The seismic cycle at subduction thrusts: Implications of geodynamic simulations benchmarked with laboratory models

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1) Abstract

The physics governing the seismic cycle at seismically destructive subduction zones remains poorly understood due to restricted direct observations in time and space, as evident from the unexpectedly large M9.0 Tohoku earthquake. We demonstrate that geodynamic modeling can contribute to our understanding by validating a quasi-static, visco-elasto-plastic numerical model to a new laboratory approach and subsequently investigating the resulting dynamics and seismicity.

Our results show velocity-weakening friction is necessary to simulate fast, frictional instabilities, i.e. earthquakes. We match lab source parameters if velocity-strengthening is applied in aseismic regions to limit the rupture and promote slip complexity. Spontaneous nucleation by coalescence of neighboring patches mainly occurs at evolving asperities near the seismogenic zone limits, with a preference for the downdip edge. Consequently, a crack-, or occasionally even pulse-like, rupture propagates toward the opposite side of the seismogenic zone by increasing stresses ahead of its rupture front. The resulting surface displacements qualitative agree with geodetic observations (without significant mantle relaxation) showing an inter-, co-, and postseismic phase. Succesfull preliminary results in a more realistic setup confirm the potential of this approach.

The agreement with laboratory results and the wide range of observed physical phenomena, including back-propagation and repeated slip, demonstrate that visco-elasto-plastic geodynamic models with rate-dependent friction represent a new tool that can greatly contribute to our understanding of the seismic cycle at subduction zones.

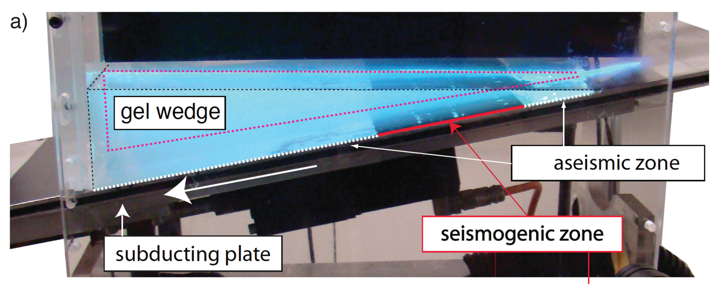
Objectives

1) Can we model short, elastic events with a geodynamic code ? What fault rheoloy do we need ?
2) How does this physically work ?
3) Do we observe phenomena comparable to nature ?

The work presented here is under review by JGR as *"van Dinther, Y., Gerya, T., Dalguer, L.A., Corbi, F., Funiciello, F., and Mai, P.M. The seismic cycle at subduction thrusts: 2. Dynamic implications of geodynamic simulations benchmarked with laboratory models"*, and is accompanied by *"Corbi, F., Funiciello, F., Moroni, M., van Dinther, Y., and Faccenna, C.. The seismic cycle at subduction thrusts: 1. insights from laboratory models."*

2) Modelling approaches

The laboratory model (Fig. 1a) includes a
- visco-elastic gelatin wedge (Di Giuseppe et al., 2009),
- rate-weakening sand paper as seismogenic zone (Fig. 2)



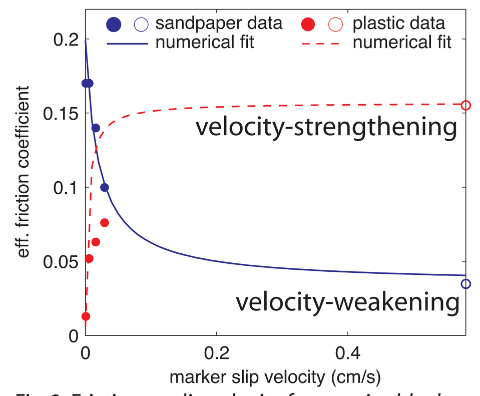


Fig. 2: Friction vs. slip velocity from springblock experiments (Corbi et al., 2011).

