British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Differentiating earthquake tsunamis from other sources; how do we tell the difference?

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Background Thesis

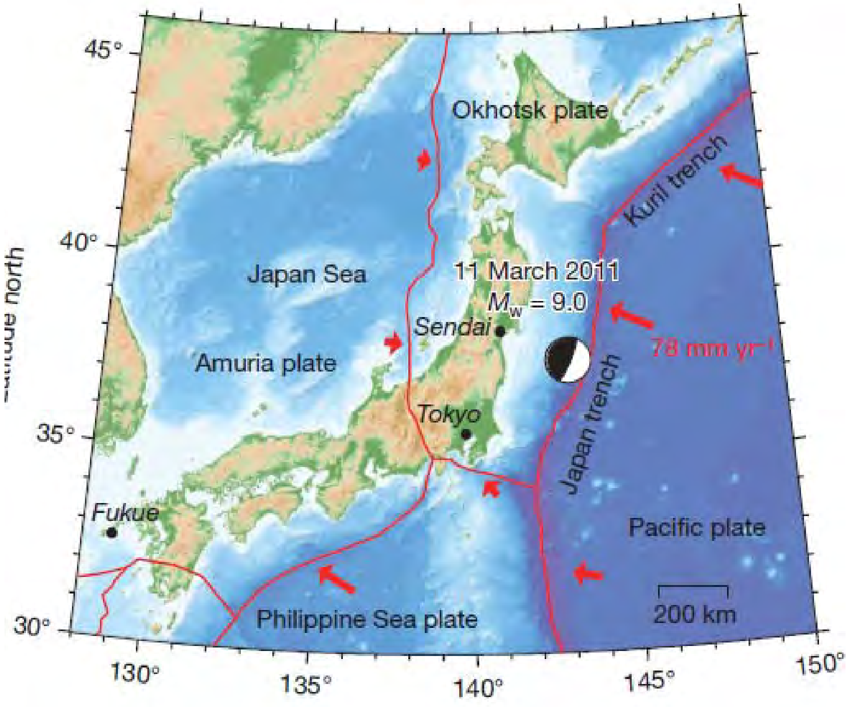
- The talk is a continuation of work led by Stephan Grilli and colleagues, co-authors on SMFs and the Japan 2011 tsunami, it's an update,
- New marine data presented,
- The Japan event raises questions on our use of established methodologies – such as tsunami wave form inversion – especially where there may be an alternative tsunami sources such as SMFs,
- Wave form inversion – very successful – with EQs,
- But, as in the title – how do we address a tsunami that may have multiple sources?

Context

- Consider briefly where we are now after 15-20 years of what appears to be the ‘Age of Tsunamis’,
- Three large EQ events over the past 9 years, with two – Indian Ocean and Japan – devastating,
- Previously to these in 1998, the PNG tsunami raised awareness of the hazard from SMFs, - not really previously recognised,
- The Indian Ocean event changed our perspective on where Great EQs may take place,
- The Japan EQ and tsunami may have similar impact with regard to how we may have to change some our preconceptions on how we perceive EQ generated tsunamis, and how our methodologies of estimating EQ rupture may have to change

Japan tsunami - 2011

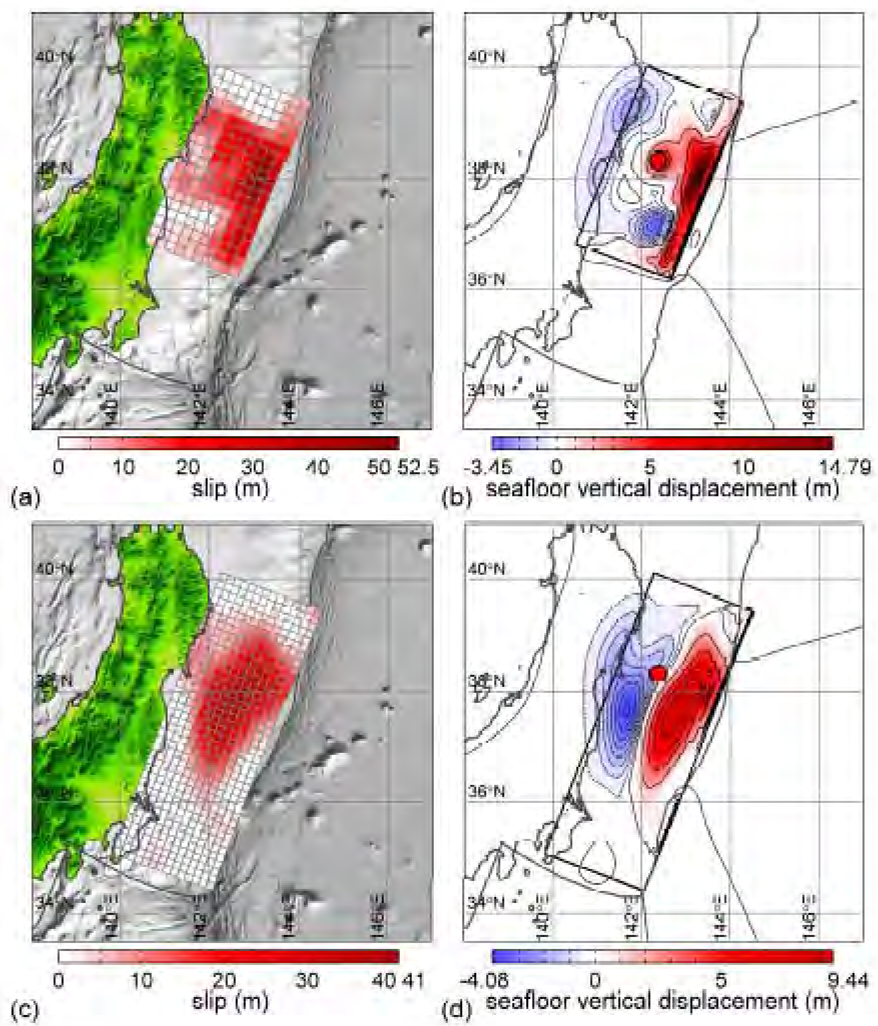
- Probably the most comprehensively geophysically recorded EQ and tsunami,
- Global and local seismic networks,
- Geodetic networks across Japan,
- Onshore tide gauges,
- Nearshore GPS pressure gauges,
- DART buoys,
- Onshore runup and inundation measurements,
- But still uncertainty in earthquake source and modelling of the tsunami,



Talk structure

- Run briefly through some of the Japan EQ rupture mechanisms,
- Some tsunami models and simulations,
- Then focus on the possible dual EQ/SMF source,
- Then some concluding comments
- It'll all be rapid

Japan 2011 Rupture - Seismic inversion



(a) Fault dislocation distribution of the finite fault inversion of *P*-waves (P-Mod).

(b) Vertical seafloor displacement for P-Mod.

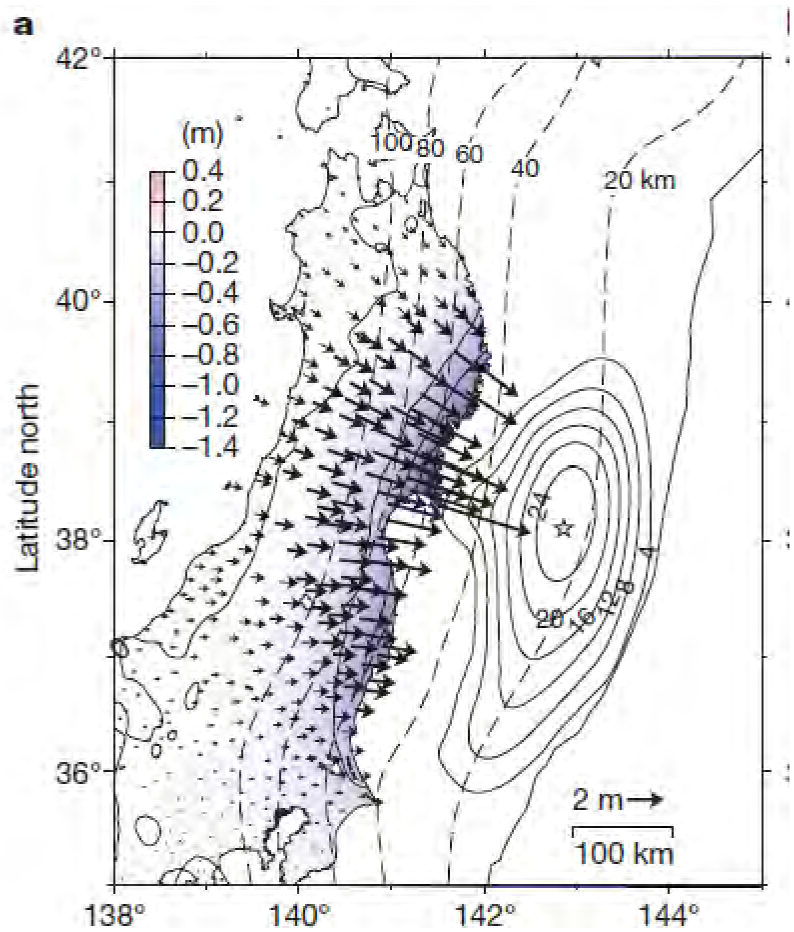
(c) Fault dislocation distribution of the finite fault inversion of *P*-waves, Rayleigh wave relative source time functions, and high-rate GPS recording (J-Mod) (Ammon *et al.*, 2011).

(d) Vertical seafloor displacement for J-Mod.

(Lay et al., 2011)

Rupture in the south

Japan 2011 Rupture - Geodetic



Coseismic displacements for 10–11 March 2011, relative to the Fukue site. The black arrows indicate the horizontal coseismic movements of the GPS sites. The colour shading indicates vertical displacement. The star marks the location of the earthquake epicentre. The dotted lines indicate the isodepth contours of the plate boundary at 20-km intervals.

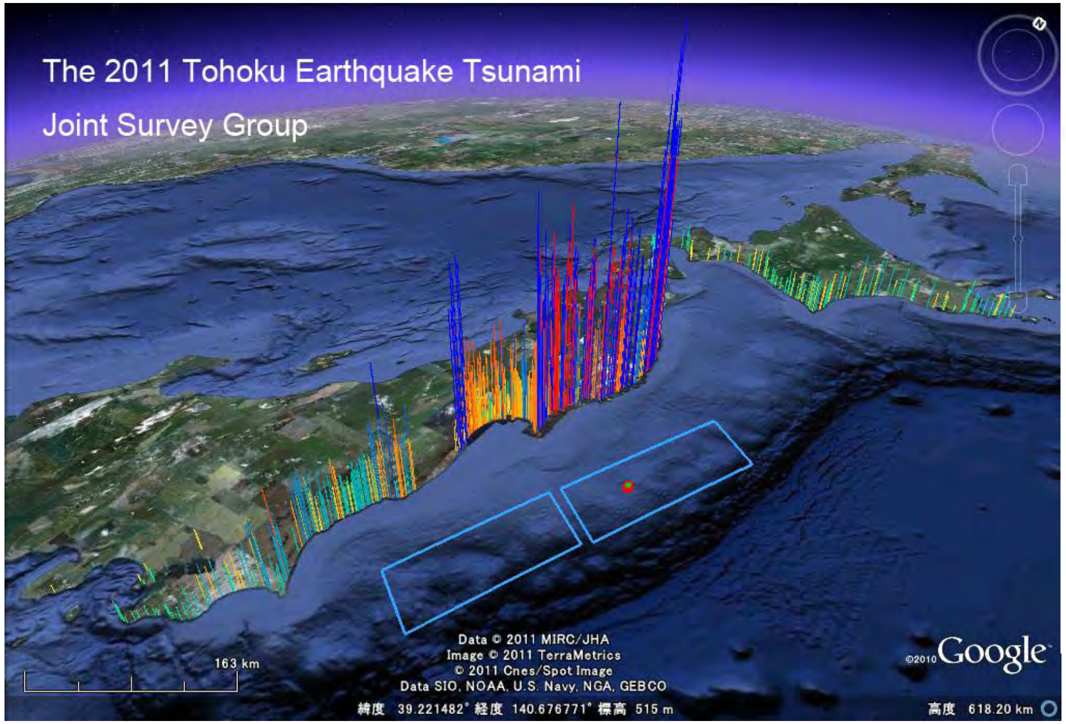
The solid contours show the coseismic slip distribution in metres.

