FRONTAL PROPAGATION OF MEGATHRUST EARTHQUAKES: the role of thermal-pressurization

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1. Observations:

Co- and post-seismic slip / Inter-seismic slip

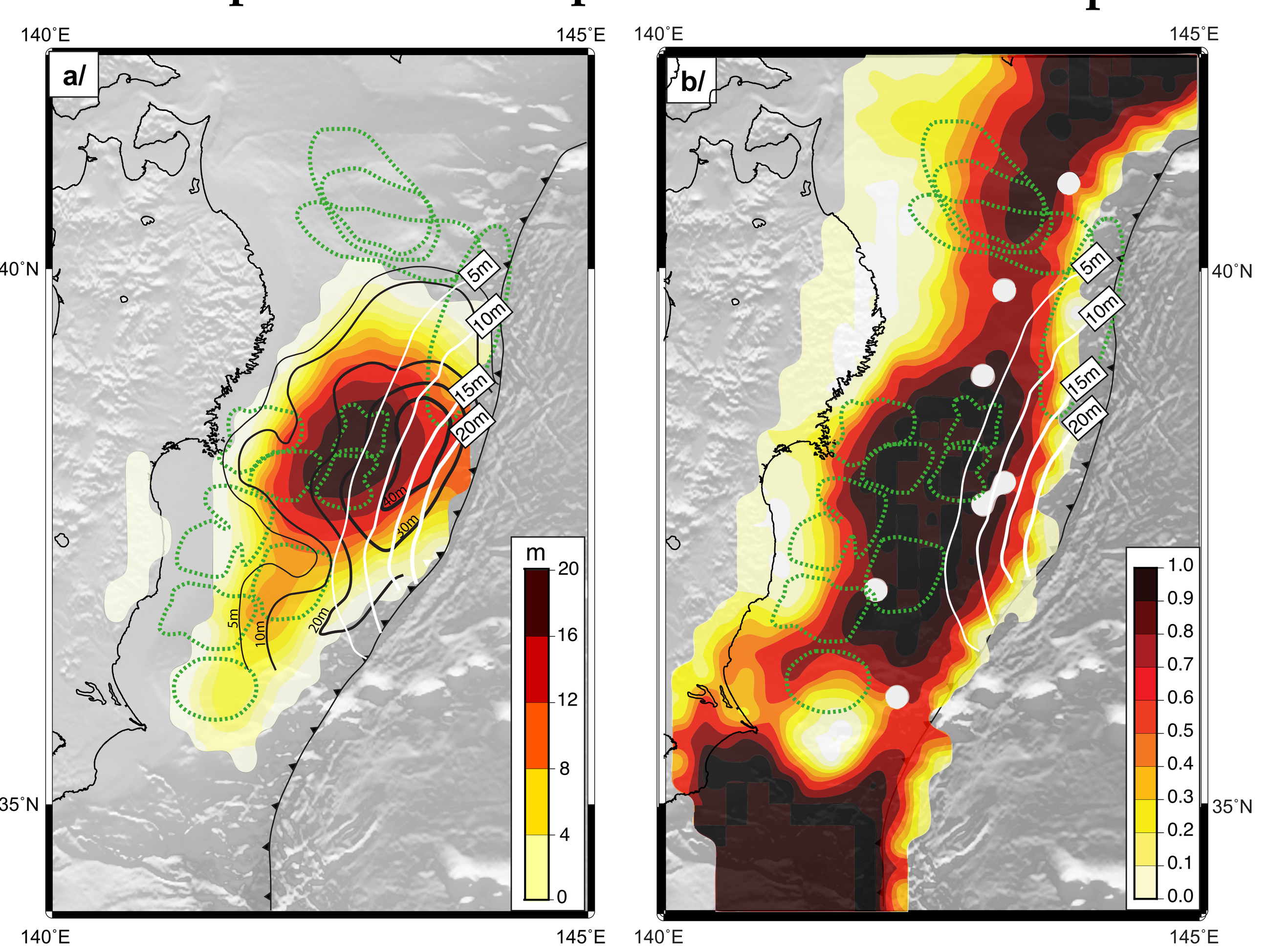


Fig. 1: a/ Tohoku-Oki March 11, 2011 coseismic slip and postseismic slip (white) from Perfettini and Avouac [subm.] assuming a co-seismically blocked trench and a post /inter-seismic free trench.
b/ Interseismic coupling and postseismic slip (white) models from Perfettini and Avouac [subm.]. Black contours: co-seismic slip from Wei et al. [2012]; dotted green contours: location of past earthquakes from Johnson et al. [2012].

