Upper plate dynamic response to a sequential elastic rebound and slab acceleration in laboratory-scale subduction megathrust

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Key Points:

- Analog megathrust earthquake experiments provide high-resolution observations to evaluate the surface deformation signals from the shallow megathrust
- Surface displacement time-series suggest a sequential elastic rebound of the upper plate and slab during great subduction megathrust earthquakes
- Dynamic slip reversal may be caused by rapid restoration of the upper plate after dynamic overshooting and amplified upper plate motion

Abstract

An earthquake-induced stress drop on a megathrust instigates different responses on the upper plate and slab. We mimic homogenous and heterogeneous megathrust interfaces at the laboratory scale to monitor the strain relaxation on the two elastically bi-material plates by establishing analog velocity weakening and neutral materials. A sequential elastic rebound follows the coseismic shear-stress drop in our elastic-frictional models: a fast rebound of the upper plate and the delayed and smaller rebound on the slab. A combination of the rebound of the slab and the rapid relaxation (i.e., elastic restoration) of the upper plate after an elastic overshooting may accelerate the relocking of the megathrust. This acceleration triggers/antedates the failure of a nearby asperity and enhances the early slip reversal in the rupture area. Hence, the trench-normal rearward displacement in the upper plate may reach a significant amount of the entire interseismic slip reversal and speeds up the stress build-up on upper plate backthrust. Moreover, the backthrust switches its kinematic mode from a normal to reverse mechanism reflecting the sense of shear on the interface during coseismic and postseismic stages.

Plain Language Summary

Subduction zones, where one tectonic plate slides underneath the other, host the largest earthquakes on earth. Two plates with different physical properties define the upper and lower plates in the subduction zones. A frictional interaction at the interface between these plates prevents them from sliding and builds up elastic strain energy until the stress exceeds their strength and releases accumulated energy as an earthquake. The source of the earthquake is located offshore; hence illuminating the plates' reactions to the earthquakes is not as straightforward as the earthquakes occur inland. Here we mimic the subduction zone at the scale of an analog model in the laboratory to generate analog earthquakes and carefully monitor our simplified model by employing a high-resolution monitoring technique. We evaluate the models to examine the feedback relationship between upper and lower plates during and shortly after the earthquakes. We demonstrate that the plates respond differently and sequentially to the elastic strain release: a seaward-rearward motion of the upper plate and an acceleration in the lower plate sliding underneath the upper plate. Our results suggest that these responses may trigger another earthquake in the nearby region and speed up the stress build-up on other faults.

1 Introduction

Large megathrust earthquakes (i.e., slip) cause a shear stress drop on the subduction interface that drives the subduction system from a quasi-steady state interseismic loading stage (i.e., stick) to a temporarily non-stationary (transient) relaxation mode. Although the static coseismic and interseismic surface deformation of subduction megathrust has been analyzed in much detail (e.g., Chlieh et al., 2008; Loveless & Meade, 2011; Moreno et al., 2010; Schmalzle et al., 2014; Simons et al., 2011), the dynamic motion of the upper plate caused by the transition from unstable (stable) to stable (unstable) deformation has received somewhat less attention (Bedford et al., 2020). The spatial and temporal resolution of the near-source observations is the main challenge of dynamic instability analysis (Kosari et al., 2020). The transition from unstable to stable (i.e., postseismic phase) involves different mechanisms over the shallow and deep parts of the subduction system, which are rheologically dominated by elastoplastic (lithosphere) and viscoelastic (asthenosphere) behavior, respectively (e.g., Wang *et al*., 2012; Weiss *et al.*, 2019). To date, several postseismic processes have been identified that can be seismic and aseismic, namely (1.) afterslip along the megathrust (e.g., Hsu *et al.*, 2006; Bedford *et al.*, 2013; Hoffmann *et al.*, 2018), (2.) viscoelastic relaxation of the lower crust and mantle of both slab and upper plate (e.g., Sun et al., 2014; Li et al., 2015) and (3.) crustal faulting in the upper plate (extensional), accretionary wedge (compressional), and shallow slab (extensional) (e.g., Kato et al., 2011; Hicks and Rietbrock., 2015; Hoskins *et al.*, 2021). All these non-stationary mechanisms are triggered from stress drop on the interface; hence, the stress drop pattern and magnitude and, on the other hand, the dynamics of the slip are the main controlling factors.

Only a handful of megathrust earthquakes are relatively densely monitored. In many of these cases, the early postseismic surface displacement above the ruptured asperity, which is remotely offshore, exhibits intriguing signals that are interpreted differently (e.g., Bedford et al., 2016; Heki & Mitsui, 2013; Tomita et al., 2017; Watanabe et al., 2014). While the postseismic viscoelastic signal from the relaxing asthenosphere appears with a characteristic long-term pattern and large-scale wavelength (far-field, hundreds of kilometers scale) (e.g., Wang *et al.*, 2012; Sun and Wang, 2015), the postseismic elastic-frictional processes (i.e., relocking and afterslip) show relatively steep gradients and short-wavelength (tens of kilometers scale) characteristics. These short-wavelength postseismic signals, typically manifested in sustained seaward motion, interfere in the

near-field with the presumably steadier interseismic re-loading process that has a reverse kinematic sense (i.e., landward motion in the upper plate). Such interference causes surface displacement above the ruptured patch and nearby regions to be characterized by short time and short distance changes in amplitude and direction, often causing local shear and vertical axis rotations. Such "enigmatic patterns" are notoriously difficult to interpret, and discourse is rising about their relevance for seismic hazard (e.g., Loveless, 2017; Melnick *et al.*, 2017; Yuzariyadi and Heki, 2021). Moreover, it is still not evident how the rupture propagation direction may cause these enigmatic patterns. We here contribute to this discussion using observations and interpretations of controlled analog megathrust experiments highlighting the potential variability of deformation signals in subduction zones.

This study aims to address the sequential upper plate and slab elastic-frictional response during the coseismic shear-stress drop and its early postseismic stage in a subduction megathrust system by employing a series of carefully monitored analog modeling experiments. To examine the feedback relationship between the upper plate and the slab, we investigate two generic seismotectonic scale models representing seismically homogeneous and heterogenous subduction

megathrust systems and capture the model's surface displacements by employing a high resolution and high speed "laboratory seimogeodetic" method.

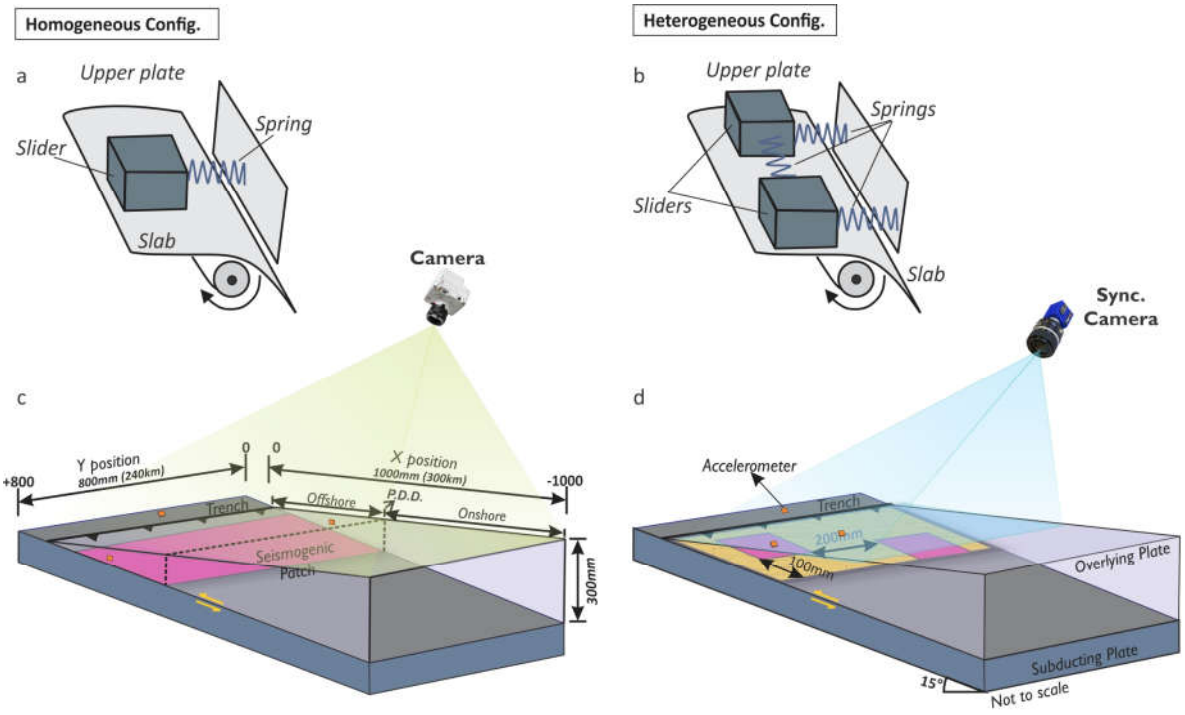

Figure 1. *Scheme of the seismotectonic scale model's geometry and configuration: a and b demonstrate our conceptual systems of coupled spring sliders as depicted by Ruff and Tichelaar, (1996). b and c represent homogenous and heterogeneous configurations, respectively. The yellow (matrix) and magenta (main slip patch) rectangles demonstrate the seismogenic patches which generate repeating earthquake and megathrust events, respectively. P.D.D. represents the projection of the down-dip limit of the seismogenic patch on the model surface. The small orange rectangles show the different configurations of accelerometers. The frictional behavior of both velocity weakening materials used in the matrix and main slip patch has been visualized in Figure 2.*

2 Methodology: Seismotectonic scale modeling

Seismotectonic scale models have been established to generate physically self-consistent analog megathrust earthquake ruptures and seismic cycles at the laboratory scale (Rosenau et al., 2009; 2017, and references therein). They have been used to study the interplay between short-term

elastic (seismic) and long-term permanent deformation (Rosenau & Oncken, 2009), slip variability (Rosenau et al., 2010), earthquake recurrence behavior and predictability (Corbi et al., 2020; 2019; 2017; Rosenau et al., 2019), the linkage between offshore geodetic coverage and coseismic slip model (Kosari et al., 2020) and to illuminate details of the seismic cycle (Caniven & Dominguez, 2021). Analog models are downscaled from nature for the dimensions of mass, length, and time to maintain geometric, kinematic, and dynamic similarity by applying a set of dimensionless numbers (King Hubbert, 1937; Rosenau et al., 2009; 2017). The models generate a sequence of tens to hundreds of analog megathrust earthquake cycles, allowing the analysis of the corresponding surface displacement from dynamic coseismic (e.g., Movi S1) to quasi-static interseismic stages.