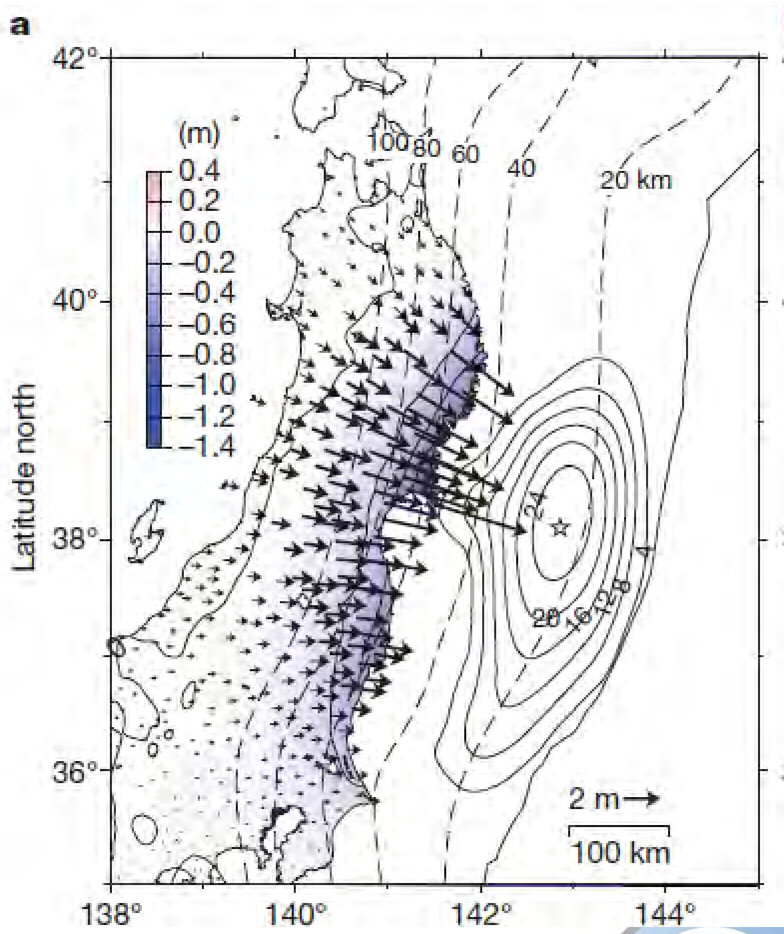
(*Ozawa et al. 2011*)

Rupture in the south

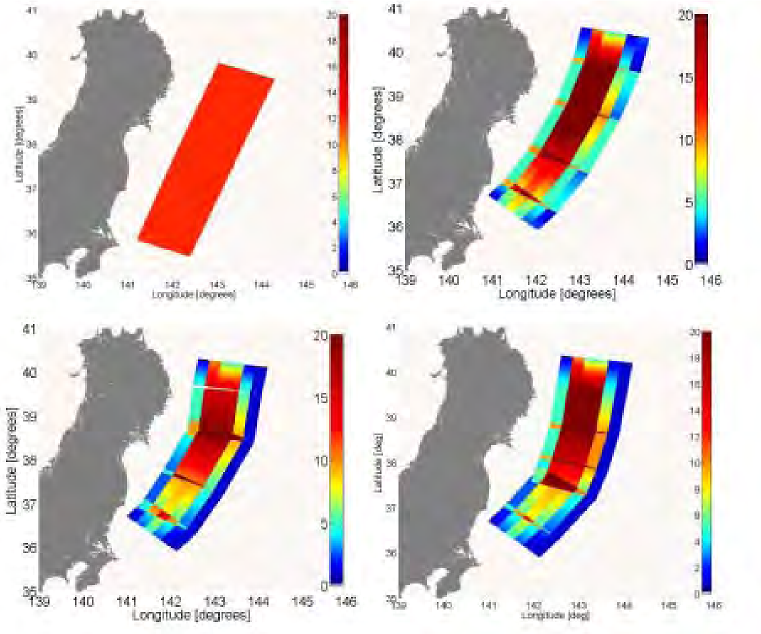
Japan tsunami runups

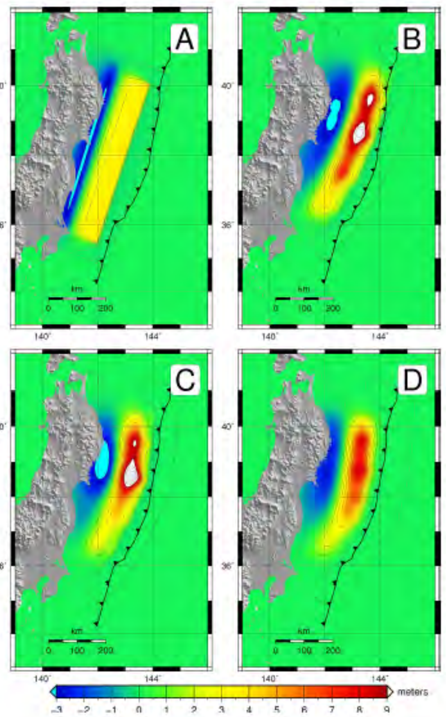
"A major issue is the 100 km latitudinal displacement of the highest runups to the largest slip"



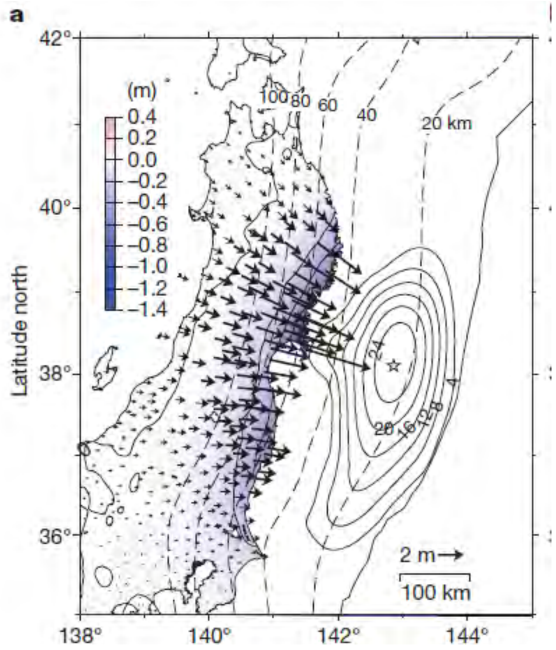


Tsunami modelling





Based on adjusted EQ sources

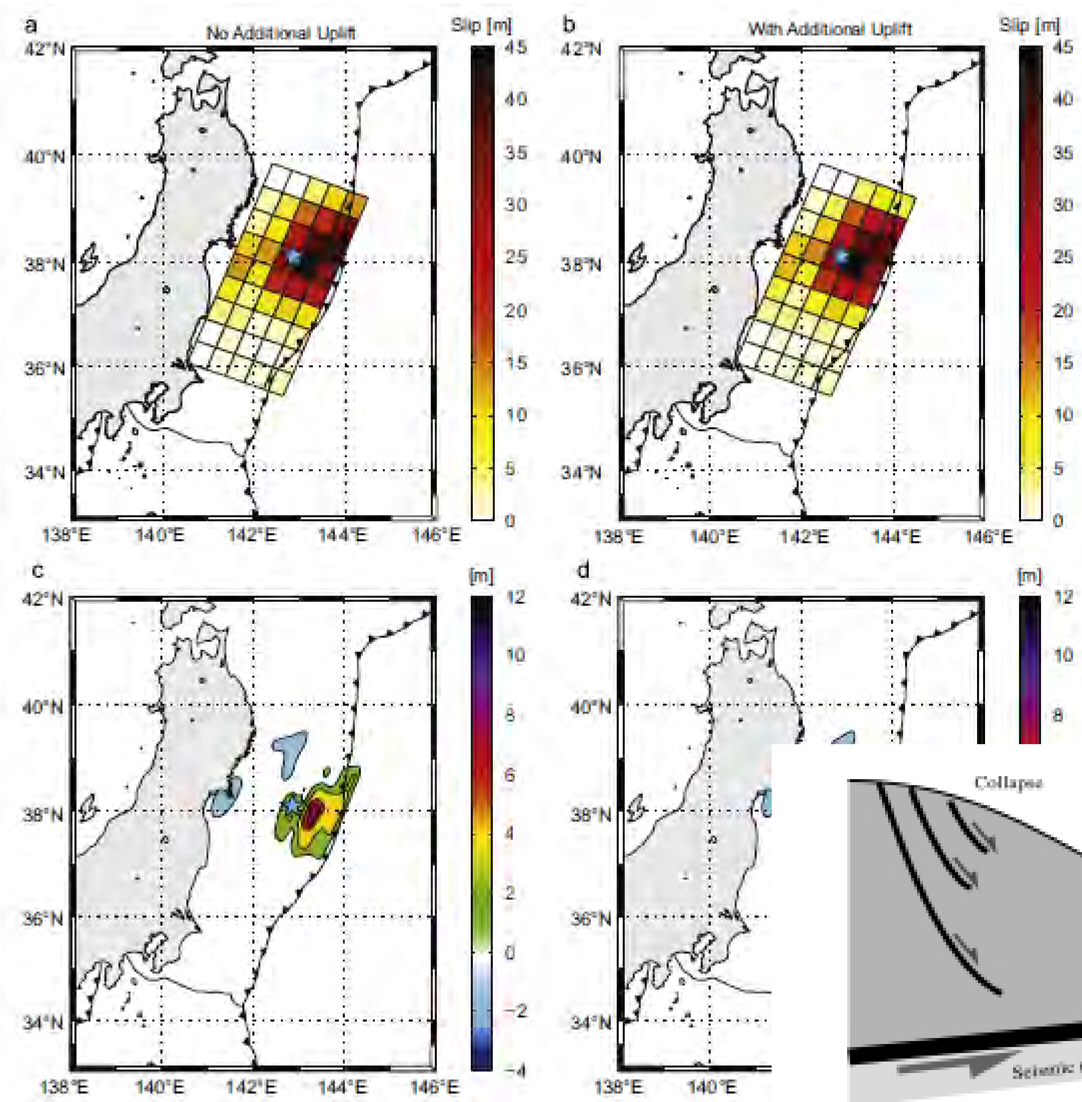


Upper Figure. Slip distribution for the four different earthquake source scenarios A–D.

Lower Figure. Initial surface elevations for the four different earthquake source scenarios A–D.

(*Lovholt et al 2012*)

Combination approach

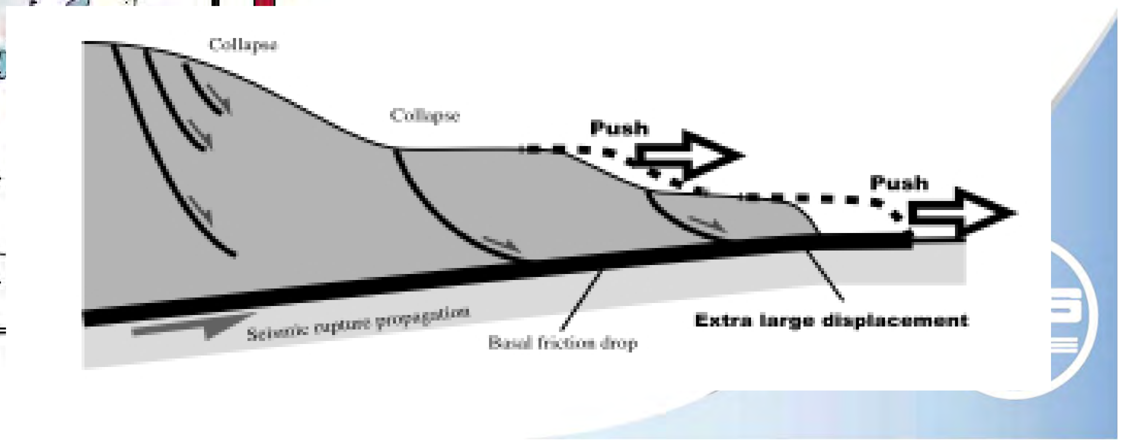


Slip distribution by a joint inversion using the tsunami waveforms and crustal deformation data.

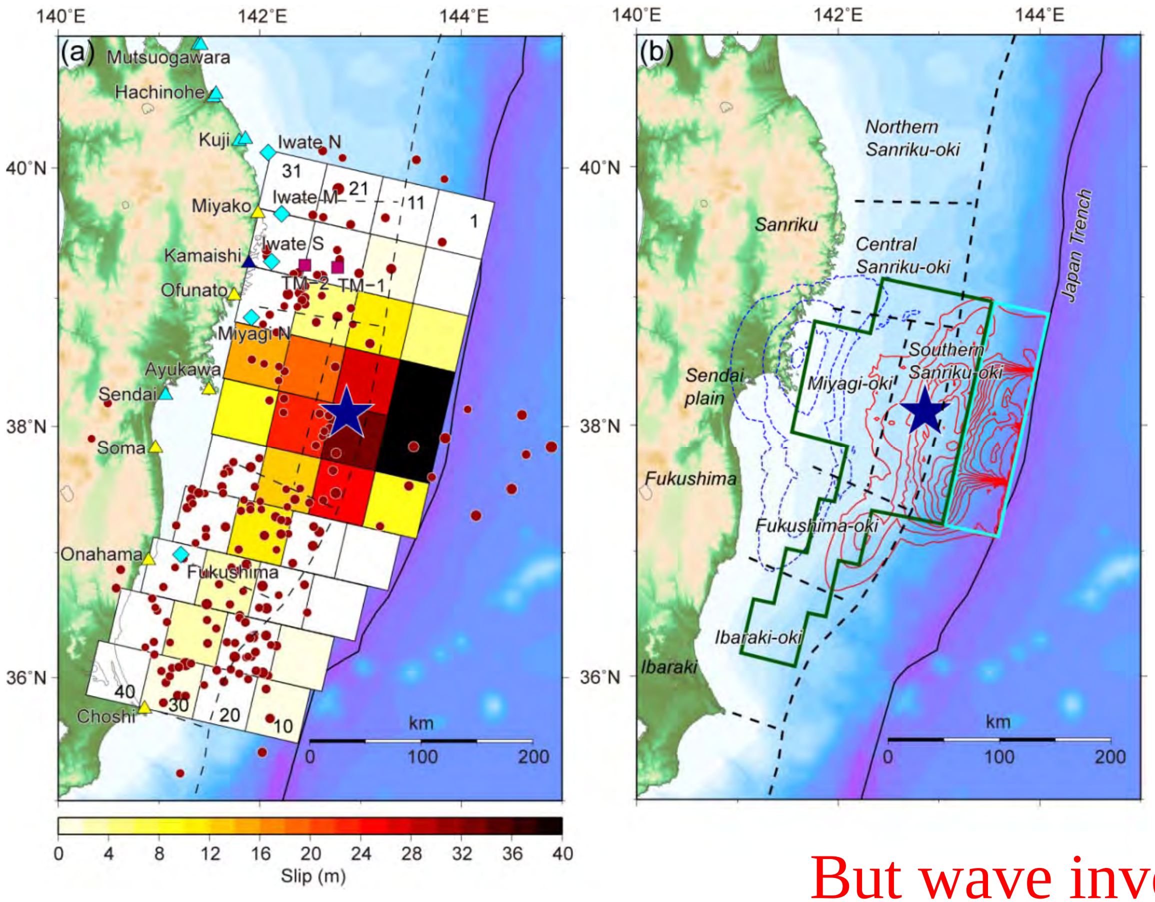
But runups still require additional uplift on the plate margin.