The 2011 Mw 9.0 Tohoku-Oki earthquake surprised the community by an unusually large shallow slip generating a major tsunami [Ozawa et al., Nature, 2011; Wei et al., EPSl, 2011; Simons et al., Science, 2011](fig.1a) . The rupture propagated all the way to the seafloor, with frontal displacement of 15 to 40 m [Ito et al., GRL, 2011; Fujiwara et al., GRL, 2011; Perfettini and Avouac, subm.]. This large shallow slip surprised the community since (1) the upper portion of Megathrust is commonly thought to slip aseismically; (2) previous magnitude 7.5 earthquakes had only been instrumentally recorded along the deeper portion of the Megathrust (fig.1), and (3) interseismic strain accumulation models were not showing a shallow locked patch before the earthquake [Hashimoto et al., Nature, 2009; Loveless and Meade, GRL, 2011]. The lack of resolution of geodetic models near the trench may have hidden an unusual shallow locked patch [Loveless and Meade, GRL, 2011]. However, post- seismic models obtained from joint inversion of offshore and onshore sites have revealed a major shallow postseismic slip, consistent with former interseismic models [Perfettini and Avouac, subm.; fig.1b]

To reconcile the seemingly contradictory observations, Noda and Lapusta [Nature, 2013] have suggested that the shallow megathrust could undergo aseismic slip at low slip rate as well as coseismic slip due to efficient weakening by thermal-pressurization. However, the thermal-pressurization can explain the overshoot as well as the extensive slip as proposed by Ide et al. [Science, 2011], regardless of the rate-strengthening or rate-weakening behavior of the shallow zone. Determining if it was due to an unusual shallow seismic patch or to the rupture of the frontal aseismic part of the megathrust is thus of fundamental importance for future seismic and tsunamigenic risk assessment.

In this study, we thus propose to investigate two opposite scenarios with 2D dynamic simulations of earthquake cycle:
(1) a shallow rate-weakening patch separated by a barrier from the deeper seismogenic zone where magnitude 7.5 earthquakes occurred, and
(2) a shallow rate-strengthening patch.
Both shallow zones will be submitted to strong co-seismic weakening by thermal-pressurization to reproduce the overshoot.
To validate the most likely scenario, simulations results are then compared to the observed seismic cycle of the last 300 years along the Fukushima-Miyagi segment. We then discuss the effect of the free surface on the large shallow slip.

