Using Persistent Rupture Asperities in Northern Japan to Infer Megathrust Frictional Properties

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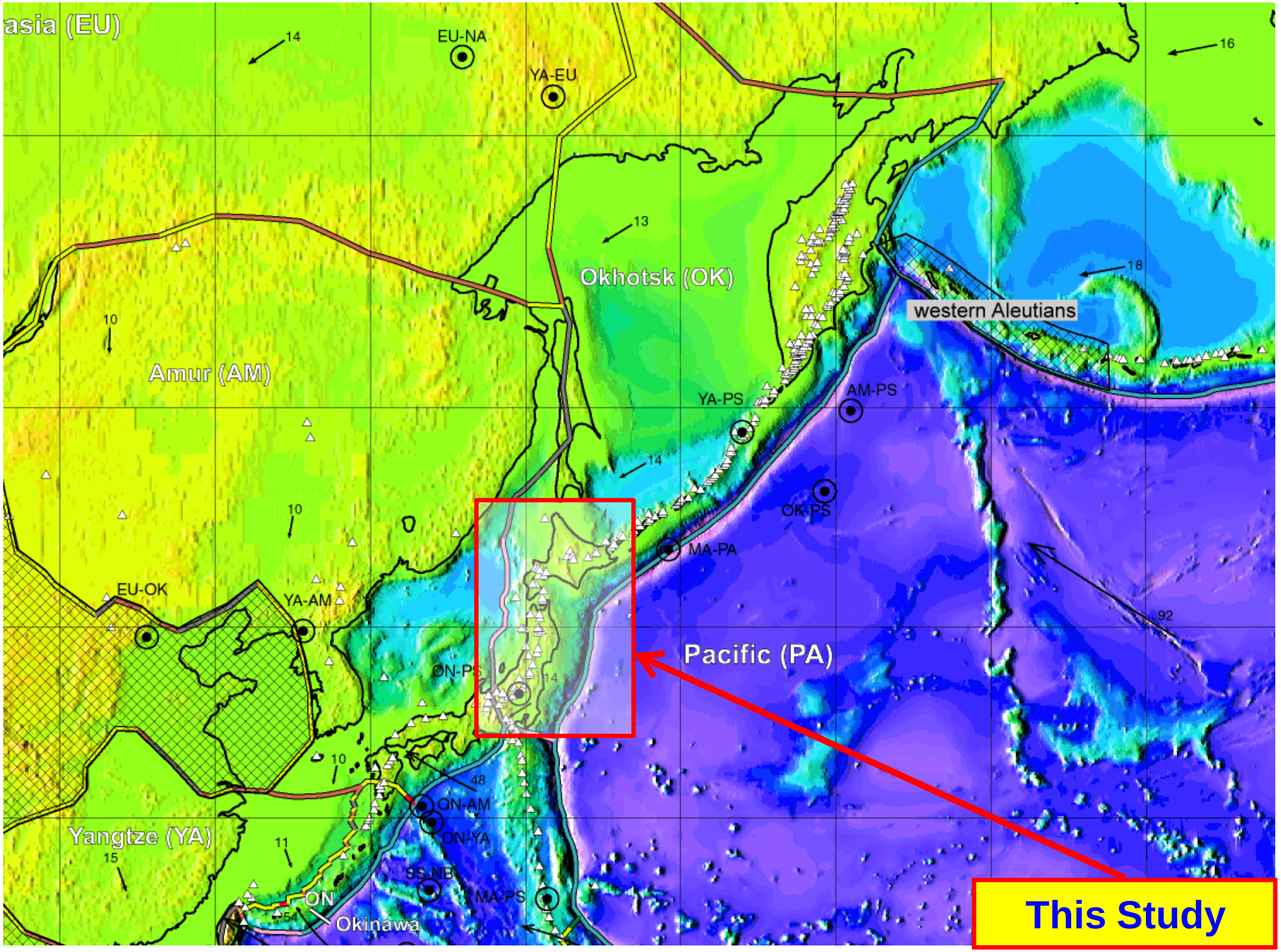
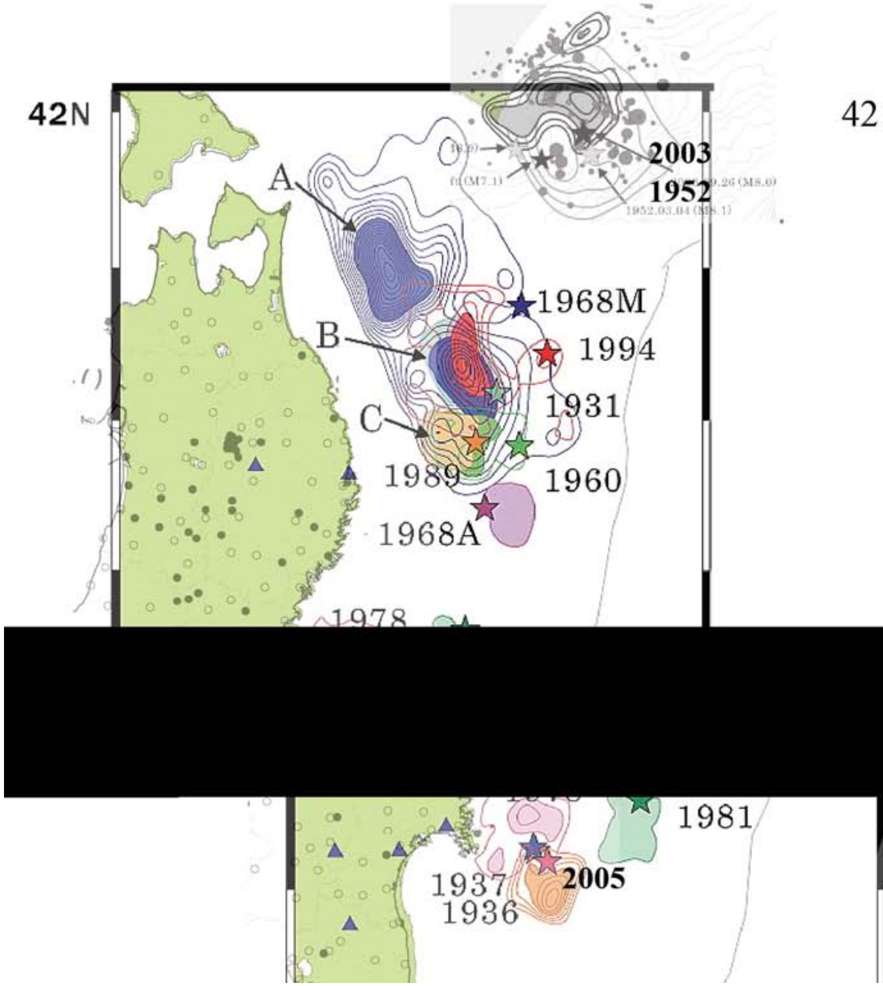
Plate Boundaries Around Japan



Peter Bird, 2003

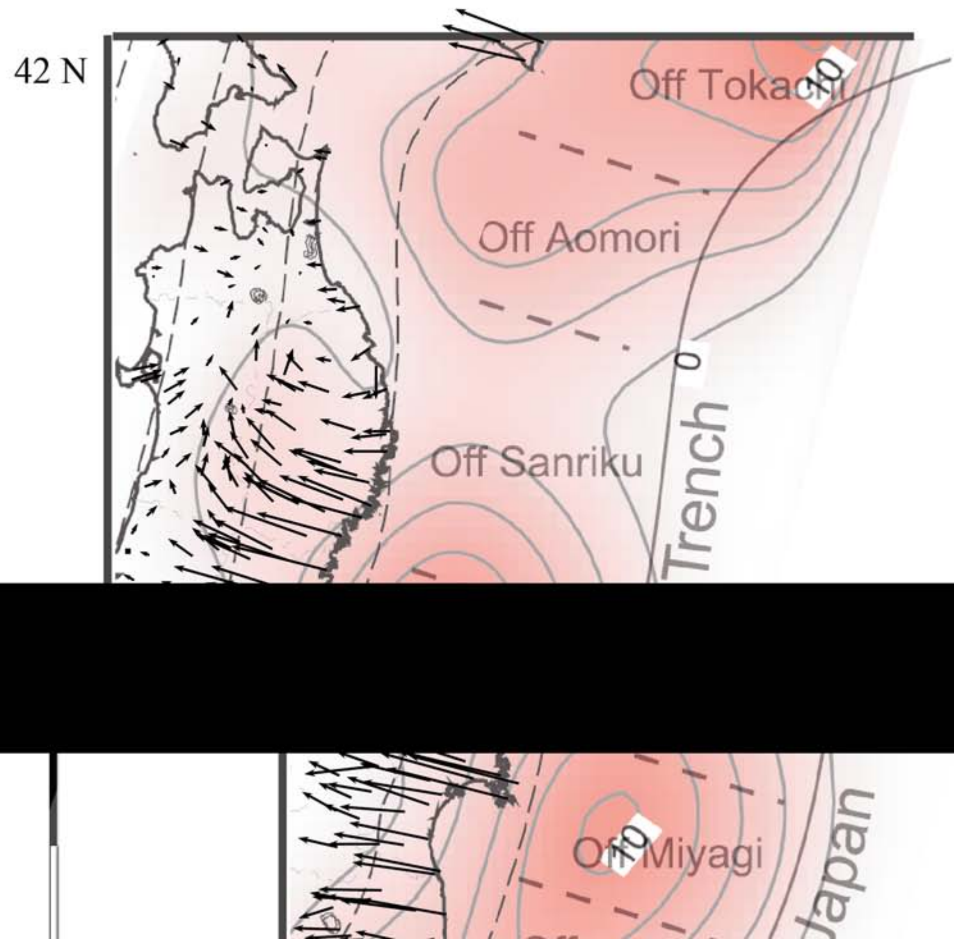
Coseismic Slip (pre-2011) vs. Interseismic Slip Deficits

Seismic Source Estimates



Adapted from Yamanaka & Kikuchi, 2003, 2004

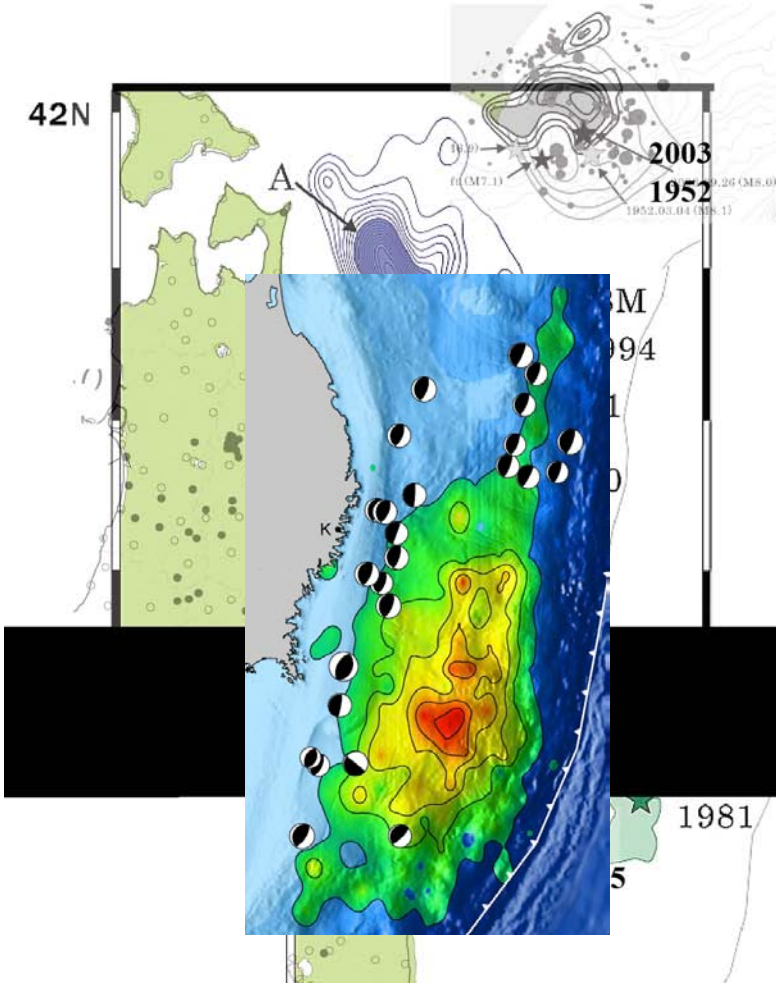
Interseismic Slip Deficit Estimates



Adapted from Suwa, 2006

Coseismic Slip (NOW) vs. Interseismic Slip Deficits

Seismic Source Estimates



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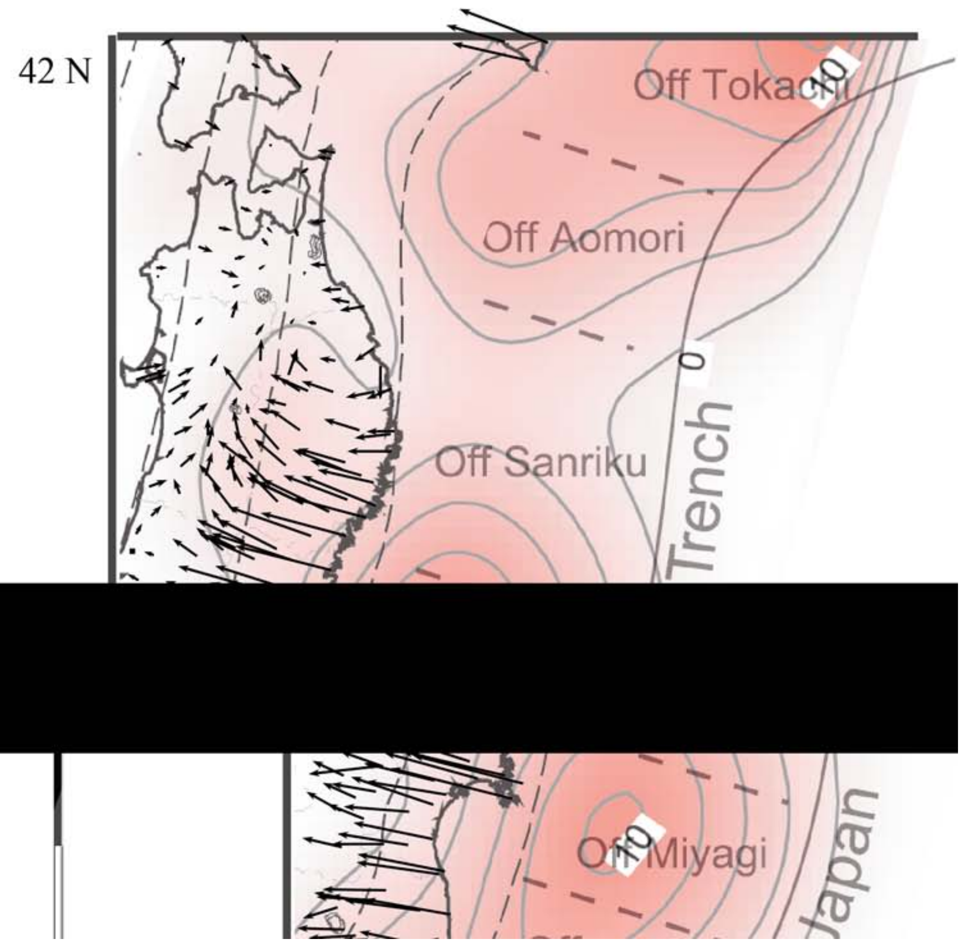
2011 M9 Miyagi-oki COSEISMIC SLIP

(Simons et al, Science, 2011)

