Role of Thermal pressurization on Megathrust ruptures

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2011 Mw 9.0 Tohoku-Oki earthquake a case for thermal pressurization ?

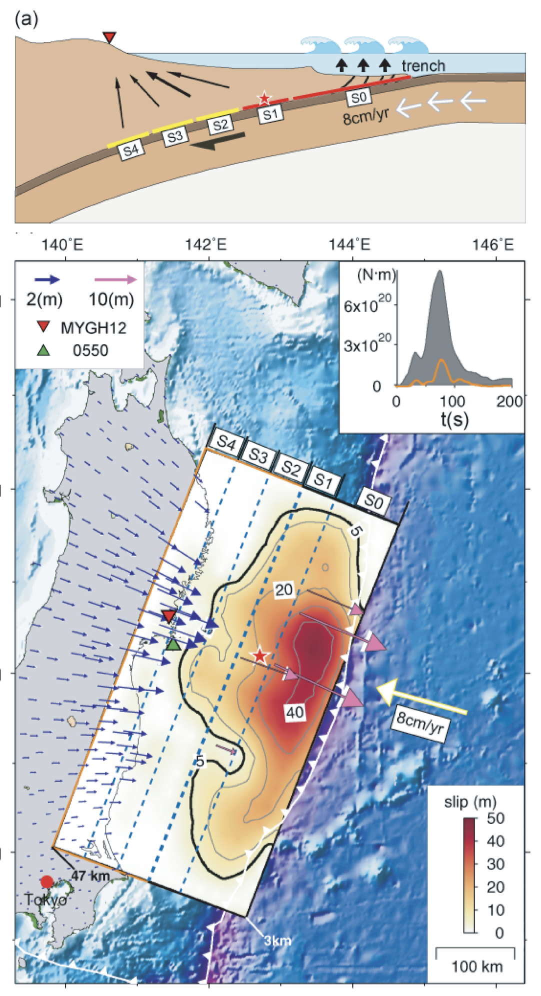


Fig.1: Tohoku-Oki rupture from inversion of accelerometric and onshore and offshore geodetic measurements from *Wei et al., in prep.*

1. Large shallow slip

The 2011 Mw9.0 Tohoku-Oki earthquake ruptured the plate interface between the Pacific Plate and Northern Honshu converging at an average rate of 8-8.5cm/yr.

Inversion from geodetic and seismic data reveals that the shaking came from the deeper part of the rupture (>30km) which released only about 18% of the total moment whereas the maximum slip, exceeding 50m, was localized at shallow depth (10-15km) (fig.1, *Wei et al., in prep*).

An ocean-bottom pressure gauge and the migration of ocean-bottom instruments installed before the earthquake on the frontal wedge even suggest displacements larger than 70m in the east-southeast direction (fig2, *Ito et al., GRL 2011*), this huge coseismic slip beneath the frontal wedge beeing reponsible for the tremendous tsunami that struck the coastal area of northeastern Japan.

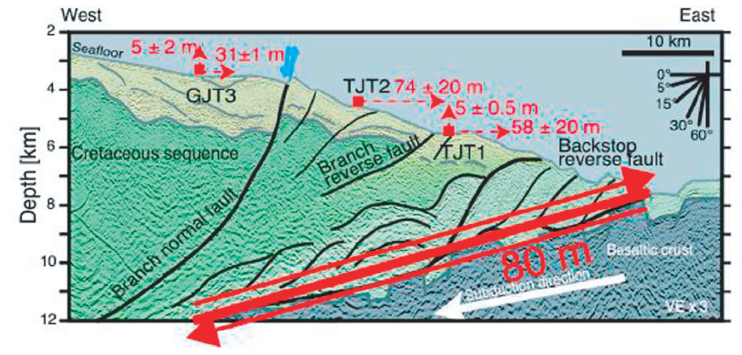


Fig.2: Pre-existing seismic structure and observed deformation of the frontal wedge (*Tsuji et al., EPS, 2011*). Red arrows indicated the observed displacements from *Ito et al, GRL 2011.*