2. Model set-up from observations:

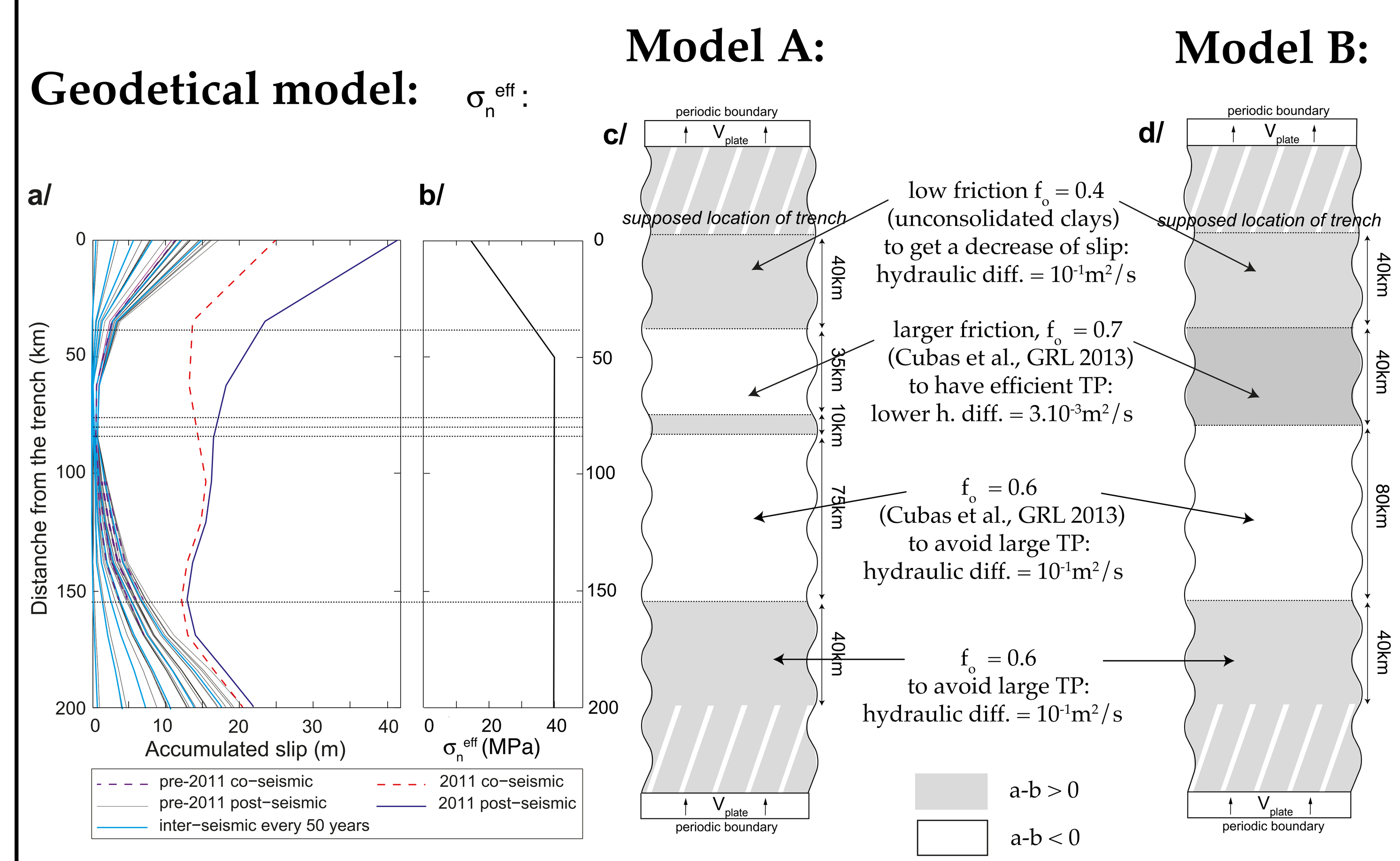


Fig.2: a/ Accumulated slip as a function of the distance from the trench as modeled from geodetic inversions (Perfettini and Avouac [subm.]). b/ Effective normal stress as a function of the distance from the trench. c/ Model A with two rate-weakening patches separated by a rate-strengthening barrier. d/ Model B with a large rate-strengthening shallow zone. All other parameters are set to standard values: $b_{RS} = 0.001$, $b_{Rw} = 0.014$, $a = 0.01$, $\alpha_{th} = 10^{-6}m^2/s$, $\Lambda = 10^5Pa$, $\rho c = 2.7MPa/K$

We used 2D dynamic simulation of earthquake cycles based on Lapusta and Liu, JGR, 2009 and Noda and Lapusta, JGR, 2010, accounting for inertial effects during seismic events and incorporating:

=>> Rate and state friction laws for low slip rate response (Dietrich, Ruina, Blanpied, Marone, Tullis, Scholtz and others),

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

unique tool for simulating earthquake cycle in their entirety
if a-b< 0 : the friction is rate-weakening (RW, EQ nucleation and stick-slip behavior)
if a-b>0: the friction is rate-strengthening (RS)

=>> Thermal pressurization due to frictional heating in a shear zone:
Rapid shear heating during seismic slip increases fault temperature which may increase the pore fluide pressure leading to co-seismic fault weakening, additional to any slow-slip friction behavior.

