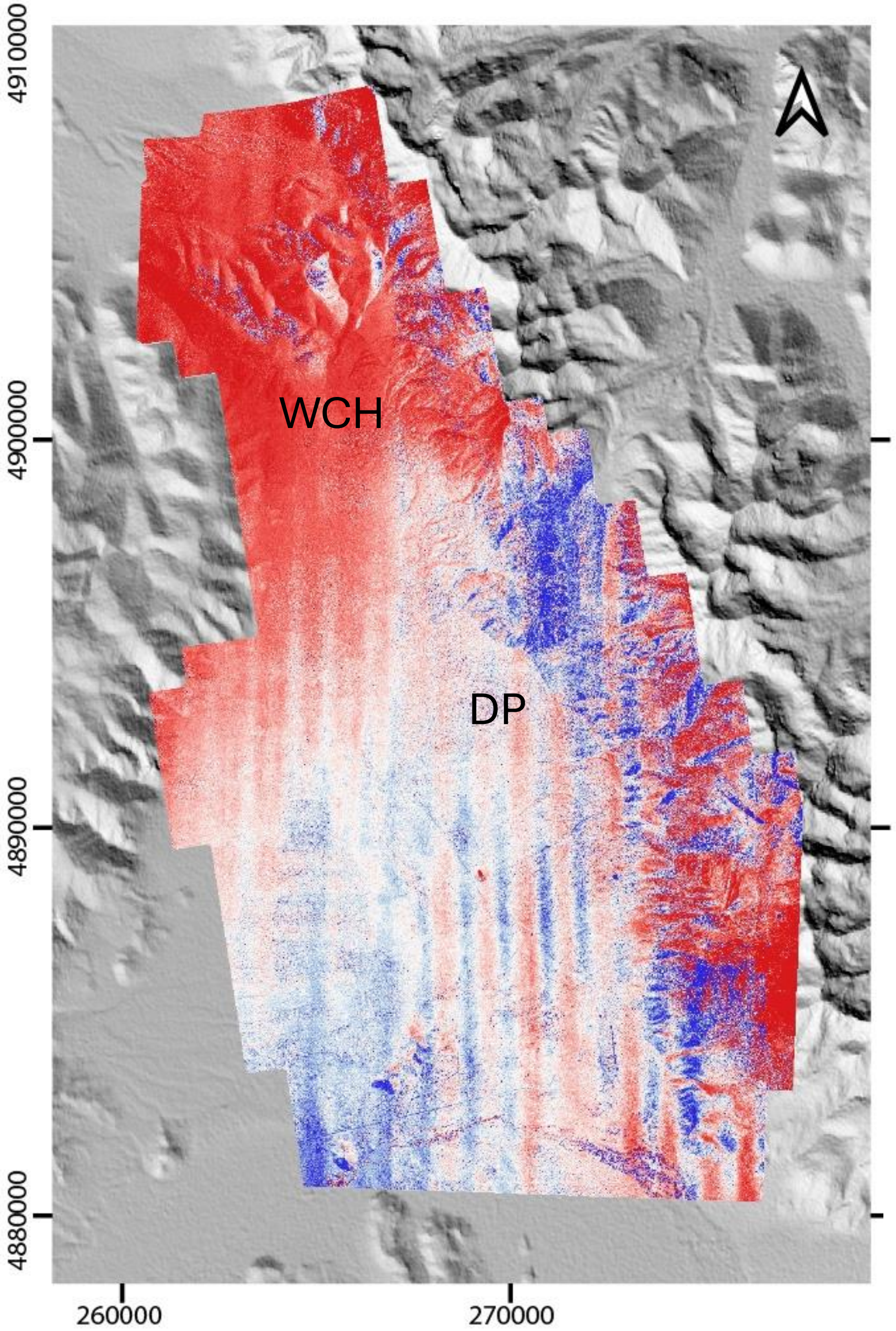
Relatively simple when:

