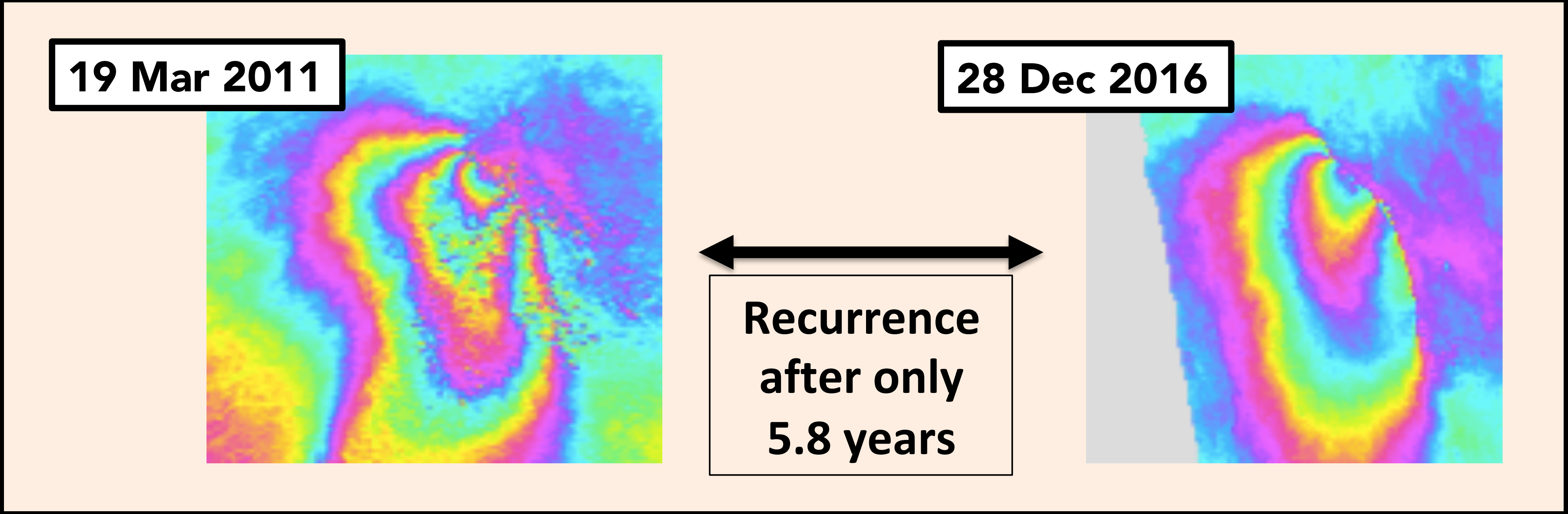
Extremely early recurrence of an M6 intraplate earthquake observed after the 2011 Tohoku-oki earthquake

[Fukushima et al., in review]



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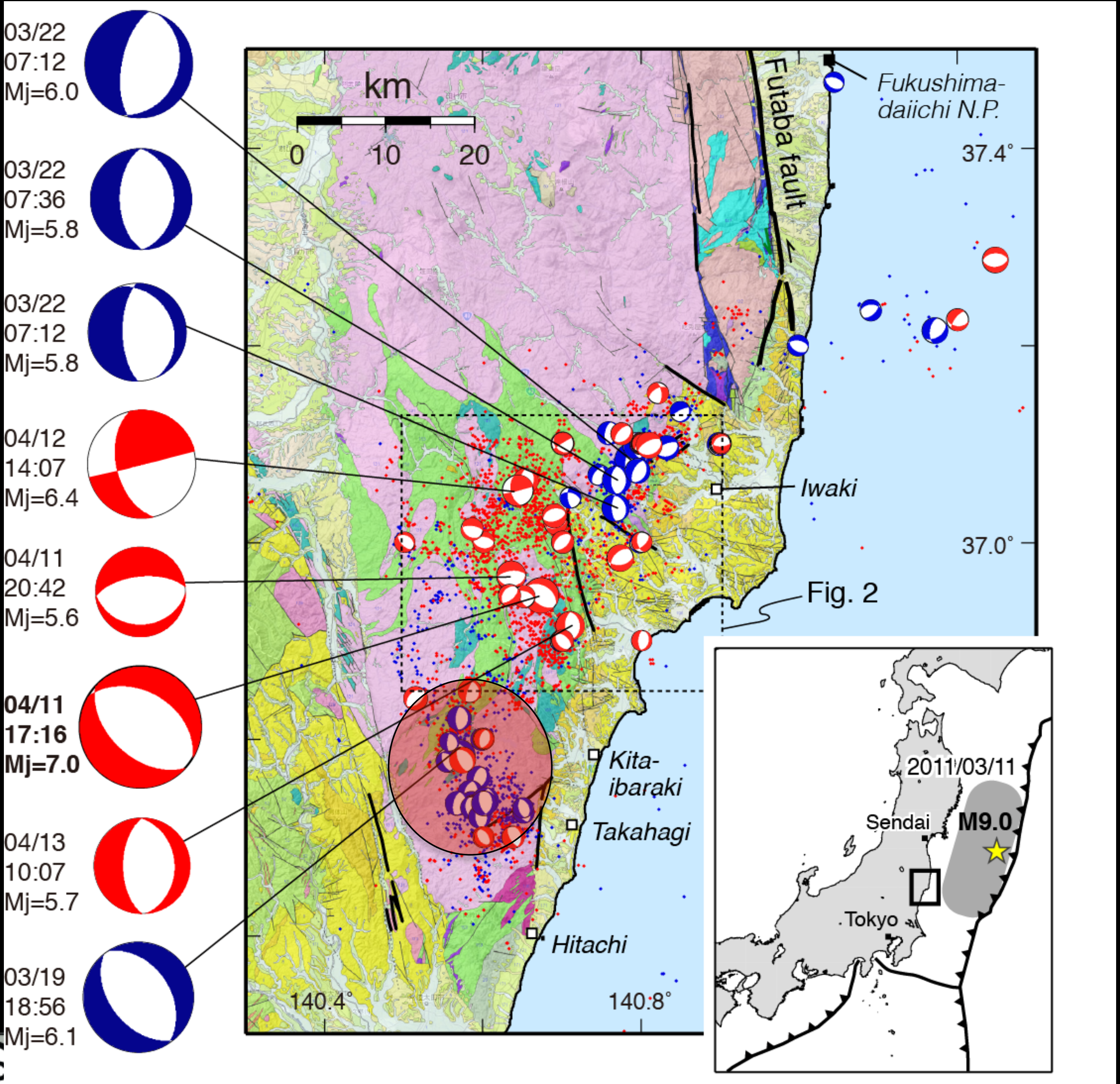


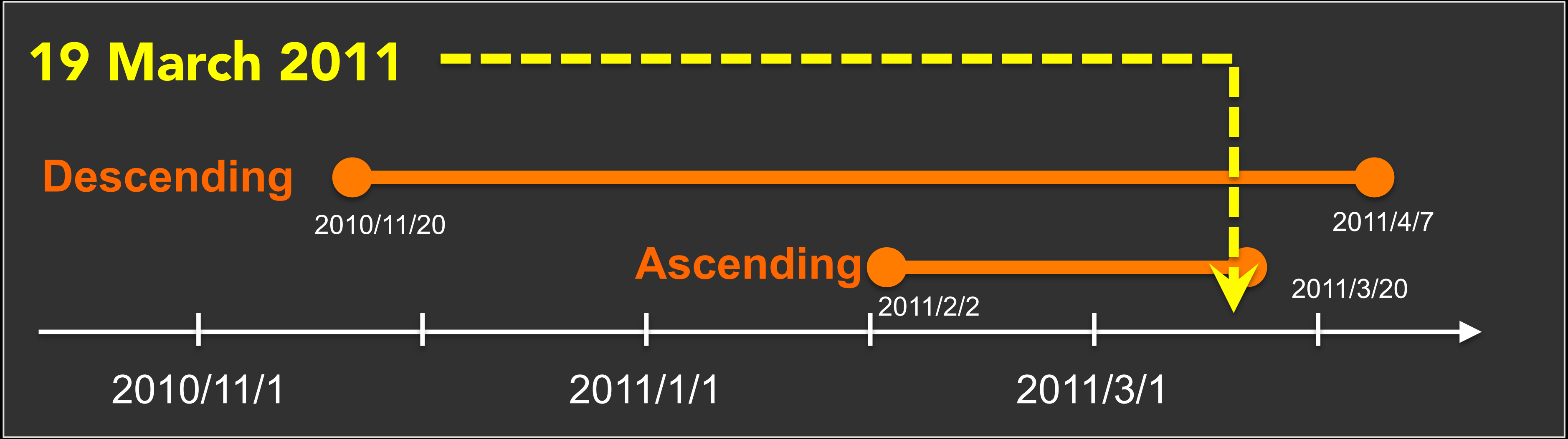
EQs in northern Kanto induced by the 2011 Tohoku-oki earthquake

(Toda and Tsutsumi, 2013; Focal mechanism data from NIED)

Used SAR data

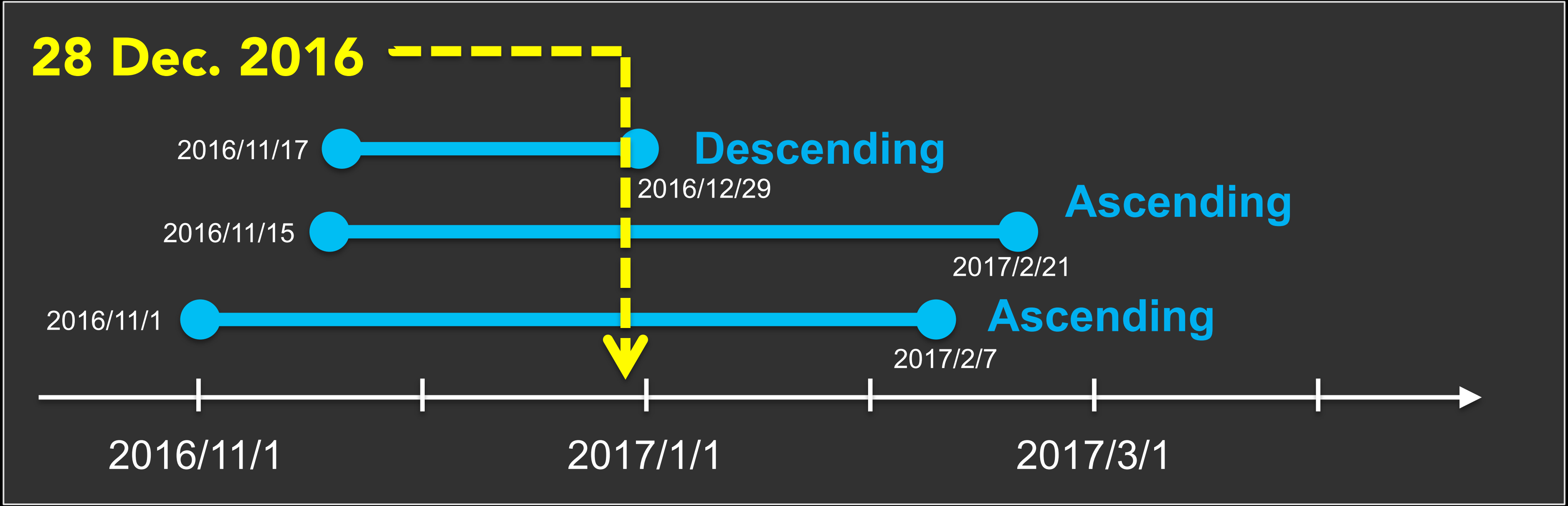
1st event

ALOS
(2006-2011)