2. Larger slip in low coupling area

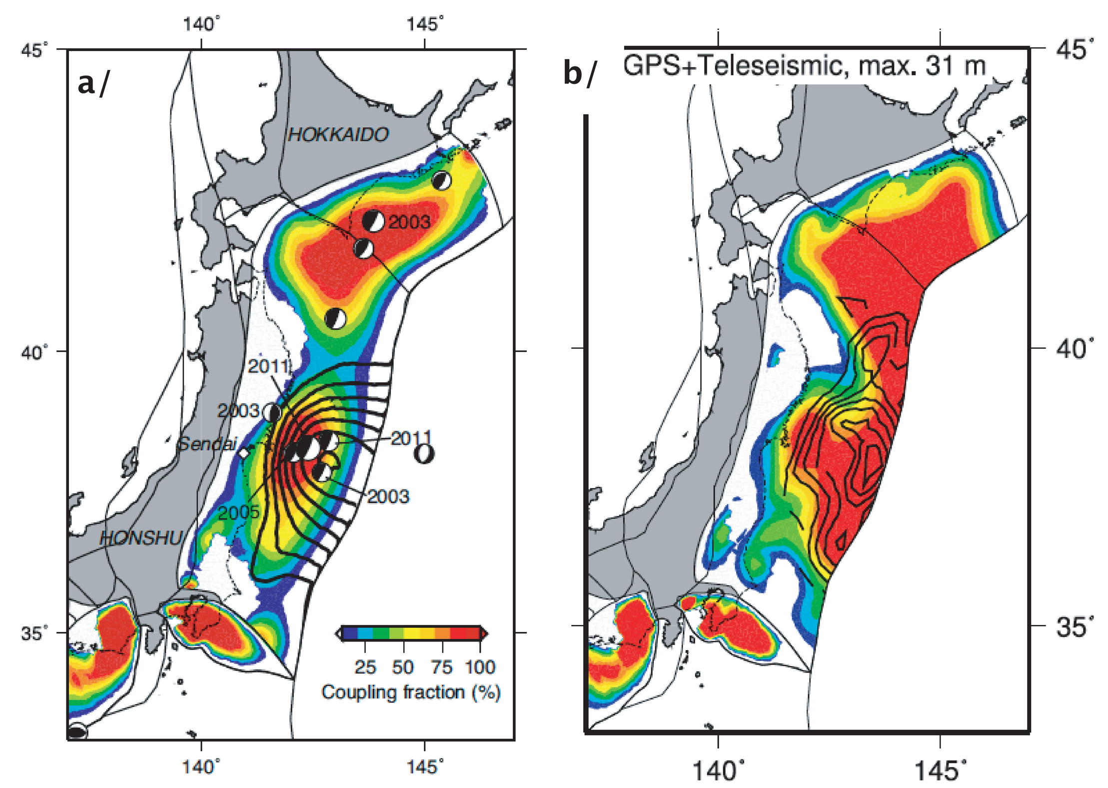


Fig.3: a/ Pre -Tohoku-Oki earthquake coupling model with no interseismic strain accumulation on the up-dip and down-dip edges, b/ Relaxing the assumption of zero interseismic coupling along the Japan trench from *Loveless and Meade, GRL 2011.*

Modeling of geodetic strain measured onshore before the earthquake had revealed a deep locked patch and no Mw>8.5 were expected. To reconcile the discrepancy between the Tohoku-Oki co-seismic slip and this first model, Loveless and Mead have proposed a new coupling model with 80% of coupling shifted trenchward. However, it would required a recurrence time of 212 to 706 years, less than the time since the 869 AD Jogan earthquake occured, considered the penultimate great earthquake in the region (*Ozawa et al., 2011*)