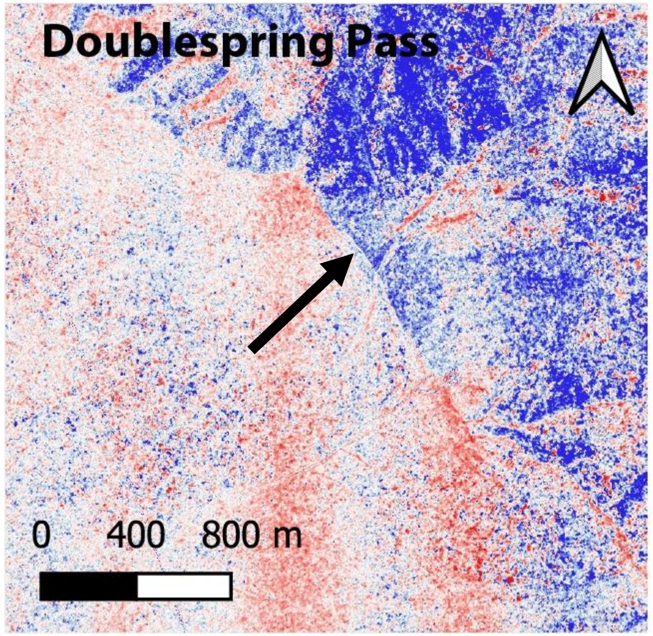
- Signal >> noise: *No, error larger*
- Same type data: *No, legacy imagery & lidar*
- Datasets tightly bracket earthquake: *No, acquired 53 years apart*

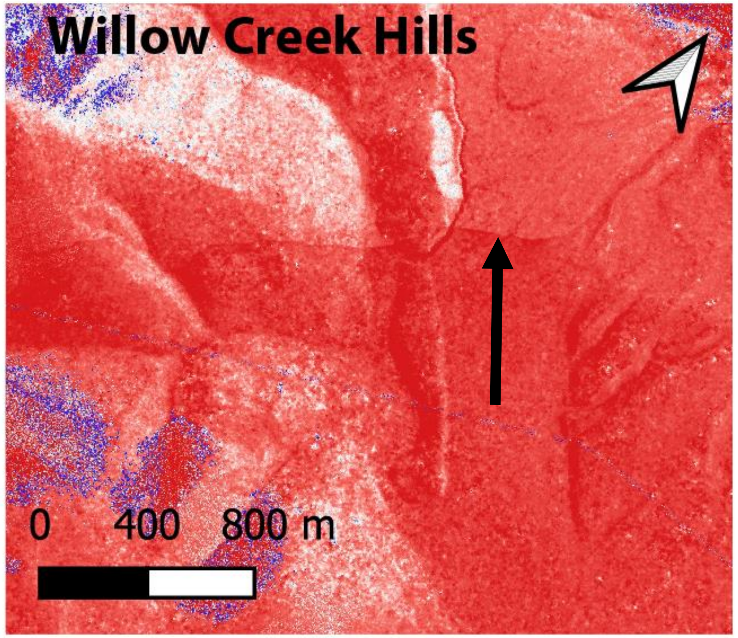




Initial Differencing Results







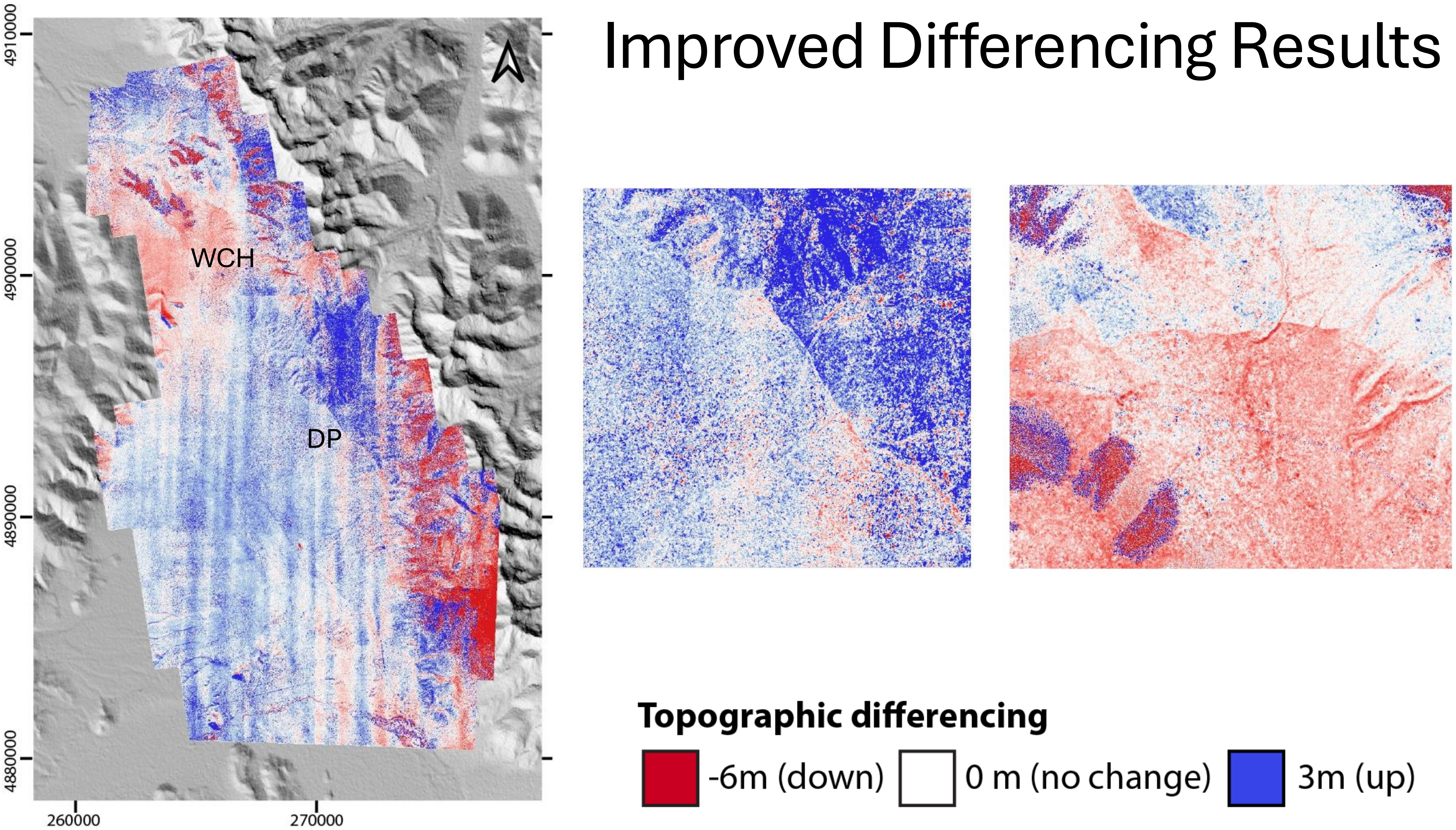
3 error sources:

- Flight line strips
- Vertical georeferencing errors
- Horizontal georeferencing errors

Topographic differencing

-6m (down) | 0 m (no change) | 3m (up)

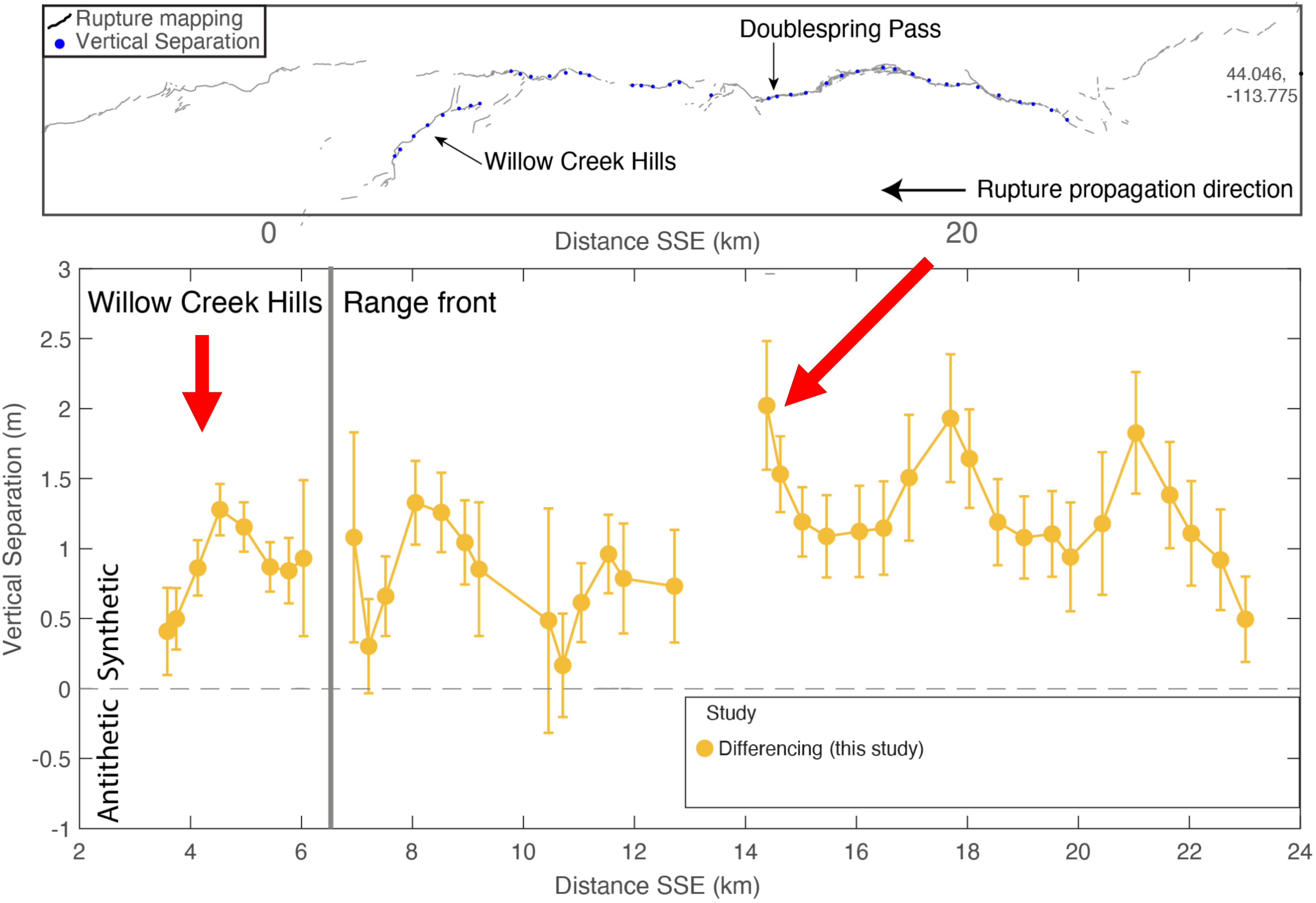
Improved Differencing Results



Topographic differencing

-6m (down) | 0 m (no change) | 3m (up)