Interseismic Slip Deficit Estimates



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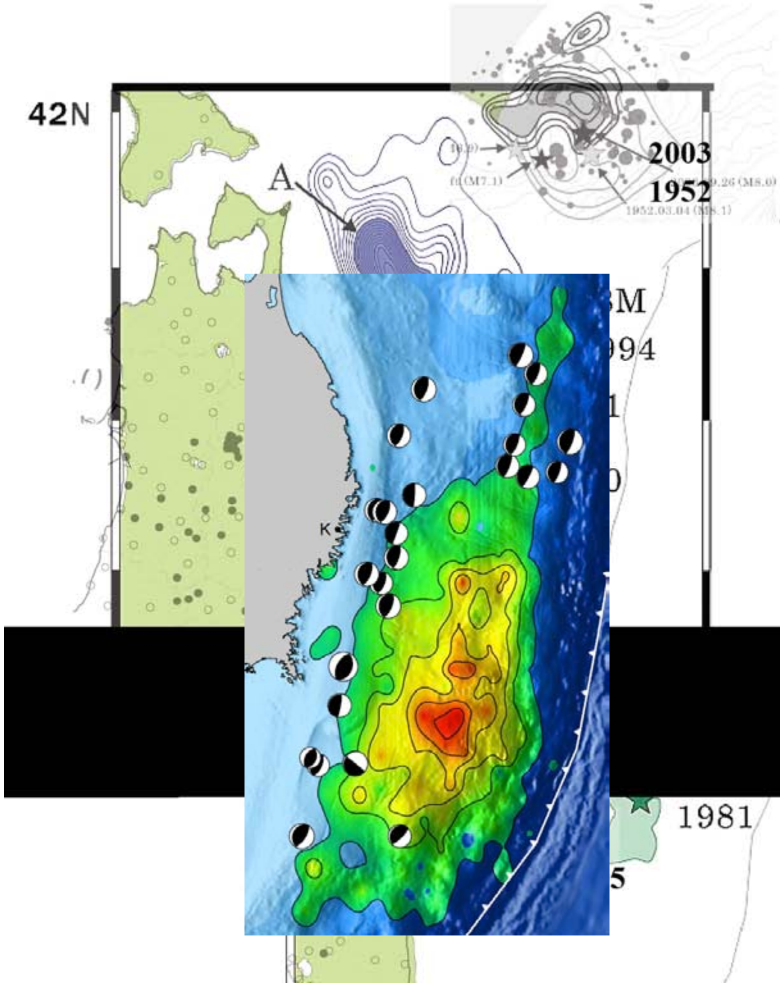
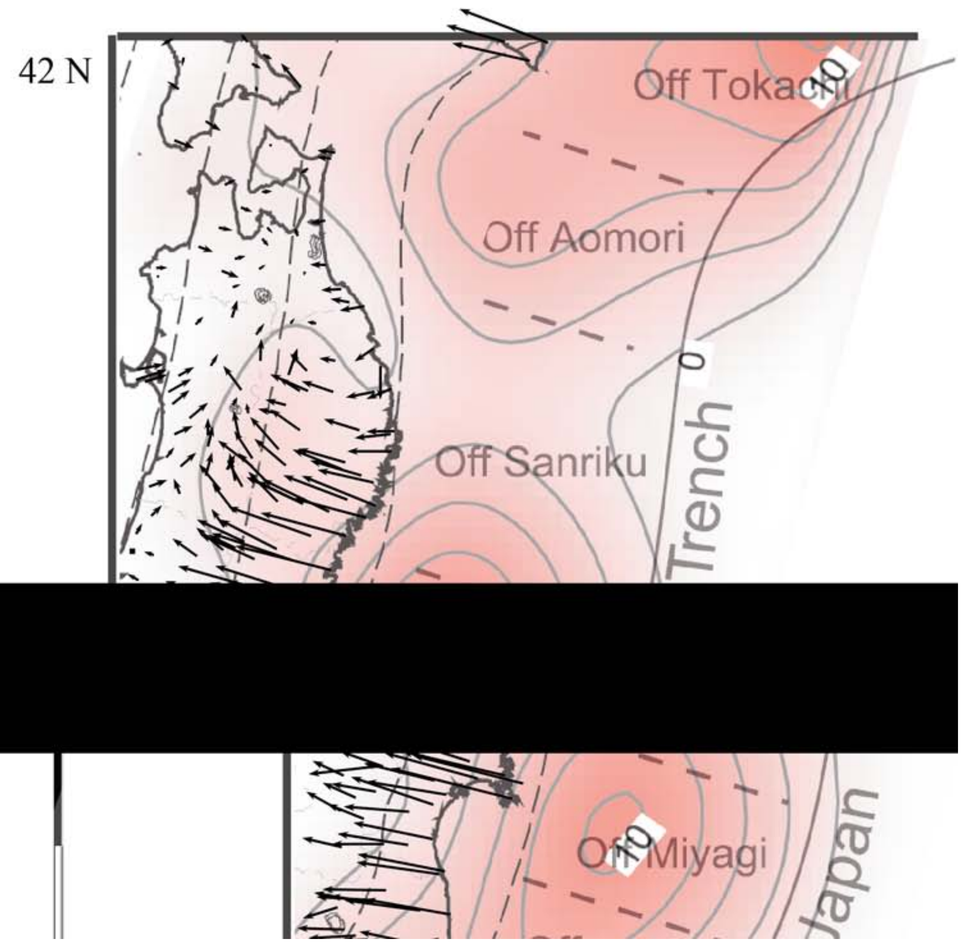
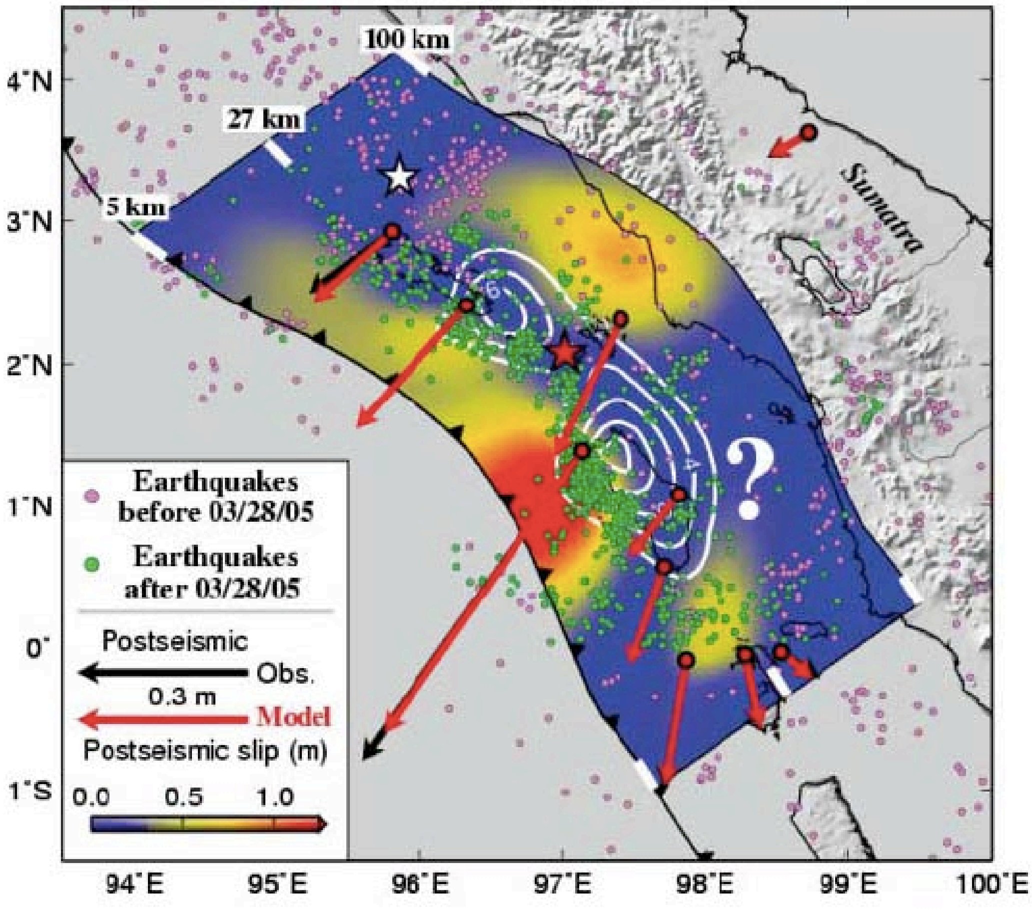


Interseismic Slip Deficit Estimates



Predicted potential seismic hazard may be very different

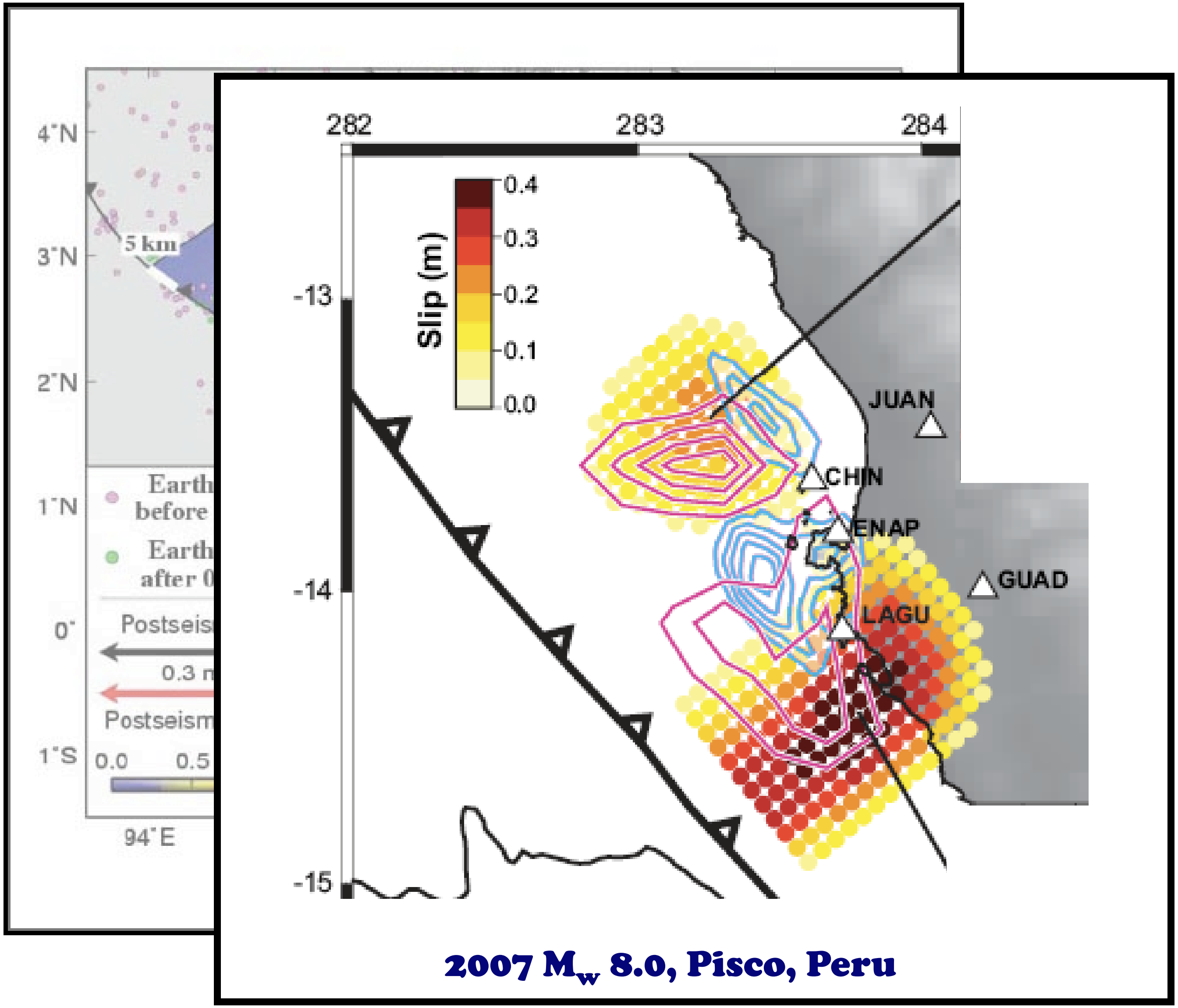
Characteristics of Coseismic and Postseismic slip



