Earthquake cycle simulations for long-term damage evolution and healing in low velocity fault zones

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Abstract

Most major strike slip fault systems are surrounded by narrow zones of damaged rocks that can have a crucial effect on earthquake dynamics. Owing to the limited timescale of seismic observations, the structural evolution of this damaged zone and its long-term effects are not well understood. We study the mechanical response of damage evolution and healing over multiple earthquake cycles using fully dynamic earthquake cycle simulations in a 2D vertical strike-slip fault. We use a spectral element method to discretize the domain and a rate-state dependent friction on the fault to simulate all the stages of the seismic cycle, including interseismic slip, earthquake nucleation, rupture propagation and postseismic slip. A narrow, compliant fault-parallel elastic layer with low seismic wave velocities is introduced to emulate near-fault damage. The low-velocity layer reflects waves during the seismic period giving rise to stress heterogeneities that persist through multiple seismic cycles. We introduce a scalar damage multiplier ‘d (01)‘ that reduces the effective shear modulus during the earthquake and increases it during the interseismic period. We study different realizations of d and h through time: the simplest model consists of a constant increase in damage and healing over each seismic cycle and the more complex model includes a heterogeneous damage proportional to the peak slip velocity along the fault. The distribution and evolution of dynamic parameters (shear stresses and slip velocities) and static earthquake parameters (cumulative slip and static stress drops) as a function of the damage is shown and compared to the existing continuum damage rheology models and field geologic observations. These simulations will provide a better insight into the partitioning of damage and healing during seismic cycles and the saturation of damage in mature fault zones.

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Earthquake Cycle Simulations for Long-Term Damage Evolution and Healing in Low Velocity Fault Zones

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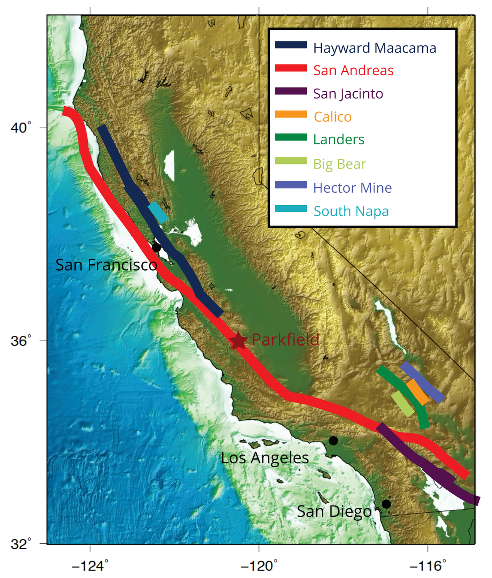
Introduction

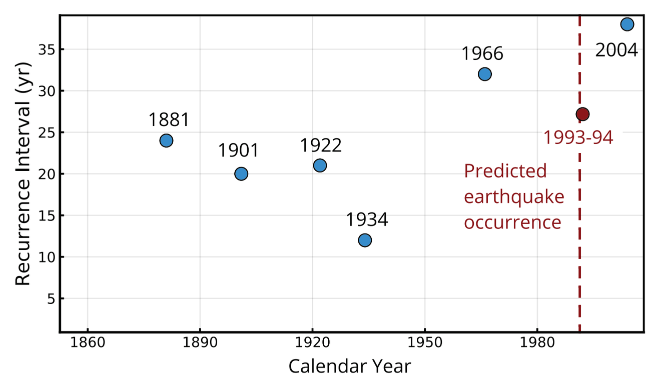
Most major strike slip fault systems are surrounded by narrow zones of damaged rocks that can have a crucial effect on earthquake dynamics. Understanding the structural evolution of this *Fault Damaged Zone* over multiple earthquake sequences is key to unraveling the location, recurrence, stressing history, and probability of subsequent earthquakes. Using fully dynamic earthquake cycle simulations in a 2-D vertical strike-slip fault, we aim to understand the variation in recurrence intervals of large earthquakes in relation to the evolution of damage and healing of the *Fault Damaged Zone*.