2.1 Experimental setup and material behavior

2.1.1 Model scaling and similarity

The small-scale laboratory models should share geometric, kinematic, and dynamic similarities with their prototype to be representative of a natural system as all lengths, time, and forces scale down from the prototype in a consistent way dictated by scaling laws (King Hubbert, 1937). According to Rosenau et al. (2009), we consider different timescales for coseismic and interseismic deformation phases. They introduced a "dyadic" timescale that recognizes two dynamically distinct regimes of the seismic cycle: the quasi-static interseismic regime, where inertial effects are negligible due to the slow deformation rates, and the dynamic coseismic regime, which is controlled by inertial effects. This allows us to slow down the earthquake rupture and speed up the loading phase, keeping dynamic similarity in both stages (Table S1).

2.1.1.1 Interseismic phase scaling

In the quasi-static regime of the inter-seismic phase, scaling is identical to the common scaling of long-term processes to the lab. For long-term tectonic studies involving materials that deform brittle or viscous material, two dimensionless numbers, the Smoluchowski and Ramberg (Ramberg, 1967) numbers, are of interest according to the deformation regime.

The Smoluchowski number is used to establish dynamic similarity in the case of brittle deformation. This dimensionless number is defined as the ratio between overburden stress and material strength.

Equation 1:

$$Sm = \frac{\rho g l}{C}$$

where ρ is density (kg.m^{-3}), g gravitational acceleration (ms^{-2}), C cohesion (Pa), and l a characteristic length.

According to the Smoluchowski number, cohesion should scale with density and length scale following the scaling law:

Equation 2:

$$C* = \rho* L*.$$

where the asterisks represent the model / prototype ratios (i.e., C∗ = C model/ C prototype, ρ∗ = ρ model/ρ prototype, L∗ = L model/ L prototype). All quantities with the stress unit (e.g., strengths) and elastic moduli share the same scaling.

2.1.1.2 Coseismic phase scaling

For a short-term time (i.e., coseismic and postseismic stages), Froude scaling is used to reach dynamic similarity (Rosenau et al., 2009):

Equation 3:

$$Fr = v/\sqrt{gl} = \text{inertia /gravitation}$$

while the timescale of the model should be the square root of the length scale:

Equation 4:

$$T* = \sqrt{L*}$$

Note that all accelerations are the same in the model as in the prototype. The Cauchy number can be used for reaching the stress scale in the dynamic regime (Rosenau et al., 2009):

Equation 5:

$$Ca = \rho v^2/B = \text{inertia/elasticity}$$

where B is an elastic modulus.

The model parameters without a dimension should be the preserved Poisson's ratio υ, the friction coefficient, and the friction rate and state parameters. An exception to this general scale independence of dimensionless parameters is the moment magnitude Mw that is related to the seismic moment (unit Nm) but defined as being dimensionless:

Equation 6:

$$Mw = 2/3 \log_{10}(M_0) - 10.7$$

Here I scale up analog earthquake moment magnitude non-linearly by applying the scale factor of seismic moment M0*:

Equation 7:

$$M^{prototype}{}_w = M^{model}{}_w - 2/3 \log M_{0^*}$$

Typically, magnitudes of analog earthquakes are in the range of −6 to −7, which correspond to earthquakes of Mw =8–9 in nature.

2.1.2 Model geometry and configuration

In the presented 3-D experimental setup modified from Rosenau *et al.* (2019) and introduced in Kosari *et al.* (2020), an ocean-continent subduction forearc model is set up in a glass-sided box (1,000 mm across strike, 800 mm along strike, and maximal 300 mm deep) with a 15° dipping, elastic basal rubber conveyor belt (the model slab), and a rigid backwall. A flat-topped wedge made of an elastoplastic sand-rubber mixture (50 vol.% quartz sand G12: 50 vol.% EPDM-rubber) is sieved into the setup representing a 240 km long forearc segment from the trench to the volcanic arc (Figures 1).

At the base of the wedge, zones of velocity weakening controlled by granular stick-slip ("seismic" behavior) are realized by emplacing compartments of either sticky-rice ("main slip patches") or fine-grained salt ("matrix"), which generate quasi-periodic large and small slip instabilities, respectively (Figures 1), mimicking megathrust earthquakes of different size and frequency. Large stick-slip instabilities in the main slip patch(es) (MSP) are almost complete and recur at low frequency (~0.2 Hz), while those in the matrix are partial (<10%) and at high frequency (~10 Hz) at a prescribed constant convergence rate of 50 µm/s. This bimodal behavior is intended to mimic rare great (M8-9) earthquakes versus small frequent repeating events (e.g., Uchida and Bürgmann, 2019; Chaves *et al*., 2020) in a creeping environment akin to established concepts of the shallow subduction megathrust (e.g., Bilek and Lay, 2002). The wedge itself and the conveyer belt respond elastically to these basal slip events similar to crustal rebound during natural subduction megathrust earthquakes. Upper plate faults (in our case, a single backthrust fault) gradually emerge self-consistently downdip and up-dip of the main slip patches and accommodate plastic upper plate

shortening over seismic cycles, as documented in earlier studies (Kosari et al., 2020; Rosenau et al., 2009, 2010; Rosenau & Oncken, 2009).

Two different seismic configurations of the shallow part of the wedge base (the megathrust) represent the depth extent of the seismogenic zone in nature. In the first configuration, hereafter named "homogeneous configuration", a single large rectangular stick-slip patch (Width*Length=200*800 mm) is implemented as the main slip patch (MSP). This setup represents a system of a homogeneous seismogenic zone with temperature-controlled depth range and no variation along strike generating M9 type megathrust events similar to the 2004 Sumatra earthquake (Ammon et al., 2005; Lay et al., 2005). In the second case, hereafter named "heterogeneous configuration", two square-shaped MSPs (200*200mm) have been emplaced, acting as two medium-size seismogenic asperities generating M8-9 type events similar to, for example, the 2010 Maule (Chile) earthquake (Moreno et al., 2010). These two patches are at a center-to-center distance of 400mm and 100mm in trench-parallel and trench-normal direction, respectively, while they are surrounded by a salt matrix hosting frequent small events (Figures 2). For minimizing boundary conditions, these MSPs are placed at a reasonable distance from the sidewalls. Backthrusts accommodating long-term permanent wedge shortening and uplift emerge in the upper plate in both configurations during the model evolution. They are rooted in the down-dip limit of the stick-slip patch(es), where compressive stresses peak along the plate interface

during the interseismic period. Because this backthrust shows normal faulting mechanism during the coseismic stage, we term this fault “antithetic fault”.

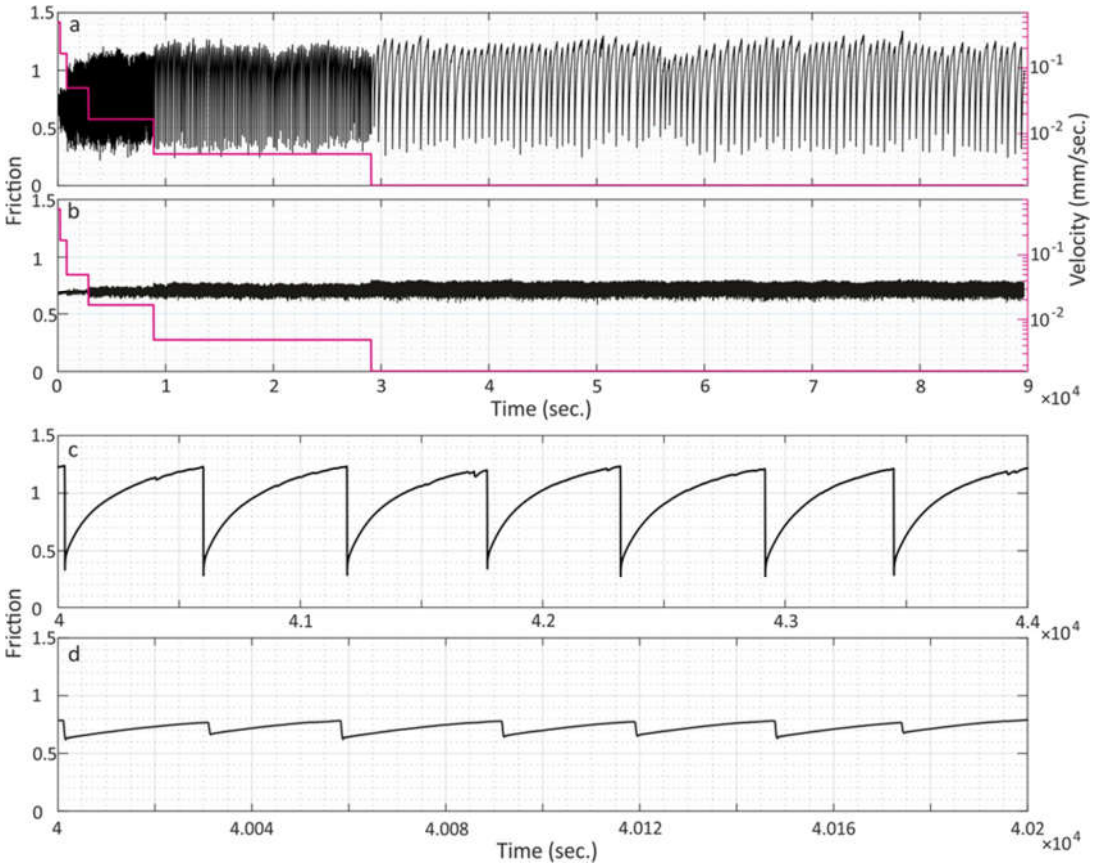

Figure 2. *Friction drop time-series measured during velocity stepping tests under constant normal load simulating coseismic and interseismic friction drop and increase. The periodic friction drops represent analog earthquakes. a and c (main slip patch in Figure 1) and magenta (matrix in Figure 1) demonstrate the seismogenic patches which generate megathrust events and repeating earthquakes, respectively. c and*

d show seven seismic cycles from both materials. Note that the recurrence of the repeating earthquake is approximately 20 times shorter than the megathrust event.

2.2 Experimental monitoring: Laboratory seismogeodesy

A combination of seismological and geodetic methods applied to laboratory-scale models allows us to monitor the model's deformation at high spatial and temporal resolution and derive observational data equivalent to natural observations.

2.2.1 Laboratory geodesy

To capture horizontal micrometer-scale surface displacements associated with analog earthquakes at microsecond scale periods, we monitor the model surface with a highspeed CMOS (Complementary Metal Oxide Semiconductor) camera (Phantom VEO 640L camera, 12 bit, 4 MPx) intermittently at 250 Hz (Figure 1). A complimentary high-speed camera (200 Hz) is added to the monitoring system for synchronizing with the accelerometer. This synchronization allows differentiating the potential quasi-harmonic oscillations caused by dynamic frictional instability (i.e., coseismic) from event signals. Digital image correlation (e.g., Adam et al., 2005) has been applied at high spatial resolution (~0.02 mm) via the DAVIS 10 software (LaVision GmbH, Göttingen/DE). Data are processed to yield observational data similar to those from an ideal dense and full coverage (on- and offshore) geodetic network, that is, velocities (or incremental displacements) at locations on the model surface. We use an analog geodetic slip inversion technique (AGSIT, Kosari et al., 2020) to invert surface displacements for model megathrust slip and backslip distribution over earthquake cycles. Note that although all observations can be

upscaled to nature using scaling laws (King Hubbert, 1937; Rosenau et al., 2009, 2017), we here report all values at the laboratory scale.