A critical numerical addition is a *slip rate-dependent friction*

$$\mu_{eff} = \mu_s(1-\gamma) + \mu_s \frac{\gamma}{1+\frac{V}{V_c}}$$

where slip velocity *V* and amount of weakening γ are

$$V = \frac{\sigma_{yield}}{\eta_m} dx \qquad \gamma = 1 - \frac{\mu_d}{\mu_s}$$

The numerical model (I2ELVIS, Gerya&Yuen, 2007)

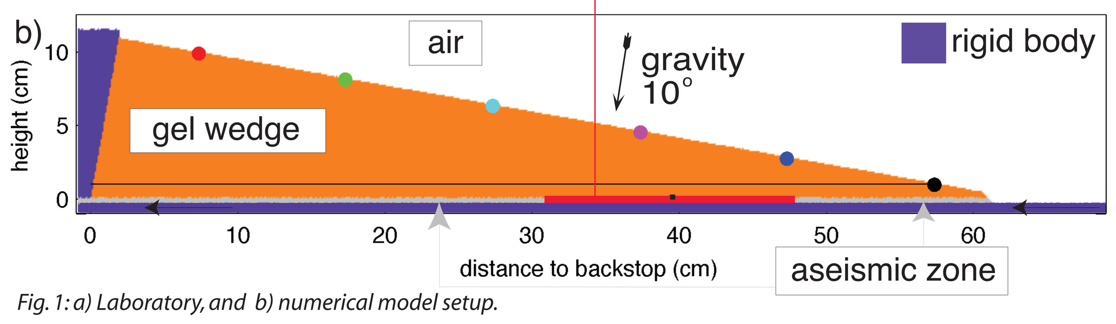


Fig. 1: a) Laboratory, and b) numerical model setup.

- solves for conservation of mass and momentum, including incompressible inertia to regularize velocities at small time steps,
- using a visco-elasto-plastic rheology, with a rate-dependent friction (above)
- and laboratory constrained parameters :

	gelatin	wall	sticky air
Shear modulus (Pa)	5000	1e14	5000
Viscosity (Pa s)	3e5	1e08	0.002
Density (kg m^{-3})	1000	1000	1

Note deformation is limited (G&eta 2 oom up, dt 2 oom down).

3) Can we model short, elastic events ?

Yes, we can ! If velocity weakening friction is included to simulate short frictional instabilitities and healing. Velocity strengthening ensures a match to analogue source parameters.

In Figure 3 we analyze the spatiotemporal evolution of horizontal velocity for three different friction laws (F. 3 a-c) in relation to laboratory results (F. 3d). These are quantitatively compared in Figure 6, in which source parameters are defined as in Figure 5 using a velocity threshold (Figure 4).

