Damage-zone healing and strike slip fault evolution: Numerical results and geophysical constraints.

Abstract:
Numerical simulations of long-term crustal deformation reveal the important role that damage healing plays in the structural evolution of strike-slip fault systems. Geophysical observations indicate that after an early postseismic stage of rapid healing, rock damage in fault zones approaches asymptotically values which may vary markedly with location. Variable interseismic damage levels may arise for a variety of reasons and estimates of damage levels have high uncertainties. Nevertheless, the observations motivate exploring a wide range of healing parameters in a continuum damage rheology used to model fault system evolution. Here we perform 3D simulations of fault evolution to assess the sensitivity of fault zone structure and evolution to reasonable variations in the healing parameters. We find that the spatial extent of damage zones and the long-term geometrical complexity of strike-slip fault systems are strong functions of the healing “effectiveness” associated with a characteristic residual damage level in the interseismic period. Specifically, simulations with highly-effective healing form localized intensively damaged fault cores that interseismically extend only a few kilometers deep, and are bracketed by wide zones of distributed off-fault damage. Ineffective healing yields deeper zones of intense damage that persist throughout the interseismic interval, and narrower zones of distributed off-fault damage. Furthermore, highly-effective healing leads to a rapid evolution of an initially segmented fault system to a simpler through-going fault, while ineffective healing along a segmented fault preserves complexities such as stepovers and fault jogs and results in long-lasting distributed deformation.

Keywords: strike-slip fault structure, damage rheology, healing, fault stepover, fault system evolution

1. Introduction:
In a typical fault zone, the principal slip surface is often surrounded by breccia and embedded within a damage zone that consists of open and healed fractures, veins, and other secondary features. Nested zones with increasing damage are present: Distributed damage may be found up to several kilometers from the fault core near the Earth’s surface around large strike-slip faults. Within about 1 km of the active fault core, a zone of more intense damage is present. This zone may produce local seismic anisotropy (e.g., Peng and Ben-Zion, 2004; Boness and Zoback, 2006), concentrate coseismic strain (e.g. Fialko et al. 2002), and elevate seismic scattering (e.g., Revenaugh, 2000; Peng and Ben-Zion, 2006). Within this zone, there is a narrower zone of intense damage at 10-100 m wide which can trap seismic waves (e.g., Li et al., 1994; Ben-Zion et al., 2003) and may be manifested at the surface by a belt of pulverized fault zone rocks (e.g., Dor et al., 2006, 2008). Recent seismic and geodetic observations at several fault zones show variable levels of interseismic damage, suggesting that healing effectiveness varies within fault systems (e.g., Hearn and Fialko, 2009; Cochran et al., 2009). Damage intensity along strike-slip faults is typically higher near stepovers, fault kinks and fault bends, which exhibit strain hardening associated with secondary fractures at different scales (Ben-Zion and Sammis, 2003; Kim et al., 2004). Persisting rigidity loss and modification of the stress state at these localities can affect rupture propagation, ground shaking, and fluid flow patterns (Biegel et al., 2008; Bhat et al., 2007, Micklethwaite and Cox, 2006). However, due to difficulties in simulating fault growth in 3D, the long-term structural evolution of fault zone damage has not been thoroughly examined so far.
Seismic and structural studies indicate that the complexity (segmentation and geometric disorder) of a fault system reduces with time as the fault accumulates slip (e.g., Wesnousky, 1994; Ben-Zion and Sammis, 2003). Ben-Zion et al. (1999) and Lyakhovsky et al. (2001) suggested that the ratio
of the timescale for material healing over the timescale of stress loading governs the evolution of fault zone structure and seismicity patterns, with high ratios (“long memory”) leading to simple localized fault systems and characteristic earthquake statistics and low ratios (“short memory”) producing persistent structural complexities and power law earthquake statistics. Laboratory and field studies indicate that rock healing is logarithmic in time, with significant rapid healing on a timescale of a day or so and slow additional small healing on longer times (e.g., Dieterich and Kilgore, 1996; Johnson and Jia, 2005; Wu et al., 2009). Since the loading rates of faults vary typically only by one order of magnitude or less, the ratio of timescales for healing over loading does not provide sufficient information to distinguish between observed variations among different faults.

In the current paper we analyze the effects material healing have on damage zone structure and fault system evolution patterns. Our simulations show that the damage zone structure along faults, the temporal stability of geometrical complexities, and the evolution of fault configuration and strain distribution patterns are all strongly affected by the effectiveness of healing. Specifically, more effective healing yields wider but shallower damage zones and shorter lived stepovers (and other fault complexities) compared to damage zones formed in conditions less favorable for healing. In the following section we introduce the damage rheology model and describe the seismic and geodetic constraints on the damage healing rate parameters. In section 3 we present the effects of healing on damage zone structure, on fault complexity, and on the evolution of fault systems in our models.