The figure below (left) shows the documented fault damaged zones in California. Several observations along these faults have quantified the temporal changes in seismic wave velocities, providing evidence for damage and healing of *Fault Zone* structures before and after large earthquakes (e.g., Vidale and Li, 2007; Li et al., 2006). The figure on the right shows the recurrence intervals of Mw 6 earthquakes in the Parkfield region of the San Andreas Fault. Parkfield is very well known for having regular earthquakes of magnitude 6 every ~30 years. Despite this regularity, the Parkfield segment still exhibits significant variability in the recurrence intervals as shown below. Based on the history of Mw 6 earthquakes, (Bakun et al., 1985) predicted that the next earthquake would occur in 1993-94, but it eventually happened in 2004.

Dynamic fracture mechanics predicts that the recurrence interval of earthquakes is fairly uniform for a crack-like rupture in a homogeneous medium. We show that the evolution of damage and healing can potentially provide an explanation for the variability in earthquake recurrence, especially in mature *Fault Damaged Zones*.



Fault Damaged Zones in California

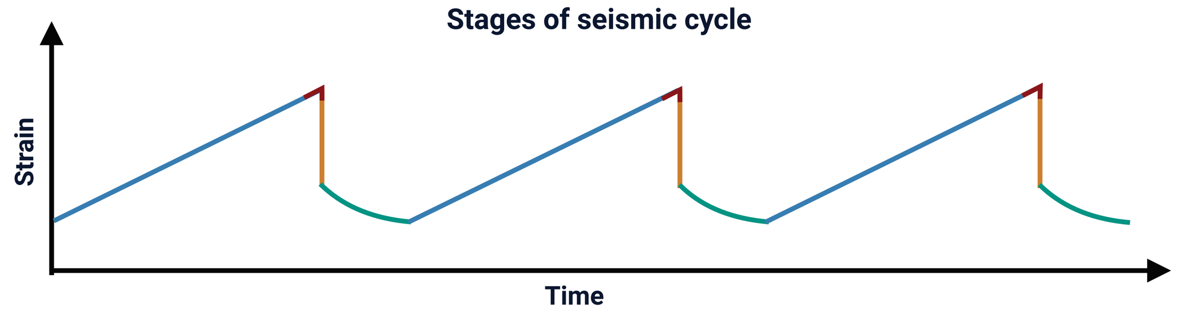


Recurrence of Parkfield earthquakes (Mw ~ 6)

Background

We simulate fully dynamic earthquake cycles on a 2-D vertical strike slip fault. We use a spectral element method written in Julia (JuliaSEM) adapted from Kaneko et al., (2011) to solve the elastodynamic equations. Rate and State friction model (Dieterich, 1979; Ruina, 1983) is used to propagate rupture along fault. These simulations can can reproduce all the stages of the seismic cycle including interseismic creep, earthquake nucleation, rupture propagation, and postseismic deformation (e.g., Lapusta et al., 2000). The seismogenic zone extends down to 15 km depth, below which it is loaded at the rate of tectonic plate motion. The top 2 km also creeps aseismically, therefore the earthquake is allowed to nucleate from 2 km - 15 km depth, which is consistent with the observations along major strike-slip faults.

Stages of seismic cycle



Interseismic
Tectonic Plate motion.

Strain accumulation on the locked fault.

Timescale of years to decades.

Nucleation
Start of Acceleration.

Nucleation size has a critical effect on the spatiotemporal complexity.

Timescale of months to years.

Coseismic
Propagation of rupture generates seismic waves.

Damaged zones cause wave reflections that promotes stress heterogeneity.

Timescale of seconds.

Postseismic
Inelastic deformation after earthquakes due to stress relaxation.

It includes afterslip, viscoelastic and poroelastic deformation.

Timescale of months to years.

