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Numerical studies of small repeating earthquakes and their source parameters

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Abstract

Sequences of small repeating earthquakes have been found on a number of faults. Since their recurrence times range from a fraction of a year to several years and their locations are known, small repeating earthquakes are an excellent observation target. This has been exploited in a number of studies, including the San Andreas Fault Observatory at Depth (SAFOD) drilling project. Repeating earthquakes are used to study an increasingly richer array of problems, from fault creeping velocities and postseismic slip to earthquake interaction and stress drops. To assimilate and properly interpret the wealth of data on small repeating earthquakes, it is important to construct a realistic model of their occurrence.

Our studies supported by USGS have developed a model of repeating earthquakes based on laboratory-derived rate and state friction laws. In our model, a small patch with rate-weakening friction is surrounded by a much larger region with rate-strengthening friction. In the previous project supported by USGS, we demonstrated that the model reproduces the observed scaling of the seismic moment of repeating earthquakes with their recurrence times, when the rate and state law in the model incorporates the aging form of the state evolution. This is not a trivial result, since the observed scaling is different from the scaling that results in a simple conceptual model that treats repeating earthquakes as circular ruptures, with only seismic slip and stress drop independent of the seismic moment. During this project, we have demonstrated that models with the slip form of state evolution also reproduce the observed scaling, for parameters that result in a large enough stress drop. This motivates the need to explore the potential importance of dynamic weakening mechanisms in this problem, and we have developed a methodology to do that. We have also shown that the simulated repeating earthquakes have typical stress drops, dimensions, and the frequency content. Finally, we have explored the effects of patch geometry and the relation between 2D and 3D models.

From a more general point of view, the study have advanced our understanding of the partition of slip into seismic and aseismic parts and their interaction. The results and the developed methodology can be applied to other cases of interaction between seismic and aseismic slip, such as aseismic slip transients and associated low-frequency seismic tremor. The resulting better understanding of fault physics will contribute to reduction of losses from earthquakes in the US.

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Chen, T. and N. Lapusta, Scaling of small repeating earthquakes explained by interaction of seismic and aseismic slip in a rate and state fault model, *J. Geophys. Res.*, 114, B01311, doi:10.1029/2008JB005749, 2009.

Lapusta, N, and Y. Liu, Three-dimensional boundary integral modeling of spontaneous earthquake sequences and aseismic slip, *J. Geophys. Res.*, 114, B09303, doi:10.1029/2008JB005934, 2009.

Chen, T. and N. Lapusta, On behavior of small repeating earthquakes in rate and state fault models: the effect of state evolution laws and model geometry, in preparation, 2010.

Noda, H. and N. Lapusta, 3D earthquake sequence simulations with evolving temperature and pore pressure due to shear heating and diffusion off a fault: Effect of heterogeneous hydraulic diffusivity, in preparation, 2010.

Model of small repeating earthquakes based on rate and state friction

Small repeating earthquakes have been found in California, Japan, and Taiwan and their observations have been used to study various aspects of earthquake physics and mechanics (e.g., Ellsworth and Dietz, 1990; Vidale et al., 1994; Marone et al., 1995; Nadeau and Johnson, 1998; Nadeau and McEvilly, 1999; Bürgmann et al., 2000; Beeler et al., 2001; Sammis and Rice, 2001; Igarashi et al., 2003; Imanishi et al., 2004; Nadeau et al., 2004; Schaff et al., 2004; Matsubara et al., 2005; Allmann and Shearer, 2007; Chen et al., 2007; Dreger et al., 2007). Because of their short recurrence times and known location, small repeating earthquakes present a rare predictable opportunity for detailed observation and study, and that has been exploited in San Andreas Fault Observatory at Depth (SAFOD) drilling project (e.g., Hickman et al., 2004; Imanishi et al., 2004). SAFOD is a unique facility for studying the earthquake source. SAFOD location ensures that seismic, pore-pressure, tilt, and temperature data are captured in unprecedented proximity for several repeating earthquakes and processes before and after them. Proximity is an important advantage of SAFOD, as it not only allows capturing variations that may not be observable at a greater distance but also significantly improves the ability to separate the signal into path effects and source contributions. This provides a unique opportunity for comparison with detailed physics-based simulations proposed in this project.