(*Gusman et al., 2012*)

Sediment contribution from



Tsunami waveform inversion



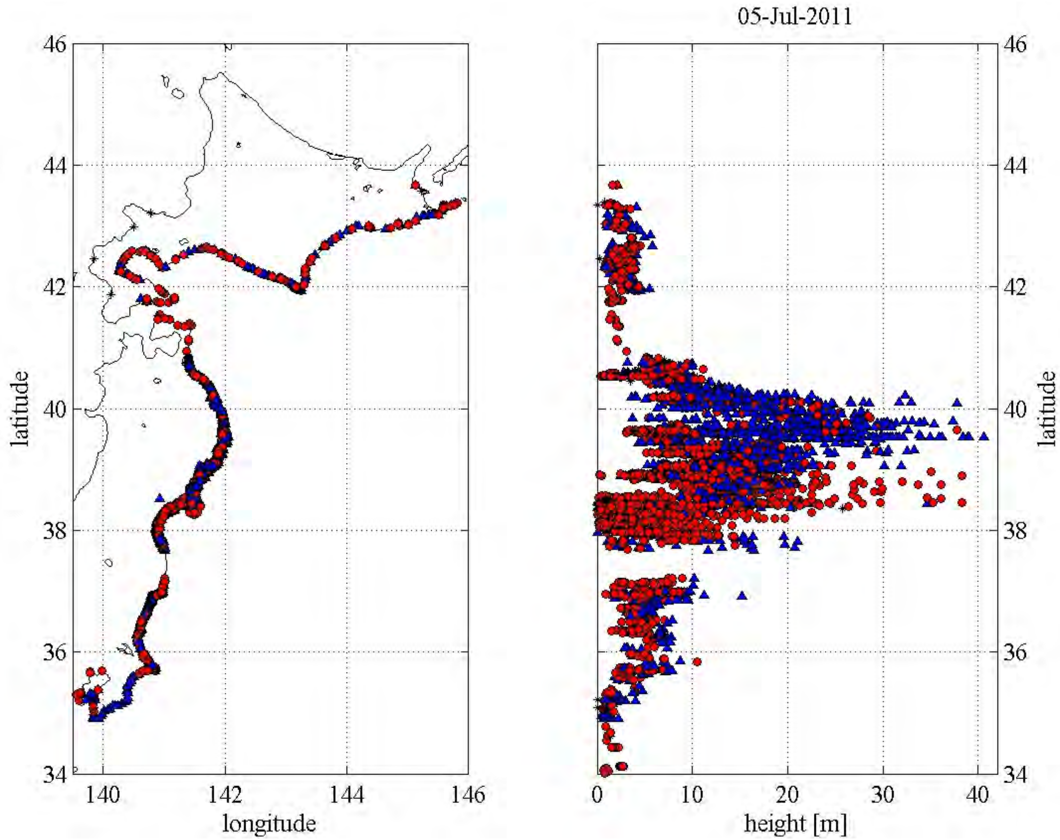
(a) Slip distributions estimated by tsunami waveform inversion.

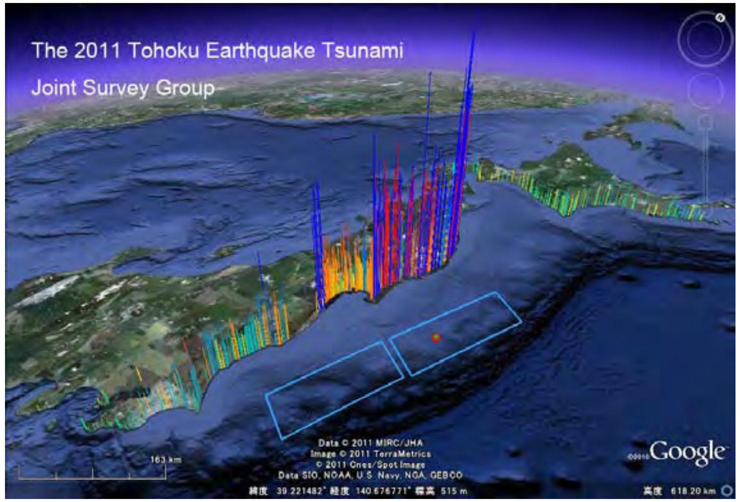
(b) Seafloor deformation computed from the estimated slip distribution(red uplift, blue subsidence.

(*Fuji et al., 2011*)

But wave inversion does not explain the high runups in the north.

Japan tsunami runups





Wave inversion does not explain the high runups in the north.

So without 'adjustments' the northern Honshu high runups remain unexplained – an additional tsunami source is required. **Thus a two source model is needed!**

Dual source approach - EQ and SMF

1. Simulating fault-slip within a complex domain

Finite element model (FEM) of the 2011 Tohoku Earthquake

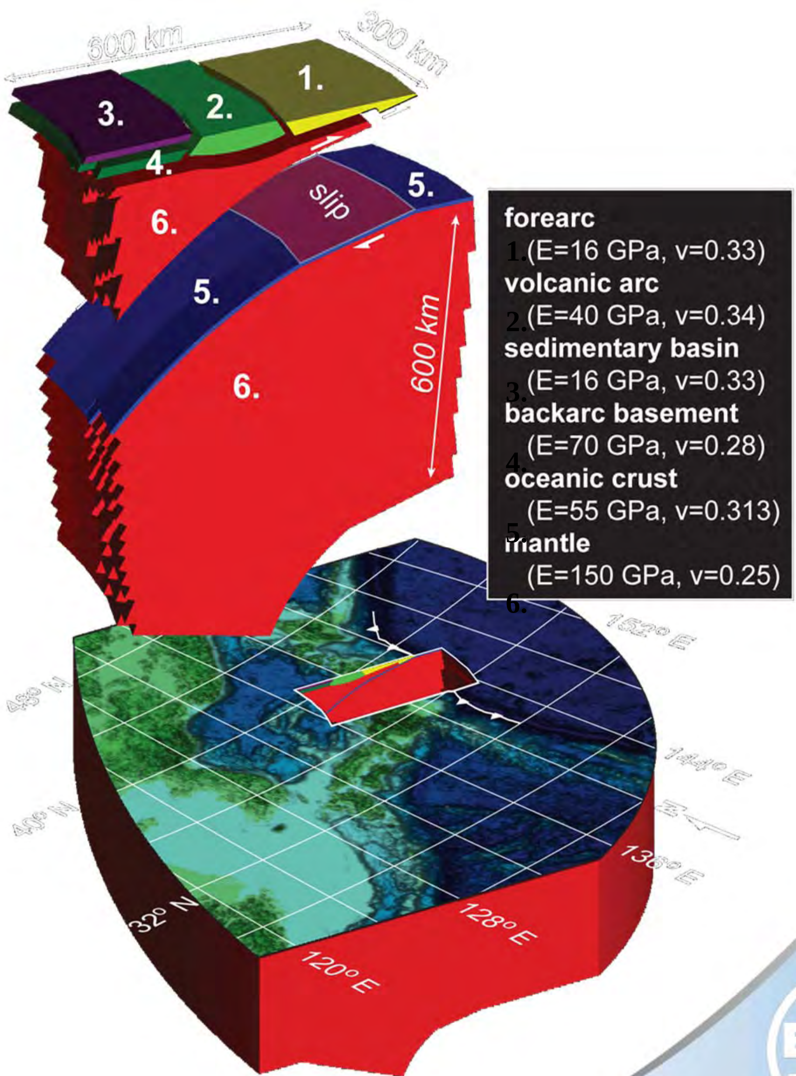
Rather than Okada

3D FEM domain:

- *360,000 nodes*
- *340,000 elements*

(Grilli et al., 2012)

Geological model



Co-seismic seafloor deformation modeling

New method: Finite Element model (FEM) with assimilation of GPS deformation data, of forearc, oceanic crust, and mantle, accounting for variations in material properties (Masterlark, NH41C-03; PAGEOH, 2012)

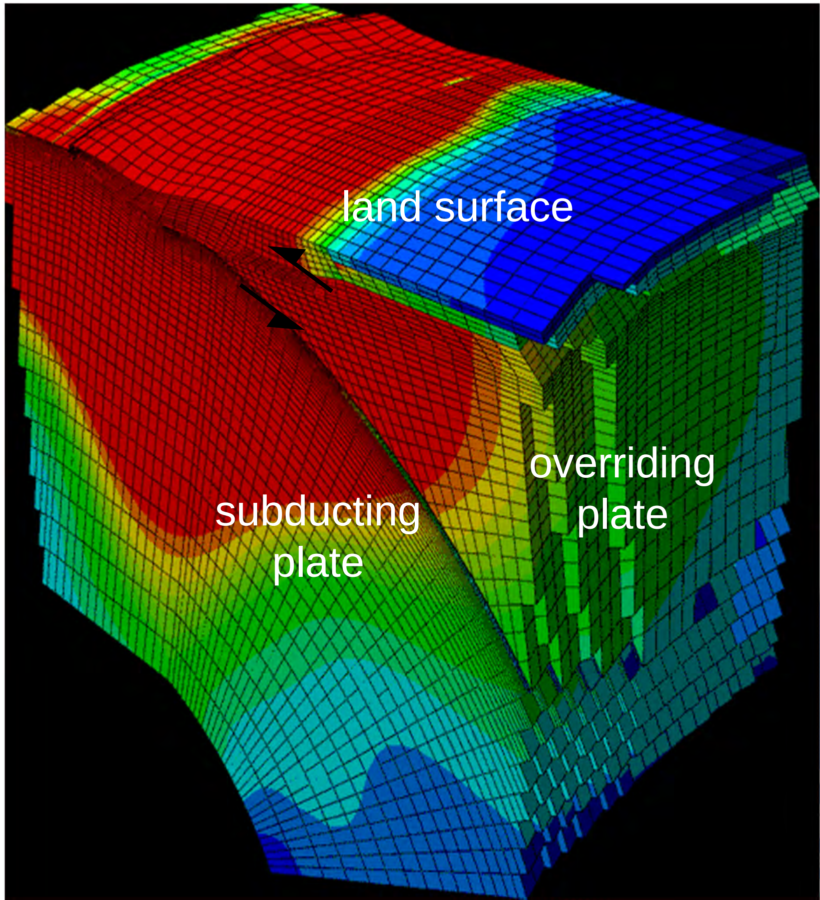
deformation
what we see
(GPS & InSAR)

inverse models

fault-slip
forward models
what we want to know !

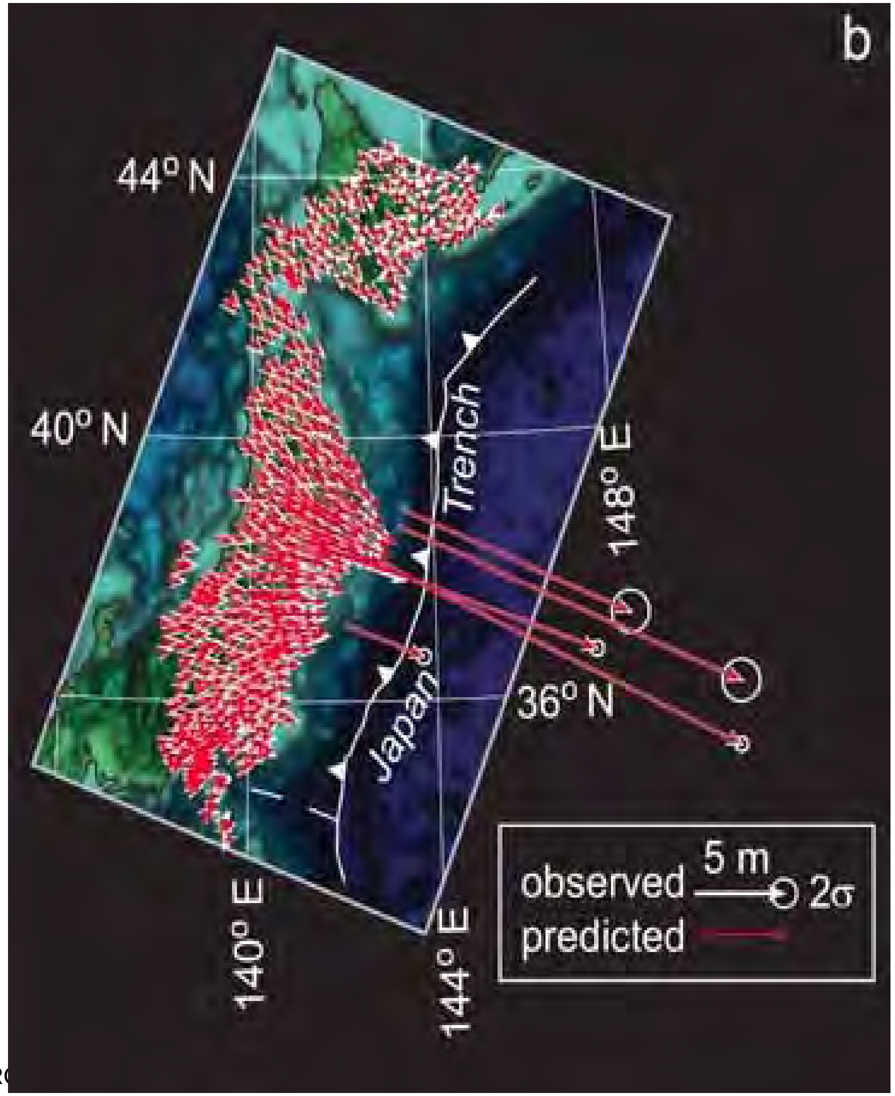
Predictions, inferences, interpretations:

- *coseismic seafloor deformation*
- *postseismic deformation*
- *Coulomb stress evolution*
- *interseismic strain accumulation*
- *rheologic properties*