2. Damage Rheology and Healing formulation

Many current theoretical fault system studies employ numerical simulations in which brittle rock is modeled as a rigid elastic-plastic solid and faults are prescribed surfaces governed by friction. The rate- and state-dependent (RS) friction model (e.g., Dieterich, 1981; Ruina, 1983) has been used in some studies to simulate various aspects of rupture propagation and seismicity evolution (e.g., Ben-Zion and Rice, 1995; Tullis, 1996; Hillers et al., 2007). However, the RS formulation and other frictional modes (e.g., Ward, 1996) assume that deformation at all stages occurs on pre-defined surfaces, and they do not provide a mechanism for understanding distributed deformation and the evolution of fault zones. Several recent studies simulated inelastic off-fault yielding in the form of plastic strain (e.g., Andrews, 2005; Ben-Zion and Shi, 2005; Ma, 2008). However, inelastic deformation in the brittle portion of the lithosphere is associated with distributed cracking that modifies the elastic properties in the inelastically-deforming regions (e.g., Lockner et al., 1977; Jaeger and Cook, 1979). Simulating the evolution of fault zones and related deformation fields require concepts such as damage rheology that account for changes in the elastic properties in regions where the yield strength is exceeded.

2.1 Damage rheology: theory

To integrate fault zone weakening and healing in numerical simulations of large-scale fault zone evolution we apply concepts of continuum damage mechanics in our rheology model. Based on the crack density formulation of Budiansky & O’Connell (1976), our damage model (Lyakhovsky et al., 1997a, 1997b) relates the elastic moduli to a single variable. This scalar damage variable ($\alpha$) reflects the extent of strength degradation due to crack formation and opening, with $\alpha = 0$ indicating undamaged rock and $\alpha = 1$ being the maximum damage level corresponding to a complete strength loss. Our damage rheology model is briefly described below. For further details and selected applications of this model we refer to previous publications (Lyakhovsky et al., 1997a, b, 2005; Hamiel et al., 2004; Ben-Zion and Lyakhovsky, 2006).
To account for the evolution of material properties, the damage rheology model introduces a third elastic modulus ($\lambda$) and makes the elastic rigidity ($\mu$) a function of the damage state variable, as follows:

$$\begin{align*}
\lambda &= \lambda_0 = \text{constant}; \\
\mu &= \mu_0 + \alpha \cdot \gamma_m \left( \xi_0 - 0.5 \xi \right) \approx \mu_0 \left(1 - \alpha\right); \\
\gamma &= \alpha \gamma_m;
\end{align*}$$

where $\lambda$ and $\mu$ are the Lamé parameters of linear Hookean elasticity, and $\xi = I_1/\sqrt{I_2}$ is referred to as the strain invariants ratio ($I_1 = \varepsilon_{kk}$ and $I_2 = \varepsilon_{ij}\varepsilon_{ij}$ are the first and second invariants of the elastic strain tensor $\varepsilon_{ij}$). The parameter $\xi_0$ separates states of material degradation ($\xi > \xi_0$) and healing ($\xi < \xi_0$) associated with positive and negative damage evolution, respectively. As the damage variable $\alpha$ increases, the shear modulus $\mu$ decreases, Poisson’s ratio $\nu$ increases, and the modulus $\gamma$ increases from 0 (damage free) to $\gamma_m$ amplifying the non-linearity of rock elasticity. This evolution of fault zone material properties controls the seismicity patterns and spatial distribution of deformation along strike-slip faults (Lyakhovsky et al., 2001; Ben-Zion et al., 1999; Ben-Zion and Lyakhovsky, 2006).

As this paper concerns natural healing of fault zones we hereafter focus on the healing aspect of our damage rheology model. At high confining pressure, low shear stress and high temperature, healing of microcracks is favored resulting in a recovery of elastic moduli. Motivated by observations of a logarithmic increase of the friction coefficient with time (e.g., Dieterich 1978), Lyakhovsky et al. (1997a) suggested the following healing function:

$$\frac{d\alpha}{dt} = C_1 \cdot \exp \left( \frac{\alpha}{C_2} \right) I_2 \left( \xi - \xi_0 \right) \quad \text{for} \quad \xi < \xi_0$$

According to equation (2) the damage state variable $\alpha$ at any given time is an integrated history of the damage process. The rate and the overall effectiveness of the healing process are primarily determined by the rate parameters $C_1$ and $C_2$. Depending on the combination of these parameters the healing process may be fast or slow and may yield insignificant healing or result in complete healing of the damaged material (Figure 1).

