Progress report for 2004 SCEC Proposal

Earthquake Dynamics in Two Classes of Heterogeneous Faults

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Proposal Category
Integration and Theory

Disciplinary Group
Fault and Rock Mechanics
Geology

Interdisciplinary Focus Areas
Earthquake Source Physics
Fault Systems

Summary

Our last year studies under this project focused on two problems attempting to incorporate realistic aspects of fault zone structure and laboratory-based rheology. The first problem is concerned with dynamic rupture in structures that include material discontinuity interfaces. The assumed model consists of a very low velocity (damage) zone between two different solids and it includes nine potential faults, two of which are material interfaces. The results indicate that ruptures that nucleate in the surrounding host rock tend to migrate spontaneously to the material interfaces, and to evolve with propagation distance to unidirectional ruptures. The second problem involves effort to model long deformation histories on a fault governed by rate- and state-dependent friction with a heterogeneous distribution of critical slip distances with depth and along-strike. Our last year work on this topic was focused primarily on developing and testing the model. The sections below give additional details on results associated with the two topics.

Numerical simulations of 2D in-plane ruptures in a multi-fault tri-material system

Brietzke and Ben-Zion (2004)

Earthquake faults with large slip are likely to bring into contact rocks with different elastic properties. The material near a geological fault is typically observed to be shattered with increased porosity and fluid content, leading to a zone of low seismic velocities, often referred to as fault-zone, between the bounding crustal blocks. Previous work has shown that ruptures along a material interface have remarkable dynamic properties which are relevant to a number of geophysical and engineering problems. In all previous theoretical and experimental works on this topic, the path of rupture propagation was prescribed rather than being allowed to develop spontaneously. While material interfaces are mechanically-efficient failure surfaces, it is not clear for which conditions ruptures that start in the bulk would migrate on their own to material interfaces. Resolution of this issue is important to clarifying whether the remarkable dynamic phenomena associated with material interfaces occur only for a (perhaps very small) subset of ruptures with hypocenters at the interface, or whether they also tend to occur in the more general case of hypocenters in a volume surrounding material interfaces. In the present work, we attempt to clarify the conditions for which ruptures that start in the bulk migrate on their own to material interfaces, and evolving properties of such ruptures.

We employ a generalized version of the second-order finite-difference code used by Andrews (1973) and Andrews & Ben-Zion (1997) to perform a numerical parameter-space study of two-dimensional in-plane ruptures in a multi-fault tri-material system. We show that material interfaces are favored locations for rupture propagation and we examine tendencies of initiated ruptures to migrate spontaneously to material interfaces. Ruptures in our work are nucleated by a symmetric bilateral expanding pore pressure source, and may then continue to propagate (or not) along one or several faults. The faults, two of which are material interfaces, are situated equidistant and parallel to each other. Using different nucleation locations, different initial stress, different velocity contrasts, different frictional fault separations, different widths of a low velocity zone, and different number of faults, we examine the range of conditions for which ruptures migrate spontaneously to material interfaces and continue to propagate in a self-sustaining manner. We perform simulation results with faults governed by pure Coulomb friction and faults governed by Prakash-Clifton friction, and discuss similarities and differences between the different cases. We also show results of faults governed by Coulomb friction surrounded by a viscoelastic media. Example results are shown in Figure 1.

Long Deformation Histories on Heterogeneous Fault Governed by RSD Friction

Hillers et al. (2004)

Previous studies of slip on a fault governed by rate- and state-dependent (RSD) friction (e.g., Rice, 1993; Ben-Zion and Rice, 1997; Tullis, 1996; Lapusta et al., 2000) employed frictional properties that correspond to a fairly homogeneous smooth fault. In most cases, the only types of heterogeneities were the lab-based variations of the *a* and *b* parameters that produce transitions between velocity-strengthening and velocity-weakening regimes. In this study we use, in addition to depth-variations of *a* and *b*, correlated heterogeneities of the critical slip distance parameter *L* to model a form of geometrical heterogeneities on a fault that is related to roughness. More specifically, we perform 3D quasi-static and quasi-dynamic simulations with a family of 2D anisotropic correlated distributions of *L* having different correlation lengths along strike and with depth. The depth-variation of *L* can be used to model an overall reduction of the gouge thickness (and hence *L*) with depth, while variations of *L* along strike can provide approximate representations of faults that are at different evolutionary stages.