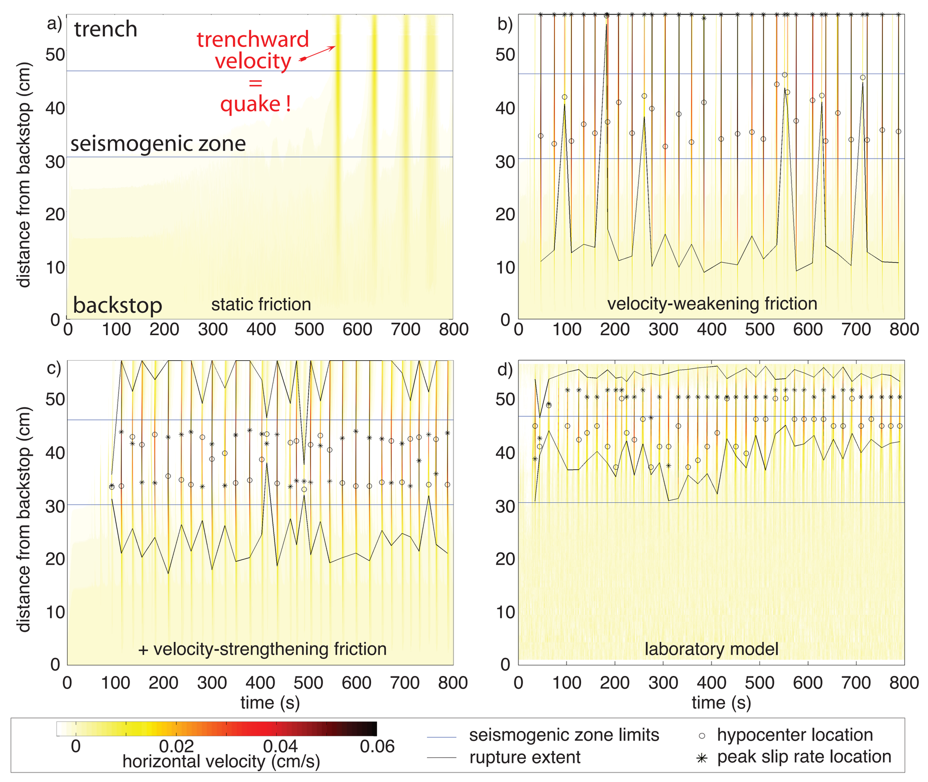


Fig. 3 Spatio-temporal evolution horizontal velocity (1 cm above interface).

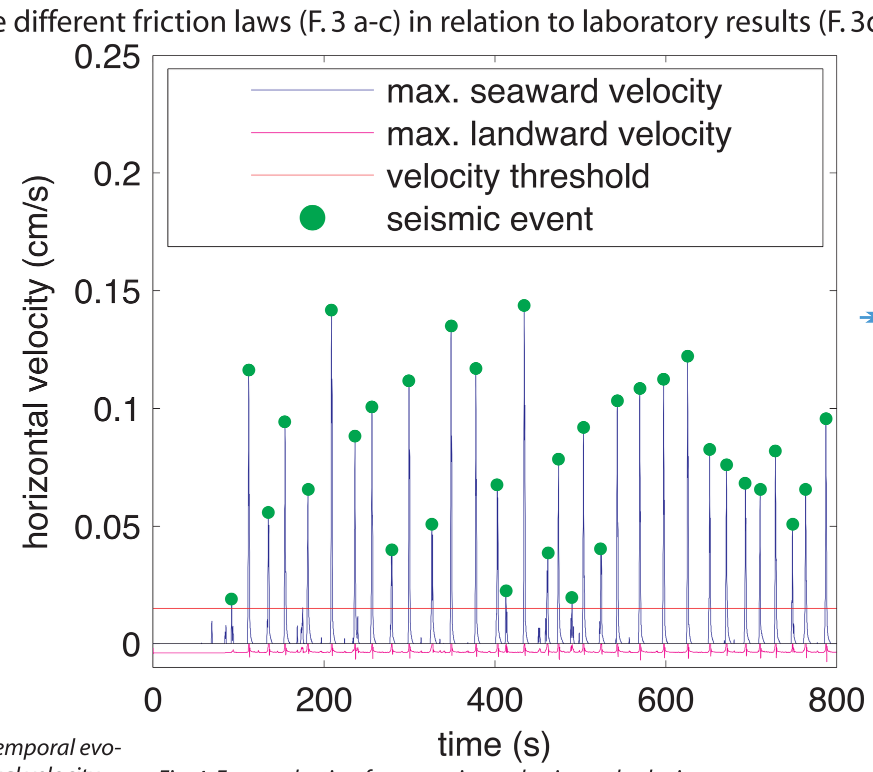


Fig. 4: Event selection from maximum horizontal velocity.

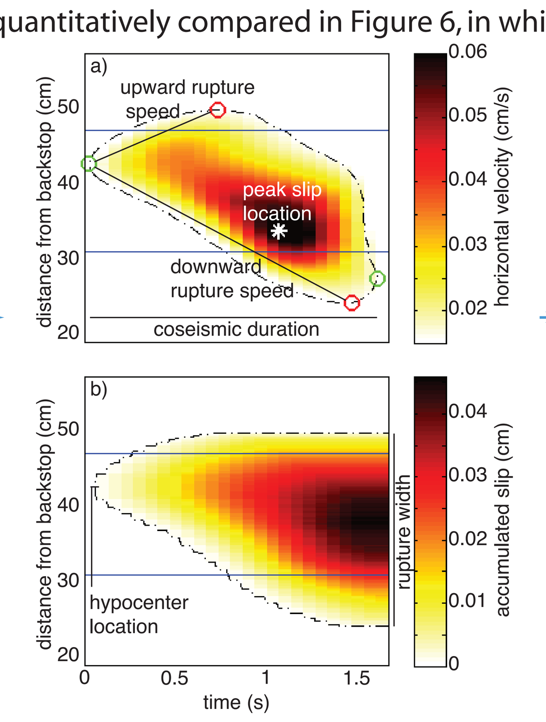


Fig. 5: Source parameter selection.

