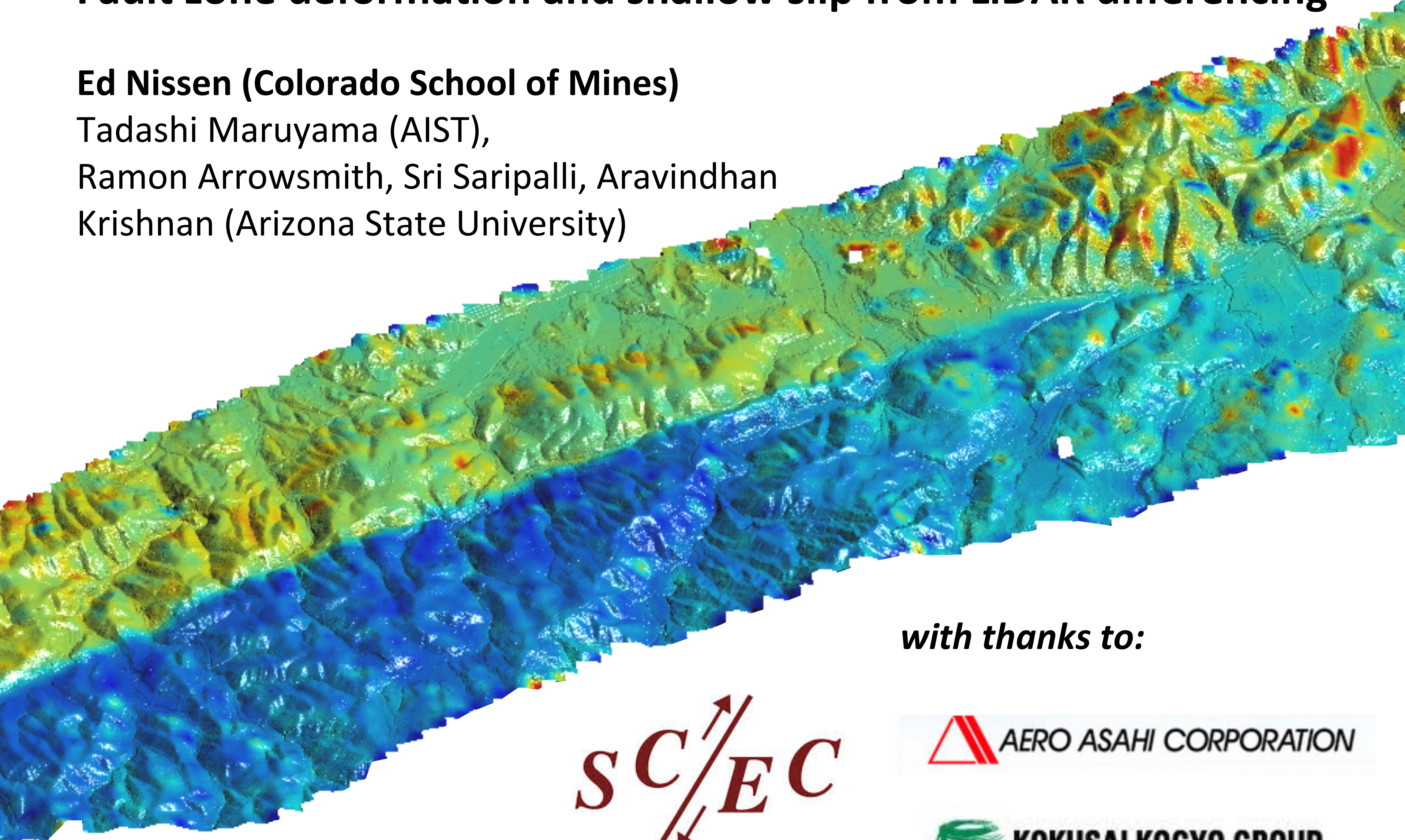
Fault zone deformation and shallow slip from LiDAR differencing

Ed Nissen (Colorado School of Mines)
Tadashi Maruyama (AIST),
Ramon Arrowsmith, Sri Saripalli, Aravindhan Krishnan (Arizona State University)



Vertical displacements in the 2011 Mw 6.6 Iwaki earthquake

with thanks to:

SCEC
an NSF+USGS center

AERO ASAHI CORPORATION

KOKUSAI KOGYO GROUP

- **Methodology**

  LiDAR differencing with the ICP algorithm

- **Case studies**

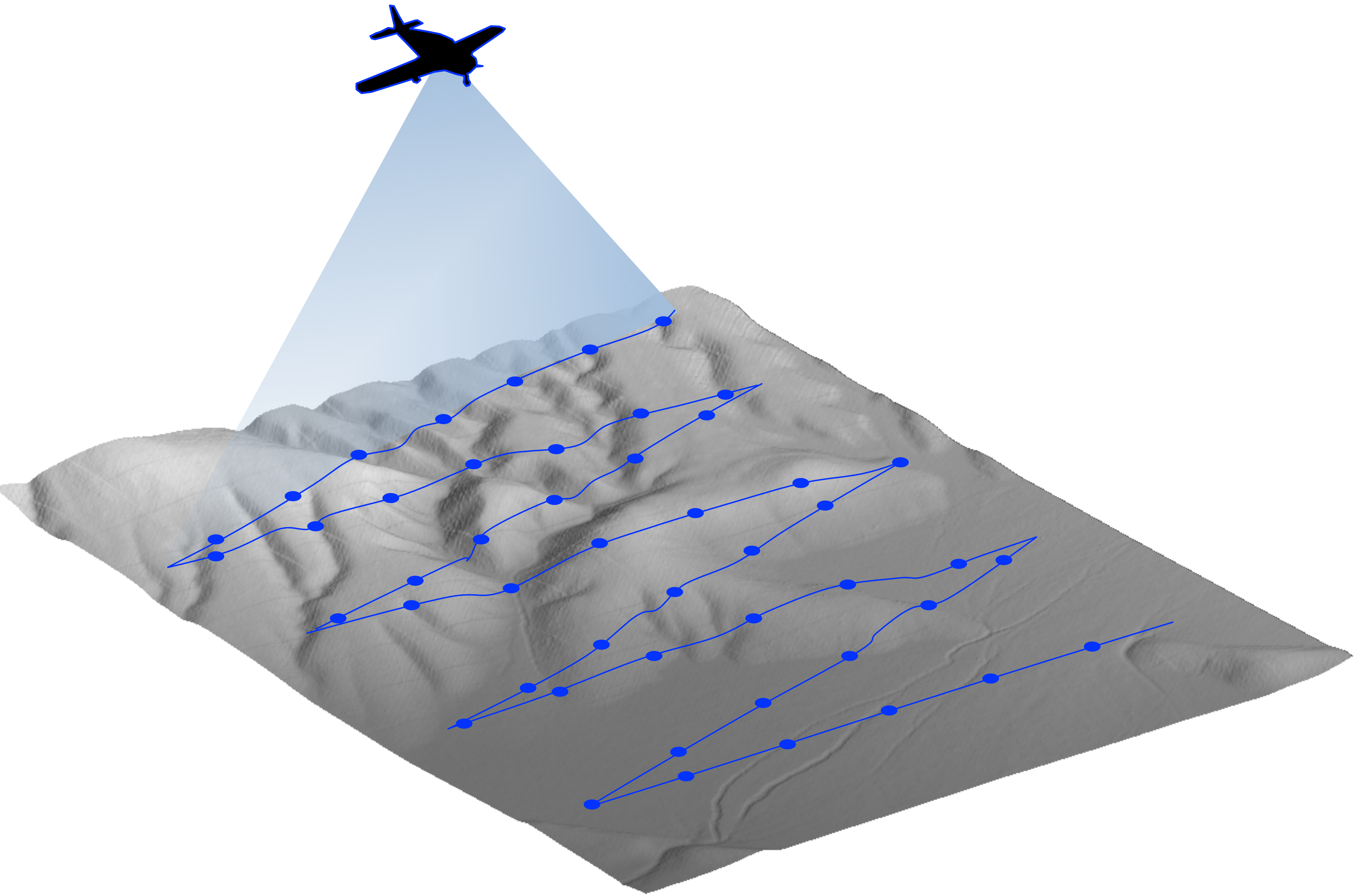
  2008 Iwate-Miyagi thrust earthquake

  2011 Iwaki normal faulting earthquake

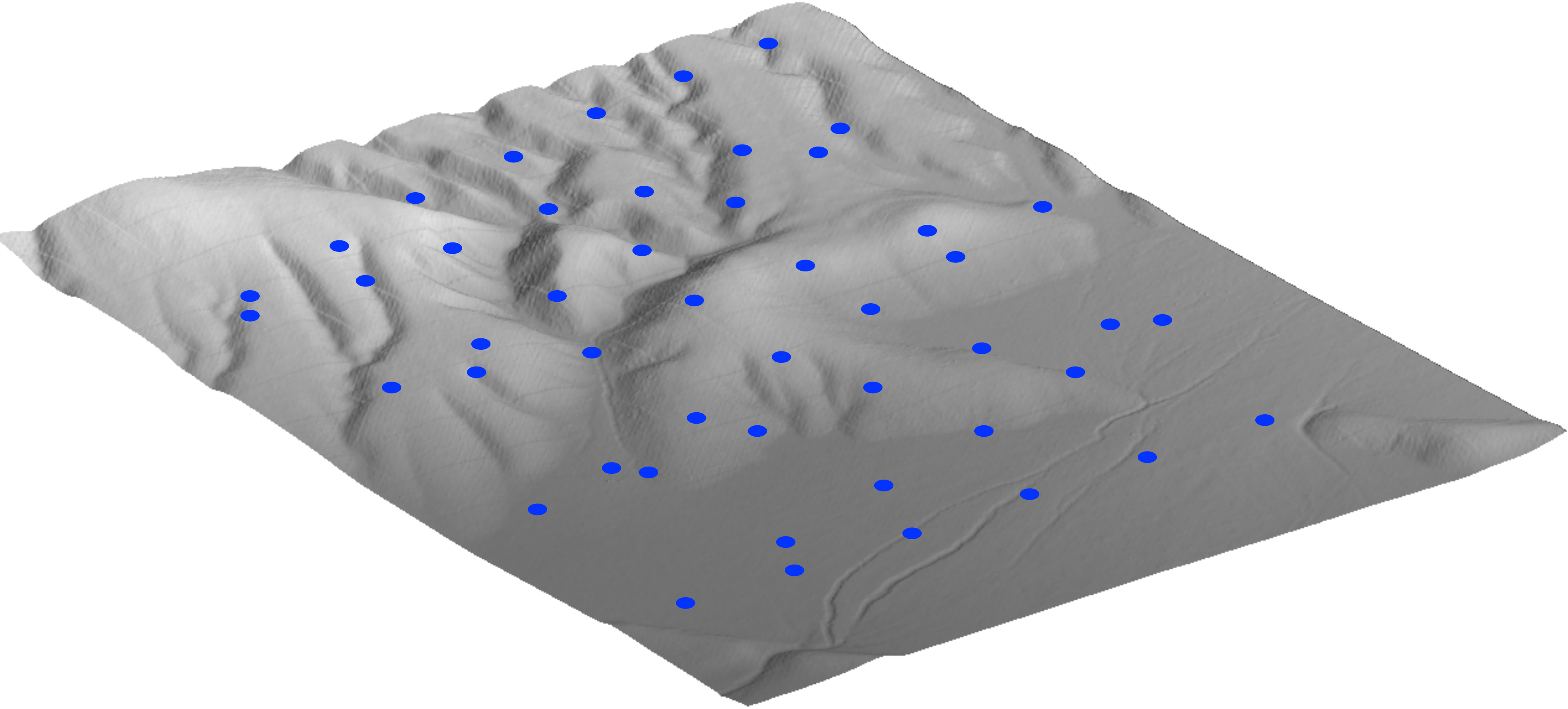
- **Conclusions**

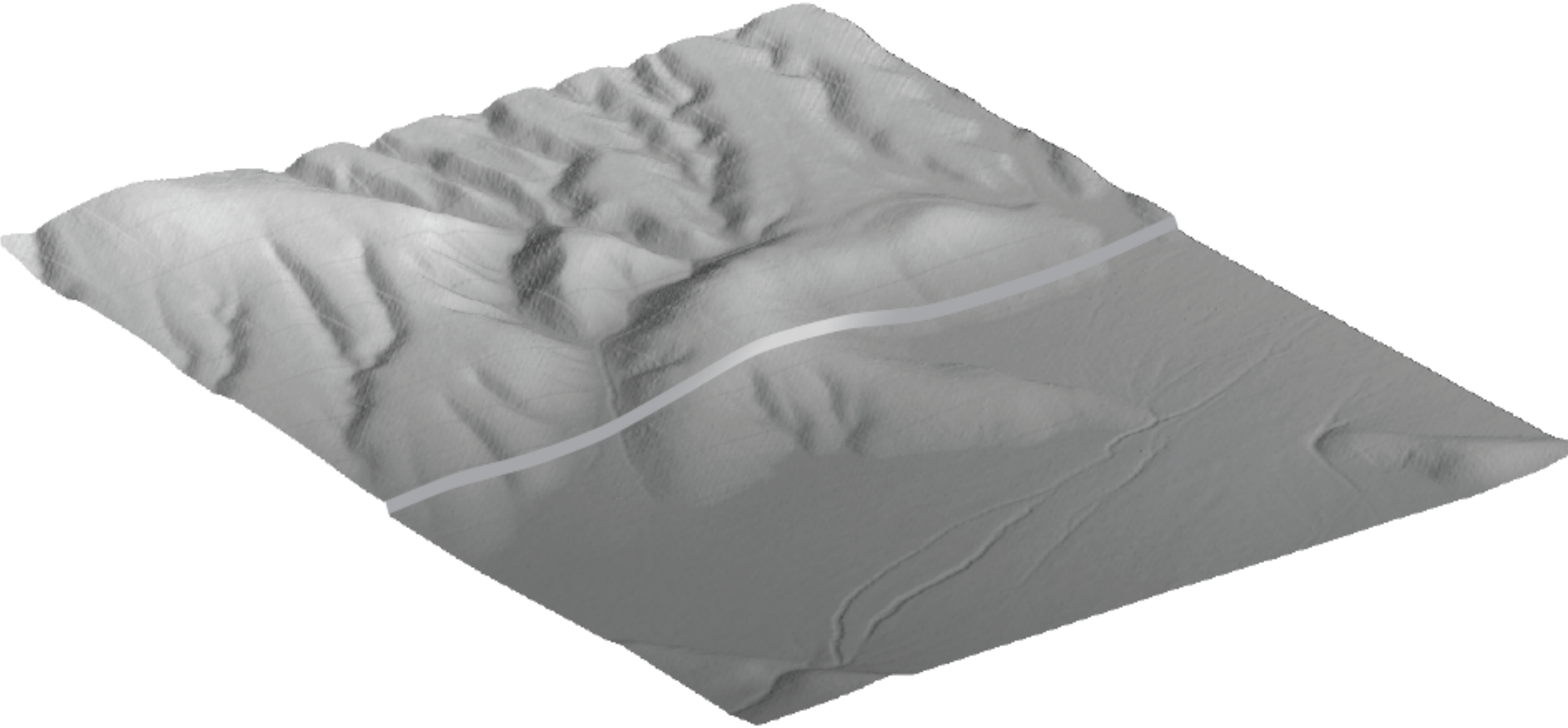
  A comparison with other geodetic techniques used for high-resolution earthquake mapping