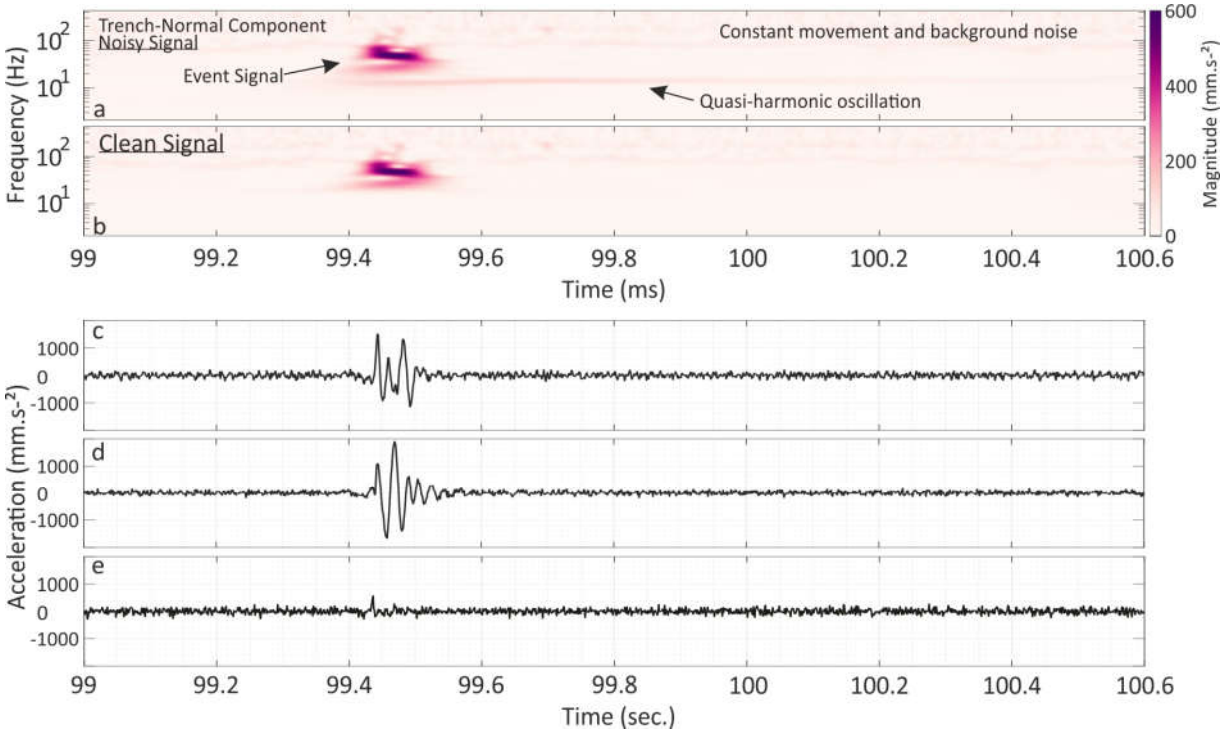

Figure 3. *Differentiating Quasi-harmonic oscillation and event-related signal. a and b represent the scalogram of the signal before and after filtering the quasi-harmonic oscillations out. c and d are the normal-trench acceleration derived from three sensors located on the wedge (c and d) and the basal rubber conveyor belt (e).*

2.2.2 Laboratory seismology

The experiments are additionally monitored using triaxial capacitive accelerometers (MEMS: micro electromechanical systems). The sensors can measure with a sampling frequency of 10 kHz and a measuring range from 0 to ± 2 g. The bandwidth of the sensors depends on the sensor type and axis, ranging from 500 Hz to 1500 Hz. We established three sensors positioning in different

configurations to cover any possible motion in the setup, from the coseismic surface motions to the harmonic oscillations. The sensors run at 1 kHz to avoid the aliasing effect.

3 Results: Observations and interpretations

In the following, we analyze high-resolution time-series of surface and slab displacements and slip along the megathrust and an emergent upper plate fault over several seismic cycles. We analyze the heterogeneous model in-depth (compared to the homogeneous configuration) to capture the details of upper plate and slab responses in the coseismic and early-postseismic stages (Figures 4 & 6). We consider the Coulomb Failure Stress Change (ΔCFS) over coseismic and early-postseismic stages and its impact on model slab velocity changes (Figures 5). Subsequently, we evaluate the elastic rebound of the slab and the upper plate in response to the mainshock-induced stress changes. Finally, we explore the combined effect of the stress changes and elastic rebounds on the accumulation of the horizontal displacement in the upper plate and earthquake triggering (Figure 10).

3.1 Kinematic observations and interpretations

3.1.1 Time-variable surface displacements and slip over an analog earthquake and the early postseismic

As the recorded signals may occur at different scales, the scalogram of the synchronized accelerometer has been used to differentiate coseismic surface displacement versus machine-related oscillation and quasi-harmonic oscillations caused by dynamic frictional instability (Figure 2). The scalogram shows the absolute value of the waveforms, plotted as a function of time and frequency. The high-frequency signals (>60 Hz) include the constant vibration of the machine and background noise. The slip event's elastic wave frequency ranges from 20 to 60 Hz, and the lower values (<20 Hz) represent the event-triggered quasi-harmonic oscillations while it can also be tracked on the model's sidewalls after each event. The oscillation is removed from the signals using a highpass filter. The timing of each snapshot from the synchronized camera is marked on

the cleaned waveform to disregard the oscillation, and accordingly, 20 snapshots are selected to cover the coseismic and early-postseismic stages.

Figures 4c and d visualize the cumulative surface displacements averaged over the area above the seismogenic zone along the strike of the megathrust for both configurations (see Figures S1 & S2 for 2D surface displacement map). Figure 5a-b shows corresponding snapshots of the inverted slip along the megathrust and upper plate fault (antithetic to the megathrust) inverted from surface

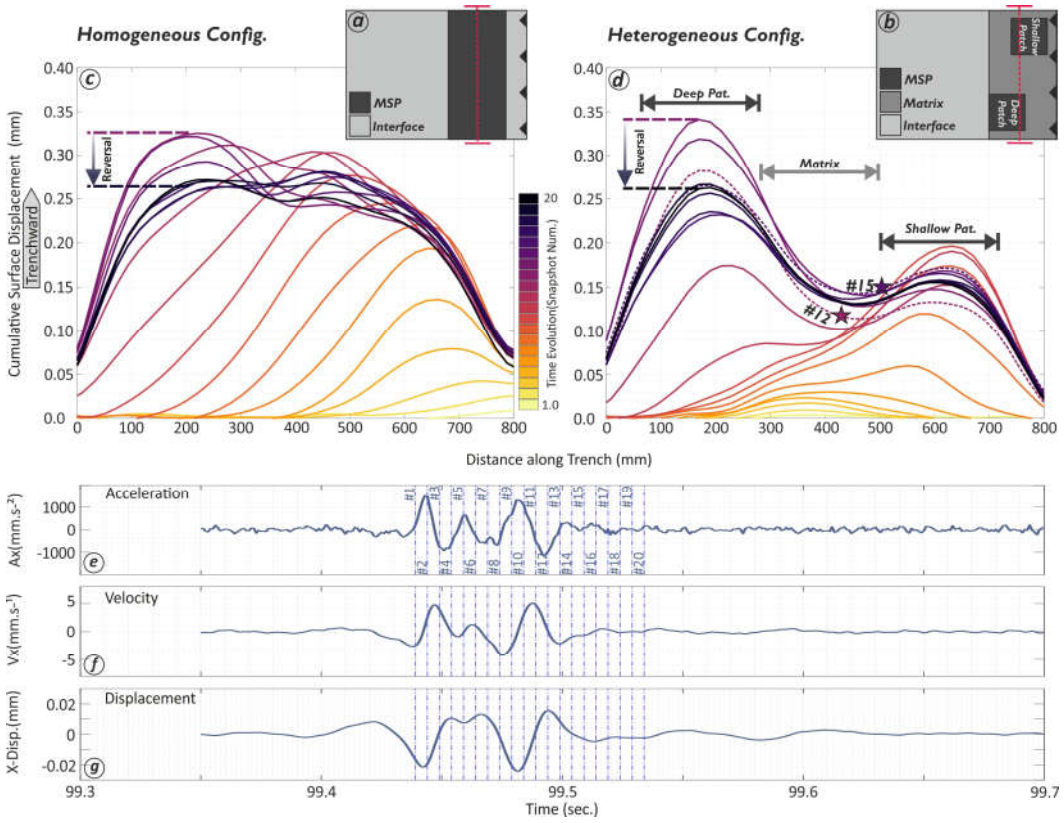

Figure 4. *Model setup and exemplary evolution of coseismic and early-postseismic surface deformation in two scenarios. a and b: Plan view of the seismotectonic scale models' configurations; Light, medium, and dark gray colors represent the velocity neutral ("aseismically" creeping) interface, a velocity weakening matrix characterized by microslips ("microseismicity"), and the main slip patch(es) (MSP) where large analog megathrust earthquake slip occurs ("seismogenic zone" or "asperity"), respectively. The red dashed lines show the profiles along which the cumulative surface displacement is shown in c and d. The downward vectors indicate surface displacement reversal during the early-postseismic stage interpreted as backslip. The corresponding surface deformation maps derived from the synchronized camera are visualized in figures S1 and S2. The stars on the dashed lines show the selected surface displacement*

snapshots for slip modeling in Figure 5. e-g show an exemplary acceleration, velocity, and displacement of the one sensor located on the wedge (Figure 2c). The timing of each snapshot has been marked on the waveforms.

displacements. In the homogeneous system, the rupture initiates at the periphery of the stick-slip zone, grows radially in a crack-like fashion, and then laterally propagates as a pulse across it (Figures 4c and S1). While the rupture arrests on the opposite side, the early rupture area seems to have relocked and apparently accumulates backslip at an even higher rate than the plate convergence rate. We term this kinematic observation "postseismic slip reversal" as it appears as a normal faulting mechanism in its formal inversion. However, the observation could also be explained by locking of the interface (no slip) combined with transient slab acceleration. Whatever the source, the slip reversal is short-lived and propagates along the interface as the pulse behind the rupture. At the surface, this early instantaneous backslip (slip reversal) on the megathrust reduces the cumulative trenchward surface displacement (Figure 3c). The lack of significant afterslip in the MSPs and the matrix immediately after the coseismic stage and the rearward surface displacement of the upper plate suggests a nearly complete stress-drop allowing the MSP and matrix to enter the relocking phase.