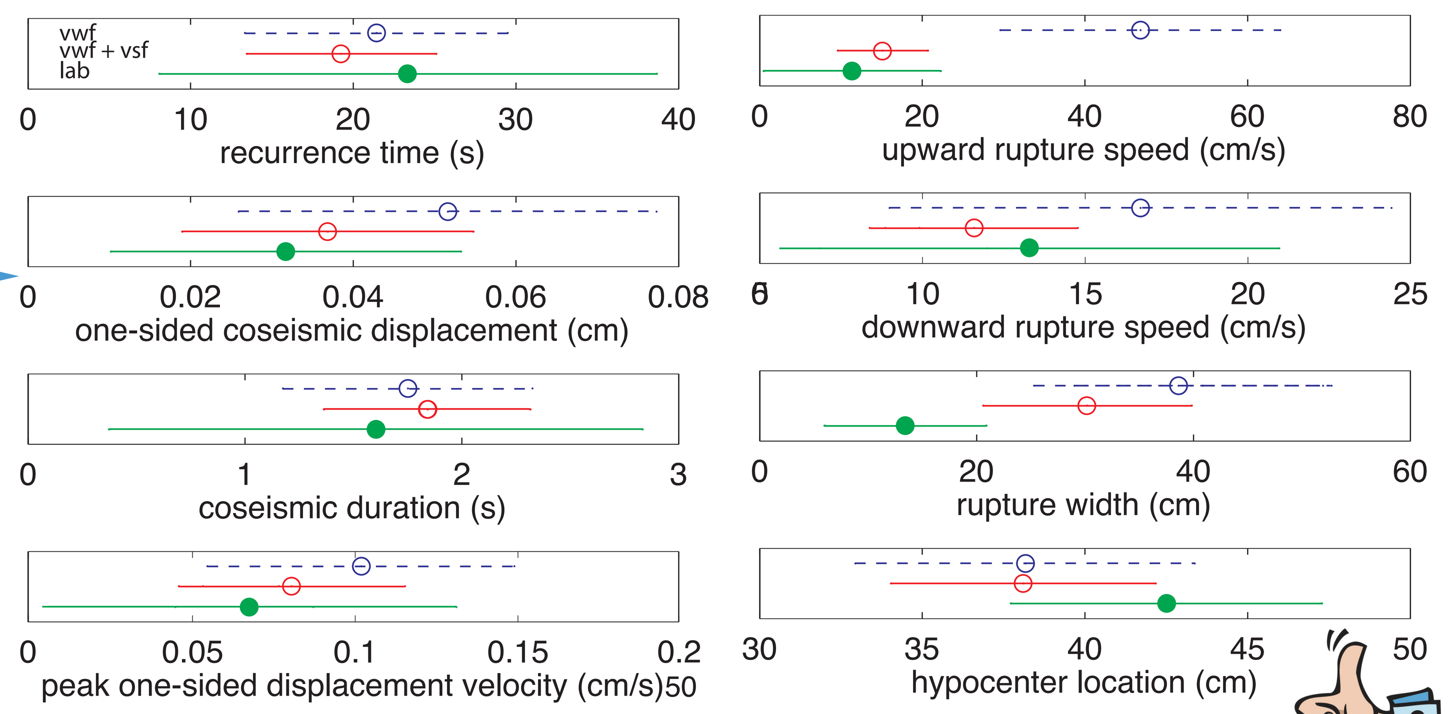


Fig. 6 : Degree of fit. Lab data (green) from 8 similar models. The red model with weakening and strengthening fits and is selected.