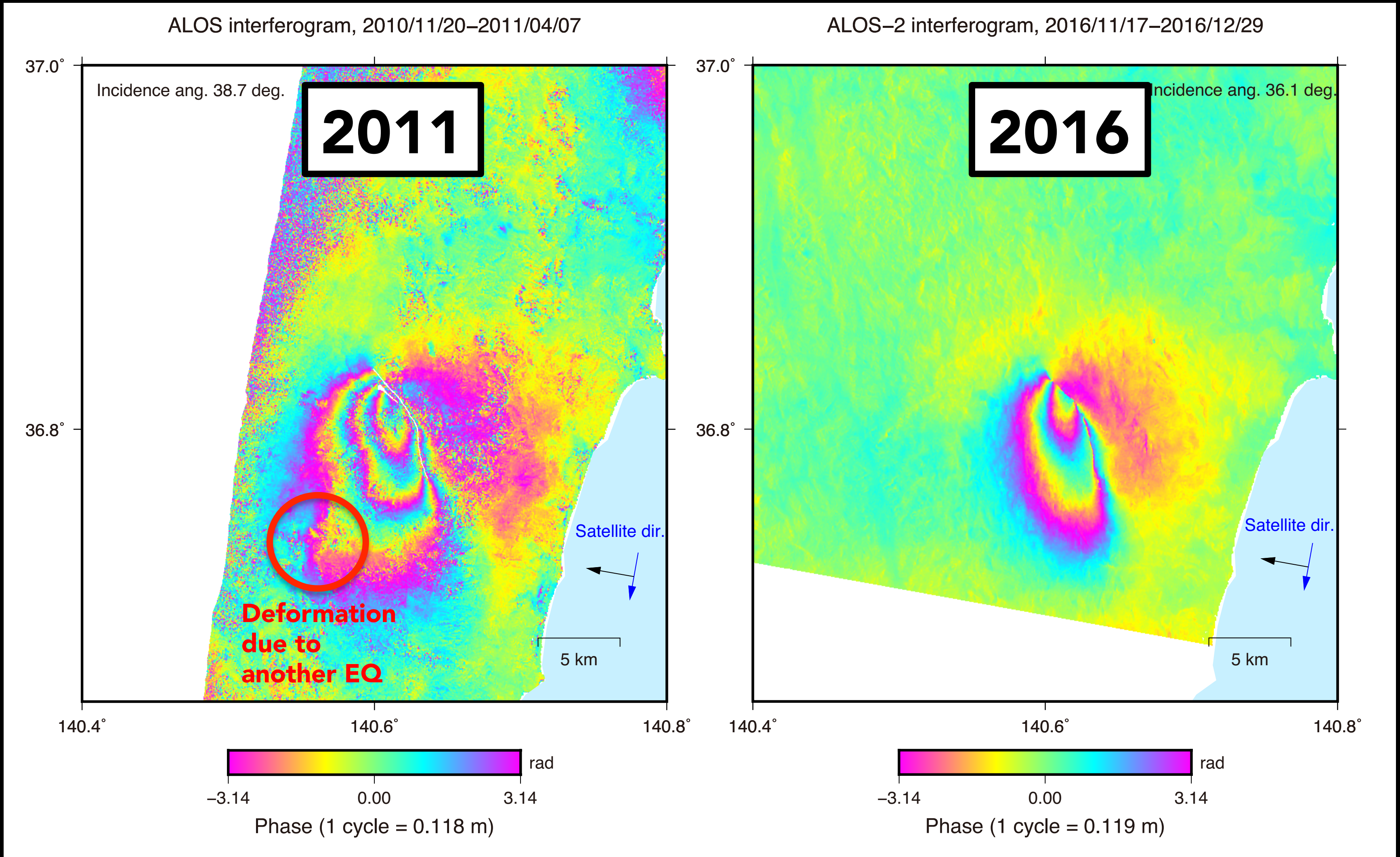


2nd event

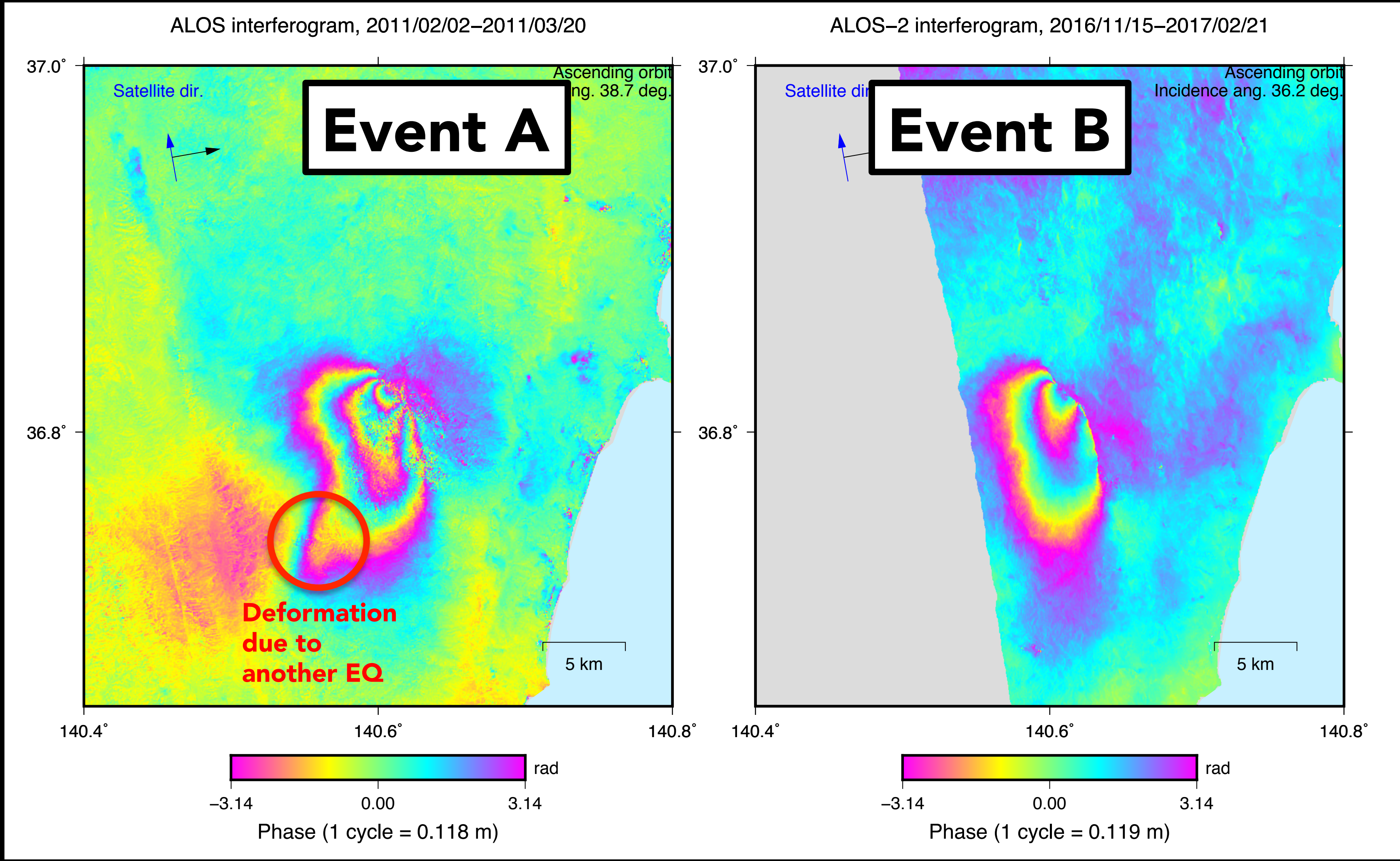
ALOS-2
(2014-)



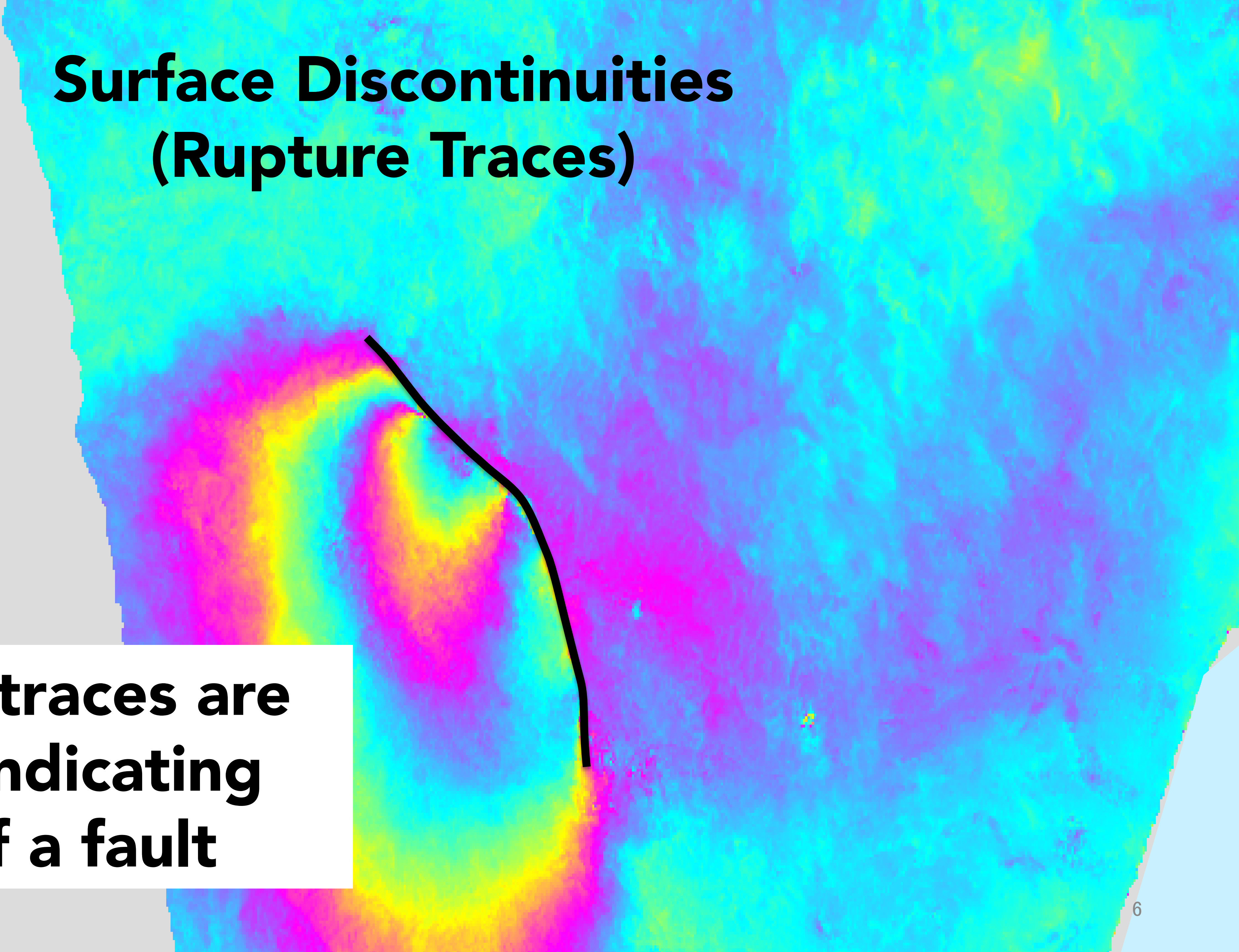
Desc. Interferograms (from East/Vert.) after removal of long-wavelength fringes