2005 M_w 8.7, Nias, Sumatra

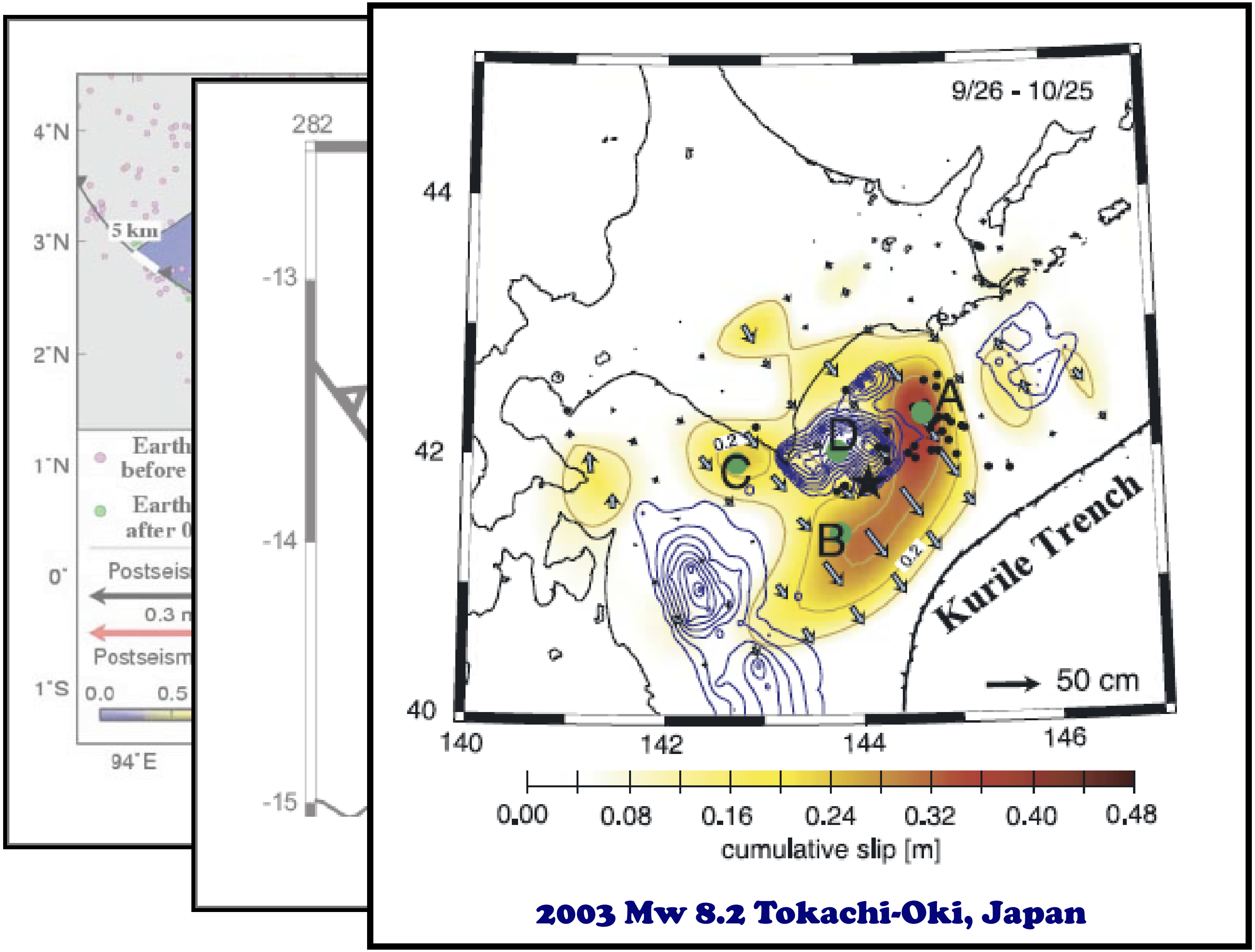
Hsu et al., 2006

Characteristics of Coseismic and Postseismic slip



Perfettini et al, 2010

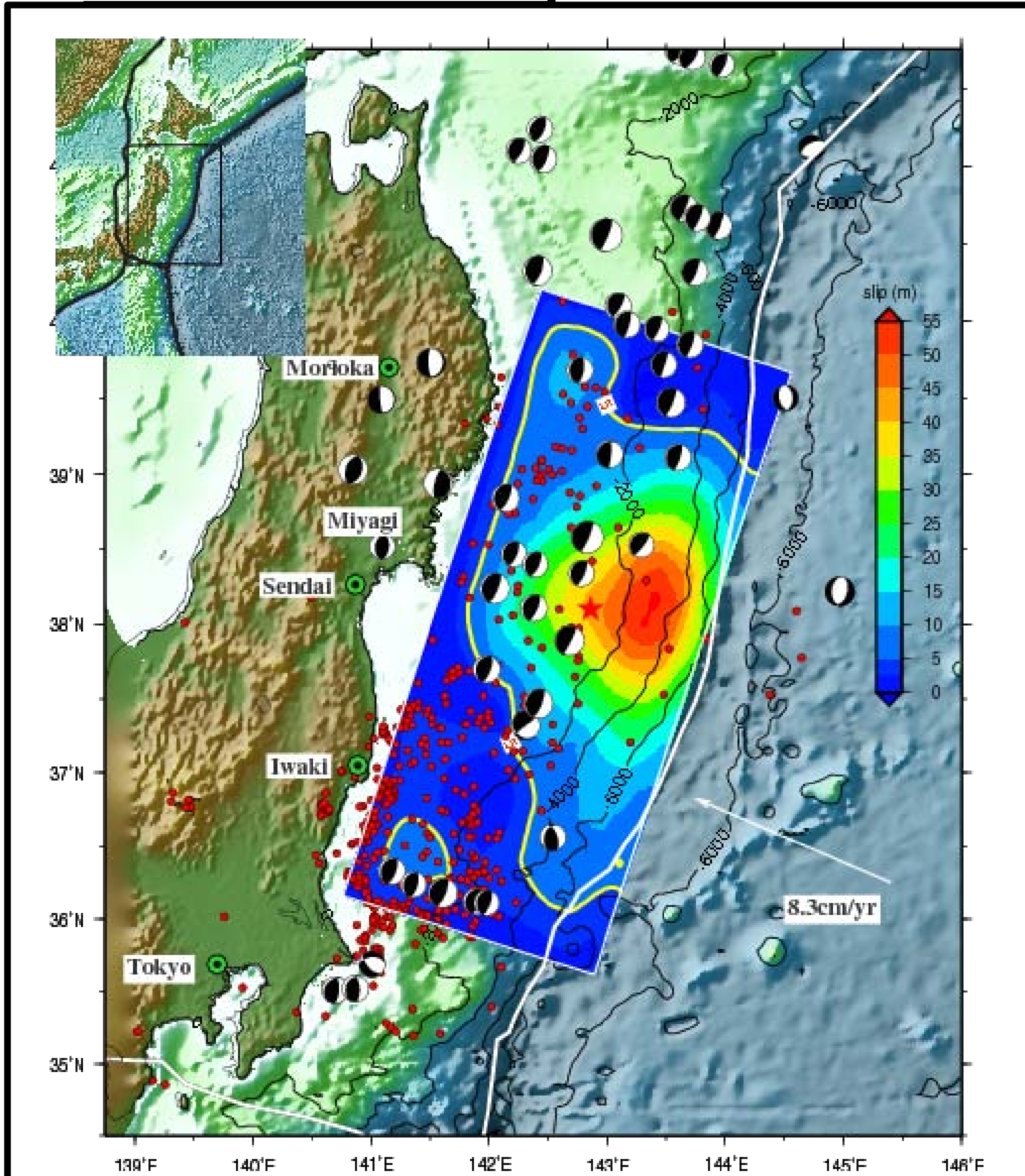
Characteristics of Coseismic and Postseismic slip

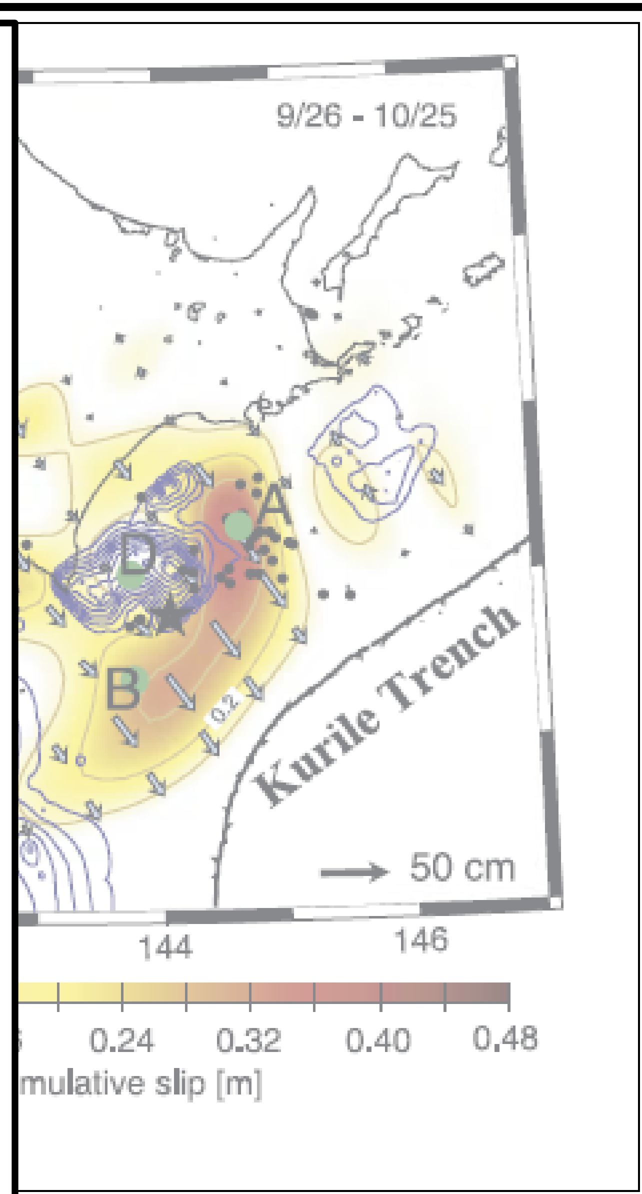


2003 Mw 8.2 Tokachi-Oki, Japan

Miyazaki et al, 2004

Characteristics of Coseismic and Postseismic slip





2009 Mw 9.0 Miyagi-Oki, Japan Seismic Source Model courtesy, Chen Ji, UCSB

Hypothesis Test

A. Is mechanical coupling on inferred megathrust asperities alone sufficient to explain available geodetic observations (1996-2000) in northern Japan?

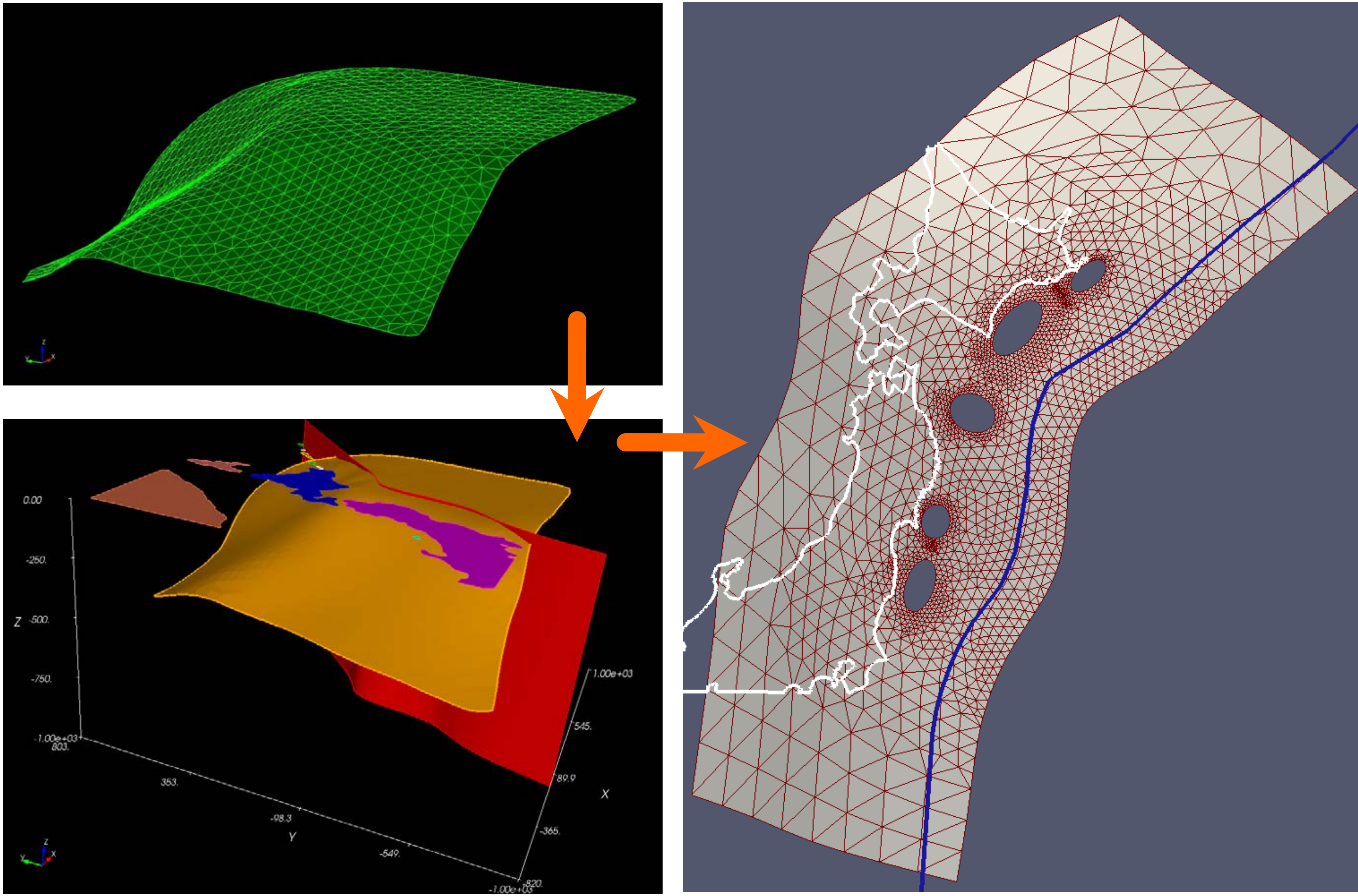
B. If so, what is the long-term frictional properties of the fault surface?

C. If not, what additional areas of the megathrust do these data require to be coupled?

TEST 2 SCENARIOS, pre-2011 & NOW, ASSUMING:

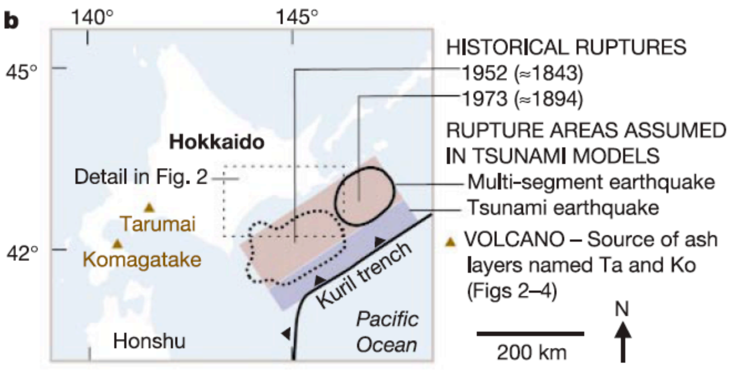
- **Known asperities persist across multiple earthquake cycles**
- **Kinematically driven system: dynamic asperity-asperity interactions are ignored**
- **Deformation is localized entirely on the megathrust**, e.g.:
  - Ignore incipient subduction along Japan Sea
  - Ignore bulk mantle/crustal relaxation processes

Megathrust Interface Discretization: II

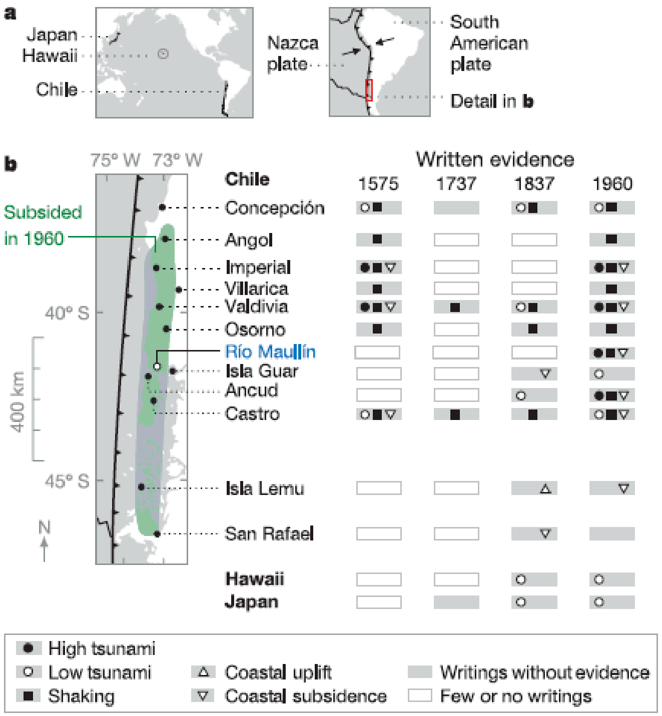


Massive Tsunami-genic Asperities on the Megathrust

- 2011 M9 Miyagi-Oki (Sendai) earthquake occurred updip of the smaller 1978 & 2005 asperities
- Similar observations from tsunami deposits off Hokkaido
- When did the M9 Sendai mega-asperity last rupture?