4) What physics drives this ?

Rupture propagation is driven by spatial stress transfer to balance static equilibrium, while the local instability arises from the velocity - friction - viscosity feedback loop. Spontaneous nucleation occurs, if stress transfer is large enough, near the differentially moving seismogenic zone edges.

The underlying physical framework is demonstrated based on the temporal evolution of a single particle (Figure 7) and snapshots of the spatial evolution of parameters for one event (Figure 8). Ruptures propagate as a frictional instability, which is fed through the feedback of decreasing viscosities. This increases slip velocities, which decreases friction and strength, and which decreases viscosities even further (F. 7a-b). This releases accumulated elastic stresses, and causes propagation as stresses are increased ahead of the rupture front to balance these dropping stresses (F. 8c). This instantaneously increases stresses to its strength (F. 7d), until a too large stress excess arrests the rupture. Asperities arise spontaneously both at the edges of the seismogenic zone due to differential coupling and within due to premature arrest of small events leading to heterogeneous stresses (F. 8b).

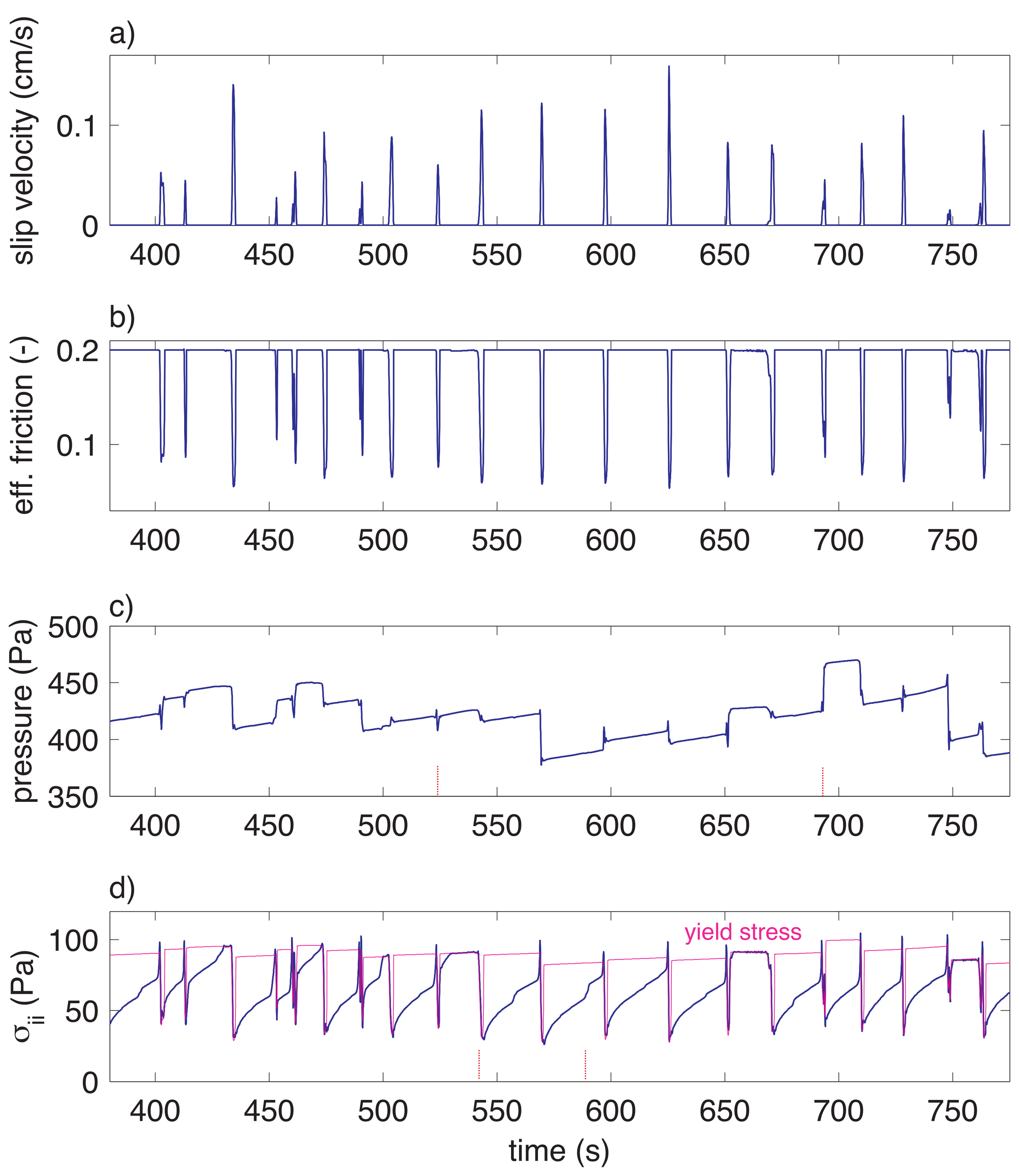


Fig. 7: Physical parameter evolution of a Lagrangian particle in the center of the seismogenic zone.