3. Backward propagation

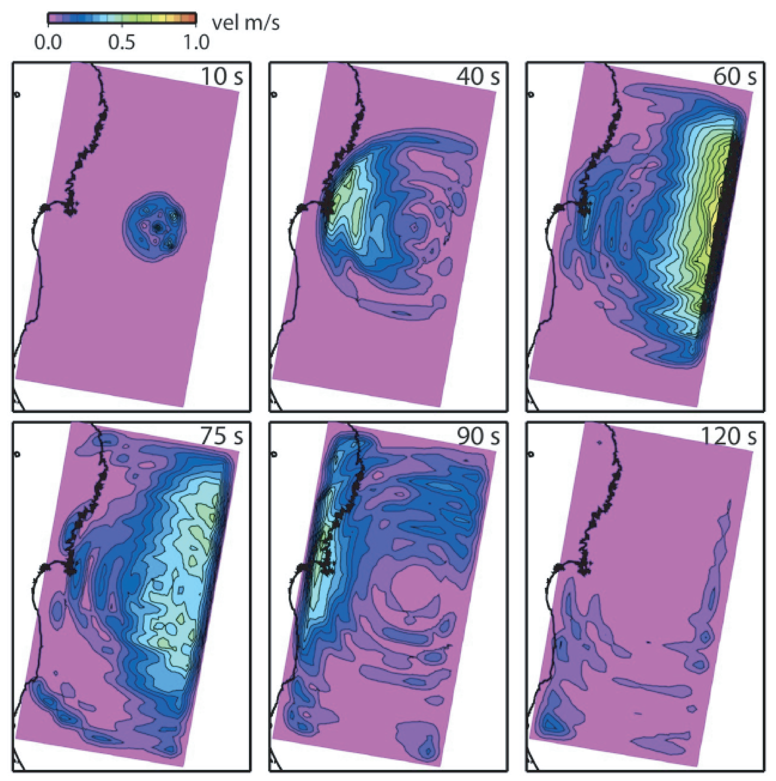


Fig.4: Snapshots of the slip-rate distribution at 6 times from *Ide et al., Science 2011.*

Finite-source imaging reveals a backward propagation: the rupture consisted of a small initial phase, deep rupture for up to 40s, extensive shallow rupture at 60-70s, and continuing deep rupture lasting over 100s from *Ide et al., Science 2011.*

4. Deep high frequency content

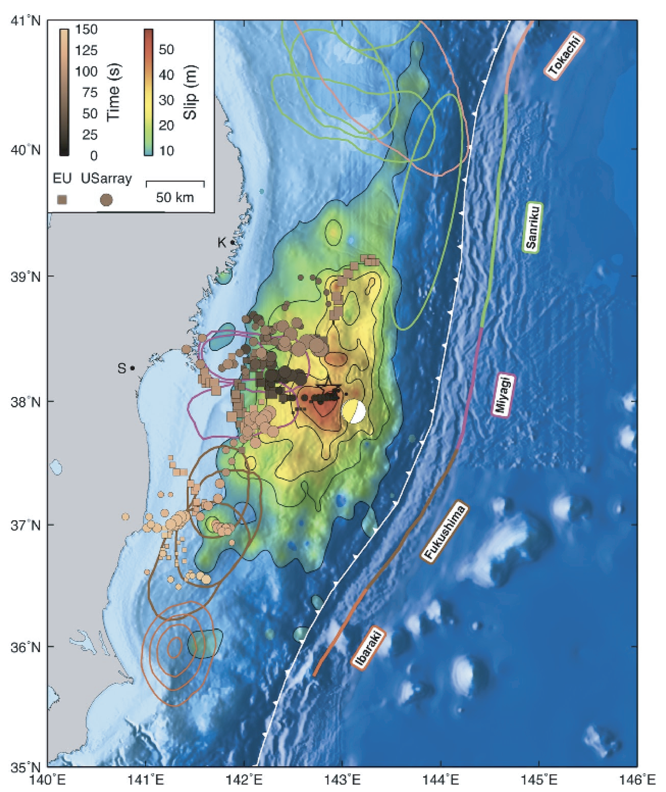


Fig. 5: Location of points of high-frequency radiation estimated using back projection methods with color intensity indicating time of the activity relative to the beginning of the event and with size of the symbol proportional to amplitude of the HF radiation normalized to the peak value from *Simons et al., Science 2011.*

Although the greatest slip is located near the trench, sources of high-frequency seismic waves delineate the edges of the deepest portions of coseismic slip and do not simply correlate with the locations of peak slip (*Simons et al., Science 2011* and *Meng et al., GRL 2011*).

5. Overshoot

Complete stress drop and dynamic overshoot beyond zero shear stress has been inferred from aftershock mechanism diversity or reversed aftershock with normal faulting focal mechanisms (*Ide et al., Science 2011*).

The Tohoku-Oki earthquake had thus two modes of rupture:
- shallow, relatively quiet rupture with dynamic overshoot and
- deep rupture that radiates high frequency waves energetically.