Asc. Interferograms (from West/Vert.) after removal of long-wavelength fringes

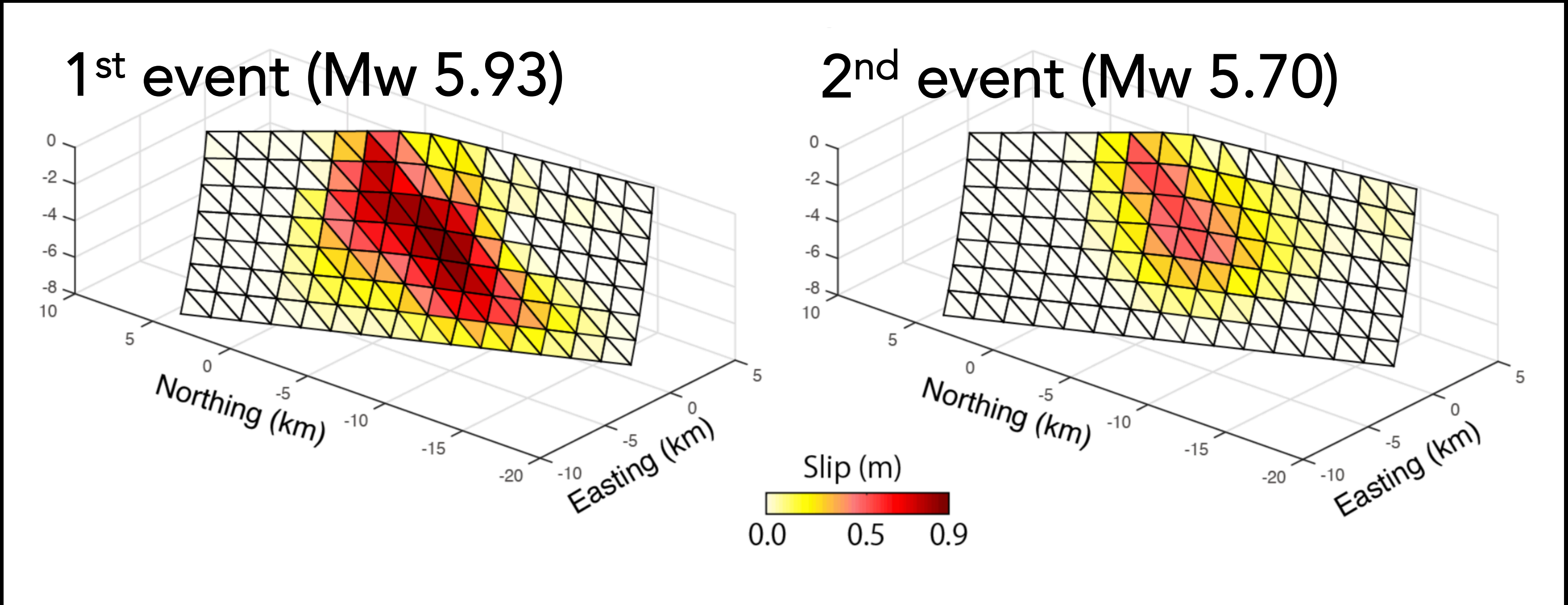


Surface Discontinuities (Rupture Traces)



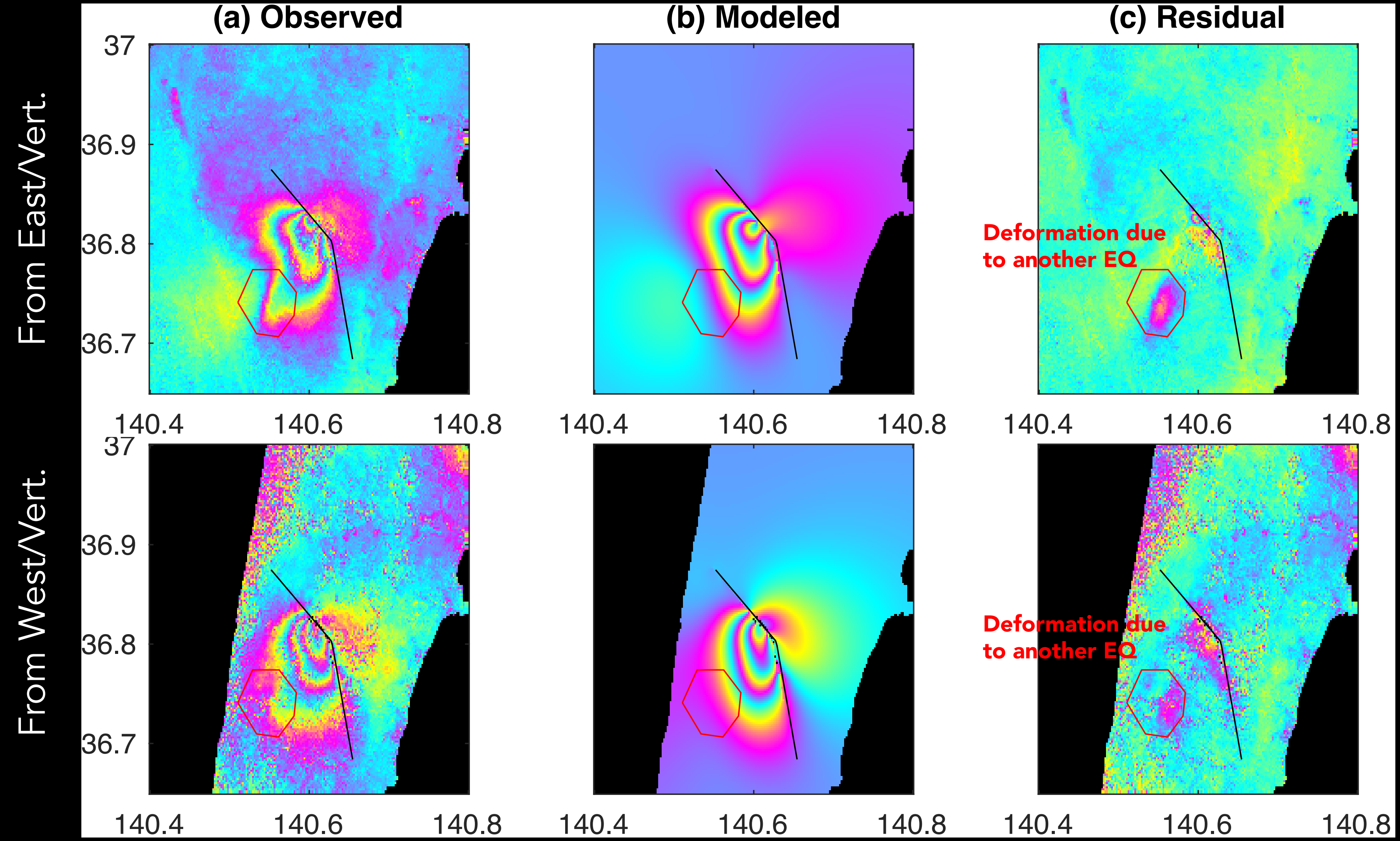
The rupture traces are co-located, indicating re-rupture of a fault

Slip inversion results
(Common fault geom., solved w/PSO+NA (See Fukushima et al. (2013 BSSA))