The modeling procedure follows the ideas developed by Rice (1993) and used extensively in subsequent studies (e.g. Rice and Ben-Zion, 1996; Ben-Zion and Rice, 1997; Lapusta et al., 2000). We consider a vertical strike slip fault plane (with *x* being the direction along strike and *z* denoting depth) embedded in an elastic half space. The response of the fault to a continuous loading by a moving substrate below the seismogenic zone is governed by RSD friction and elasticity as follows. The shear stress acting on each computational cell in the seismogenic zone on the fault is given by

$$\tau(x,z,t) = \tau^0(x,z,t) + S_u(x,z,t) - \eta[v(x,z,t) - v^\infty] \tag{1}$$

where $S_u(x,z,t) = \sum_{x',z'} K_{x-x',z,z'}[u(x,z,t) - v^\infty t]$ with the stiffness matrix $K_{x-x';\, z,\, z'}$ governed by the solution of Chinnery (1963) for dislocation on a rectangular patch in elastic half space. The damping term $\eta = G/2v_s$, with G being rigidity and v_s the shear wave velocity of the surrounding bulk, respectively, accounts for radiation perpendicular to the fault and guarantees solutions during dynamic instabilities. Clearly, its contribution to τ is significant only during slip events when the slip velocity v is sufficiently high. For speeding up the computations we sometimes use $\eta = 10^4\eta_0$, which results in lower coseismic slip velocities, therefore lower stress drops and hence shorter interevent times. The rationale for this procedure is given in detail in Rice (1993).

The frictional response on the fault surface to external loading is given by rate/state formalism, where the friction coefficient μ follows

$$\tau^f(x,z,t) = \mu(x,z,t)\bar{\sigma}(z) \tag{2}$$

$$\mu(x,z,t) = \mu_0 + a(z)\ln[v(x,z,t)/v_0] + b(z)\ln[v_0\theta(x,z,t)/L(x,z)] \tag{3}$$

Within this notation, τ^f denotes the frictional resistance and $\bar{\sigma}(z)$ is the effective normal stress (lithospheric normal stress minus pore pressure in the fault). The parameters governing the frictional evolution are the nominal friction, μ_0, laboratory-derived values for *a* and *b*, a reference sliding velocity v_0, state θ and the characteristic slip distance *L* over which the response evolves. The state variable θ evolves according to the Dieterich-Ruina version of the RSD formulation with

$$d\theta(x,z,t)/dt = 1-[\theta(x,z,t)v(x,z,t)/L(x,z)] \quad (4)$$

We solve the above four coupled ODEs by a Runge-Kutta scheme of order four (DOPRI5) or eight (DOP853) as developed by Hairer and Wanner (Hairer et al., 1993). The stress update is calculated using an algorithm that performs a FFT in the along strike direction. The accuracy of the employed numerical procedure was verified by duplicating results of Rice (1993).

Initial results

Having verified the numerical procedure, we started to perform a parameter space study with a depth-dependent distribution of *L* while keeping it uniform along strike. In contrast to previous studies, we apply in this first set of simulations a constant negative a-b value that allows for instabilities throughout the entire fault plane (Figure 2a). Transitions of *L* at the top 4 and lower 10 km of the fault to larger values than the background *L* = 0.1 m are sufficient to produce stable sliding regions. We show that this particular parameterization of the problem leads to the same characteristic stick slip response at seismogenic depth, stable sliding portions above 4 km and a creeping section below 16 km depth (Figure 2b).

At present we are continuing to examine additional cases with chessboard patterns of *L* values in an effort to find general rules (or at least trends) that govern the interaction between heterogeneous fault patches. A typical implementation example is given in Figure 3a, where the fault plane has been divided into 32 x 4 patches, each patch consisting of 32 cells. Other simulations use 16 x 2 patches with 64 cells and different random distributions of *L* values. We assign one single *L* value from the interval log10[Lmin, Lmax] to each cell which is illustrated by the histogram in Figure 3b. Since the 2D L-function shown in 3a has no particular depth dependence, we apply an *a-b* profile that stabilizes fault slip at depth having the unstable zone extended to the surface (Figure 3c). The resulting slip-velocity, slip and stress at a given time are shown in Figure 4. In this case of a regular distribution of *L* values, it is possible to associate heterogeneities in the simulated fields with the heterogeneities of *L* values. In the continuing work we will search for characteristic informative correlations between the employed fault properties and resulting fields.