In the heterogeneous system, the rupture nucleates in the matrix, where a small foreshock event first triggers the failure of the shallow patch followed by failure of the deeper patch (Figures 4d and S2). Because of the limited along-strike dimension of the MSP, megathrust failure occurs as a sequence of two discontinuous crack-like failures in contrast to the more continuous pulse-like failure in the uniform model. Again, a postseismic slip reversal occurs in the shallow MSP while the deep MSP is still in the process of failing (Figure 5a) and where slip reversal occurs slightly later. The rearward displacement of the upper plate predominantly occurs above the site of the two moderate-size MSPs. In other words, the MSPs, which host large slips, undergo larger postseismic slip reversal than the matrix.

3.1.2 Upper plate displacement accumulation

In both configurations, the postseismic backslip initiates immediately following the main event on the patches. The maximum amount of the backslip-caused surface displacement could reach 30% of the maximum coseismic surface displacement. The trench-normal surface displacements of the

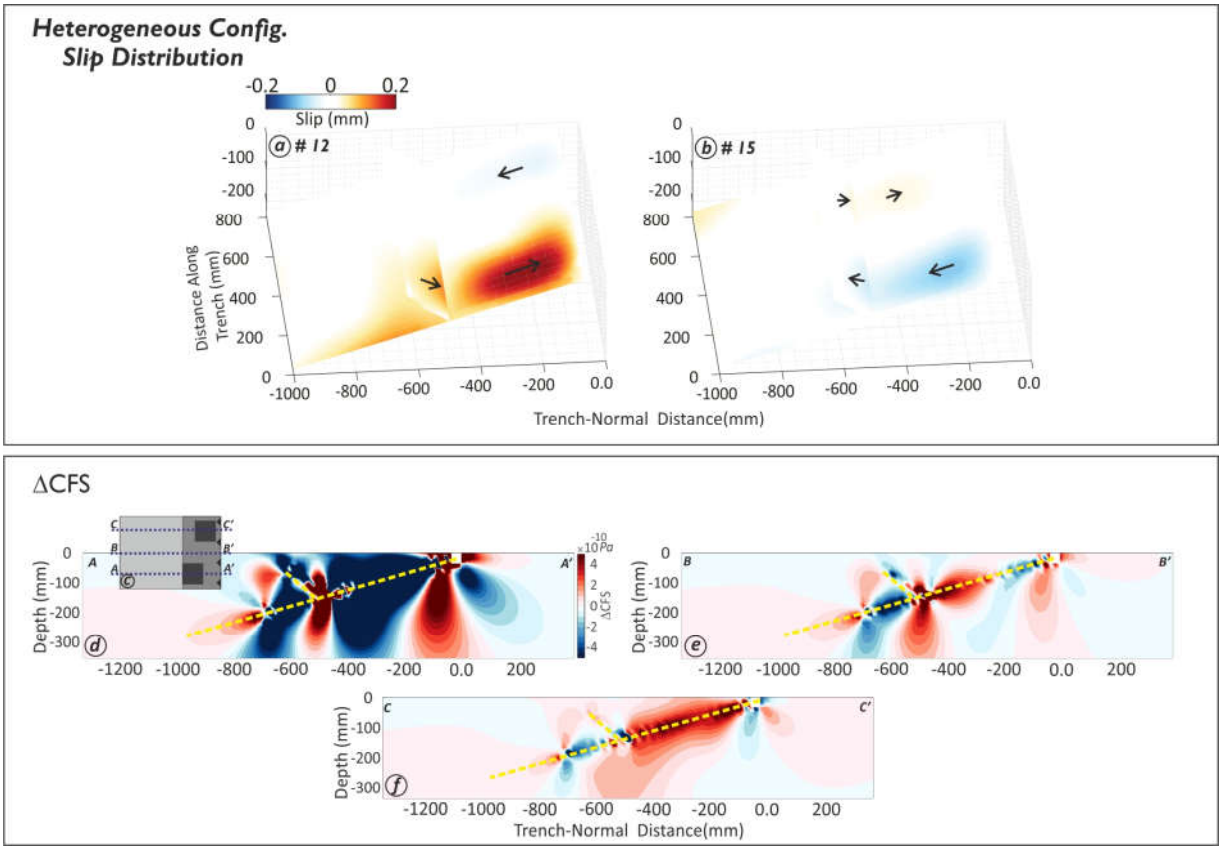

Figure 5. *Upper panel: Slip models of the selected increments (marked in Figure 1d) in the heterogeneous system for demonstrating slip/backslip distribution in the MSPs and the antithetic upper plate fault. The vectors indicate the relative sense of slip but are not to scale. The lower panel represents three trench-normal profiles of Coulomb failure stress changes (ΔCFS) from the slip model snapshot #12 in the heterogeneous configuration. Inset shows the location of profiles on the model surface.*

coseismic, postseismic, and interseismic stages of an earthquake cycle have been visualized in Figure S5. Comparing the magnitude of the cumulative surface velocities reveals that the horizontal surface displacement (mostly seafloor in nature) during the early parts of the postseismic stage could reach up to 20-30% of the entire interseismic backslip.

In the upper plate, we observe a synthetic and kinematically consistent reactivation of the backthrust, i.e. as a normal fault during the coseismic megathrust slip phase and as a thrust in

response to backslip on the megathrust. A slip ('trenchward') or backslip rearward ('landward') on the interface may re-activate the antithetic fault in the upper plate with a normal (e.g., #12 in Figure 5a) and/or a reverse sense of movement (e.g., #15 in Figure 5b), respectively. Following the slip distribution model (Figure 5a & b), two segments of the upper plate fault may move in opposite directions. This behavior likely reflects the shear sense on the MSPs. Particularly, in the upper plate fault, which in our experiments is rooted in the plate interface at the down-dip end of the seismogenic zone, the sense of slip (slip/backslip) on the seismogenic zone directly controls the slip mechanism of the antithetic fault.

Based on the antisymmetric part of the two-dimensional velocity gradient tensor, we calculate the vertical axis rotation of the upper plate (Figure 8, the methodology can be found in Allmendinger et al., 2007). The uniform and dense distribution of the observation points at the model surface allows us to use the nearest neighbor points to calculate each point's rotation around a vertical axis. In the case of coseismic trenchward displacement of the upper plate, a divergent motion in the surface velocities above the rupture zone leads to a (sub-) symmetric vertical rotation while it may also rotate the adjacent areas. However, there is no significant rotation above the nearby (deeper) asperity. On the other hand, in the stage that two MSPs are on opposite modes (loading vs. unloading), the surface velocities above the loading MSP show a convergence mode as it may enhance the shortening rate in the early postseismic stage.

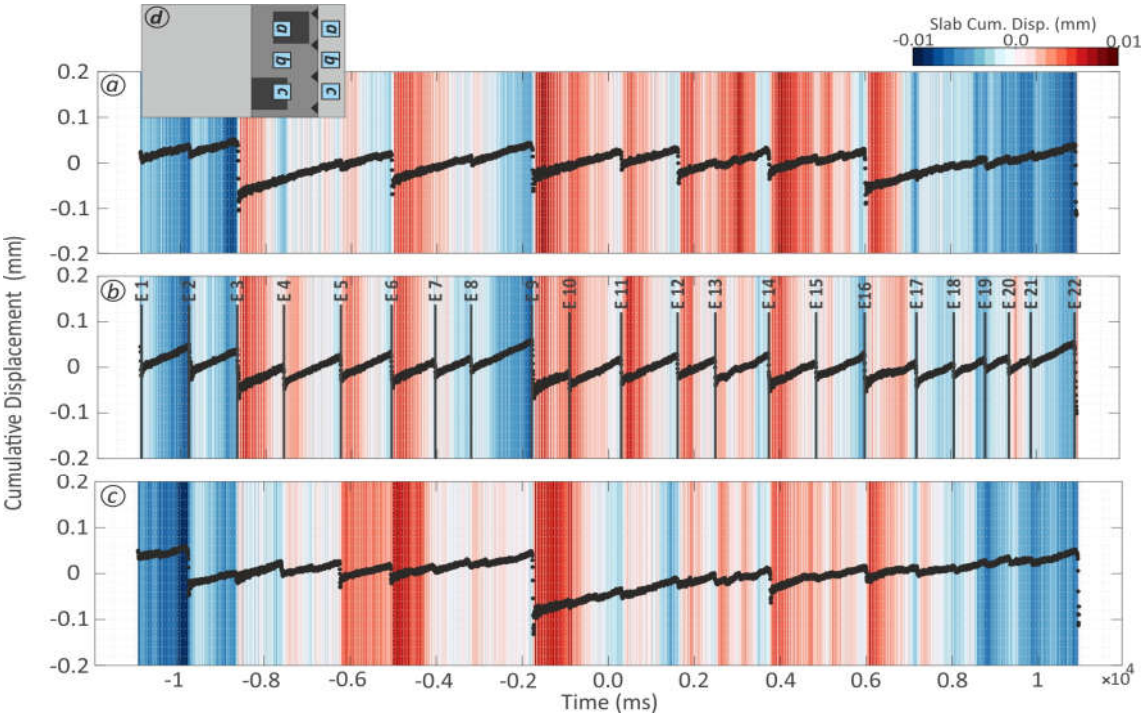

***Figure 6**. Upper plate time-series overlayed on the slab time-series (background colormap) from the heterogeneous configuration (see Figure S4 for the homogenous configuration). Note the location of the profiles relative to the upper plate and slab. The vertical lines (E1-E22) indicate abrupt surface displacement changes above the matrix. The warm color shows the landward displacement of the slab. Larger events instigate greater slab responses (Figure 7).*

3.2 Dynamic interpretations: Coulomb failure stress changes

To constrain the triggering dynamics, we consider static stress changes in our models. Based on the slip and backslip pattern documented above, we derive Coulomb failure stress changes (ΔCFS) (e.g., Lin and Stein, 2004) induced by the mainshock on the megathrust and the antithetic fault to get insight into zones of enhanced/decreased CFS (lower panel in Figure 5 and S3). We calculate the ΔCFS for the coseismic and postseismic stages of an event for the heterogeneous system on the receiver faults with the same sense and orientation as slip (thrust receiver faults in Figure 5) and backslip (normal receiver faults Figure S4) on the interface. In the shallow part of the plate interface (profile c-c'), a negative ΔCFS lobe is bounded by two positive ΔCFS lobes. The ΔCFS is highly enhanced at the upper limit of the rupture, where the shallow part of the interface ruptures and is adjacent to the main slip zone on the slab. The ΔCFS on the normal receiver fault (Figure S3) shows a decrease and an increase at the up-dip limit of the deep (in slip phase) and shallow (in backslip phase) MSPs on the slab, receptively.