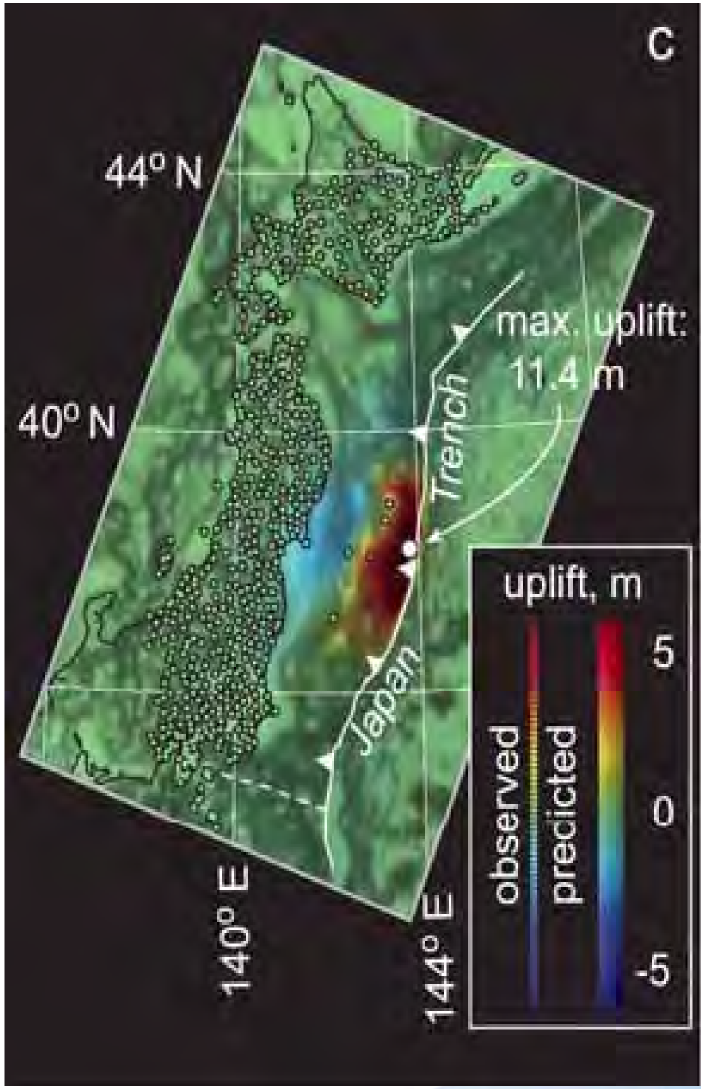


Co-seismic seafloor deformation modeling

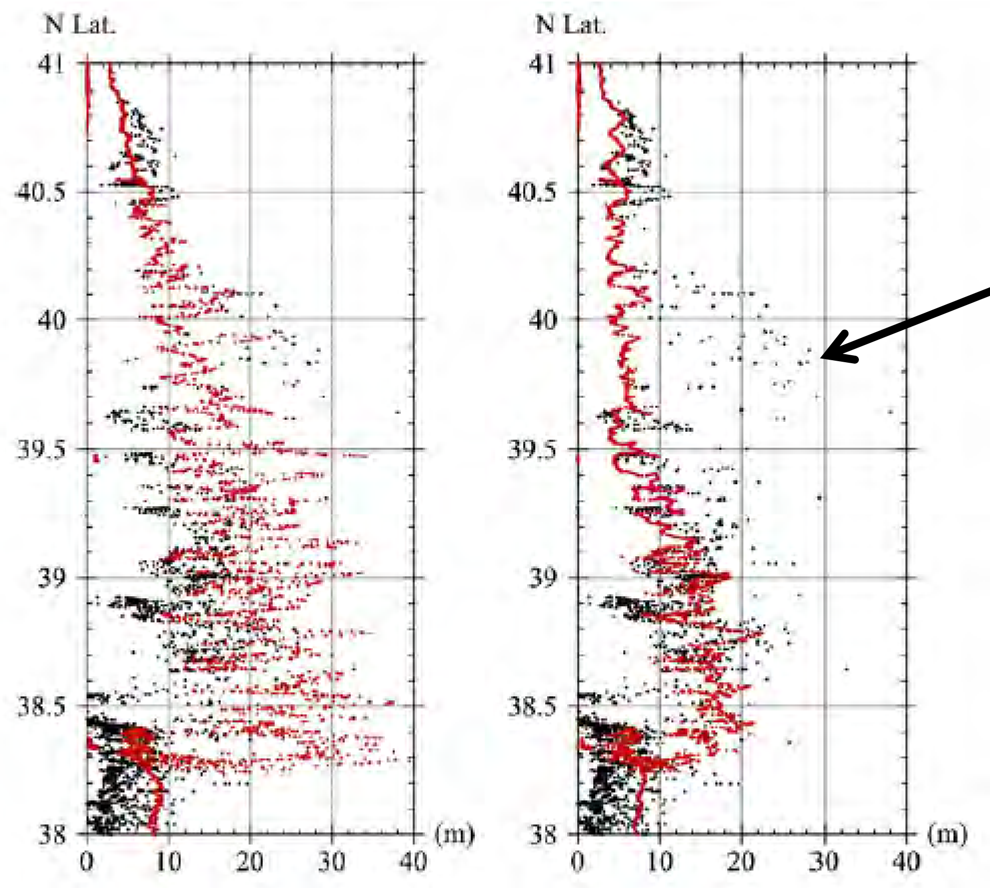
(b) Horizontal deformation



(c) Vertical deformation



Model (red) vs. measured (black) inundation: Sanriku coast – north of 38ºN

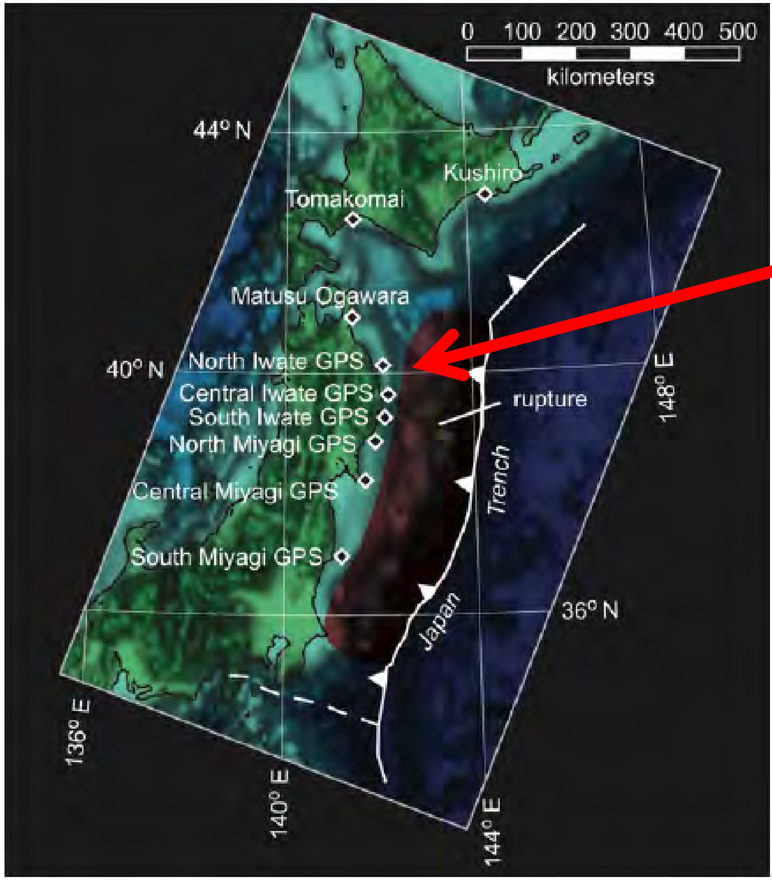


Northern high runups not modelled

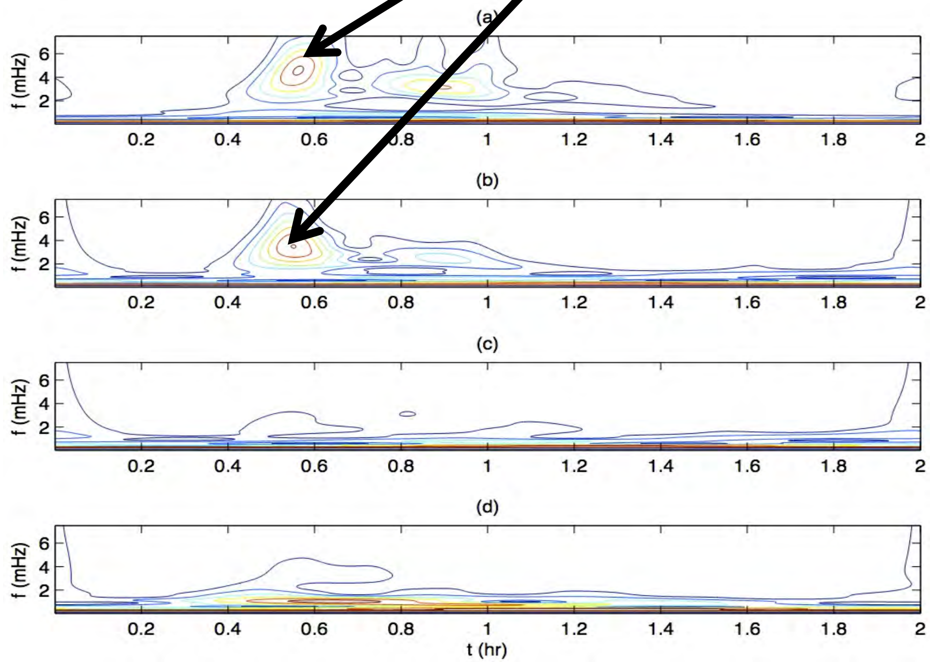
Left: a M9 UCSB source; and
Right: a M8.8 UA source.

(*Grilli et al., 2011*)

Wavelet analysis of time-frequency structure at buoys



Closest correlation

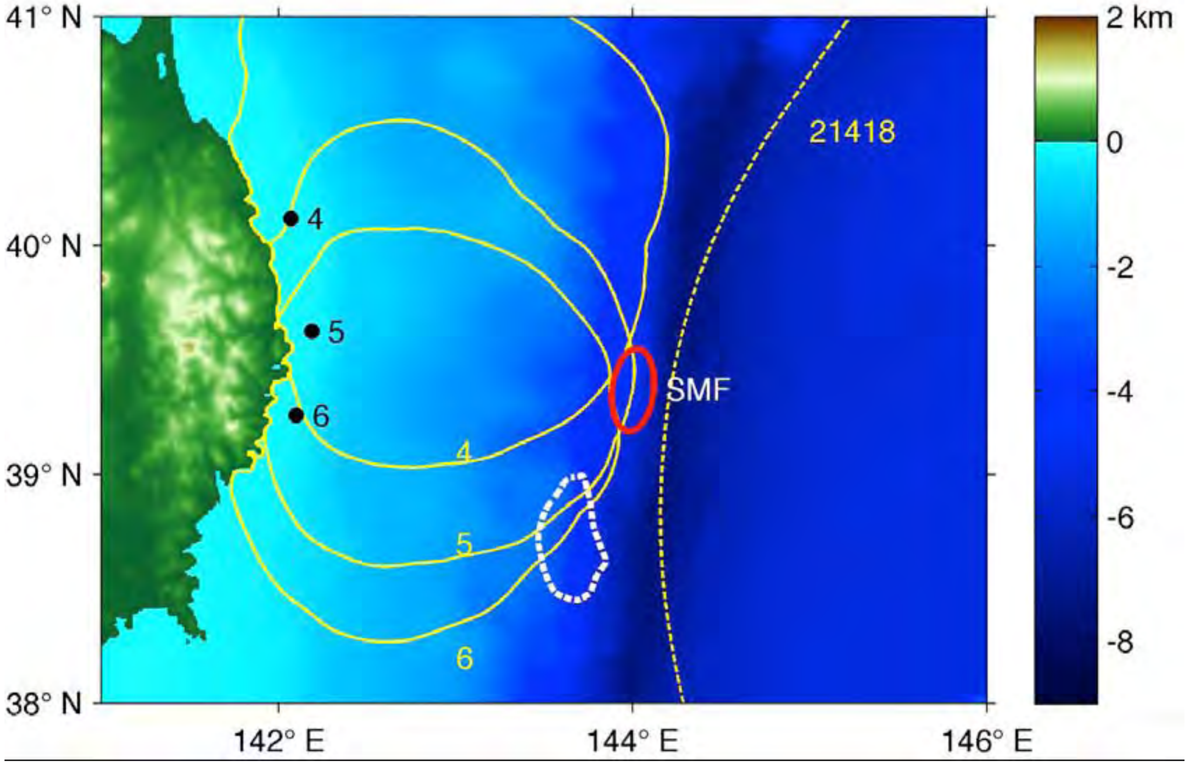


a) observed; b) FEM + slump;
c) FEM; d) Caltech.

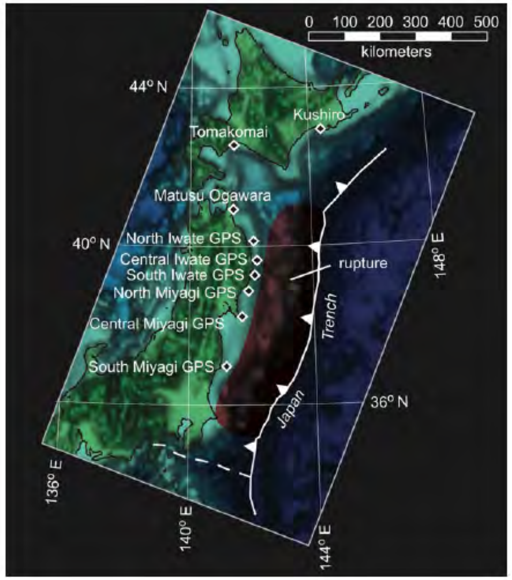
Submarine landslide source?