Our model for the occurrence of small repeating earthquakes, in its current form, contains a small circular seismogenic patch surrounded by a much larger creeping fault zone (Figure 1; Chen and Lapusta, 2009) and embedded into an elastic medium. Outside of the creeping zone, sliding with the loading rate V_L is imposed on the fault to represent the effect of the surrounding steadily creeping segment. The seismogenic and creeping parts of the fault are modeled by rate and state friction laws. We used the standard rate and state formulations (e.g., Dieterich, 1979, 1981; Ruina, 1983). The formulations model variations of frictional shear strength τ_f due to its dependence on the effective normal stress $\bar{\sigma}$, slip rate V (which we also call slip velocity), and evolving properties (state) of the contact population represented by the state variable θ:

$$\tau_f = \bar{\sigma} f = (\sigma - p)[f_o + a\ln(V/V_o) + b\ln(V_o\theta/L)],$$
$$\frac{\partial\theta}{\partial t} = 1 - \frac{V\theta}{L} \text{ (aging law) or } \frac{\partial\theta}{\partial t} = -\frac{V\theta}{L}\ln\frac{V\theta}{L} \text{ (slip law),} \tag{1}$$

where σ is the normal traction, p is the pore pressure (which could be evolving but is fixed in the current version of the model), f_o, V_o, a, b, and L are parameters of the standard rate and state friction, with L being the characteristic slip for state variable evolution.

We solve for spontaneous long-term slip history of this model by using the 3D simulation methodology of Lapusta and Liu (2009), which is the extension of the 2D methodology of Lapusta et al. (2000). The methodology incorporates laboratory-derived rate and state friction laws, slow tectonic-type loading, and all dynamic effects of self-driven dynamic rupture**.** Such modeling is very challenging, especially in 3D, because of the variety of temporal scales involved. Slow loading requires years in simulated time. At the same time, rapid changes in stress and slip rate at the propagating dynamic rupture tips occur over times of order a small fraction of a second. The algorithm combines these scales and allows to treat accurately long deformation histories and to calculate, for each earthquake episode, initially quasi-static accelerating slip (nucleation process), the following dynamic rupture break-out and propagation, postseismic response, and ongoing slippage throughout the loading period in creeping fault region. There are no kinematic assumptions in our model other than the steady slip of the fault far from the location of the repeating earthquake.

As predicted by studies of stability of frictional sliding (Rice and Ruina, 1983; Dieterich, 1992; Rubin and Ampuero, 2005), most of the velocity-strengthening part of the fault in our model accumulates slip through stable sliding with the imposed long-term slip rate V_L. For given friction parameters, the behavior of the velocity-weakening patch depends on the relation between its radius r, consistent with the findings of stability studies. For sufficiently small values of r, the velocity-weakening patch accumulates slip through perturbed but aseismic sliding. Velocity-weakening patches of larger sizes produce repeating earthquakes. For the aging formulation, the critical patch radius is well-approximated by the estimate of Rubin and Ampuero (2005) with a 3D correction (Chen and Lapusta, 2009).

The ability of model to reproduce the observed scaling of seismic moment with recurrence time: the aging form of state variable evolution

To obtain repeating earthquakes of different sizes, we first change radius r of the velocity-weakening patch, keeping all other parameters the same and representative of the rate and state friction properties measured in the lab. The resulting scaling relationship between the recurrence time T and the seismic moment M_0 in our model reproduces the observed scaling $T \sim M_0^{0.17}$ (Nadeau and Johnson, 1998) as shown in Figure 2a for the model with the aging law of state evolution. The loading rate of 23 mm/yr results in shorter recurrence times than the observed ones (the fit to observations is given by the top line). If we use the loading rate of 4.5 mm/yr, which is within the range of 4 to 35 mm/yr suggested by Harris and Segall (1987) for the portion of the San Andreas fault with repeating earthquakes, then our model can reproduce both the scaling and the absolute values of the observed repeat times, as shown by blue triangles. Moreover, if, in addition to the variation in the patch radius, the rate and state parameters a and (b – a) are also varied within the factors of 0.5 to 2, the simulations produce repeating

earthquakes with moment magnitudes from 0.3 to 3.7, all of which follow the observed scaling (Figure 2b).