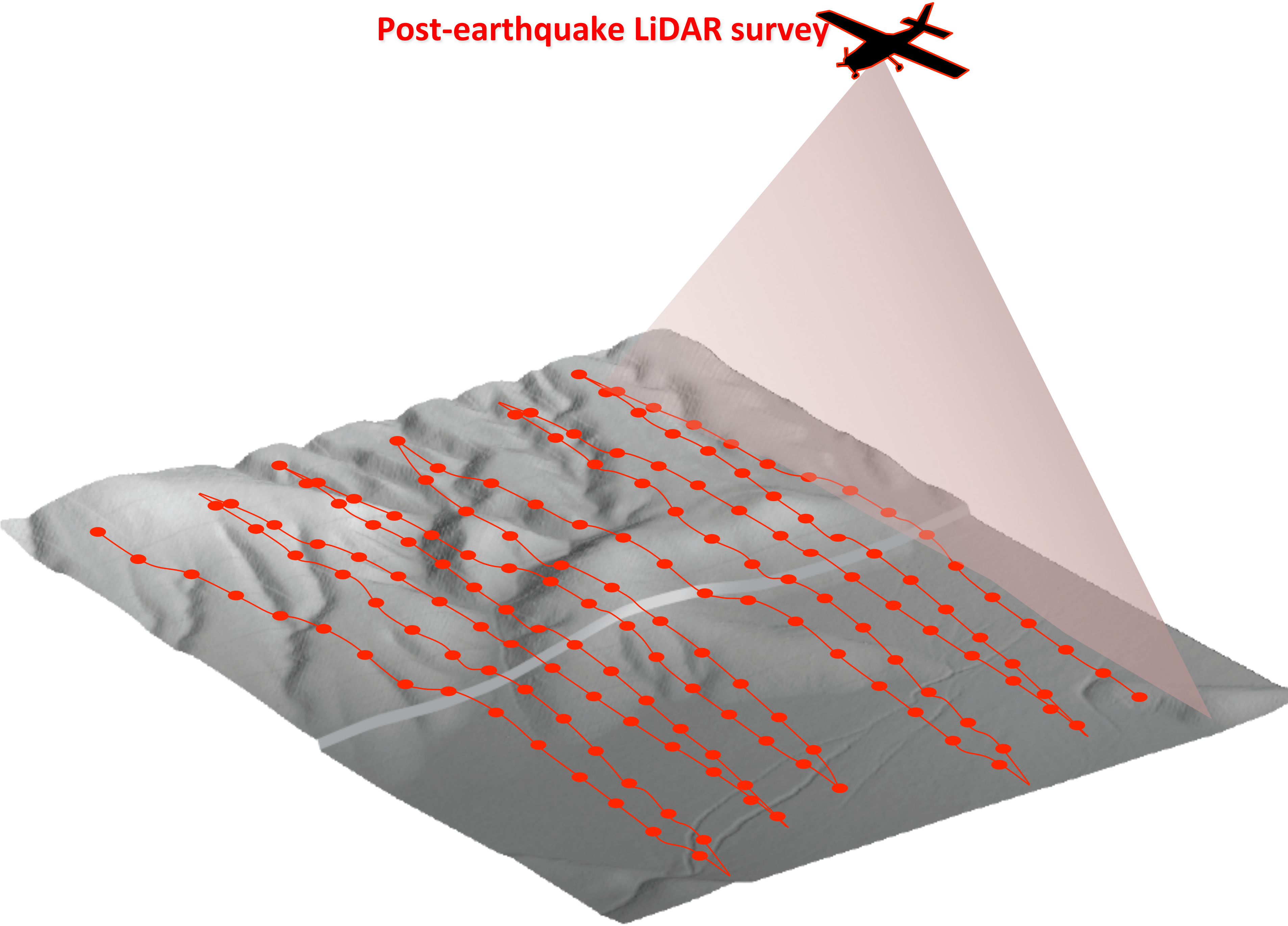
Pre-earthquake LiDAR survey



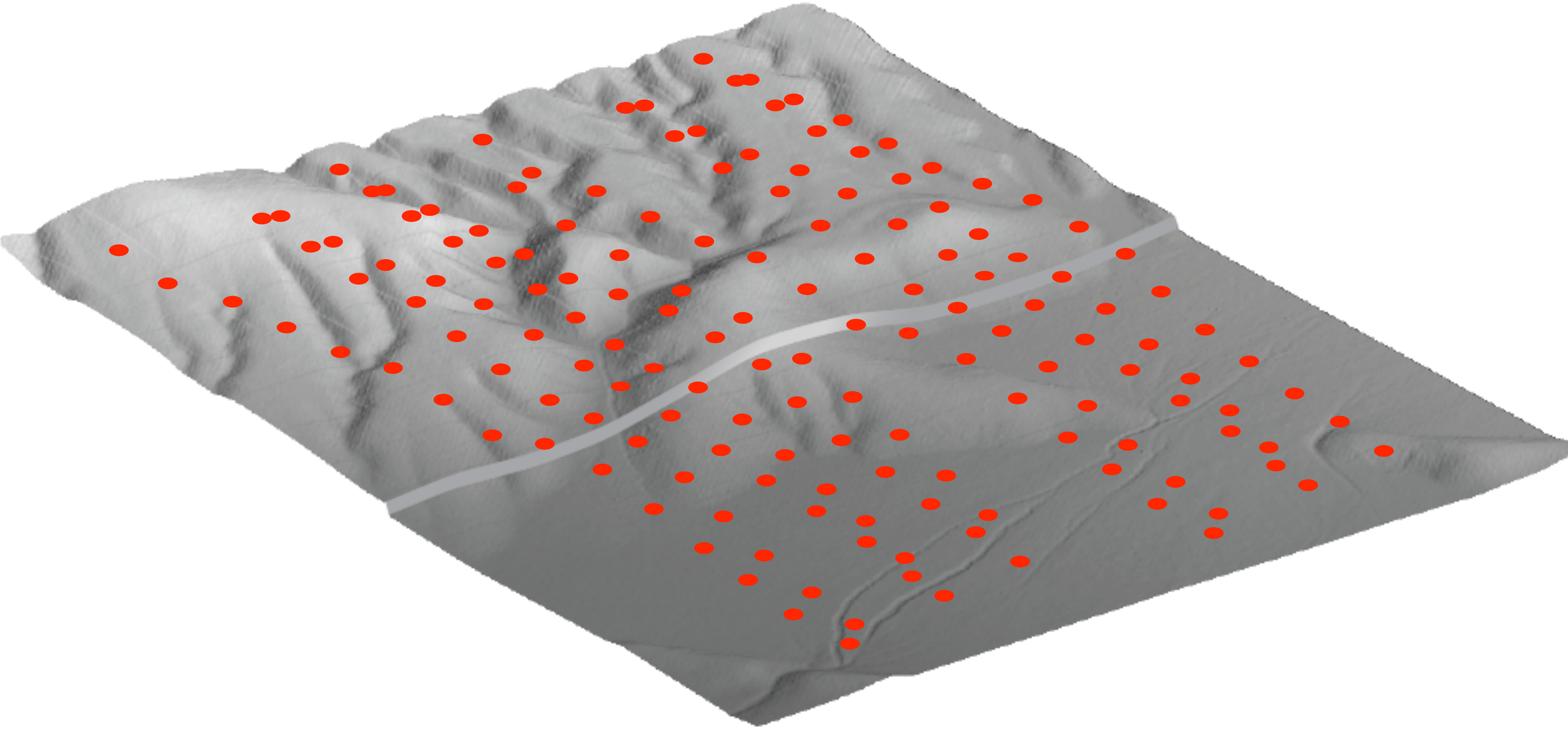
Pre-earthquake point cloud



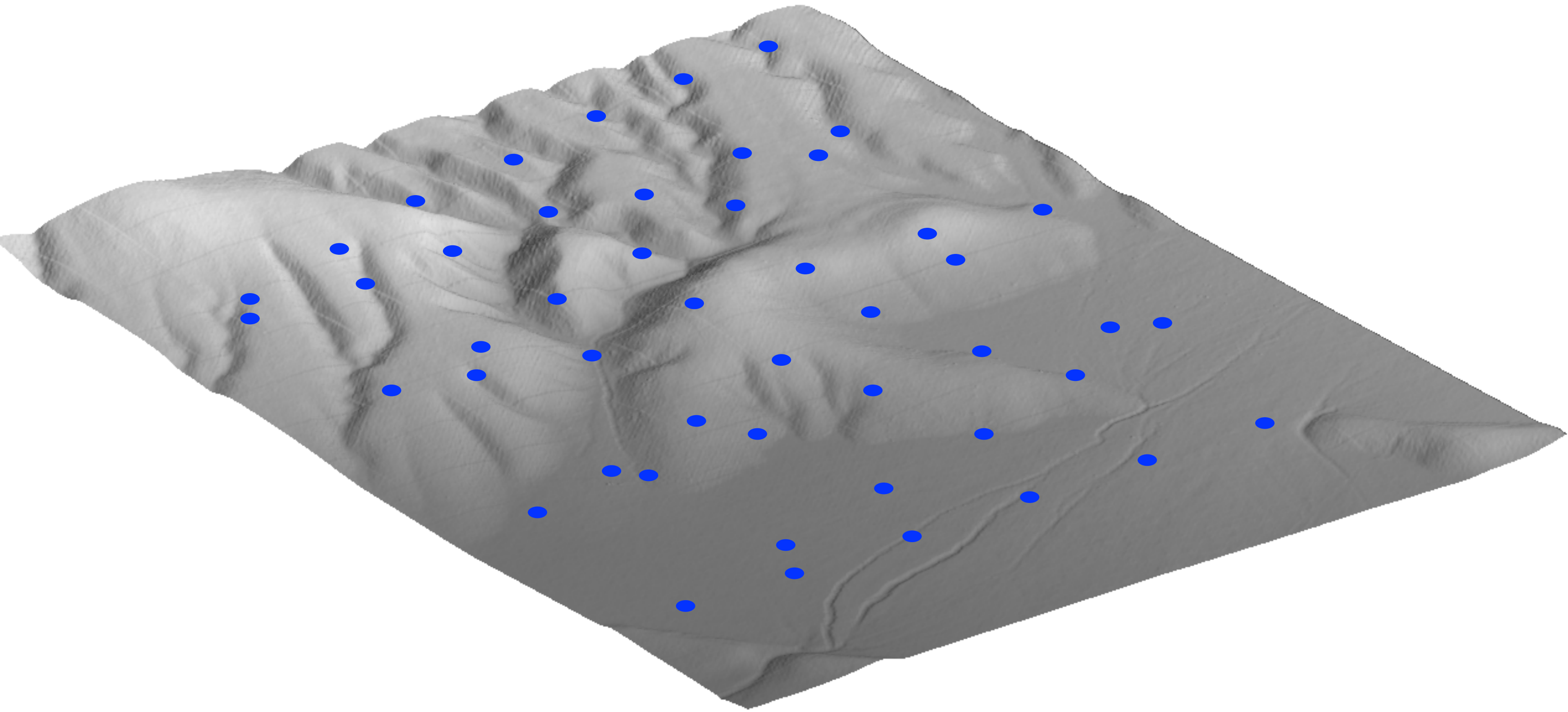



Post-earthquake LiDAR survey

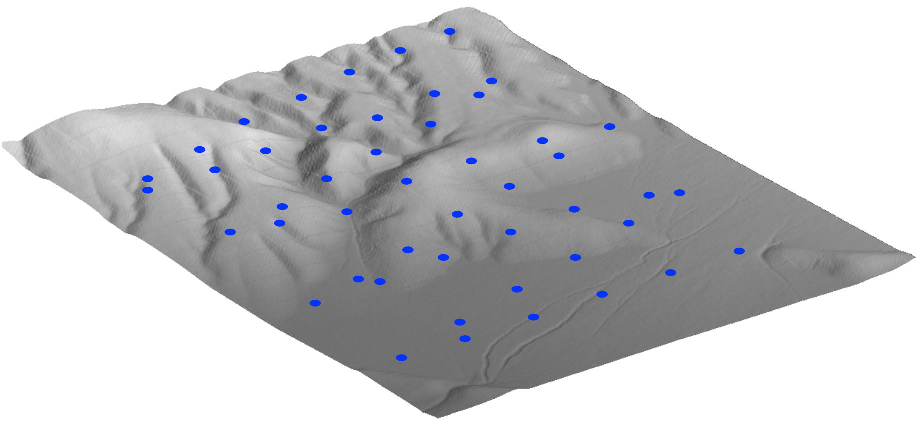
Post-earthquake point cloud



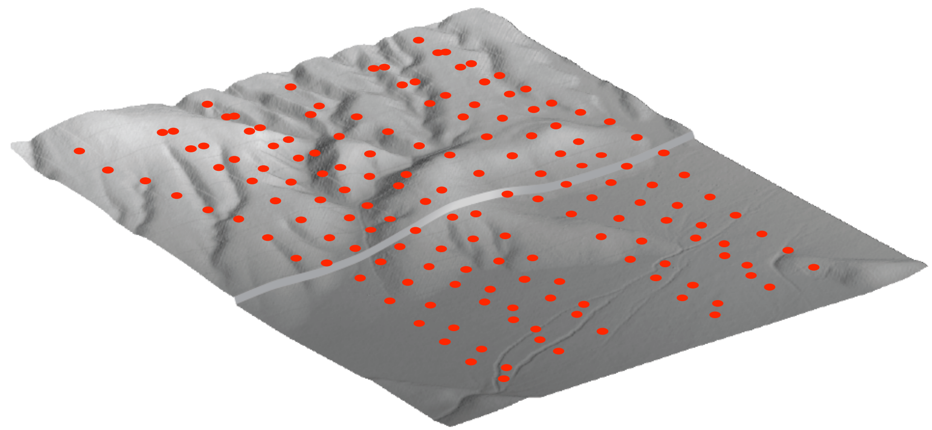
Pre-earthquake point cloud



Pre-earthquake point cloud



Post-earthquake point cloud



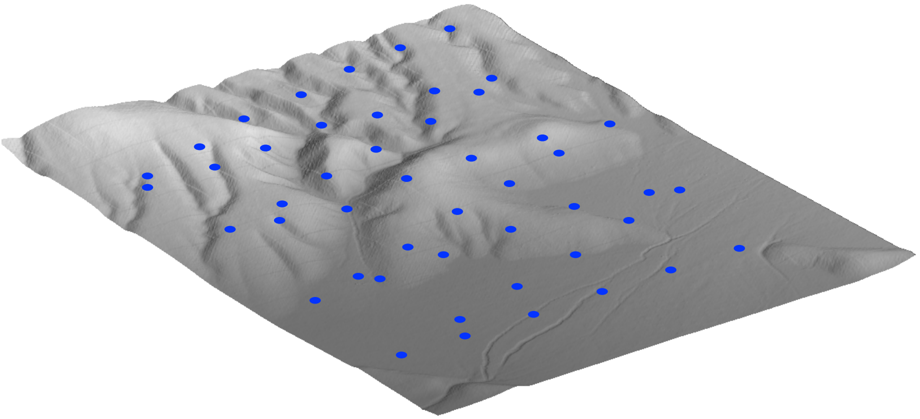
The Challenges of LiDAR differencing

- Data are irregularly spaced
  (we can rasterize them, but we lose information doing so).

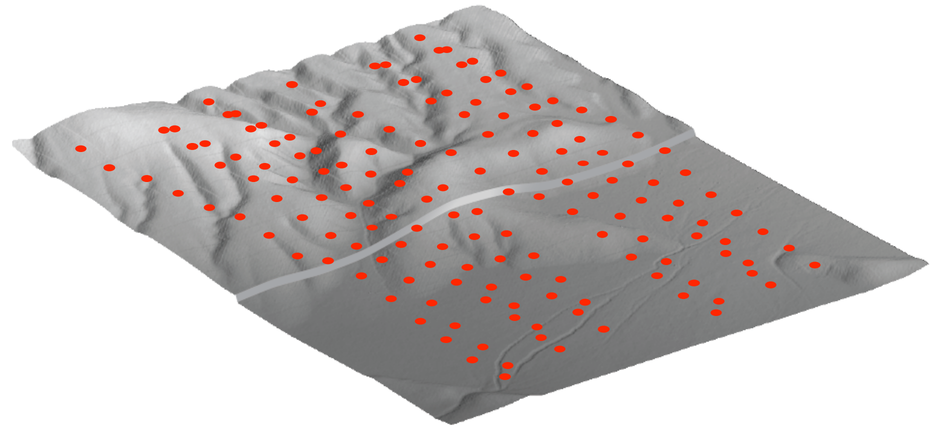
- There can be large mismatches in point density
  (typically the newer dataset is denser than the older one).

- There may also be large errors in absolute point positioning
  (for instance at the edges of scan lines, as we saw at El Mayor).

Pre-earthquake point cloud



Post-earthquake point cloud



The **Iterative Closest Point** algorithm: a method for registering (aligning) two sets of points

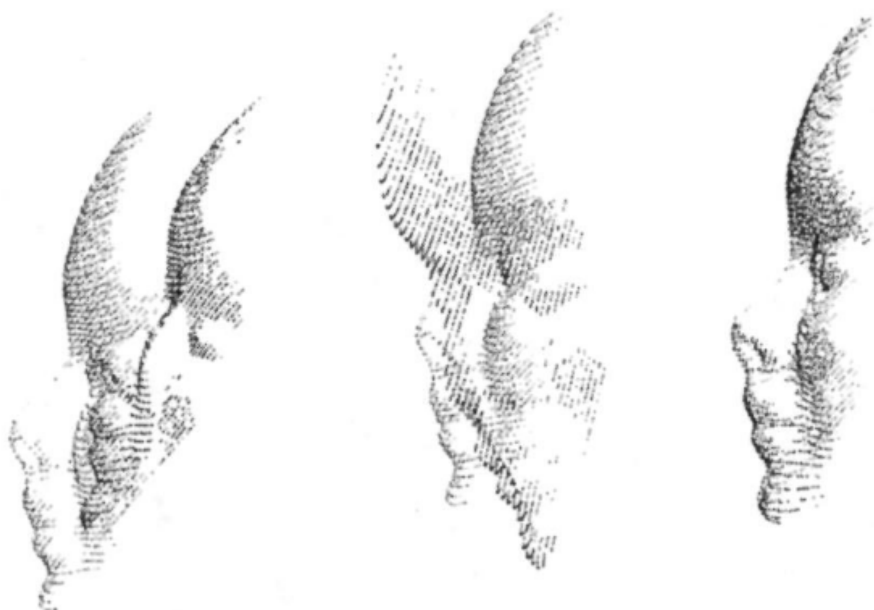
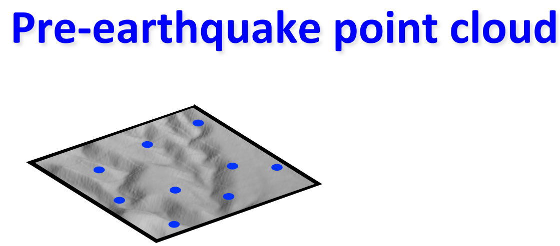
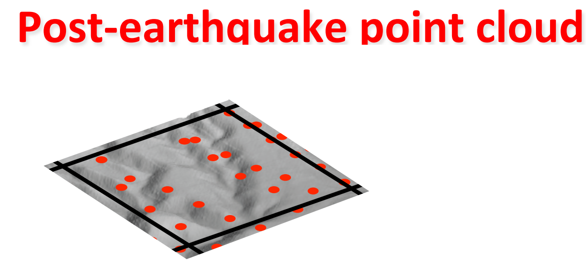


Fig. 4. Iterative point-based registration of phantom face range data



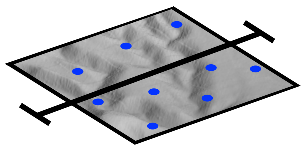


The **Iterative Closest Point** algorithm: a method for registering (aligning) two sets of points

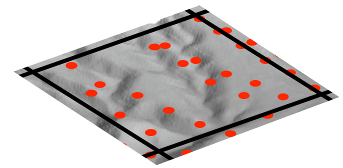
- the two point clouds are first split into square "windows", 50 m in diameter
- ICP is run separately on each pair of windows. (An additional "fringe" of 5 m is included in the post-event window in order to capture the coseismic displacement)
- ICP finds the displacement and rotation that best aligns the pre-event and post-event point clouds.
- This alignment corresponds to the local coseismic displacement for that window.

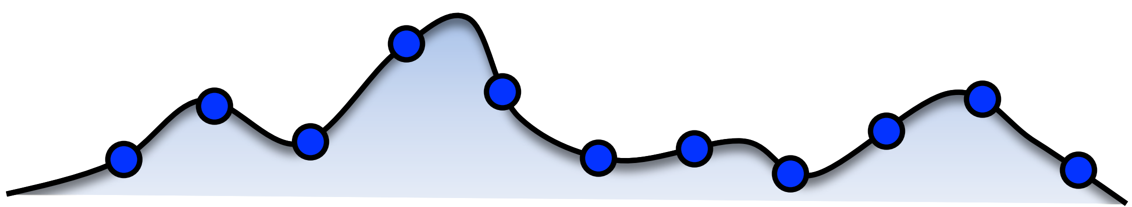
see Nissen et al. (2012), Geophys. Res. Lett., for details

Pre-earthquake point cloud

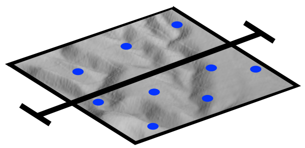


Post-earthquake point cloud

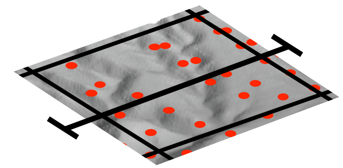


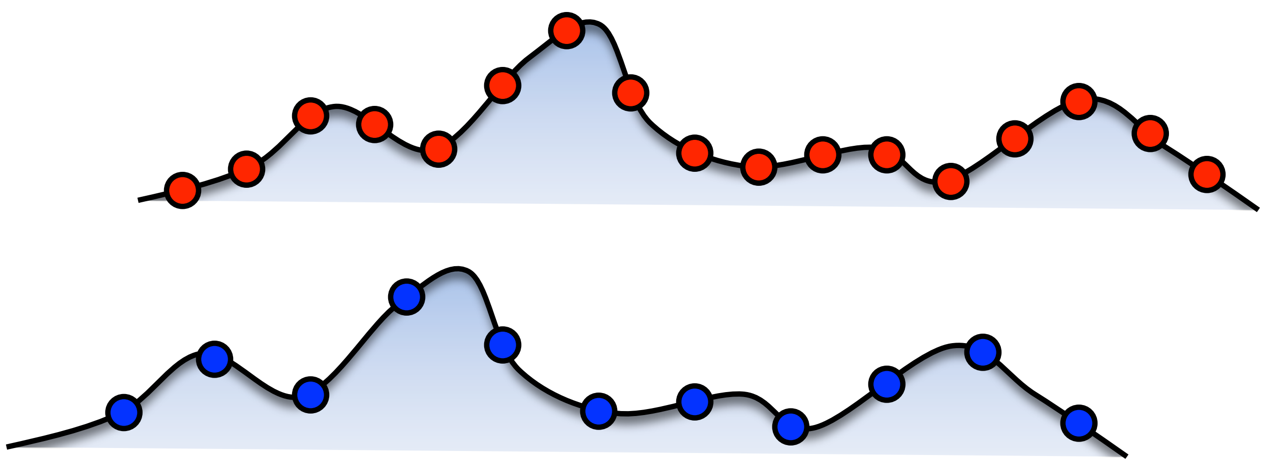


Pre-earthquake point cloud

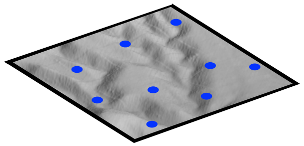


Post-earthquake point cloud

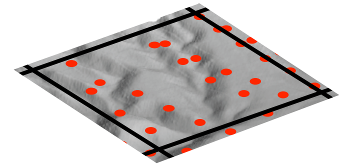


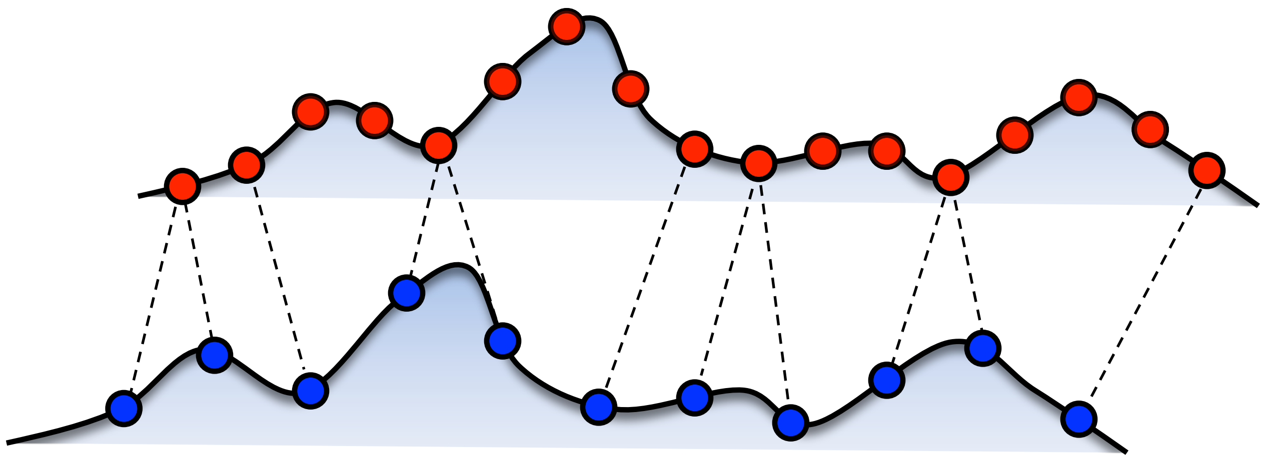


Pre-earthquake point cloud

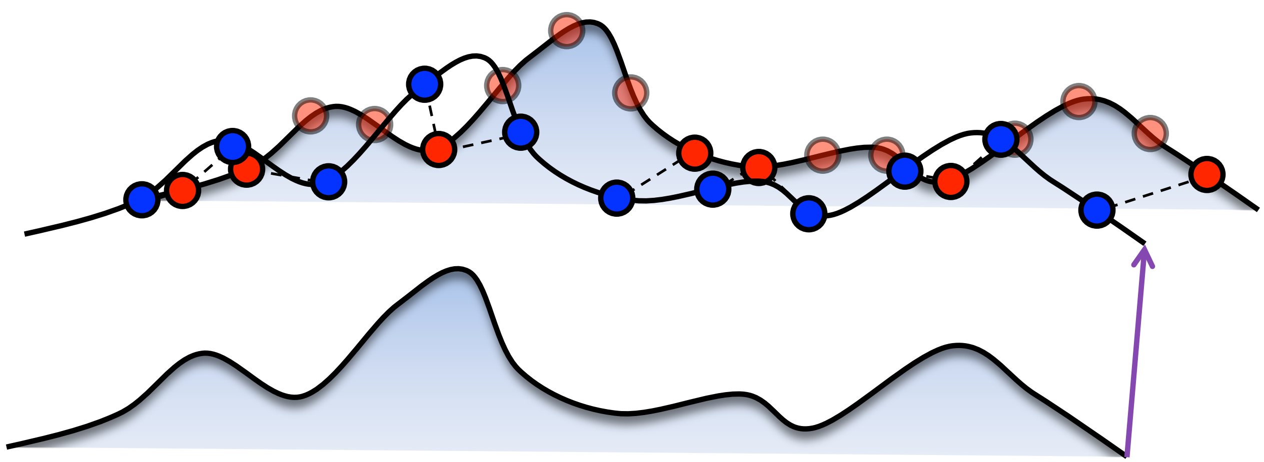


Post-earthquake point cloud





Find closest points

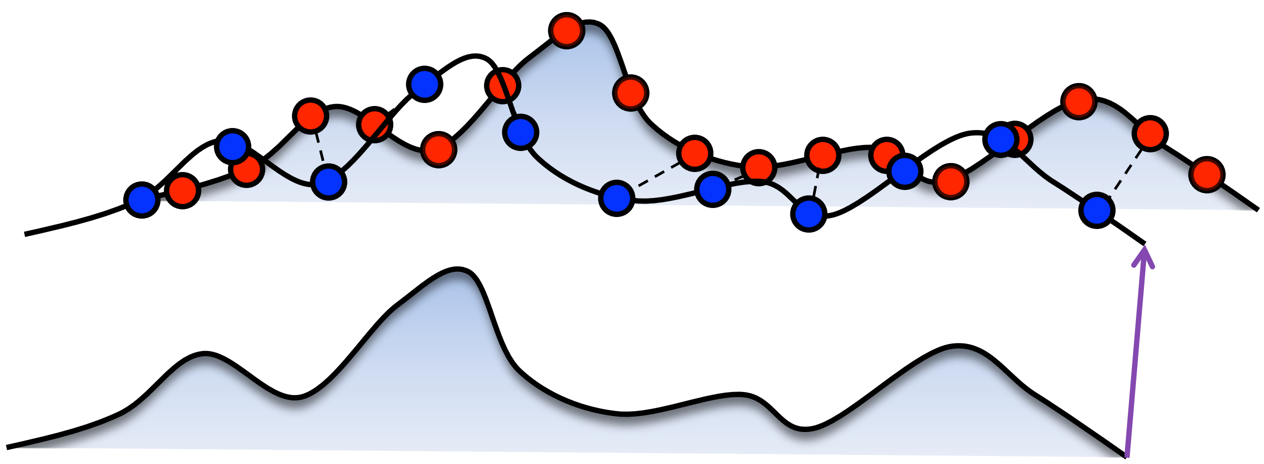


Iterate

Find closest points

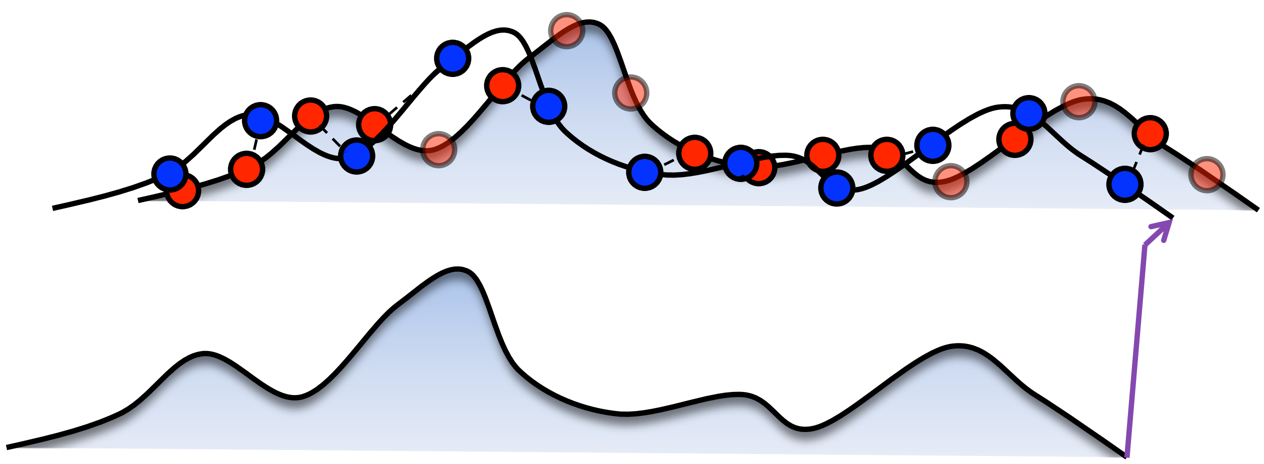
Transform point cloud

$$\phi = \begin{pmatrix} 1 & -\gamma & \beta & t_x \\ \gamma & 1 & -\alpha & t_y \\ -\beta & \alpha & 1 & t_z \\ 0 & 0 & 0 & 1 \end{pmatrix}$$



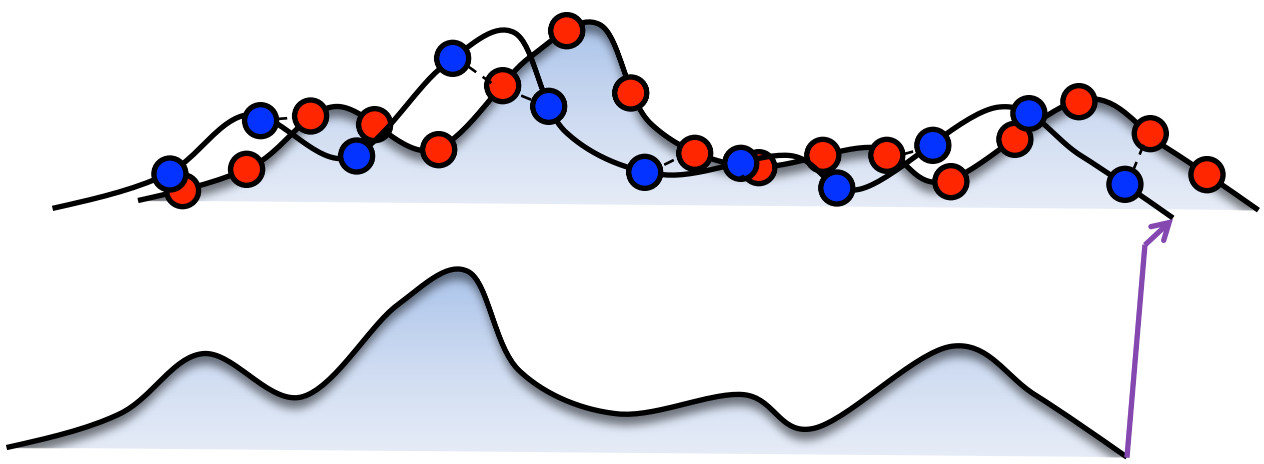
Find closest points

Transform point cloud



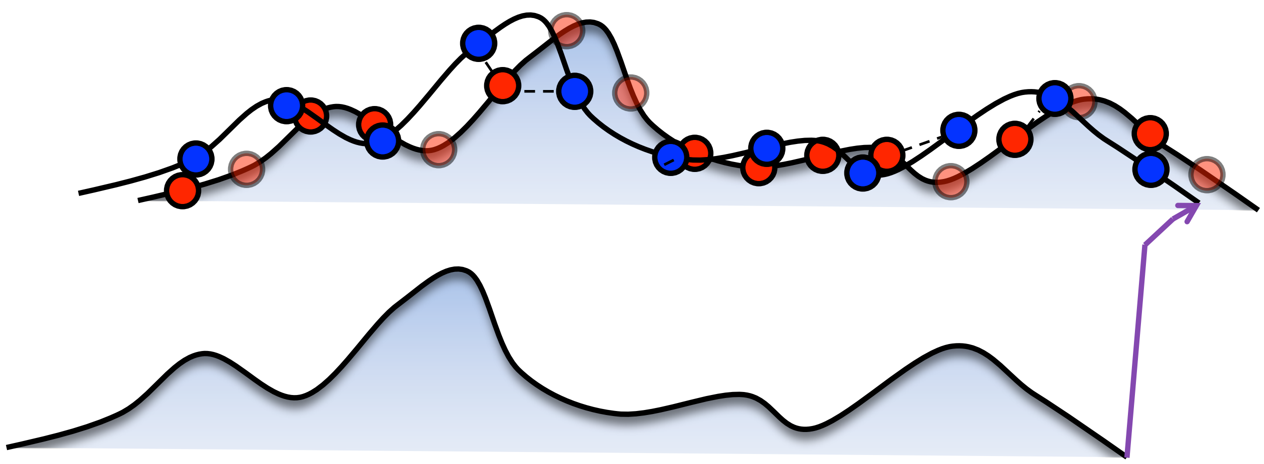
Find closest points

Transform point cloud



Find closest points

Transform point cloud



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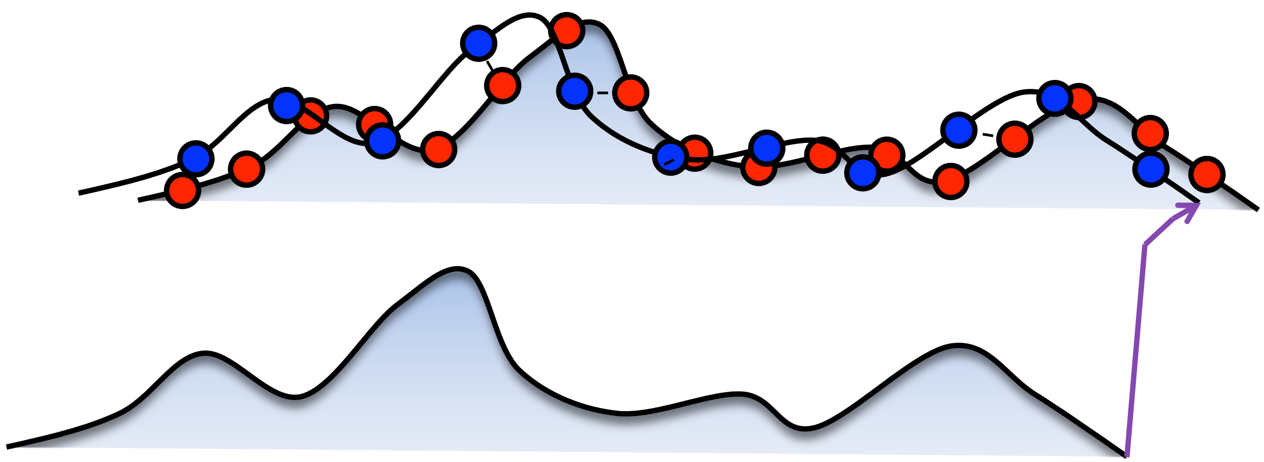
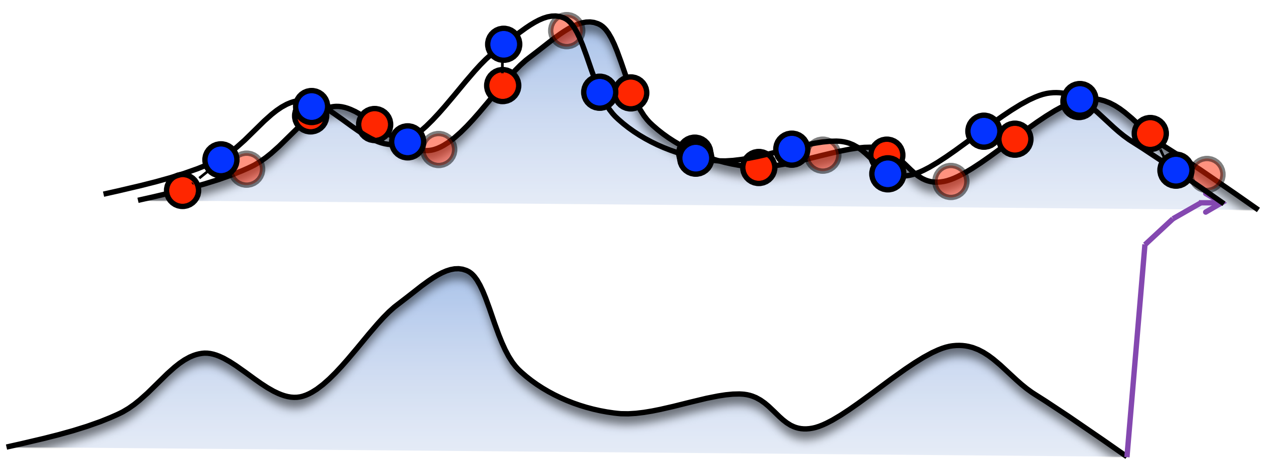
Transform point cloud