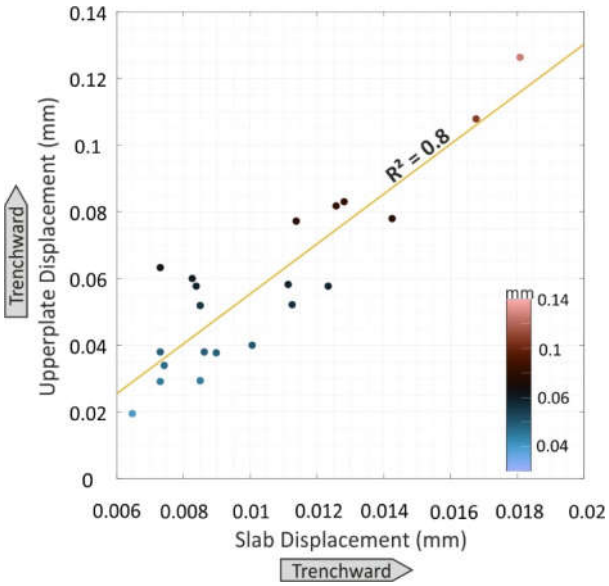

Figure 7. *Correlation between the upper plate and slab trenchward (landward) displacements during coseismic and early-postseismic stages.*

Another lobe of positive ΔCFS is extended to the down-dip limit of the main rupture area, where the antithetic fault in the upper plate appears during the model evolution (Figure 5). The deep-rooted antithetic fault, which imposes a significant discontinuity in the upper plate, perturbs the inner-wedge stress state and highly increases the CFS at the conjunction of the interface and the antithetic fault. Hence, it builds up stress and enhances the ΔCFS in the upper plate. However, the uncertainties in the slip distribution models at the conjugation zone may affect the ΔCFS's uncertainty. A relatively strong increase in CFS is predicted for the deeper MSP. Likely, it results from a combination of backslip on the deeper MSP and the mainshock-induced stress transfer.

4 Discussion and conclusion

4.1 Inertia-dominated instability

The behavior of frictional properties is commonly defined in the framework of rate-and-state friction (RSF). The rate-and-state friction law can lead to stable (a - b) > 0 or unstable slip (a - b) < 0 depending on the friction parameters (Rice, 1993; Rice & Ruina, 1983):

Equation 8:

$$\mu(V,\theta) = \mu^* + aln\left(\frac{V}{V^*}\right) + b\,ln\left(\frac{V^*\theta}{Dc}\right)$$

where μ* is the coefficient of friction measured at sliding velocity V*. The parameters a and b represent the frictional properties of the material. The parameter (a − b) represents the velocity-dependence of μ at steady-state, with positive values (i.e., a > b) resulting in velocity-strengthening and negative values resulting in velocity-weakening behavior (seismogenic zone). Rice and Tse (1986) propose an inertial scale set and a state relaxation scale in a single degree of freedom elastic system in frictional constitutive models. They suggest that once inertia exerts its control of acceleration while the slip velocity is very high, the state relaxation can be neglected. In other words, during high slip motion in unstable phase (a-b<0), full dynamic effects have to be considered as the slip stages, including acceleration, deceleration, and arrest, that are all controlled by inertia:

Equation 9:

$$(T/2\pi)^2 \frac{d^2\delta}{dt^2} = (\delta_0 - \delta) - \tau/k$$

where $T/2\pi$ is inertia time (characteristic vibrational time), δ_0 and δ represent distances, and τ and k show frictional stress and stiffness.

Rice and Ruina (1983) show that sliding at the velocity V_l can be stable only when the system stiffness (K) is larger than the critical stiffness (Kc):

Equation 10:

$$K_c = \frac{(b-a)\sigma'}{D_c}\left[1 + \frac{MV_l^2}{\sigma' a D_c}\right]$$

The critical stiffness is written as the sum of a quasi-static critical stiffness ($K_{c,qs}$) and a dynamic critical stiffness ($K_{c,\,\mathrm{dyn}}$) as the first term shows a quasi-static critical stiffness, and the second term is a dimensionless number representing the dynamic effect. The transition from a quasi-static stick-slip to a harmonic oscillation can be described by the emergence of the dynamic instability coefficient η (Im et al., 2019; Im & Avouac, 2021):

Equation 11:

$$\eta = \frac{MV_l^2}{\sigma' a D_c}$$

This parameter shows that the system tends to become unstable for a larger mass or velocity and is sensitive to the loading velocity ($\eta \sim V_l^2$) representing the contribution of inertia to frictional instability (Im & Avouac, 2021). In the case of a single-degree-of-freedom spring and slider system, the inertial vibration tends to emerge when $\eta > 1$ (Im et al., 2019). In the cases that the inertial instability, MV_l^2, is high or normal stress is low, friction-induced vibration (harmonic oscillation) may appear in any system exhibiting velocity weakening friction ($a - b < 0$).

Comparable with nature, the normal load in the shallow part of the subduction megathrust (i.e., the offshore portion in nature) is sufficiently low (Gao & Wang, 2017) and does not change during the coseismic period considerably. However, loading velocity increases significantly. These normal stress and velocity conditions prompt the system, which is already in unstable mode (i.e.slip; $a - b < 0$), to the $\eta > 1$ domain (Figure 1 in Im and Avouac., 2021) and lead to an inertia-dominated instability appearing as a harmonic oscillation in our elastoplastic wedge (i.e., upper plate). This inertia-dominated instability is evident with the onset of the megathrust event (Figure 3) and may enhance the slip/backslip on the interface, similar to the effect of "dynamic shaking" on the plate interface coupling in Southern Cascadia (Materna et al., 2019).

4.2 Sequential elastic rebound of upper plate and slab?

We combine kinematic and dynamic results from above to shed light on the mechanism active during an analog earthquake. We analyze and interpret the cumulative displacement fields of a few earthquake cycles for both configurations to reach an accurate view of the elastic responses from the slab and upper plate to the stress drop on the interface (Figure 6 & S4). Starting simple and in line with the *elastic rebound theory* (Reid, 1910), the coseismic strain release (i.e., shear-stress drop) leads to the rebound of the interseismically strained upper plate and slab and transfers stress to the adjacent and nearby regions. The elastic response manifests itself in the strain energy converted to kinetic energy and consumed to accelerate the upper plate and (subordinately) the slab. The rebounds on the upper plate and slab (i.e., opposite sides of the megathrust interface) are in opposite directions (Savage, 1983). When we examine the velocity changes of the plates, we find that the model slab accelerates landward (Figures 6 & S4). The slab velocity increases by 50%-300% of the long-term velocity co- and early postseismically, depending on the event's magnitude. The magnitude of the events and slab accelerations indicate a positive correlation: the

larger the earthquake, the stronger is the response generated (Figures 6 & 7). While we cannot measure the elastic rebound of the slab in the asperity area on the interface directly, these values should be considered minimum values of local slab acceleration.

4.3 Effect of the slab acceleration on the rapid relocking

Our simplified seismotectonic megathrust model suggests different rebounds (i.e., in terms of timing, magnitude, and direction) in the upper plate and slab, triggering the immediate early-postseismic signals. An immediate relocking starts after rupture arrest and leads to a reversed surface displacement. While the rapid relocking is apparently limited on the two MSPs (in the heterogeneous system), it may postseismically reach a significant amount of the coseismic slip increments. The elastic response of the slab ("delayed rebound"), which comes into play as local acceleration, speeds up the stress build-up and results in this accelerated backslip. The large normal faulting aftershocks in the slab following a megathrust event seaward of the megathrust event, such as occurring after the Maule (Ruiz & Contreras-Reyes, 2015) Tohoku-Oki earthquakes

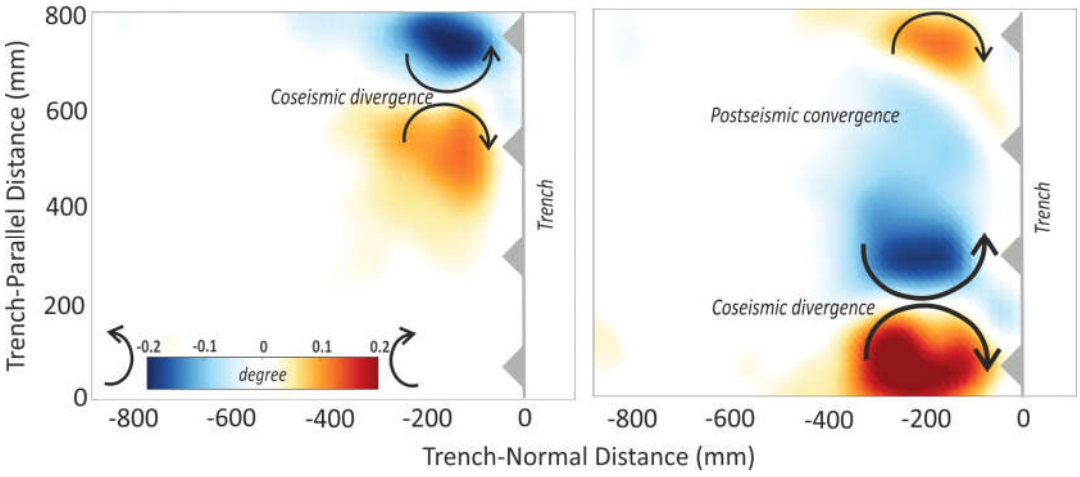

***Figure 8**:Exemplary clockwise and anticlockwise upper plate rotation during coseismic and early postseismic stages derived from selected surface displacements increments. Their associated surface displacements (E07 and E11) are visualized in Figure S2.*

(Asano *et al.*, 2011; Lay *et al.*, 2011) reflect slab extension and thus the same elastic response of the slab.

While the acceleration's impact appears as rearward surface displacements above the MSPs, the surface displacements above the matrix follow the slip sense of the MSPs in the heterogeneous configuration (S2). The significant amount of backslip suggests that the delayed rebound may not be the only possible mechanism involved in the rearward surface displacement. An extreme coseismic stress-drop overshoots the strained upper plate trenchward coseismically. The upper plate postseismically responds to this overshoot such that its elastic restoring force drags it back to a quasi-equilibrium state, which may appear as localized upper plate rearward surface displacements to a quasi-equilibrium state (Figure 9).

An immediate relocking and a high backslip velocity have been modeled based on land-limited GPS stations for the 2007 Pisco (Remy et al., 2016) and the 2010 Maule (Bedford et al., 2016) megathrust earthquakes, respectively. In the Tohoku-Oki earthquake region, the sparse sites directly above the high-slip zone postseimically moved landward faster than the pre-earthquake velocity (Tomita et al., 2015). This fast postseismic velocity has been explained via a slab acceleration driven by the recovery of force balance (Heki & Mitsui, 2013; Yuzariyadi & Heki, 2021) and the mantle relaxation (Sun et al., 2014; Watanabe et al., 2014). But it is expected that the mantle relaxation affects surface velocities at a relatively large wavelength. Also, the viscoelastic relaxation could not explain the trenchward motion of the stations above the slip zone further landward from the trench (Yuzariyadi & Heki, 2021). Afterslip might be the responsible mechanism for this surface displacement contrast at a relatively short distance (e.g., Sun & Wang, 2015; Tomita et al., 2017). Nevertheless, the coarse sampling rate of near-source observations prevents monitoring how the signals appear and evolve. Our analog model supports the occurrence of significant postseismic velocity changes with the slab deceleration following Omori-Utsu's decay law (Figure S4) of aftershock activity (Utsu et al., 1995). However, any viscoelastic behavior of the mantle may modify the elastic response of the slab and lead to a different response time scale. It means that the acceleration may last longer postseismically and decay with another characteristic time-constant in a coupled brittle-viscous system.