Note that the observed scaling reproduced by our model is significantly different from $T \sim M_0^{1/3}$, the scaling that results from a simple conceptual model in which earthquakes are treated as circular ruptures with stress drop independent of the seismic moment and seismic slip $V_L T$. The observed scaling is achieved in our model due to the fact that part of the slip on the repeating earthquake patch occurs aseismically, as detailed in the previous report. Several other explanations for the discrepancy in scaling have been proposed, including dependence of stress drop on seismic moment, with much higher stress drops for small events (Nadeau and Johnson, 1998), and occurrence of repeating earthquakes at a border between large locked and creeping patches (Sammis and Rice, 2001). However, there is no evidence for a large locked asperity, and recent studies based on SAFOD data (Imanishi et al., 2004; Allmann and Shearer, 2007) have pointed to stress drop values of the order of 1 to 10 MPa, the typical range for earthquakes in general (Abercrombie, 1995). Beeler et al. (2001) considered the model of a fixed-area patch governed by a conceptual law that incorporated strain hardening. They showed that aseismic slip on the patch can explain the observed scaling relation. However, the work pointed out that there was no experimental evidence for the strain-hardening law used in the model. Our model reproduces the observed scaling due to significant aseismic slip on the patch, using laboratory-derived friction law and interactions between the locked and creeping areas.

Scaling in the models with the slip form of the state variable evolution

The scaling for simulations with the slip law of state evolution also matches the observed one for a range of parameters (Figure 3). Note that for the slip law, unlike for the aging law, the behavior depends on the value of ($b - a$) in the velocity-weakening patch. As the value of ($b - a$) is increased, the simulated scaling get closer to the observed one and finally matches it. Note that, for a comparable range of patch radii and friction parameters, the range of earthquake magnitudes obtained with the slip law is narrower than that obtained with the aging law. We can extend the range of the scaling for the slip law by choosing a wider range of patch radii. Note that we used the loading rate of 23 mm/yr for this study. Using a smaller value, comparable to 4.5 mm/yr as in the case of the aging law, would make the simulations match not only the exponent of the observed scaling but also the absolute values of the recurrence times.

The difference in the qualitative features of the model response between the two laws highlights the importance of using the state evolution law best supported by experimental data. This has been already pointed out in the studies of earthquake nucleation by Rubin and Ampuero (2005) and Ampuero and Rubin (2008).

The fact that models with larger values of ($b - a$) (and hence with larger stress drops) reproduce the correct scaling points to the potential importance of incorporating dynamic weakening mechanisms in this model. We have developed a stable methodology for incorporating shear-heating effects such as flash heating into our simulations (Noda and Lapusta, 2010), as discussed later in this report.

Source properties for simulated small repeating earthquakes

Despite aseismic slip on the same patch, sometimes quite significant, the earthquakes produced in our model have typical source dimensions and stress drops, similar to those of small events in general (Abercrombie,1995), as shown in Figure 4. The source parameters in our model are also consistent with inversions for the repeating earthquakes at Parkfield (Imanishi et al., 2004; Allmann and Shearer, 2007).

We have also looked at the moment rate function and the corresponding source spectra of the simulated repeating earthquakes (Figure 5). For both aging law (Figures 5a, 5b) and slip law (Figures 5c, 5d), and different rupture patterns - the one in which seismic slip occurs only on a part of the velocity-weakening patch (Figure 5a) and the one in which seismic slip reaches the whole velocity-weakening patch (Figures 5b, 5c, 5d), the slopes of the source spectra are all close to -2, similar to seismological observations (e.g. Abercrombie, 1995).

Furthermore, we find that the seismological estimates of source parameters from the source spectra match well the source parameters determined directly from the simulations. The source radius determined from the corner frequency and standard rupture speed of 3 km/s approximately reproduces the size of the ruptured area. The stress drop determined from the corner frequency and the amplitude of the flat part of the spectra correctly predicts the average stress drop over the ruptured area.