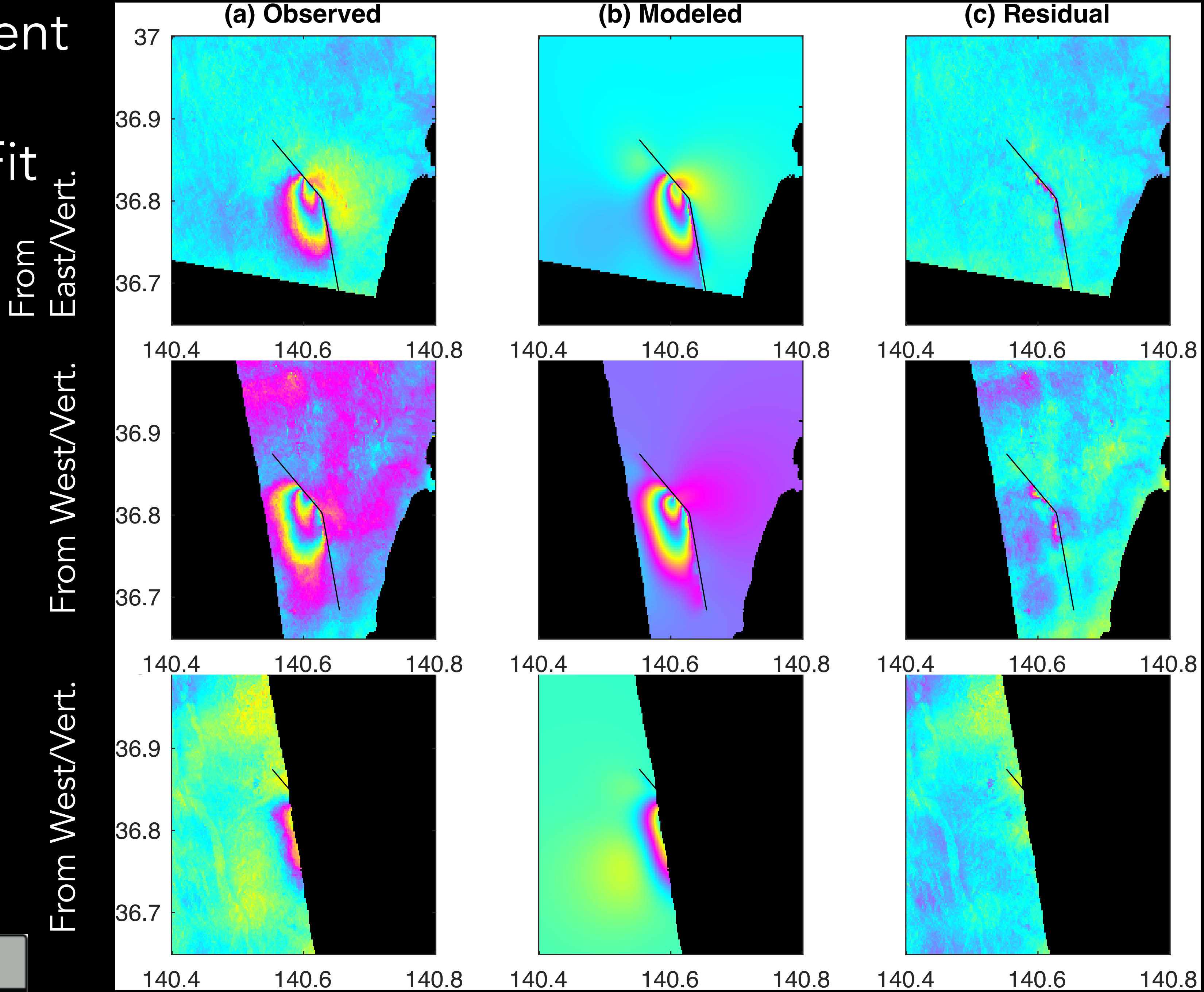


- Slip areas largely overlap
- Slip_1st (max 90cm) > Slip_2nd (max 55cm)
- Shallow slip (> 7 km (1st) and > 5 km (2nd))

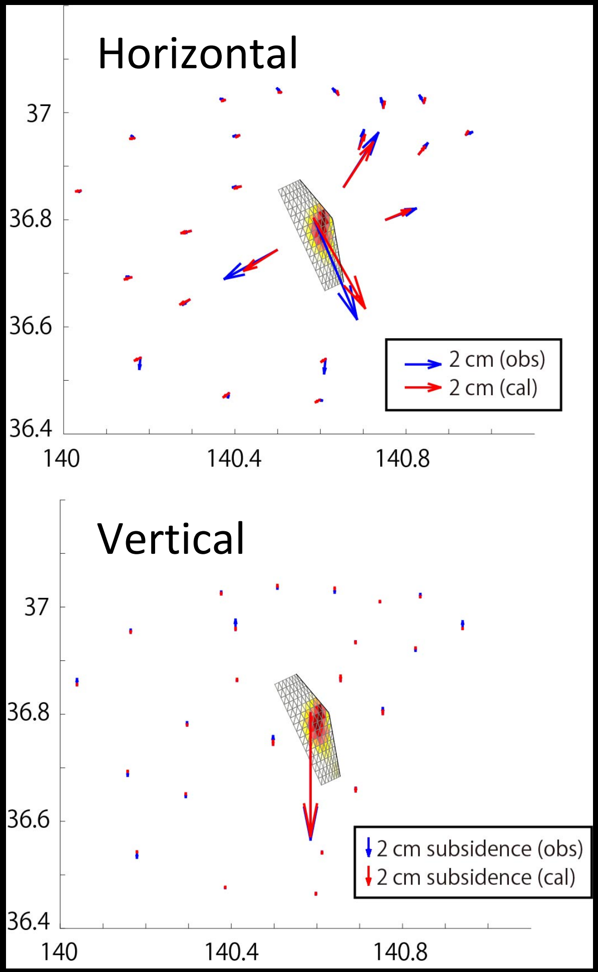
1st event (2011)
Data Fit



2nd event (2016) Data Fit

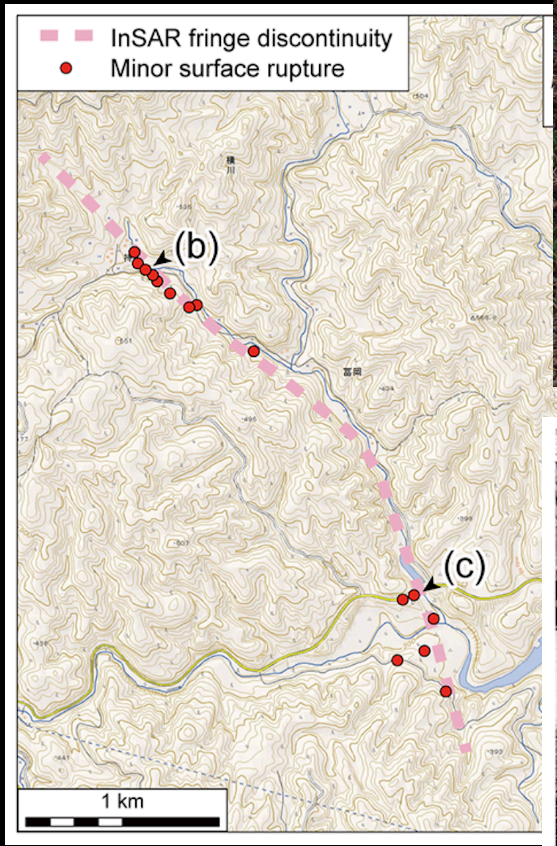


GNSS



Other lines of evidence for the re-rupture of a single fault

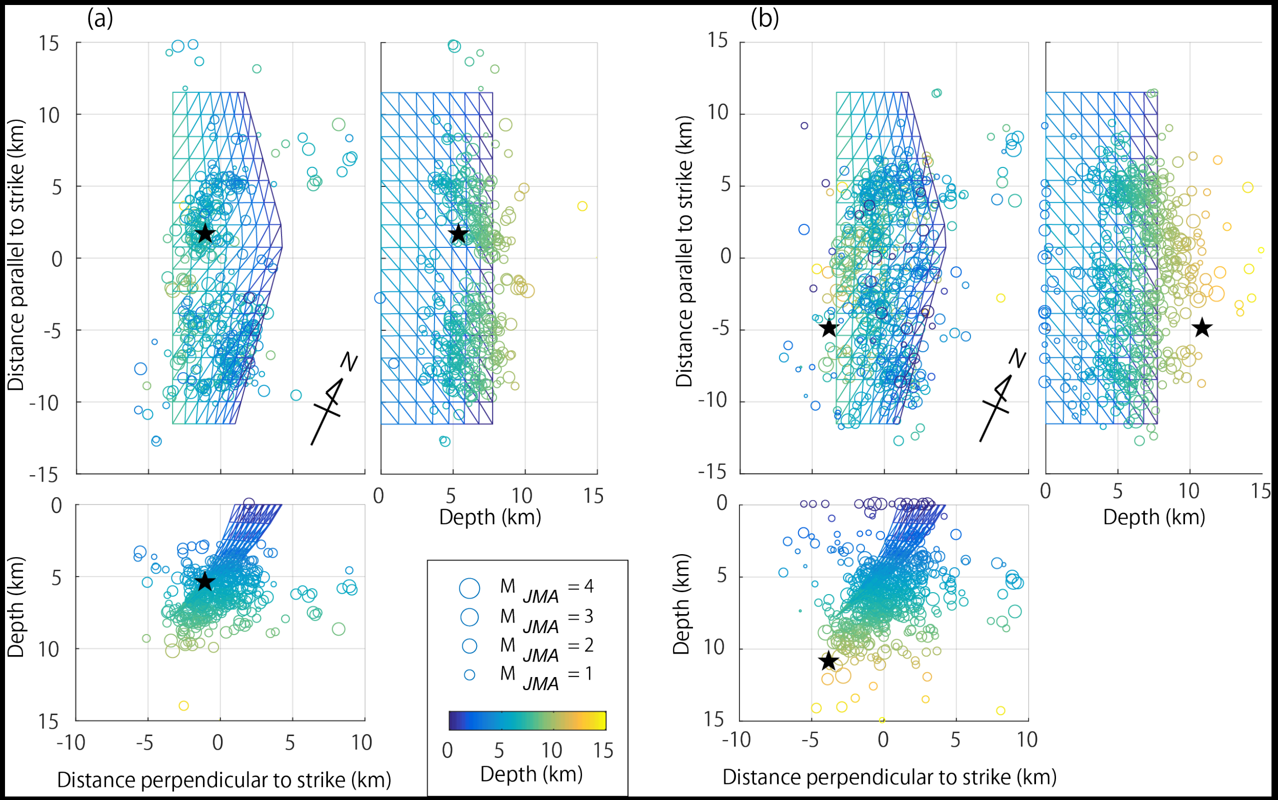
(1) Surface rupture at same sites



(2) Similar aftershock distribution

1st event (2011)