Long-term fault slip = elastostatics + elastodynamic waves + fault friction

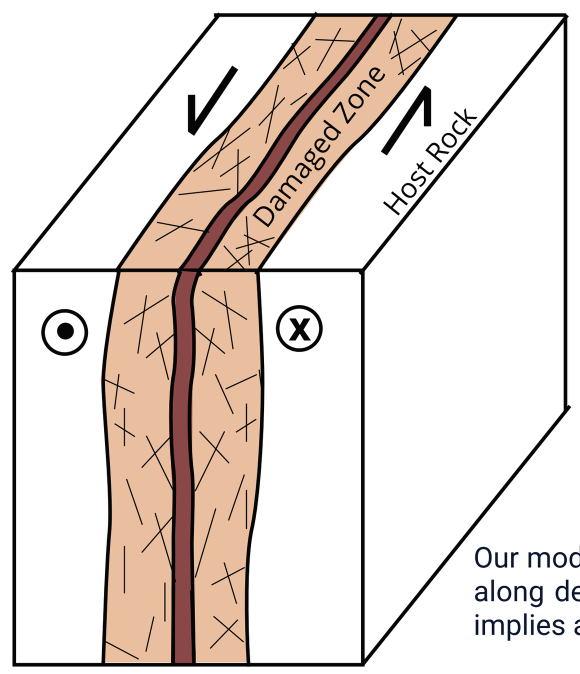
$$-\nabla . \sigma + f_{source} = 0$$

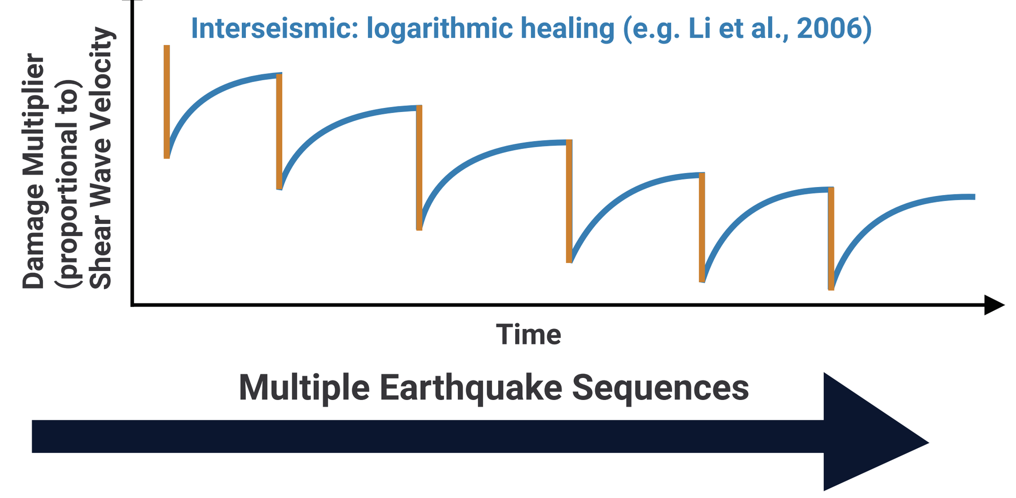
Stress Divergence: Contains the material properties and the deformation gradient of the whole medium.

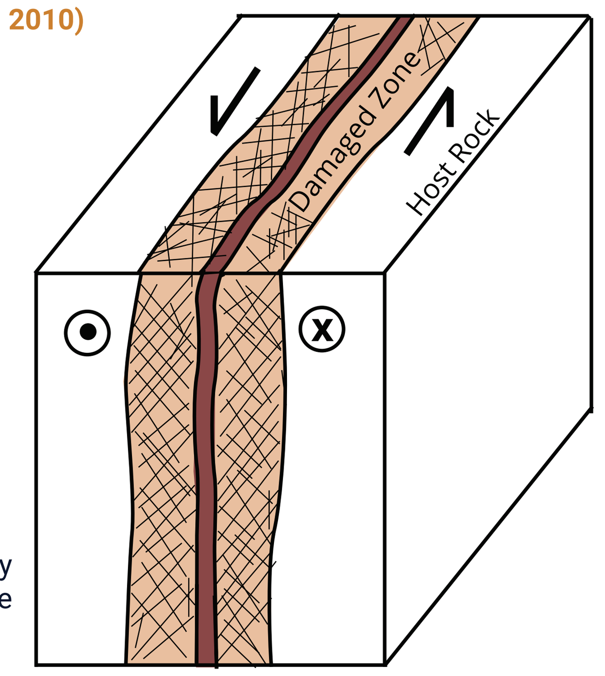
Source Term: Contains the on-fault stresses and slip, governed by the rate-state friction laws.