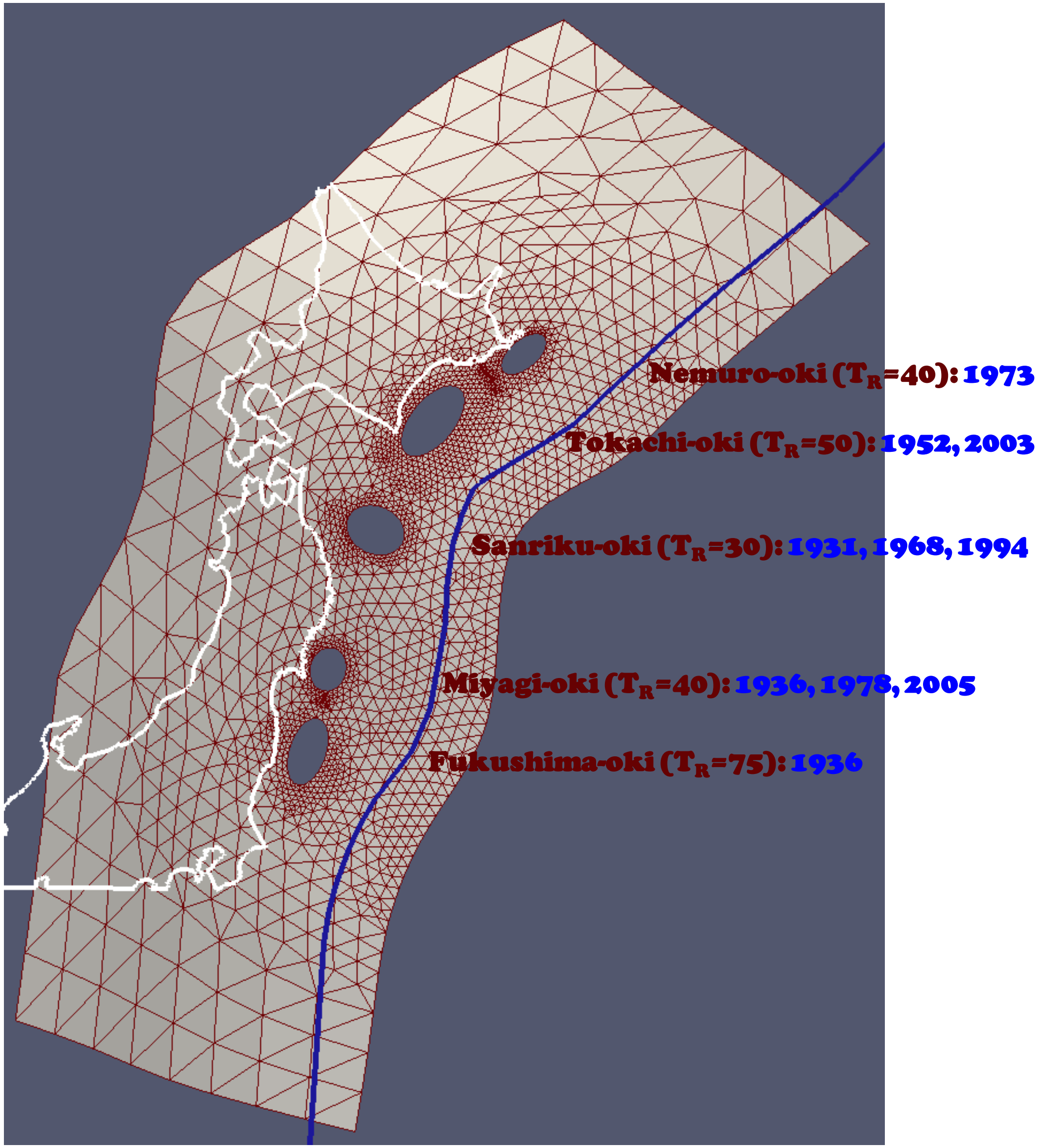


Nanayama et al., 2003



Cisternas et al., 2005

Rupture Catalog for Characteristic Asperities



Methodology

i. Honor Seismic Moment $M_w = \mu S A = \mu V_p T_r A$

ii. Trade-off between rupture interval and asperity size

iii. Honor last rupture on each asperity

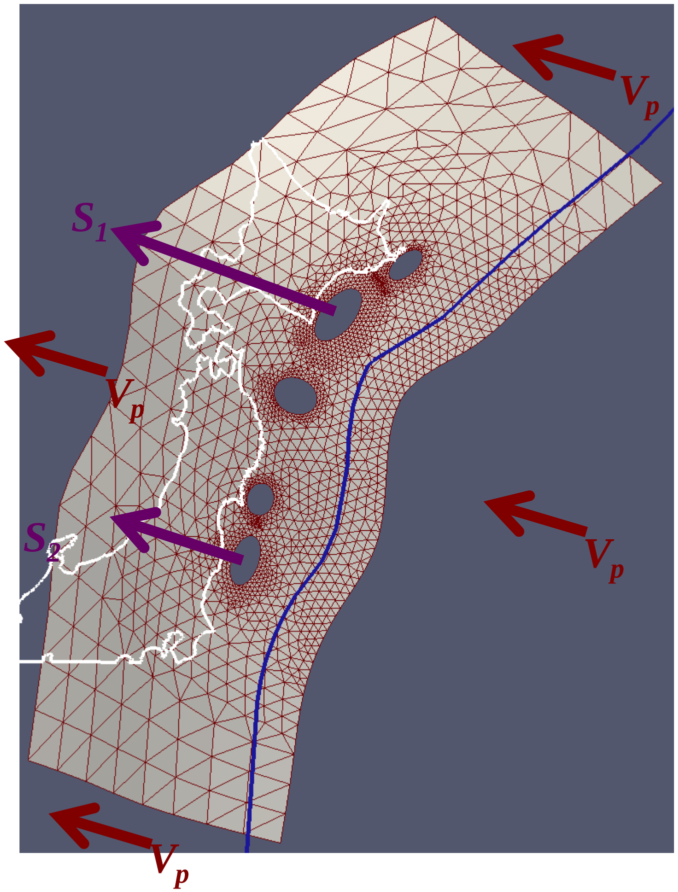
iv. Round to nearest 5-yrs

v. Stress drops ~ 5-10 MPa (high, but below max observed)

vi. Characteristic earthquake sequence catalog, backwards from the present time

Simulation of Slip

Continuous External Loading (Backslip):
Plate Interface Creep at Local Plate Velocity, V_p



'Periodic' Characteristic Ruptures:
Coseismic slip with periodicity, T_i ($S_i = V_p T_i$)

Solve the quasi-static equilibrium equation (Rice, 1993):

$$\tau'_i = \underbrace{(s'_j - t' V'_j) K'_{ji}}_{\text{(Backslip)}} + \underbrace{\sum_a S_{ja} K'_{ji}}_{\text{(Ruptures)}}$$

Relation between slip-rate and stress determined by rheology (e.g., Dietrich-Ruina rate strengthening friction):

$$\dot{s}'_i = f(\tau'_i, \alpha'_i) = e^{(-\rho_i)} \sinh\left(\frac{\tau'_i}{\alpha'_i}\right)$$

Typically, $\alpha \approx 10^{-2}$–10^{-1}, $\rho \approx 1$-10

Surface Displacements

$$u'_k = \underbrace{(s'_j - t' V'_j) G'_{jk}}_{\text{(Backslip)}} + \underbrace{\sum_a S_{ja} G'_{jk}}_{\text{(Ruptures)}}$$

Simulation of Slip

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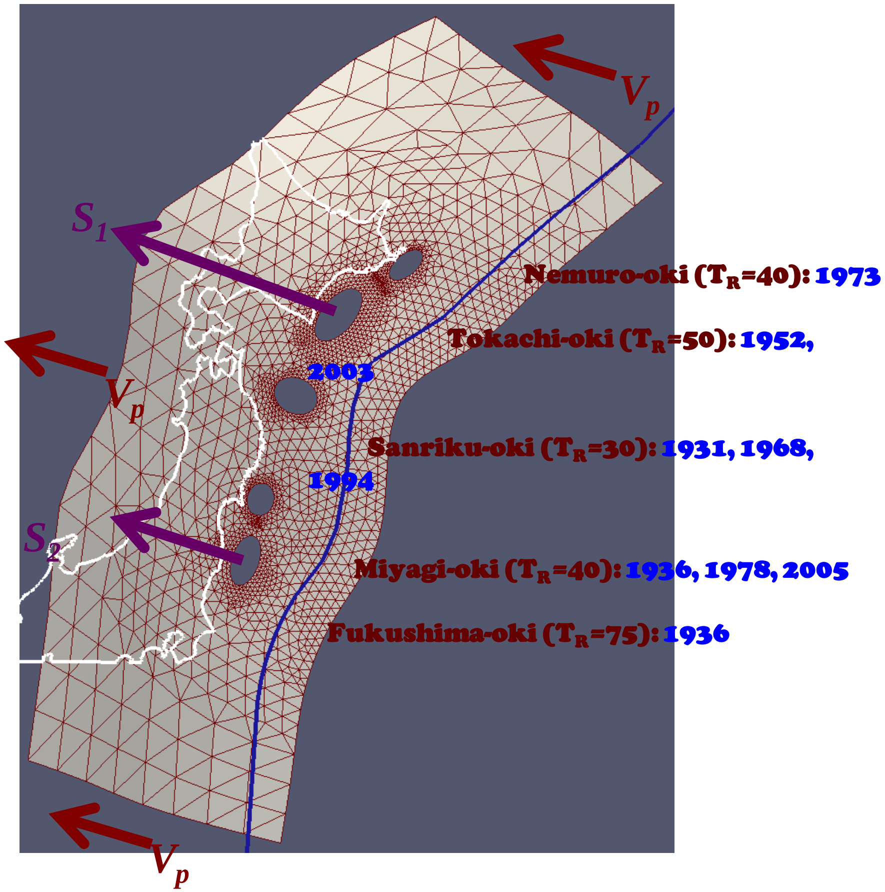
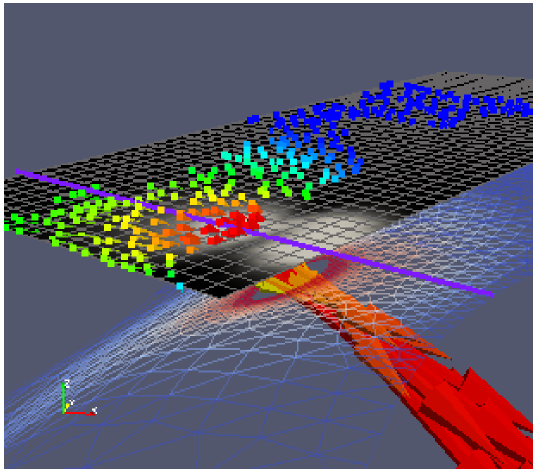
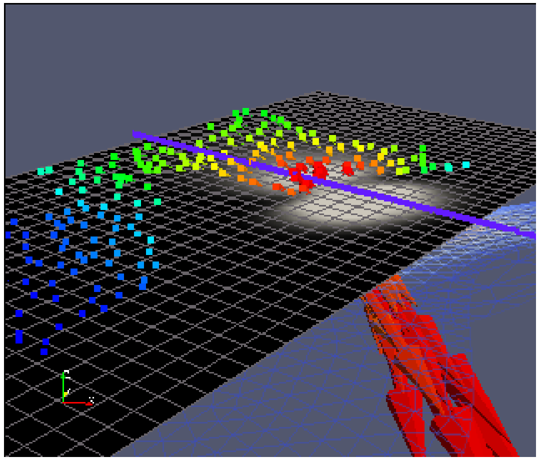
Plate Interface Creep at Local Plate Velocity, V_p



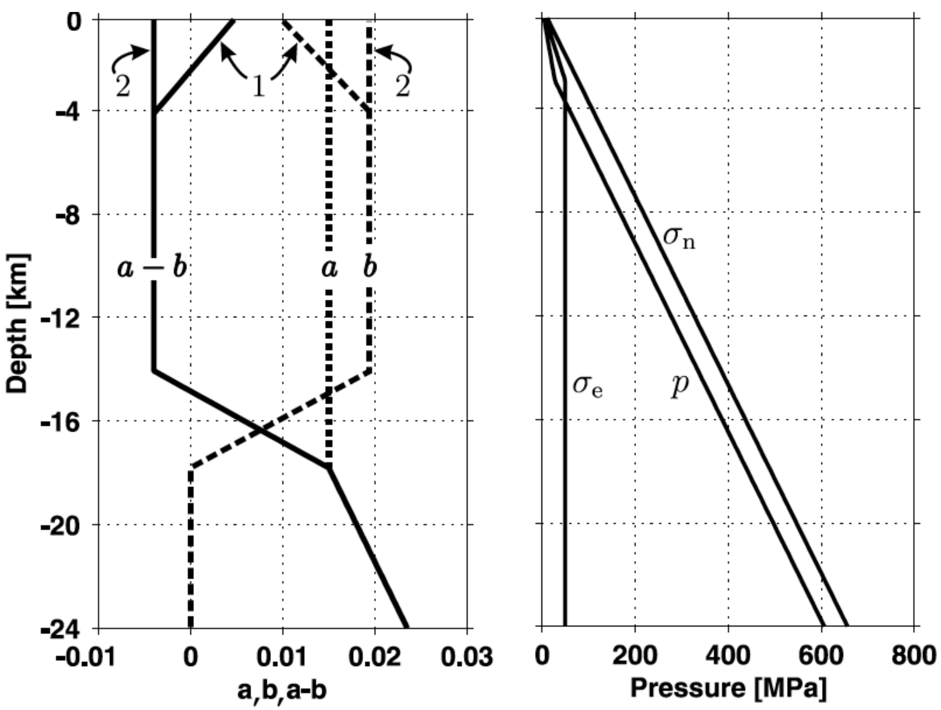




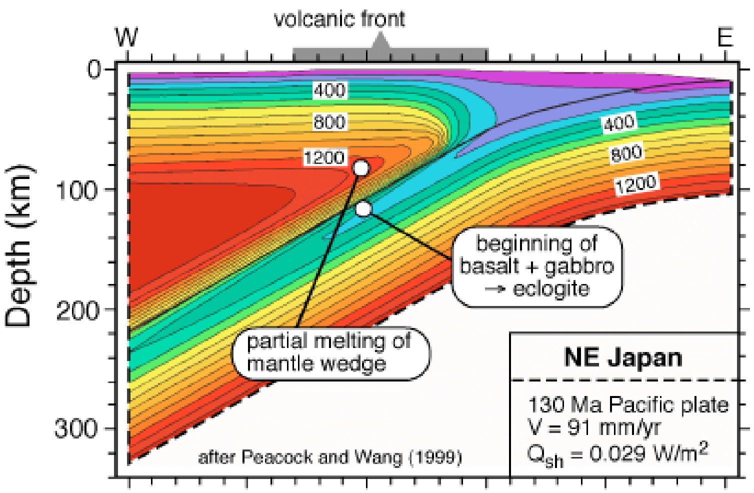
'Periodic' Characteristic Ruptures:
Coseismic slip with periodicity, T_i ($S_i = V_p T_i$)

Depth Dependent Rate Strengthening Friction

- **Interpolate temperature-dependent frictional parameters from Blanpied et al. 1991 over NE Japan thermal structure (e.g., Peacock & Wang, 2006)**



