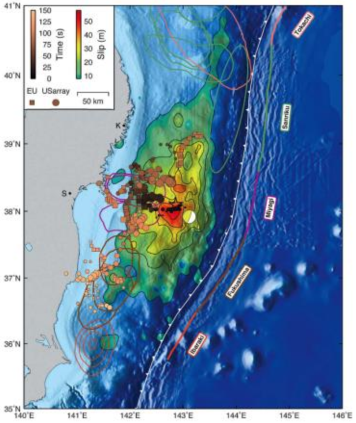
Adaptive fault discretization for the inversion of geodetic data

Yosuke Aoki (yaoki@eri.u-tokyo.ac.jp)

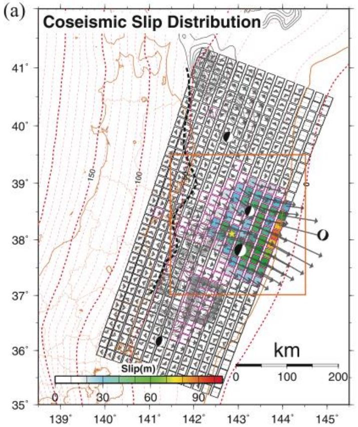
Earthquake Research Institute, The University of Tokyo

13 September 2018
19th General Assembly of WEGENER
Grenoble, France

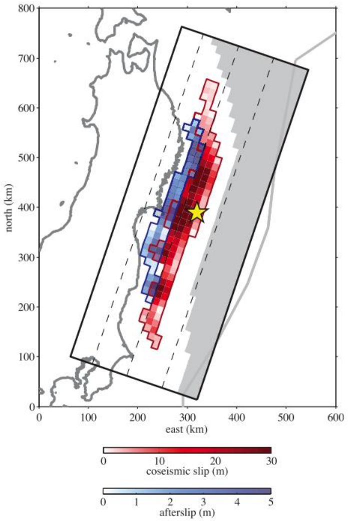
Various slip models from the same dataset



Simons *et al.* (*Science*, 2011)



Iinuma *et al.* (*JGR*, 2012)



Evans & Meade (*GRL*, 2012)

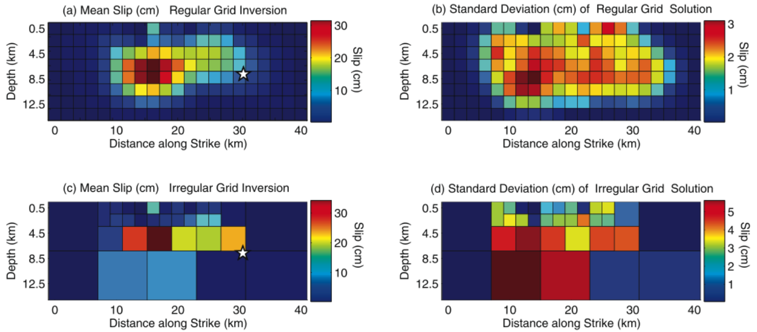
✓ Different methods (e.g., regularization) give different results.

✓ Can simple regularization (e.g., Laplacian or Tikhonov regularization) extract as much information as the data are supposed to have?

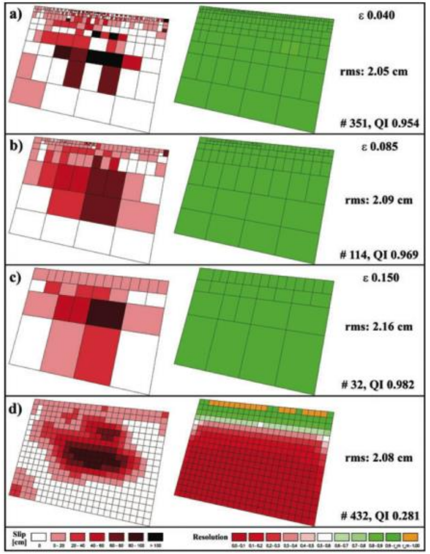
✓ How can we quantify the spatial resolution of the solution?

✓ Need to understand what the data can and cannot tell us with a minimum number of model parameters (transdimensional inference; e.g., Sambridge et al., *Phil. Trans. Royal Soc. A*, 2013; Dettmer et al., *GJI*, 2014, Sparse modeling; e.g., Nakata *et al., Sci. Rep.*, 2017).