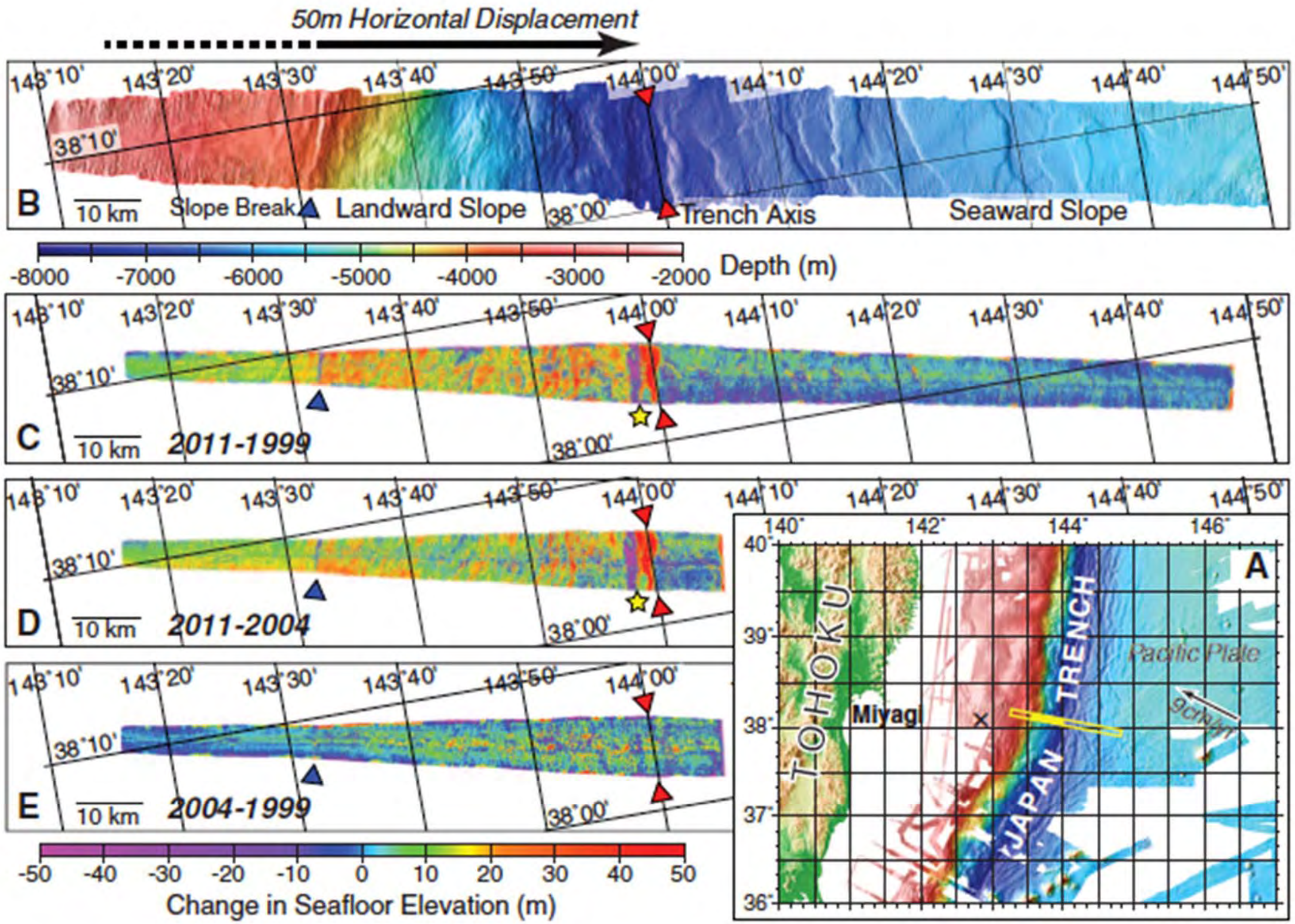
Backward ray tracing from offshore GPS buoys indicates possible SMF location

Higher frequency waves = SMF source



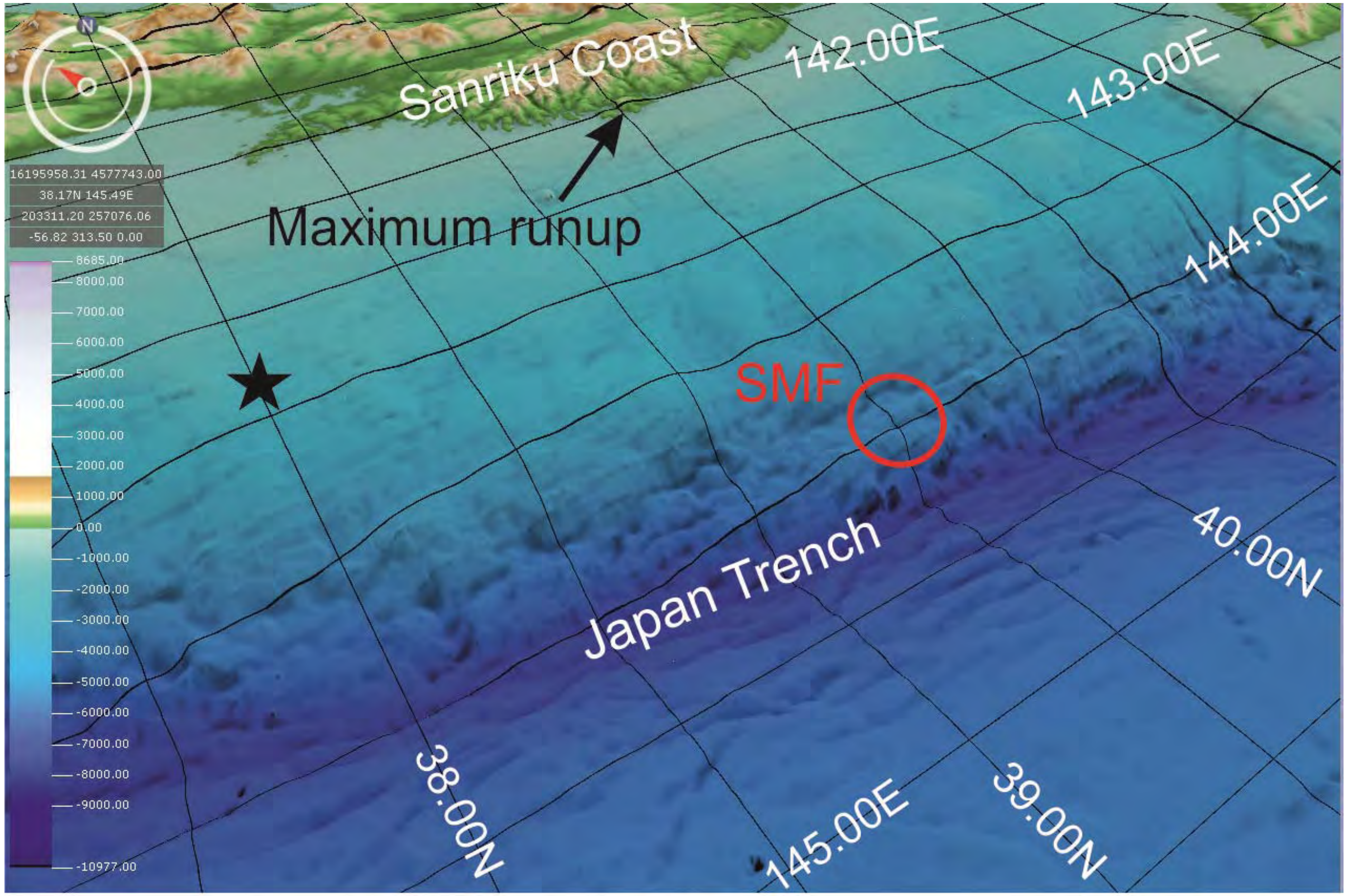
For 3’-4’ period (higher frequency) waves in the records (dashed: Kawamura et al., 2012)





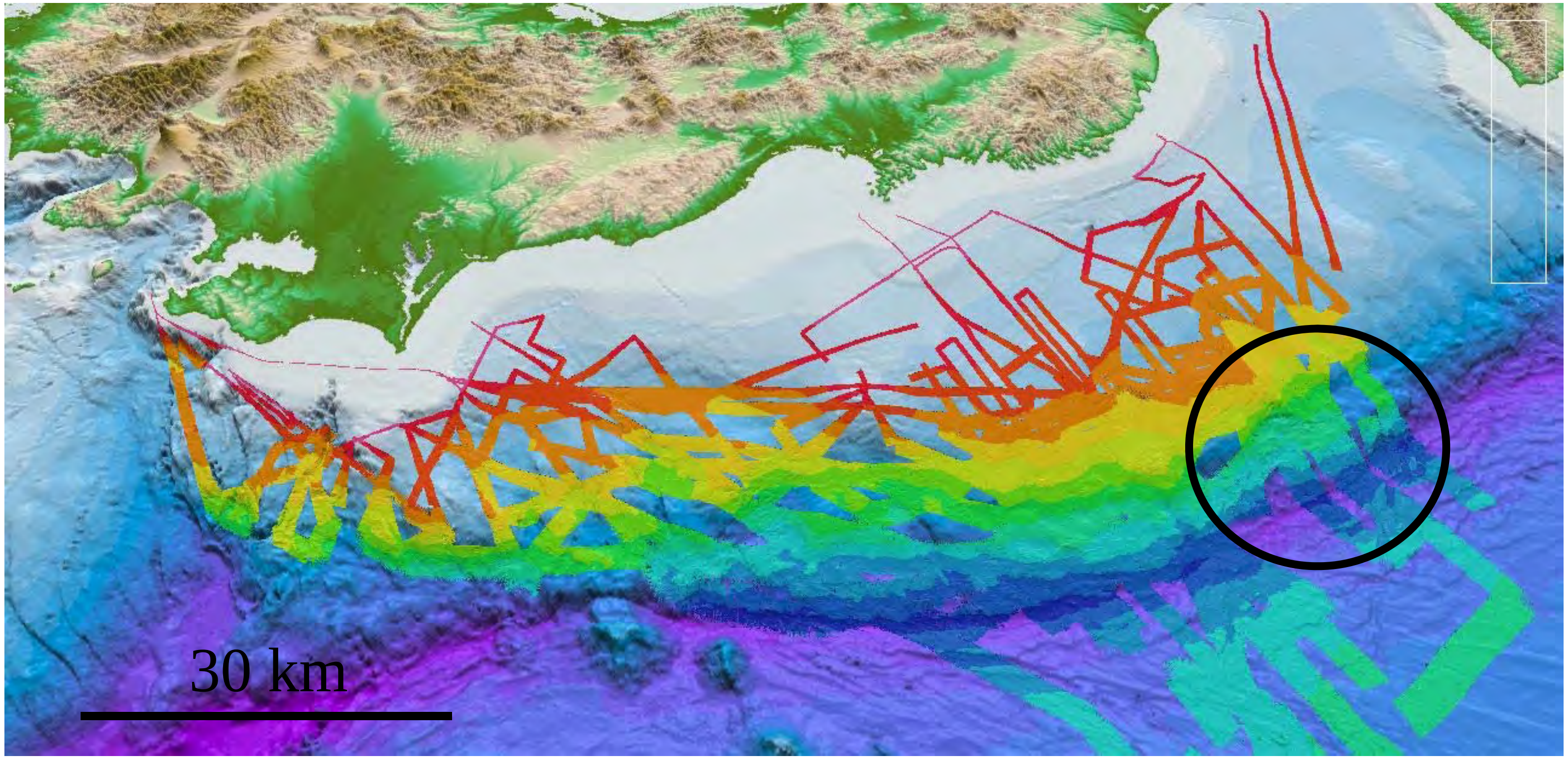
Pre- and Post-event surveys near epicentre suggest seafloor motion all the way to forearc boundary
(Fujiwara et al, Science 2011)

Submarine landslide source?



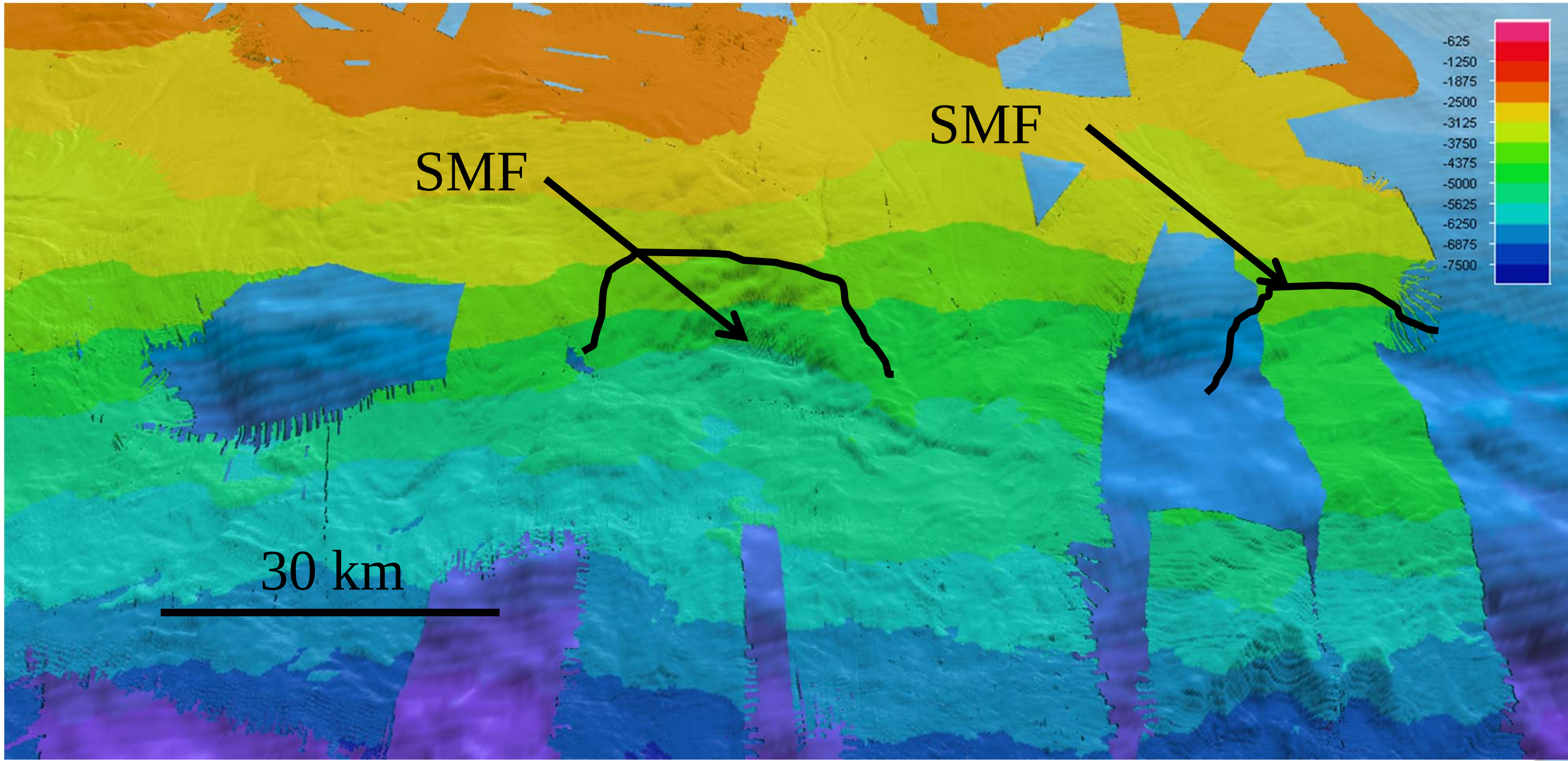
Is a SMF present where the ray tracing suggests?