Find closest points

Transform point cloud



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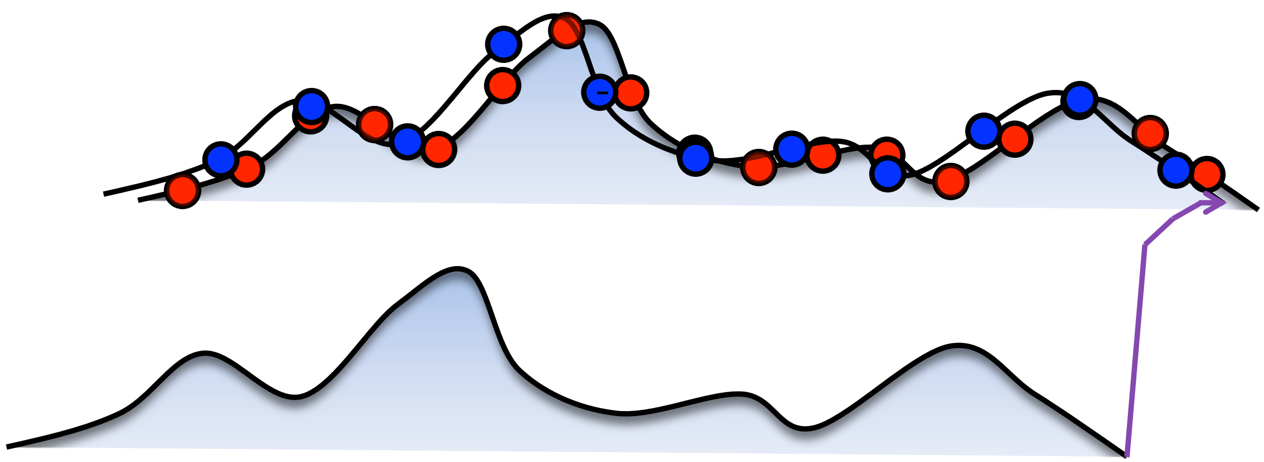

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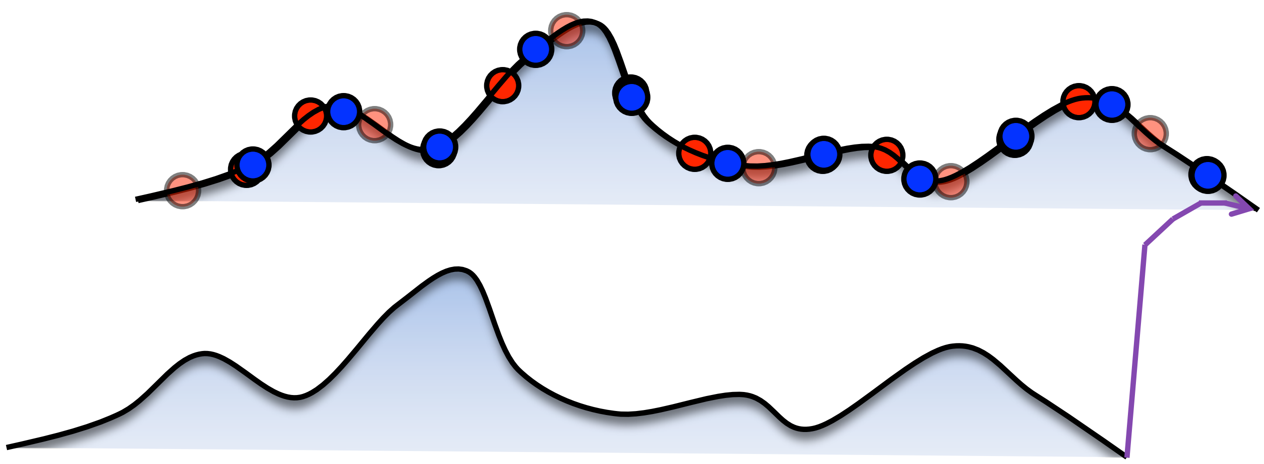
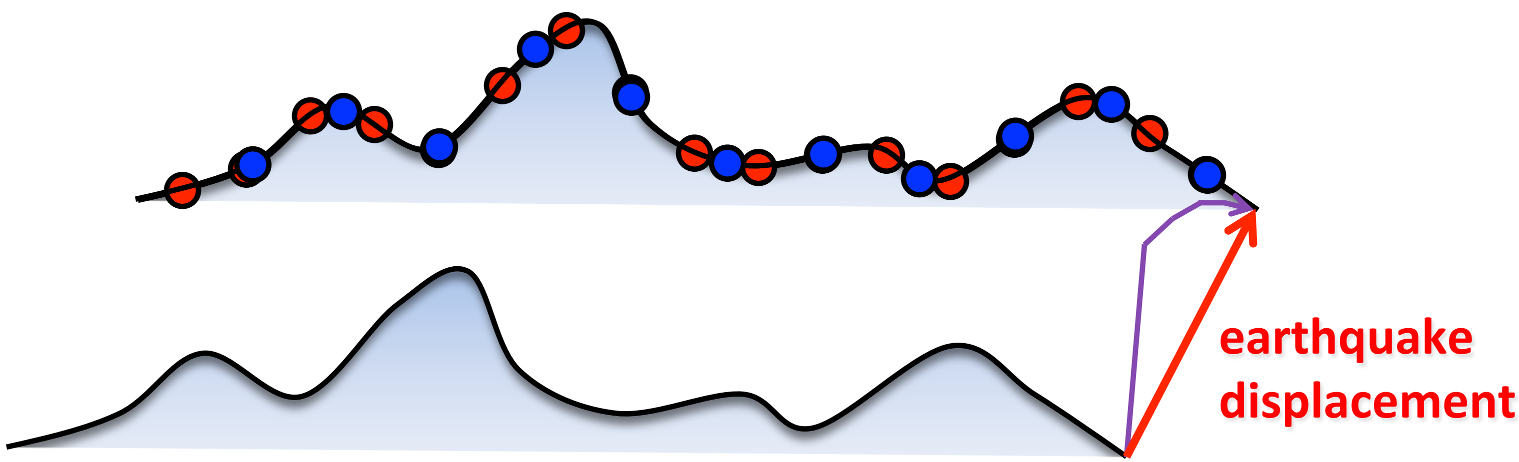
Transform point cloud



Find closest points

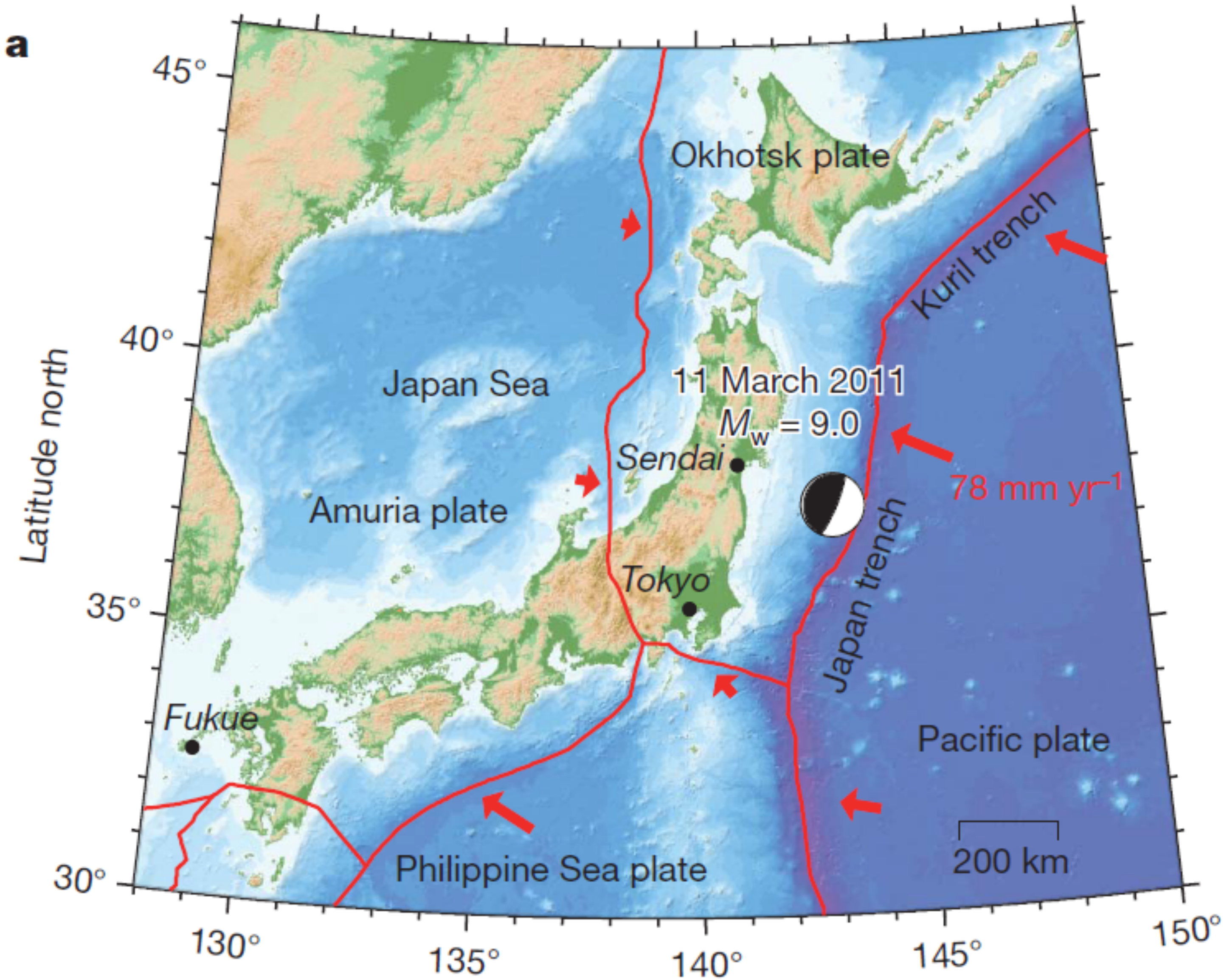
Transform point cloud



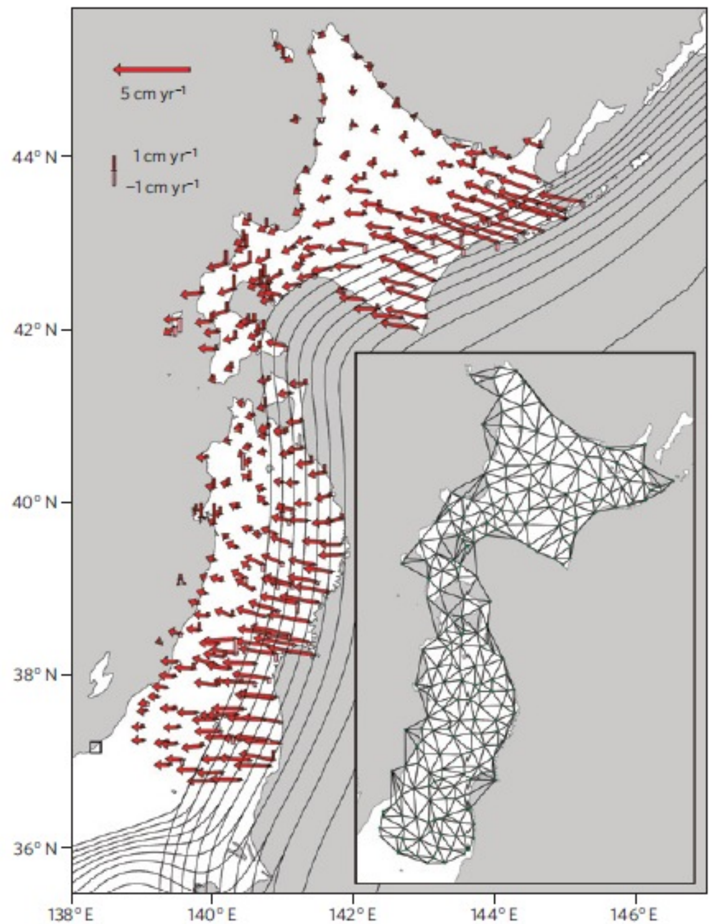
Find closest points

Transform point cloud

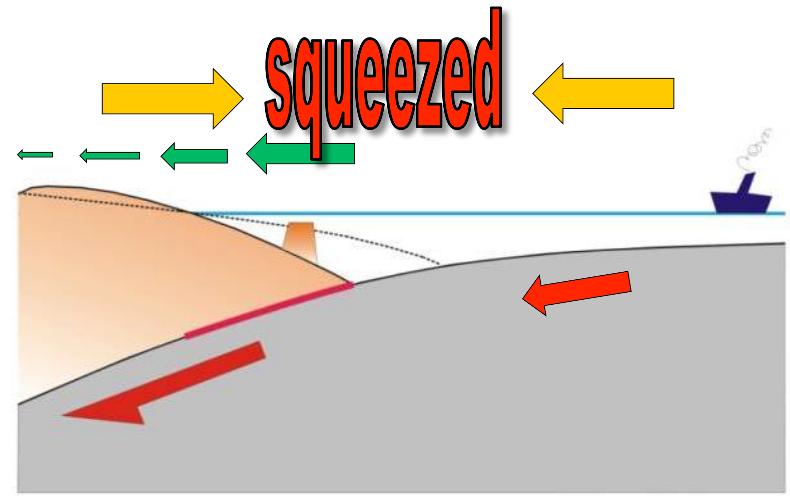
Case studies



Case studies

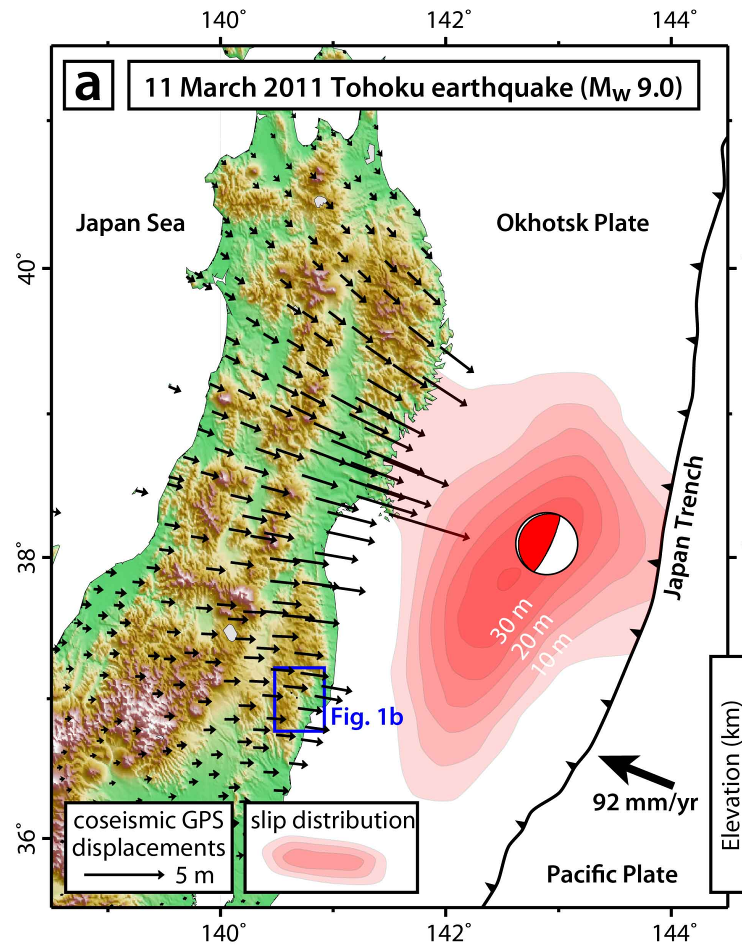


Interseismic GPS velocities, 1996-2000
from Hashimoto et al. (2009)

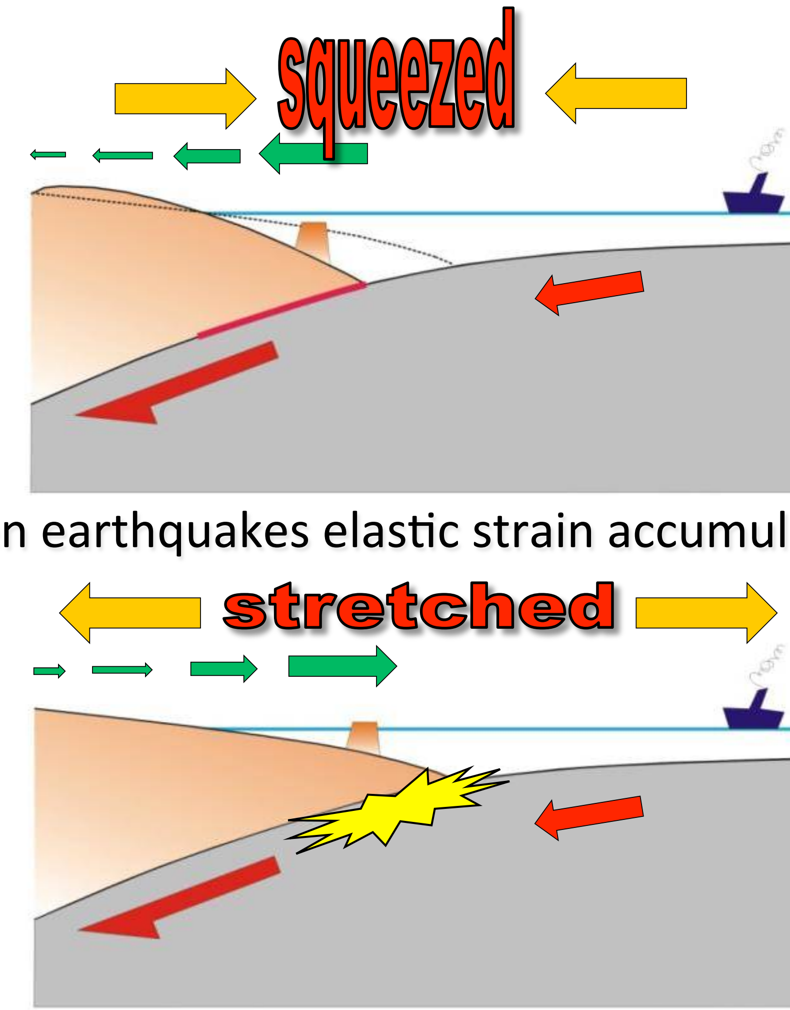


between earthquakes elastic strain accumulates

Case studies



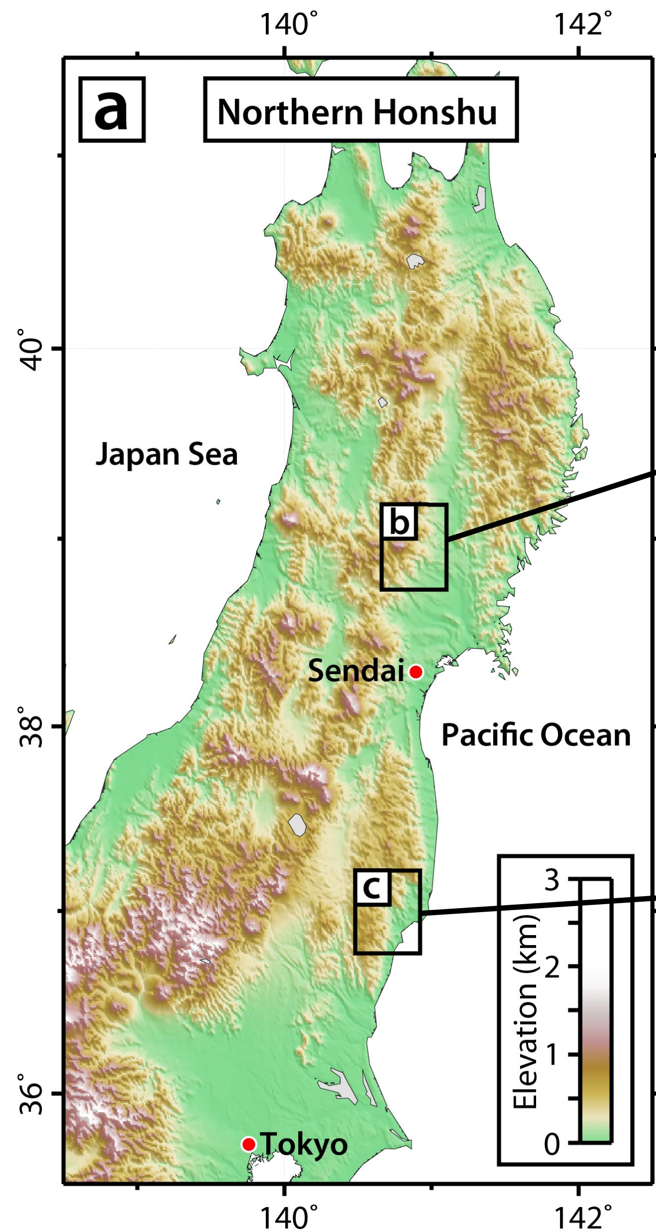
Coseismic GPS velocities from March 11 2011 from Ozawa et al. (2011)

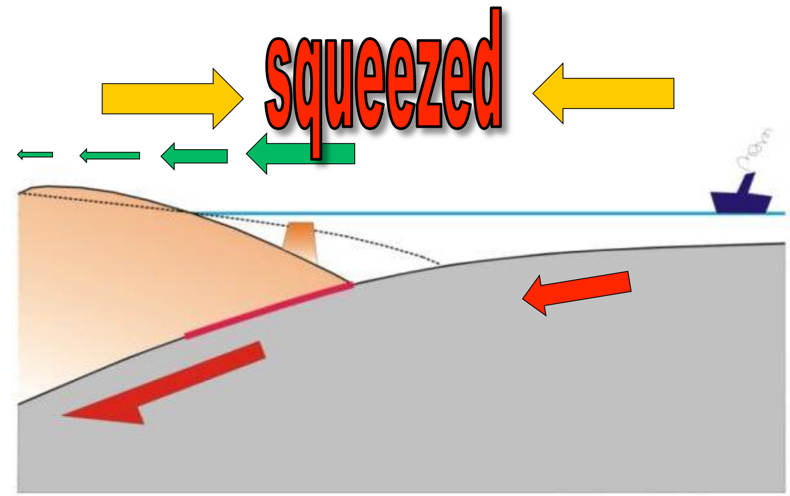


between earthquakes elastic strain accumulates

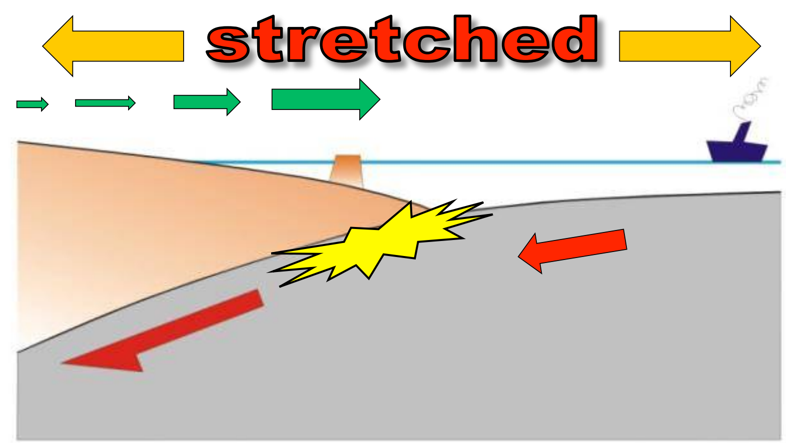
during earthquake elastic strain is released