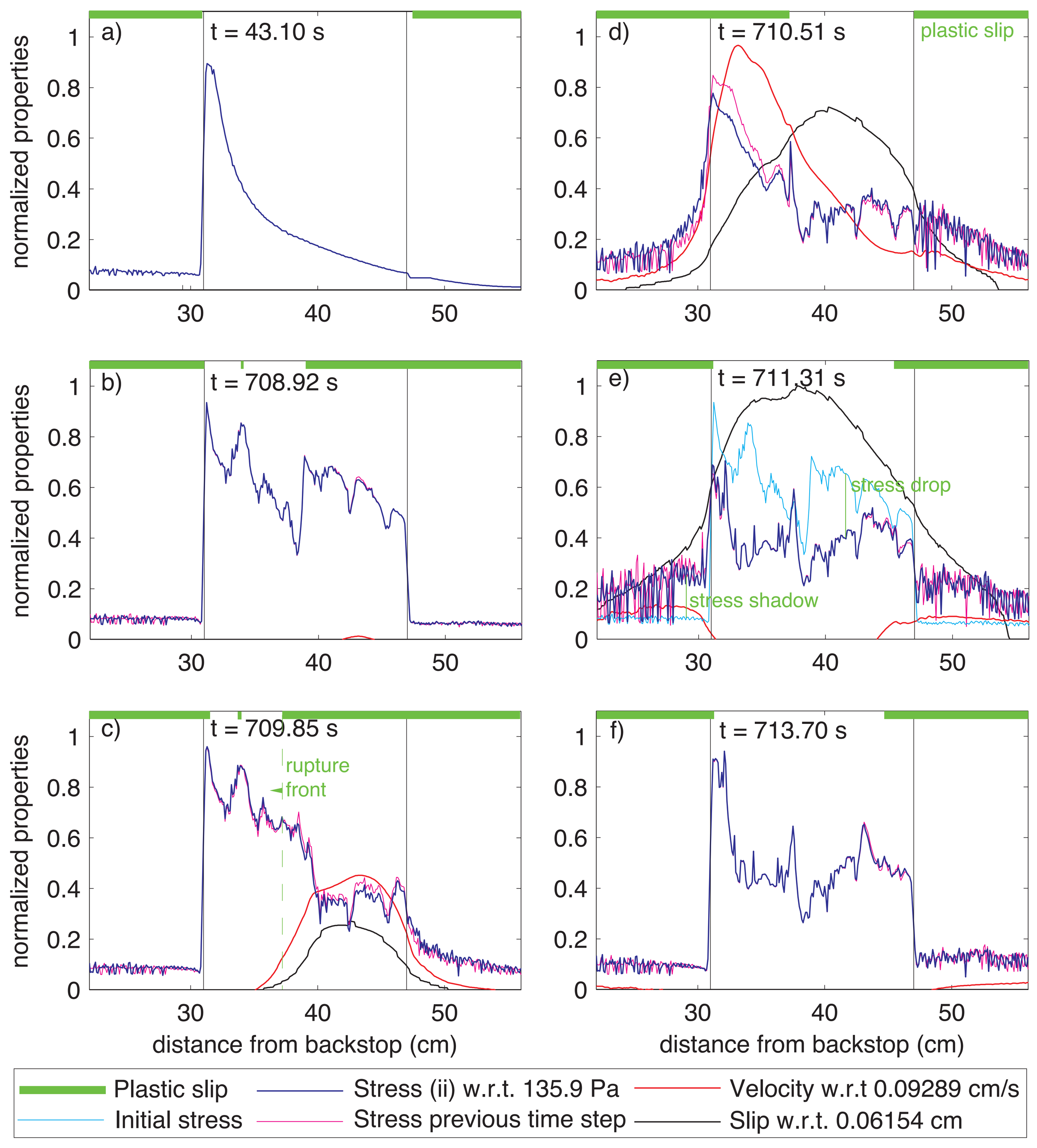


Fig. 8: Typical earthquake evolution.

5) Can we apply this to nature ?

Yes, we can ! We observe both interesting 'dynamic' and geodetic features. Ruptures occasionally occur as a pulse instead of a crack, and can even re-rupture patches. GPS displacements capture inter-, co-, and postseismic features via afterslip. In summary, this new tool can contribute to understanding seismic cycles !