Dependence of the model response on the model geometry

The circular velocity-weakening patch – that has been used in most of our simulations – is the simplest representation of a seismogenic patch. However, the streak-like nature of earthquake locations on creeping faults indicates that velocity-weakening fault materials may be present in stripes (W. Ellsworth, private communication, 2007). Hence a model that obtains earthquakes of different magnitudes by considering rectangular patches of a fixed width and increasing aspect ratio is an interesting alternative to the circular patches.

That is why we have investigated models with a rectangular velocity-weakening patch. Events of different size are obtained by keeping the width of the patch fixed, and the length of the patch varied. Different widths of the patch are studied. We find that the scaling obtained from this model is similar to the model with a circular patch (Figure 6a).

3D simulations are much more expensive numerically than 2D ones. That is why we have considered a 2D anti-plane model with a 1D fault. The details of the model response differ in the 2D and 3D models. For example, events that rupture only a part of velocity-weakening patch in 3D disappear in 2D. If the seismic moment is computed directly from the 2D simulation, then the scaling between the seismic moment and recurrence time is also not the same as in 3D models (and not the same as observed for natural earthquakes). However, when the results of a 2D simulation are reinterpreted as those in an axisymmetric 3D problem, the scaling is similar to that of a 3D model (Figure 6b).

Methodology for incorporating additional dynamic weakening into simulations of seismic events

A point on an active fault experiences a wide range of slip rates, from orders of magnitude below the tectonic loading rate (< 10^{-9} m/s) to coseismic slip rates (~ 0.1-10 m/s). Our simulations of repeating earthquakes, based on the developments of Lapusta and Liu (2009), successfully reproduce key features of the earthquake cycle: nucleation and dynamic propagation of ruptures, post-seismic slip, and interseismic stress accumulation. However, the simulations consider the behavior of a fault governed by a standard logarithmic rate- and state-dependent friction law.

At the same time, experimental and theoretical studies of the mechanical behavior of a fault have revealed that the fault strength reduces tremendously during rapid slip from what is commonly observed at low slip rates, due to a number of physical processes that depend on the rock type and the fault conditions. They include thermal pressurization of pore fluids, flash heating of the microscopic asperities, frictional melting, and other mechanisms (e.g., Rice, 2006 and references therein). Most of the mechanisms are activated by frictional heating during rapid slip characteristic of seismic events. Also, the temperature rise in the vicinity of a fault is sometimes discussed based on geological observations (e.g. the existence of pseudotachylytes, the change in the ESR signal near the fault [Fukuchi et al., 2004], and the recovery of fission-track [e.g. d'Alessio et al., 2003]). It is important to incorporate the frictional heating and resulting weakening processes into simulations of repeating earthquakes, as studies show that these processes can be relevant even for small slips of these events (e.g., Rice, 2006).

With a combined funding from NSF and USGS, we have developed a methodology for simulating long-term history of fault slip that incorporates variations in the temperature and pore pressure due to frictional heating and diffusion from the fault (Noda and Lapusta, 2010). During dynamic events, such methodology allows for the thermal pressurization of pore fluids. Previously, this weakening mechanism was incorporated during dynamic rupture propagation or quasi-dynamic rupture nucleation by using the finite difference method [e.g. Noda et al., 2009] and the boundary integral method [e.g. Andrews 2002; Schmitt and Segall, 2008]. These previous approaches have limitations in their applicability to simulating the entire earthquake cycle with long simulated times (thousands of years) and adaptive timesteps (typically from milliseconds to years). The finite difference method requires small timesteps for stability. The boundary integral method requires the storage of the history of frictional dissipation on the fault which can be a limiting factor even if truncation is introduced. In our approach, the equations for thermal pressurization are integrated analytically in the wavenumber domain, assuming constant frictional dissipation rate during each timestep, and incorporated within the simulation methodology of Lapusta and Liu (2009). This diffusion solver is stable regardless of the length of the timestep and has turned out to be very efficient.