$$\rho \ddot{u} = -\nabla . \sigma + f_{source}$$

Acceleration of the medium.







Our model is a two-dimensional vertical cross section where the friction and stresses vary along depth and the motion of the fault is in and out of the plane. In this study, damage implies a **reduction in elastic shear modulus**, and therefore the shear wave velocity.

Immature (young) fault damaged zone

Diffused damage boundary.

Lower fracture density, which implies lower rigidity contrast with the host rock and therefore lower shear wave velocity contrast.

Examples: Ridgecrest-California, Pelopponese-Greece.

Mature (old) fault damaged zone

Sharp Damaged Boundary.

Higher fracture density, which implies higher rigidity contrast with the host rock and therefore higher shear wave velocity contrast.

Examples: San Andreas Fault, North Anatolian Fault.

Conclusions

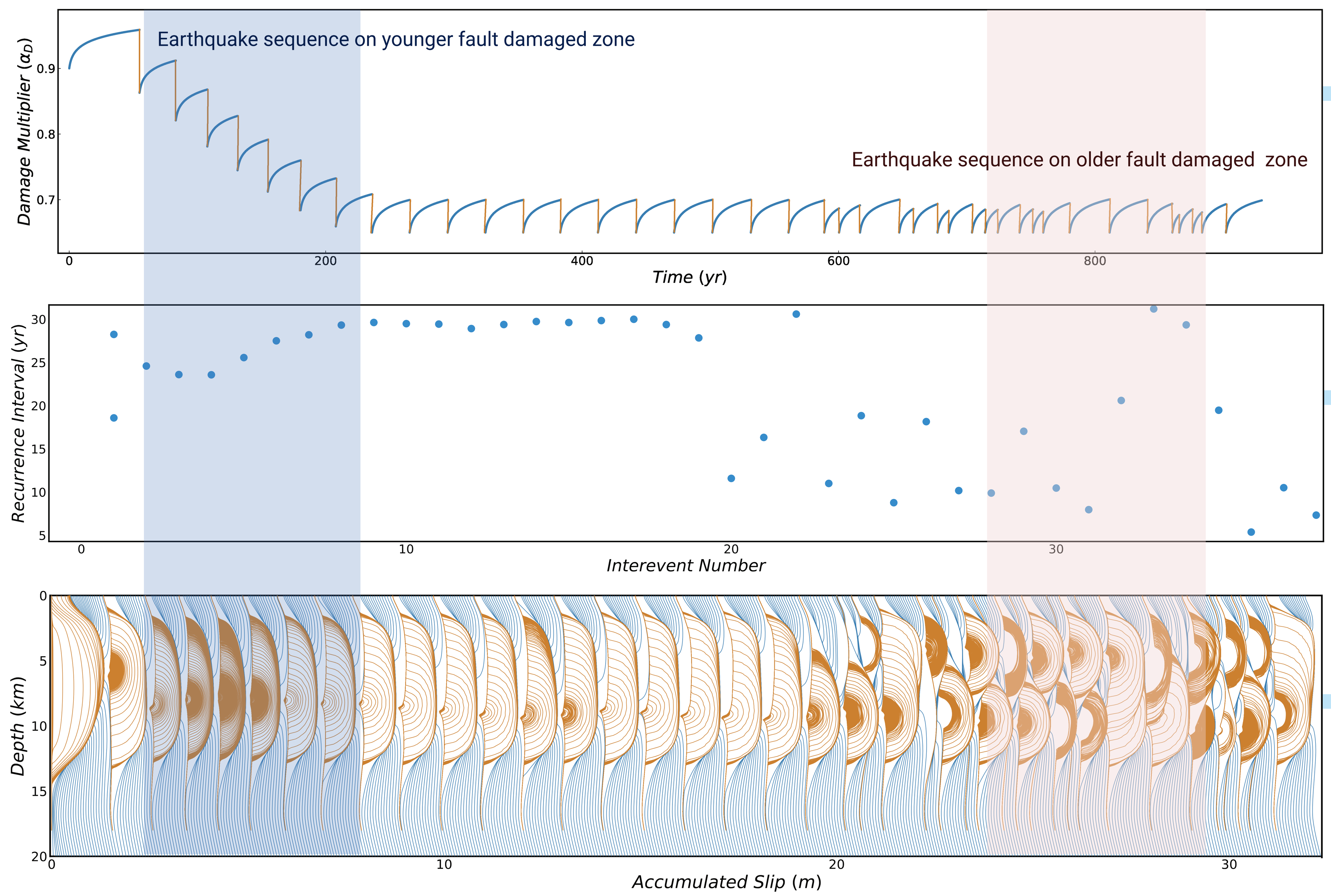
Time-dependent damage and healing in Fault Damaged Zones lead to much shorter recurrence intervals of large earthquakes as compared to a homogeneous medium.