Submarine landslide source



Post 2011 tsunami multibeam bathymetry –
(Courtesy JAMSTEC)

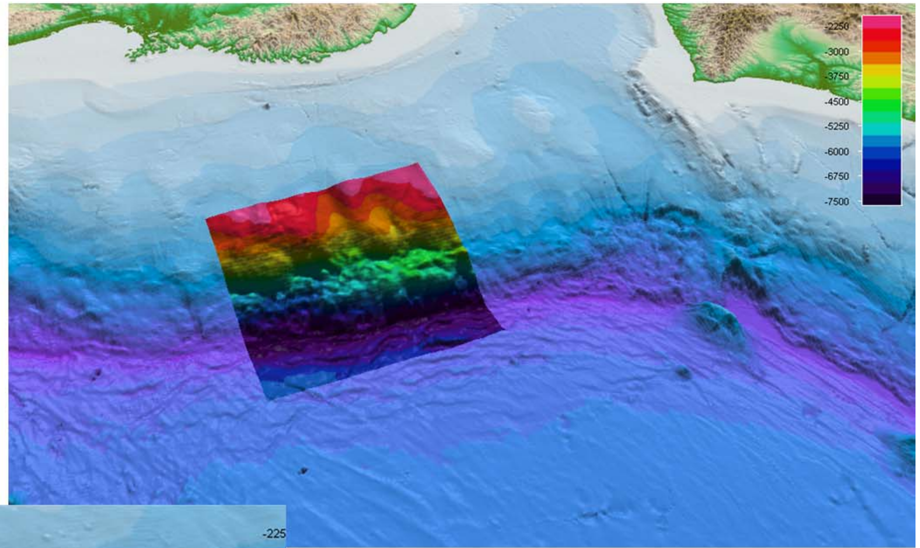
Submarine landslide source

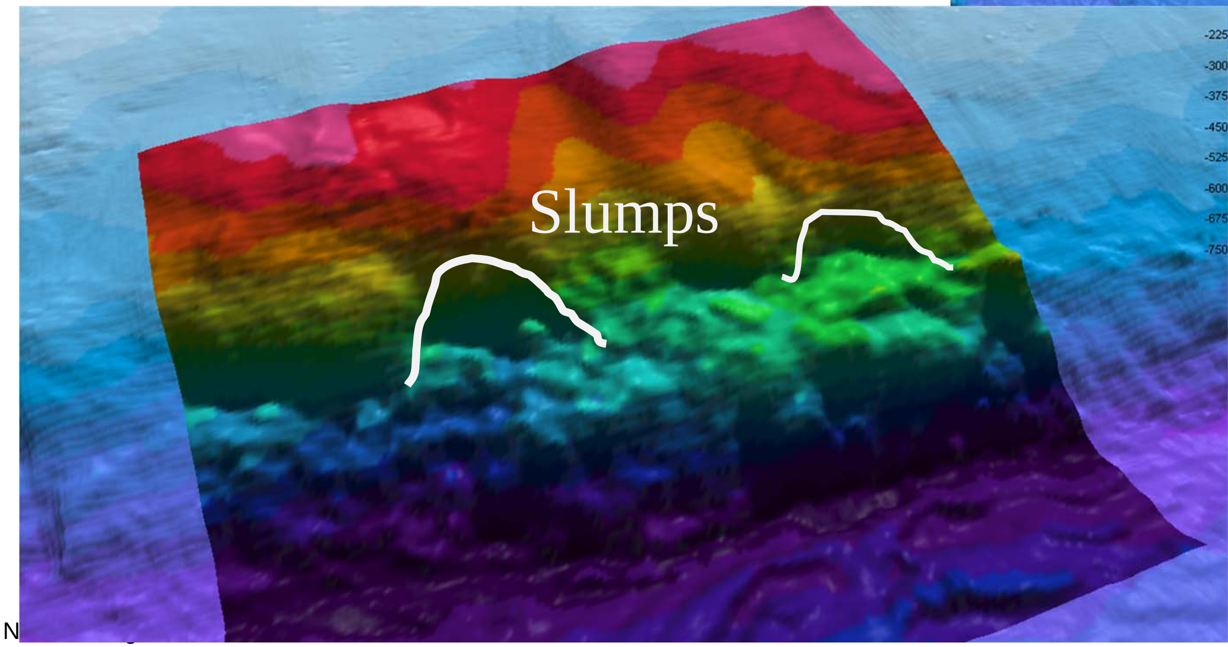


Several large SMFs (slumps) present

Bathymetry: pre-2011

500m grid
(JODC)





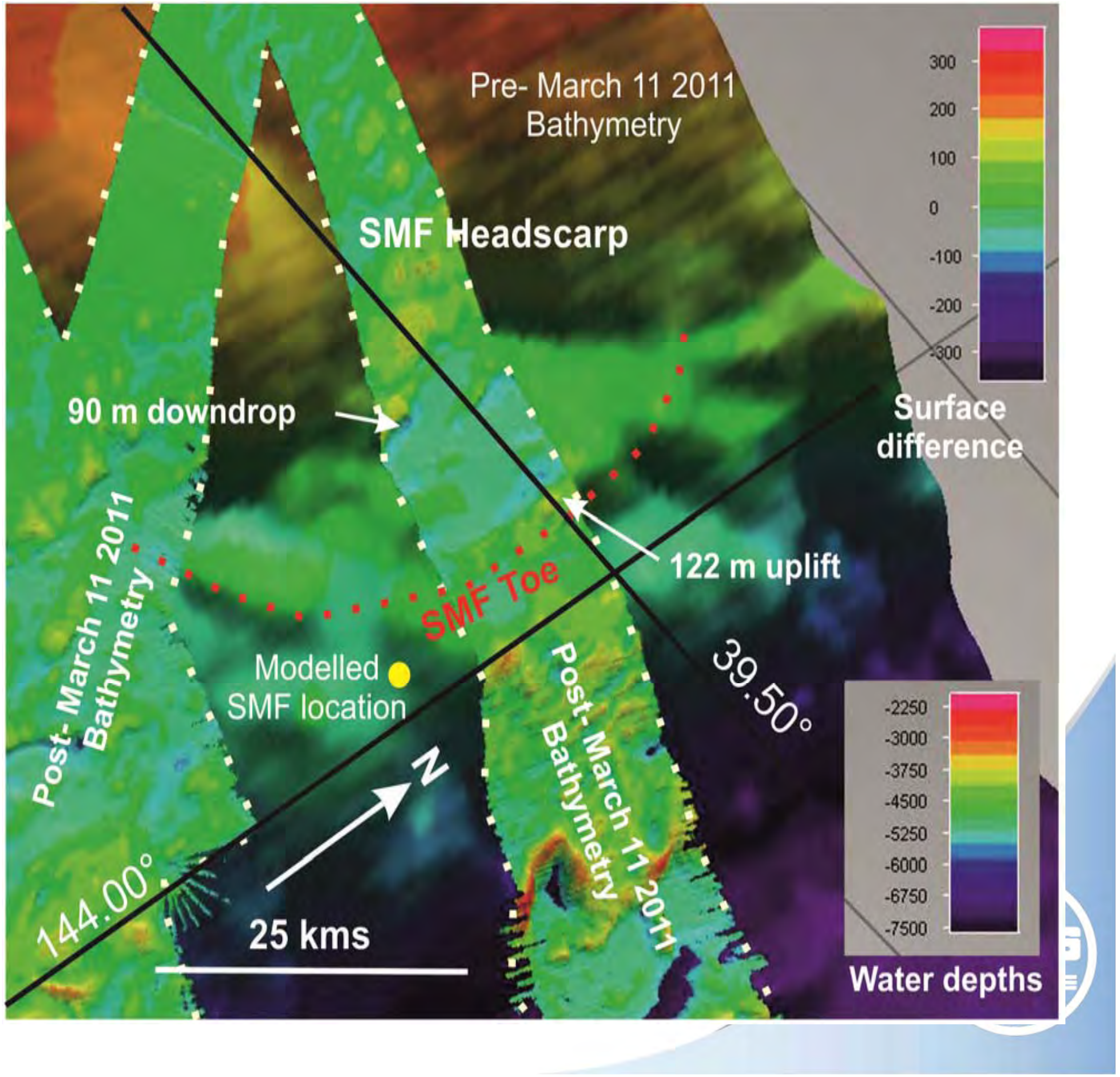
Bathymetry of seafloor failures

Direct observations of SMF ?

Difference [multibeam echosounder swath data, acquired during the R/V YOKOSUKA cruise YK11-E06] shows SMF/slump with average -100, +100 m displacement

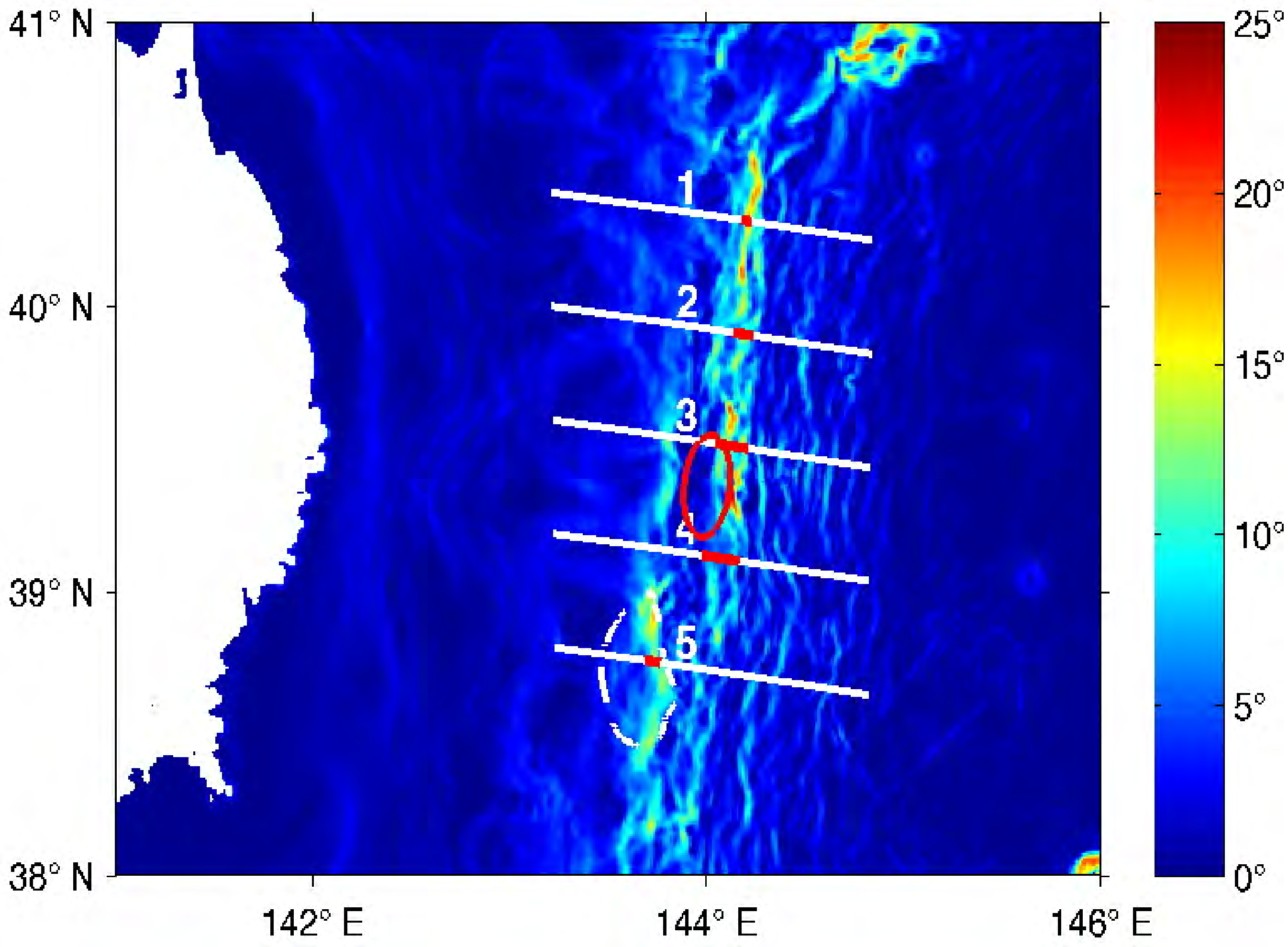
(Data JODC, JAMSTEC)