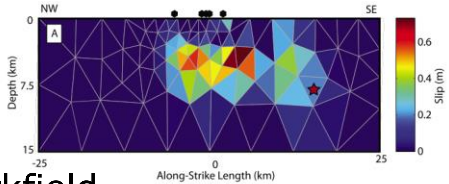
Inversion of geodetic data with various mesh sizes



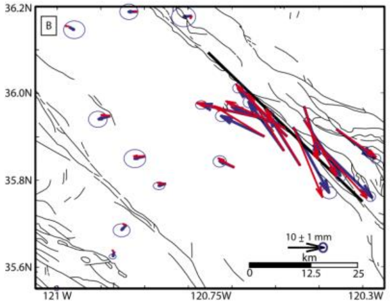
2004 Parkfield
(*Page et al.*, *JGR*, 2008)



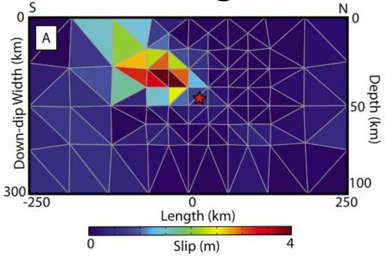
2009 L'Aquilla
(Atzori & Antonioli, *GJI*, 2009)

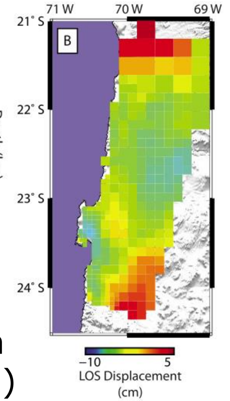


2004 Parkfield



1995 Antogafasta





Barnhart & Lohman
(*JGR*, 2010)

Principles of the inversion

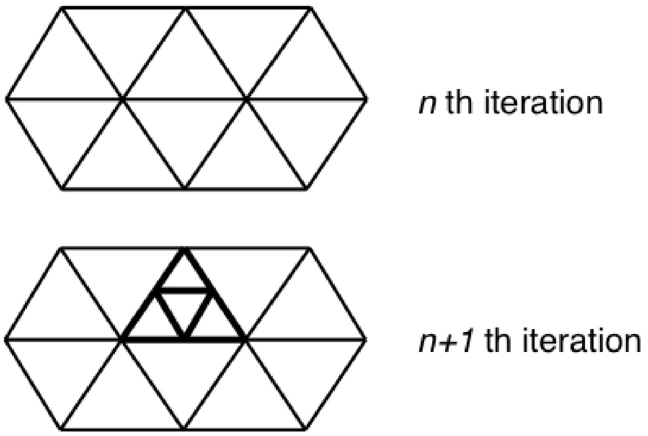
✓ Elastic, homogeneous, and isotropic halfspace.

✓ Fault geometry predetermined and meshed by a collection of very small triangular elements (Meade, *Comp. Geosci.*, 2007), allowing us to work with curved, as well as plane, faults.

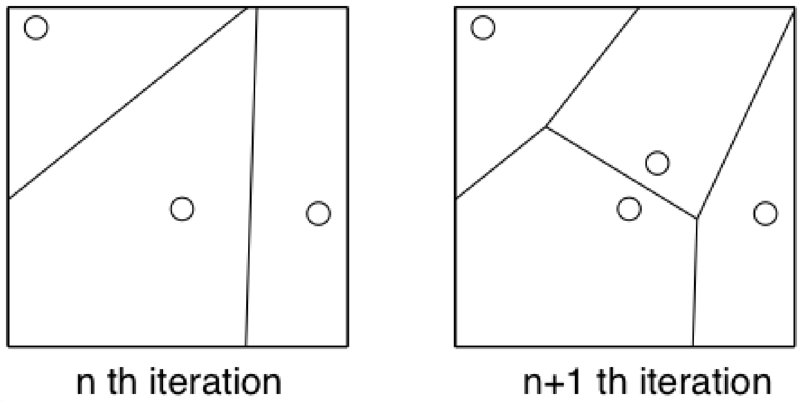
✓ No spatial smoothing rather than spatially variable smoothing parameters (Wang *et al., Tectonophysics*, 2016).

✓ Start from coarse elements, then refined as long as the spatial resolution satisfies a threshold.