The stress evolution model for the extreme weakening observed during the Tohoku-Oki earthquake suggests a 20% slip reversal in the rupture's final stage, consistent with the postseismic stress stage derived from breakout data (Brodsky et al., 2017, 2020). However, our models suggest that the localized slip reversal may reflect the early postseismic stage due to a slab acceleration and/or a rapid restoration of the upper plate after experiencing elastic overshooting. Moreover, a

506 dynamic slip reversal has been reported in the 2011 Mw 9.0 Tohoku-Oki earthquake by Ide et al
507 (2011). It has been suggested that the reversal of rupture propagation direction (from updip to
508 downdip) and amplified upper plate displacement is caused by coseismic dynamic overshooting,
509 which is consistent with our experimental observation. If the mechanisms of these observations in
510 our experiment and the case of Tohoku-Oki earthquake are compatible, the normal mechanism
511 aftershocks on the interface close to the maximum slip area (Ide et al., 2011; Yagi & Fukahata,
512 2011) may be comparable to our proposed early postseismic backslip.

513 4.4 Effects of the acceleration on the upper plate fault activity

514 Apart from the consequences on the asperities, the accelerated relocking also affects upper-plate
515 shortening and upper-plate fault activity. The antithetic fault in our experiments switches its
516 kinematic mode and acts as a normal fault coseismically due to its location relative to the
517 megathrust earthquake centroid (e.g., deDontney et al., 2012; Li et al., 2014; Xu et al., 2015). This
518 discontinuity inside the upper plate responds to stress perturbation and stress enhancement. When
519 the MSPs are in opposite modes in the heterogeneous system (loading vs. unloading), they cause
520 compressional (postseismically) and extensional (coseismically and/or early postseismically)
521 stress regimes on the two segments of the antithetic upper plate fault, respectively. The high
522 amount of the early postseismic shortening (Figure S5; postseismic/interseismic=20-25%) may
523 increase the stress level in the upper plate, which is consistent with the reported upper-plate
524 seismicity after megathrust earthquakes (e.g., Asano et al., 2011; Hoskins et al., 2021; Toda et al.,
525 2011).

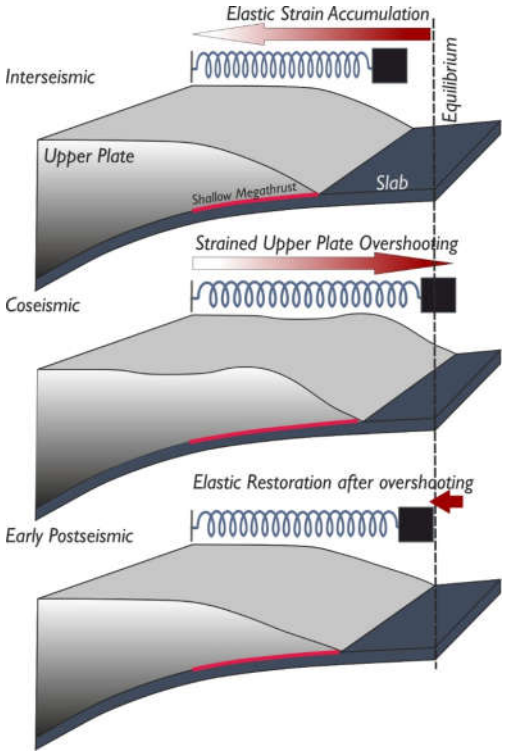

Figure 9. *Schematic diagram of upper plate elastic behavior during coseismic overshooting and postseismic restoration. The interseismically strained upper plate is overshot trenchward (seaward) due to an extreme coseismic stress-drop on the interface. Subsequently, an elastic restoring force drags the upper plate back to its equilibrium state.*

4.5 Effects of the acceleration on event triggering

The early-postseismic ΔCFS enhancement in the slab may increase the tensional load in the slab (e.g., Lay *et al.*, 1989; Tilmann *et al.*, 2016) such that the postseismic extensional domain hosts the large normal mechanism aftershocks early after the megathrust event (e.g., Asano *et al.*, 2011; Lay *et al.*, 2011; Ruiz and Contreras-Reyes, 2015). The stress enhancement on either receiver MSP (direct effect) or subducting plate (indirect effect) may bring the second MSP close to failure. In the heterogeneous configuration, the stress drop of the former event enhances ΔCFS on the second MSP, such that it directly increases the probability of failure. On the other hand, comparing the timing of slab acceleration and the latter event (t2 versus t3) shows that the acceleration occurs ahead of the later event. This interestingly suggests that the acceleration caused by the delayed

elastic response of the slab has antedated the later event on the shallow MSP (Figures 10 & S6). Hence, the acceleration perturbs the MSP's seismic cycle and causes a “clock advance” in the loading cycle of the MSP (Figures S6 and S7).

The rupture of one asperity enhances the stress changes on the adjacent asperity and may bring it closer to failure. For example, Melnick *et al.* (2017) suggest that, besides static stress changes, the increased locking appears in segments adjacent to the failed asperity due to a combination of viscoelastic mantle relaxation and afterslip-controlled vertical axis rotation in the upper plate. The studies on the Wenchuan-Lushan sequential events on the Longmenshan fault show accelerated healing on an asperity in response to an earthquake on the adjacent asperity (Pei et al., 2019; Zhao et al., 2020). Accordingly, the enhanced postseismic compression and the accelerating accumulation of the elastic strain triggered the second event on the nearby asperity (Li et al., 2018).

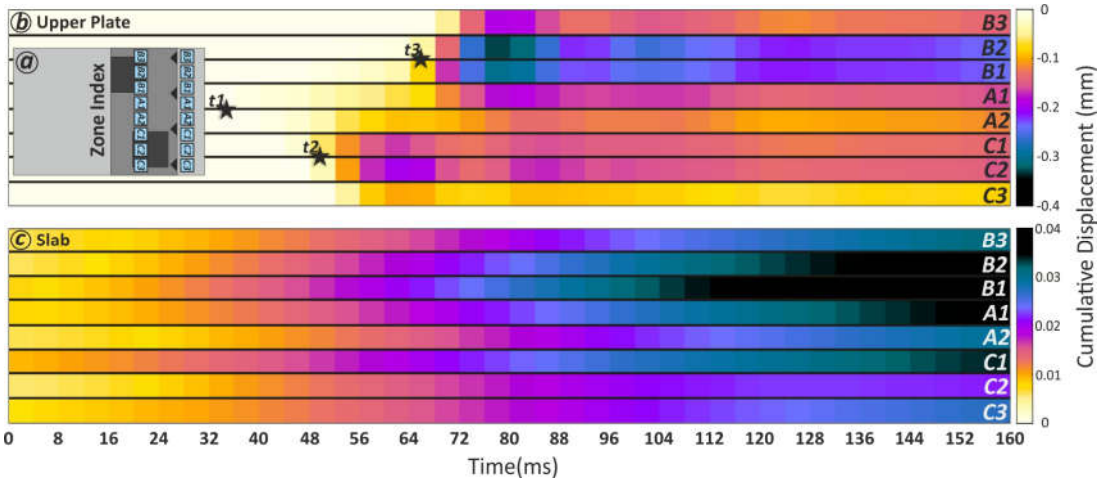

Figure 10. *Timing of coseismic and postseismic elastic responses of the upper plate and slab for a representative event. a: relative location of the time-series on both plates shown as zone index; b: the elastic response of the upper-plate. t1 to t3 indicates the relative timing of the events; c: the elastic response of the slab.*

5. Summary and conclusion

An earthquake-induced stress drop on a megathrust is related to different responses on the upper plate and slab. In an attempt to monitor and document these observations, we established two generic seismotectonic scale models to mimic homogeneous and heterogenous subduction megathrust (i.e., shallow interface) to generate analog earthquakes. The submillimeter surface displacement during rupture propagation and early-postseismic period is captured by high resolution (temporally and spatially) laboratory seismogeodetic method.

Our result shows a sequential elastic rebound following the coseismic shear-stress drop in our elastic-frictional models as the rebound of the upper plate is faster and more prominent compared to that of the slab. The delayed rebound of the slab, along with rapid relaxation of the upper plate after an elastic overshooting, may accelerate the relocking of the megathrust. The laboratory seismogeodetic observations show how the upper plate responds to this overshoot postseismically such that the elastic restoring force may appear as localized upper plate rearward surface displacements. This acceleration triggers/antedates the failure of a nearby asperity and enhances the early backslip in the rupture area. However, depending on the scaling factors, this sequence of dynamic overshooting, amplified motion of the upper plate, and upper plate rearward restoration may alternatively be considered as the coseismic phase. We suggest that the immediate backslip following the main event on the patches could reach up to 30% of coseismic and the entire interseismic backslip. The slip models of the upper plate fault demonstrate that the different segments of the upper plate backthrust may move in opposite directions (normal versus reverse), reflecting the sense of shear on the MSPs (slip versus backslip). This deep-rooted backthrust fault generates a discontinuity in the upper plate and perturbs the inner-wedge stress state. Consequently, the discontinuity may highly enhance the ΔCFS in the upper plate.

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References

Adam, J., Urai, J. L., Wieneke, B., Oncken, O., Pfeiffer, K., Kukowski, N., Lohrmann, J., Hoth, S., Van Der Zee, W., & Schmatz, J. (2005). Shear localisation and strain distribution during tectonic faulting—New insights from granular-flow experiments and high-resolution optical image correlation techniques. *Journal of Structural Geology*, *27*(2), 283–301.