Pre and post tsunami bathymetry



Slope stability analysis along Sanriku coast

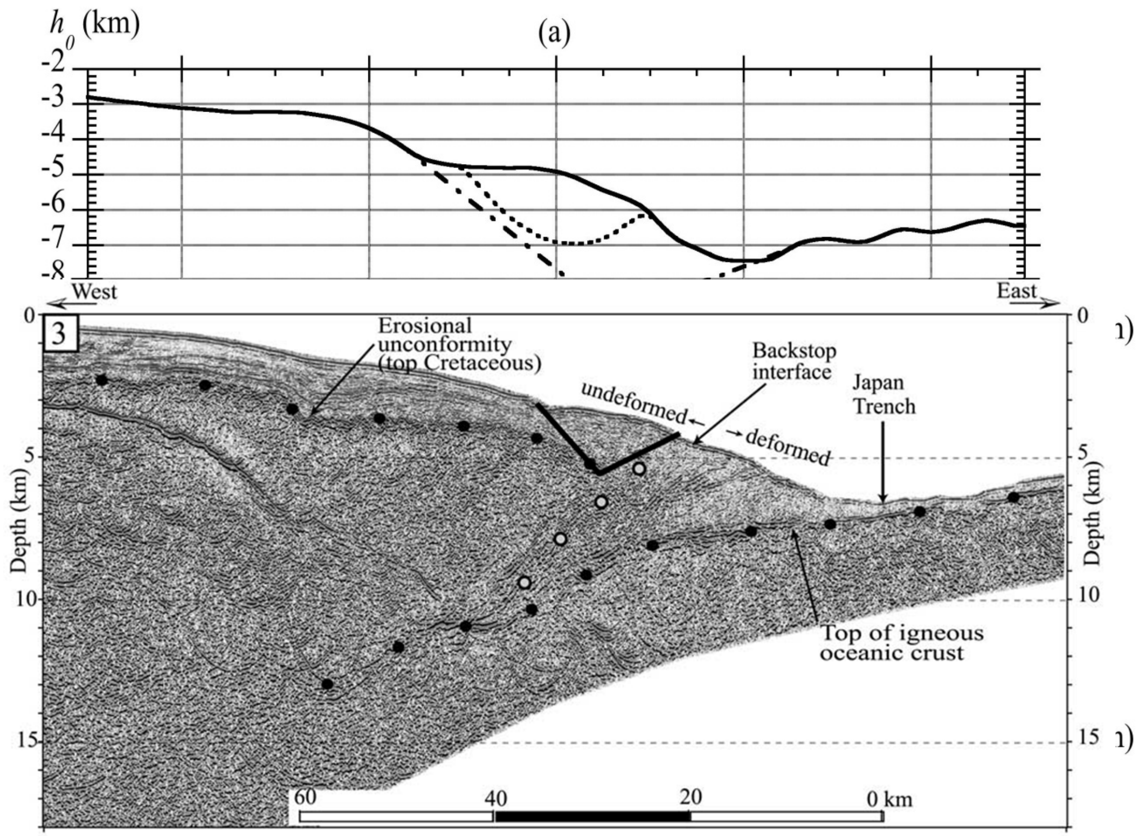
Five bathymetric transects studied, based on seafloor slope and morphology:



[Bottom slope (color) and Transects]

Slope stability analysis along Sanriku coast

- Dashed line: assumed SMF failure plane.
- Chain lines: approximate headwall and subducting plate angles



<u>Transect through SMF</u>

w = 38 km; b = 20 km

T = 2 km; s_0 = 300 m

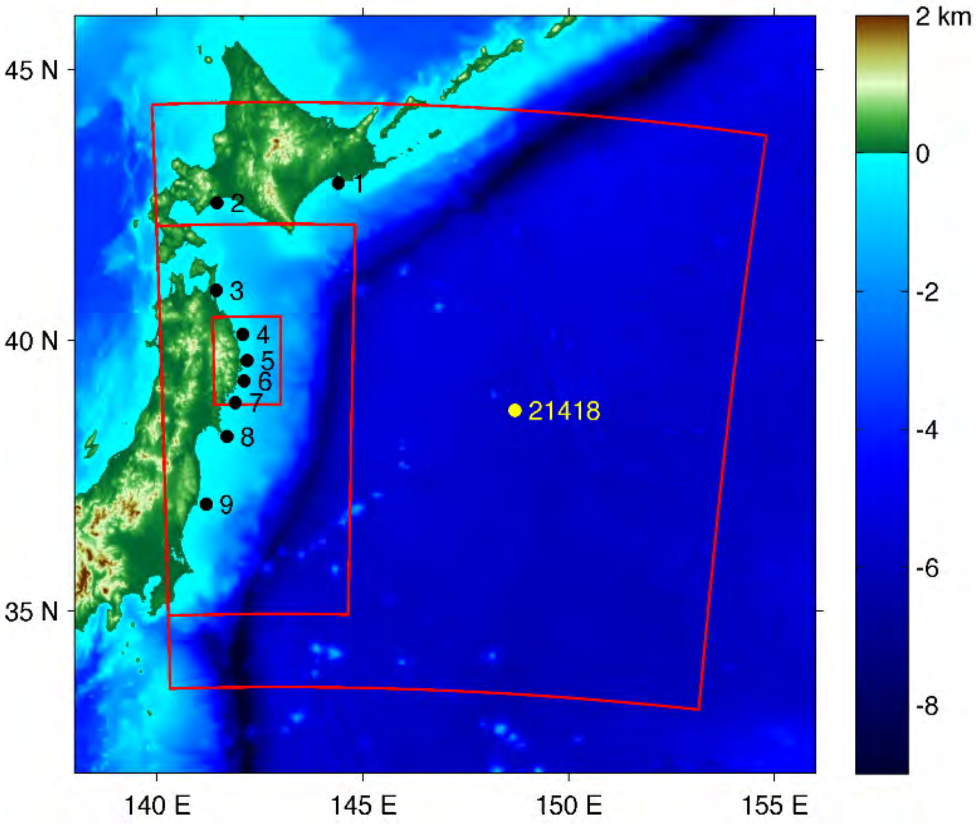
Triggered after 135 s

<u>Rupture mechanism</u>:

Slump motion

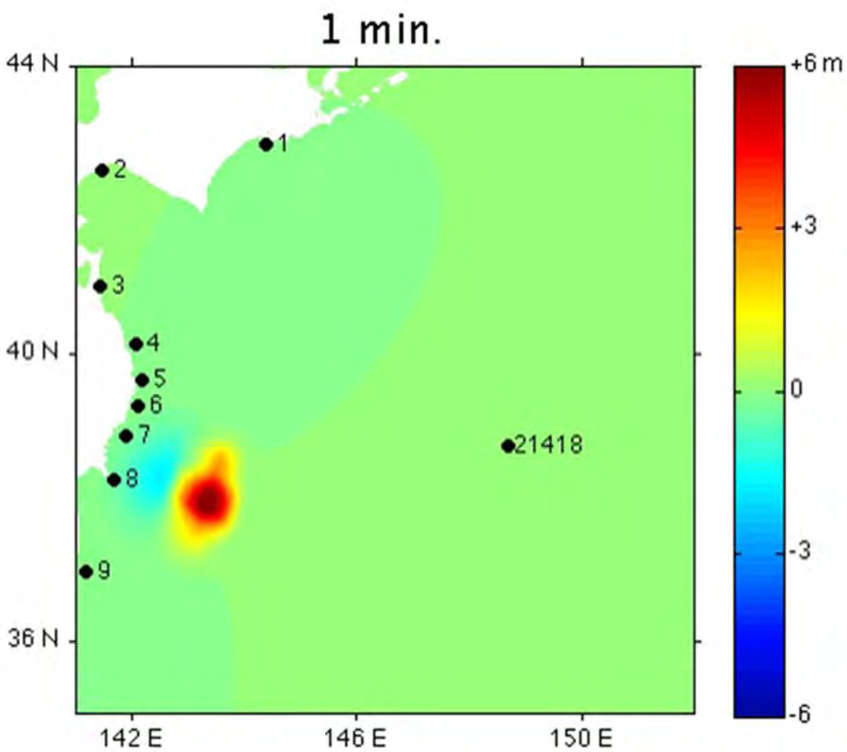
constrained by period and amplitude of observed high frequency waves

=> NHWAVE (300 s) & FUNWAVE Simulation of FEM co-seismic source + SMF (best location)



Nested Grids

Near field: 50m, 250m, 1000m; and Ocean (2’) tsunami grids



Response at GPS and DART buoys

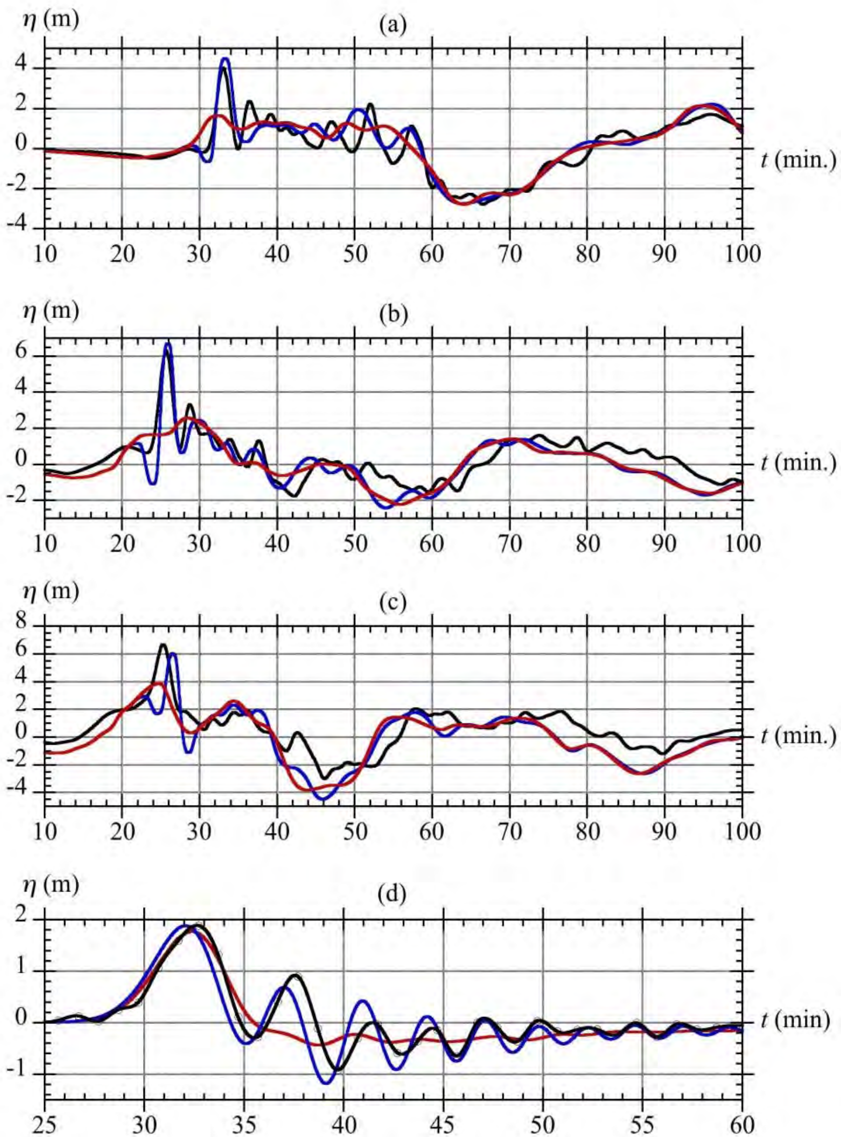
[black (measured); red (FEM – coseismic), blue (FEM + slump)]