Two ways of meshing



Down-sampling of elements
Depends on the initial meshing



Unstructured meshing by a Voronoi diagram

A Monte-Carlo based method

How the inversion works

$$\boldsymbol{d} = \boldsymbol{Gm} + \boldsymbol{\varepsilon}$$

Observation equation

$$\boldsymbol{G} \sim \boldsymbol{U_p \Lambda_p V_p}^T$$

Decompose the data kernel in *p* modes by Singular Value Decomposition

$$diag(\boldsymbol{\Lambda}_p) = \lambda_1, \lambda_2, \cdots, \lambda_p$$

$$\frac{\lambda_p}{\lambda_1} \geq r_{min}$$

Retains modes with eigenvalues larger than a threshold

$$\boldsymbol{R}_m = \boldsymbol{V_p V_p}^T$$

If all the diagonal component of the resolution matrix exceeds 1-exp(-1/2)=0.3935 then all meshes are considered resolved.

The data kernel depends only on the geometry of meshes and station distribution so we gain insights into the spatial resolution without any observations.

How to determine r_{min}

✓ Smaller r_{min} leaves more modes and makes the fit between observation and calculation better but gives higher uncertainties in model parameters.

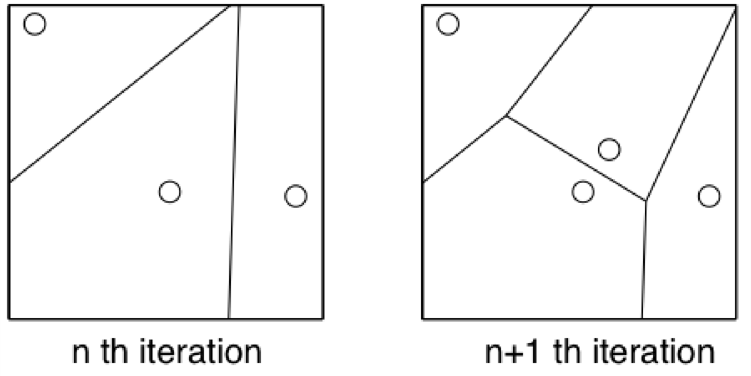
✓ Theoretically, r_{min} is related to signal-to-noise ratio in the data

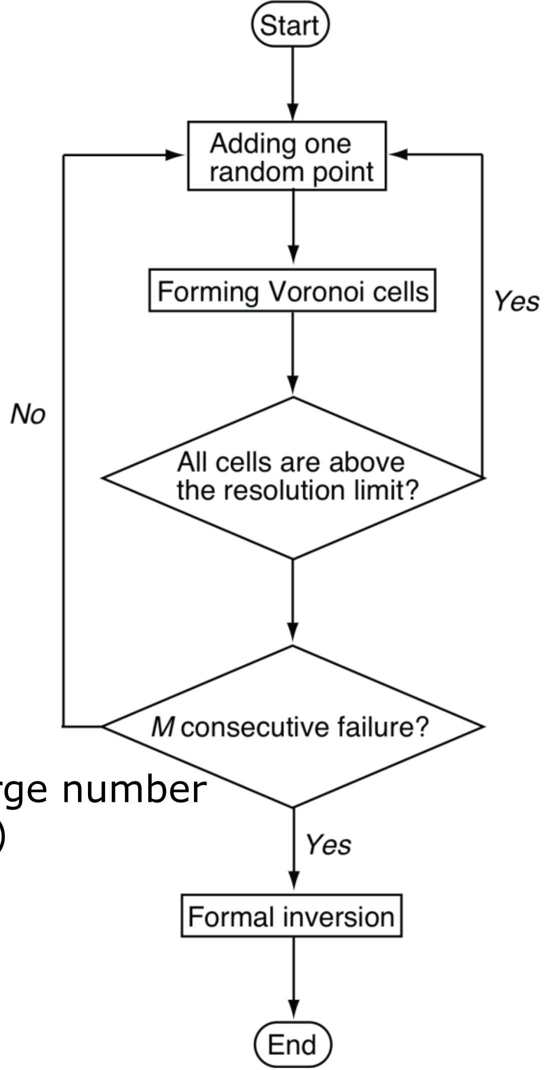
✓ In other words, r_{min} tend to be smaller with a case of larger earthquakes or larger earthquakes.

✓ But it is difficult to define in this case.

✓ r_{min} is set rather subjectively to be 0.01.