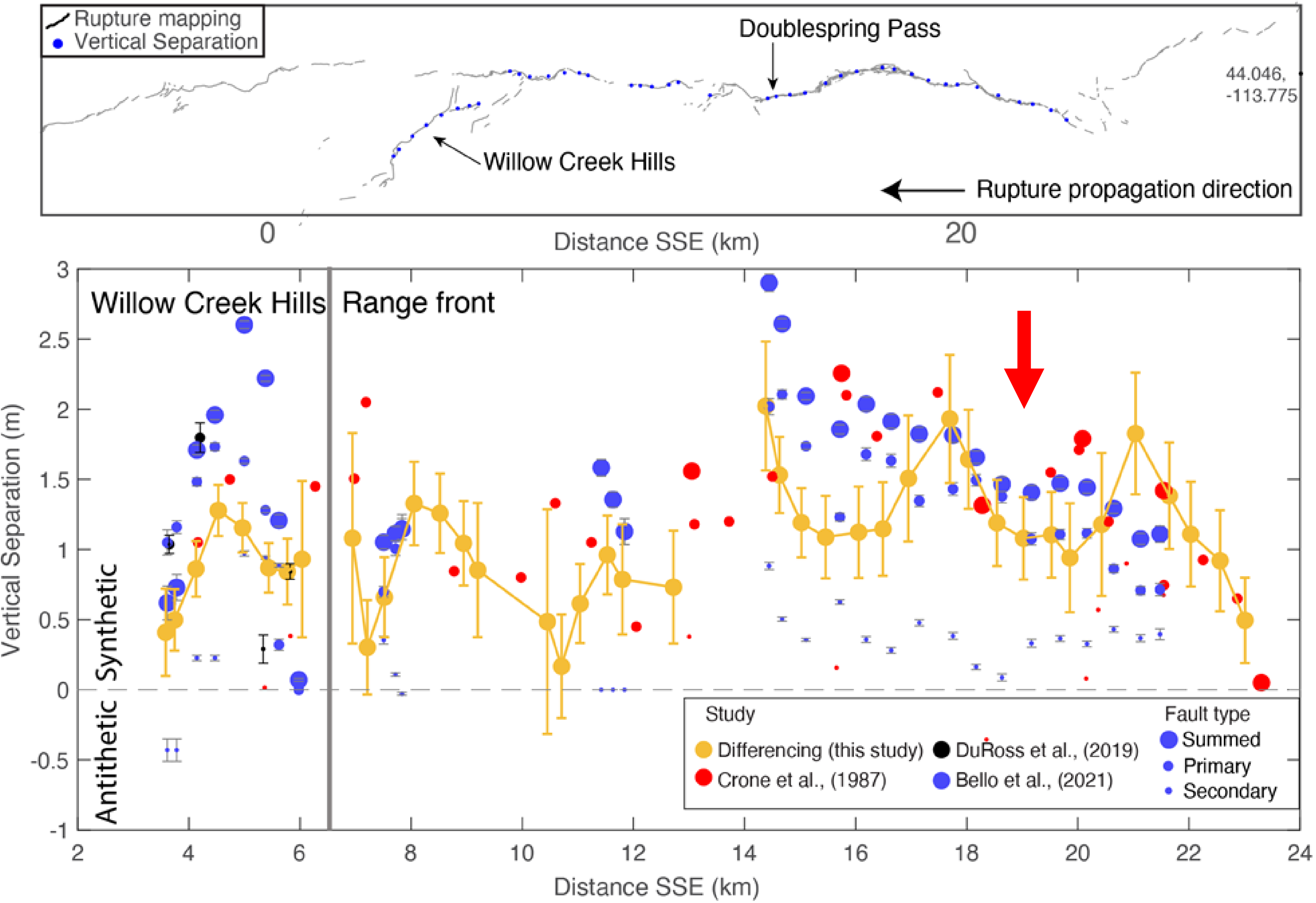
Vertical Separation



Maximum VS: 2.0 ± 0.5 m at Double Springs Pass

Willow Creek Hills: Mean 0.9 m VS

Vertical Separation: Comparison



Overall consistency, but other studies are a little higher

Why?
Fault scarp degrades immediately post earthquake.
Hard to distinguish 1987 from earlier EQ's. (Crone et al '87)

San Andreas Fault Creep

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Geophysical Research Letters

RESEARCH LETTER
10.1029/2020GL090628

Distribution of Aseismic Deformation Along the Central San Andreas and Calaveras Faults From Differencing Repeat Airborne Lidar