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

3. Dynamic simulations of earthquake cycles:

Model A: Shallow RW patch submitted to efficient TP

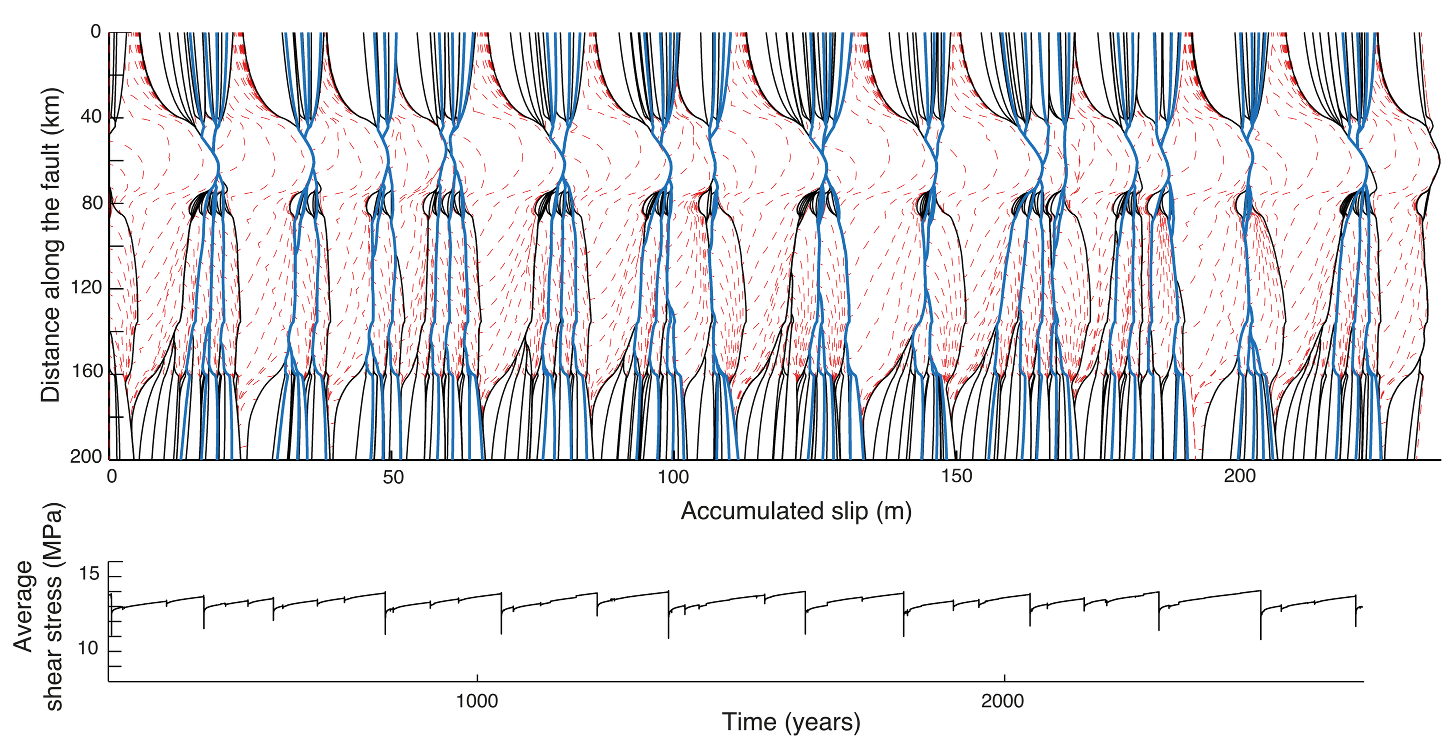


Fig.3: a/ Accumulated slip as a function of the distance along the fault. Dashed red: coseismic slip every 4 seconds, dashed-blue: interseismic slip every 50 years, black: end of each earthquakes. b/ Average shear stress over the fault as a function of time.

- Alternation of moderate and large events
- Large shallow co-seismic and post-seismic slip
but
- Nucleation in the shallow rate-weakening patch
- No re-rupturing of the down-dip patch
- Recurrence time of ~ 200years