Case studies



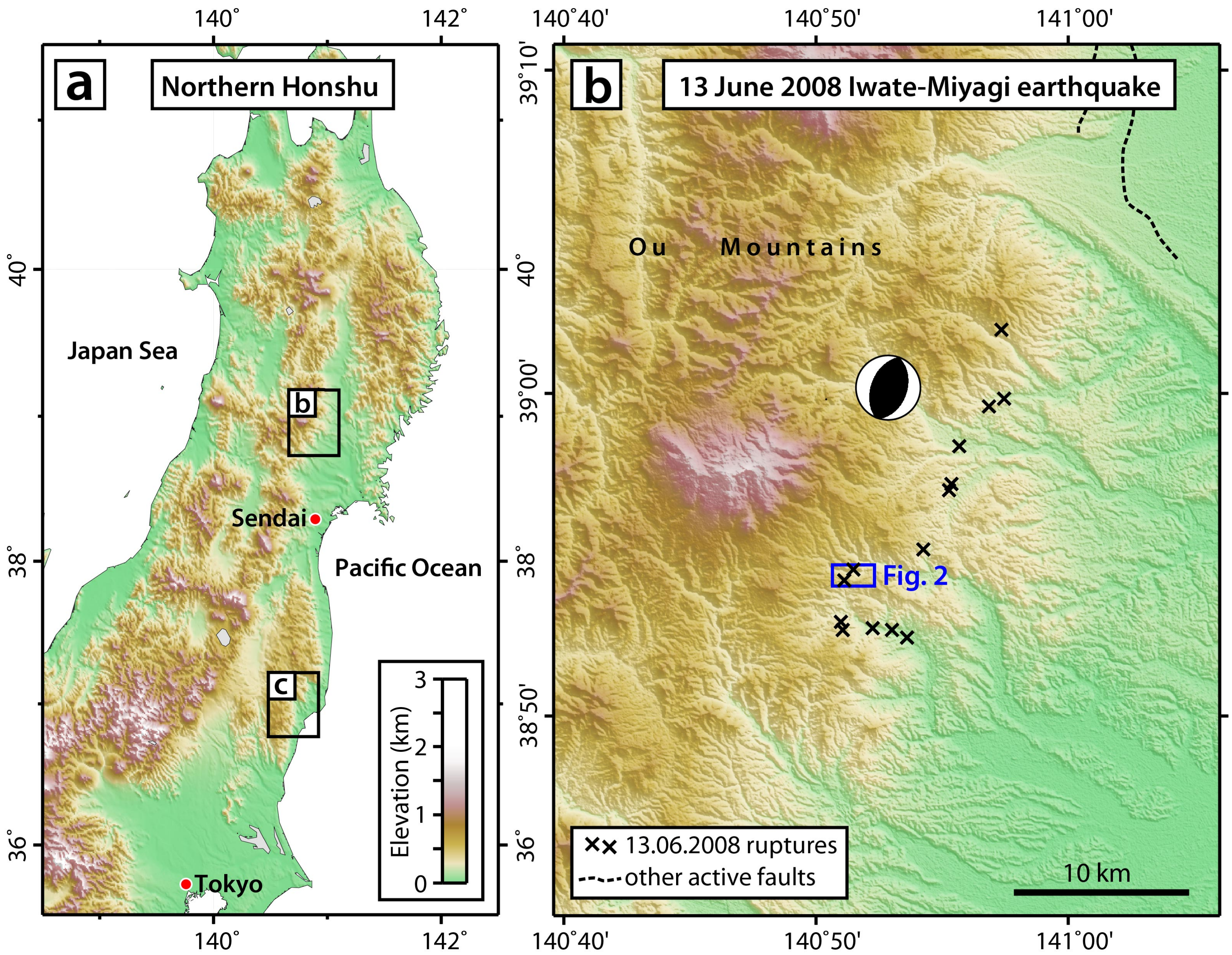


between earthquakes elastic strain accumulates



during earthquake elastic strain is released

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



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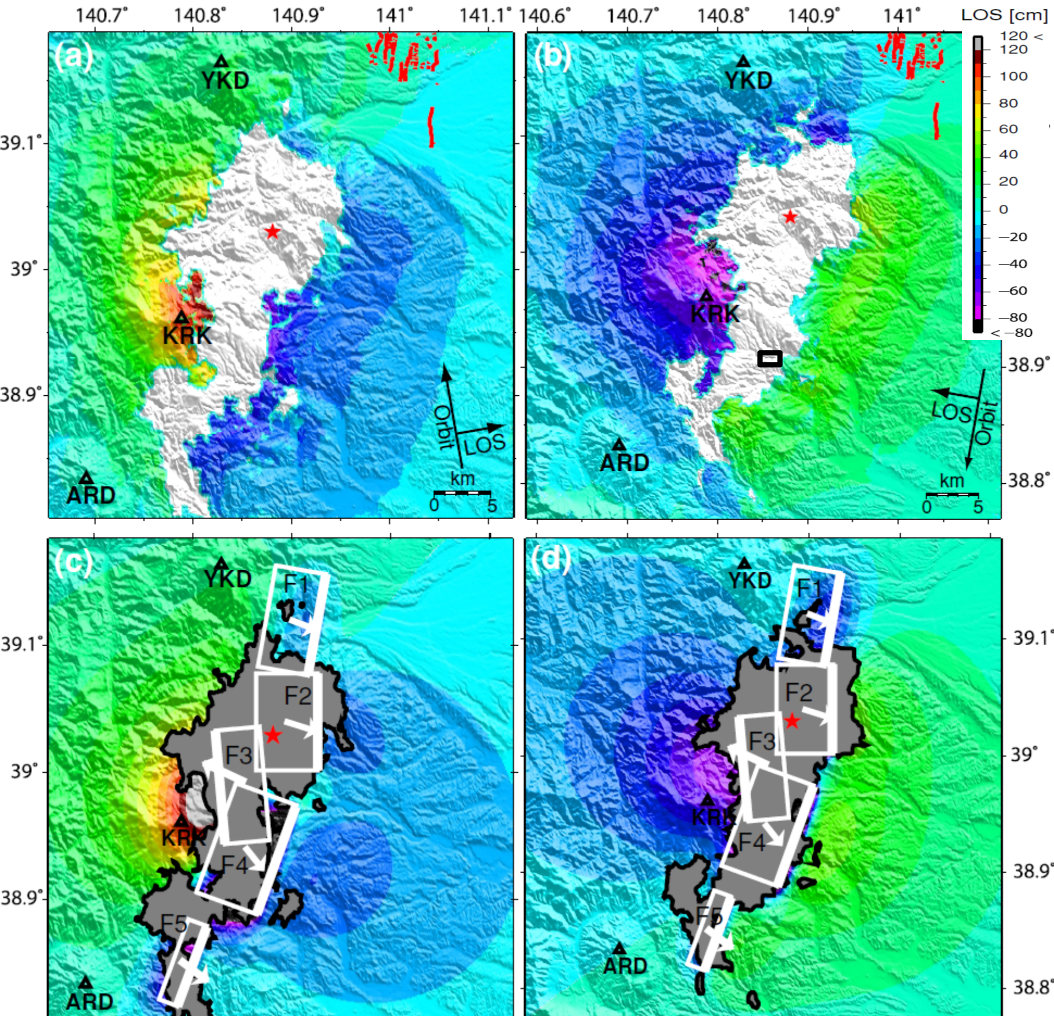
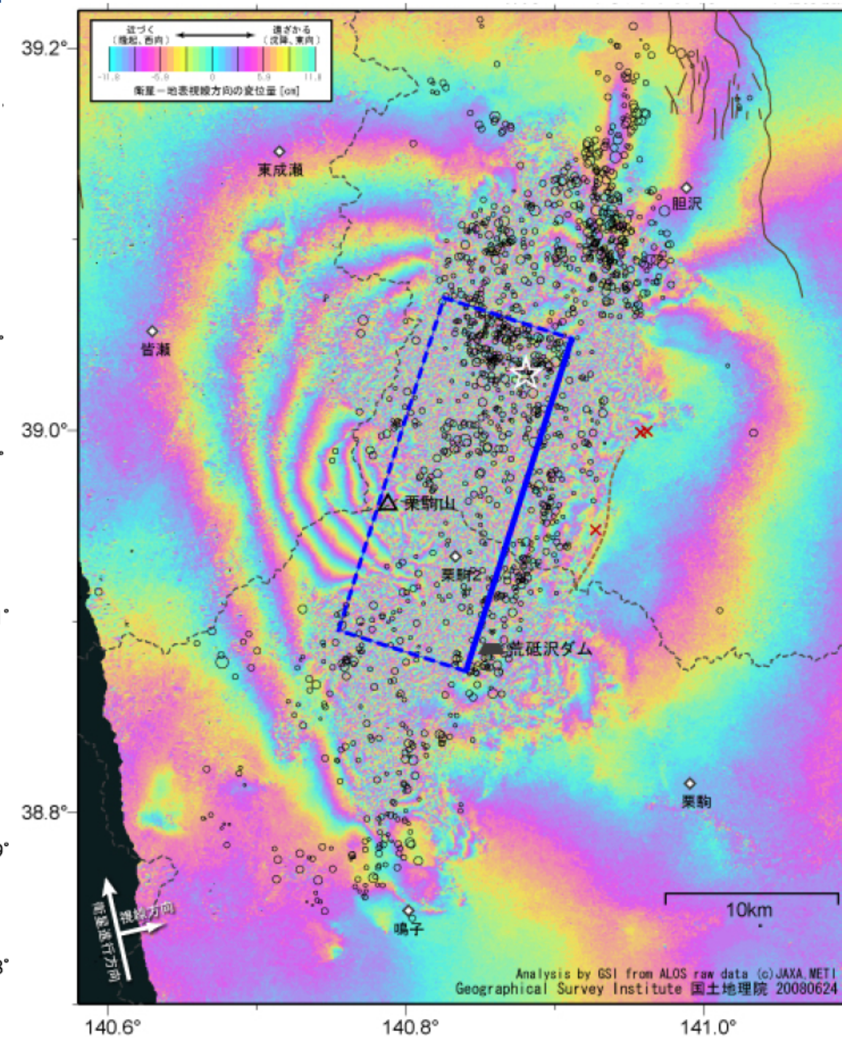


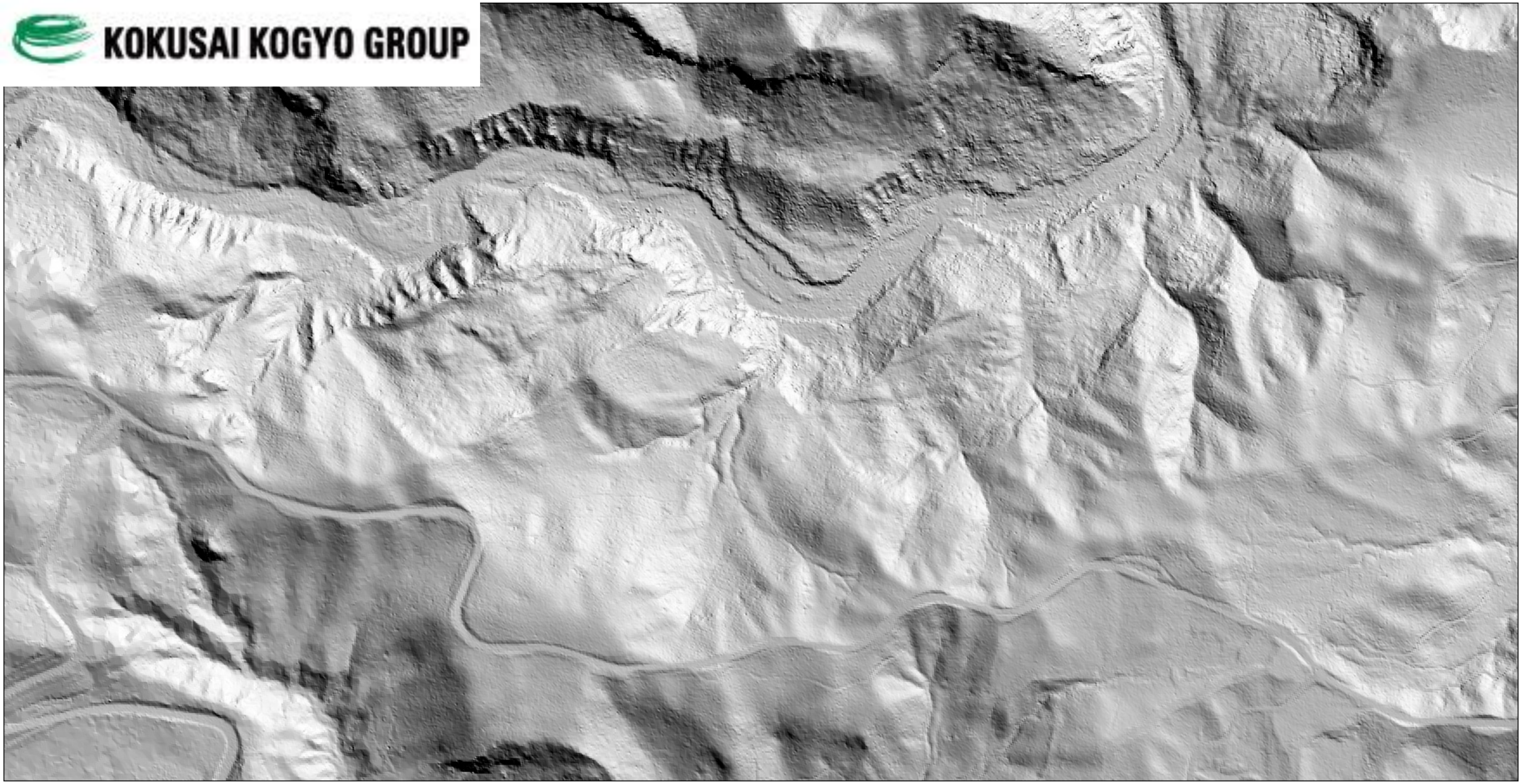
Takada et al. (2009), Earth Planets Space



Japan Geographical Survey Institute

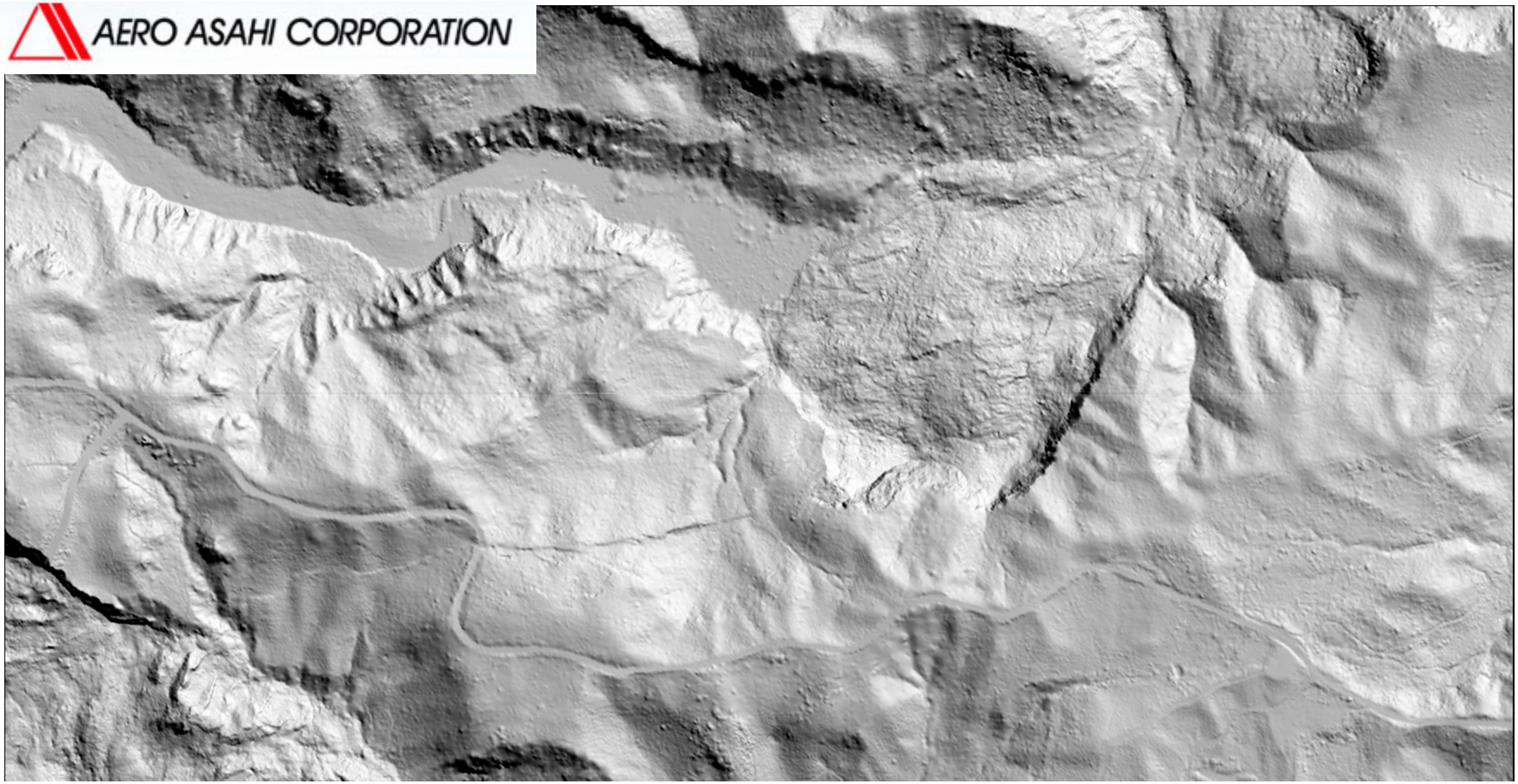
The 2008 Iwate-Miyagi earthquake (Mw 6.9), Japan

KOKUSAI KOGYO GROUP



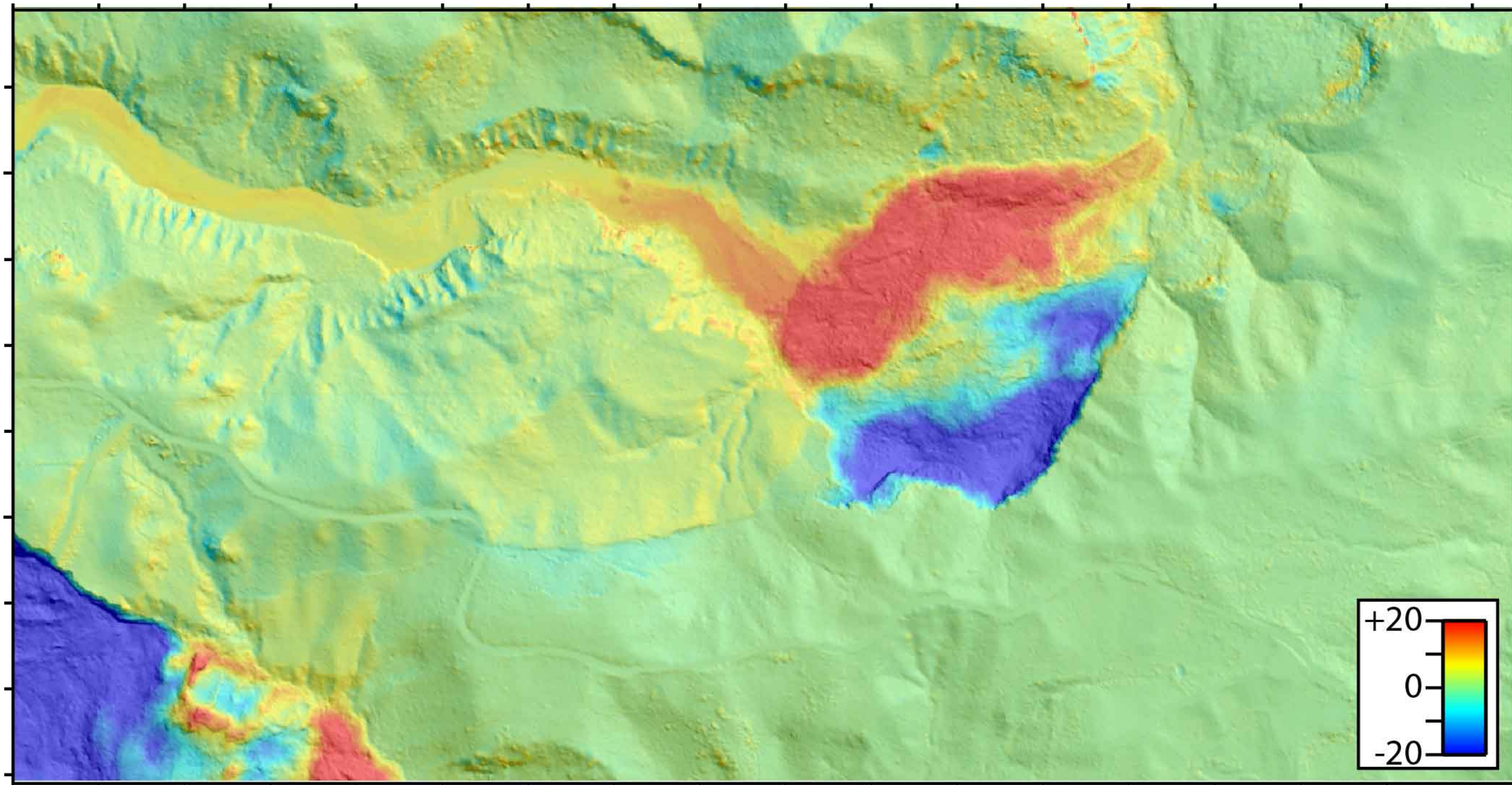
Pre-earthquake DEM (2m)

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



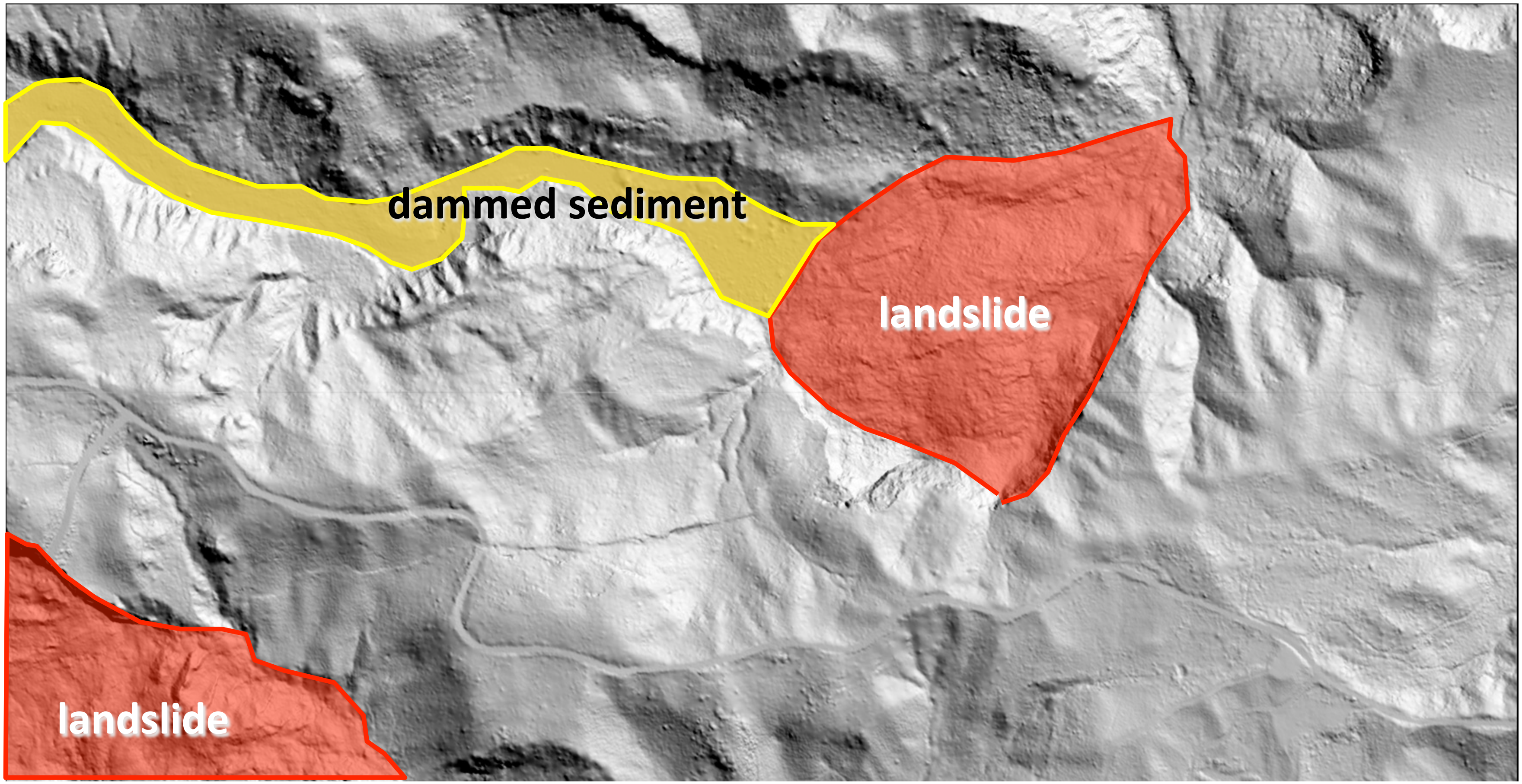
Post-earthquake DEM (1m)

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



DEM subtraction (height change, m)