Chelsea Phipps Scott[1], Stephen B. DeLong[2], and J Ramón Arrowsmith[1]

Key Points:
- Aseismic fault creep rates are measured over 11–13 years in central California by differencing

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JGR Solid Earth

RESEARCH ARTICLE
10.1029/2020JB019762

Creep Along the Central San Andreas Fault From Surface Fractures, Topographic Differencing, and InSAR

Chelsea Scott[1], Michael Bunds[2], Manoochehr Shirzaei[3], and Nathan Toke[2]

Key Points:
- We measure tectonic creep along the

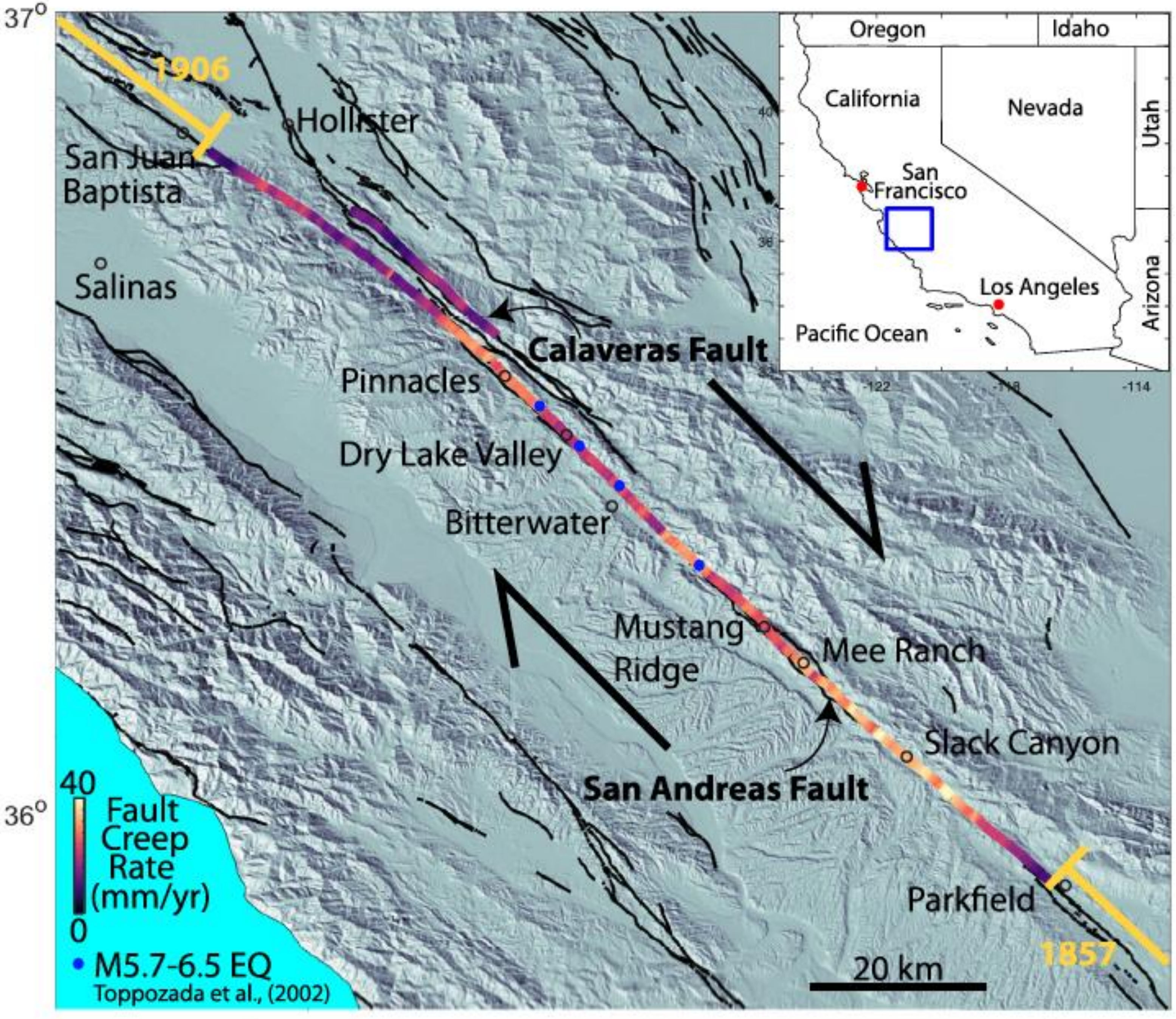
Why study creep:

Fast enough to measure

Earthquake mechanics

Interaction with damaging earthquakes

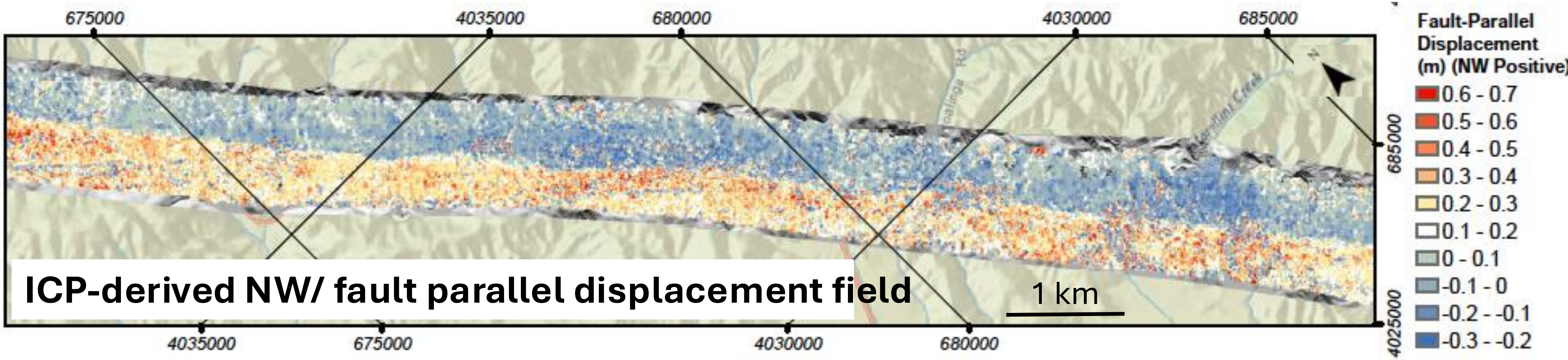
Central California

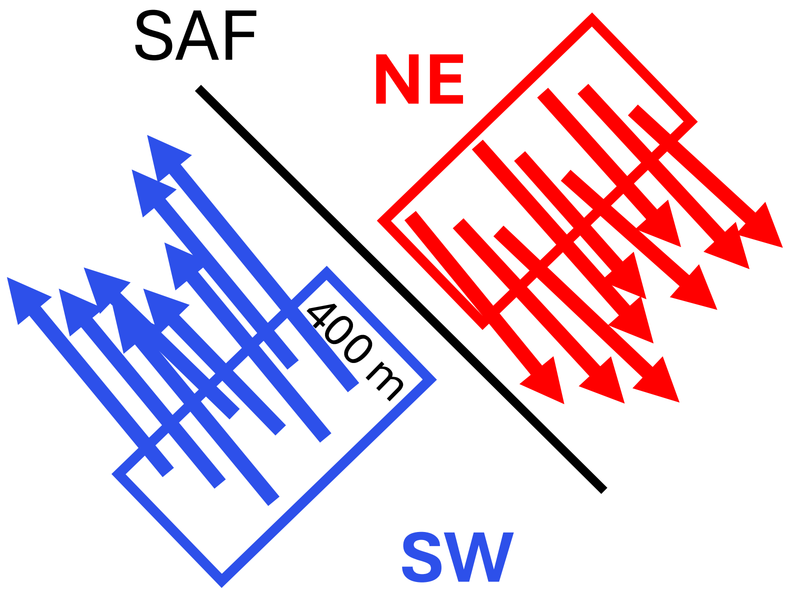


Scott et al. (2020)