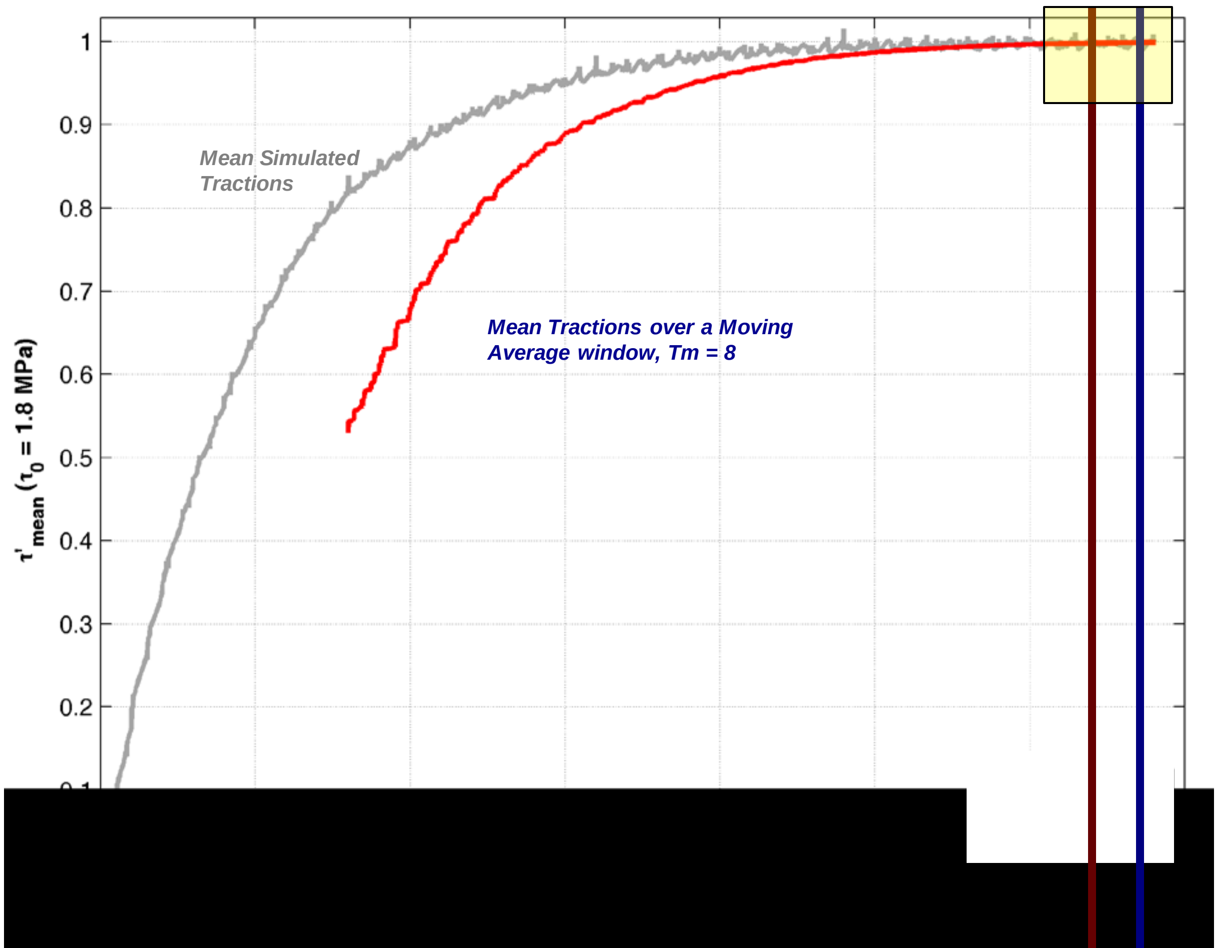
Hillers et al., 2006



Peacock & Wang, 1999

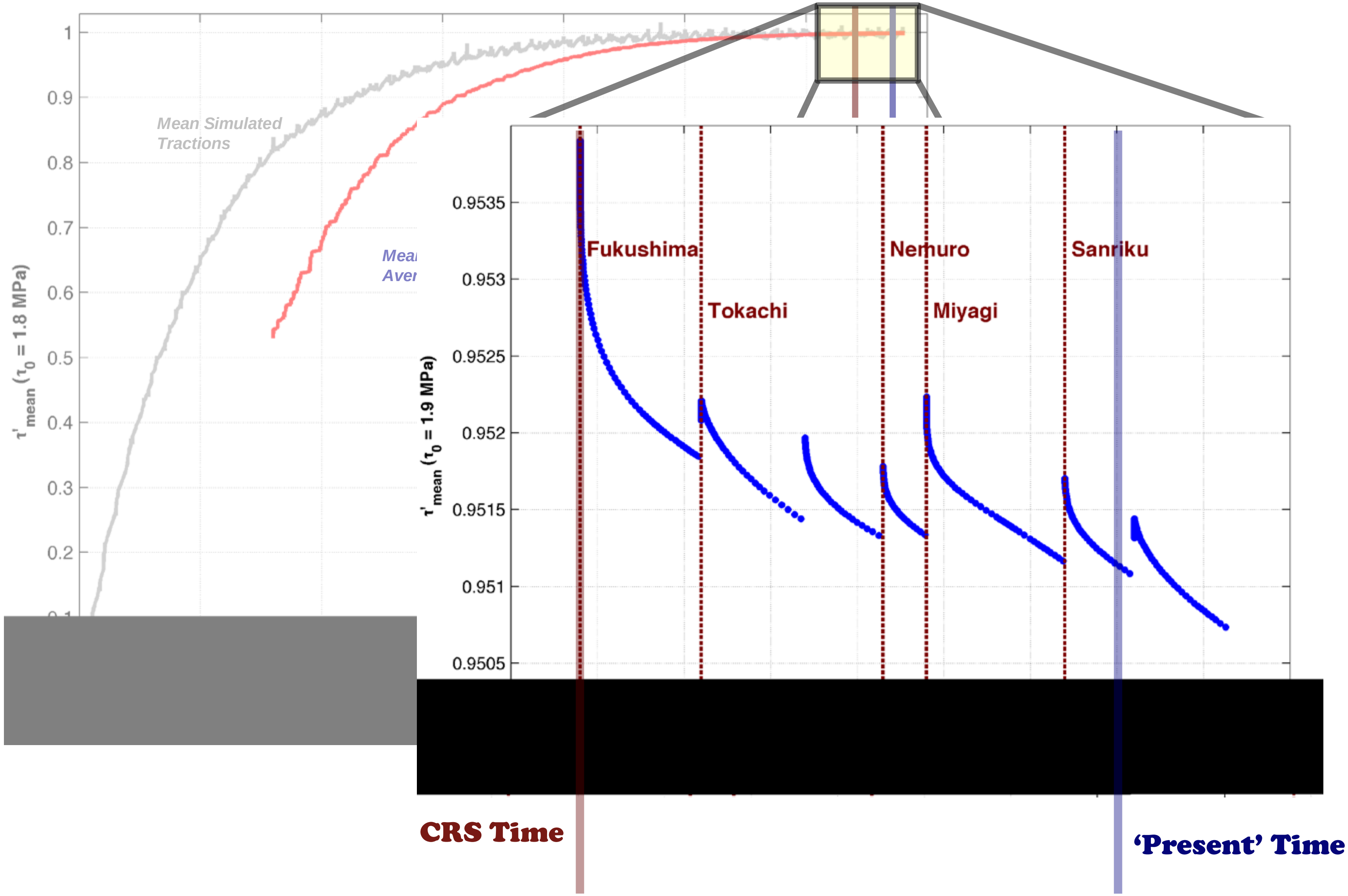
SPIN-UP OF MEAN TRACTIONS

Rate Strengthening Friction (RF): α'=0.1, ρ=10,



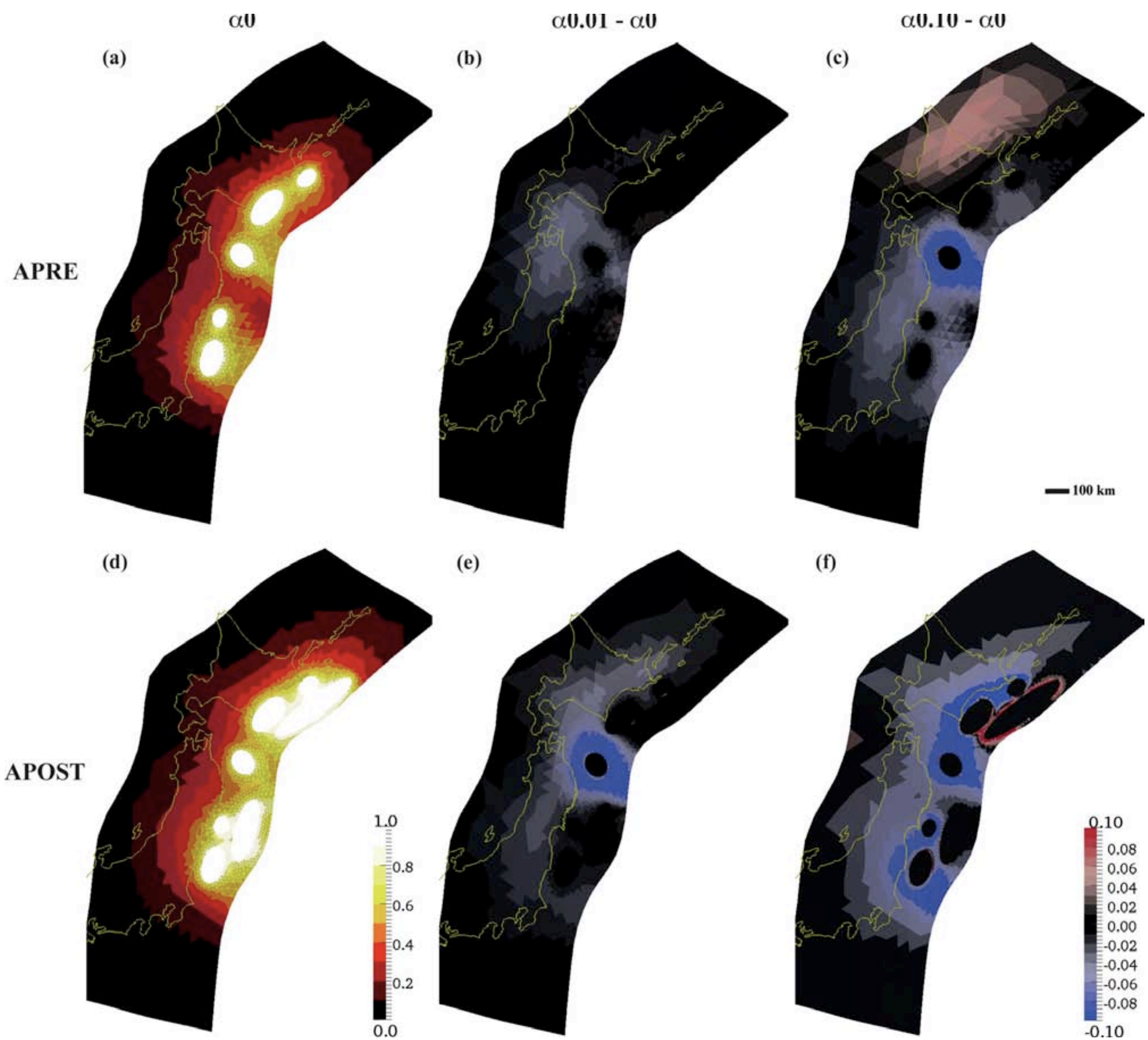
Characteristic Rupture Sequence Time (CRS) **'Present' Time (GPS end-time)**

SPIN-UP OF MEAN TRACTIONS
Rate Strengthening Friction (RF): α'=0.1, ρ=10,

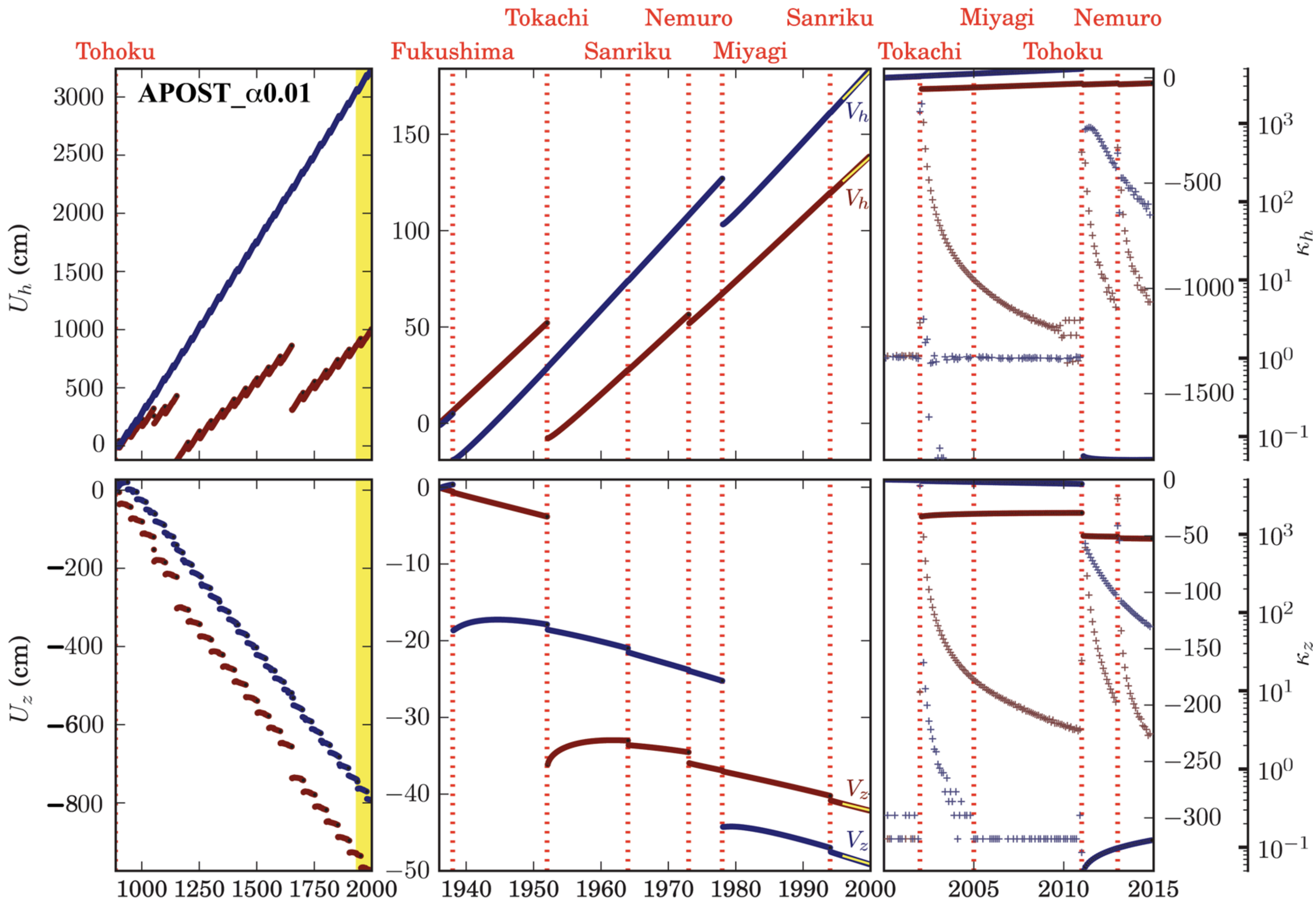


Surface Displacements & Fault Slip Rate Evolution

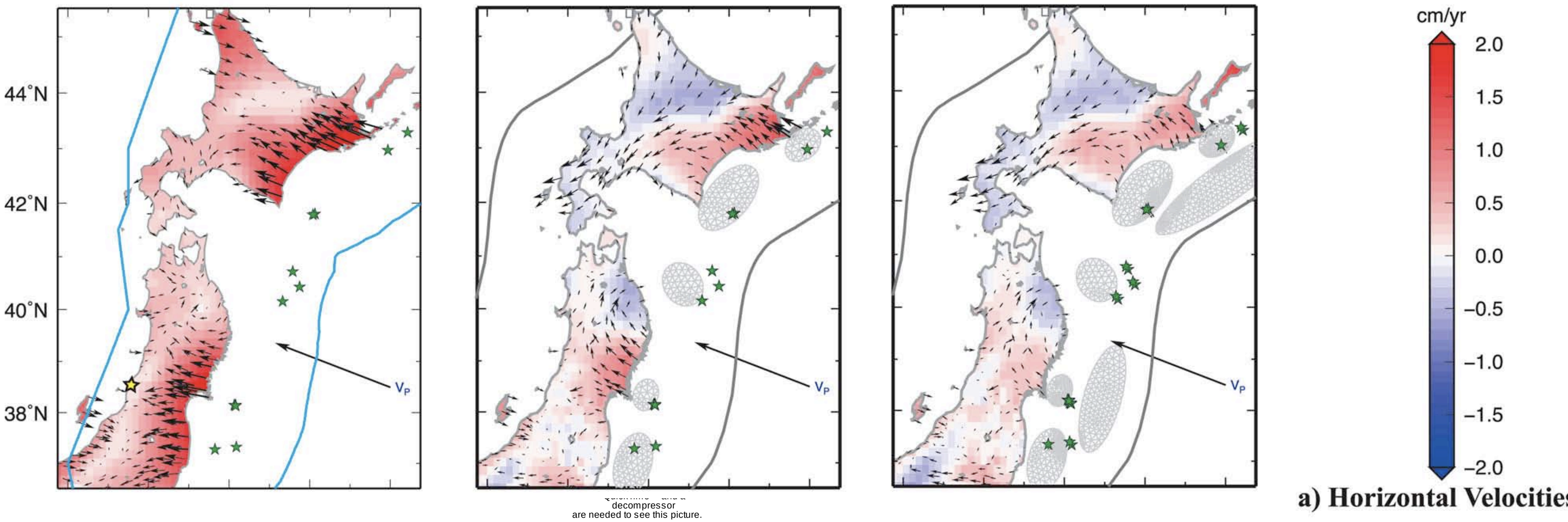
Fault Stress Shadows for Six Asperity Models