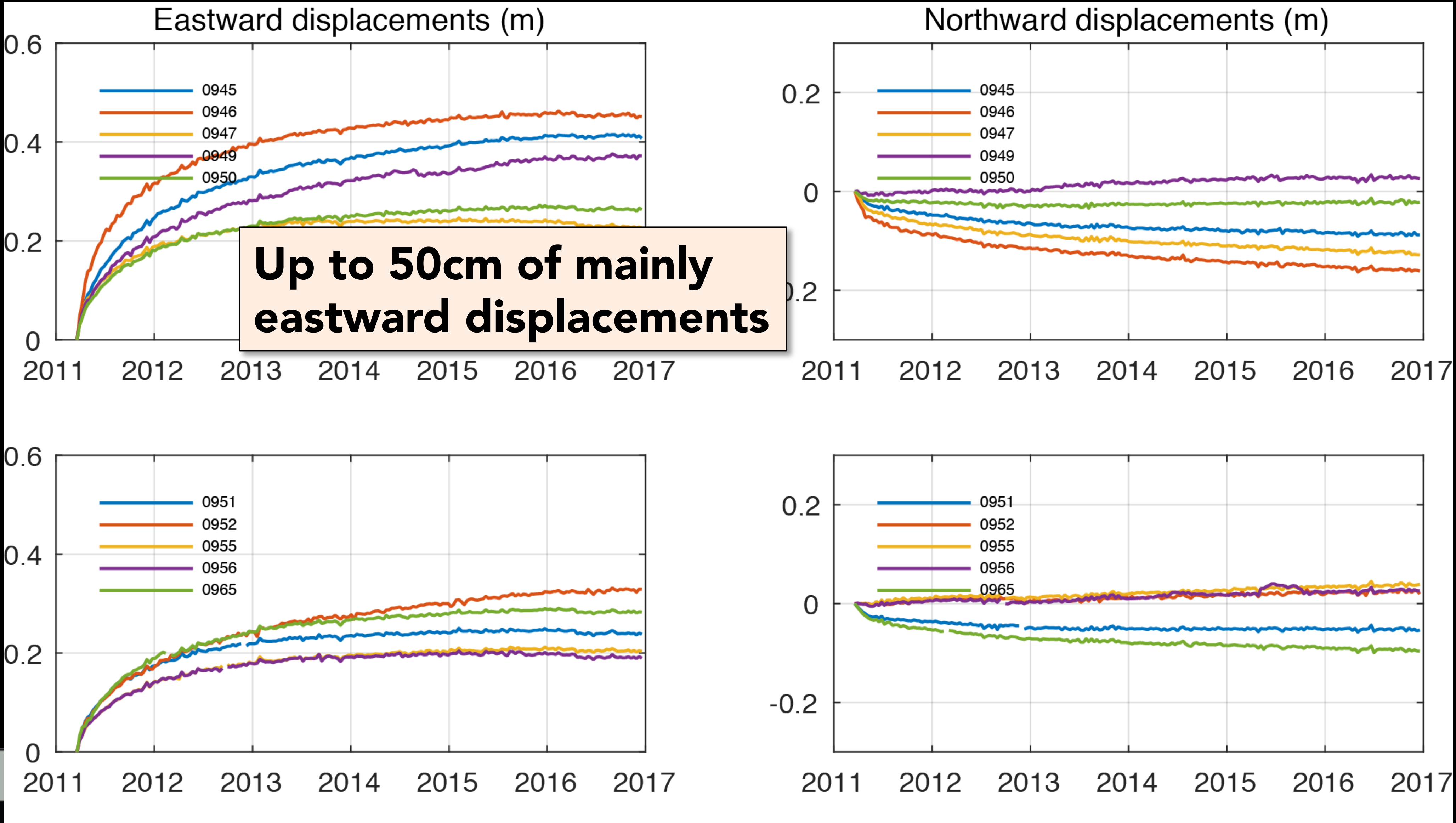
2nd event (2016)



Cause of extremely early recurrence:

Rapid and large postseismic deformation of the 2011 Tohoku-oki EQ

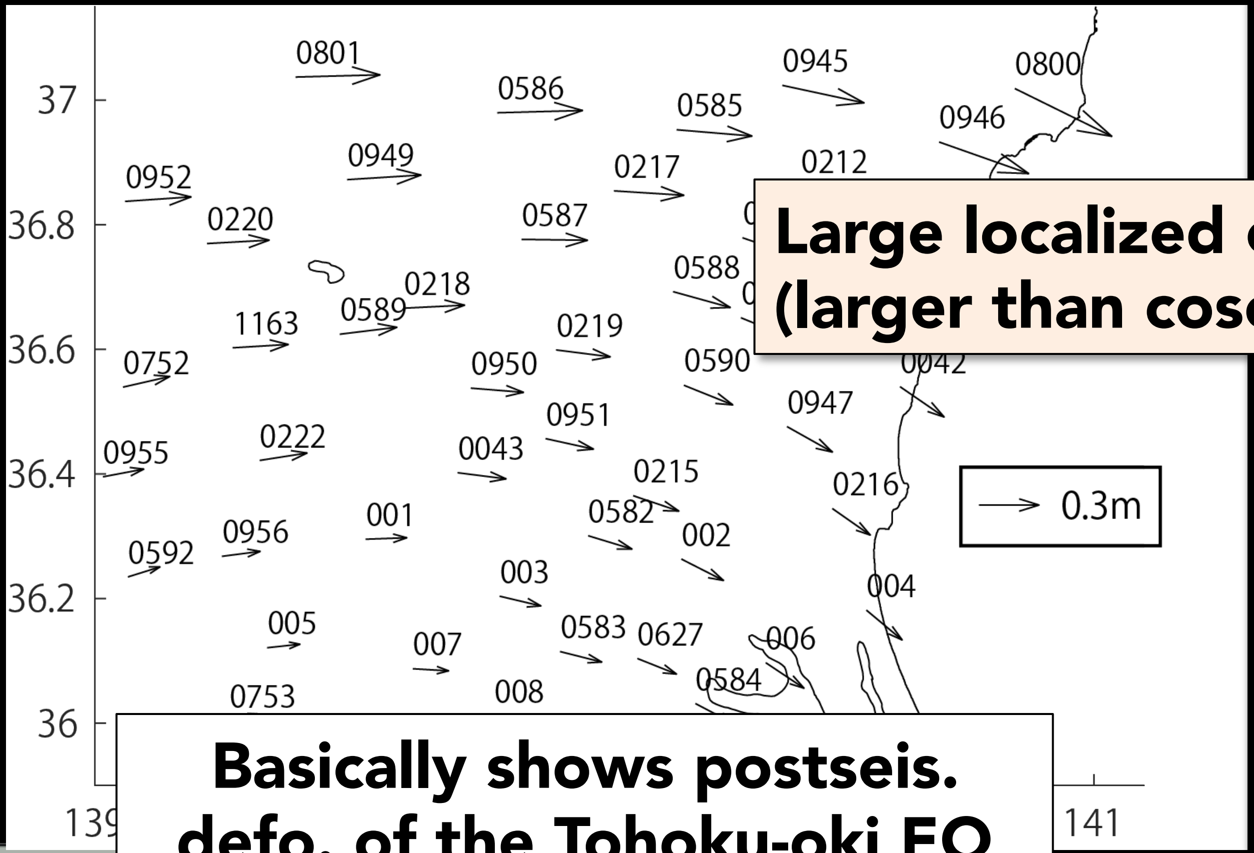
Example of GNSS displacements in the area during the inter-event period (5.8 yrs, 20 Mar 2011 – 27 Dec 2016)



Up to 50cm of mainly eastward displacements

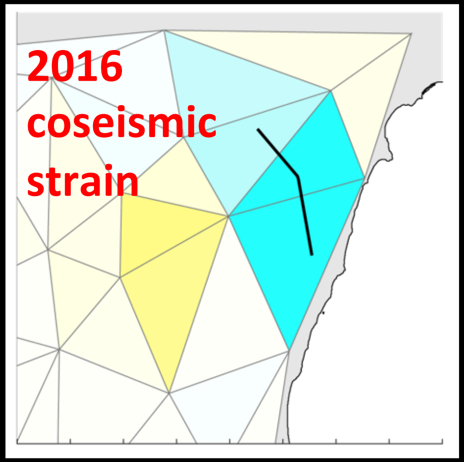
Deformation in the inter-event period of 5.8 yrs

Displacements



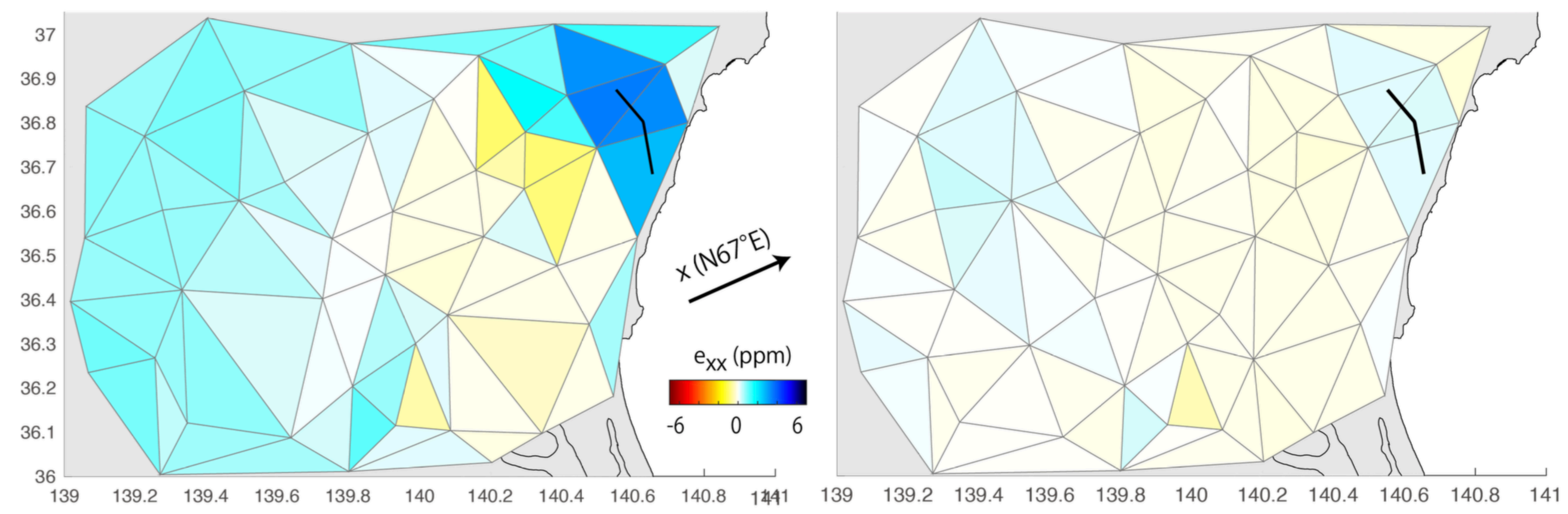
Large localized extensional strain (larger than coseismic strain change)

Basically shows postseis. defo. of the Tohoku-oki EQ



e_{xx} in 408 days after 1st event
LARGE local strain

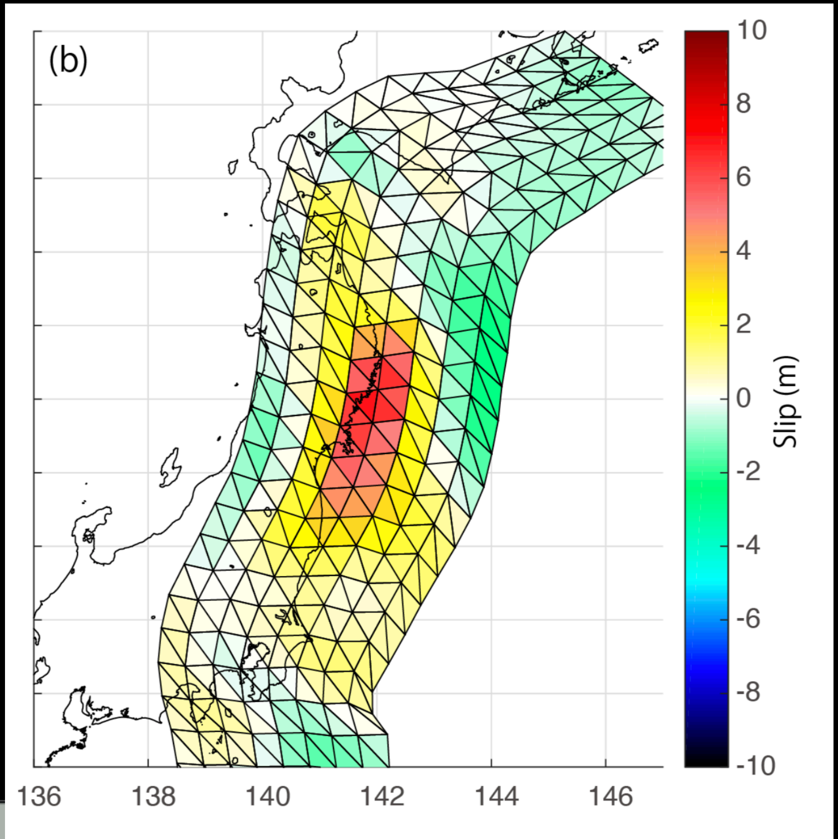
e_{xx} in 408 days after 2nd event
SMALL local strain

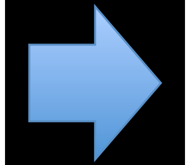


The difference is the presence of large postseismic defo. of the M9 2011 Tohoku-oki EQ after the 1st event.