Model B: Large RS zone submitted to efficient TP

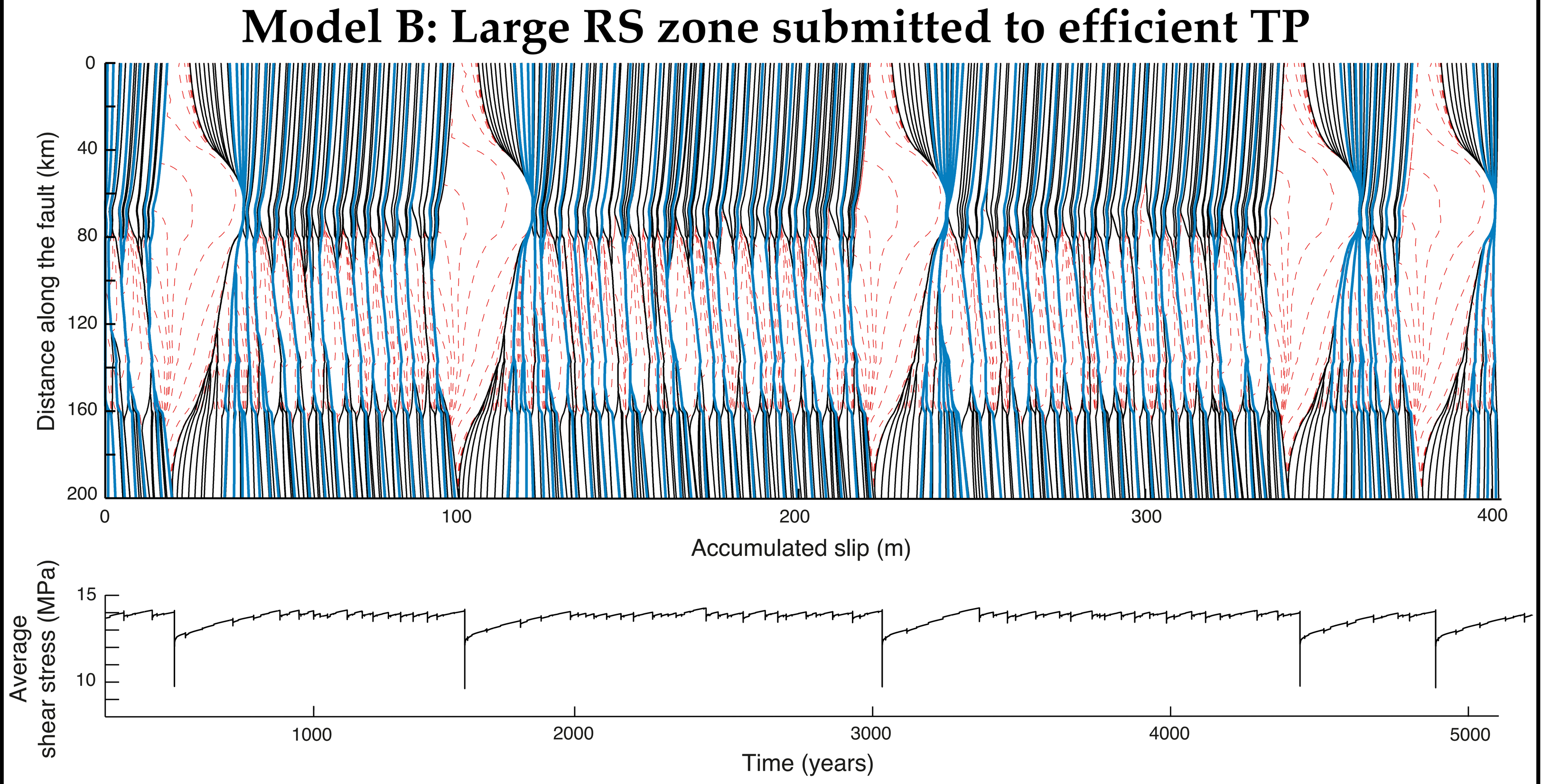


Fig.4: a/ Accumulated slip as a function of the distance along the fault. Dashed red: coseismic slip every 4 seconds, blue: interseismic slip every 50 years, black: end of each earthquakes. b/ Average shear stress over the fault as a function of time.]

- Alternation of moderate and large events
- Large shallow co-seismic and post-seismic slip
- No shallow nucleation
- Re-rupturing of the down-dip patch during large events
- Recurrence time of ~ 1000years