Sample Synthetic Displacement Time Series

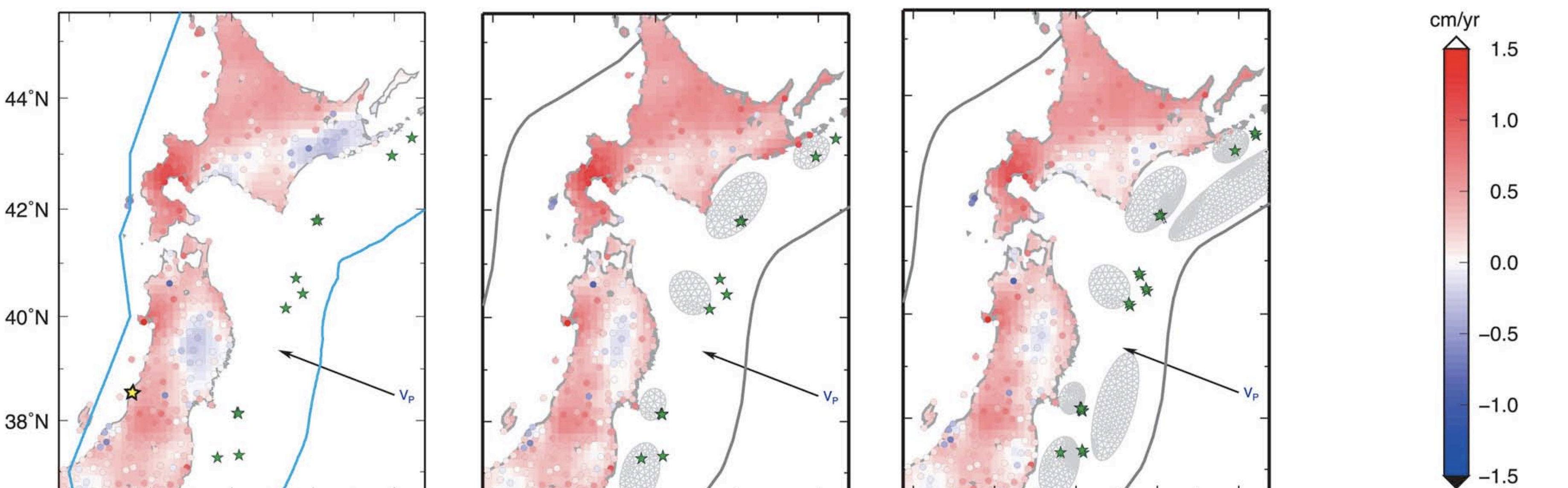


Surface Velocities: Horizontals (cm/yr)
Assumed RSF: α'=0.01 & 0.1, ρ=10



a) Horizontal Velocities

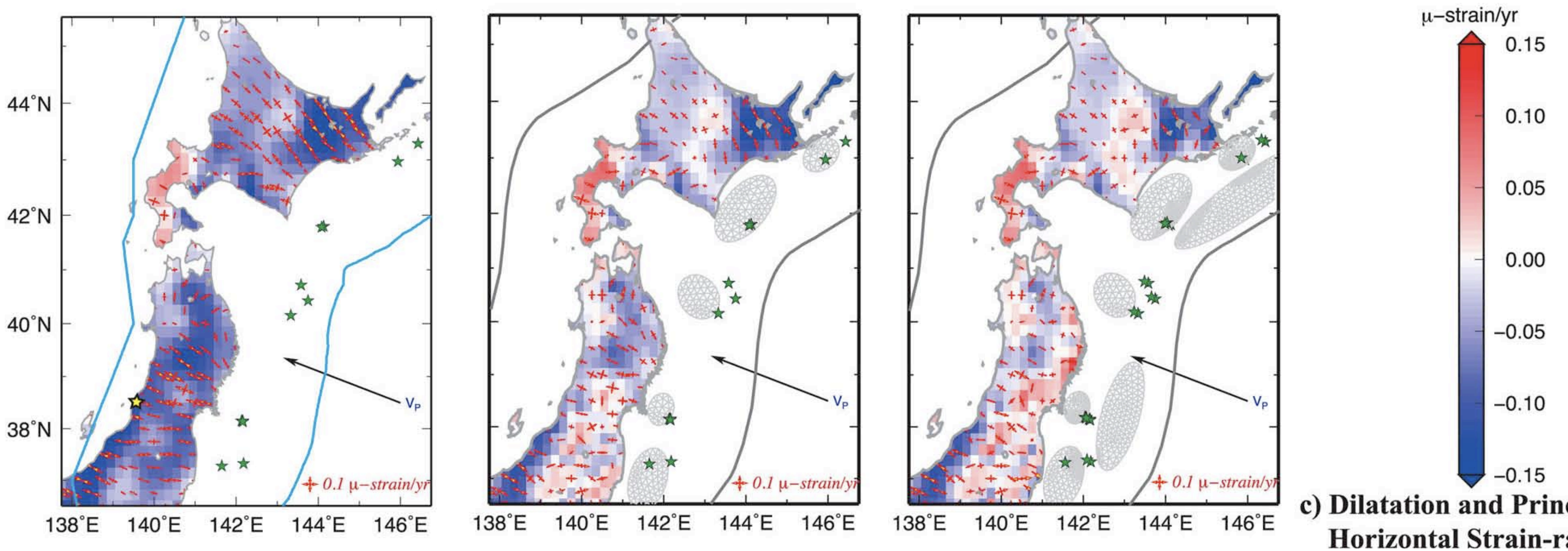
Surface Velocities: Verticals (cm/yr)
Assumed RSF: α'=0.01 & 0.1, ρ=10



decompressor
are needed to see this picture.

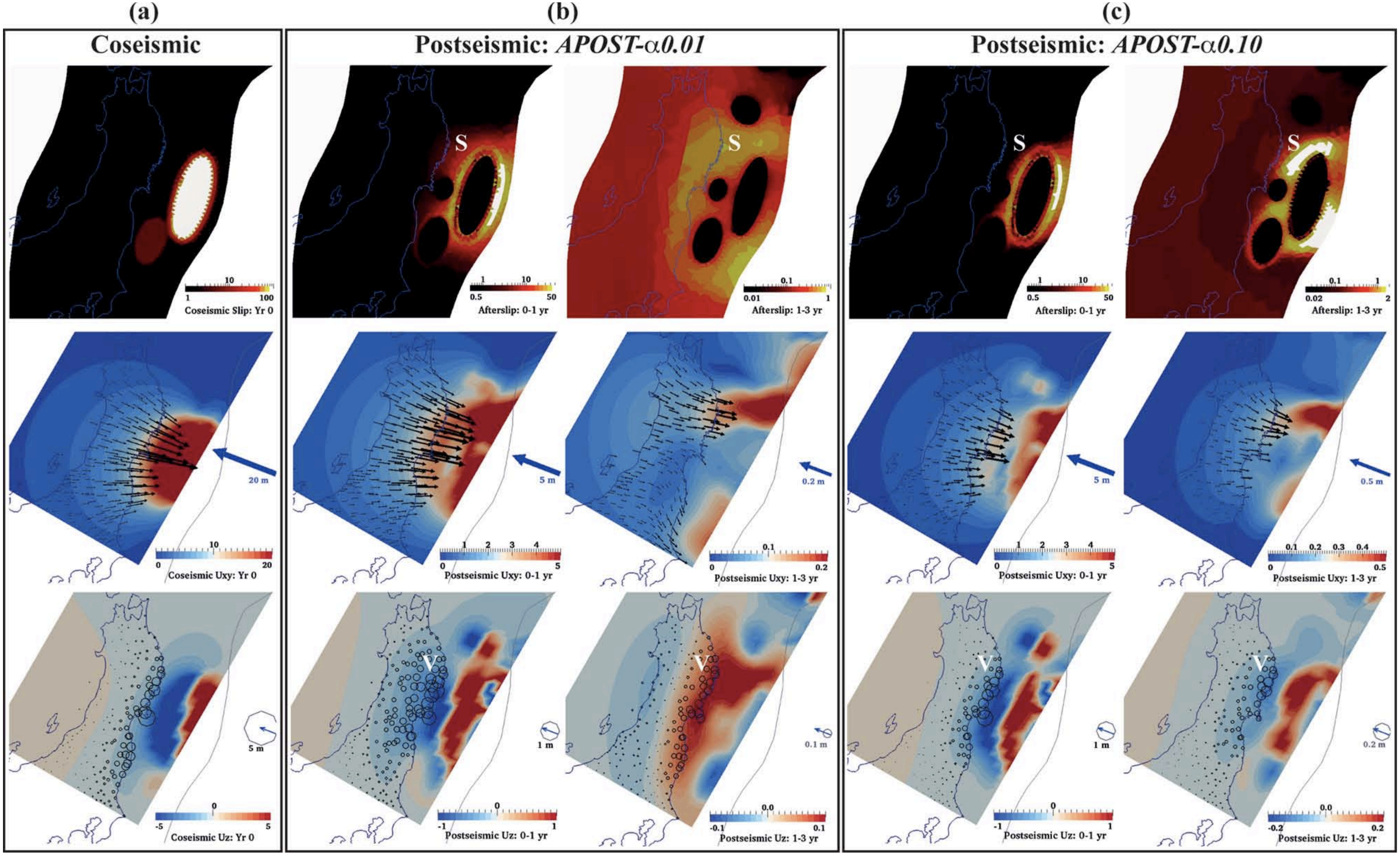
b) Vertical Velocities

Surface Dilatation Rates (µ-cm/yr)
Assumed RSF: α'=0.01 & 0.1, ρ=10



c) Dilatation and Principa Horizontal Strain-rates

POSTSEISMIC Fault Slip-Rates & Surface Velocities: Assumed RSF: α'=0.01 & 0.1, ρ=10



Conclusions

- Assuming mega-asperities, mechanical coupling along existing asperities can explain a significant fraction of the observed geodetic velocities (both horizontal and vertical).
- Simulations with mega asperities seem to suggest a weak megathrust interface: 0.1 MPa $< (a-b)\sigma <$ 0.5 MPa
- Our methodology allows prediction of the full spatio-temporal evolution of surface displacements over the seismic cycle
- Potential to invert geodetic data over entire seismic cycle for fault rheological parameters, and perhaps, their distribution.
- However, code needs to be optimized before attempting inversions

THANKS FOR COMING!

Plate Boundaries Around Japan

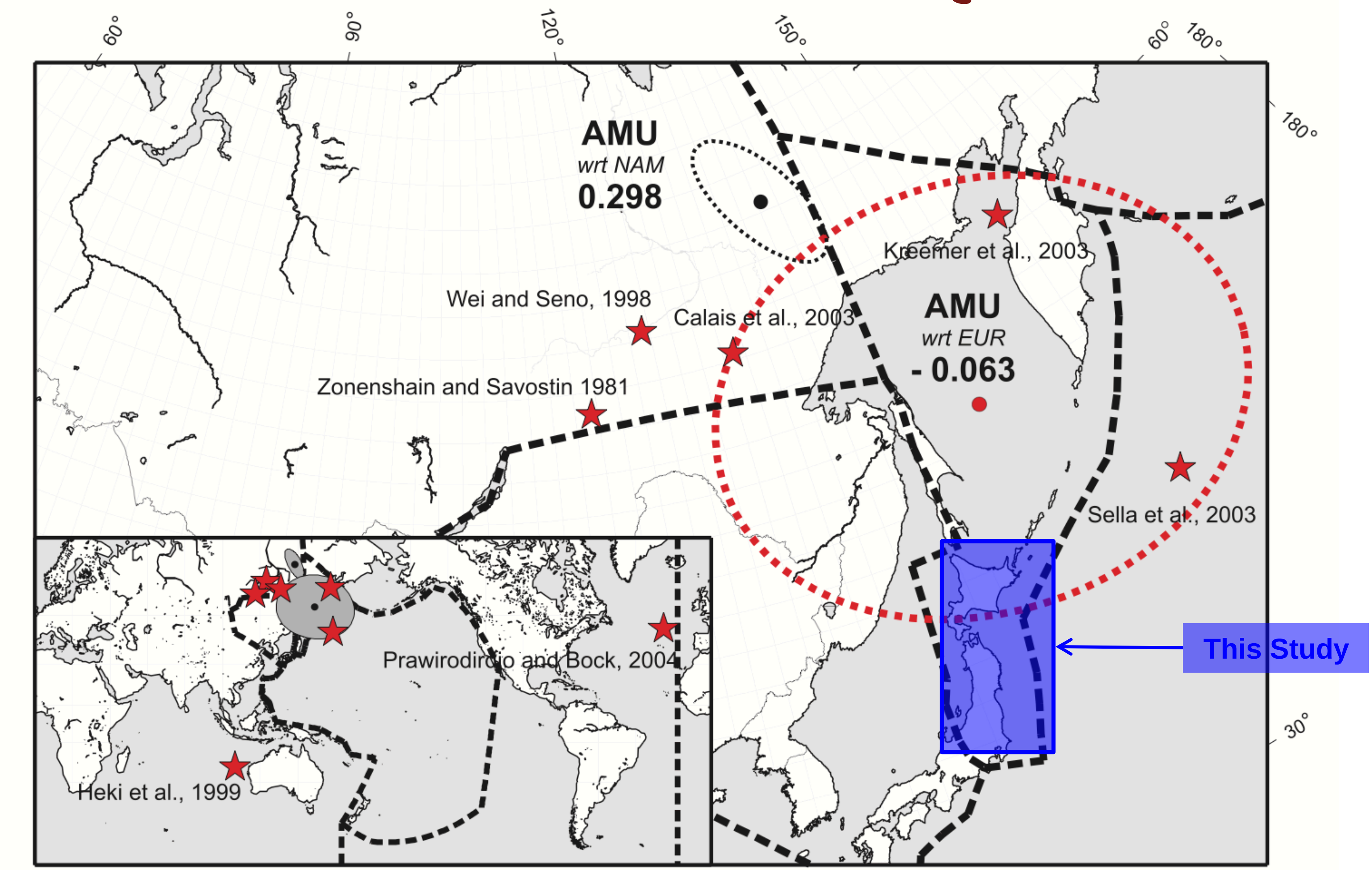
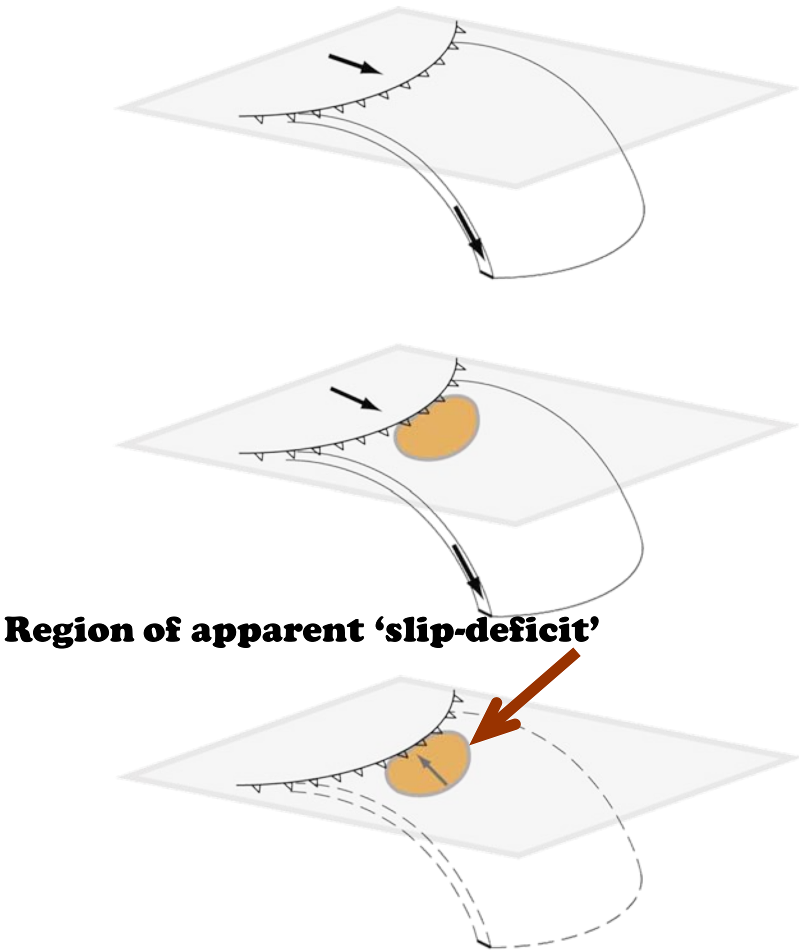


Figure S3 - Poles of rotation from this study for the Amurian plate shown with respect to Eurasia and North America with linearly propagated 2 sigma error ellipses. Stars show the locations of previously published Amurian-Eurasian poles.