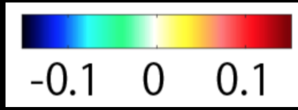
Stress change due to the postseismic defo. of the M9 Tohoku-oki EQ

Afterslip model in the inter-event period

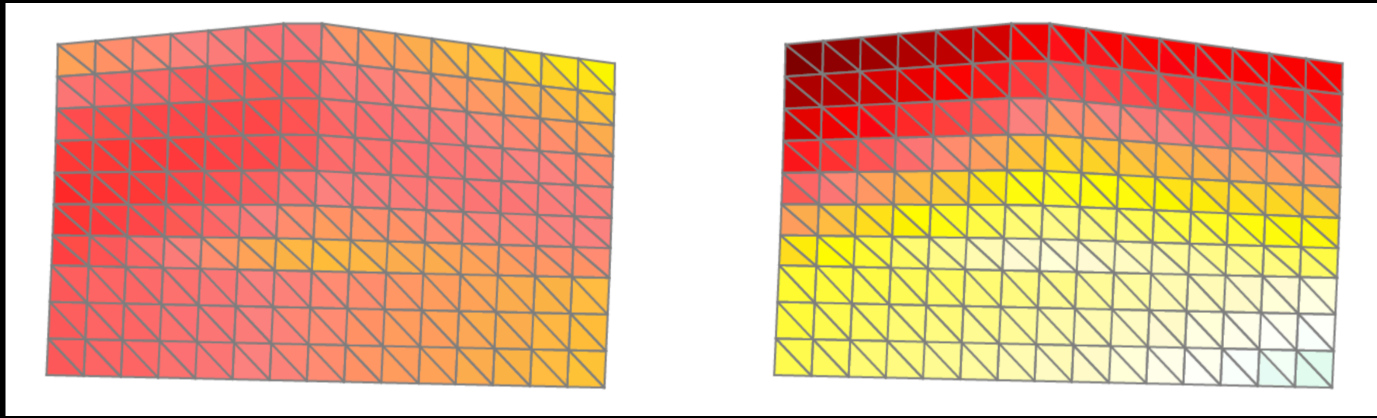




Stress Changes on the fault (MPa)



Shear | **Normal**

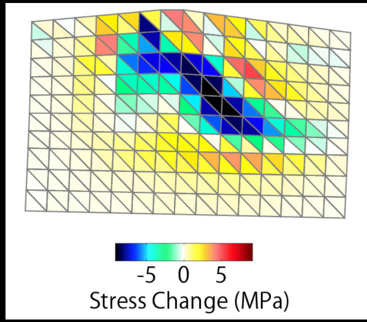


Increases fault stress

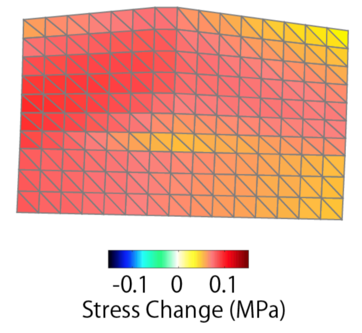
Unclamping
Decreases fault strength

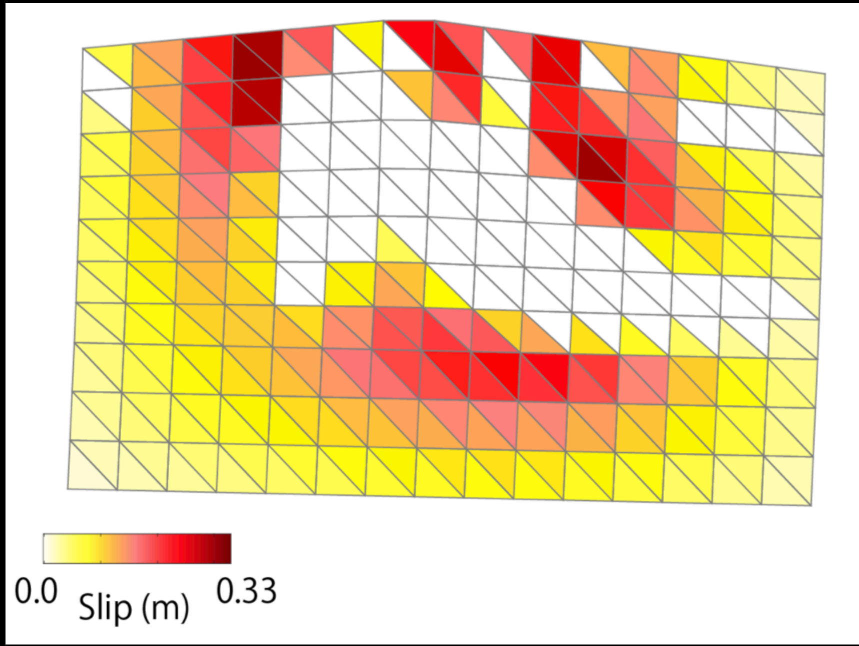
Predicted stress-driven slip (relaxation of the increased shear stress)

Shear stress change due to the 1st event

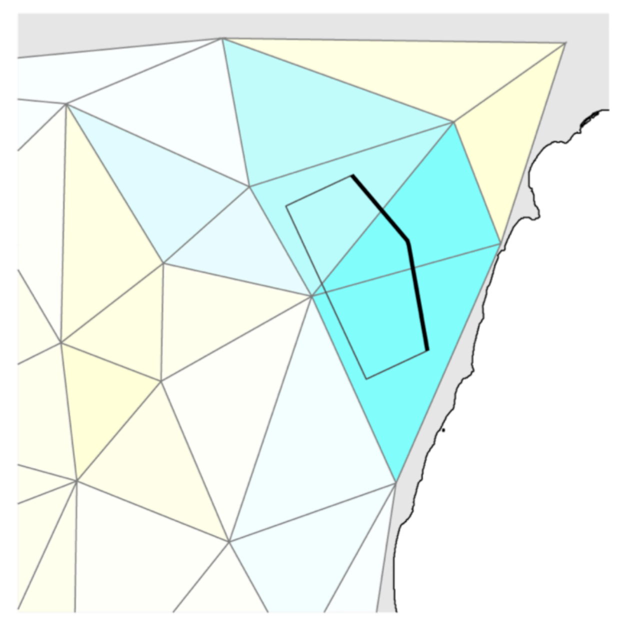


Shear stress change due to the Tohoku-oki afterslip





Predicted strain



Localized strain pattern is reproduced (even more prominent afterslip is suggested by observation).

Conclusions with additional remarks

For the two intraplate M～6 events on 19 Mar. 2011 and 28 Dec. 2016 in Japan,

- We showed that the fault re-ruptured in extremely short time interval of 5.8 years, whereas average recurrence time can be larger than10,000 years.
- Strain analysis using the data of GNSS reveals that the first M6 earthquake was followed by exceptionally large post-seismic deformation. Such deformation is consistent with afterslip around the rupture area that rebuilds the shear stress on the fault.
- Considering that the large localized deformation was not observed after the 2016 earthquake, the afterslip (+viscoelastic deformation) of the 2011 Tohoku-oki earthquake must have contributed to this phenomenon. We speculate that the decrease in the fault strength (unclamping) triggered the large afterslip on the M6 fault.

Slip Inversions for Each Events

(Inversion scheme: Fukushima et al., 2013, BSSA)

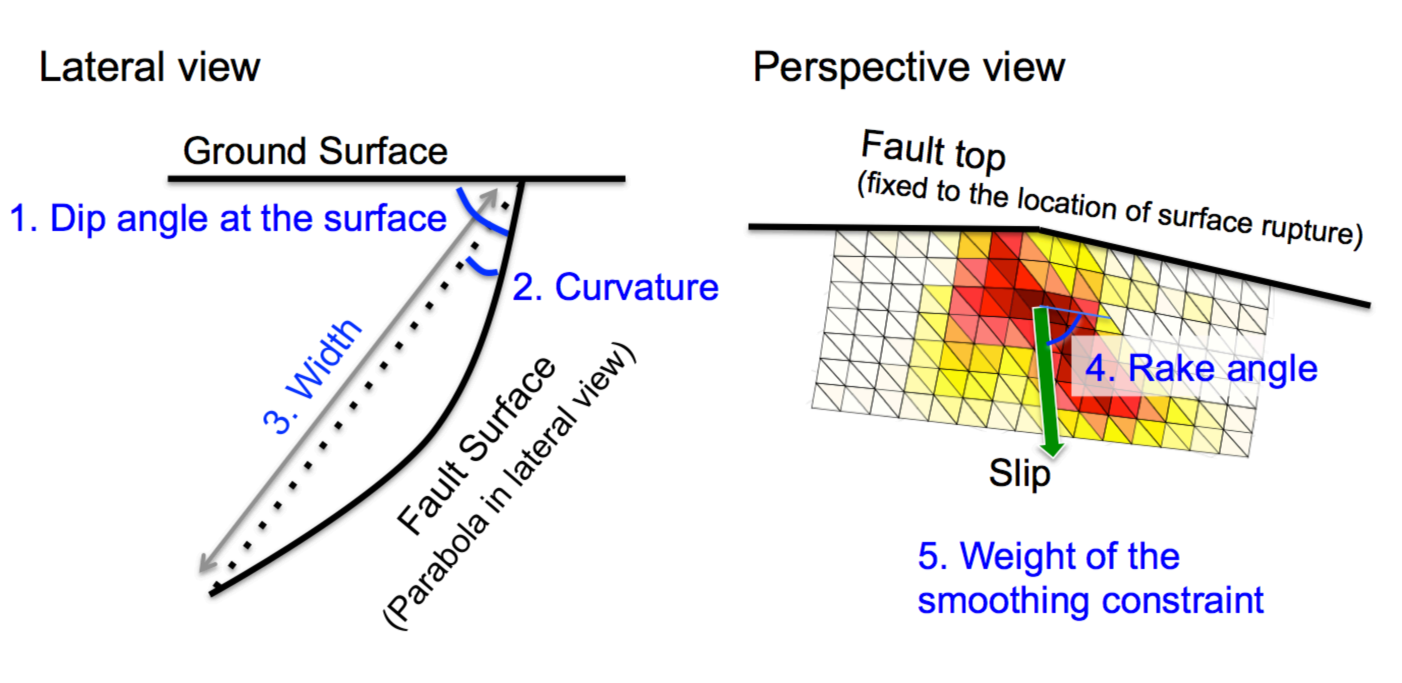
Solve for the geometrical and other nonlinear parameters and slip distribution (linear parameters) simultaneously.