4. Comparison with observations

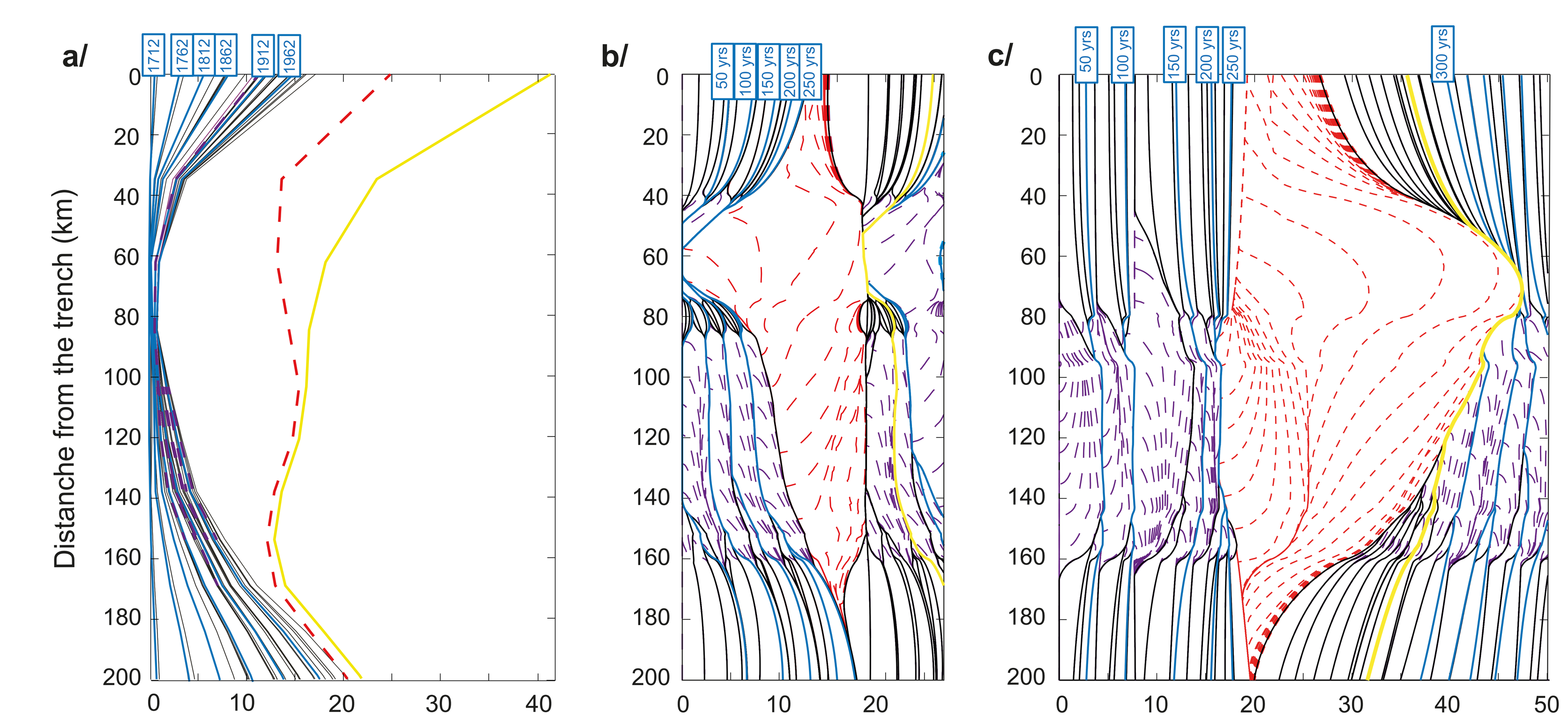


Fig.5: a/ Co-seismic slip in dashed-red; for other events, coseismic slip in purple; interseismic slip every 50 years in blue, end of each earthquakes in black; afterslip from march 11 2011 to 2013 in yellow. b/ and c/ Coseismic slip: dashed-red for major events, purple for minor events, slip every 4 seconds; blue: interseismic slip every 50 years, black: end of each earthquakes; yellow: afterslip of large events.