Finzi et al. (2009) express the healing parameter space in terms of two descriptive parameters: the healing time scale ($\tau_h$) and the characteristic interseismic damage level ($\alpha_{ch}$). We define the time scale for healing as the time during which the relative change of elastic moduli is above an arbitrarily chosen rate of 0.1% yr$^{-1}$ ($d\alpha/dt=3e^{-11}$ sec$^{-1}$). The characteristic interseismic damage level (termed the “final” damage level- $\alpha_f$ in Finzi et al., 2009), is a first-order predictor of the damage level along a simple fault segment at the time that healing rate has reduced to the above arbitrary rate (i.e. after $t=\tau_h$ years of healing). To estimate $\alpha_{ch}$ we assume a strain invariant ratio suitable for healing ($\xi-\xi_0=-1$), set the healing rate in equation 2 to the chosen threshold, and derive the damage level expected as the healing becomes slower than 0.001yr$^{-1}$:

$$\alpha_{ch} = C_2 \ln \left[3e^{-11}/C_1I_2 \right]$$

It is important to note that the interseismic damage level (both in our numerical simulation and along
natural fault zones), is expected to depart from \( \alpha_{ch} \) values as a result of local variations in stress, in loading history and in fault geometry. Nevertheless, a material with healing parameters corresponding to high \( \alpha_{ch} \) (e.g., \( \alpha_{ch} > 0.6 \)) is expected to undergo ineffective healing, whereas a material with parameters \( C_1 \) and \( C_2 \) corresponding to low \( \alpha_{ch} \) (e.g., \( \alpha_{ch} < 0.3 \)) is expected to undergo effective healing. The parameter \( \alpha_{ch} \) also depends on the applied strain and the depth at which the healing occurs. In this paper all \( \alpha_{ch} \) values are calculated assuming a depth of 3-5 km and a strain invariant ratio suitable for healing. Finally, to derive the time scale for healing, we integrate equation 2 (assuming constant strain) and get an analytic expression of \( \alpha(t) \) which is rewritten to express the healing time required for the damage level to decrease from \( \alpha=1 \) to \( \alpha=\alpha_{ch} \):

\[
\tau_h = \frac{I_2 C_1}{C_2} \exp\left( \frac{1}{C_2} \right)
\]

The time scale for healing \( (\tau_h) \) indicates how fast a damaged material heals to a quasi-steady state of very slow healing, however it does not reveal the effectiveness of healing or the characteristic damage level (Fig. 1). The healing time scales associated with parameters previously considered admissible for simulations of natural fault zones (Lyakhovsky et al., 2005) range between \( \tau_h=10 \text{ yr} \) and \( \tau_h=110 \text{ yr} \). For example, healing parameters corresponding to \( \tau_h=40 \text{ yrs} \) are expected to yield healing rates of 0.1% yr\(^{-1} \) after 40 years of healing, and rates lower than 10% yr\(^{-1} \) after 4-5 months of healing.

As evident from Figure 1, to fully determine the healing parameters of a material one would need either (1) the damage level at two different times after failure, or (2) the current damage level, the time elapsed since failure, and the time scale relevant to the specific healing process. Until recently damage-healing data from fault zones was unavailable and model parameters could only be constrained based on analytical considerations and laboratory experiments. In such an effort, Lyakhovsky et al. (2005) obtained an important relation between the two healing parameters based on empirical rate and state friction results:

\[
C_1 \approx BC_2 \exp\left( -\frac{\alpha_0}{C_2} / \varepsilon_{cmp}^2 \right)
\]

where \( B \) (1-2 s\(^{-1} \)) is a laboratory-determined time scale for the evolution of the friction coefficient with hold time (Dieterich, 1978) and \( \varepsilon_{cmp} \) is the compaction strain estimated by the ratio between lithostatic stress and the bulk modulus \( (K) \). Finzi et al. (2009) used this relation between \( C_1 \) and \( C_2 \) to narrow the range of admissible healing parameters, showing that natural healing processes may be represented by \( C_2 \) values between 0.015 and 0.035, and \( C_1 \) values between \( C_1 \sim 10^{-24} \) s\(^{-1} \) and \( 10^{-10} \) s\(^{-1} \). As detailed in the following subsection, the current analysis, which incorporates new geophysical data, supports our earlier conclusion and slightly increases the range of healing parameters considered for simulations of natural fault systems (Fig. 2).