Burgmann et al., 2006

Slip-Deficit: ‘Backslip’ Model (BSM, Savage 1983)



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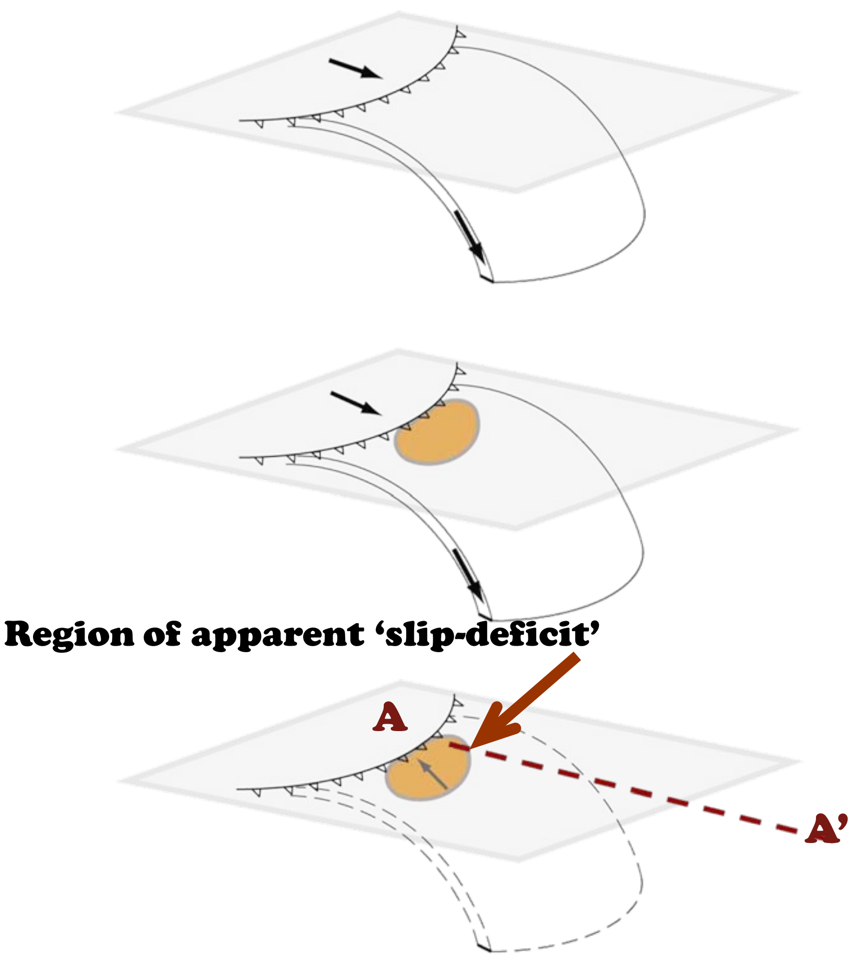
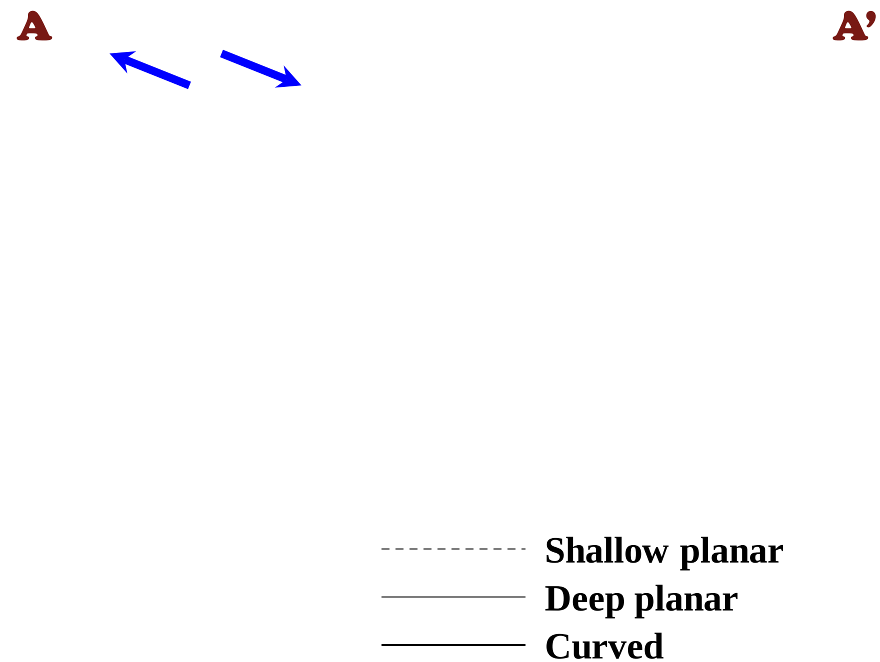
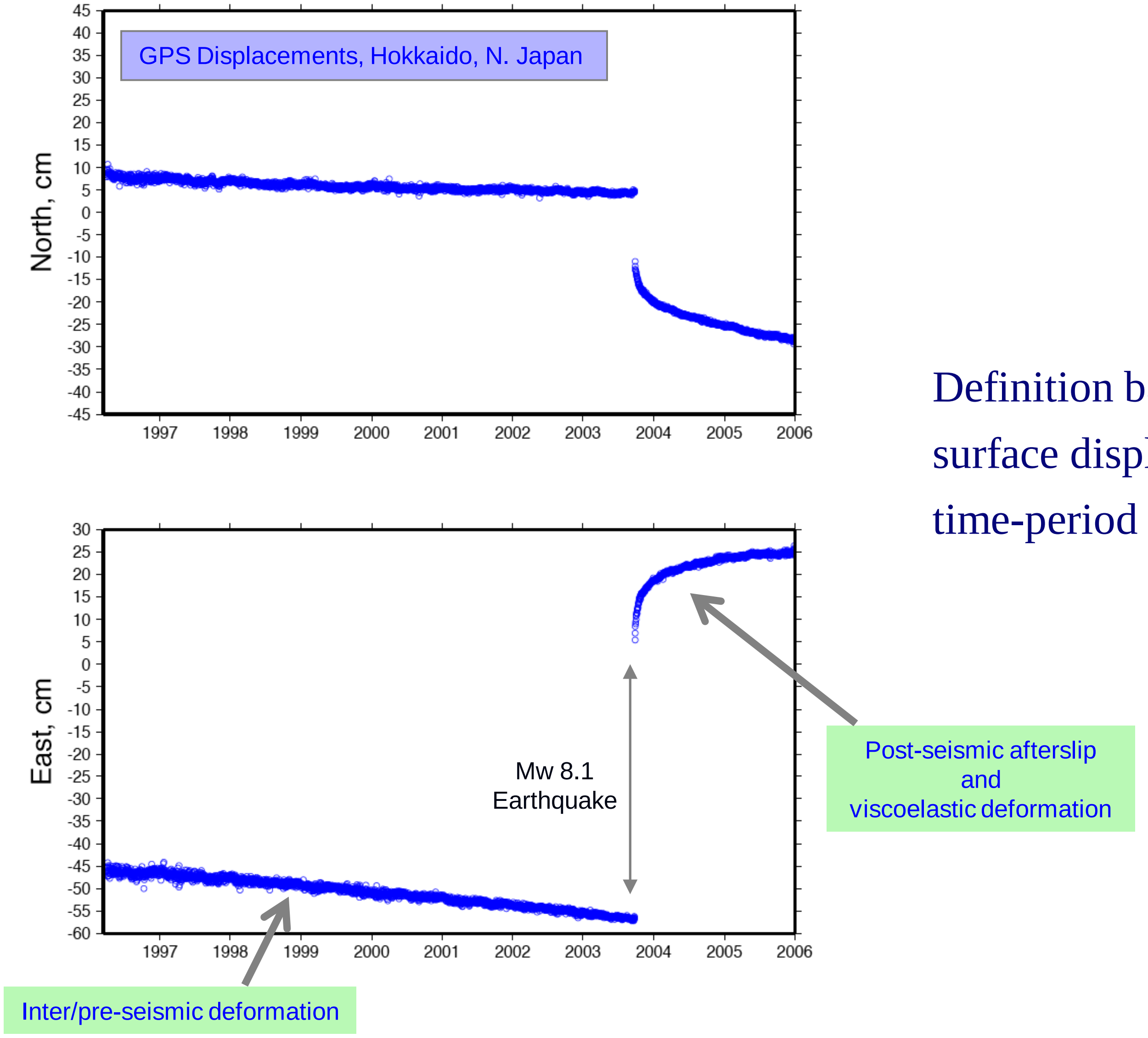




Adapted from Kanda & Simons 2010

Interseismic Velocity Profiles controlled by region of SLIP-DEFICIT

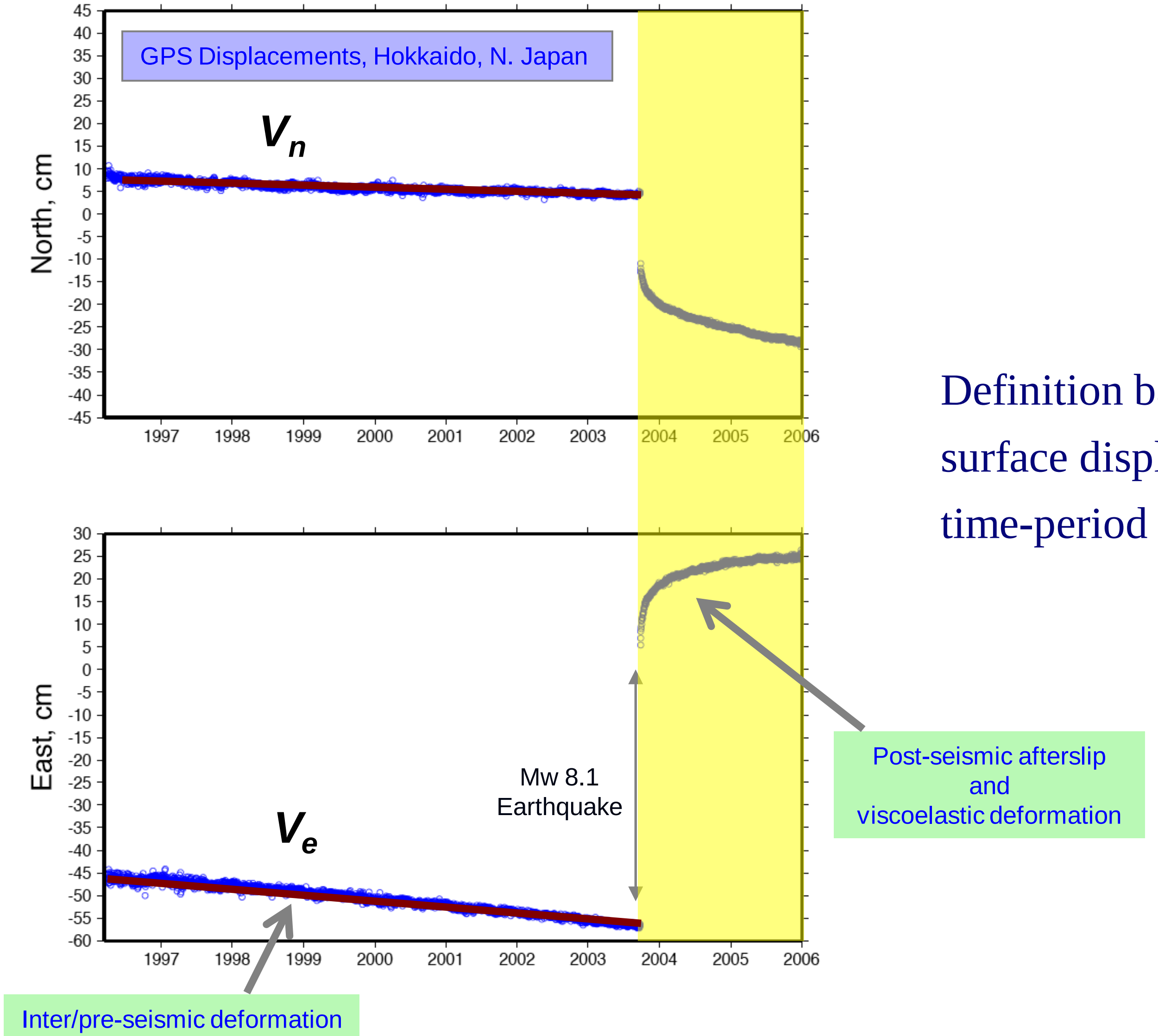
The Seismic Cycle



Definition based on evolution of surface displacements over the time-period between earthquakes

Adapted from figure by Sue Owen, JPL

The Seismic Cycle



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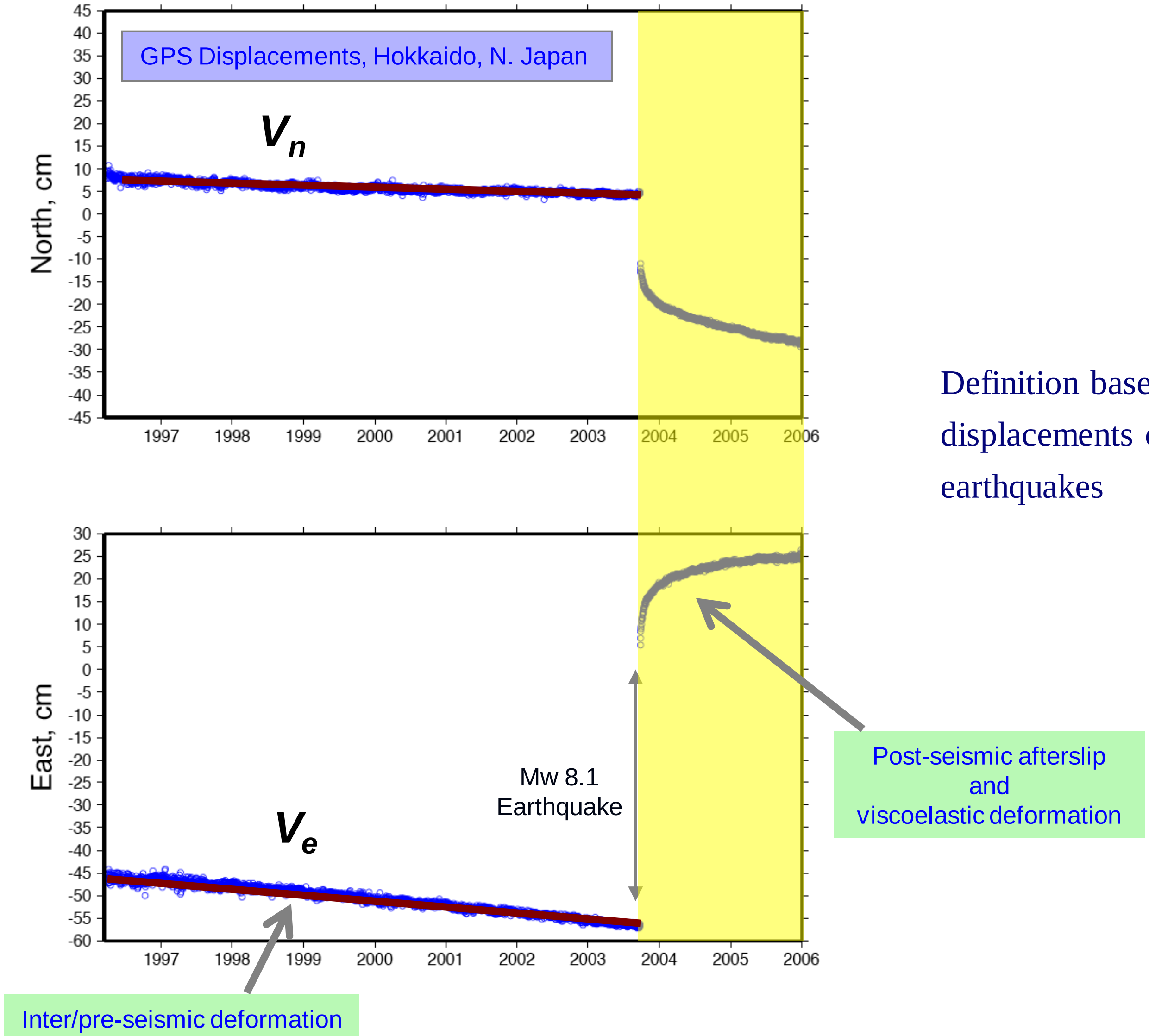


Definition based on evolution of surface displacements over the time-period between earthquakes

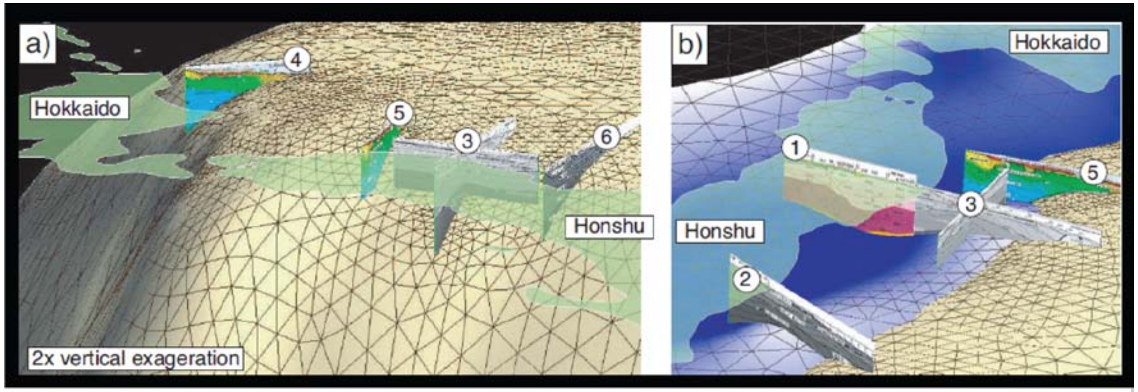
Adapted from figure by Sue Owen, JPL

Models for Postseismic Slip Evolution

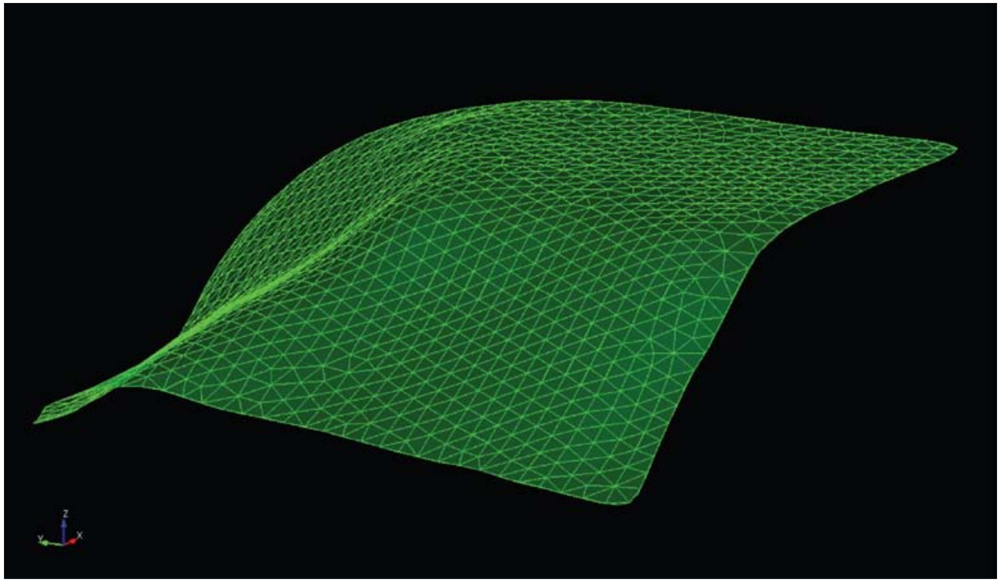
- Spring-slider models (e.g., Perfettini and Avouac, 2004; Fukuda et al, 2009)
- Vertical strike-slip faults discretized into patches obeying rate-state friction (e.g., Johnson et al., 2006; Perfettini and Avouac, 2007)
- **Our fault-creep model (Hetland et al., 2010; Hetland and Simons, 2010):**