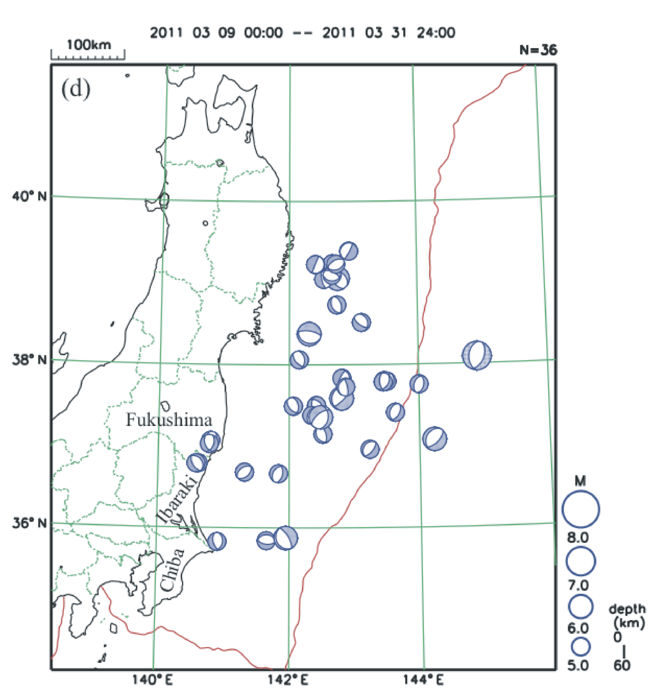


Fig.6: Distributions of normal fault focal mechanisms determined by CMT analysis from *Hirose etal., EPS 2011.*