**Figure 1.** Damage as a function of time (after failure) for various sets of parameters \( C_1 \) and \( C_2 \). The healing processes plotted in red have short healing time scales \( (\tau_h \sim 16 \text{ yr}) \) and therefore exhibit fast initial healing and slow insignificant healing at \( t > \tau_h \). The healing processes with long time scales \( (\tau_h \sim \ldots) \) are expected to exhibit very slow healing, however it does not reveal the effectiveness of healing or the characteristic damage level (Fig. 1). The healing time scales associated with parameters previously considered admissible for simulations of natural fault zones (Lyakhovsky et al., 2005) range between \( \tau_h=10 \text{ yr} \) and \( \tau_h=110 \text{ yr} \). For example, healing parameters corresponding to \( \tau_h=40 \text{ yrs} \) are expected to yield healing rates of 0.1% yr\(^{-1} \) after 40 years of healing, and rates lower than 10% yr\(^{-1} \) after 4-5 months of healing.
50 yr; blue curves) exhibit slower initial healing but may undergo some possibly significant healing long after \( t = \tau_h \). The effectiveness of healing (i.e. the expected typical interseismic damage level) depends primarily on \( \alpha_{ch} \) and is independent of \( \tau_h \). The healing time scales and characteristic damage levels are noted as diamond symbols on the healing curves.

2.2 Healing of damaged material: Constraints from fault zone observations

Due to a shortage of observations of damage levels in individual fault zones, for a range of different times in the earthquake cycle, previous attempts to constrain healing parameters have been based on laboratory experiments and analytic considerations (Ben-Zion et al., 1999; Lyakhovsky et al., 2001; Finzi et al., 2009). Laboratory stick-slip experiments on a wide range of materials show logarithmic fault strength recovery with time (e.g., Dieterich and Kilgore, 1996; Johnson and Jia, 2005). Logarithmic healing is also compatible with various seismic observations of fast active fault-zone healing over time scales of days to months, followed by very little additional healing during the interseismic stage of the earthquake cycle (e.g., Baisch and Bokelmann, 2001; Peng and Ben-Zion, 2006; Karabulut and Bouchon, 2007; Wu et al., 2009). Based on the above observation and on a limited set of trapped seismic wave and geodetic studies (e.g., Ben-Zion et al., 2003; Lewis et al., 2005; Fialko et al., 2002; Hamiel and Fialko, 2007), we previously constrained the healing parameters so they correspond to a healing time scale of \( \tau_h < 40 \) yrs and a characteristic interseismic damage level of \( \alpha_{ch} > 0.4 \) (Finzi et al., 2009). To constrain the maximum characteristic interseismic damage, Finzi et al. (2009) indicated that with the convexity condition used in our damage model as a criterion for macroscopic failure, shallow material \( (z < 3 \text{ km}) \) could not sustain damage levels higher than \( \alpha = 0.75 \) for long time periods.

In our simulations, the \( C_1 \) and \( C_2 \) values correspond to healing time scales similar to those
applied in previous studies (within the range represented in Figures 1, 2), but the range of $\alpha_{ch}$ values is broader than that previously applied. In accordance with recent geodetic observations from the ECSZ (Hearn and Fialko 2009; Cochran et al., 2009; Barbot et al., 2009), $\alpha_{ch}$ is currently varied between 0.25 and 0.65, whereas previously values between 0.4 and 0.5 were assumed. This wider range of admissible values is a more conservative assumption, given uncertainties in estimates of interseismic damage levels and likely variability. In addition, replacing the analytic-numeric constraint on the maximum interseismic damage level ($\alpha < 0.75$) with a constraint based on fault zone observations ($\alpha_{ch} < 0.65$) assures that our simulations better represent natural fault zone healing. The healing parameter space suggested for simulations of natural fault zone evolution is outlined in Figure 2.

Figure 2. Geophysical, analytical and laboratory-based constraints on healing parameters. Minimum and maximum expected interseismic damage ($\alpha_{min} = 0.25$, $\alpha_{max} = 0.65$) and maximum healing time scale ($T_h = 40$ yr) superimposed on the parameter space resulting from the analytic considerations (Eq. 5). The space between the minimum and maximum damage levels and above the 40 yr healing time scale represents natural fault zone healing processes, and it is comparable to the parameter space previously suggested based on fewer fault-zone observations (Finzi et al., 2009).

3. Results
3.1 Fault zone structure as a function of healing

To investigate the structure of damage zones associated with evolving strike slip fault systems, we use three dimensional realizations of a strike-slip fault within a layered seismogenic crust governed by damage rheology, underlain by viscoelastic layers representing the lower crust and upper mantle.
We use diabase and dunite flow laws and assume a fixed geotherm (20°C/km) in our simulations. The modeled region is 100 to 250 km long (along strike), 100 km wide and 50 km deep. More details of our typical model setups and parameters are given by Finzi et al. (2009).