- **Characteristic 'Asperities' – that slip only coseismically – surrounded by a region of velocity strengthening friction**
- **Spin-up of model stresses: Fault tractions at any time result from imposed loading history – Characteristic earthquakes & Tectonic loading**
- **3D fault surfaces adaptively discretized using triangular dislocation elements (Comminou and Dunders, 1975; Meade 2007)**
- **Consider heterogeneous fault rheology**

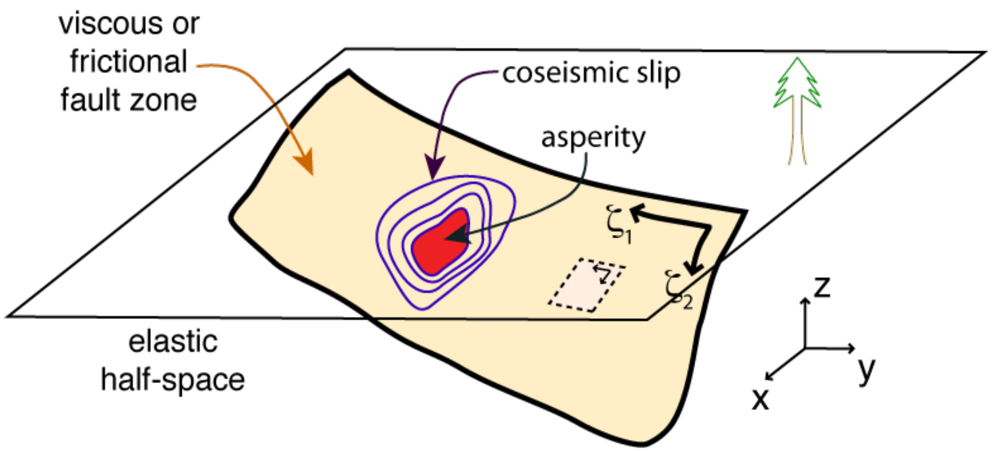
Megathrust Interface Discretization: I



Models of the slab surface (a) and the Japan Moho (b); for reference, a few of the seismic lines used as constraints are shown: 1, Iwasaki et al., 2001; 2, Miura et al., 2003; 3, Ito et al., 2004; 4, Nakanishi et al., 2004; 5, Takahashi et al., 2004; 6, Miura et al., 2005. Courtesy: Eric Hetland



Interseismic Fault Creep Framework



Hetland et al., 2010; Hetland & Simons, 2010

Features

- Handles 3D, non-planar fault in elastic half-space
- Driven by slip on extension of fault
- Both dip- and strike-slip
- Multiple asperities
- Irregular earthquake sequences
- Heterogeneous fault-zone rheology
- Friction, linear/non-linear viscous
- Spin-up model over multiple ruptures: fault tractions at any time are a consequence of the previous earthquakes and fault loading

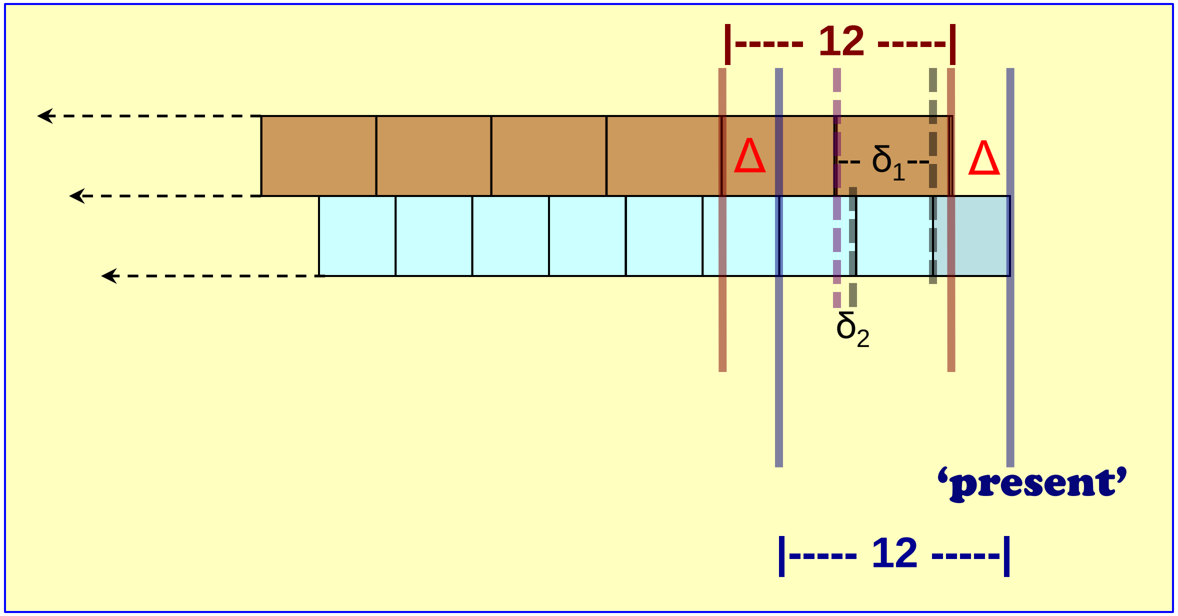
Characteristic Rupture Sequence Time (CRS-time)

Example: Two asperities rupture every once every 4 and 6 yrs

CRS-time = 12 yrs (Least Common Multiple of 4 & 6).

Synthetic Catalog

The ‘blue’ asperity ruptures exactly ‘Δ’-yrs before the ‘red’ asperity every 12 years.



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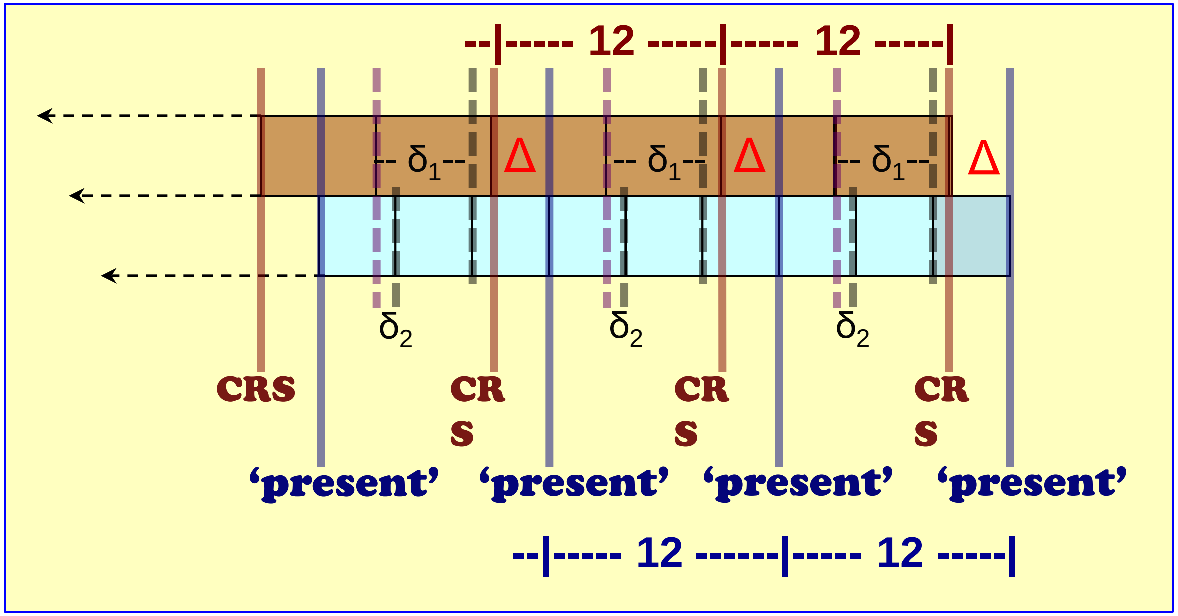
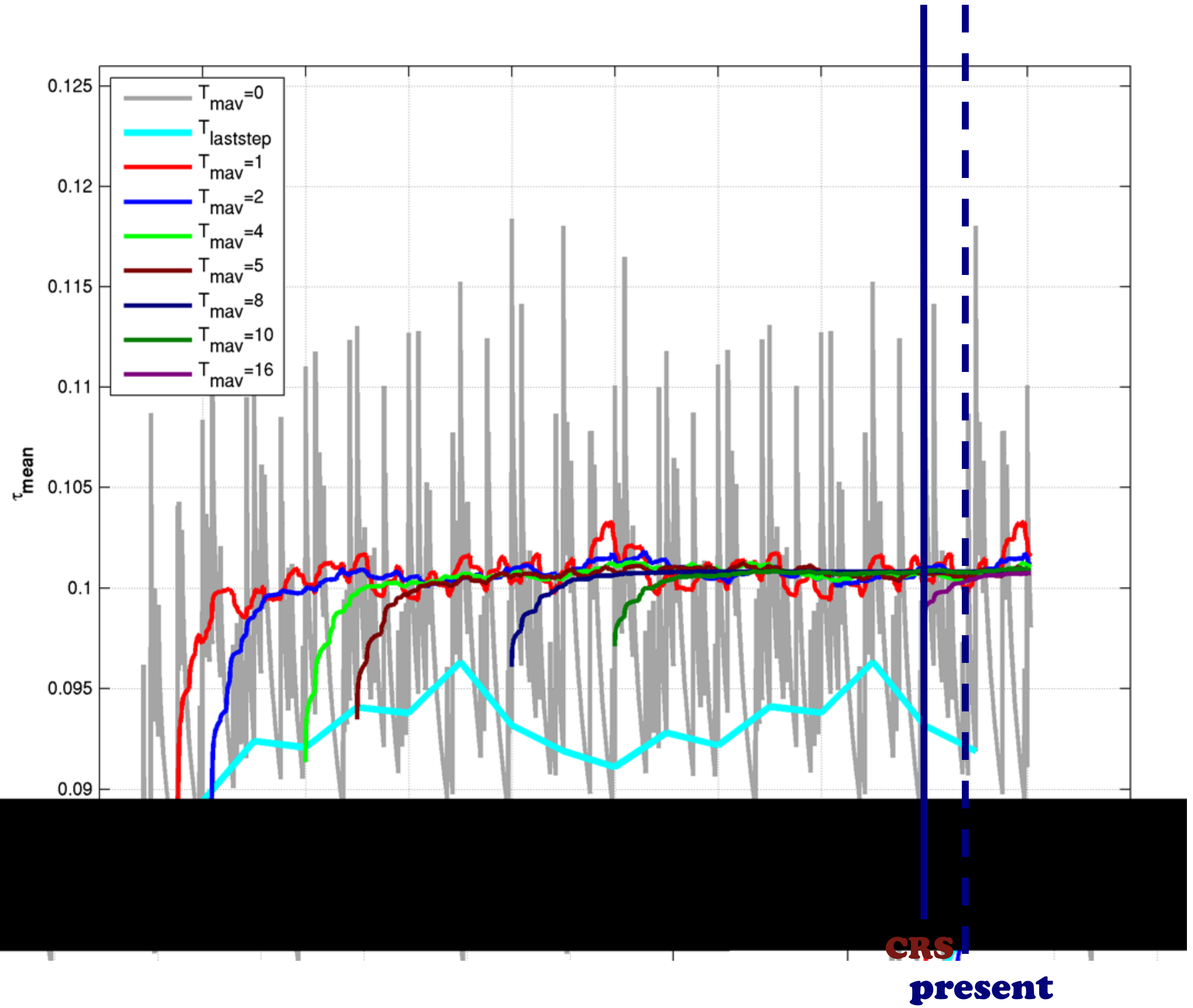
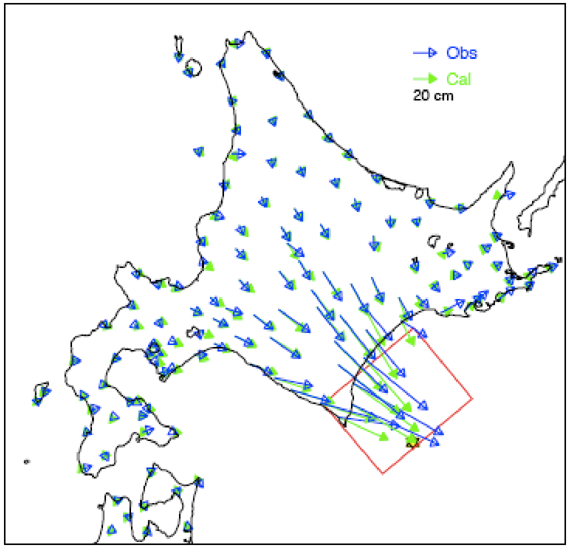


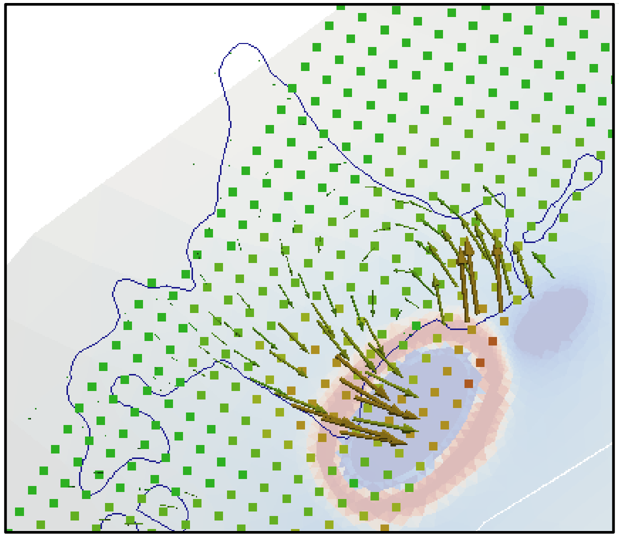
Measuring Model Spin-Up (Moving averages & CRS-time)

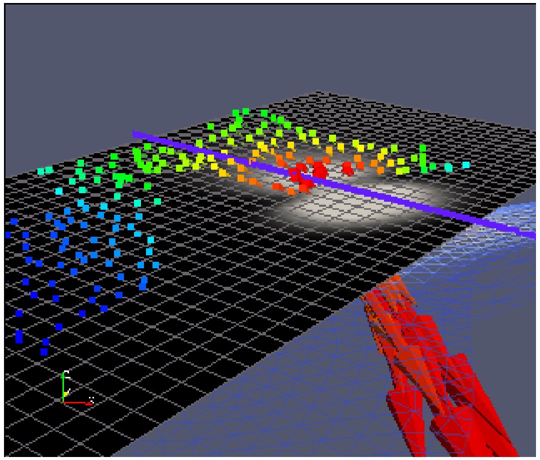


Simulation of Slip



Koketsu et al., 2004





Peak observed value ~ 80 cm

Peak value from inversion ~60 cm

Peak simulated value ~ 0.06*6.4 m ~ 40 cm