6. High pore pressure anomaly

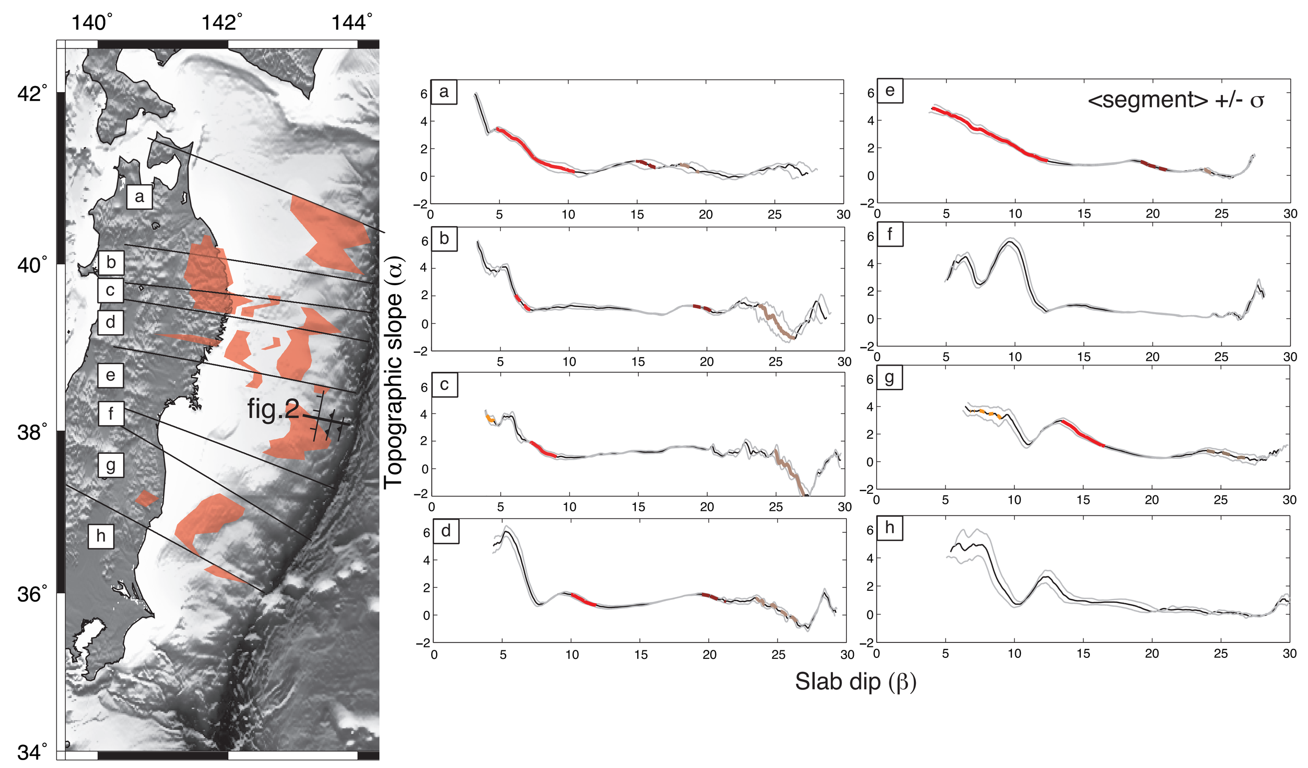


Fig.7: left : Critical mechanical areas where internal and basal friction and fluid pore pressure can be inferred.

right: Mean +/- σ of the taper for each segment, critical accretionary prism in red.

Critical areas (*Davis et al, JGR 1983*) are distributed around the previously determined locked patch (fig.3), and are in good agreement with the observed forearc deformation (fig.2). The highest slip patch is at critical state and shows a strong high pore pressure anomaly (λ=0.8) compared to other critical areas where a hydrostatic pore pressure is more likely. In addition, we also observe a lower effective basal friction (7°). Since the pore pressure is high and the basal friction low, a small dynamic decrease of the effective basal friction could allow normal faults activation.

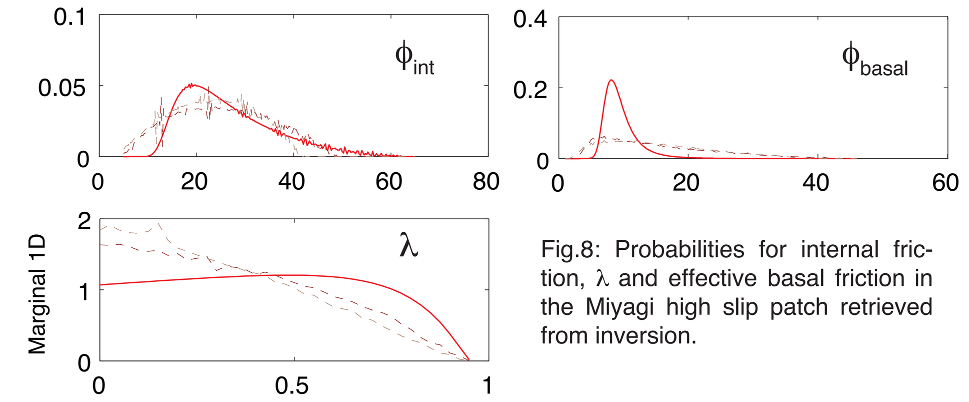


Fig.8: Probabilities for internal friction, λ and effective basal friction in the Miyagi high slip patch retrieved from inversion.

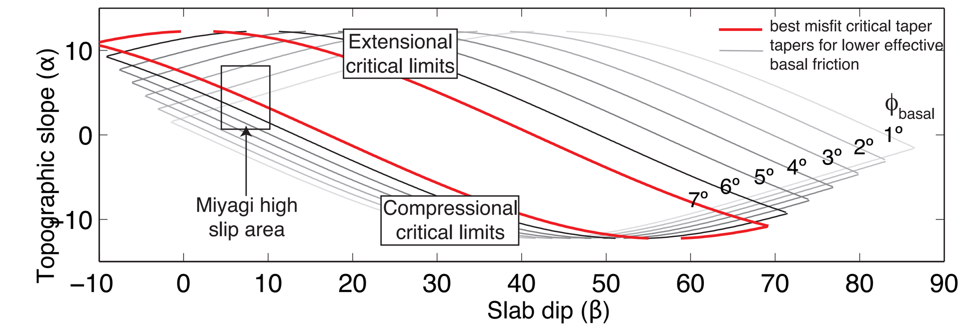


Fig.9: Critical envelops for basal friction (ϕ_{basal}) ranging from 1° to 7°, with λ=0.8. In red: critical envelop for values of the best misfit. A decrease of 5° could lead to normal faults activation.