Mature Fault Damaged Zones have more variability in recurrence intervals.

The earthquakes in the sequence do not rupture through the surface, possibly due to aseismic creep penetrating into the locked region. This arises from the logarithmic healing prescribed during the interseismic period.

We see smaller earthquakes with a bimodal distribution of hypocenters during later stages of Fault Damaged Zone maturity.

Results



Damage multiplier indicates the shear wave velocity contrast between the host rock and the damaged medium. A value of 0.9 implies that the damaged zone has a shear wave velocity 90% of the surrounding host rock. We prescribe a **10% decrease in shear wave velocity after every earthquake** and a time-dependent **logarithmic healing** during the interseismic period**.** The decrease in shear wave velocity during an earthquake becomes constant (a value of 0. 65) as the fault zone matures.

Here we show the recurrence interval between the earthquakes. On average, the earthquakes repeat after ~25 years, which is a **much shorter recurrence interval** compared to equivalent homogeneous medium exhibiting a recurrence of ~ 100 years. Initially, we see a sinusoidal change in recurrence when our fault is very young and damage is accumulating during earthquakes. This recurrence becomes relatively constant as the fault matures. However, in the later stages of the mature fault, we see highly oscillatory recurrence intervals due to more complexities in the earthquake sequence.

This figure shows the accumulated slip contours on fault. The blue lines (representing aseismic creep) are plotted every 2 years and the orange lines (representing seismic slip) are plotted every 0. 5 seconds. The earthquakes (orange lines) are **predominantly sub-surface events**. As the fault zone becomes mature, we see the emergence of earthquakes with **bi-modal distribution of hypocenters** and variable sizes when compared to an immature fault damage zone. We also see a **variable rupture duration** as suggested by the density of orange lines in the sequence.

In the figures above, we show the evolution of the damage as a function of time, the recurrence intervals of the earthquakes and the cumulative slip distribution along the fault. In a homogeneous medium, the damage multiplier will be 1 such that rigidity is constant and equal to that of the host rock. With the same initial friction and stress conditions along the fault, the **homogeneous medium shows a constant recurrence of ~100 years** with periodic Mw 7 earthquakes occuring along the fault. In contrast, a **damaged medium with time dependent damage and healing shows variability in the earthquake recurrence**, especially at the later stages when the fault damaged zone becomes more mature. We also observe predominantly **sub-surface events** with **variable hypocenter** locations, as opposed to a homogeneous medium where the ruptures break through the surface for similar friction parameters.

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