Figure 9 demonstrates the occurence of both cracks (F. 9a) and a few pulses (F. 9b, before and after the moment of re-rupture in red). These ruptures may even re-rupture patches during the same event (F. 9b, after red line) by back-propagation or re-rupture at the hypocenter.

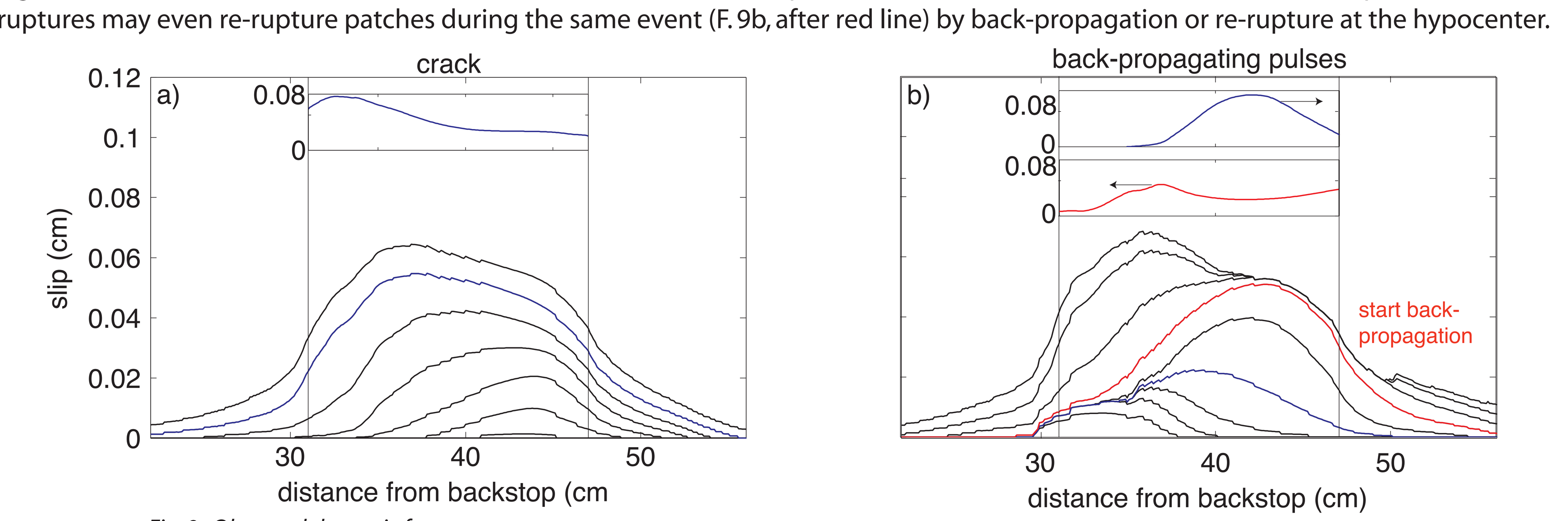


Fig. 9: Observed dynamic features.