Dynamic simulation of a thermopressurized rate-strengthening patch: reproducing Tohoku-Oki EQ particularities

3D Dynamic simulation of earthquake cycle accounts for inertial effects during seismic events and incorporates

Rate and state friction for low-slip-rate response

Laboratory derived (*Dieterich, Ruina, Blanpied, Marone, Tullis, Scholz and others*): Unique tool for simulating earthquake cycles in their entirety, from accelerating slip in slowly expanding nucleation zones to dynamic rupture propagation (turn into linear slip weakening) to post-seismic slip and interseismic creep to fault restrengthening between seismic events.

$$\tau = \bar{\sigma} f = (\sigma - p)\left[f_o + a\ln\frac{V}{V_o} + b\ln\frac{V_o\theta}{L}\right];\quad \frac{d\theta}{dt} = 1 - \frac{V\theta}{L}$$

a,b: material parameters
fo: static friction
θ: state variable
Vo: Reference slip rate
L: characteristic slip for the state evolution

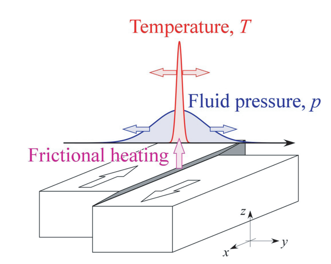
(a-b) < 0 : velocity-weakening (earthquake nucleation, stick-slip behavior)

(a-b) > 0 : velocity-strengthening (aseismic slip during interseismic period)

Thermal pressurization due to frictional heating in a shear zone

Rapid shear heating during seismic slip increases fault temperature, and since the thermal expansivity of water is much larger than that of rocks, shear heating may increase the pore fluid pressure leading to co-seismic fault weakening, additional to any slow-slip friction behavior.

$$\tau = f\sigma_e = f(\sigma_n - p)$$



Some laboratories experiments have shown that rate-strengthening accretionary prism mainly composed of clays submitted to thermal pressurization could allow earthquake propagation (*Faulkner et al., GRL 2011*).

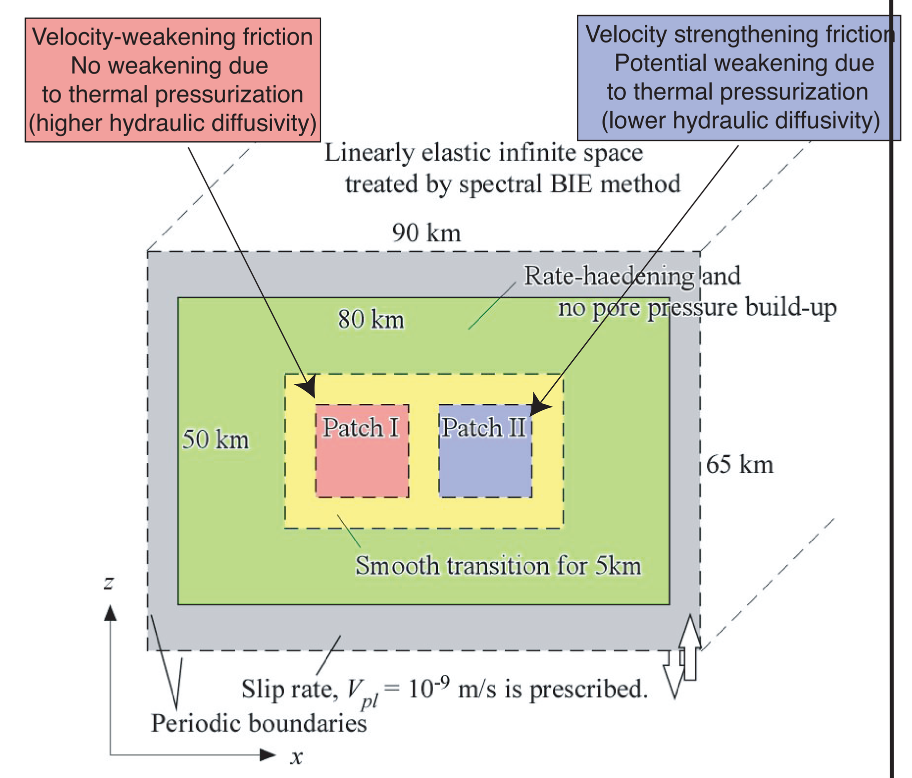


Fig.10: Model Set-up (*Noda and Lapusta, JGR 2010, in prep.*)