Once we obtained a basic understanding of the results, we will perform systematic simulations using a family of 2D anisotropic correlated distributions of *L* having different correlation lengths along strike and with depth. The depth-variation of *L* will be chosen to model an overall reduction of the gouge thickness (and hence *L*) with depth. The variations of *L* along strike will be chosen to provide approximate representations of faults that are at different evolutionary stages.

Publications Supported by this grant

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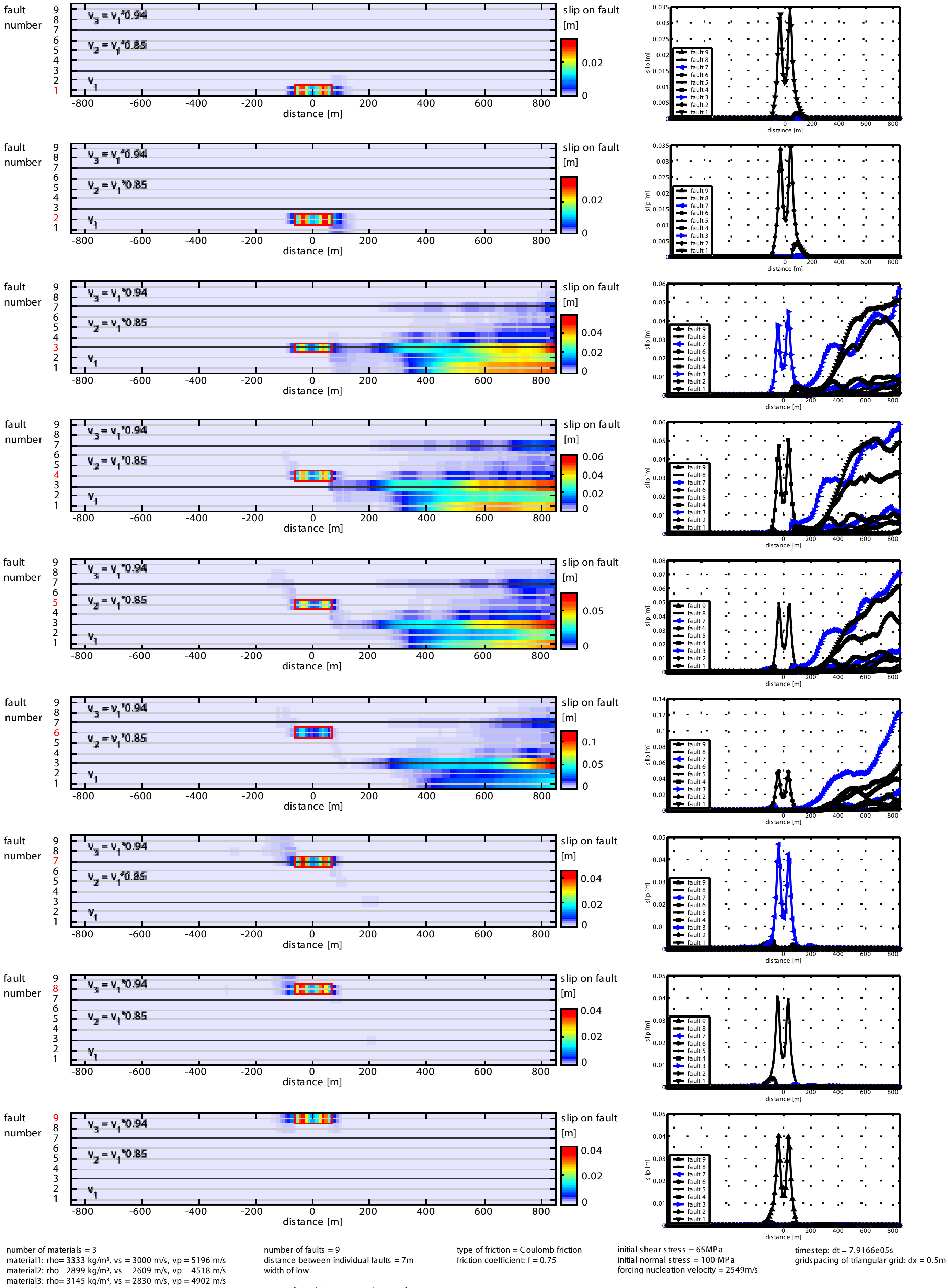
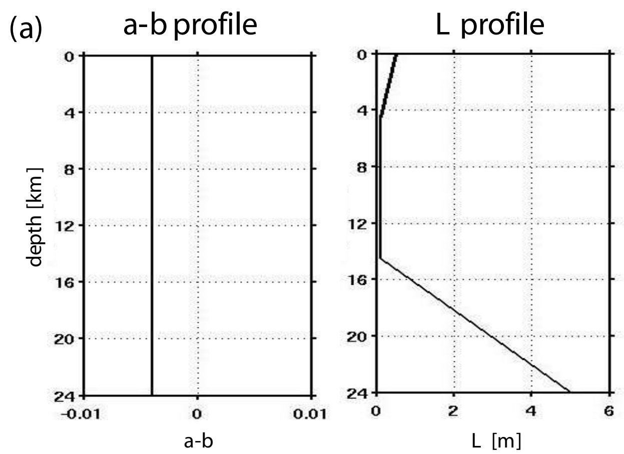