Allmendinger, R. W., Reilinger, R., & Loveless, J. (2007). Strain and rotation rate from GPS in Tibet, Anatolia, and the Altiplano. *Tectonics*, *26*(3). https://doi.org/10.1029/2006TC002030

Ammon, C. J., Ji, C., Thio, H. K., Robinson, D., Ni, S., Hjorleifsdottir, V., Kanamori, H., Lay, T., Das, S., Helmberger, D., Ichinose, G., Polet, J., & Wald, D. (2005). Rupture process of the 2004 Sumatra-Andaman earthquake. *Science*, *308*(5725), 1133–1139. https://doi.org/10.1126/SCIENCE.1112260/SUPPL_FILE/AMMON.SOM.PDF

Asano, Y., Saito, T., Ito, Y., Shiomi, K., Hirose, H., Matsumoto, T., Aoi, S., Hori, S., & Sekiguchi, S. (2011). Spatial distribution and focal mechanisms of aftershocks of the 2011 off the Pacific coast of Tohoku Earthquake. *Earth, Planets and Space*, *63*(7), 669–673. https://doi.org/10.5047/eps.2011.06.016

Bedford, J., Moreno, M., Baez, J. C., Lange, D., Tilmann, F., Rosenau, M., Heidbach, O., Oncken, O., Bartsch, M., Rietbrock, A., Tassara, A., Bevis, M., & Vigny, C. (2013). A high-resolution, time-variable afterslip model for the 2010 Maule Mw = 8.8, Chile megathrust earthquake. *Earth and Planetary Science Letters*, *383*, 26–36. https://doi.org/10.1016/j.epsl.2013.09.020

Bedford, J., Moreno, M., Li, S., Oncken, O., Baez, J. C., Bevis, M., Heidbach, O., & Lange, D. (2016). Separating rapid relocking, afterslip, and viscoelastic relaxation: An application of the postseismic straightening method to the Maule 2010 cGPS. *Journal of Geophysical Research: Solid Earth*, *121*(10), 7618–7638. https://doi.org/10.1002/2016JB013093

Bedford, J. R., Moreno, M., Deng, Z., Oncken, O., Schurr, B., John, T., Báez, J. C., & Bevis, M. (2020). Months-long thousand-kilometre-scale wobbling before great subduction earthquakes. *Nature 2020 580:7805*, *580*(7805), 628–635. https://doi.org/10.1038/s41586-020-2212-1

Bilek, S. L., & Lay, T. (2002). Tsunami earthquakes possibly widespread manifestations of frictional conditional stability. *Geophysical Research Letters*, *29*(14), 18–1. https://doi.org/10.1029/2002GL015215

Brodsky, E. E., Mori, J. J., Anderson, L., Chester, F. M., Conin, M., Dunham, E. M., Eguchi, N., Fulton, P. M., Hino, R., Hirose, T., Ikari, M. J., Ishikawa, T., Jeppson, T., Kano, Y., Kirkpatrick, J., Kodaira, S., Lin, W., Nakamura, Y., Rabinowitz, H. S., … Yang, T. (2020). The State of Stress on the Fault Before, During, and After a Major Earthquake. *Annual Review of Earth and Planetary Sciences*, *48*(1), 49–74. https://doi.org/10.1146/annurev-earth-053018-060507

Brodsky, E. E., Saffer, D., Fulton, P., Chester, F., Conin, M., Huffman, K., Moore, J. C., & Wu, H.-Y. (2017). The postearthquake stress state on the Tohoku megathrust as constrained by reanalysis of the JFAST breakout data. *Geophysical Research Letters*, *44*(16), 8294–8302.

https://doi.org/10.1002/2017GL074027
Caniven, Y., & Dominguez, S. (2021). Validation of a Multilayered Analog Model Integrating Crust-Mantle Visco-Elastic Coupling to Investigate Subduction Megathrust Earthquake Cycle. *Journal of Geophysical Research: Solid Earth*, *126*(2), e2020JB020342. https://doi.org/10.1029/2020JB020342
Chaves, E. J., Schwartz, S. Y., & Abercrombie, R. E. (2020). Repeating earthquakes record fault weakening and healing in areas of megathrust postseismic slip. *Science Advances*, *6*(32), eaaz9317. https://doi.org/10.1126/sciadv.aaz9317
Chlieh, M., Avouac, J. P., Sieh, K., Natawidjaja, D. H., & Galetzka, J. (2008). Heterogeneous coupling of the Sumatran megathrust constrained by geodetic and paleogeodetic measurements. *Journal of Geophysical Research: Solid Earth*, *113*, 5305. https://doi.org/10.1029/2007JB004981
Corbi, F., Sandri, L., Bedford, J., Funiciello, F., Brizzi, S., Rosenau, M., & Lallemand, S. (2019). Machine Learning Can Predict the Timing and Size of Analog Earthquakes. *Geophysical Research Letters*, *46*(3), 1303–1311. https://doi.org/10.1029/2018GL081251
Corbi, Fabio, Bedford, J., Sandri, L., Funiciello, F., Gualandi, A., & Rosenau, M. (2020). Predicting imminence of analog megathrust earthquakes with Machine Learning: Implications for monitoring subduction zones. *Geophysical Research Letters*, *47*(7), e2019GL086615. https://doi.org/10.1029/2019GL086615
Corbi, Fabio, Herrendörfer, R., Funiciello, F., & van Dinther, Y. (2017). Controls of seismogenic zone width and subduction velocity on interplate seismicity: Insights from analog and numerical models. *Geophysical Research Letters*, *44*(12), 6082–6091. https://doi.org/10.1002/2016GL072415
deDontney, N., Rice, J. R., & Dmowska, R. (2012). Finite element modeling of branched ruptures including off-fault plasticity. *Bulletin of the Seismological Society of America*, *102*(2), 541–562. https://doi.org/10.1785/0120110134
Gao, X., & Wang, K. (2017). Rheological separation of the megathrust seismogenic zone and episodic tremor and slip. *Nature 2017 543:7645*, *543*(7645), 416–419. https://doi.org/10.1038/nature21389
Heki, K., & Mitsui, Y. (2013). Accelerated pacific plate subduction following interplate thrust earthquakes at the Japan trench. *Earth and Planetary Science Letters*, *363*, 44–49. https://doi.org/10.1016/j.epsl.2012.12.031
Hicks, S. P., & Rietbrock, A. (2015). Seismic slip on an upper-plate normal fault during a large subduction megathrust rupture. *Nature Geoscience*, *8*(12), 955–960. https://doi.org/10.1038/ngeo2585
Hoffmann, F., Metzger, S., Moreno, M., Deng, Z., Sippl, C., Ortega-Culaciati, F., & Oncken, O. (2018). Characterizing Afterslip and Ground Displacement Rate Increase Following the 2014 Iquique-Pisagua Mw 8.1 Earthquake, Northern Chile. *Journal of Geophysical Research: Solid Earth*, *123*(5), 4171–4192. https://doi.org/10.1002/2017JB014970
Hoskins, M. C., Meltzer, A., Font, Y., Agurto-Detzel, H., Vaca, S., Rolandone, F., Nocquet, J. M., Soto-Cordero, L., Stachnik, J. C., Beck, S., Lynner, C., Ruiz, M., Alvarado, A., Hernandez, S., Charvis, P., Regnier, M., Leon-Rios, S., & Rietbrock, A. (2021). Triggered crustal earthquake swarm across subduction segment boundary after the 2016 Pedernales, Ecuador megathrust earthquake. *Earth and Planetary Science Letters*, *553*, 116620. https://doi.org/10.1016/j.epsl.2020.116620
Hsu, Y. J., Simons, M., Avouac, J. P., Galeteka, J., Sieh, K., Chlieh, M., Natawidjaja, D.,

Prawirodirdjo, L., & Bock, Y. (2006). Frictional afterslip following the 2005 Nias-Simeulue earthquake, Sumatra. *Science*, *312*(5782), 1921–1926. https://doi.org/10.1126/science.1126960

Ide, S., Baltay, A., & Beroza, G. C. (2011). Shallow dynamic overshoot and energetic deep rupture in the 2011 M w 9.0 Tohoku-Oki earthquake. *Science*, *332*(6036), 1426–1429. https://doi.org/10.1126/science.1207020

Im, K., & Avouac, J. P. (2021). Tectonic tremor as friction-induced inertial vibration. *Earth and Planetary Science Letters*, *576*, 117238. https://doi.org/10.1016/J.EPSL.2021.117238

Im, K., Marone, C., & Elsworth, D. (2019). The transition from steady frictional sliding to inertia-dominated instability with rate and state friction. *Journal of the Mechanics and Physics of Solids*, *122*, 116–125. https://doi.org/10.1016/J.JMPS.2018.08.026

Kato, A., Sakai, S., & Obara, K. (2011). A normal-faulting seismic sequence triggered by the 2011 off the Pacific coast of Tohoku Earthquake: Wholesale stress regime changes in the upper plate. *Earth, Planets and Space*, *63*(7), 745–748. https://doi.org/10.5047/eps.2011.06.014

King Hubbert, M. (1937). Theory of scale models as applied to the study of geologic structures. *Bulletin of the Geological Society of America*, *48*(10), 1459–1520. https://doi.org/10.1130/GSAB-48-1459

Kosari, E., Rosenau, M., Bedford, J., Rudolf, M., & Oncken, O. (2020). On the Relationship Between Offshore Geodetic Coverage and Slip Model Uncertainty: Analog Megathrust Earthquake Case Studies. *Geophysical Research Letters*, *47*(15). https://doi.org/10.1029/2020GL088266

Lay, T., Ammon, C. J., Kanamori, H., Kim, M. J., & Xue, L. (2011). Outer trench-slope faulting and the 2011 Mw 9.0 off the Pacific coast of Tohoku Earthquake. *Earth, Planets and Space*, *63*(7), 713–718. https://doi.org/10.5047/eps.2011.05.006

Lay, T., Astiz, L., Kanamori, H., & Christensen, D. H. (1989). Temporal variation of large intraplate earthquakes in coupled subduction zones. *Physics of the Earth and Planetary Interiors*, *54*(3–4), 258–312. https://doi.org/10.1016/0031-9201(89)90247-1

Lay, T., Kanamori, H., Ammon, C. J., Nettles, M., Ward, S. N., Aster, R. C., Beck, S. L., Bilek, S. L., Brudzinski, M. R., Butler, R., Deshon, H. R., Ekström, G., Satake, K., & Sipkin, S. (2005). The great Sumatra-Andaman earthquake of 26 December 2004. *Science*, *308*(5725), 1127–1133. https://doi.org/10.1126/SCIENCE.1112250/SUPPL_FILE/LAY_SOM.PDF

Li, S., Moreno, M., Bedford, J., Rosenau, M., & Oncken, O. (2015). Revisiting viscoelastic effects on interseismic deformation and locking degree: A case study of the Peru-North Chile subduction zone. *Journal of Geophysical Research: Solid Earth*, *120*(6), 4522–4538. https://doi.org/10.1002/2015JB011903

Li, S., Moreno, M., Rosenau, M., Melnick, D., & Oncken, O. (2014). Splay fault triggering by great subduction earthquakes inferred from finite element models. *Geophysical Research Letters*, *41*(2), 385–391. https://doi.org/10.1002/2013GL058598

Li, Y., Zhang, G., Shan, X., Liu, Y., Wu, Y., Liang, H., Qu, C., & Song, X. (2018). GPS-Derived Fault Coupling of the Longmenshan Fault Associated with the 2008 Mw Wenchuan 7.9 Earthquake and Its Tectonic Implications. *Remote Sensing*, *10*(5), 753. https://doi.org/10.3390/rs10050753

Lin, J., & Stein, R. S. (2004). Stress triggering in thrust and subduction earthquakes and stress interaction between the southern San Andreas and nearby thrust and strike-slip faults. *Journal of Geophysical Research: Solid Earth*, *109*(B2).