In the follow-up project that we are conducting now, we will use the developed methodology to study the potential importance of additional dynamic weakening due to shear heating for repeating earthquakes and their potential effect on the balance of seismic and aseismic slip and other properties of repeating earthquakes.

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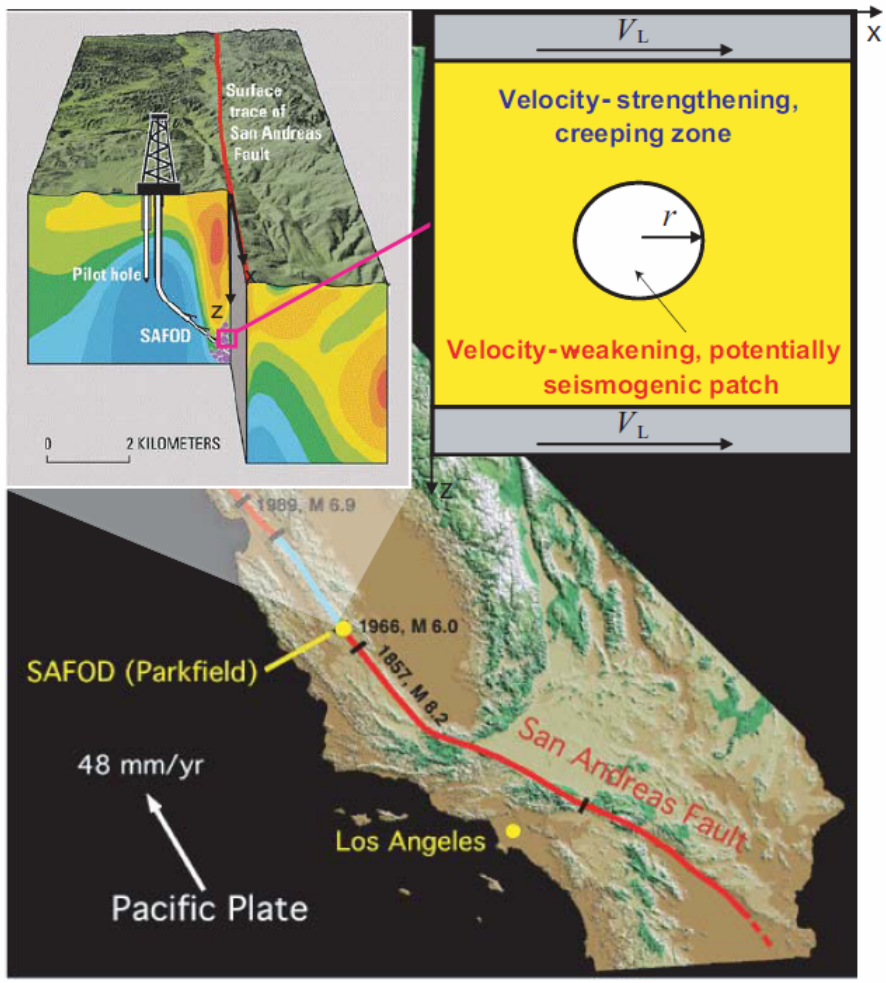

Figure 1. Schematics of the model. To simulate repeating earthquakes, such as the targets of SAFOD drilling project on the Parkfield segment (shown in blue) of the San Andreas fault, we consider a segment of a vertical strike-slip fault embedded into an elastic medium and governed by rate and state friction laws. On the fault, a small, potentially seismogenic, patch with steady state velocity-weakening properties (shown in white) is surrounded by a creeping, velocity-strengthening segment (shown in yellow). Outside of the simulated fault segment, steady sliding is imposed with the long-term slip velocity V_L.