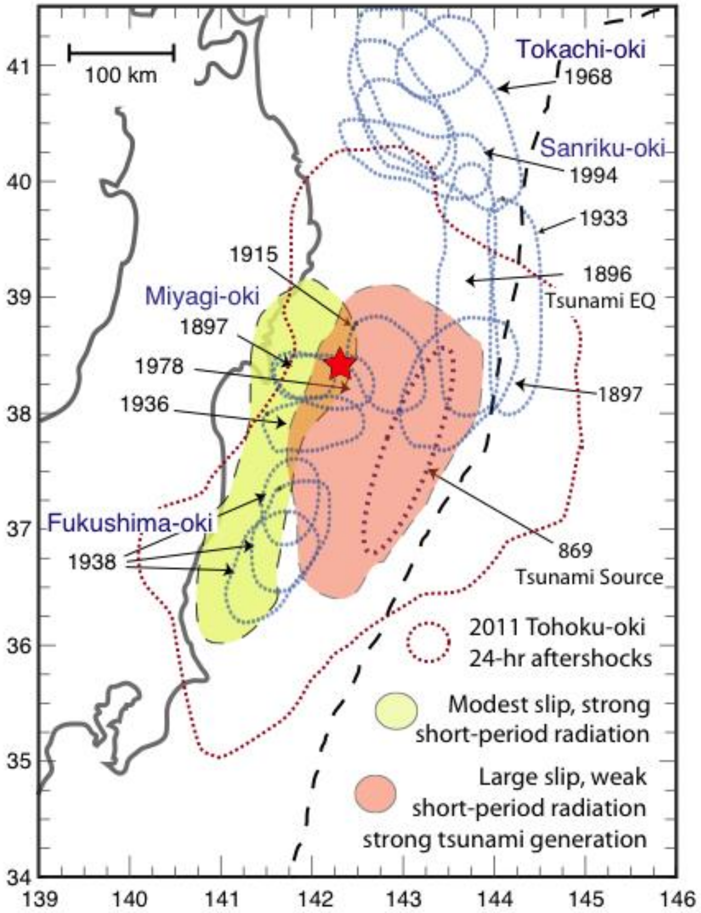
Flow chart





M: An arbitrary large number (1000 in this case)

The 2011 Tohoku-oki earthquake



✓ Mw = 9.0

✓ Killed ~20,000 people, 90 % by tsunami.

✓ Slow and large slips at shallower depths.

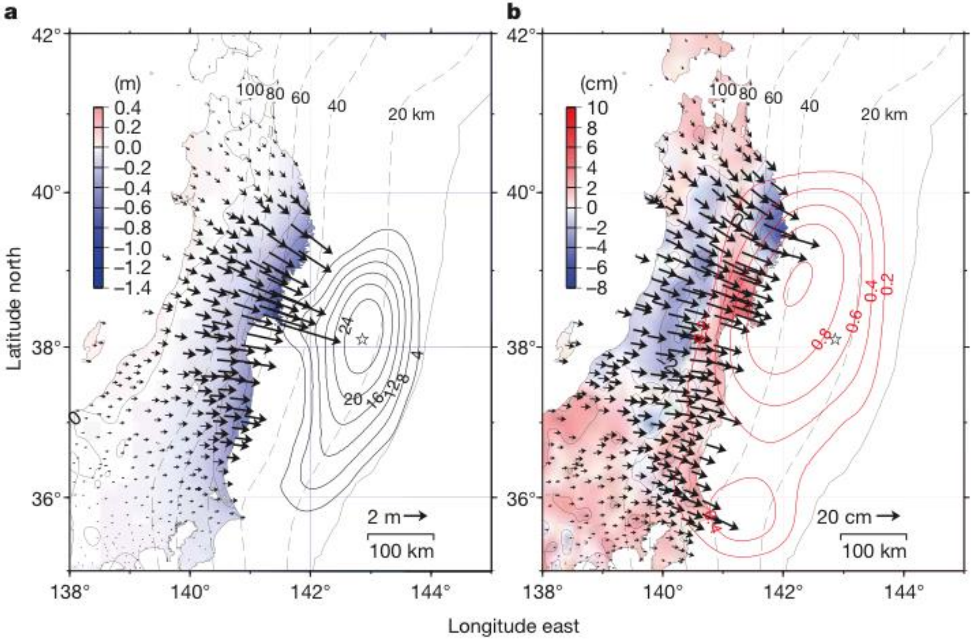
✓ Fast and smaller slips at depth.

✓ Most slips occurred offshore.