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



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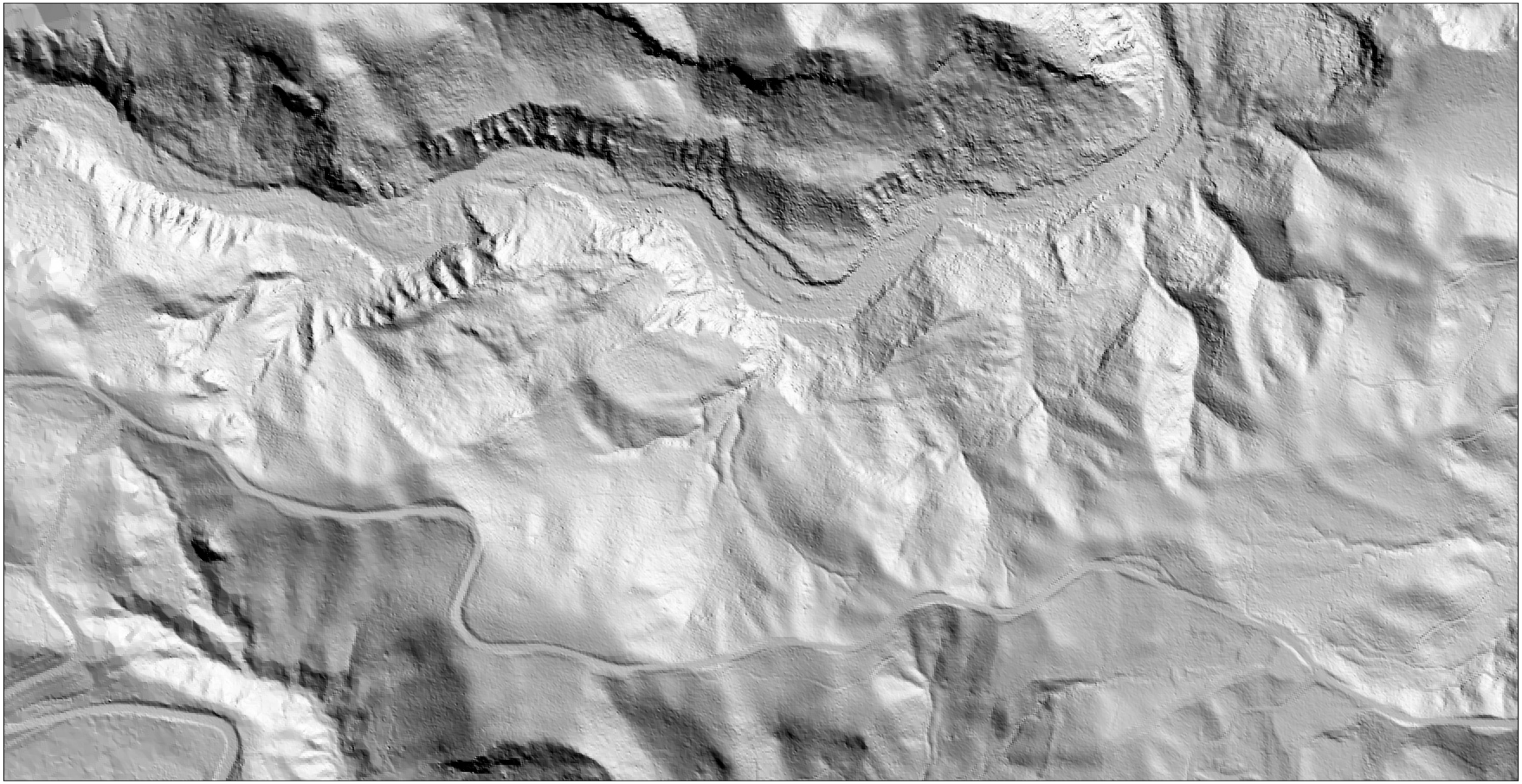

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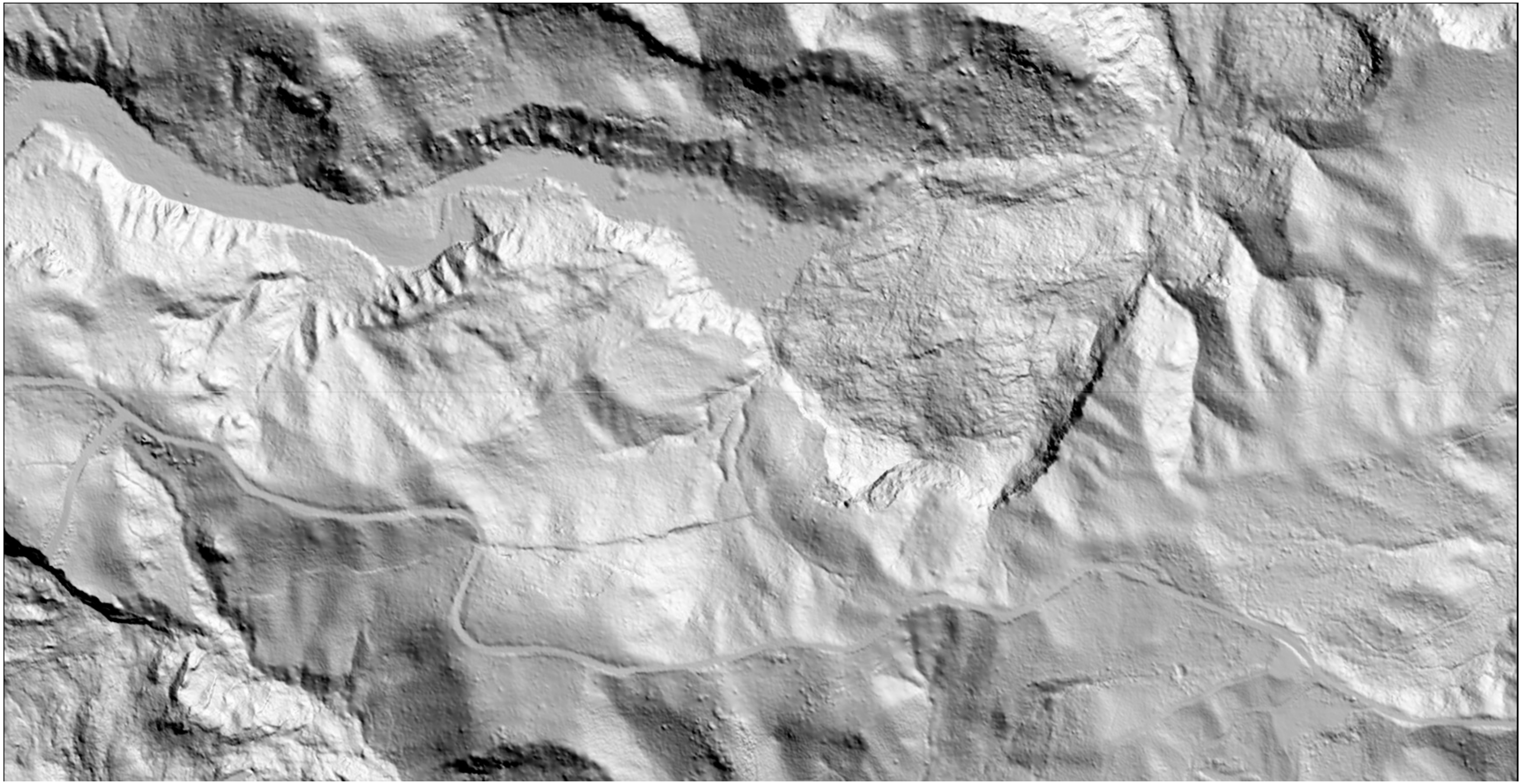

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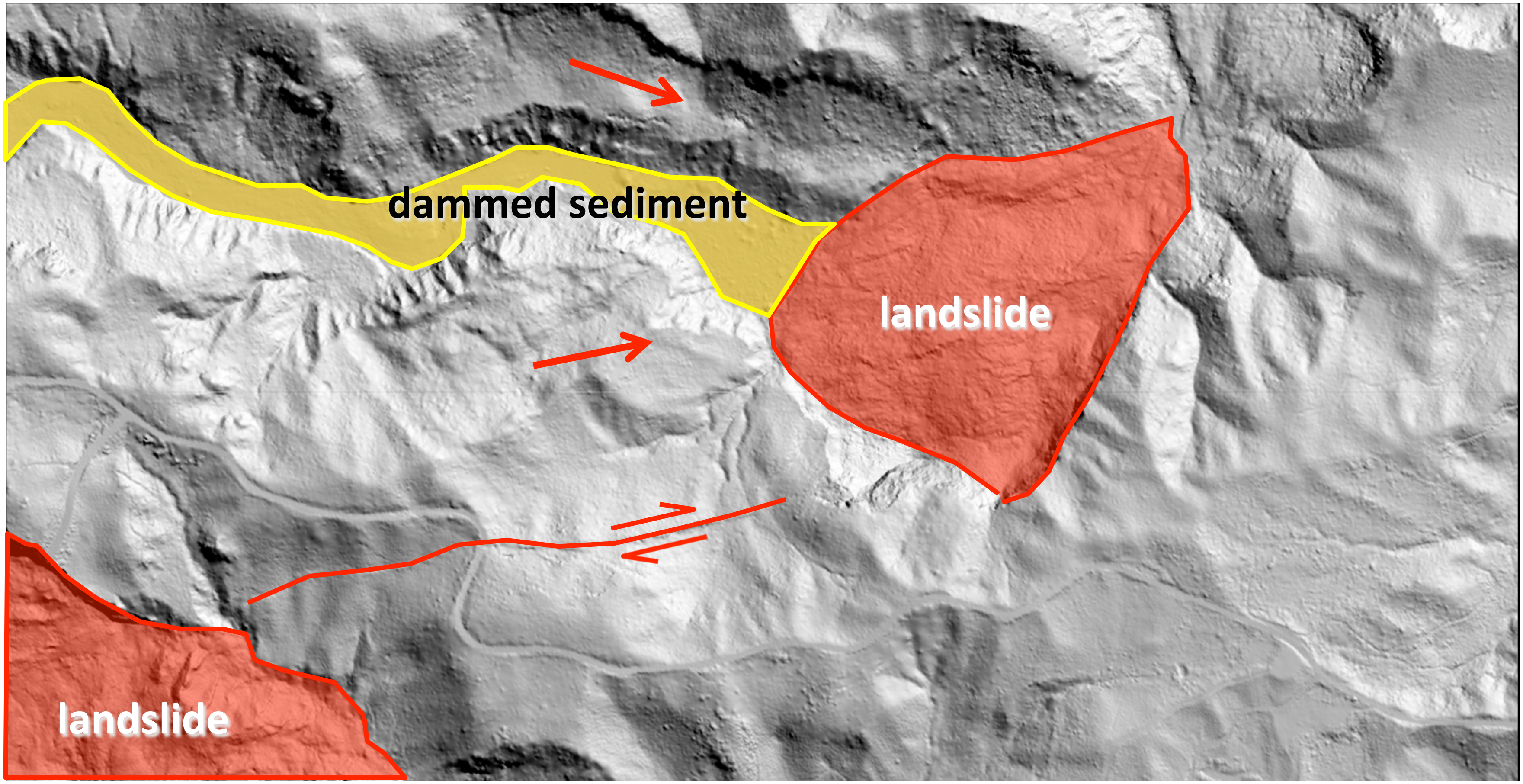
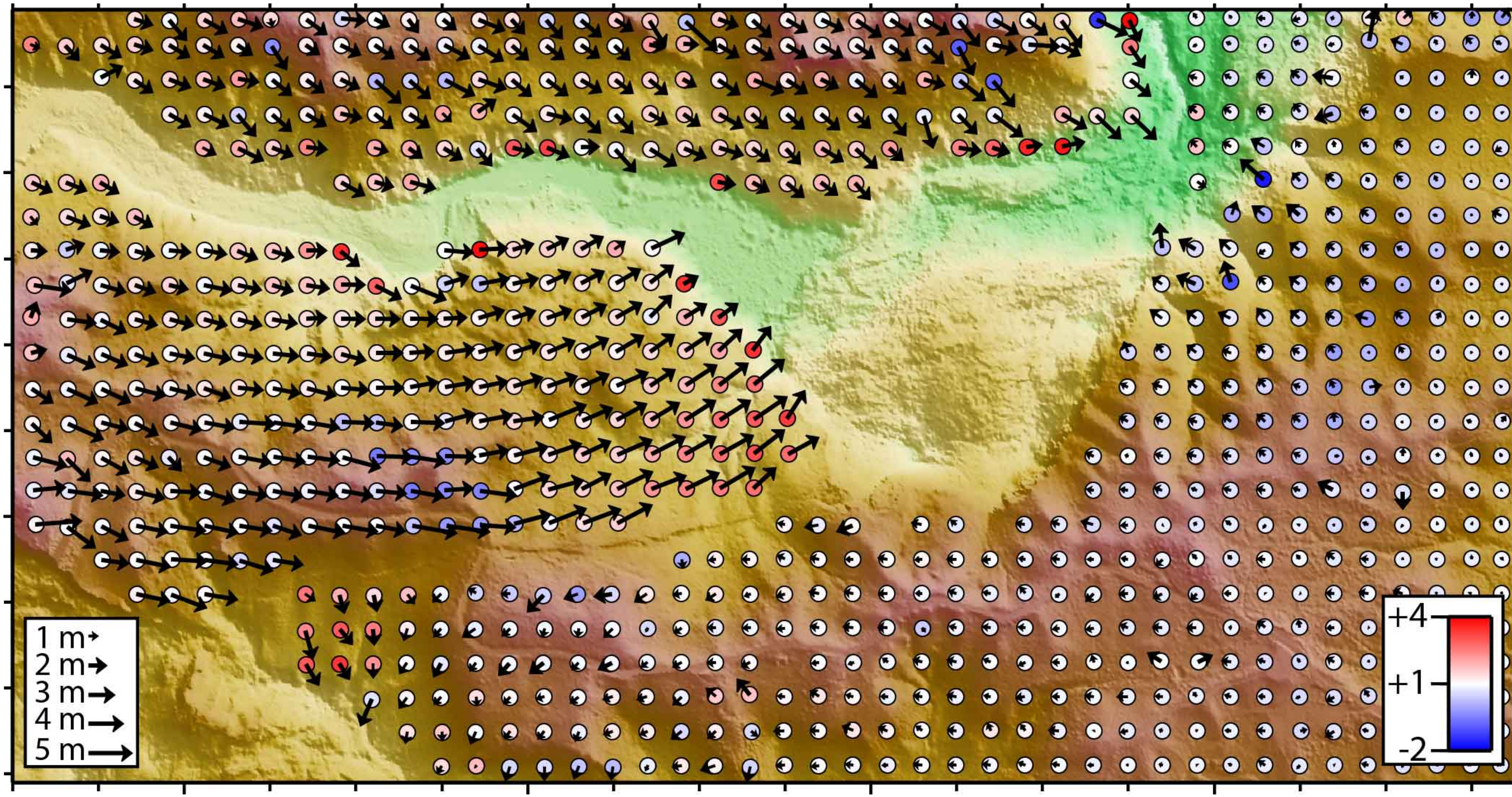
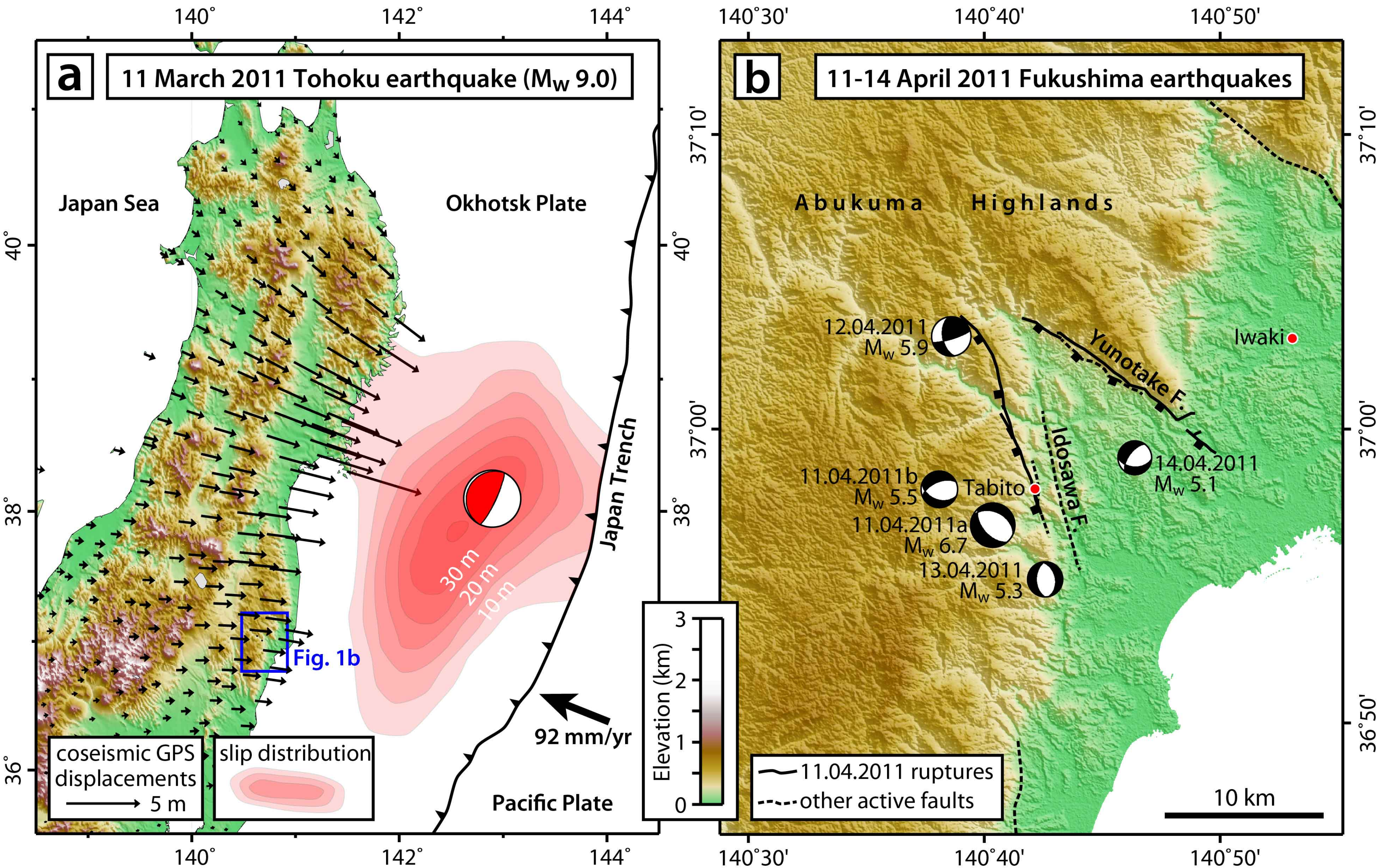


The 2008 Iwate-Miyagi earthquake (Mw 6.9), Japan



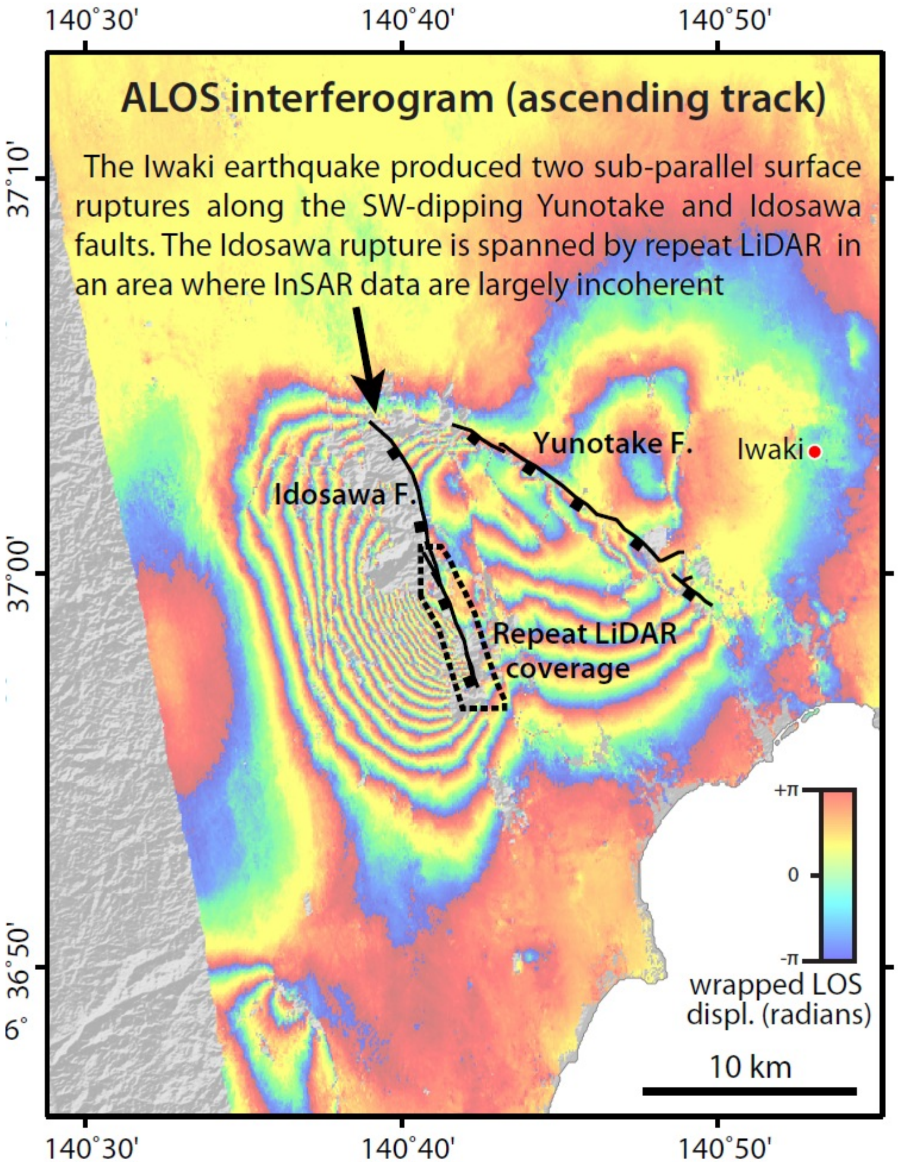
Dense 3-D displacements in an area InSAR cannot image

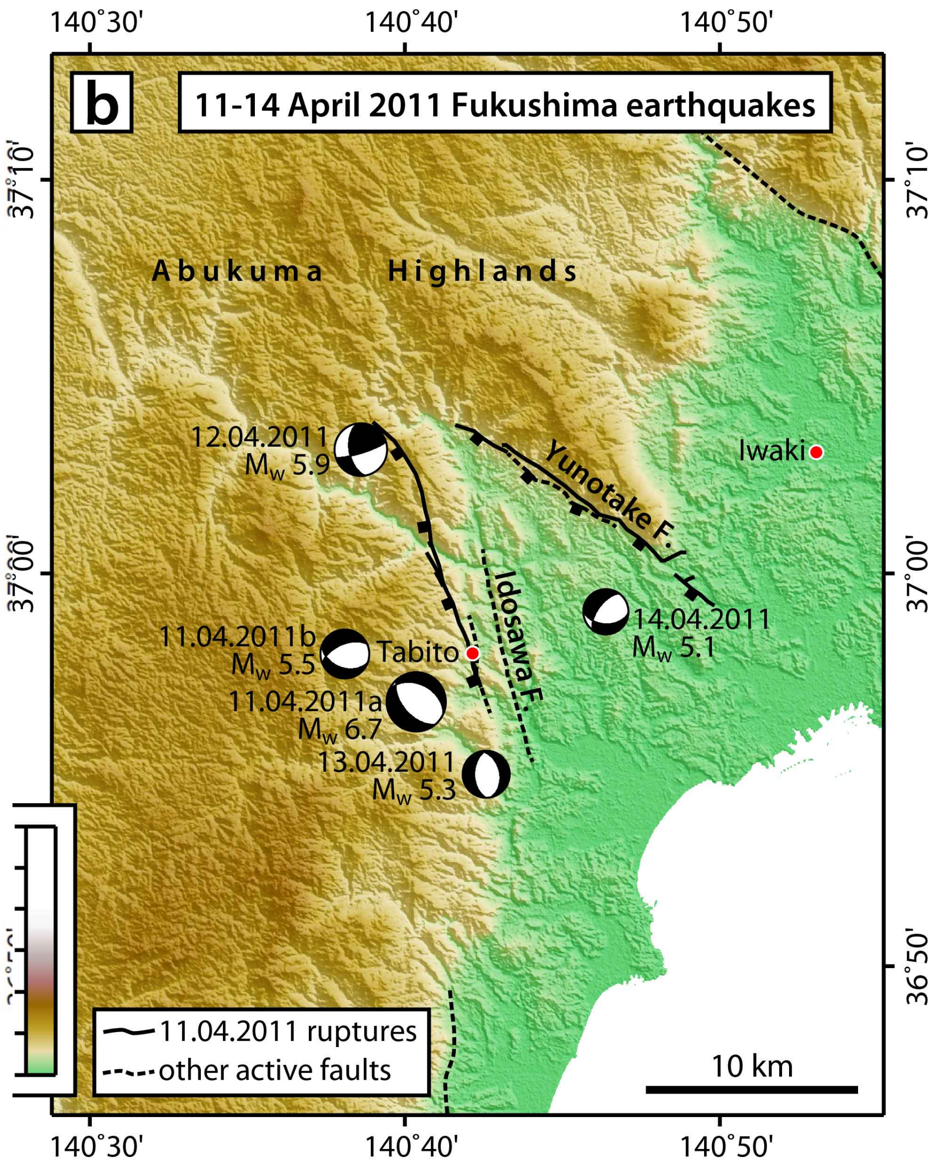
The displacement sense and magnitude agrees with (limited) field observations