Backward propagation

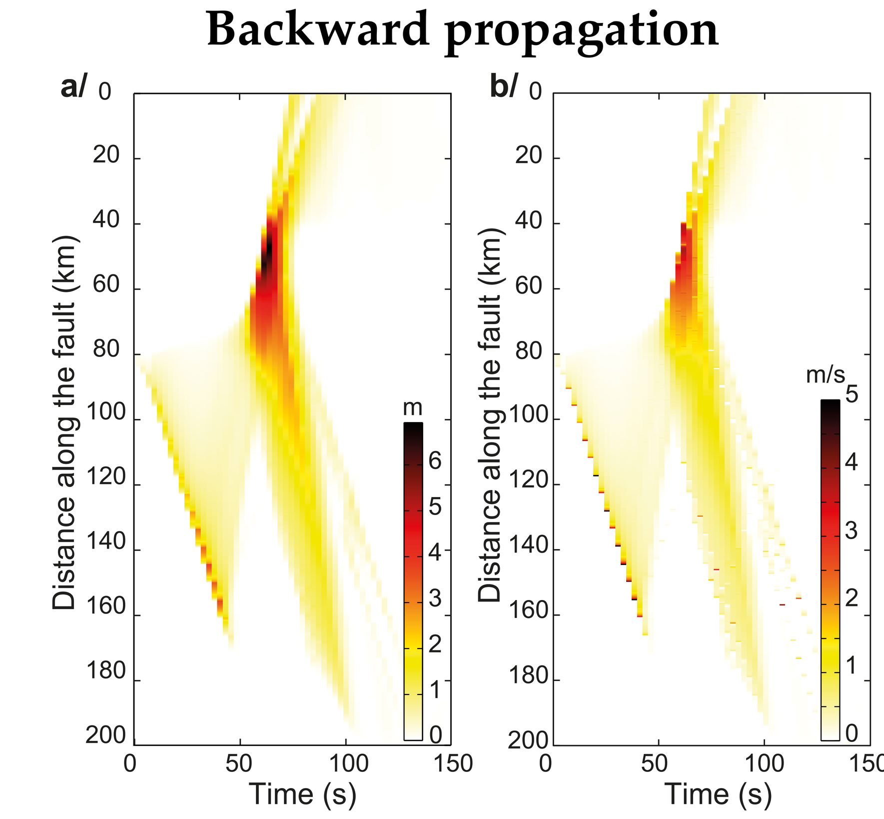


Fig.6: Backward propagation when a large earthquake nucleates at the rate-strengthening/rate-weakening transition (fig. 5). a/ Slip as a function of time and distance from the trench . b/Slip rate as a function of time and distance from the trench (saturated at 5m/s).

Difference in frequency content

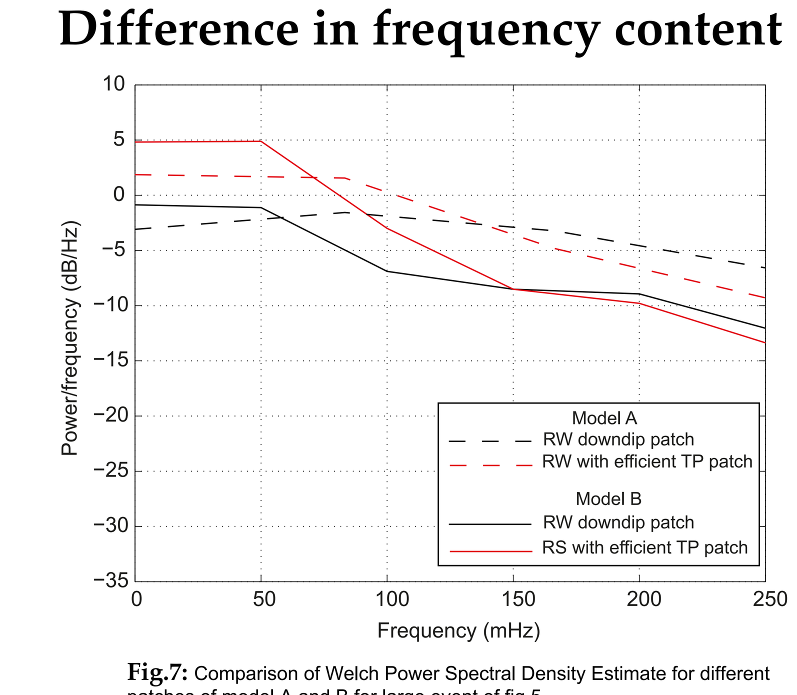


Fig.7: Comparison of Welch Power Spectral Density Estimate for different patches of model A and B for large event of fig.5