Since we are not trying to characterize surface damage structures, and as frequent failure of surface elements due to low confining stress would be computationally time consuming, we suppress damage accumulation in the simulated surface layer (typically top 3 km of the crust). Various test models with damage not suppressed within the surface layer (not presented here) lead us to expect that the surface damage zone may be slightly wider and consists of locally higher damage levels than the damage zone in our simulations.

A variable force boundary condition (Lyakhovsky and Ben Zion, 2008) is applied to the sides and bottom of the model domain, simulating a constant far field fault parallel velocity with relative rate of 32 mm/yr (corresponding to the San Andreas Fault). The boundary driving forces are set to represent imposed fault zones outside the model domain, and they induce faulting near the centers of the north and south edges of the model (Lyakhovsky and Ben-Zion, 2008; Finzi et al., 2009).

Our simulations output the strain distribution and material properties within the model domain, from which we can calculate surface velocities, rigidity and other related quantities throughout the model domain. Figure 3 illustrates some features which correspond to observed geological structures such as fault segments, stepovers, and flower structures. Contiguous sets of elements that fail repeatedly, resulting in a higher damage level and lower rigidity than their surroundings, are interpreted as fault segments (Fig. 3). Because of their relative weakness, these fault segments are also the centers of high velocity gradients and high strain rate. Cross-sections through modeled fault segments (Fig. 3) display “flower structures” with depth, which comprise of localized damage along the active fault core and a broader zone of distributed damage in the top 3-10 kilometers of the crust (Fig. 3). The overall geometry of the “flower-like” damage zones in our simulations is compatible with field observations (e.g., Sylvester, 1988; Rockwell and Ben-Zion, 2007) and with numerical simulations of dynamic ruptures with off-fault yielding in the form of plasticity (Ben-Zion and Shi, 2005; Ma, 2009).

Based on these observations, we define two damage sub-zones that are distinct in their evolution patterns, damage level, and spatial distribution. Localized Active Fault (LAF) damage represents the highly localized damage along the active fault cores (Fig. 3). LAF damage is coseismically very high along the primary slip zone, but it rapidly heals at depth. Distributed Off Fault (DOF) damage is the sustained, cumulative damage resulting from many earthquakes. The DOF damage develops during the early stages of fault system evolution, and thereafter its spatial extent is stable and the degree of damage within it evolves locally (Fig. 3). The width of the DOF damage is 6-13 km in our simulations, and its depth is taken to the average depth extent of the shallow distributed damage away from the active fault core (up to 7 km; Fig. 3). The width of the LAF damage represents the maximum width of the localized damage along the fault core (between a fraction of an element to several kilometers wide), and its depth is the maximum depth extent of the damage zone (Fig. 3). Descriptive analyses of damage structures along simulated strike-slip fault segments and along fault stepover zones are given in Finzi et al. (2009).

**Figure 3.** Distributed off fault (DOF) and localized active fault (LAF) damage along a simulated strike-slip fault. The vertical cross-section (left) shows a simulated flower structure with localized damage at depth (along the active fault) overlain by distributed damage which is the cumulative effect of past earthquakes. The horizontal sections (right) show persistent distributed damage along fault traces (typically in the top 3-5 km) and at considerable depth within fault stepovers.
Our previous analysis showed that the flower structure is a robust feature in our simulations that shows limited sensitivity to variations in the healing parameters $C_1$ and $C_2$ (Finzi et al., 2009). However, in that work we did not consider that the effect of healing on damage zone structure may be enhanced when varying both parameters together. Our current analysis shows that the healing parameter space is best described in terms of the healing time scale ($\tau_h$) and the characteristic interseismic damage level ($\alpha_{ch}$). Thoroughly exploring a broader, geophysically constrained healing parameter space, we confirm that the properties of simulated fault zone structures and related deformation field are significantly affected by $\alpha_{ch}$.