Lidar data spanning a decade: ~2007-2017

Displacement field -> Fault creep, creep rate & uncertainty





Displacement Discontinuity:

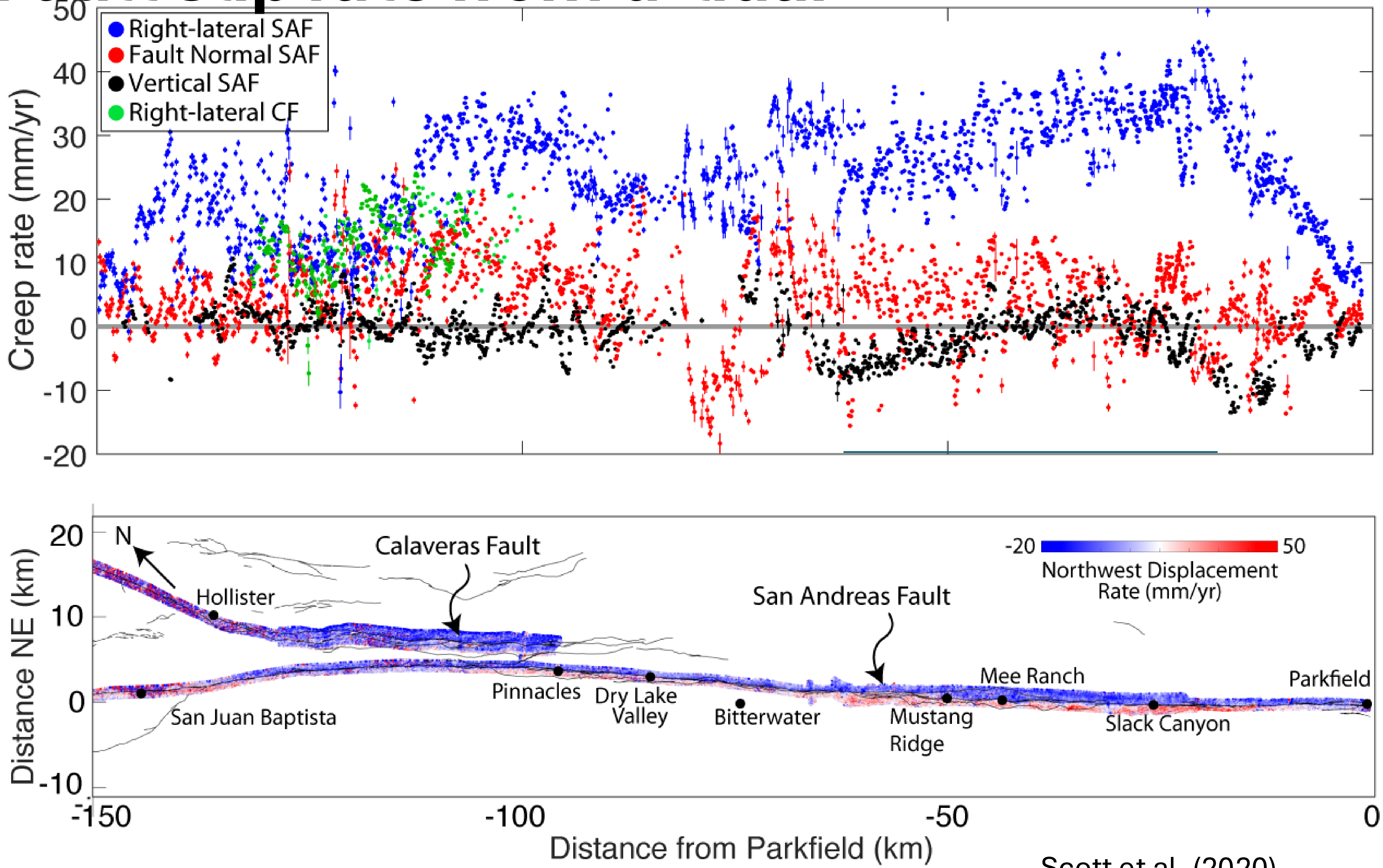
$$Fault\ Creep = \boldsymbol{d}sw\ \text{-}\ \boldsymbol{d}ne$$

$$Fault\ Creep\ rate = \frac{fault\ creep}{time}$$

$$Creep\ Rate\ \mathrm{Error} = \sqrt{\Delta \boldsymbol{d}sw^2 + \Delta \boldsymbol{d}ne^2}$$