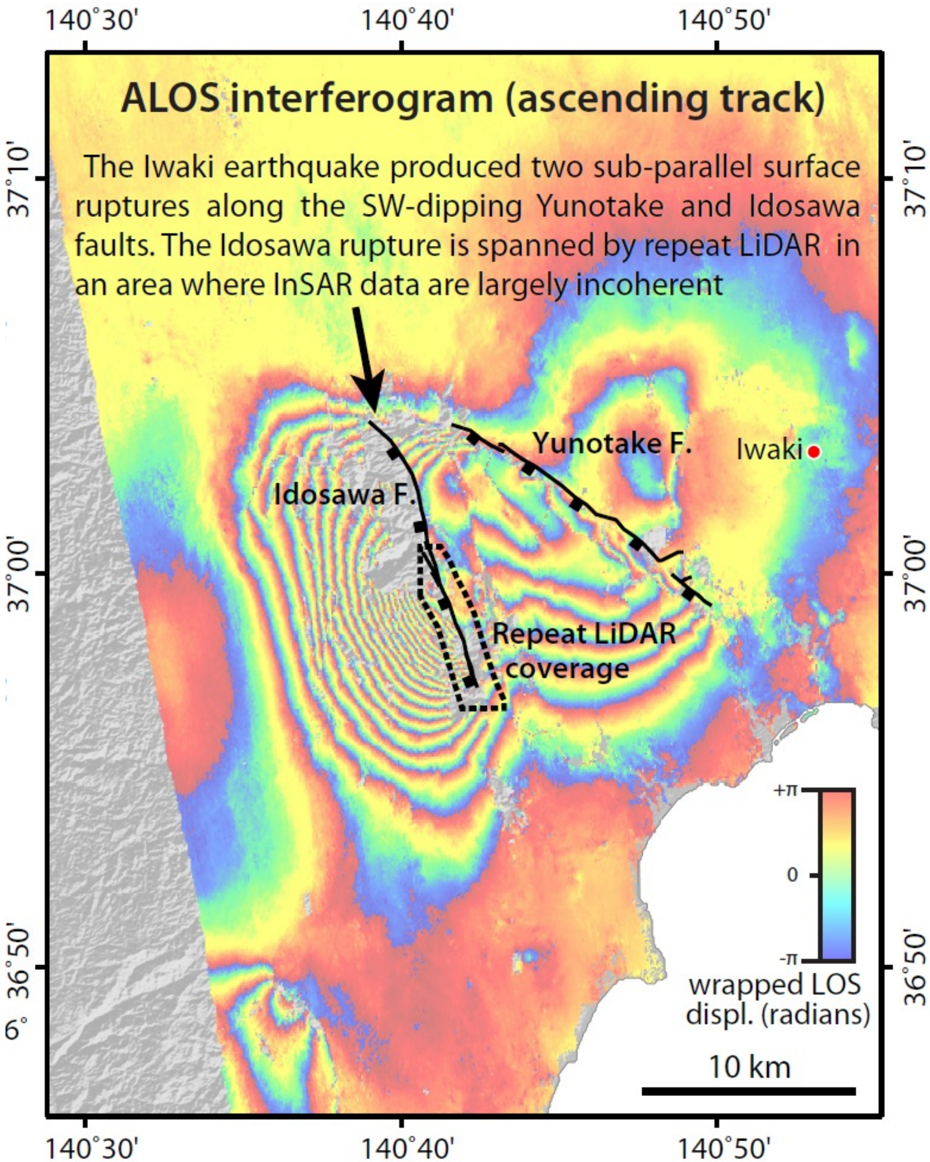
a
11 March 2011 Tohoku earthquake (M_W 9.0)
Japan Sea
Okhotsk Plate
Japan Trench
Pacific Plate
92 mm/yr
30 m
20 m
10 m
Fig. 1b
coseismic GPS displacements
5 m
slip distribution
140°
142°
144°
36°
38°
40°
Elevation (km)
0
1
2
3
b
11-14 April 2011 Fukushima earthquakes
Abukuma Highlands
12.04.2011
M_w 5.9
11.04.2011b
M_w 5.5
11.04.2011a
M_w 6.7
13.04.2011
M_w 5.3
14.04.2011
M_w 5.1
Tabito
Iwaki
Yunotake F.
Idosawa F.
11.04.2011 ruptures
other active faults
10 km
140°30'
140°40'
140°50'
36°50'
37°00'
37°10'

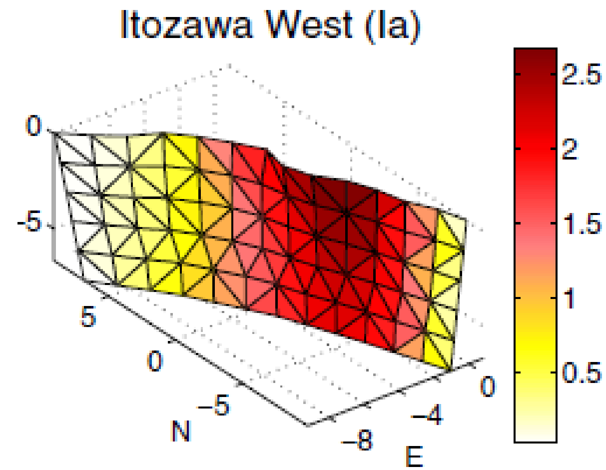
The 2011 Iwaki earthquake (Mw 6.7), Japan

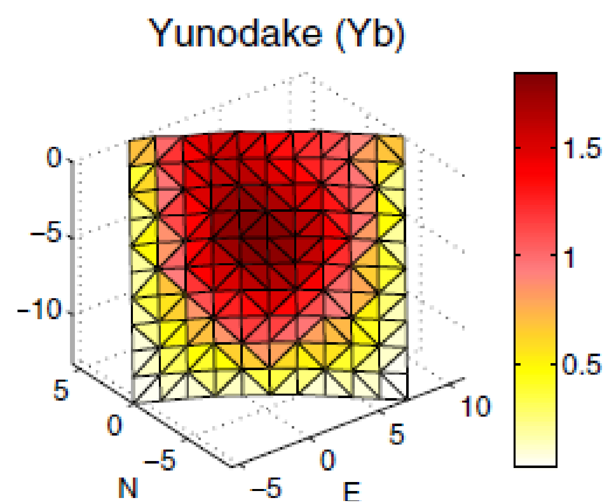




The 2011 Iwaki earthquake (Mw 6.7), Japan

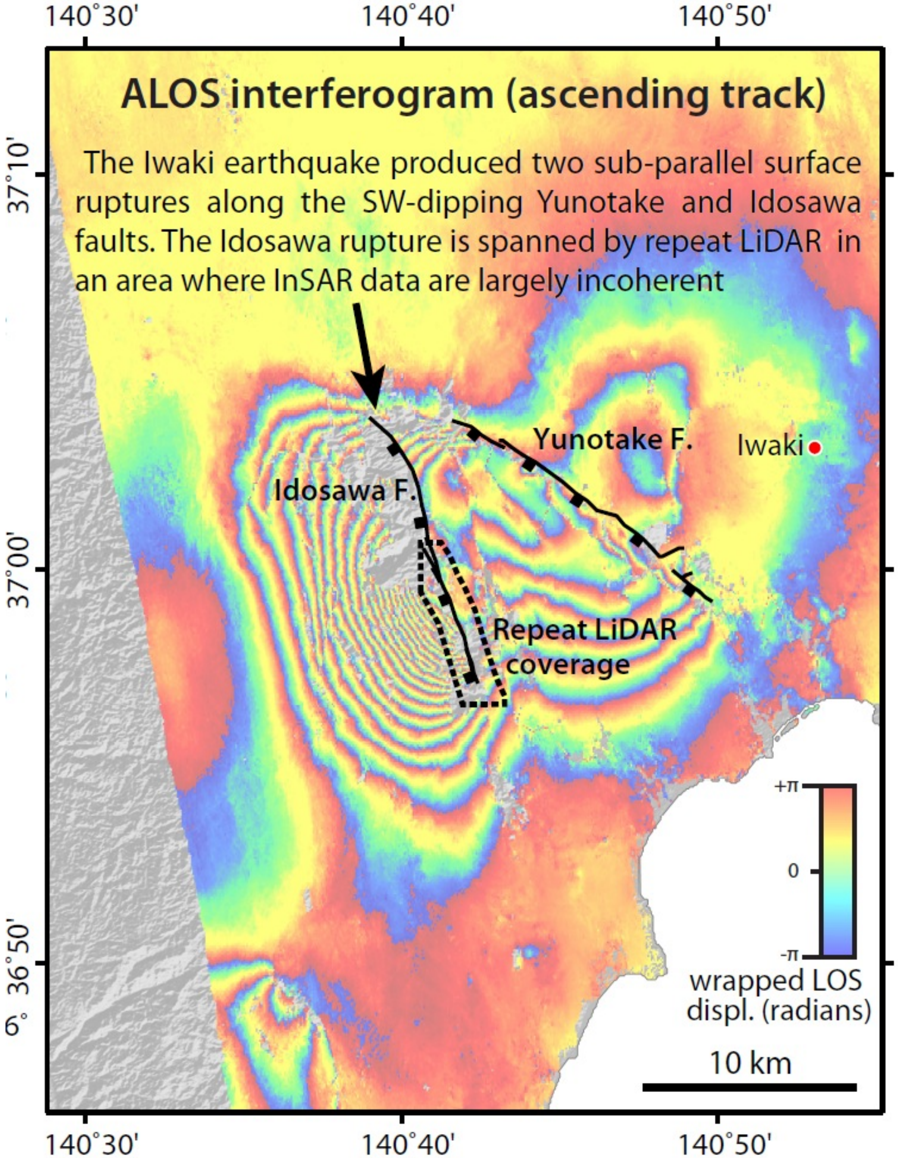


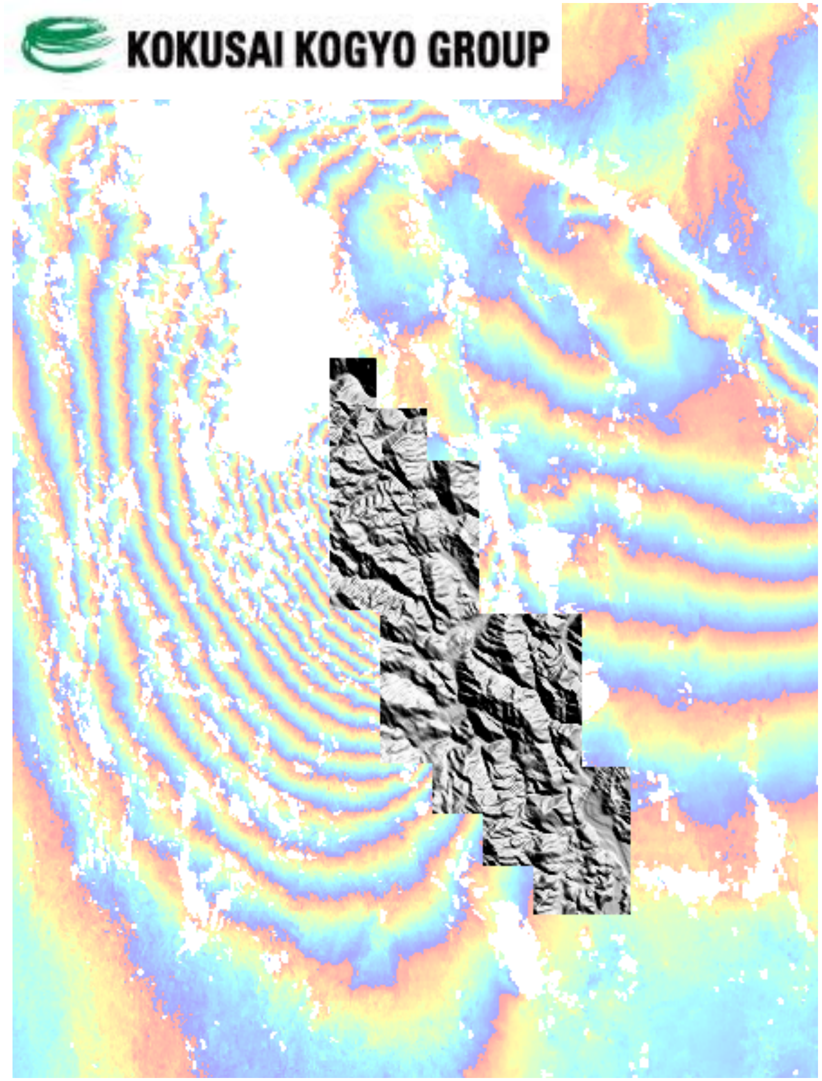




InSAR model from Fukushima et al. (2013), BSSA

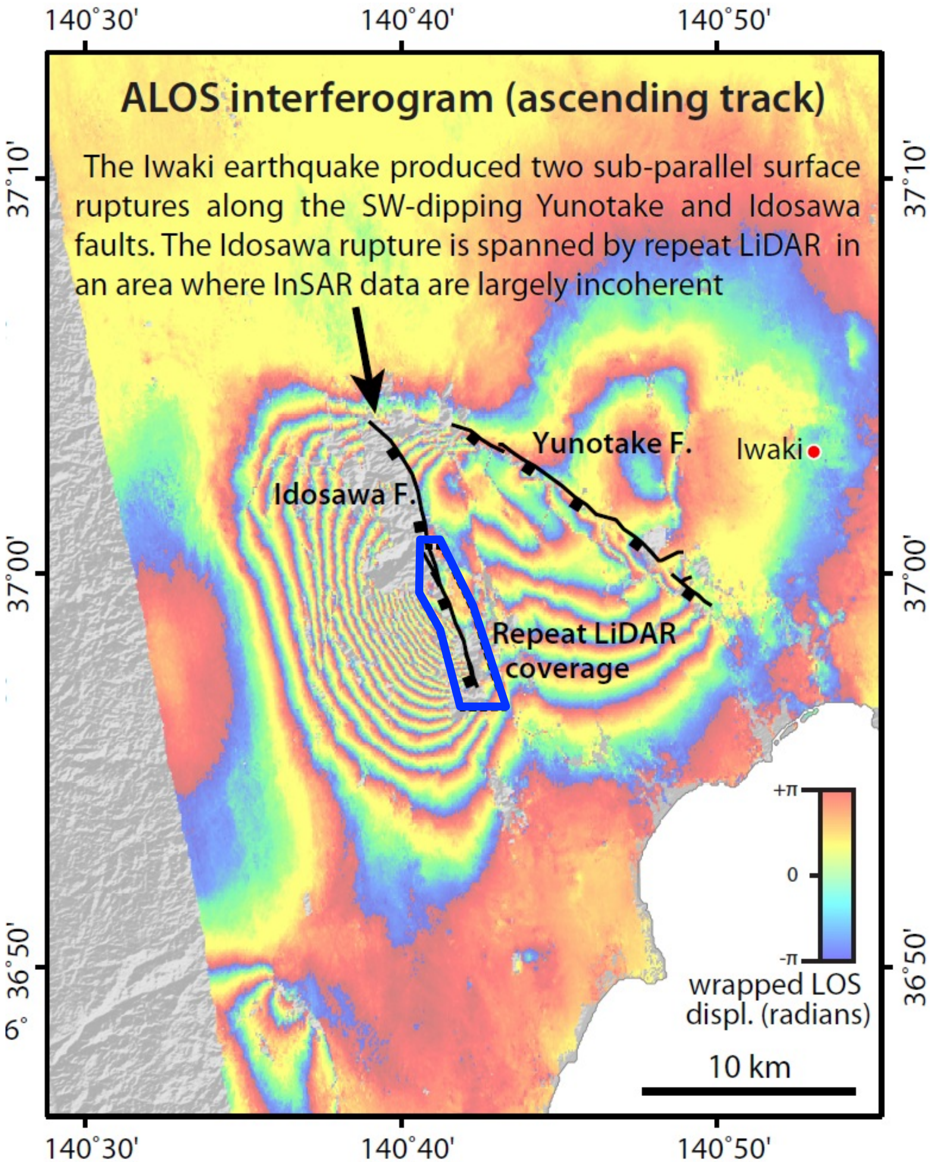
The 2011 Iwaki earthquake (Mw 6.7), Japan

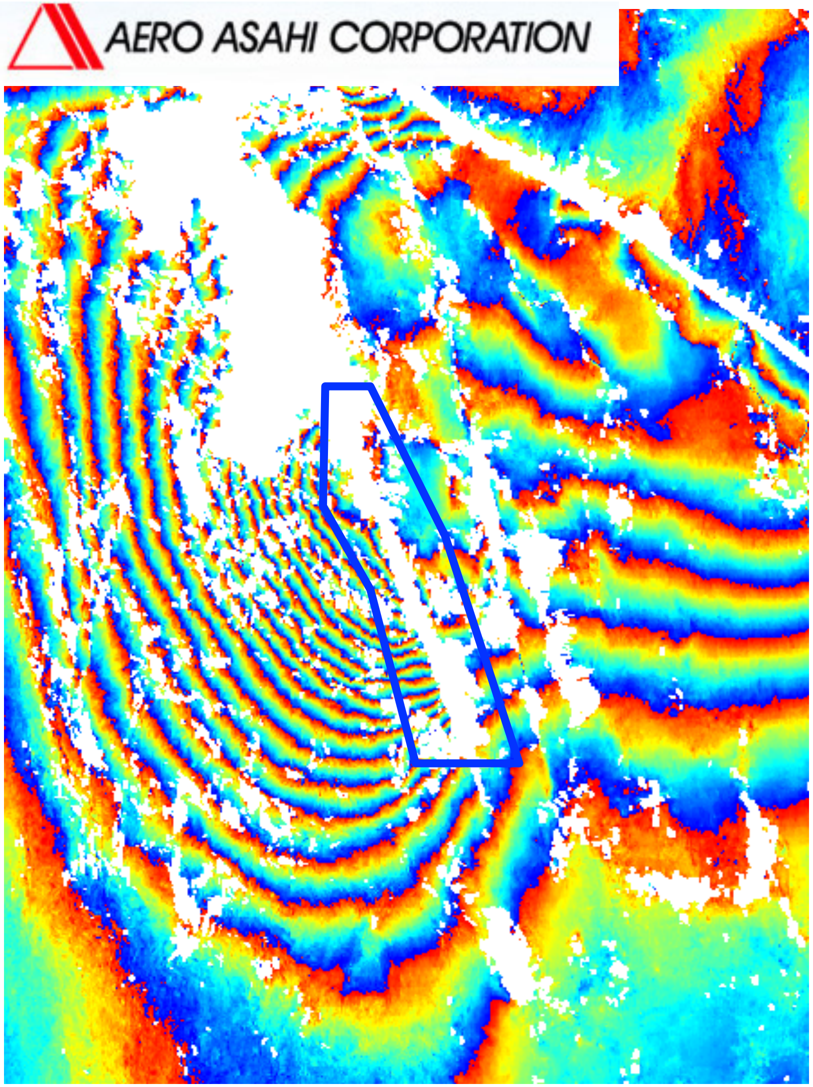




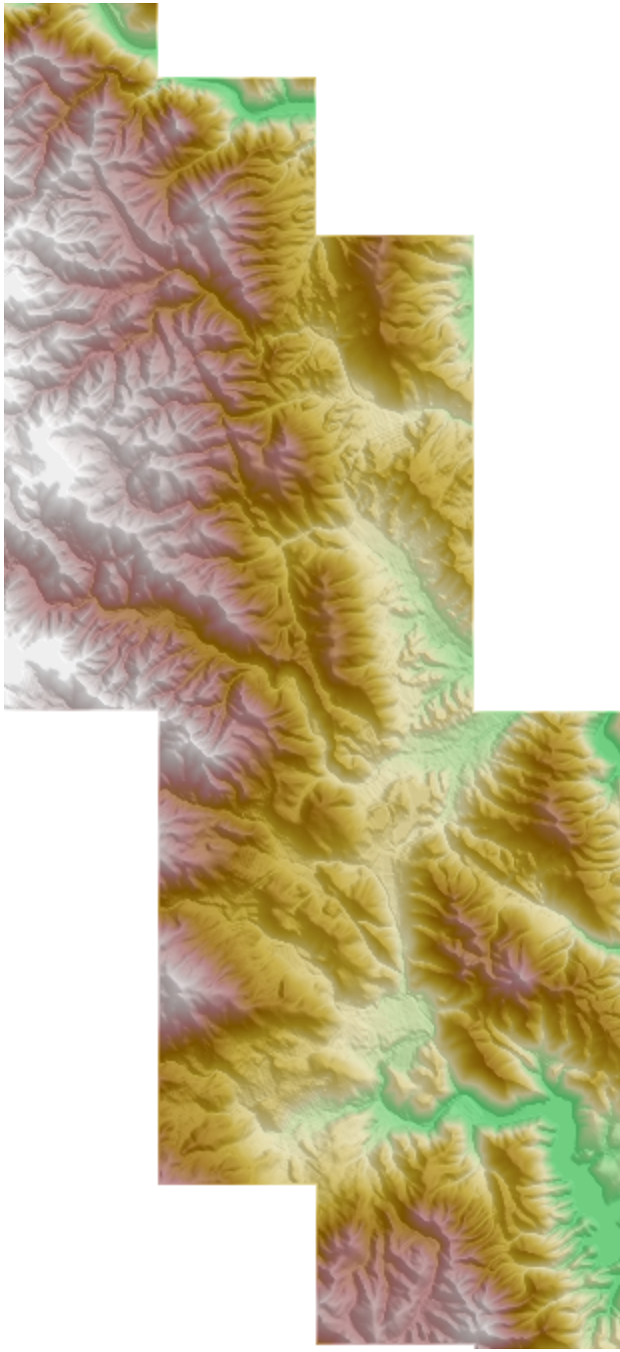
Pre-event data: 2 m Bare Earth DEM, Kokusai Kogyo Co. Ltd.

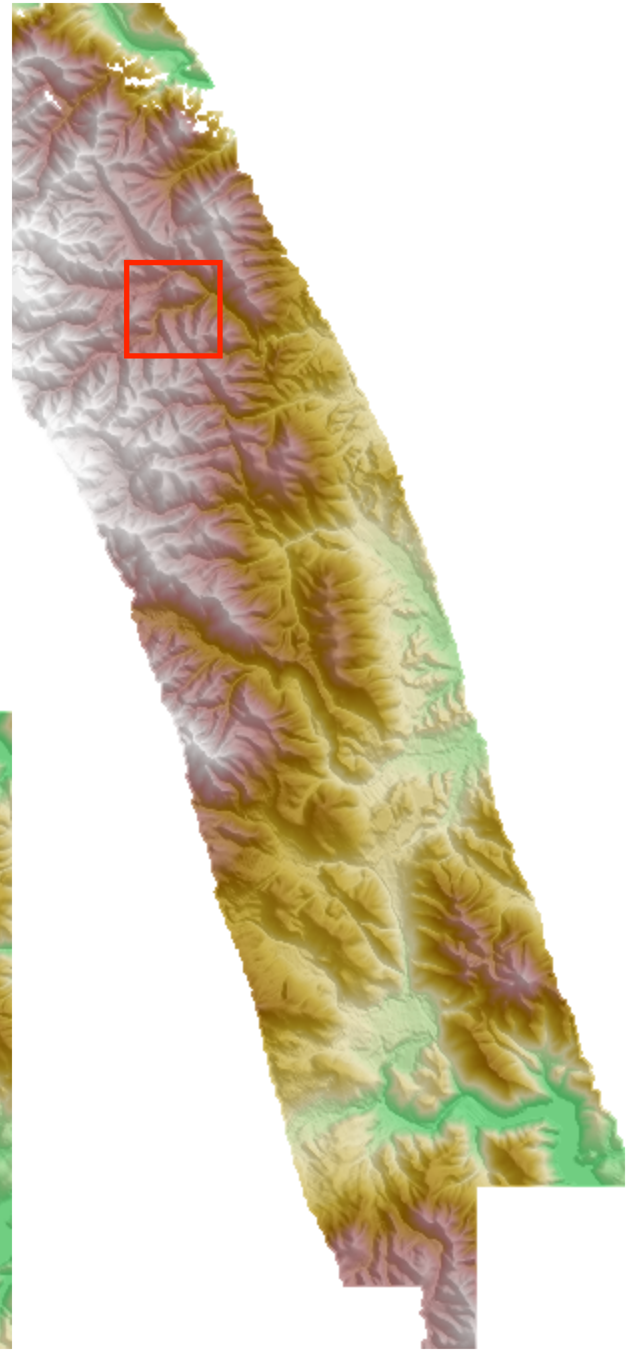
The 2011 Iwaki earthquake (Mw 6.7), Japan