The direct result of healing in our simulations is postseismic restrengthening of the fault-zone and therefore a reduction of the damage zone extent. However, simulations applying healing parameters that represent the full (realistic) range of healing effectiveness (yielding a wide range of interseismic fault-zone material strength) reveal how damage zone structures evolve in different fault-zone healing conditions. The deeper section of the fault zone (the deep LAF damage) is most susceptible to healing due to the relatively high confining stress, and is therefore most sensitive to variations in the healing parameters. Our results indicate that the depth extent of the LAF damage (after the early postseismic interval) ranges from the entire seismogenic crust in fault zones experiencing ineffective healing ($\alpha_{ch} > 0.65$; Fig. 4 bottom panel; Fig. 5) to a few kilometers in fault zones experiencing effective healing ($\alpha_{ch} < 0.4$; Fig. 4 top panel; Fig. 5). During most of the seismic cycle intense and contiguous LAF damage is typically limited to the top section of the crust (e.g., Fig. 3, Fig. 4 top panel; Fig. 5). The dimensions of the shallow DOF damage are also sensitive to variations in the healing parameters, with ineffective healing resulting in faster (more complete) strain localization and therefore narrower fault zones and more effective healing yielding wider fault zones. Our simulations indicate that the maximum width of the damage zone ranges between 6 km and 13 km and the width of the DOF damage at 5 km depth
ranges between 2 km and 7 km (Fig. 5). It should be noted that these values probably overestimate the maximum width of fault damage zones as our models do not incorporate depth-dependent damage-rate parameters (suggested by Lyakhovsky et al., 2005). The simulated LAF damage and the deeper parts of the DOF damage zone are typically one model element wide and may appear discontinuous (Fig. 3, 4), indicating that they could be narrower than our model element dimensions, in agreement with observed extreme localization of active slip zones (e.g., Chester et al., 1993; Sibson, 2003; Rockwell and Ben-Zion, 2007).

**Figure 4.** Cross-sections displaying evolving damage levels along two strike-slip faults representing effective (top, $\alpha_{ch}=0.4$) and ineffective (bottom, $\alpha_{ch}=0.7$) healing conditions.

**Figure 5.** Damage zone dimensions as a function of healing effectiveness. The width of the DOF damage decreases in simulations with ineffective healing (higher $\alpha_{ch}$), and the depth of the LAF damage (during the interseismic stage) increases in simulations with ineffective healing (higher $\alpha_{ch}$).
3.2. Fault zone evolution patterns and temporal stability of fault stepovers.

Strike-slip fault systems evolve over time. As total offset increases, asperities and other frictional barriers to slip are reduced, segment length increases, en-echelon segments coalesce, and the fault straightens and simplifies, reducing overall resistance to slip. Detailed mapping of exhumed fault zones (e.g., Chester et al., 1993; Sibson, 2003) indicate that the internal structure of fault zones evolves from distributed deformation and band-limited fractal structures, through localization to principal slip zones, to mature large-scale faults with tabular damage zones and narrow cores of ultra-cataclasites (e.g., Lyakhovsky and Ben-Zion, 2009). The structural evolution of fault systems is also characterized by evolving seismicity patterns and fault slip-rate. The slip rate along any new propagating fault by definition must experience a finite period of acceleration, and as it matures and the slip resistance decreases, the fault will accelerate to some steady state slip rate until the tectonic driving force or the fault configuration changes. Ben-Zion and Sammis (2003) describe fault evolution through localization as an eventual consequence of strain weakening rheology, common in crustal materials. However, due to data limitations various aspects of fault evolution are not well understood, and clear distinctions of evolution stages and definitions of mature and immature faults are lacking.

Our previous simulations of damage zone evolution indicated that newly formed and propagating fault segments undergo a very short stage of complexity increase and DOF damage build-up (Finzi et al., 2009). During this early stage strain is distributed within widening damage zones, and fault segments interact to form damaged linking zones. Based on the simulated evolution of the DOF damage width, we previously suggested that this complexity-increase stage ends when the fault has accumulated an offset of about 0.05-0.1 km, and is thereafter followed by a long-term state of complexity decrease. Acknowledging that the above time scale is short, we recently analyzed the depth extent of the LAF damage and the slip-rate evolution as additional indicators of fault evolution. We also examined the sensitivity of these fault evolution time scales to variations in the healing parameters.
Our analysis indicates that the LAF damage reaches its maximum depth extent (i.e. the fault core is established down to the bottom of the seismogenic zone) after the fault has accumulated an offset of about 0.1-0.2 km, with little sensitivity to the applied healing parameters. Even though the DOF in our simulations fully forms before the LAF damage reaches its maximum extent, the similarity in time scales of these evolution indicators suggests that damage zone width may be used as an indicator for the establishment of the damage zone at depth. The long-term (tectonic) slip-rate in our simulations is first achieved after the first system-size earthquake on the fault ($t=1500$ years in Fig. 6) followed by a significant decrease in slip rate. After the accumulation of approximately 0.1 km of strike-slip offset ($\sim 3000$ model years), the fault experiences $\sim 2000$ years of relatively small slip rate fluctuations around the tectonic slip-rate (Fig. 6). This occurs when the fault DZ is almost fully established, and it may indicate that the fault is starting to mature (i.e. the fault is transitioning into a state of complexity decrease). After this transition the slip-rate experiences several large fluctuations that slowly subside until the rate stabilizes at the long-term rate or until the system is perturbed by a change in fault configuration. Our results indicate that modeled fault systems maintain a near tectonic slip rate only after deformation has localized along narrow slip-zones and after the faults are fully formed down to the bottom of the seismogenic zone. The duration (and cumulative slip) required for modeled damage zones to reach their final dimensions does not show significant sensitivity to the healing parameters.