Figure 1. Example results for 2D in-plane ruptures in a multi-fault tri-material system for parameters shown in the bottom. The nucleation zone in each case is indicated by a box. The results show that rupture tends to migrate spontaneously to material interfaces.



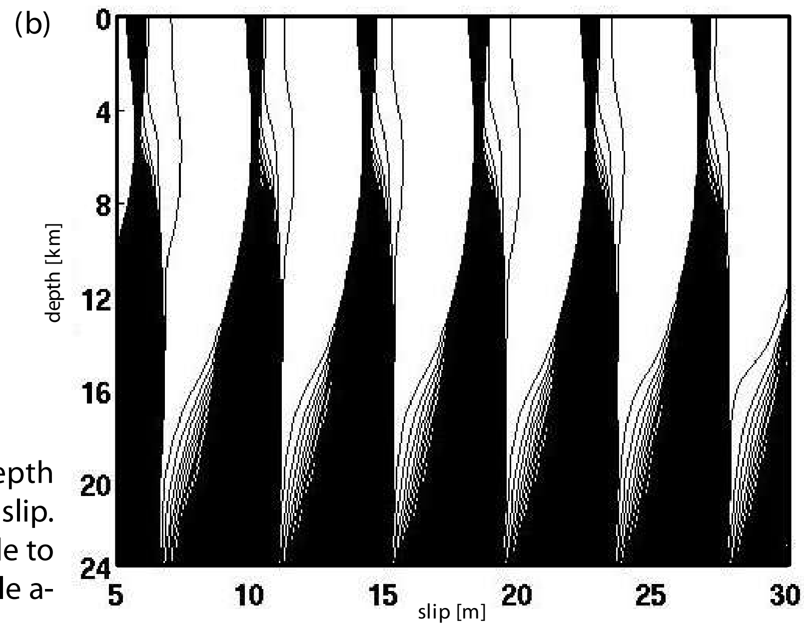


Figure 2: (a) Employed constant a-b and depth dependant L profiles. (b) Resulting cumulative slip. Transitions of L values cause transitions from stable to stick-slip behavior even in the presence of unstable a-b throughout the entire fault plane.