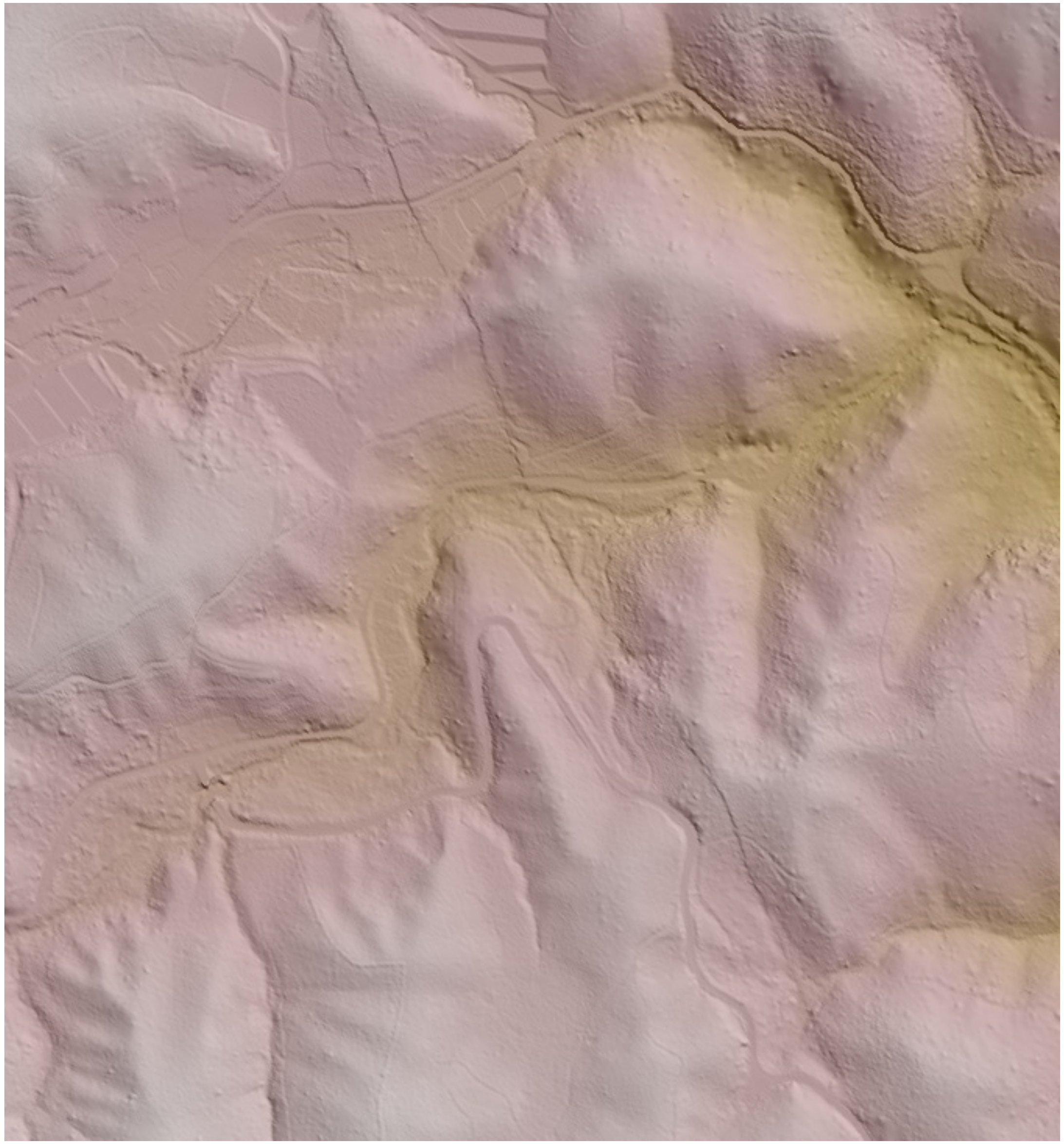


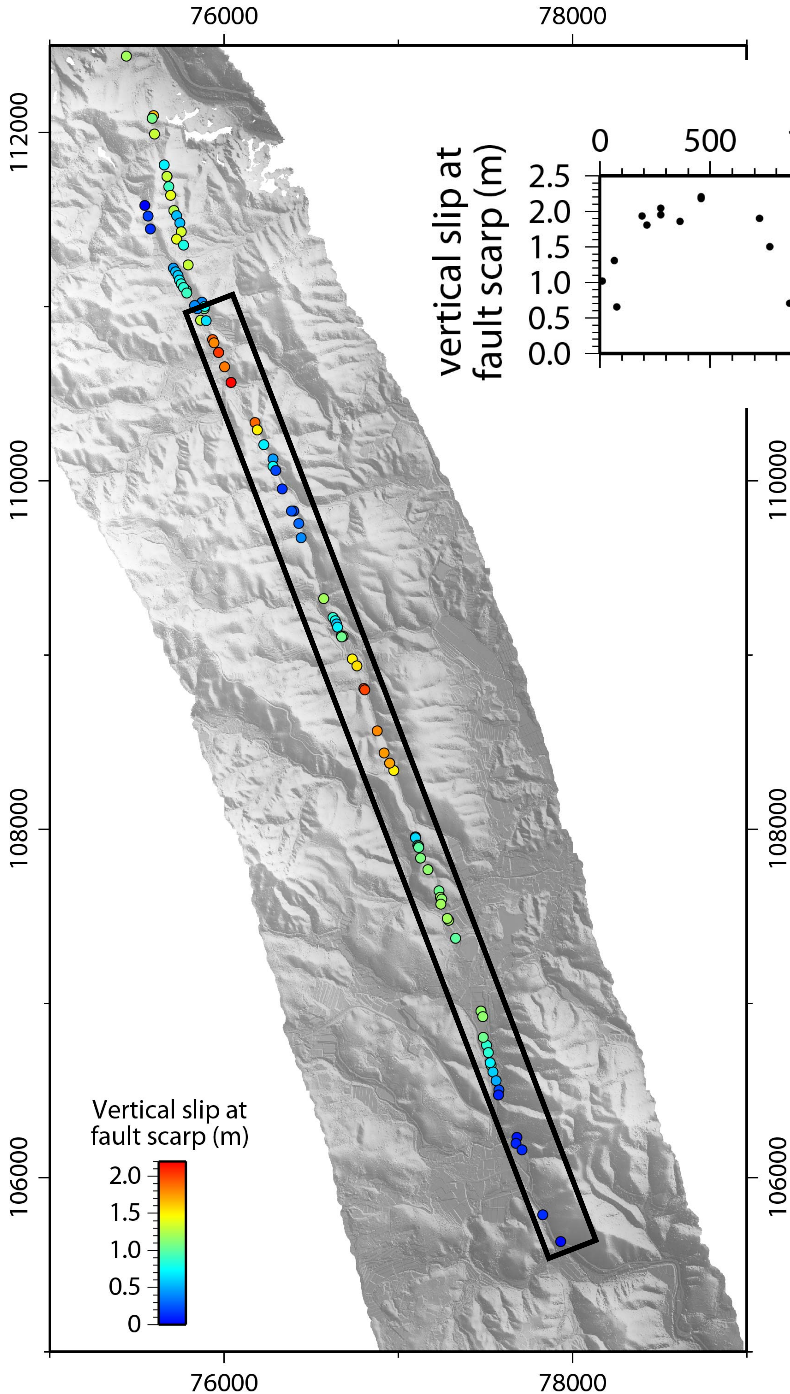


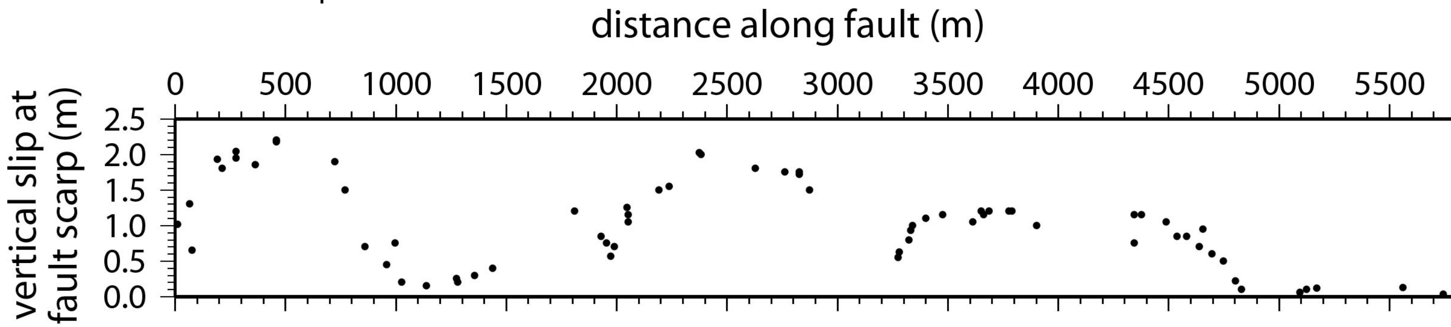
Post-event data: 1 m Bare Earth DEM, Aero Asahi Corp.



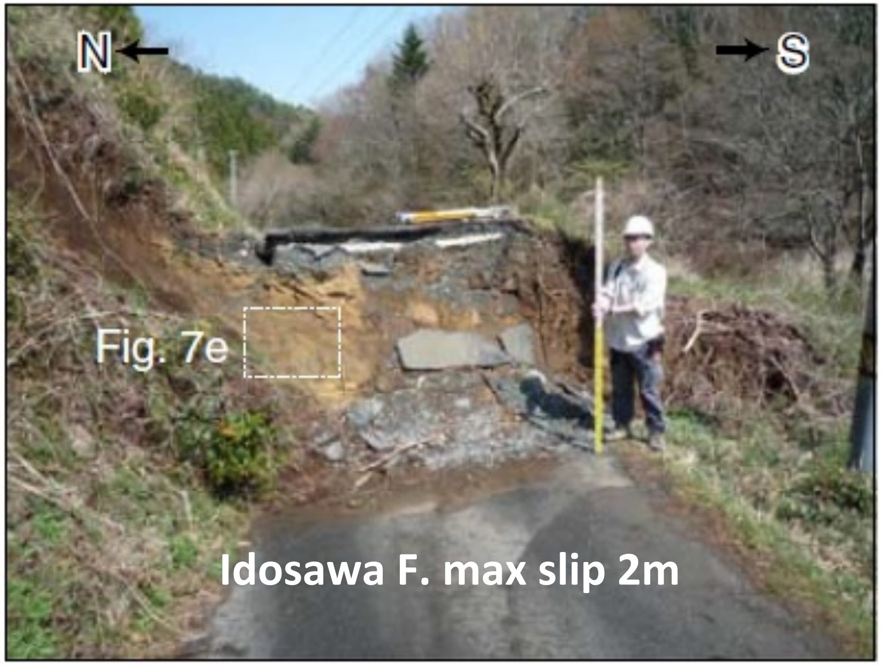




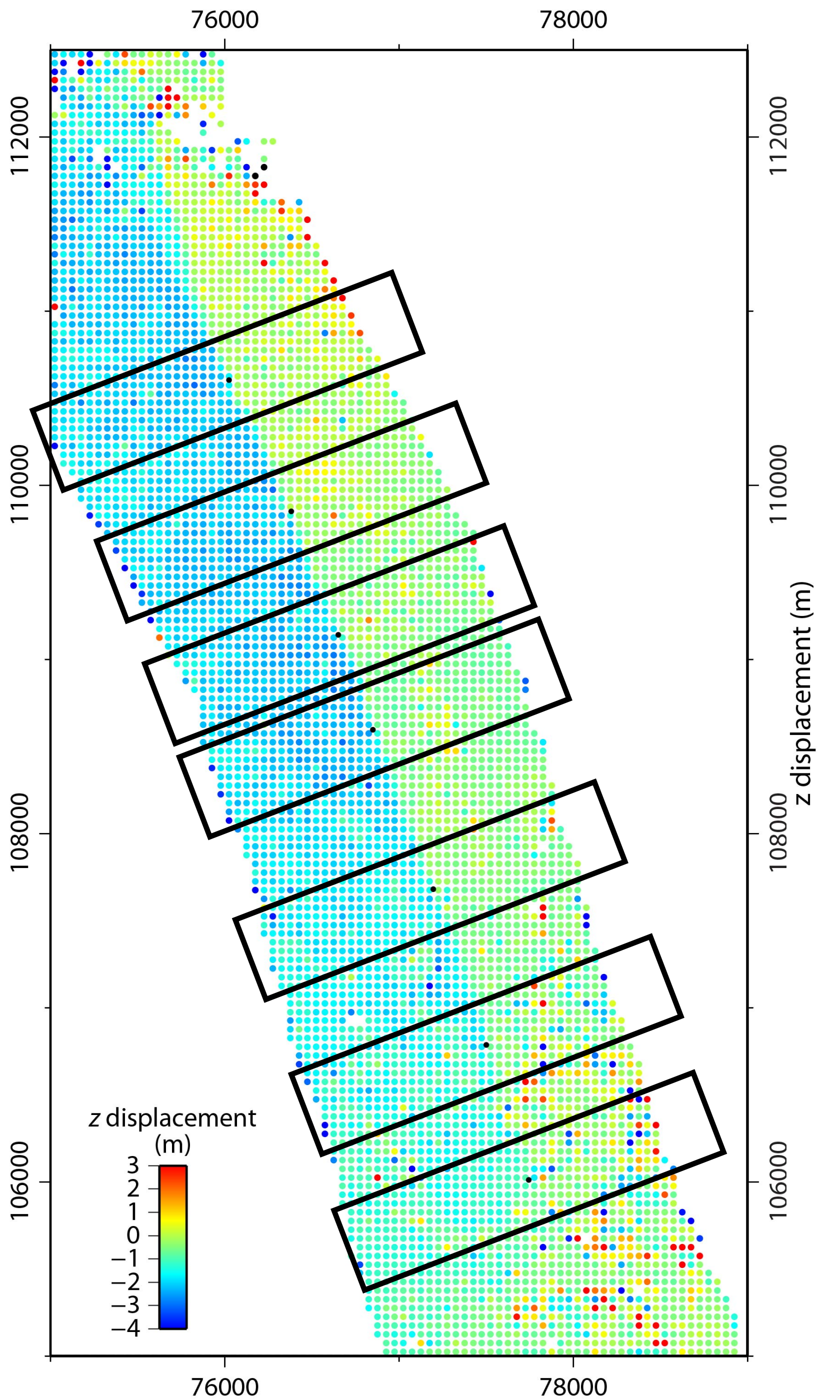


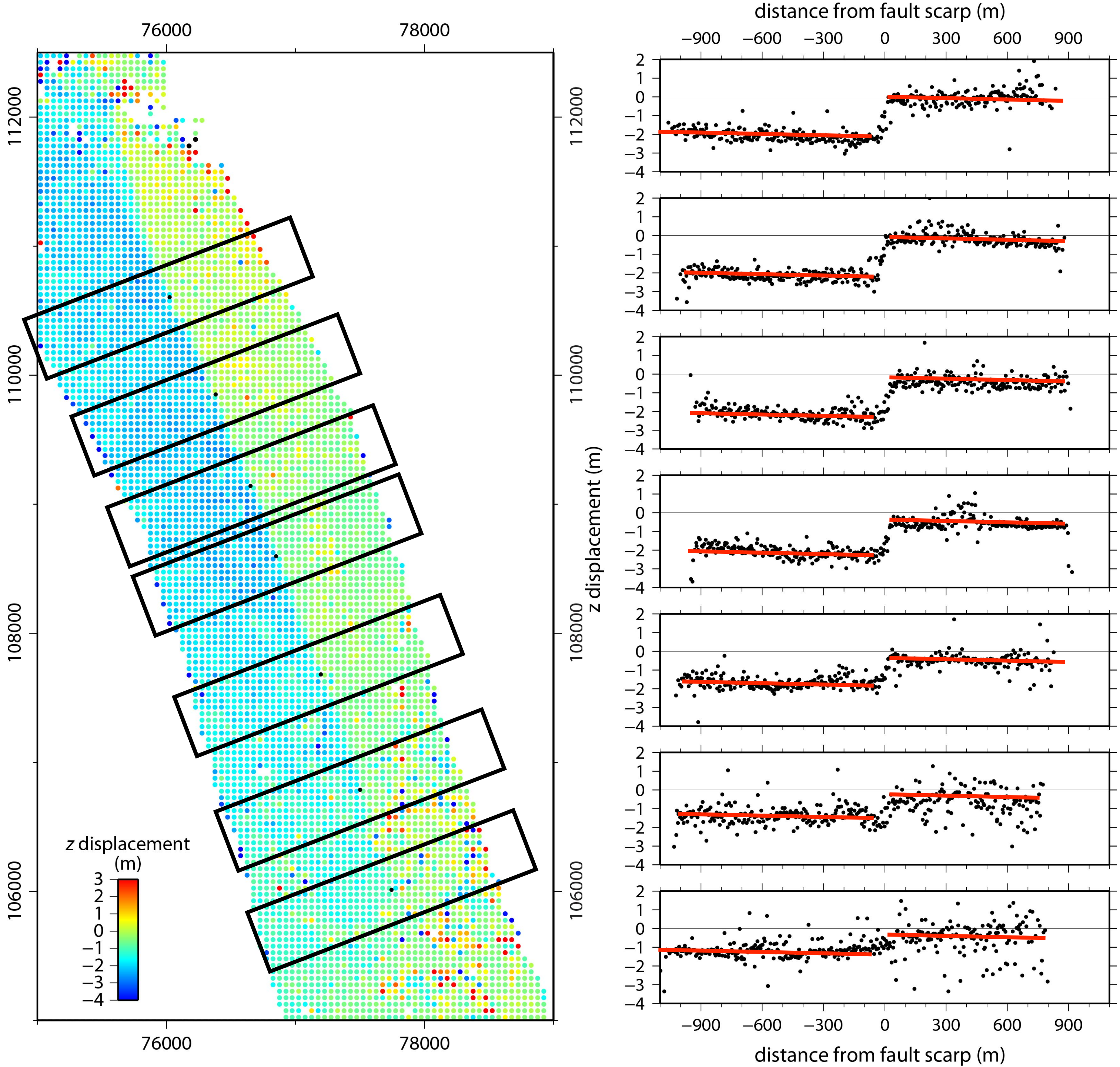


Field measurements by Tadashi Maruyama

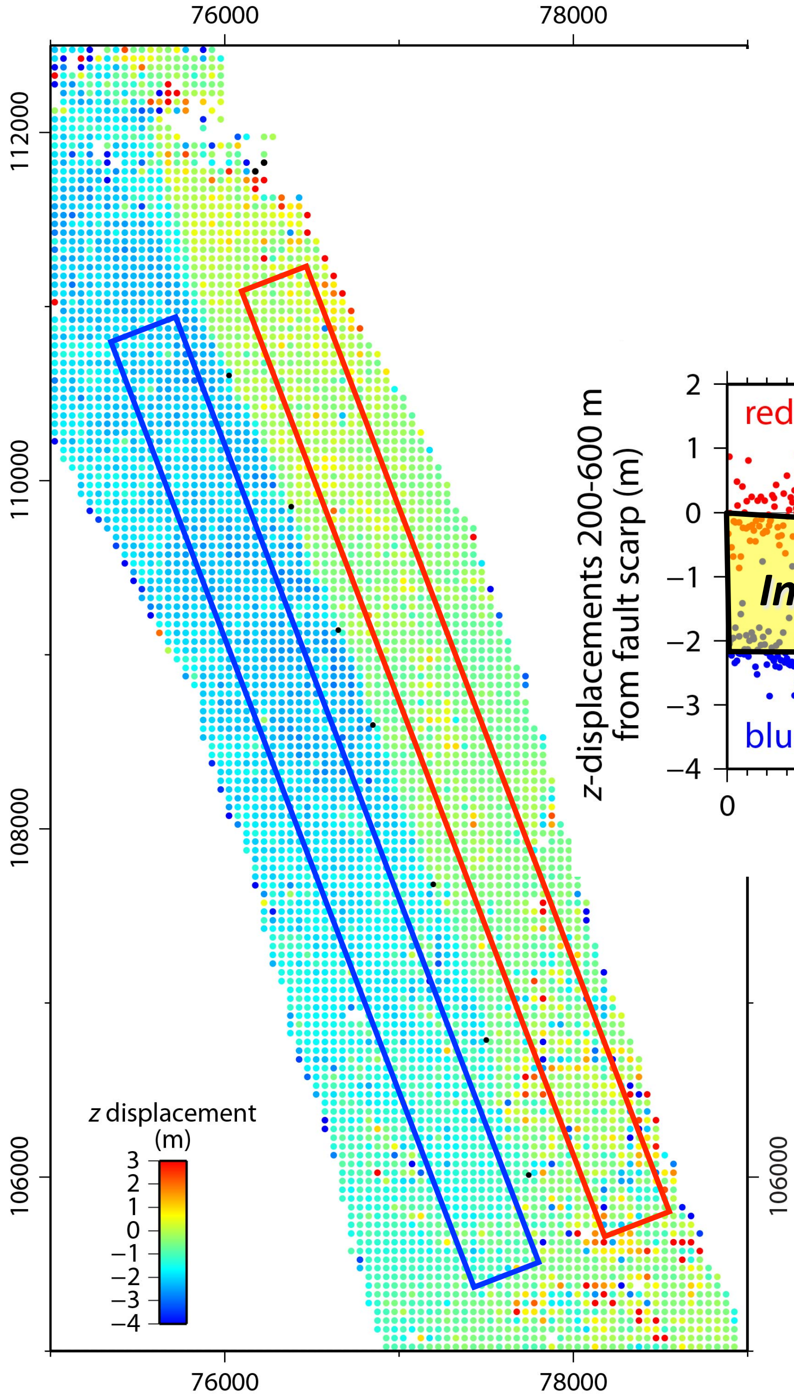


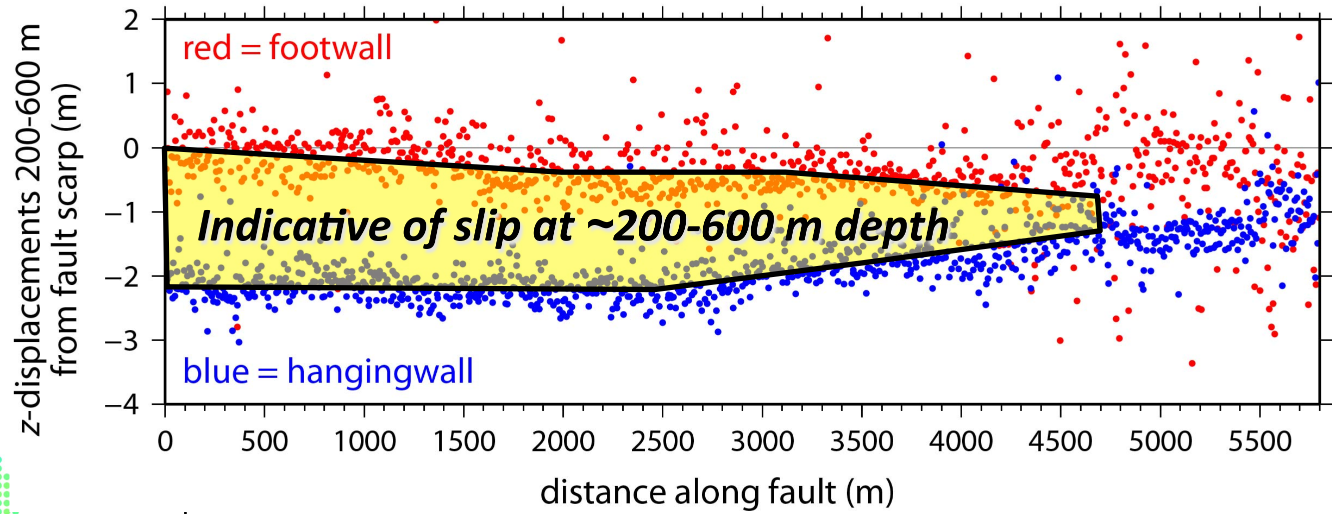
Toda & Tsutsumi (2013), Bull. Seism. Soc. Am.


76000
78000
112000
110000
108000
106000
z displacement (m)
z displacement
(m)
3
2
1
0
−1
−2
−3
−4

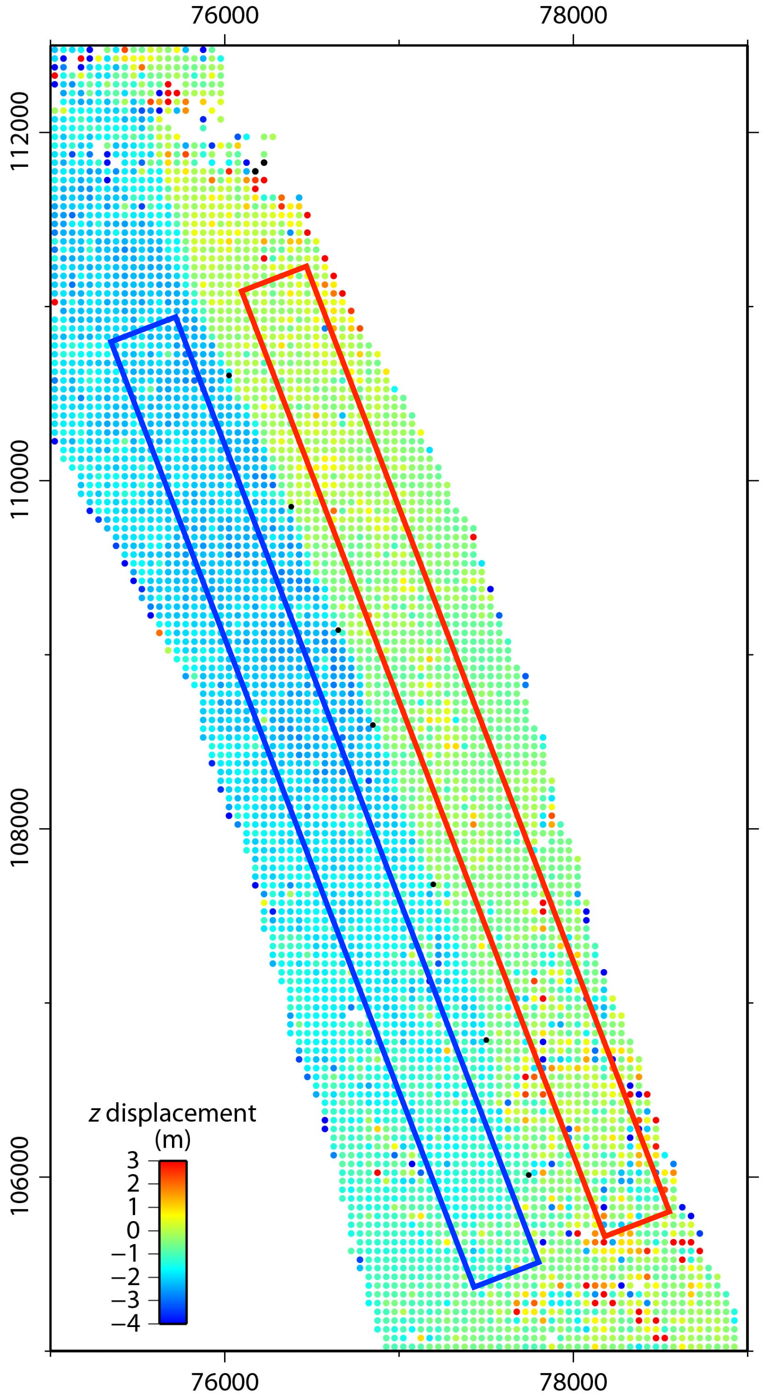


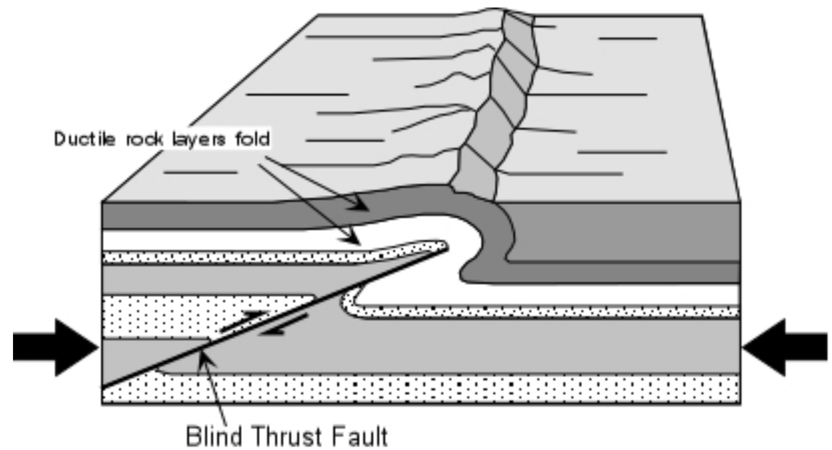
distance from fault scarp (m)
z displacement (m)
z displacement
(m)
76000
78000
112000
110000
108000
106000
−900
−600
−300
0
300
600
900