Koper *et al.* (*Earth Planet. Space*, 2011)

Coseismic deformation of onshore GPS sites

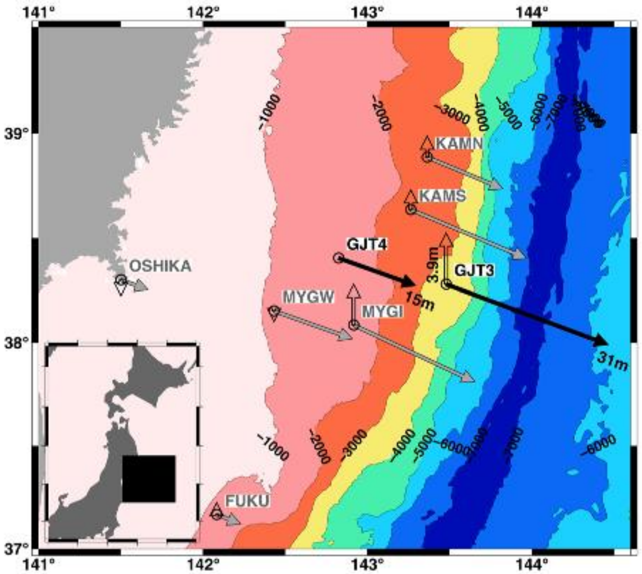
Coseismic Postseismic (first two weeks)



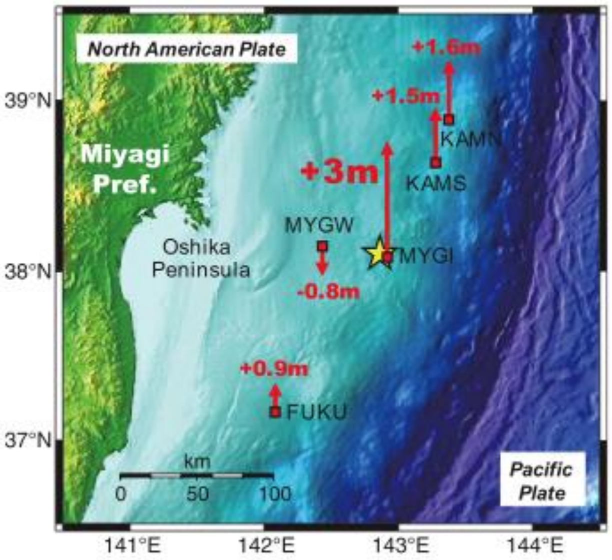
Ozawa *et al.* (*Nature*, 2011)

✓ Eastward displacement up to 5.3 meters.
✓ Coseismic subsidence up to 1.1 meters.

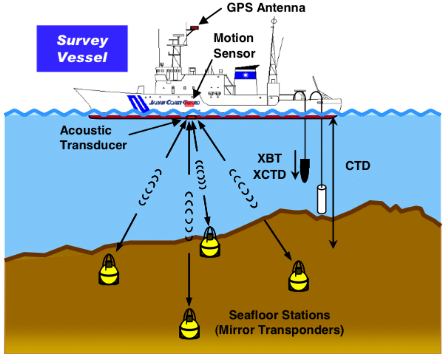
Coseismic deformation of offshore GPS sites



Kido *et al.*
(*GRL*, 2011)



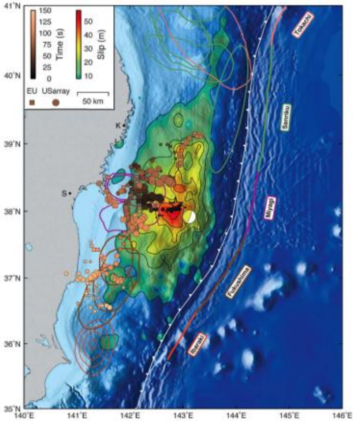
Sato *et al.*
(*Science*, 2011)



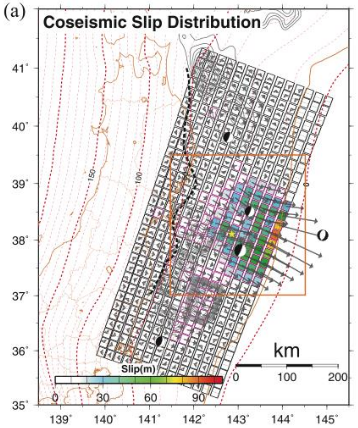
✓ East-southeastward displacement up to 31 meters.

✓ Uplift up to 3 meters.