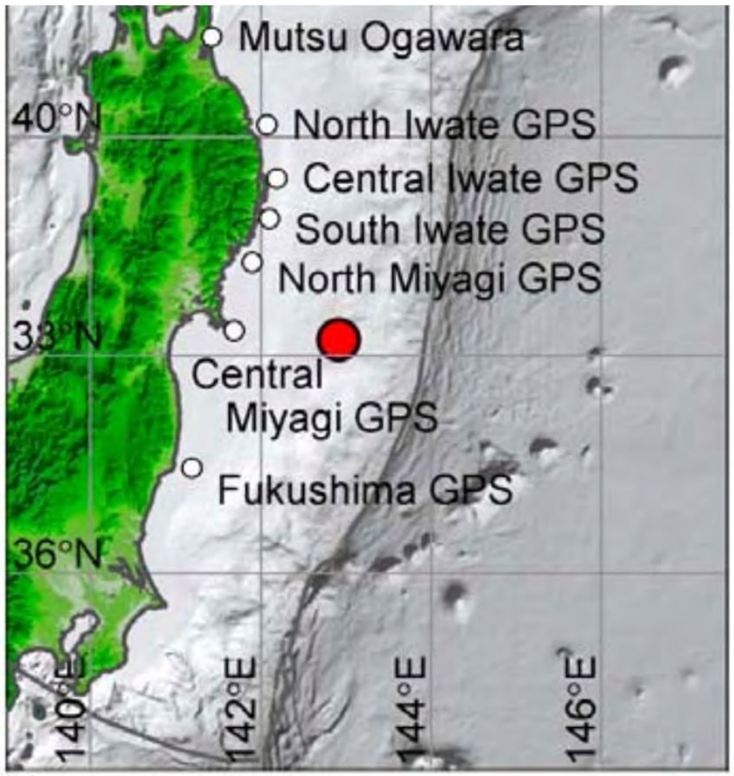
North Iwate

Central Iwate

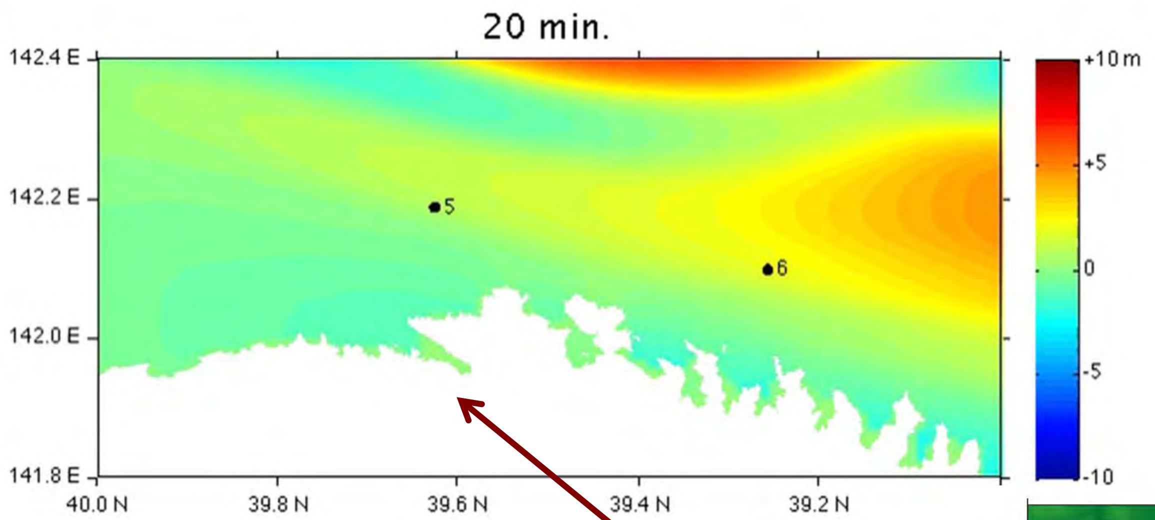
South Iwate

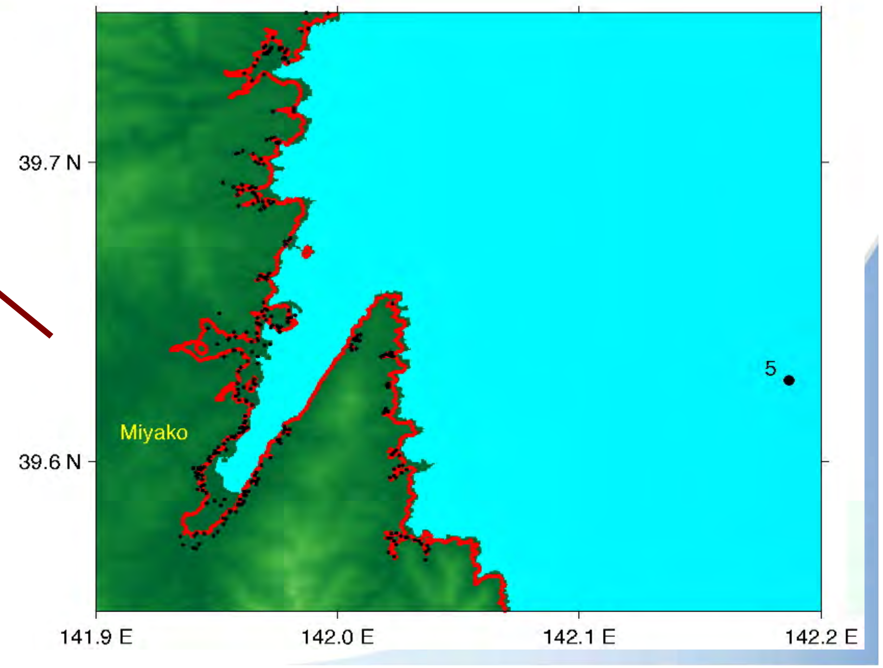
DART #2141ξ





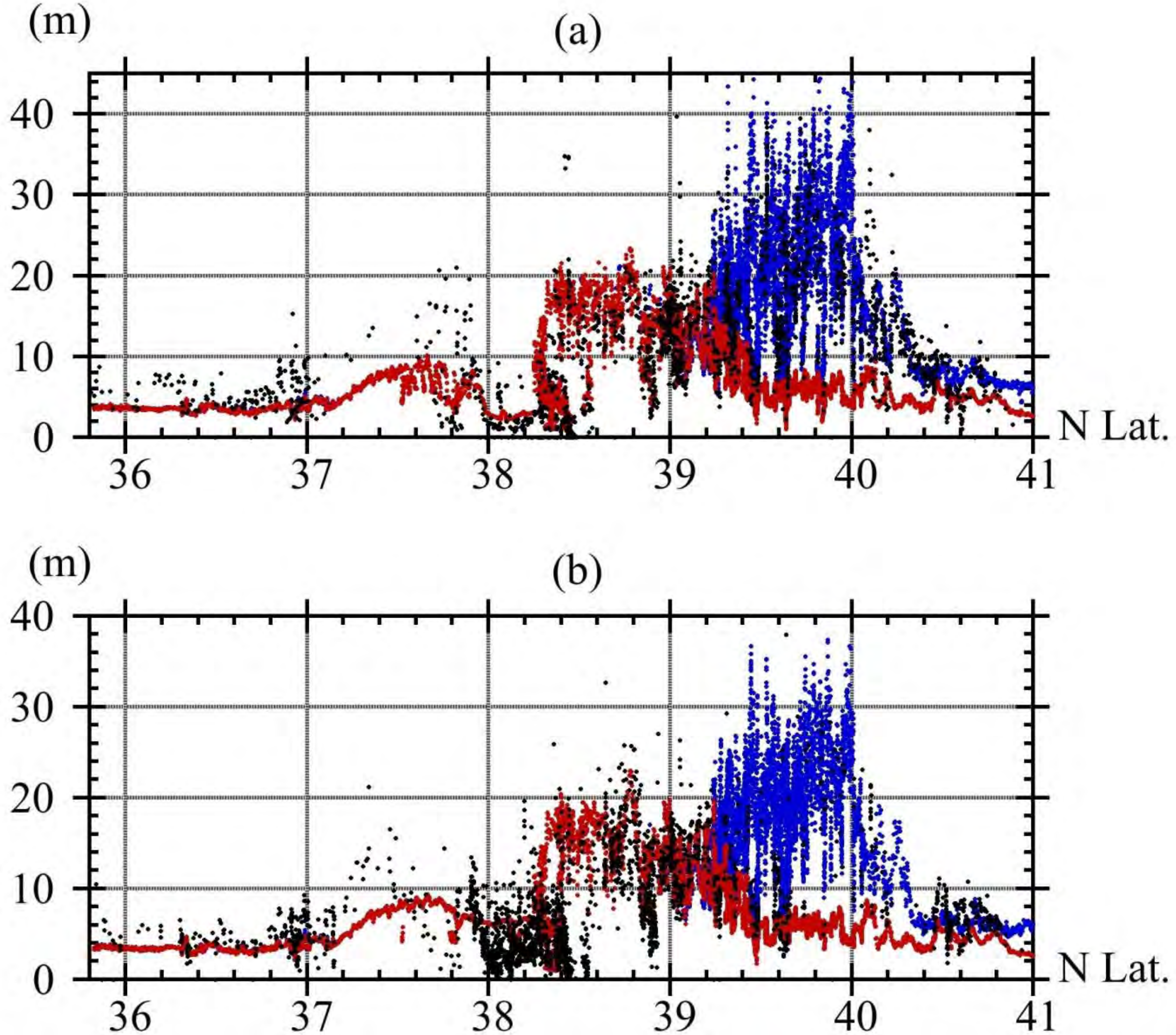
Coastal impact along Sanriku coast





Partial plot of modeled (red) and measured (black) horizontal inundation limits near Miyako.

Coastal impact along Sanriku coast



a) Inundation and

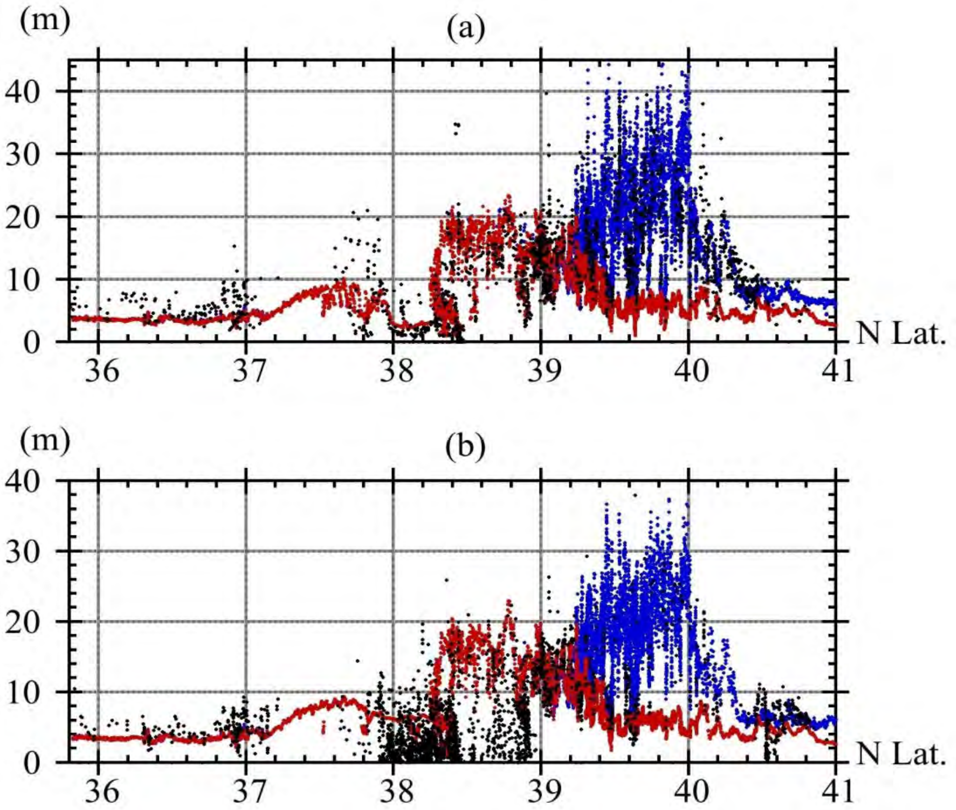
b) runup

along Japanese coast.

Measured (black), FEM (red), FEM + slump (blue)

Tohoku Tsunami source – EQ and SMF combined

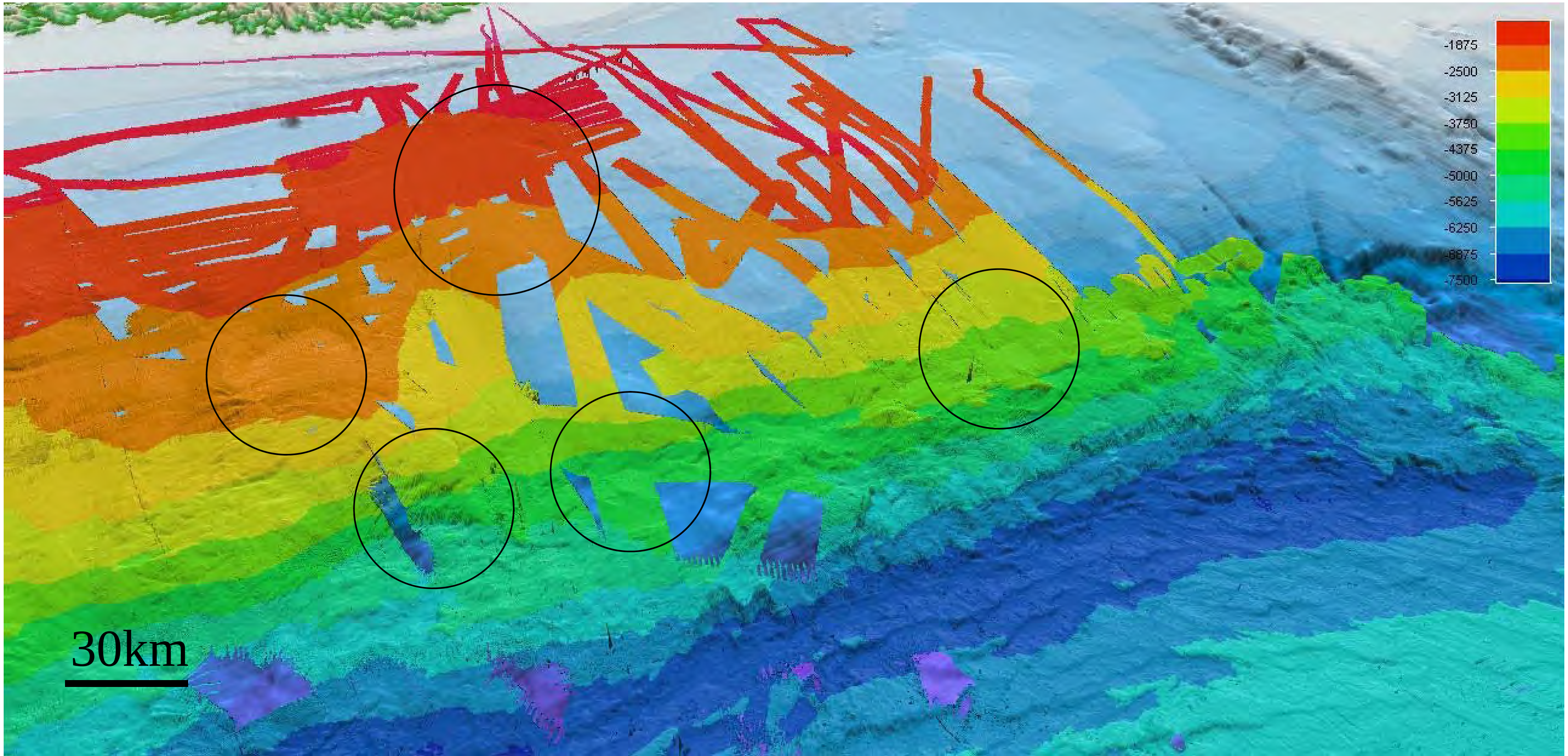
- Tsunami simulations from a solely earthquake source cannot explain the 40 m runups in northern Honshu, the Sanriku coast,
- Explained by focussing along the ria coast – NO!
- An additional (SMF) source is required



Differentiating earthquake tsunamis from other sources; how do we tell the difference?

- With the Japan 2011 tsunami, numerous models based on different data-sets, but still a problem with high runups along the Sanriku coast,
- A dual source (EQ and SMF) is one model, and may well be the most likely,
- Notwithstanding, the possible dual source should warn that with large (Great?) earthquakes the EQ may not be the only tsunami source,
- Previous examples – Aleutians, 1946, possibly Java 2006 could have an SMF component (although these are not Great EQs),
- When using tsunami wave form inversion – OK for EQ rupture, but where there are major differences to other data sets - seismic/geodetic inversion may indicate additional source mechanism,
- Seabed topography/bathymetry (MBES) essential, but pre- and post data rare,
- Need more bathymetry, still few convergent margins are mapped in detail,

Overview northern Honshu



Pre-2011 bathymetry - numerous SMFs