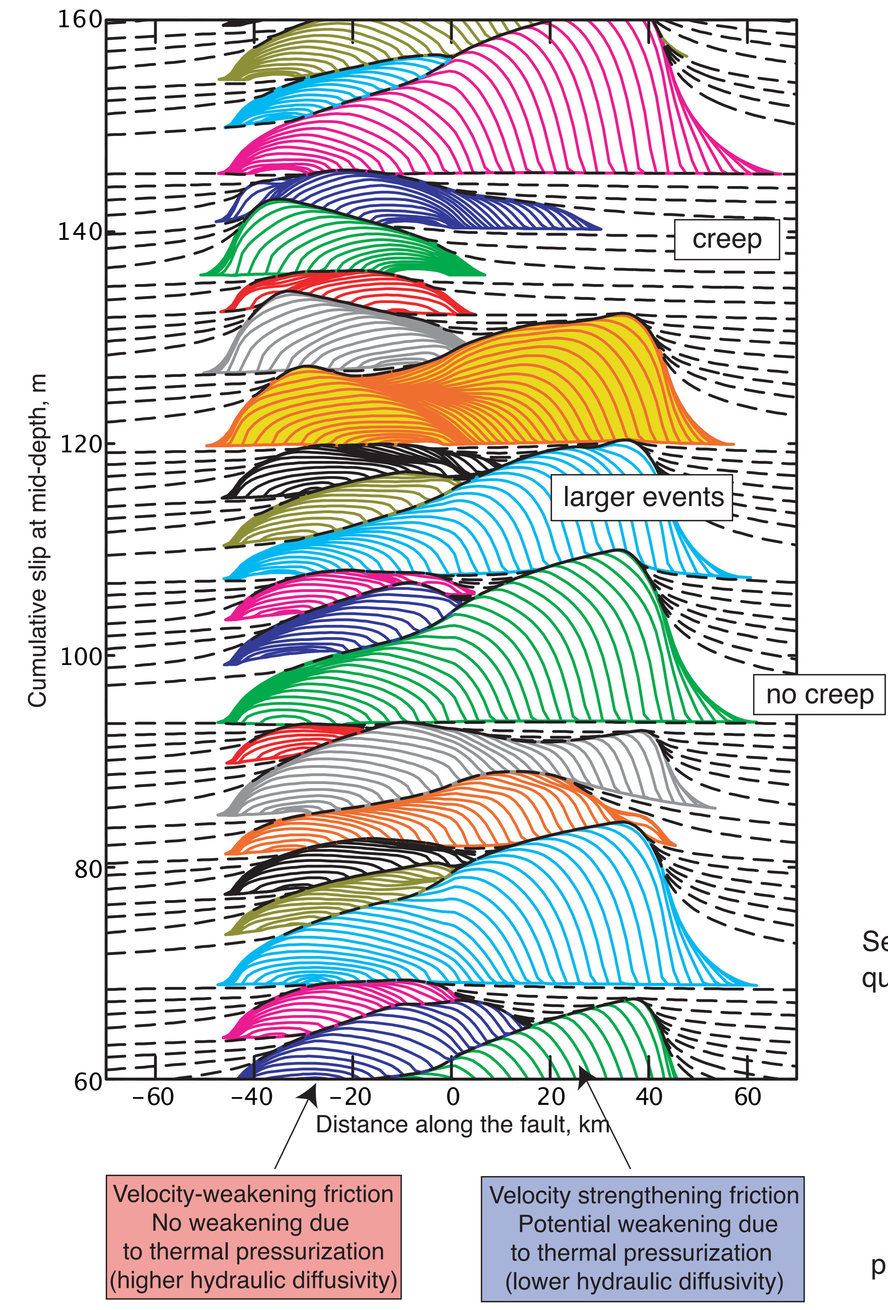


Fig.11: Accumulated slip along the fault (*Noda and Lapusta, in prep.*)
dashed lines : every 50 yrs, solid lines: every 1s