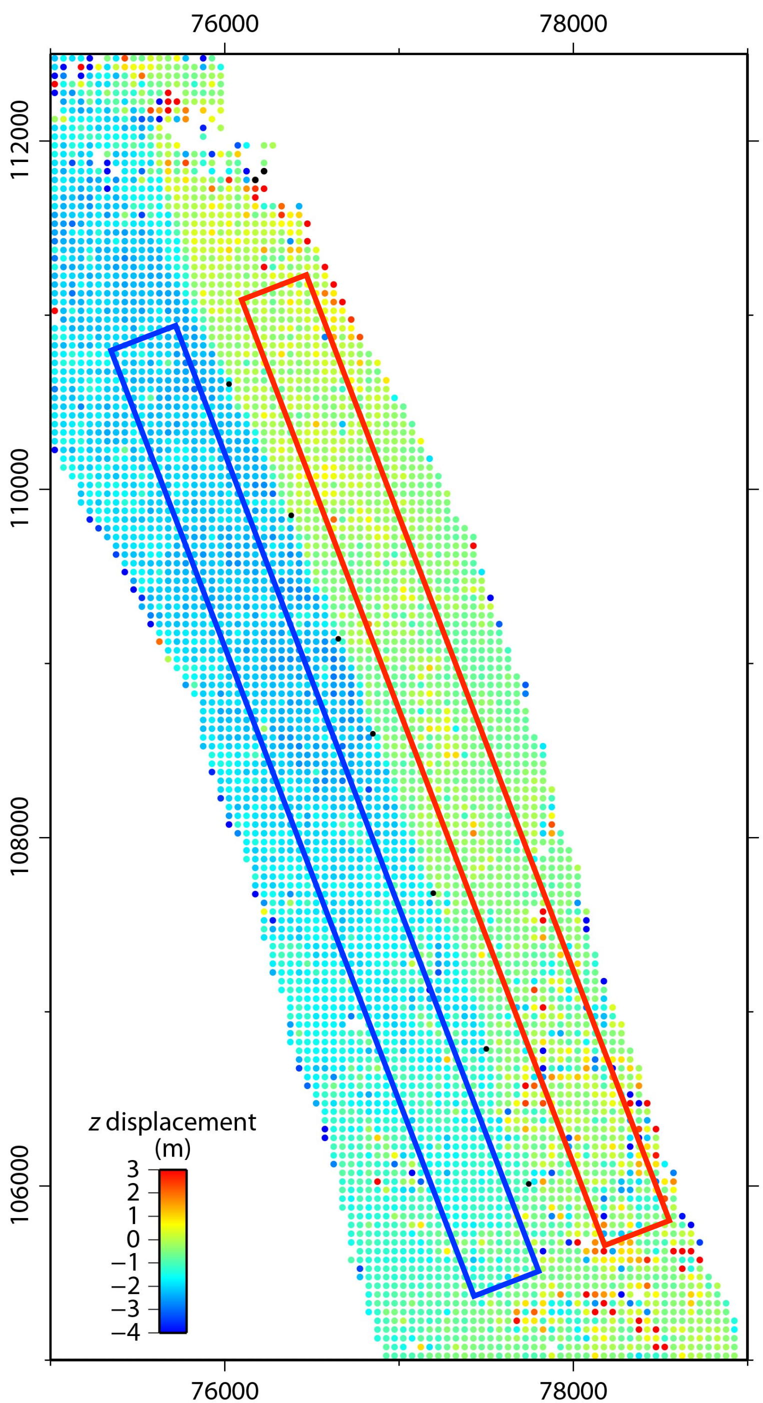
In many places, only a small proportion of the slip makes it to the surface



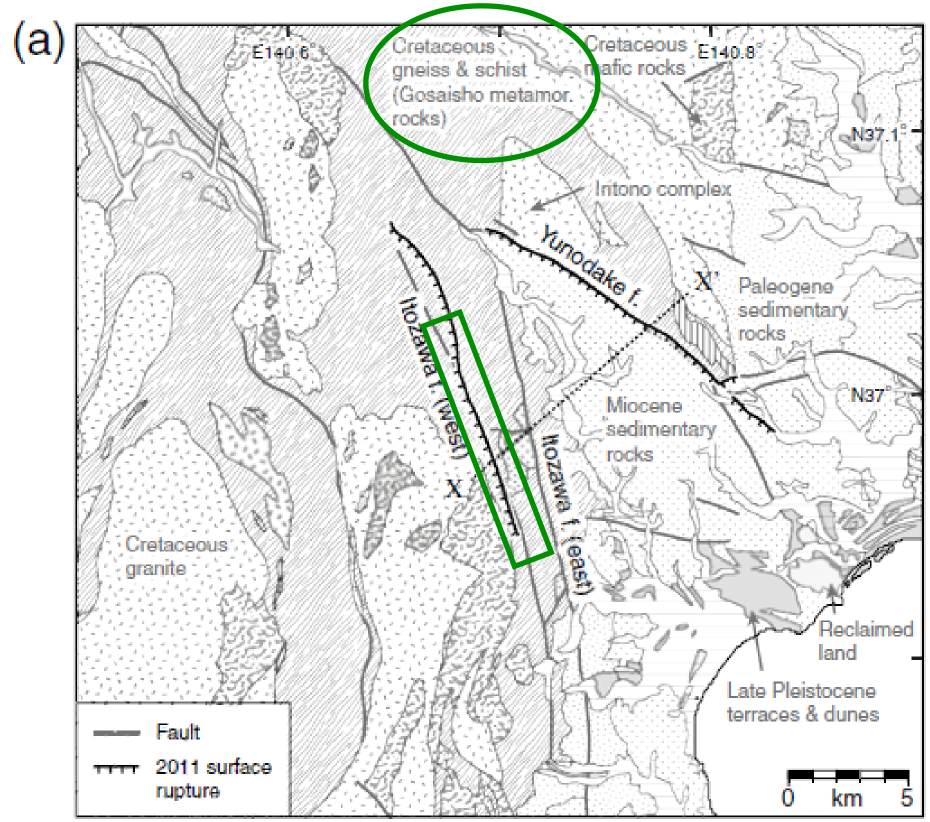


In many places, only a small proportion of the slip makes it to the surface

This is a common phenomenon for thrust faults that rupture upwards through unconsolidated sediment

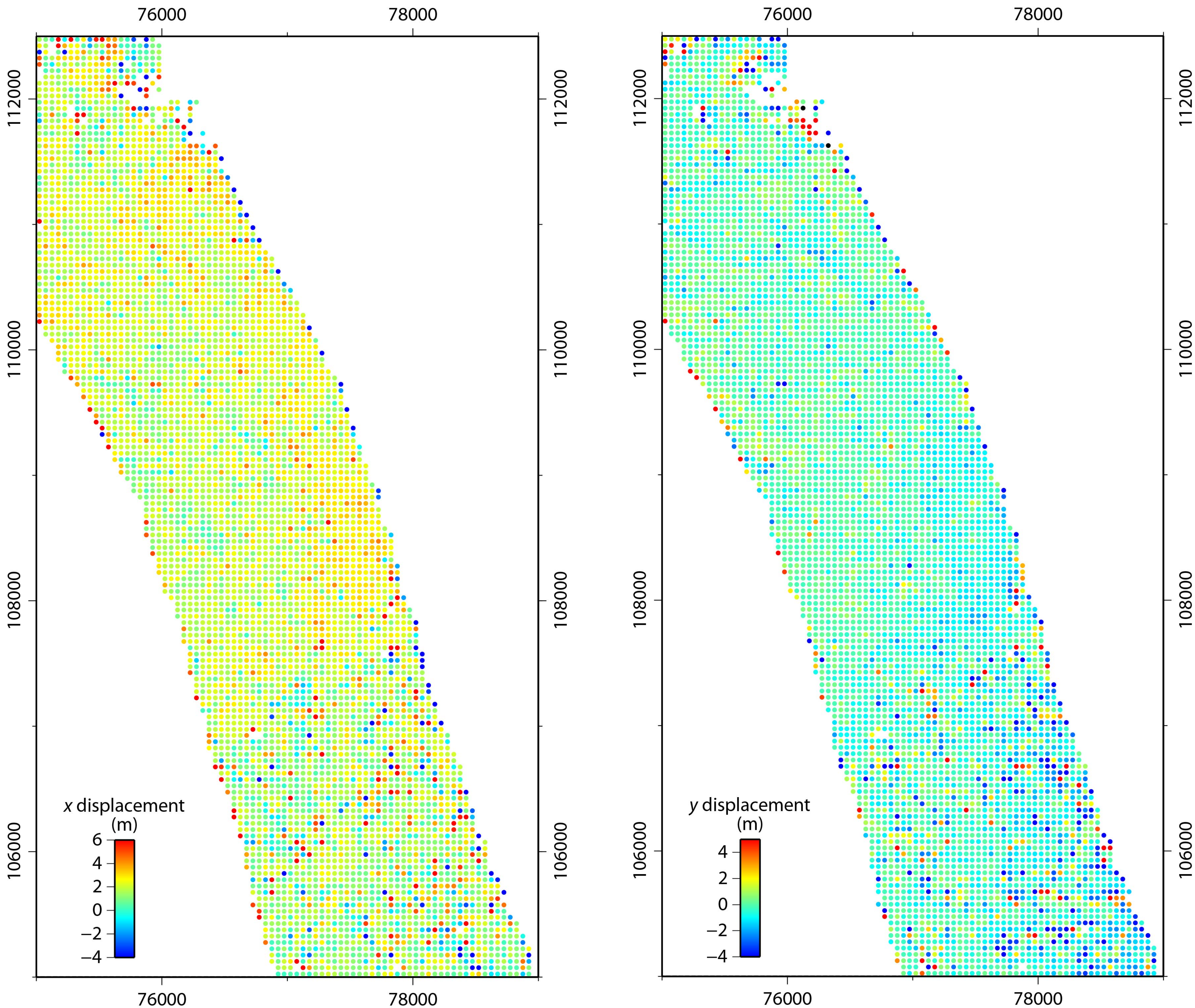


Geological map from Toda & Tsutsumi (2013)

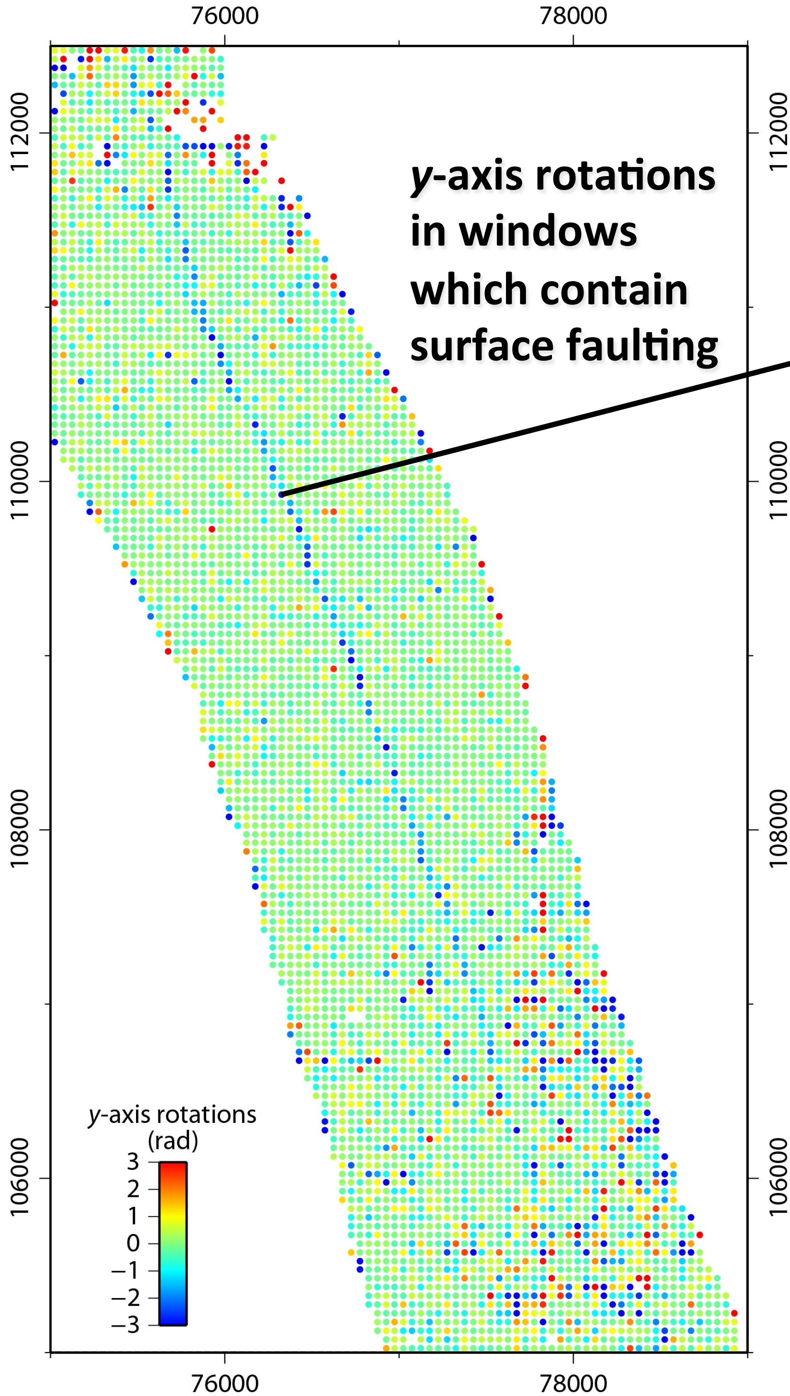


In many places, only a small proportion of the slip makes it to the surface

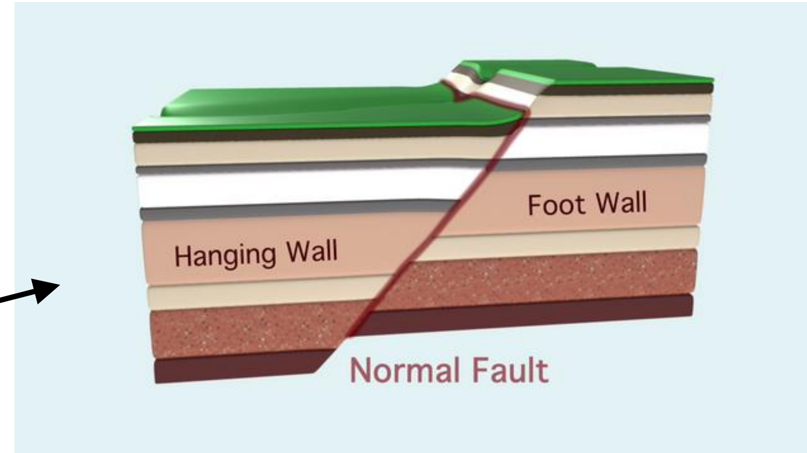
This is a common phenomenon for thrust faults that rupture upwards through unconsolidated sediment

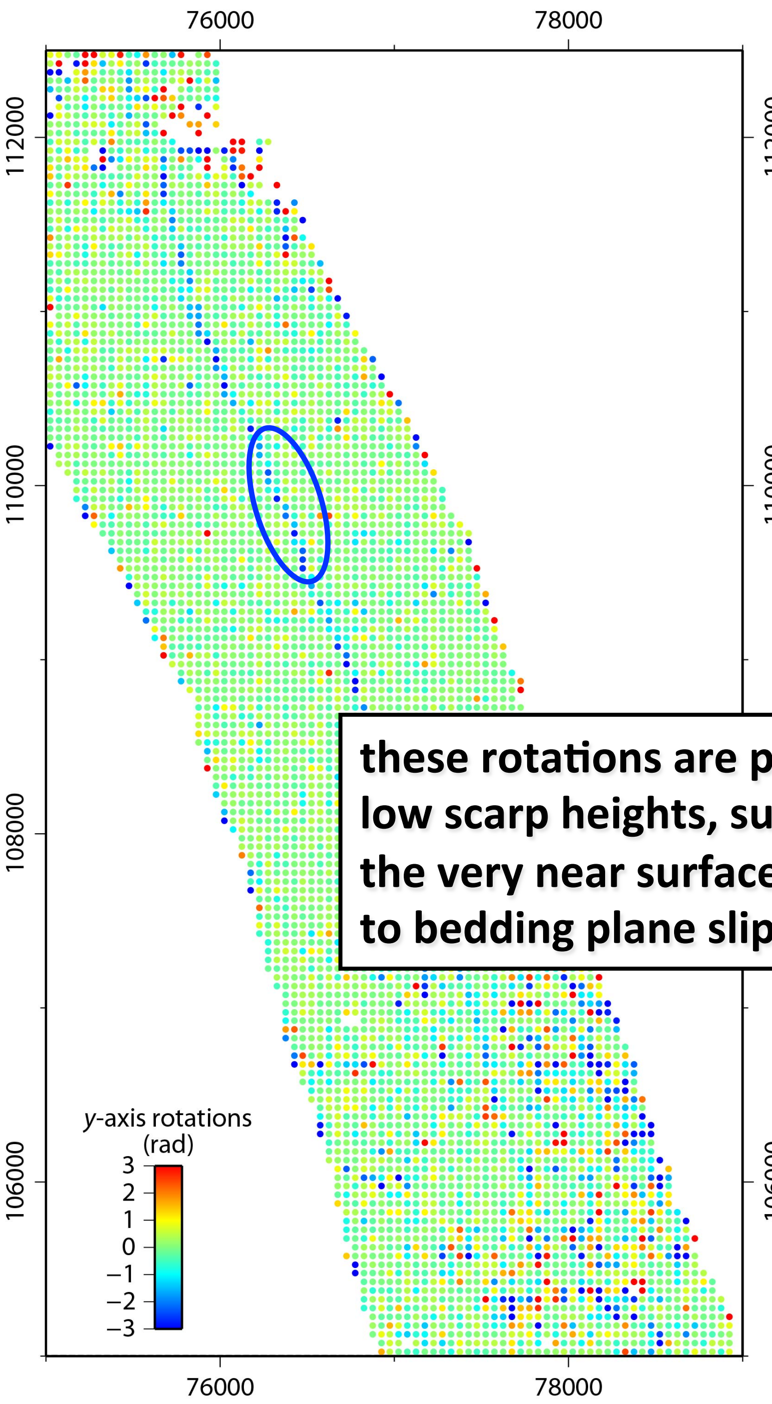


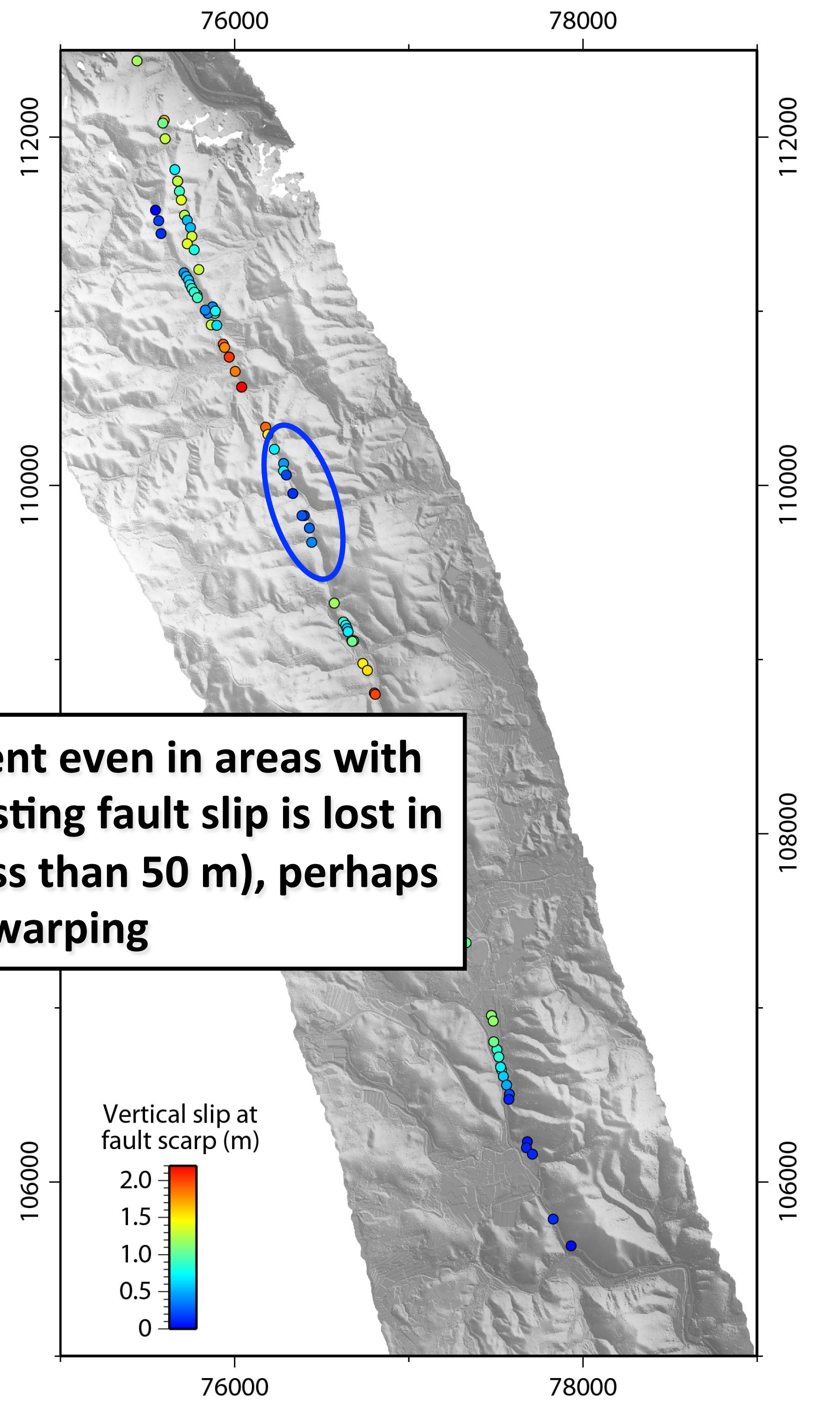
76000
78000
112000
110000
108000
106000
x displacement
(m)
6
4
2
0
−2
−4
y displacement
(m)
4
2
0
−2
−4



***y*-axis rotations in windows which contain surface faulting**



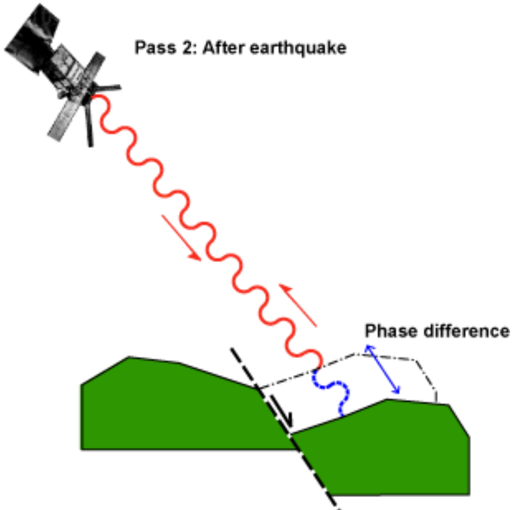


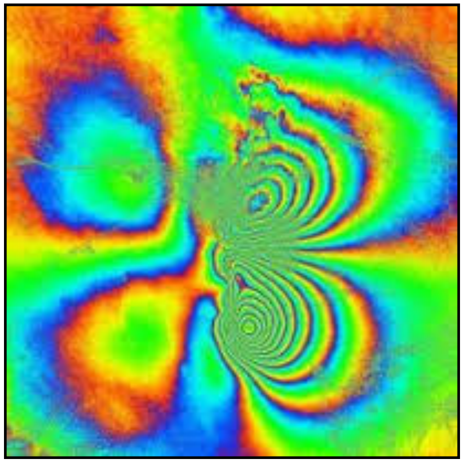


these rotations are present even in areas with low scarp heights, suggesting fault slip is lost in the very near surface (less than 50 m), perhaps to bedding plane slip or warping

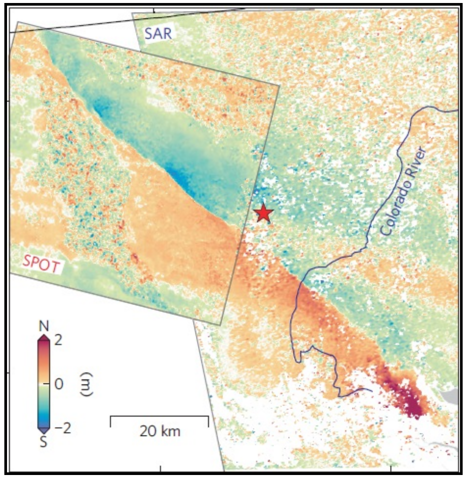
ICP LiDAR differencing: strengths and weaknesses

Synthetic Aperture Radar Interferometry (InSAR)





Sub-pixel matching



InSAR measures deformation in the satellite line of sight. **Pixel matching** usually only measures horizontal displacements.

*ICP can resolve displacements and rotations in **3-D.***

Pixel matching can be applied to LiDAR imagery, but requires gridding (rasterization) of the point clouds, resulting in information loss.

ICP works on the original point clouds.

InSAR is good at measuring **far-field deformation** but often break down close to surface faulting

LiDAR** is typically focused along active faults, so ICP will be useful for obtaining **near-field deformation