The design matrix G is a function of nonlinear model parameters m

Likelihood Function

$$p(\mathbf{s}, \mathbf{m}, \sigma^2, \alpha^2 | \mathbf{d}) = C(\sigma^2)^{-N/2}(\alpha^2)^{-M/2} \exp\left[-\frac{1}{2}\left(\frac{1}{\sigma^2}(\mathbf{d} - \mathbf{G}(\mathbf{m})\mathbf{s})^T \Sigma_d^{-1} (\mathbf{d} - \mathbf{G}(\mathbf{m})\mathbf{s}) + \frac{1}{\alpha^2}(\mathbf{L}(\mathbf{m})\mathbf{s})^T(\mathbf{L}(\mathbf{m})\mathbf{s})\right)\right]$$

Nonlinear parameters



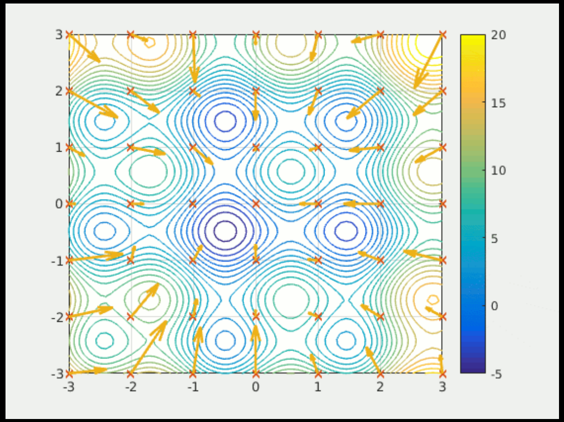
Nonlinear Inversion Methods

(Inversion scheme: Fukushima et al., 2013, BSSA)

Inversion step 1: Sampling (and getting the best-fit)

Particle Swarm Optimization

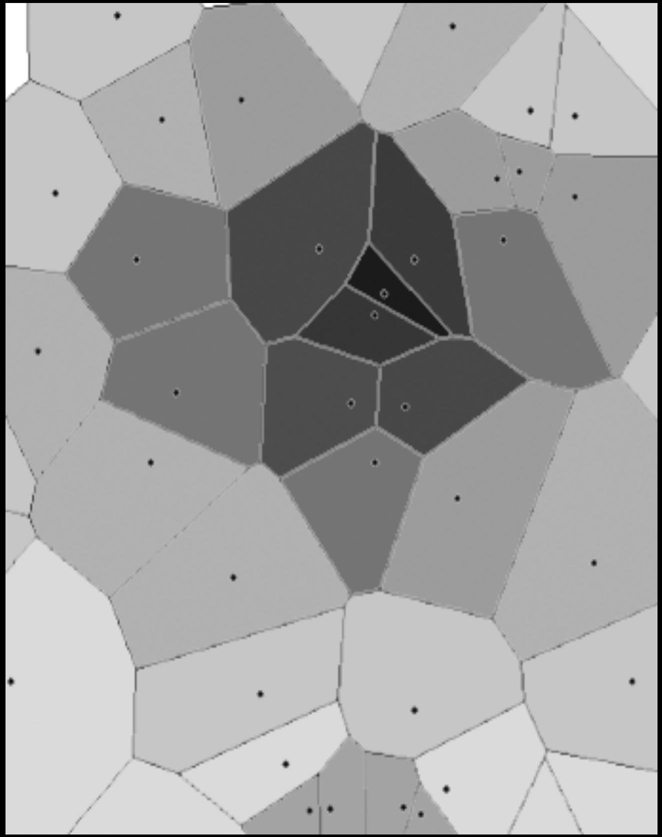
Eberhart and Kennedy (1995)



Inversion step 2: Obtaining model PDF

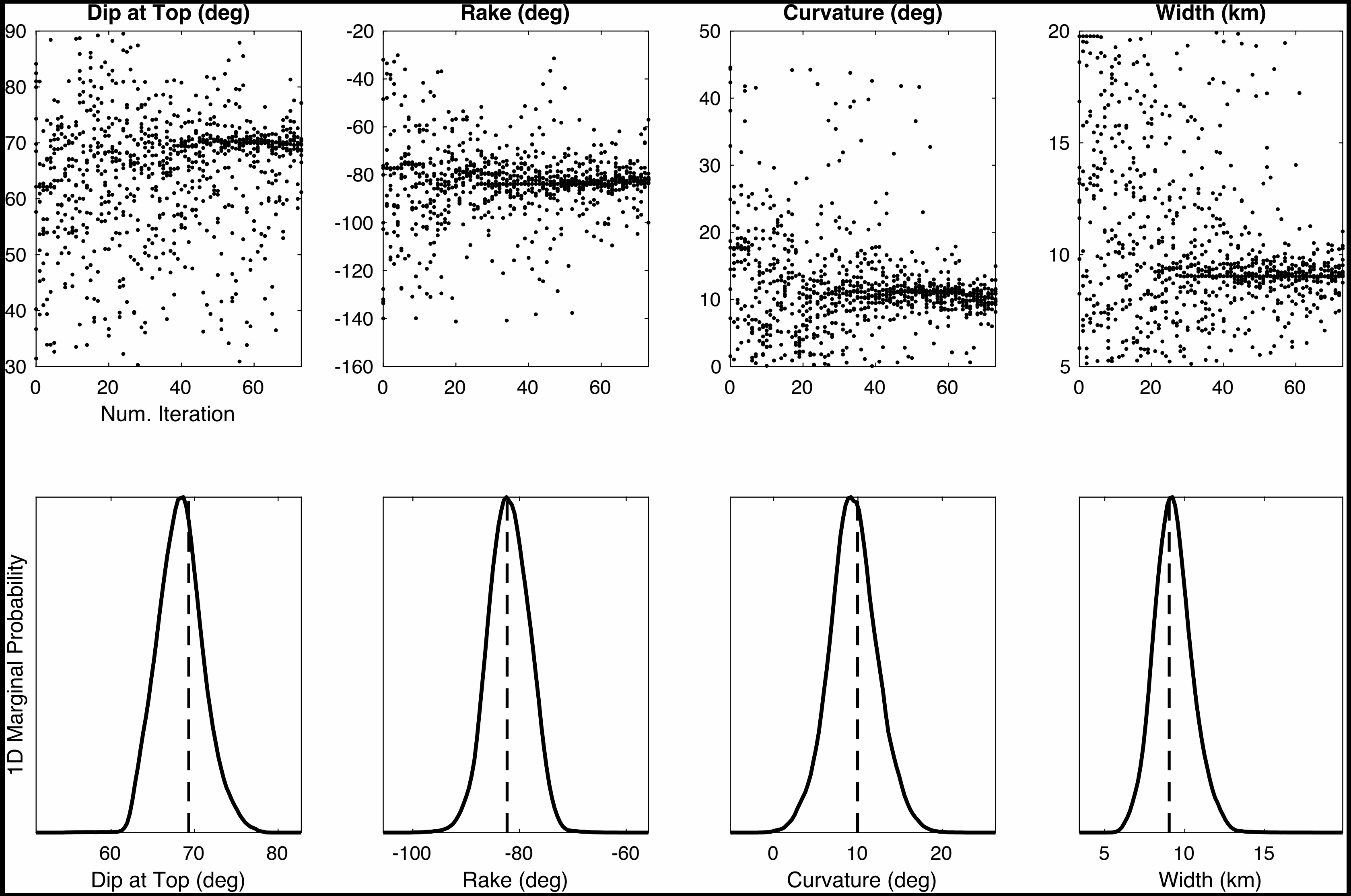
Neighbourhood Algorithm

Sambridge (1999)



(Up) Https://www.datasciencecentral.com/profiles/blogs/swarm-optimization-goodbye-gradients
(Bottom) https://en.wikipedia.org/wiki/Particle_swarm_optimization

Examples of convergence (above) and obtaining confidence intervals (below)



Chain of inversions (simplified)