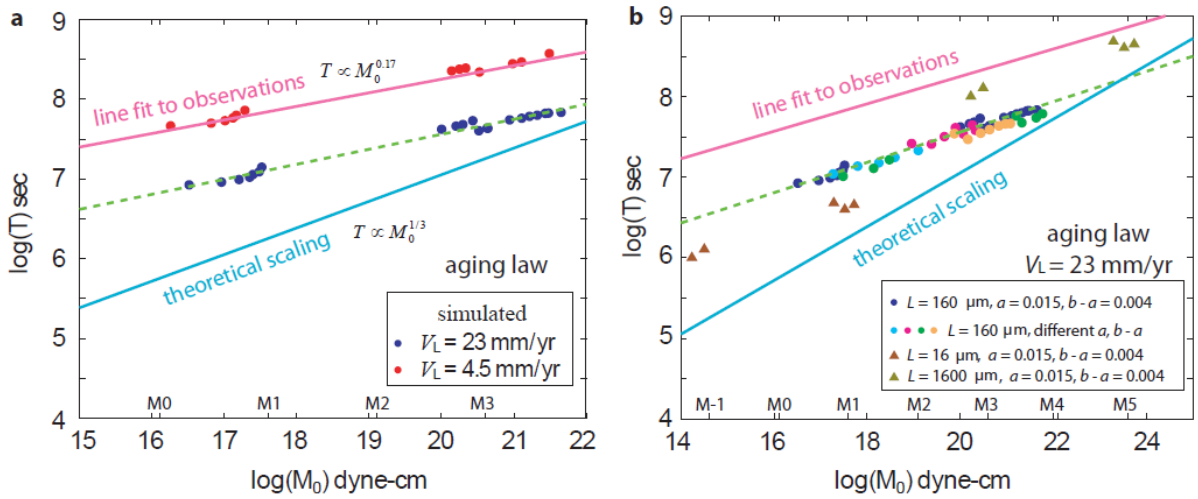

Figure 2. (a) Scaling of seismic moment M_0 with recurrence time T for different patch radii r and loading rates V_L of 23 mm/yr and 4.5 mm/yr. For each V_L, earthquakes of different sizes are obtained by varying the radius of the velocity-weakening patch; all other model parameters are the same. The lines fit to observations of Nadeau and Johnson [1998] is indicated by the magenta line. The best fit to simulations with V_L = 23 mm/yr is shown by the green line. For both values of V_L, the observed scaling exponent is reproduced; the simulations with V_L = 4.5 mm/yr also fit the absolute values of T.

(b) Simulation results for V_L = 23 mm/yr, L = 160 μm, and several different rate and state parameters a and b all produce the same scaling, with events of all magnitudes between 0.3 and 3.7. V_L = 23 mm/yr was used in (b)-(d) for computational efficiency. Simulations for different values of L also reproduce the observed scaling exponent.

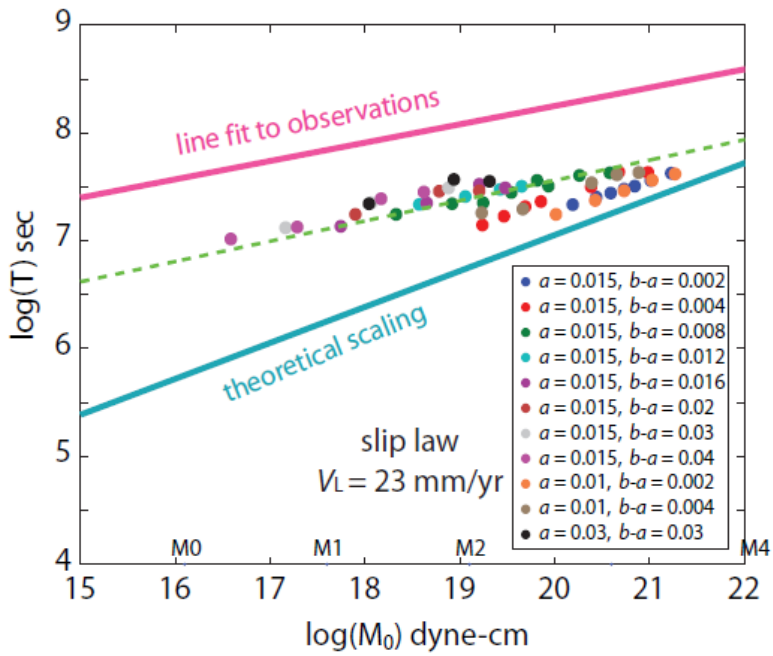

Figure 3. Simulation results for the slip law, V_L = 23 mm/yr, L = 160 μm, and several different rate and state parameters a and b. Note that simulations with the slip law also reproduce the observed scaling exponent (green dashed line) for large enough values of ($b - a$). Please see the main text for further discussion.