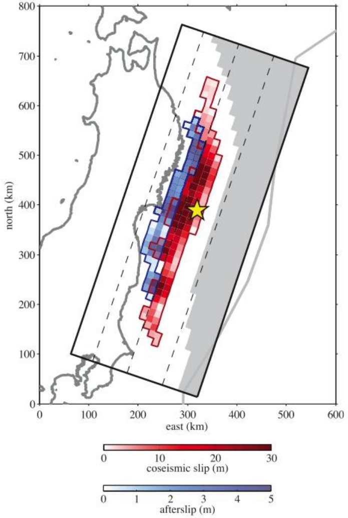
The 2011 Tohoku-oki EQ coseismic slip models



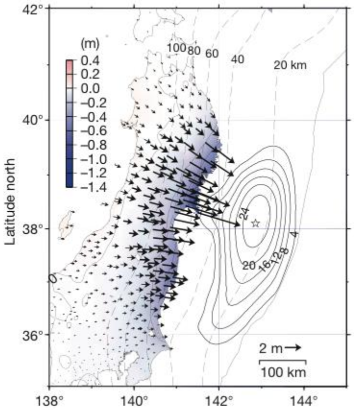
Simons *et al.* (*Science*, 2011)



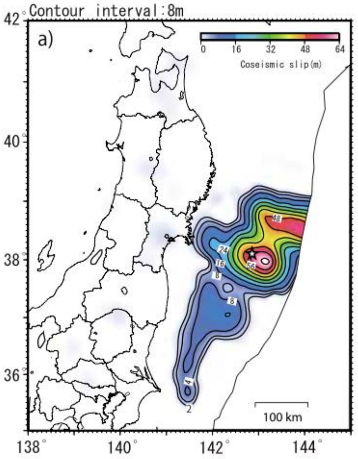
Iinuma *et al.* (*JGR*, 2012)



Evans & Meade (*GRL*, 2012)



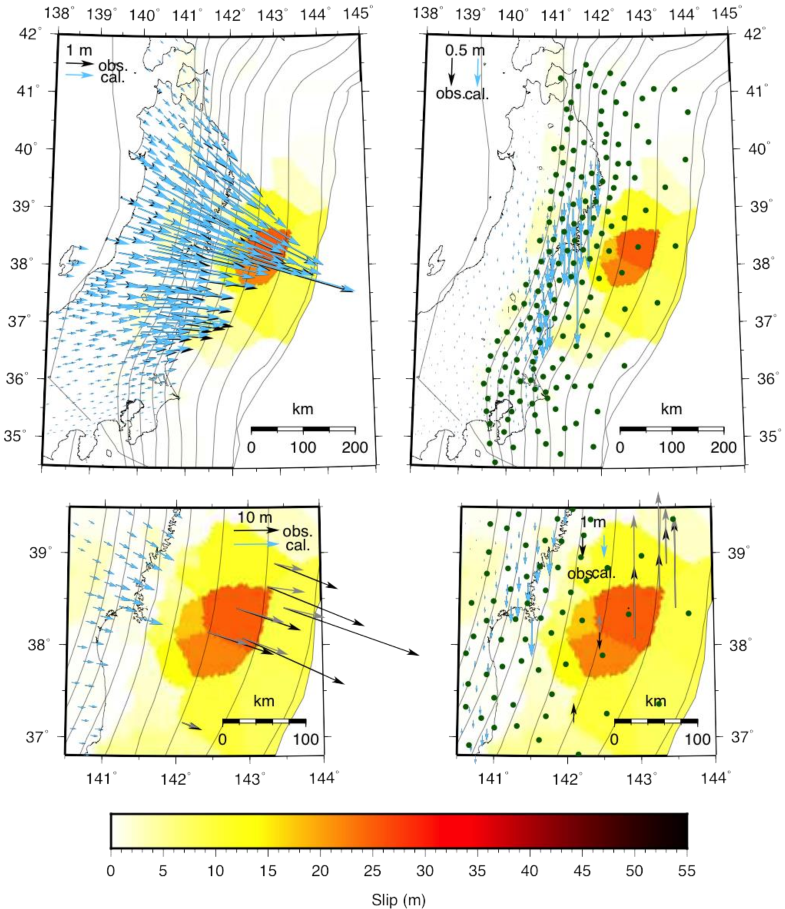
Ozawa *et al.* (*Nature*, 2011)



Ozawa *et al.* (*JGR*, 2012)