Surface displacements qualitatively agree with geodetic observations (Figure 10). Interseimic displacements move land- and upward and rebound coseismically. Postseismic signals include persistent seaward motions due to afterslip that relaxes stress shadows (see Fig. 8e).

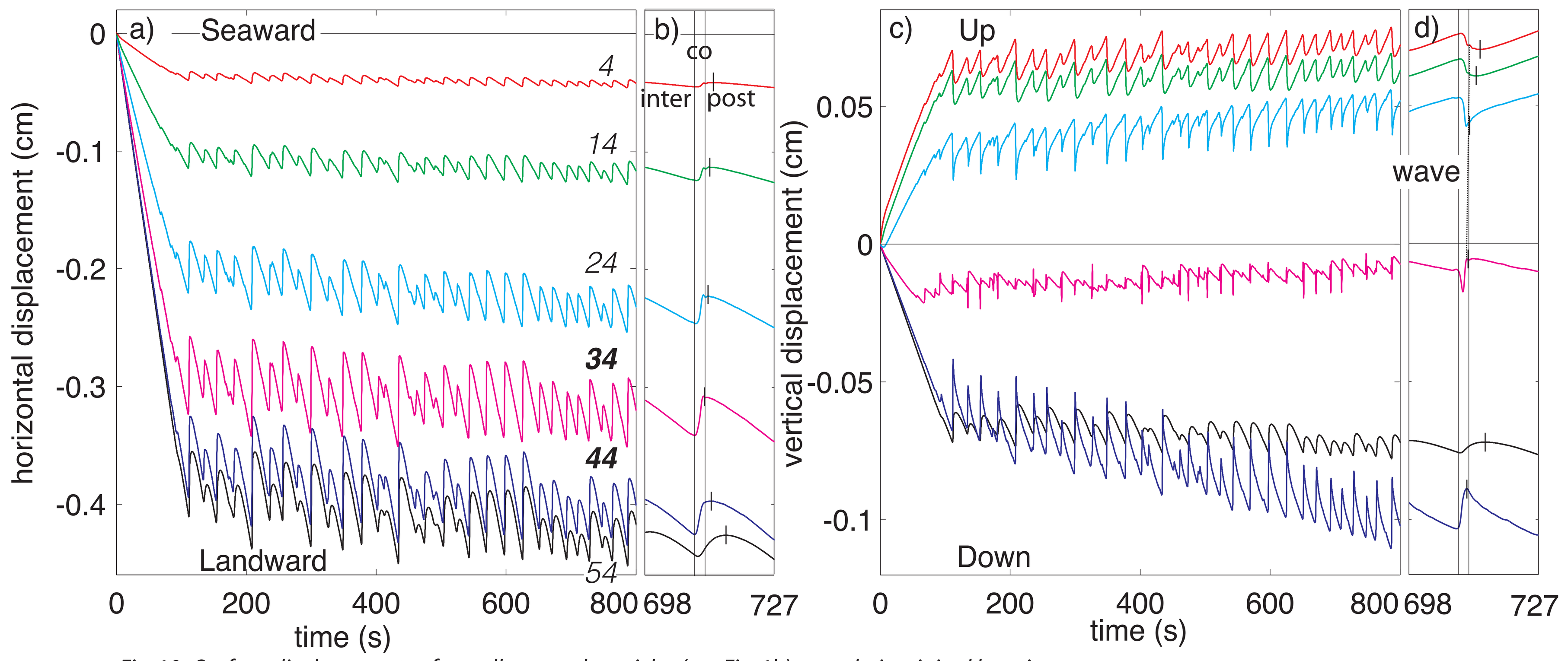


Fig. 10 : Surface displacements of equally spaced particles (see Fig. 1b) w.r.t. their original location. Note minor displacements due to the propagation of a shear wave, although inertia is not important in this specific laboratory setup.