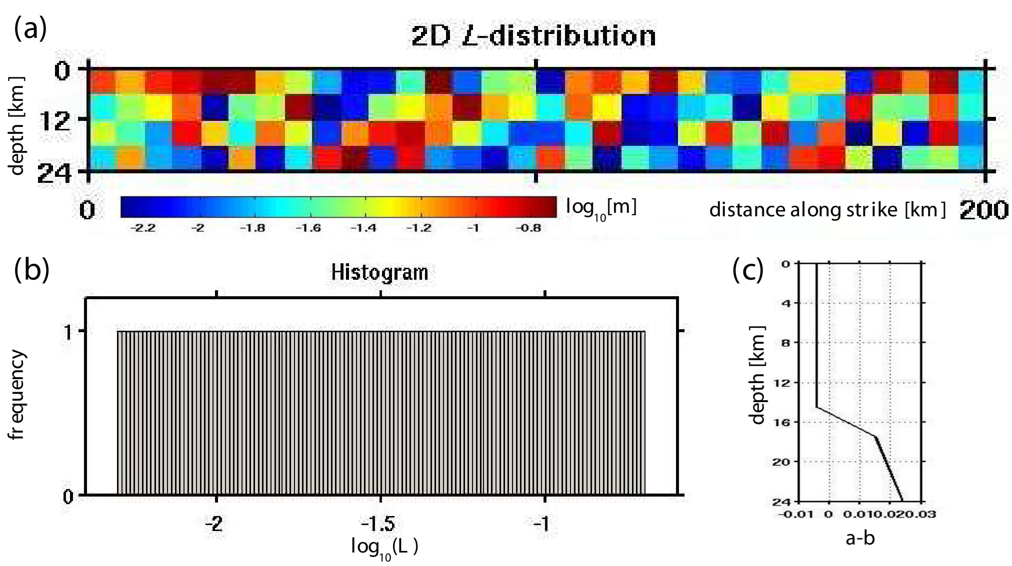


Figure 3: (a) 2D L-distibution in form of a chess board pattern to explore the basic respose of the system to hetogeneous functions. (b) Histogram displaying the occurrence of each L-value in the logarithmic L interval [0.005m 0.2m]. This boxcar shaped function is expected to be sufficient to produce events in a broad magnitude range. (c) Applied a-b profile. Top part is unstable while the bottom part is stable.

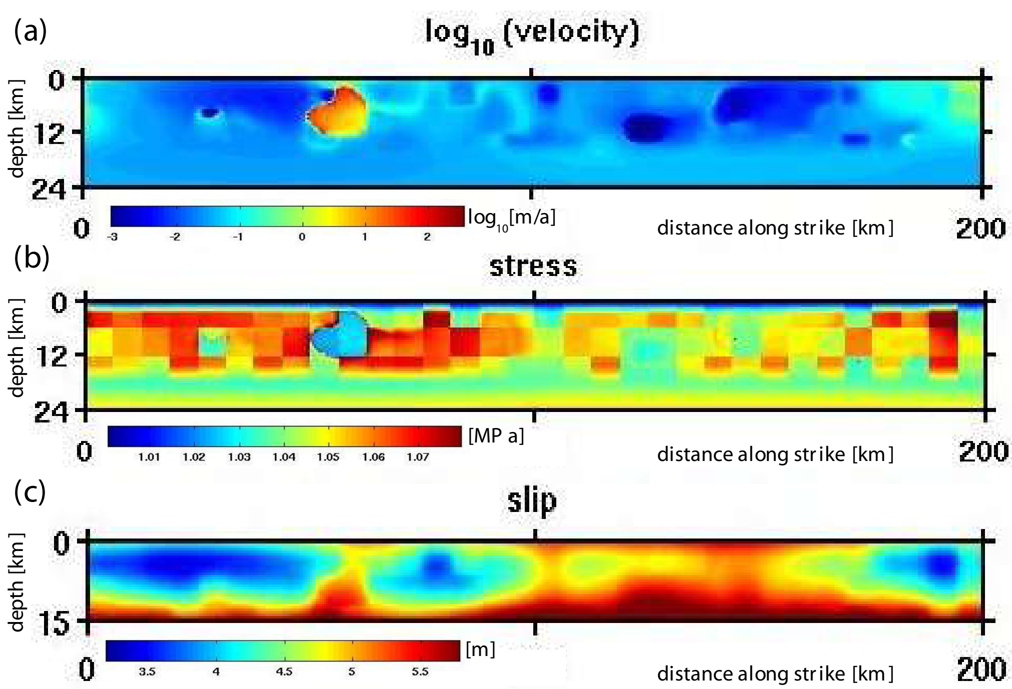


Figure 4: Snapshot at t=319 years. (a) Slip velocity. An instability nucleated in a region of lowered L-values. (b) Corresponding normalized shear stress. Generally, regions of large L exhibit larger stresses, which is due to the slip deficit displayed in (c) in these regions. They accumulate slip preferably while sliding stably and thus aseismically. Stress dropped where the fault became unstable. (c) Cumulative slip. The slip evolution is heterogeneous, displaying regions of low slip (large L-values) against regions of high slip (small L-values).