Iinuma *et al.* (*EPS*, 2011)
Ito *et al.* (*EPS*, 2011)
Koketsu *et al.* (*EPSL*, 2011)
Miyazaki *et al*. (*EPS*, 2011)
Nishimura *et al*. (*EPS*, 2011)
Pollitz *et al.* (*GRL*, 2011)
Yokota *et al*. (*EPS*, 2011)
Feng & Jónsson (*GRL*, 2012)
Romano *et al.* (*Sci. Rep.*, 2012)
and many others

Unstructured meshing with onshore GPS only



Geometry of plate interface by seismicity (Kita *et al.*, *EPSL*, 2010) and seismic tomography (Nakajima and Hasegawa, *JGR*, 2006).

Slip direction constrained to the plate convergence.

Mo = 3.96×10^{22} Nm
(Mw = 9.07)

RMS = 29.4 mm
(horizontal component of onshore GPS sites)

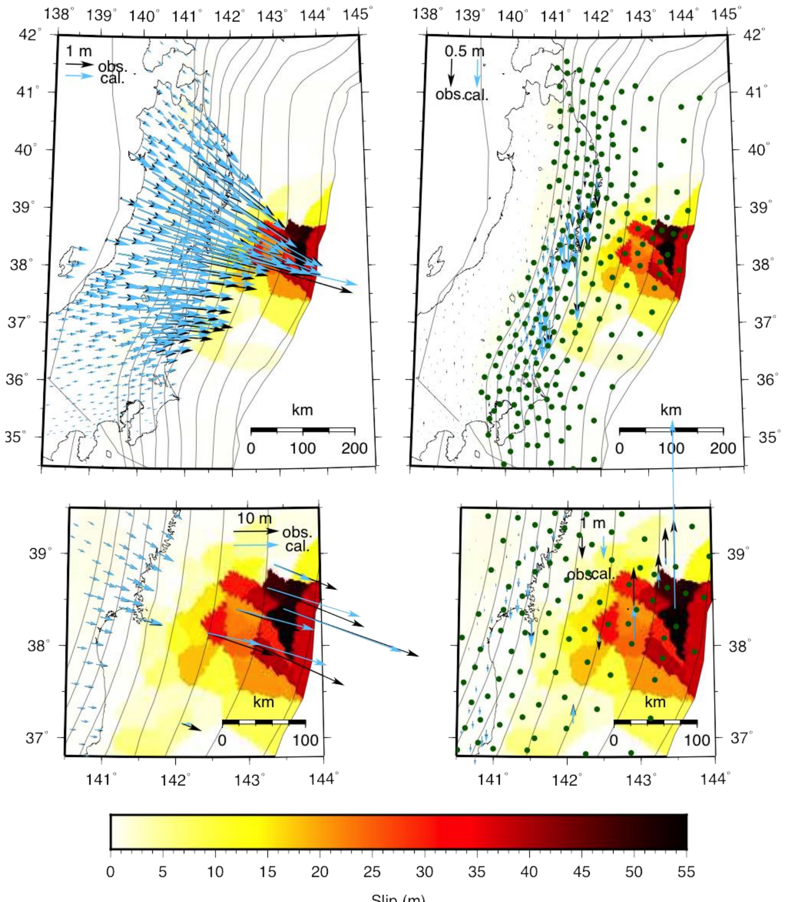
Maximum slip ~ 25.2 m

Underestimate offshore displacements.

The spatial resolution is visualized by distances of centers of triangle meshes.

Spatial resolution is poorer near the coast and about 30 km at a depth of 50 km.

Unstructured meshing with onshore+offshore GPS



Mo = 5.01×10^{22} Nm
(Mw = 9.13)

RMS = 41.8 mm
(horizontal component of onshore GPS sites)

Maximum slip ~ 54.3 m

The spatial resolution is visualized by distances of centers of triangle meshes.

Improved resolution near offshore GPS sites.

Summary of the method

✓ No need to apply smoothing constraints.

✓ Objective mesh construction.

✓ Mesh sizes directly correspond to the spatial resolution.

✓ Will give an insights into an optimum design of an observation network.

✓ Possible applications to various datasets, i.e. coseismic, (early) postseismic, slow slip, (and interseismic) displacements as long as something other than the elastic contribution (e.g., viscoelastic deformation) is ignored.

✓ The final product is an ensemble set of solutions because of the method is based on Monte Carlo inferences.

✓ Assessment of uncertainties required.