https://doi.org/10.1029/2003jb002607
Loveless, J. P. (2017). Super-interseismic periods: Redefining earthquake recurrence. In *Geophysical Research Letters* (Vol. 44, Issue 3, pp. 1329–1332). Blackwell Publishing Ltd. https://doi.org/10.1002/2017GL072525
Loveless, J. P., & Meade, B. J. (2011). Spatial correlation of interseismic coupling and coseismic rupture extent of the 2011 MW = 9.0 Tohoku-oki earthquake. *Geophysical Research Letters*, *38*(17), 17306. https://doi.org/10.1029/2011GL048561
Materna, K., Bartlow, N., Wech, A., Williams, C., & Bürgmann, R. (2019). Dynamically Triggered Changes of Plate Interface Coupling in Southern Cascadia. *Geophysical Research Letters*, *46*(22), 12890–12899. https://doi.org/10.1029/2019GL084395
Melnick, D., Moreno, M., Quinteros, J., Baez, J. C., Deng, Z., Li, S., & Oncken, O. (2017). The super-interseismic phase of the megathrust earthquake cycle in Chile. *Geophysical Research Letters*, *44*(2), 784–791. https://doi.org/10.1002/2016GL071845
Moreno, M., Rosenau, M., & Oncken, O. (2010). 2010 Maule earthquake slip correlates with pre-seismic locking of Andean subduction zone. *Nature 2010 467:7312*, *467*(7312), 198–202. https://doi.org/10.1038/nature09349
Pei, S., Niu, F., Ben-Zion, Y., Sun, Q., Liu, Y., Xue, X., Su, J., & Shao, Z. (2019). Seismic velocity reduction and accelerated recovery due to earthquakes on the Longmenshan fault. *Nature Geoscience*, *12*(5), 387–392.
Ramberg, H. (1967). Model Experimentation of the Effect of Gravity on Tectonic Processes. *Geophysical Journal International*, *14*(1–4), 307–329. https://doi.org/10.1111/J.1365-246X.1967.TB06247.X
Reid, H. F. (1910). The mechanism of the earthquake, the california earthquake of April 18, 1906, Report of the state earthquake investigation commission. In *Washington DC: Carnegie Institution* (Vol. 2).
Remy, D., Perfettini, H., Cotte, N., Avouac, J. P., Chlieh, M., Bondoux, F., Sladen, A., Tavera, H., & Socquet, A. (2016). Postseismic relocking of the subduction megathrust following the 2007 Pisco, Peru, earthquake. *Journal of Geophysical Research: Solid Earth*, *121*(5), 3978–3995. https://doi.org/10.1002/2015JB012417
Rice, J. R. (1993). Spatio-temporal complexity of slip on a fault. *Journal of Geophysical Research: Solid Earth*, *98*(B6), 9885–9907. https://doi.org/10.1029/93JB00191
Rice, J. R., & Ruina, A. L. (1983). Stability of Steady Frictional Slipping. *Journal of Applied Mechanics*, *50*(2), 343–349. https://doi.org/10.1115/1.3167042
Rice, J. R., & Tse, S. T. (1986). Dynamic motion of a single degree of freedom system following a rate and state dependent friction law. *Journal of Geophysical Research: Solid Earth*, *91*(B1), 521–530. https://doi.org/10.1029/JB091IB01P00521
Rosenau, M., Corbi, F., & Dominguez, S. (2017). *Analogue earthquakes and seismic cycles: experimental modelling across timescales. Solid Earth, European Geosciences Union*. *8*(3), 597–635. https://doi.org/10.5194/se-8-597-2017ï
Rosenau, M., Horenko, I., Corbi, F., Rudolf, M., Kornhuber, R., & Oncken, O. (2019). Synchronization of Great Subduction Megathrust Earthquakes: Insights From Scale Model Analysis. *Journal of Geophysical Research: Solid Earth*, *124*(4), 3646–3661. https://doi.org/10.1029/2018JB016597
Rosenau, M., Lohrmann, J., & Oncken, O. (2009). Shocks in a box: An analogue model of subduction earthquake cycles with application to seismotectonic forearc evolution. *Journal of Geophysical Research: Solid Earth*, *114*(B1), 1409.

https://doi.org/10.1029/2008JB005665
Rosenau, M., Nerlich, R., Brune, S., & Oncken, O. (2010). Experimental insights into the scaling and variability of local tsunamis triggered by giant subduction megathrust earthquakes. *Journal of Geophysical Research: Solid Earth*, *115*(9). https://doi.org/10.1029/2009JB007100
Rosenau, M., & Oncken, O. (2009). Fore-arc deformation controls frequency-size distribution of megathrust earthquakes in subduction zones. *Journal of Geophysical Research*, *114*(B10), B10311. https://doi.org/10.1029/2009JB006359
Ruff, L. J., & Tichelaar, B. W. (1996). What Controls the Seismogenic Plate Interface in Subduction Zones? *Geophysical Monograph Series*, *96*, 105–111. https://doi.org/10.1029/GM096P0105
Ruiz, J. A., & Contreras-Reyes, E. (2015). Outer rise seismicity boosted by the Maule 2010 Mw 8.8 megathrust earthquake. *Tectonophysics*, *653*, 127–139. https://doi.org/10.1016/j.tecto.2015.04.007
Savage, J. C. (1983). A dislocation model of strain accumulation and release at a subduction zone. *Journal of Geophysical Research*, *88*(B6), 4984–4996. https://doi.org/10.1029/JB088iB06p04984
Schmalzle, G. M., McCaffrey, R., & Creager, K. C. (2014). Central Cascadia subduction zone creep. *Geochemistry, Geophysics, Geosystems*, *15*(4), 1515–1532. https://doi.org/10.1002/2013GC005172
Simons, M., Minson, S. E., Sladen, A., Ortega, F., Jiang, J., Owen, S. E., Meng, L., Ampuero, J.-P., Wei, S., Chu, R., Helmberger, D. V., Kanamori, H., Hetland, E., Moore, A. W., & Webb, F. H. (2011). The 2011 Magnitude 9.0 Tohoku-Oki Earthquake: Mosaicking the Megathrust from Seconds to Centuries. *Science*, *332*(6036), 1421–1425. https://doi.org/10.1126/SCIENCE.1206731
Sun, T., & Wang, K. (2015). Viscoelastic relaxation following subduction earthquakes and its effects on afterslip determination. *Journal of Geophysical Research: Solid Earth*, *120*(2), 1329–1344. https://doi.org/10.1002/2014JB011707
Sun, T., Wang, K., Iinuma, T., Hino, R., He, J., Fujimoto, H., Kido, M., Osada, Y., Miura, S., Ohta, Y., & Hu, Y. (2014). Prevalence of viscoelastic relaxation after the 2011 Tohoku-oki earthquake. *Nature*, *514*(7520), 84–87. https://doi.org/10.1038/nature13778
Tilmann, F., Zhang, Y., Moreno, M., Saul, J., Eckelmann, F., Palo, M., Deng, Z., Babeyko, A., Chen, K., Baez, J. C., Schurr, B., Wang, R., & Dahm, T. (2016). The 2015 Illapel earthquake, central Chile: A type case for a characteristic earthquake? *Geophysical Research Letters*, *43*(2), 574–583. https://doi.org/10.1002/2015GL066963
Toda, S., Stein, R. S., & Lin, J. (2011). Widespread seismicity excitation throughout central Japan following the 2011 M=9.0 Tohoku earthquake and its interpretation by Coulomb stress transfer. *Geophysical Research Letters*, *38*(7). https://doi.org/10.1029/2011GL047834@10.1002/(ISSN)1944-8007.MEGAQUAKE1
Tomita, F., Kido, M., Ohta, Y., Iinuma, T., & Hino, R. (2017). Along-Trench variation in seafloor displacements after the 2011 Tohoku earthquake. *Science Advances*, *3*(7), e1700113. https://doi.org/10.1126/sciadv.1700113
Tomita, F., Kido, M., Osada, Y., Hino, R., Ohta, Y., & Iinuma, T. (2015). First measurement of the displacement rate of the Pacific Plate near the Japan Trench after the 2011 Tohoku-Oki earthquake using GPS/acoustic technique. *Geophysical Research Letters*, *42*(20), 8391–8397. https://doi.org/10.1002/2015GL065746

Uchida, N., & Bürgmann, R. (2019). Repeating earthquakes. *Annual Review of Earth and Planetary Sciences*, *47*(1), 305–332. https://doi.org/10.1146/annurev-earth-053018-060119

Utsu, T., Ogata, Y., S, R., & Matsu'ura. (1995). The Centenary of the Omori Formula for a Decay Law of Aftershock Activity. *Journal of Physics of the Earth*, *43*(1), 1–33. https://doi.org/10.4294/jpe1952.43.1

Wang, K., Hu, Y., & He, J. (2012). Deformation cycles of subduction earthquakes in a viscoelastic Earth. *Nature*, *484*(7394), 327–332. https://doi.org/10.1038/nature11032

Watanabe, S., Sato, M., Fujita, M., Ishikawa, T., Yokota, Y., Ujihara, N., & Asada, A. (2014). Evidence of viscoelastic deformation following the 2011 Tohoku-Oki earthquake revealed from seafloor geodetic observation. *Geophysical Research Letters*, *41*(16), 5789–5796. https://doi.org/10.1002/2014GL061134

Weiss, J. R., Qiu, Q., Barbot, S., Wright, T. J., Foster, J. H., Saunders, A., Brooks, B. A., Bevis, M., Kendrick, E., Ericksen, T. L., Avery, J., Smalley, R. S., Cimbaro, S. R., Lenzano, L. E., Barón, J., Báez, J. C., & Echalar, A. (2019). Illuminating subduction zone rheological properties in the wake of a giant earthquake. *Science Advances*, *5*(12), 6720–6738. https://doi.org/10.1126/sciadv.aax6720

Xu, S., Fukuyama, E., Ben-Zion, Y., & Ampuero, J. P. (2015). Dynamic rupture activation of backthrust fault branching. *Tectonophysics*, *644*, 161–183. https://doi.org/10.1016/j.tecto.2015.01.011

Yagi, Y., & Fukahata, Y. (2011). Rupture process of the 2011 Tohoku-oki earthquake and absolute elastic strain release. *Geophysical Research Letters*, *38*(19). https://doi.org/10.1029/2011GL048701

Yuzariyadi, M., & Heki, K. (2021). Enhancement of interplate coupling in adjacent segments after recent megathrust earthquakes. *Tectonophysics*, *801*, 228719. https://doi.org/10.1016/j.tecto.2021.228719

Zhao, J., Ren, J., Liu, J., Jiang, Z., Liu, X., Liang, H., Niu, A., Yue, C., & Yuan, Z. (2020). Coupling fraction and relocking process of the Longmenshan Fault Zone following the 2008 Mw7. 9 Wenchuan earthquake. *Journal of Geodynamics*, 101730.