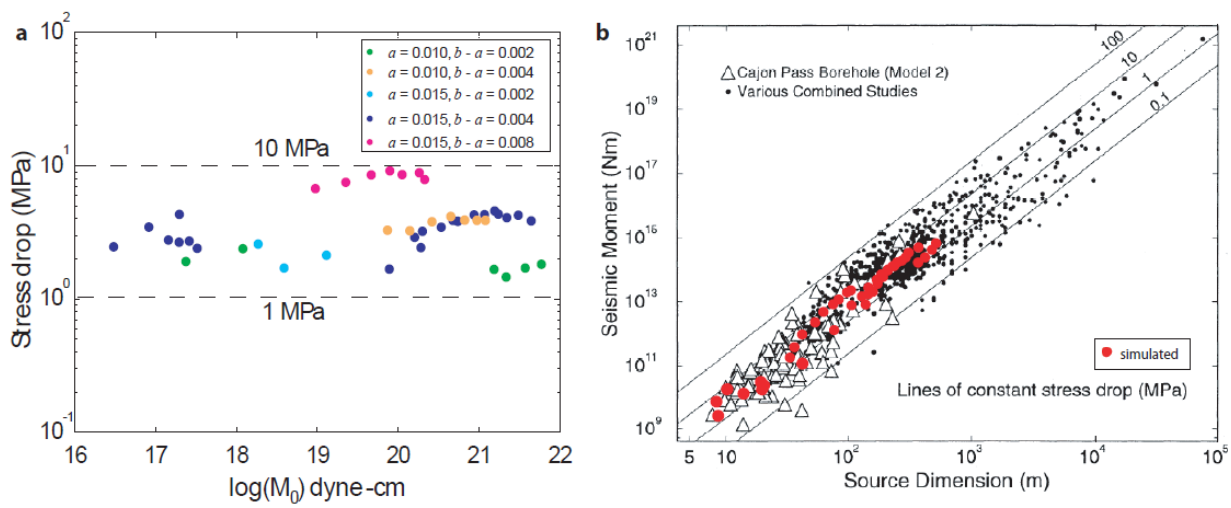

Figure 4. (a) Stress drops averaged over the source (i.e., the area of positive stress drop) for all simulations with L = 160 μm. The stress drops are in the range 1–10 MPa of typical stress drops, consistent with recent inversions for small repeating earthquakes. (b) Values of seismic moment and source dimensions, calculated from our simulations and plotted on top of seismic estimates for small and medium earthquakes [Abercrombie, 1995]. The source parameters in our simulations are consistent with the seismic observations.