Scott et al. 2020

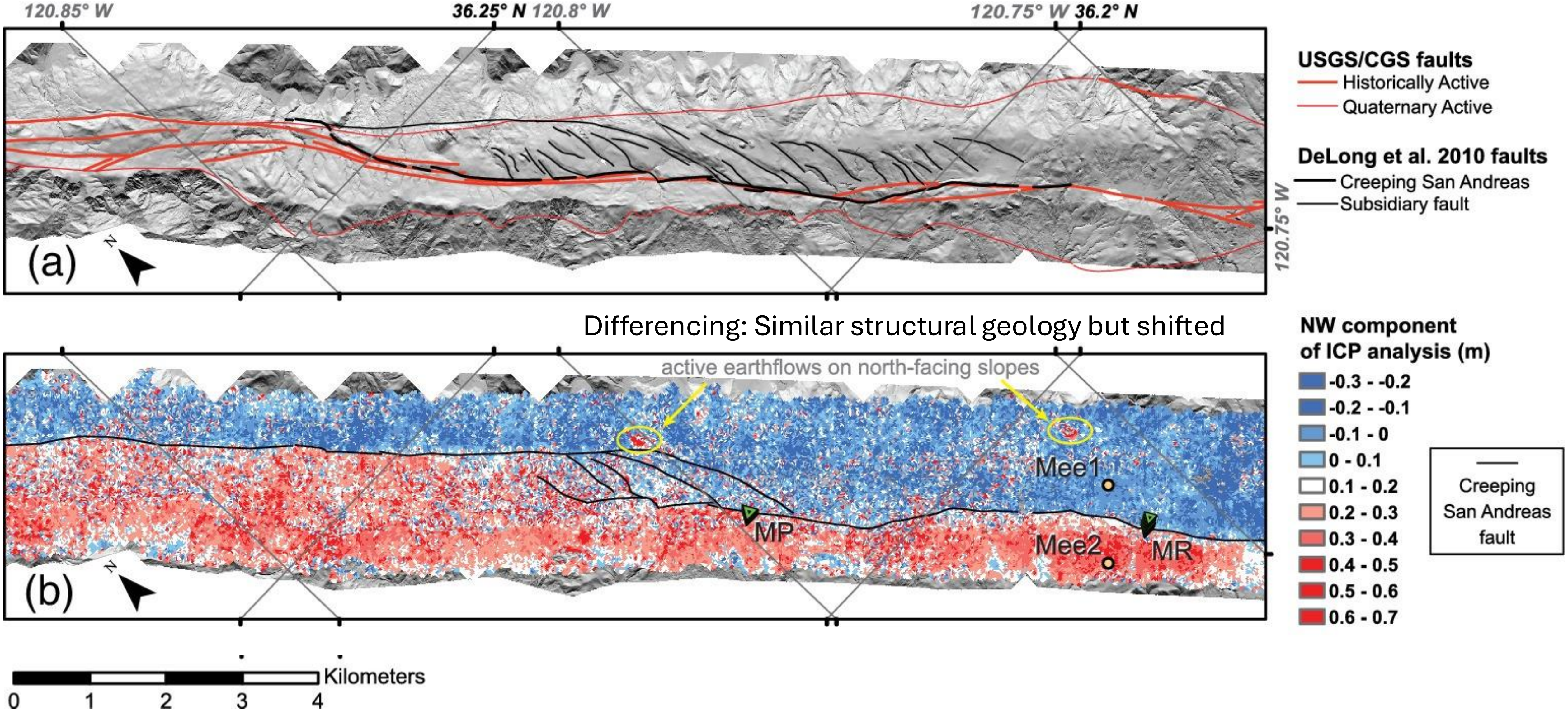
Fault slip rate from d-lidar



Scott et al. (2020)

Mustang Ridge

Right-step through en echelon faults



Differencing: Similar structural geology but shifted

Fault displacement hazard: The active fault may not be most pronounced geomorphically

Conclusions

Topographic differencing measures vertical and 3D deformation surrounding faults.

2016 M7 Kumamoto earthquake: 3D deformation & inelastic strain

1983 M6.9 Borah Peak earthquake: Old pre-data, field vs. remote sensing displacements

Central San Andreas Fault creep: First creep measured with differencing, rates and active fault