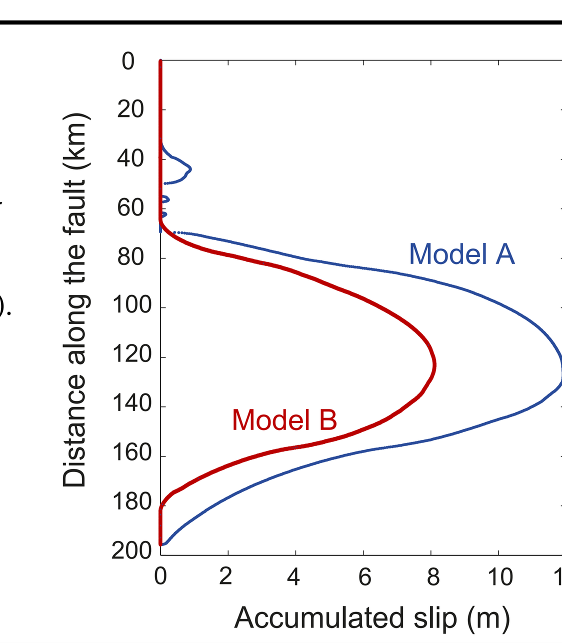
Model A reproduces the distribution with depth of co-seismic slips (from past Mw 7.5 earthquakes and from the 2011 Tohoku-Oki event), as well as interseismic and postseismic slips (Fig.5b). The amount of slip is underestimated with respect to the geodetic model. This is mainly due to the lack of backward propagation of model A. Seince the shallow portion of the megathrust is locked, a large event is necessary to complete a cycle. Each cycle is thus completed in 250 years.

In model B case, the slip distribution is also close to the geodetic observations (fig. 5c). The slip of past Mw 7.5 like earthquakes seem overestimated compared to the geodetical model, due to the 2D profile of the geodetic model. Less interseismic slip is observed between 40 and 80km depth, that can be explained by the resolution of the geodetic model. Large events can occur without any strain accumulation deficit, but a large number of 7.5 magnitude like earthquakes will then be needed to complete a cycle.

In addition, Model B reproduces more Tohoku-Oki characteristics, such as the backward propagation. In the case of a nucleation at the transition between the rate-strengthening and rate-weakening patches, the timing of the rupture propagation is very well reproduced (fig. 6.) The rupture first propagates during 45s downdip, we then observe extensive shallow slip between 55 and 80s, and a re-rupture of the downdip megathrust over 100s, very similar to what as been observed by Ide et al. [2011] for the Tohoku-Oki event.
During the Tohoku-Oki event, we also observed high frequencies along the deep portion of the Megathrust which experienced less slip and low frequencies along the shallow Megathrust where the maximum of slip occured [Simons et al., Sciences, 2011; Meng et al., 2011]
The difference in frequency content is observed for both models (fig.7). This difference had already been reported by Noda and Lapusta [Nature, 2013], and is mainly due to the difference in thermal-pressurization efficiency. The difference is however stronger with model B probably because of the enhanced thermal-pressurization.

5. Free Surface

To investigate the role of the free surface on the large shallow slip, we ran dynamic simulations using Pylith software (CIG, Aagaard et al., 2013) accounting for free surface but no shear induced temperature variations. The objective is to run two end-member simulations:
- with same properties as Models A and B but without thermal-pressurization (fig.8).
- with a slip weakening law to get enhanced weakening. The lower effective friction distribution reached by our previous simulations will be used as the final friction. L will be set to the amount of slip necessary to reach the lower effective friction with our previous model.
In both cases, with the normal and shear stress distributions of our previous simulations at the initiation of a large earthquake at the transition between the RS and RW patch, we found larger slip. Lower stresses were then used for fig. 8.
Without strong weakening, earthquakes do not reach the surface.



6. CCL

Both models reproduce the alternation of deep moderate events and large events with a major shallow slip. However, the seismic cycle characteristics are better reproduced by Model B: the thousand years reccurrence time of major events, the updip interseismic slip without shallow events, as well as the large shallow postseismic slip.
Model B also reproduces more specific characteristics of the Tohoku-Oki event: the distribution of slip, the backward propagation as well as the difference in the frequency content.
We thus conclude that a megathrust characterized by a shallow low permeability can undergo efficient thermal-pressurization leading to the frontal propagation of earthquakes, regardless of their rate-and-state behavior.
However, in the case of a rate-strengthening zone, the recurrence time of such events is larger and can not be deduced from accumulated strain deformation models. As a consequence, seismic and tsunamigenic risk assessment of megathrust might need to be revisited.