1st event

Estimation of the geometry + slip

2nd event

Estimation of the geometry + slip

↘ ↙

Resulted in very similar geometry and other nonlinear parameters

↓

Use common geometry, rake angle (-81) and smoothing weight

↙ ↘

Estimation of the slip distribution

Final model

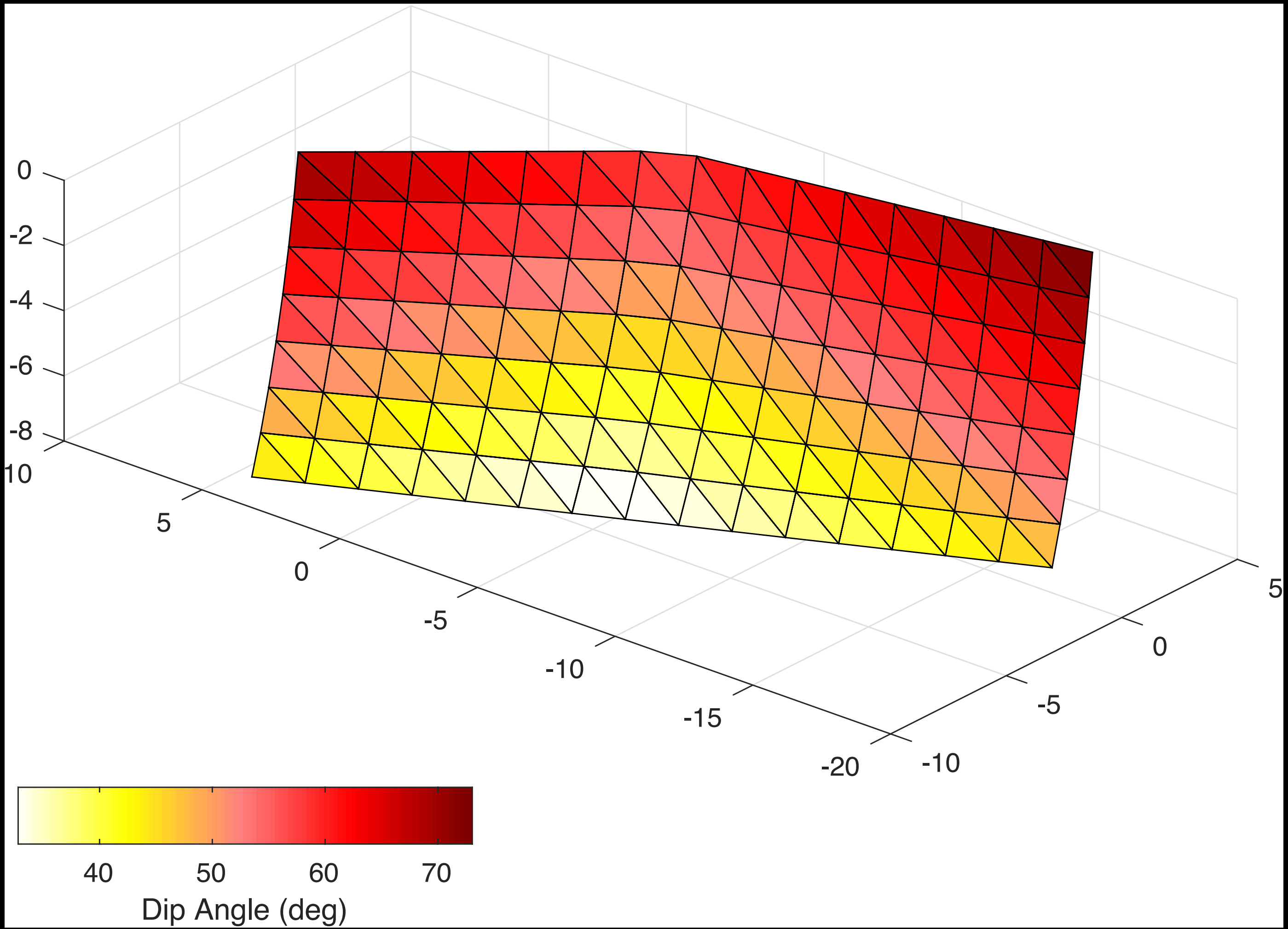
Estimation of the slip distribution

Final model

Results of separate inversions

	March 2011 event			December 2016 event		
	Minimum	Best-fit	Maximum	Minimum	Best-fit	Maximum
Dip at the surface (deg)	63.5	69.3	74.1	72.3	77.8	80.0
Rake (deg)	-89.0	-82.3	-74.9	-82.6	-80.3	-77.7
Curvature (deg)	4.1	10.0	15.2	15.6	19.3	24.5
Width (km)	7.2	9.0	11.9	6.0	6.7	8.6

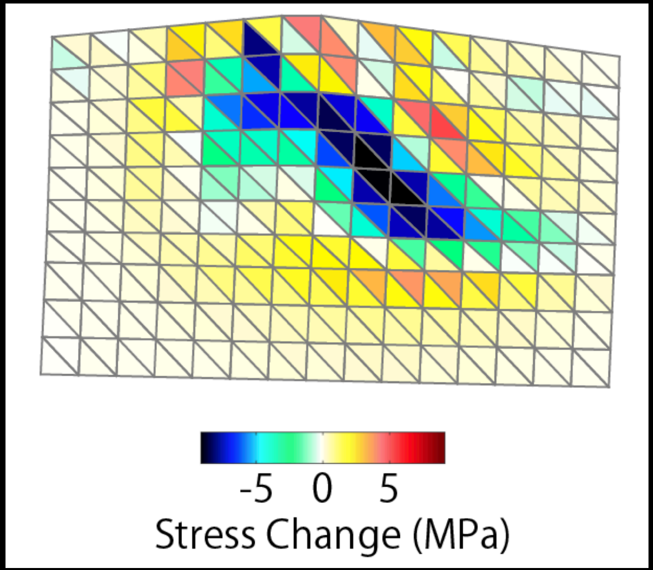
Mean Fault Geometry



Listric

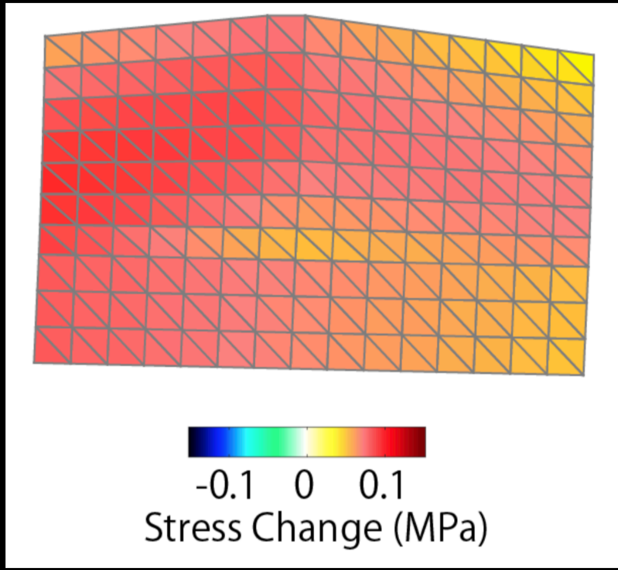
(dip 70±5 deg near the surface and ~40 deg at 8km)

Shear stress change caused by the Event A slip (parallel to the slip direction)

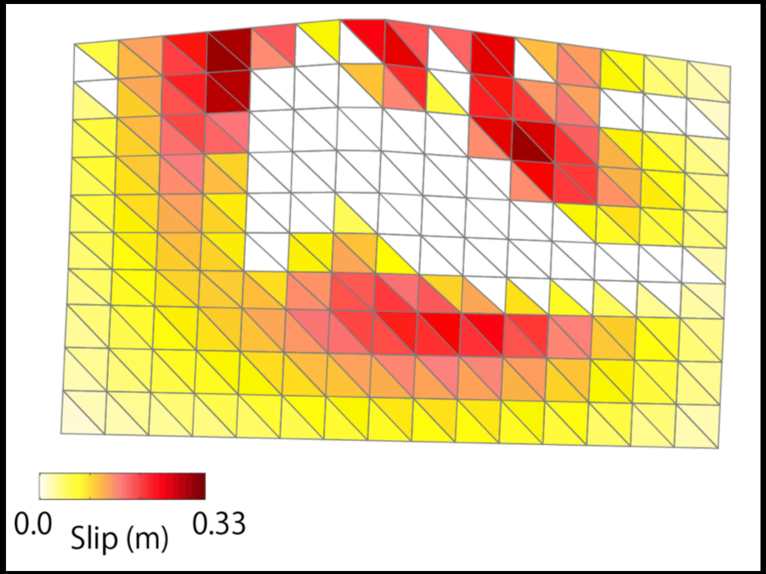


+

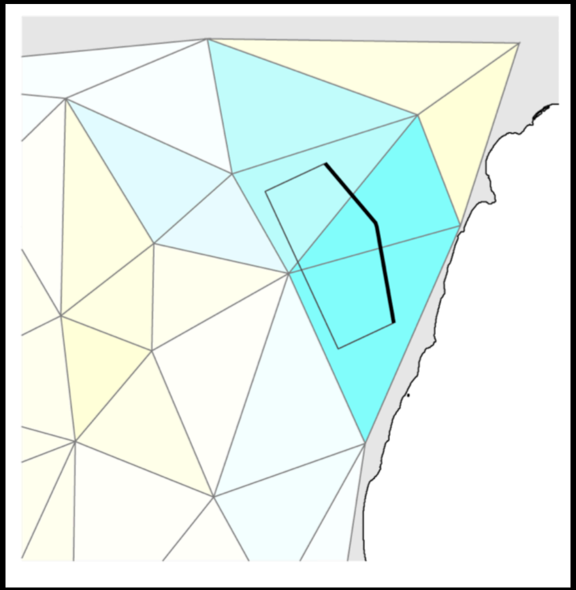
Shear stress change caused by the 2011 Tohoku-oki afterslip



Predicted stress-driven slip



Predicted strain

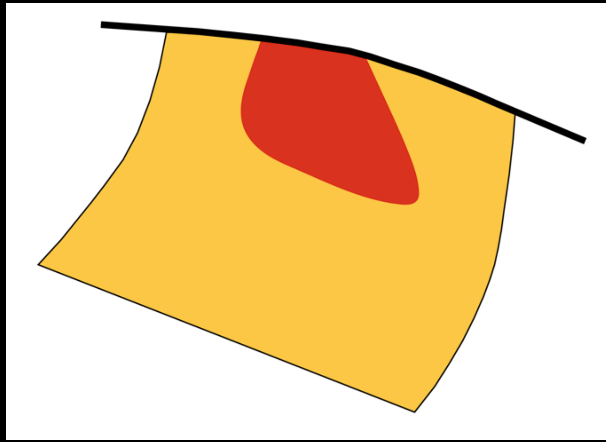


Localized strain pattern is reproduced (even more prominent afterslip is suggested by observation).

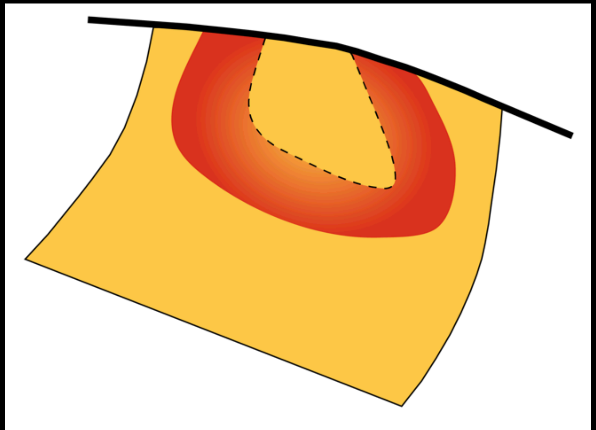
Such slip could have been triggered by the unclamping caused by the Tohoku-oki afterslip.

Summary of fault slips

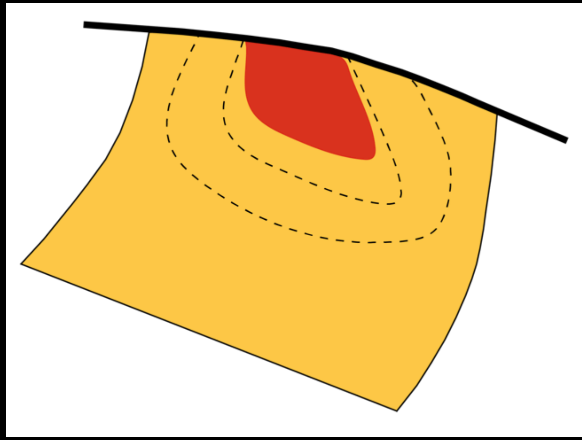
19 March 2011: EQ rupture



2011-2016 (inter-event): Large strain revealed by GNSS, consistent with afterslip



28 Dec 2016: EQ re-rupture, largely overlapped



After Dec 2016: Little strain revealed by GNSS, consistent with little afterslip