**Figure 6.** Slip-rate and damage zone evolution with time. Slip rate averaged over several earthquake cycles (red), geologic (cumulative) slip rate since the formation of the fault system (green), DOF damage width (yellow) and LAF damage maximum (coseismic) depth extent (blue). The damage zone width and depth and the slip rate initially increase rapidly (in association with the first large earthquake), then the slip rate fluctuates around the tectonic rate eventually approaching the long-term geologic rate (32mm/yr). The healing parameters in this simulation correspond to $\alpha_{ch}=0.5$, $\tau_{h}=30$ yr.
The time-scale outlined above describes the structural evolution of a single fault segment, and it does not incorporate the effect of large-scale persistent fault complexities that may impede localization. To study this effect we constructed a series of models simulating deformation patterns associated with a stepover zone between two en-echelon strike-slip fault segments. As with our previous simulations (Finzi et al., 2009), we find that large volumes of damage within the stepover zones exhibit ongoing interseismic deformation and distributed inelastic strain. These deformation patterns suppress earthquake propagation and strain localization within the stepover zone resulting in a significantly slower process of complexity reduction and fault system maturation. Eventually, through-going faults may bridge the stepover zone and the tips of the en-echelon fault segments may re-align and link into a contiguous curved fault, however this process is strongly dependent on the effectiveness of healing processes along the fault zone.

In simulations with parameters that favor effective (near-complete) healing and yield low interseismic damage levels, fault stepovers evolve quickly into a single, contiguous fault segment that rapidly retains the characteristics of a mature fault segment (Fig. 7). In simulations with settings that favor ineffective (limited) healing, fault stepovers persist, slowing the simplification of the fault geometry (Fig. 7). Figure 7 compares the evolution of fault stepovers experiencing effective (top; \( \alpha_{ch}=0.4 \)) and ineffective (bottom; \( \alpha_{ch}=0.7 \)) healing, showing snapshots of the fault structure at 5 km depth during the initial 5000 model years after the formation of the stepover (imposed as initial conditions in our simulations). It is apparent from the top panel in Figure 7 that with effective healing the en-echelon faults link rapidly and the stepover is readily gapped changing the original structure to a through-going fault that localizes deformation. This active contiguous fault exhibits damage levels significantly higher than its surrounding residual damage. Setting the healing to be inefficient (bottom panel of Figure 7) results in a persistent stepover which displays an array of active secondary faults within the original stepover structure. The original en-echelon faults show no sign of evolution after 5000 years (0.16 km of cumulative offset), suggesting that while damage accumulates within the stepover it does not localize deformation on one through-going fault and does not yield a reduction in fault complexity. Extrapolating this pattern to longer time scales leads us to speculate that with very limited healing, stepovers and other fault complexities may only grow with time and they are not expected to become inactive or to yield localization of deformation on a through-going (mature) fault. This evolution pattern would yield long-lasting basins or push-up swells with ongoing internal deformation, as is widely observed along segmented strike-slip faults.

**Figure 7.** Damage maps (depth = 5 km) displaying two evolving stepover zones along two segmented strike-slip faults representing effective (top, \( \alpha_{ch}=0.4 \)) and ineffective (bottom, \( \alpha_{ch}=0.7 \)) healing conditions. While effective healing (top) leads to rapid smoothing of the fault system and turns the stepover into an inactive structure, ineffective healing keeps the stepover structure active and the fault system remains segmented through-out the duration of the simulation.
4. Discussion and conclusions:

Using an analysis of our damage rheology healing parameters, fault-zone geophysical observations, and numerical simulations, we have evaluated how material healing affects fault zone complexity, damage zone structure, and long-term fault system evolution.

Healing effectiveness controls both the dimensions of the fault damage zone (Fig. 5) and the complexity of fault systems (Fig. 7). This suggests that observable structural characteristics of a fault system and long-term evolution patterns may be linked with gouge-scale healing processes. Establishing such a link would yield a powerful tool to study fault systems where detailed observations of fault zone properties are not available. Furthermore, such a link could help in evaluating the temporal stability of complex fault configurations and local fault structures (e.g., stepovers). However, the variability of damage levels along simulated faults as well as along faults of the ECSZ (Hearn and Fialko 2009, Cochran et al 2009, Barbot et al., 2009) suggests that healing effectiveness may vary
significantly within a single fault system. Alternatively, it could indicate that other factors such as local loading geometry and seismic histories may contribute to the variability of interseismic damage levels. In any case, the natural variability of healing conditions is a very plausible outcome of the heterogeneity of permeability, fluid content and temperature, all of which have an important effect on healing processes. Additional postseismic and interseismic observations of fault zone material properties correlated with maps of fault structures and strain distribution within fault systems are needed to study the spatial and temporal characteristics of such a link.