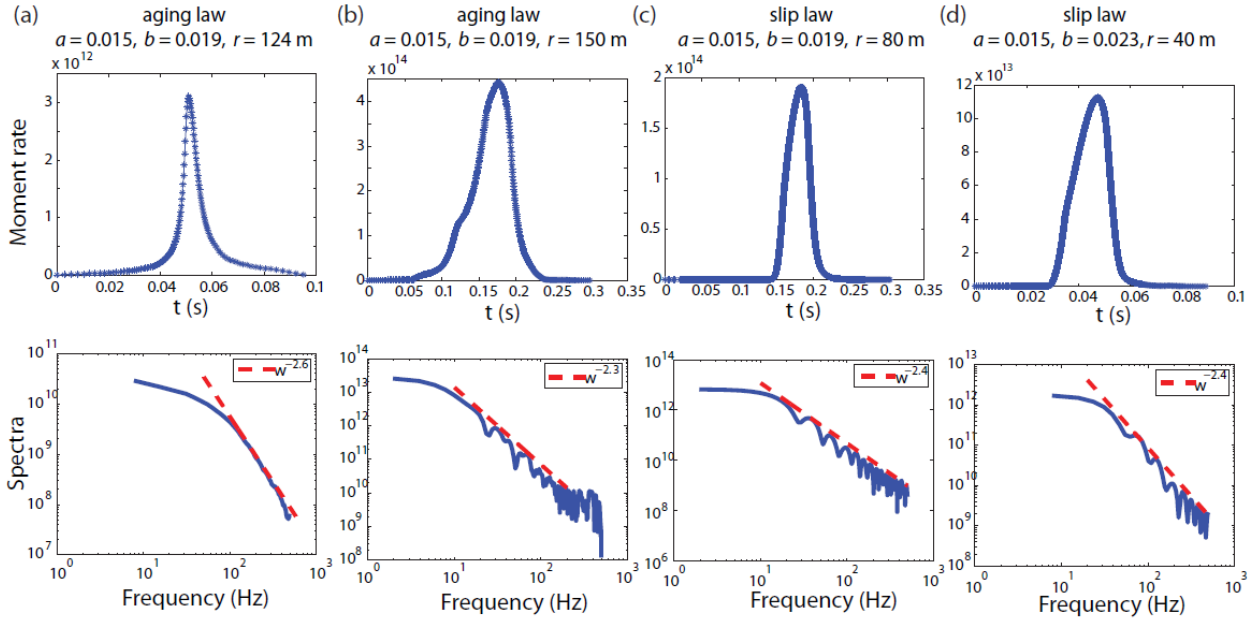

Fig 5. Upper row: Moment rate function for the simulated events with different forms of state-variable evolution law and different model parameters. Lower row: The corresponding source spectra (blue) and best-fit slopes (red).

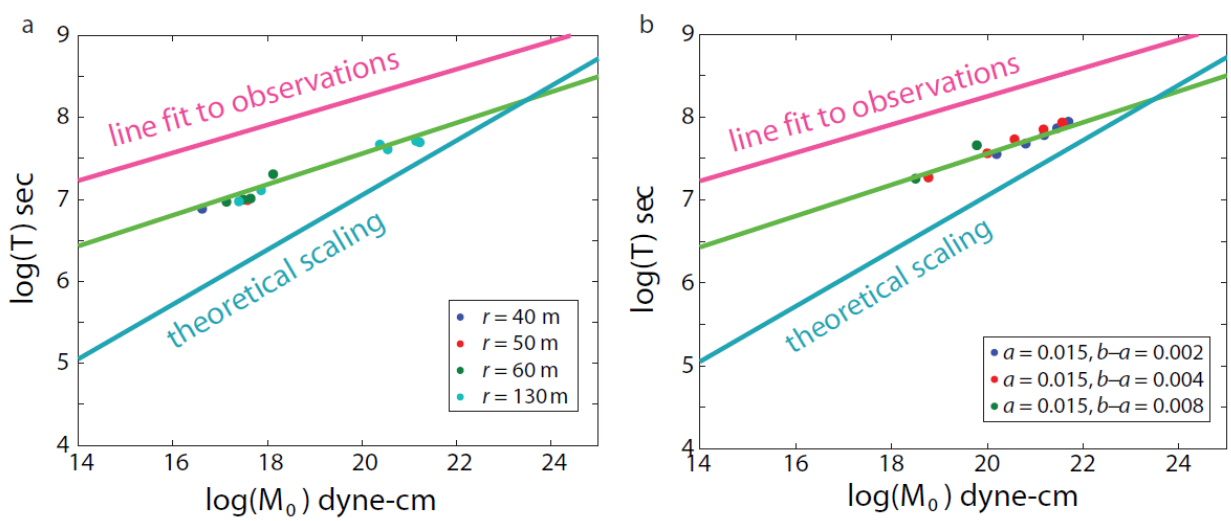

Fig 6. (a) Scaling of seismic moment M_0 with recurrence time T for the model with a rectangular velocity-weakening patch. Simulations with the same patch width ($2r$) and different lengths are shown in the same color. The overall scaling is similar to the results with a circular patch as shown in Fig 1. (b) Scaling of seismic moment M_0 with recurrence time T for 2D simulations, with results reinterpreted for a 3D axisymmetric problem. Simulations with different friction parameters a, b are shown in different color. The scaling is similar to 3D simulation results as shown in Fig 1.