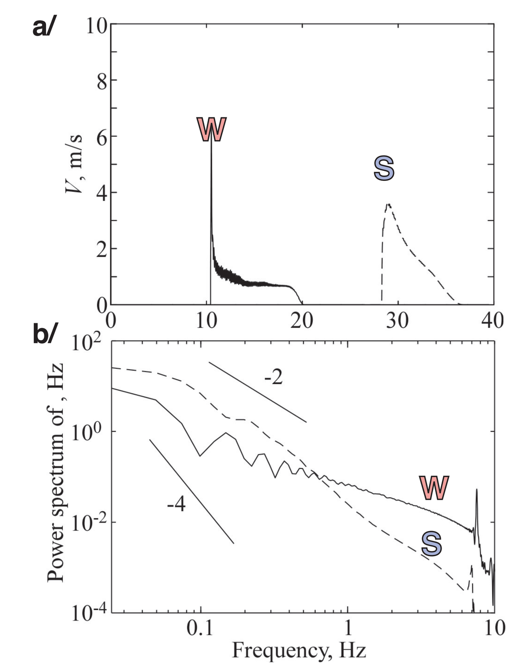


Fig.13: a/ Slip velocity evolution
b/ Power spectrum

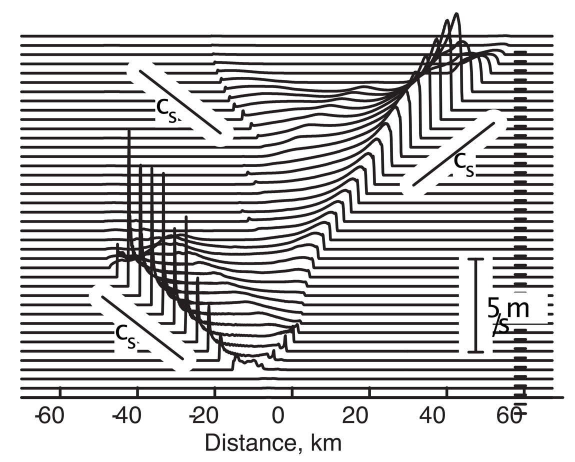


Fig.14: Snapshots of slip rate of the 26th event (*Noda and Lapusta, in prep.*)

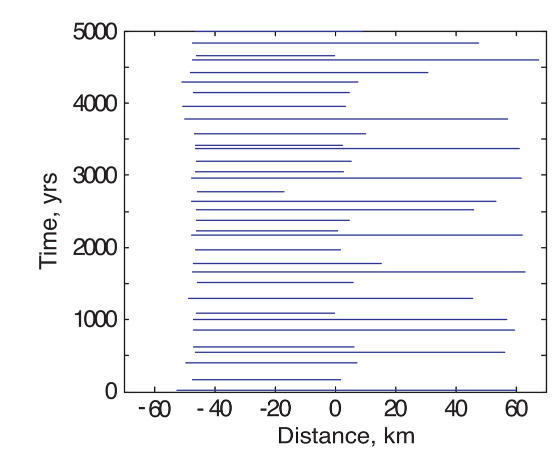


Fig.15: Rupture extent and recurrence time (*Noda and Lapusta, in prep.*).

Several seemingly contradictory Tohoku-Oki earthquake particularities are qualitatively reproduced:

> nucleation in rate-weakening patch (fig.11)
> propagation in rate-strengthening patch, leading to very large slip, even though creep is observed during interseismic period (fig.11)
> the strengthening patch is subjected to larger recurrence time (fig.15).
> Backward propagation is also observed (fig.14) and it would be more prominent in a model with a larger contrast between the high-slip and low-slip areas.
> The area of lower slip shows higher frequencies and higher slip velocity (fig.13).

Conclusions:

The combined effect of shear-heating-induced pore pressurization and velocity-strengthening friction coefficient leads to fault areas of larger slip having smaller high-frequency content, similarly to what was observed in the 2011 Tohoku-Oki earthquake.

The area of largest slip could be creeping with the plate rate before the earthquake (and hence appear fully de-coupled) explaining the stress overshoot and larger recurrence time. This creep occurs before some large events but not others, and can be enhanced or eliminated by choosing different parameters.

To match the Tohoku-Oki observations quantitatively, we now need 3D modeling with the correct geometry and adjusted parameters.