The fault stepover simulations here and in Finzi et al. (2009) show extensive damage and elasticity degradation sustained over many earthquake cycles. Simulated tensional stepovers exhibit damage patterns consistent with intense tensile fracturing and dilation, and are expected to sustain enhanced permeability. Such damage patterns are consistent with recent structural evolution models for dilational stepovers (De Paola et al., 2007), and with studies that of permeability evolution patterns along segmented faults (Micklethwaite and Cox, 2004; Sheldon and Micklethwaite, 2007). We suggest that healing effectiveness has an important effect on the structural properties and temporal stability of fault stepovers, and therefore may have important implications for earthquake propagation and seismic hazard studies. We further suggest that long-lived stepover zones represent unfavorable conditions for healing that should also correlate with significant material weakening down to the lower parts of the seismogenic zone.

Ben-Zion et al. (1999) and Lyakhovsky et al. (2001) suggested that the ratio between healing and loading timescales controls fault zone complexity, where relatively fast healing and slow loading results in a disordered fault system. The ratio of the healing and loading timescales may provide a general guideline for situations where both the healing and loading timescales vary by many orders of magnitudes. However, for cases that appear to characterize fault zone rocks, with healing timescales that may vary by many orders of magnitudes and far less variable loading time scales, additional factors can play a dominant role in determining the properties of the evolving damage zones. Our results indicate that one such key parameter is $\alpha_{ch}$ (Fig. 1), which controls the rigidity and fracture strength of the fault zone during most of the interseismic period. In our simulations (and probably also in natural fault zones), the effectiveness of the healing process is characterized primarily by the healing parameter $\alpha_{ch}$. Effective healing with low residual $\alpha_{ch}$ produces fault segments with a wide shallow damage zone. However, our simulations indicate that faults having effective healing rapidly supersede pre-existing stepovers, whereas ineffective healing (high residual $\alpha_{ch}$) produces fault systems with long-lived stepovers. In the effective healing case, a stepover is permanently weak to only a shallow depth. Below a few kilometers, confining stresses are large and the fault zone heals rapidly to the (low) characteristic damage level. The stepover has less of an influence on the propagation of large ruptures, which break through it, eventually allowing a through-going fault to form. Residual damage persists in this case only over the top few kilometers of the remaining shallow inactive stepover zone. These results, based on fully 3D simulations and wide range of healing parameters (both timescale and effective residual $\alpha_{ch}$), provide important refinements to the earlier general findings of Lyakhovsky et al. (2001) Ben-Zion et al. (1999) based on simpler simulations and analytic considerations. The current study also improves on the analysis of Finzi et al. (2009), by demonstrating that co-varying both healing parameters ($C_1$ and $C_2$ of equations 2-5), and particularly the resulting variations of the characteristic residual damage level $\alpha_{ch}$, have large effects on the damage zone structure and fault system evolution.

While the discussed links between observable fault structures and long-term deformation patterns
require additional support from fault zone observations and further numerical analysis, the following features of DZ structure and evolution appear to be robust in our simulations and are well supported by field observations:

- Fault zone healing is very rapid with most (>50%) of the healing occurring within hours to days after an earthquake. In addition, fault zones exhibit a wide range of quasi-steady state interseismic damage levels, with $\alpha$ between (approximately) 0.25 and 0.65 (i.e., a rigidity reduction of 25%-65%, and shear wave velocity reduction of 15%-40%). These independent geophysical observations are reproduced in simulations applying healing parameters within the parameter space suggested in our analysis.

- Healing effectiveness is an important factor in the evolution of fault zone structures. Conditions favoring complete healing yield wider DOF damage in the top few kilometers of the crust and shallower fault-core LAF damage, whereas conditions favoring ineffective (limited) healing yield narrower DOF damage and deeper LAF damage zones.

- Healing effectiveness is an important factor in the temporal stability of fault stepovers. Fault complexities such as stepover zones are expected to be shorter-lived (transient features) if fault zone conditions favor more complete healing.

- Active fault stepovers typically consist of damaged material down to the lower seismogenic zone, and should be detectable seismically and geodetically. The current analysis supports our previous conclusion that attaining information regarding material properties within stepover zones would aid future analysis of fault zone healing and fault system evolution.
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