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Damage in step-overs may enable large cascading earthquakes

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[1] Seismic hazard analysis relies on the ability to predict whether an earthquake will terminate at a fault tip or propagate onto adjacent faults, cascading into a larger, more devastating event. While ruptures are expected to arrest at fault discontinuities larger than 4–5 km, scientists are often puzzled by much larger rupture jumps. Here we show that material properties between faults significantly affect the ability to arrest propagating ruptures. Earthquake simulations accounting for fault step-over zones weakened by accumulated damage provide new insights into rupture propagation. Revealing that lowered rigidity and material interfaces promote rupture propagation, our models show for the first time that step-overs as wide as 10 km may not constitute effective earthquake barriers. Our results call for re-evaluation of seismic hazard analyses that predict rupture length and earthquake magnitude based on historic records and fault segmentation models. **Citation:** Finzi, Y., and S. Langer (2012), Damage in step-overs may enable large cascading earthquakes, *Geophys. Res. Lett.*, *39*, L16303, doi:10.1029/2012GL052436.

1. Introduction

[2] Earthquakes rupturing several fault-segments, where single- or two-segment events were anticipated, have recently shocked the Indian Ocean (M9.1), Chile (M8.8) and Japan (M9) [*Bilham*, 2005; *Lay*, 2011; *Stein and Okal*, 2011]. The implications of under-predicting the magnitudes of such earthquakes are sadly portrayed by the toppled sea-walls designed to protect Japan's communities and nuclear plants from an $M \leq 8$ earthquake [*Stein and Okal*, 2011].

[3] Predicting the maximal size of an earthquake expected to occur along complex fault-systems is a key challenge in seismic hazard analysis. To do this, scientists often use maps of historical earthquake traces to associate rupture endpoints with discontinuities between major fault segments (i.e., fault step-overs). For instance, ruptures along strike-slip faults are expected to arrest at dilational step-overs wider than 4–5 km [*Wesnousky*, 2006]. This rule of thumb postulates that fault geometry be a sufficient criterion for predicting rupture propagation. However, there is a growing body of observations indicating that ruptures can jump across larger step-overs [*Wesnousky*, 2006]. The largest rupture jump documented to date (10 km) was in the M7.8 Kunlun, China earthquake in 2001 [*Xu et al.*, 2002; *Antolik et al.*, 2004; *Duan and Oglesby*, 2006](see auxiliary material, section A5).[1] To explain such puzzling observations, modelers assume these step-overs were significantly pre-stressed [*Harris et al.*, 2002; *Duan and Oglesby*, 2005; *Olsen et al.*, 1997] or that rupture propagated along an unmapped linking-fault [*Antolik et al.*, 2004; *Oglesby*, 2005]. While such assumptions can be used to explain past ruptures, the lack of information on pre-seismic conditions limits their relevance to future hazard analysis.

[4] Fault step-overs are typically damaged by distributed fractures, veins, and other deformation features that reduce the strength of rocks and introduce stress concentrations. While faults typically exhibit rapid post-seismic healing at depth, step-over zones do not fully heal and rather display persistent, extensive damage and strain hardening throughout the seismogenic crust [*Finzi et al.*, 2011; *Ben-Zion and Sammis*, 2003]. Such deep, damage-zones, the lasting results of many previous earthquakes, were recently observed in the Eastern California Shear Zone [*Cochran et al.*, 2009]. Many studies have characterized fault-zone damage [e.g., *Kim et al.*, 2004; *Manighetti et al.*, 2004; *Ben-Zion and Sammis*, 2003] and some have provided rheology models to describe the evolution of damage and fault zones [e.g., *Lyakhovsky et al.*, 1997; *Nanjo et al.*, 2005, and references therein]. Recent studies have also accounted for material-degradation in models of long-term fault evolution and seismicity patterns [*Finzi et al.*,2009; *Lyakhovsky and Ben-Zion*, 2008; *Duan and Oglesby*, 2005], and others addressed the effect of off-fault damage on ruptures [*Ma and Andrews*, 2010; *Hok et al.*, 2010]. However, to date none has combined off-fault damage in step-over zones and rupture dynamic simulations to yield insights into the stability of segmented fault-systems. Here we demonstrate that assessing the material properties of step-overs could provide important information on pre-seismic conditions and help identify which step-over would arrest an earthquake and which would enable large rupture jumps between fault-segments.

2. Static Loading and Dynamic Rupture of a Damaged Step-Over Zone

[5] To determine how damage affects the stability of fault-systems, we simulate tectonic loading and subsequent rupture along a strike-slip fault with a damaged, releasing step-over (with dilational stresses; Figure 1a). Our 2D finite element method, implemented in the *esys.escript* software [*Gross et al.*, 2007], consists of a quasi-static loading phase followed by a dynamic rupture phase [*Langer et al.*, 2010, 2012]. The first phase involves solving the elastic deformation equation $\sigma_{ij,j} = 0$ to apply far field normal stress ($\sigma_N = -200$MPa) and shear stress ($\tau = -69$MPa). The

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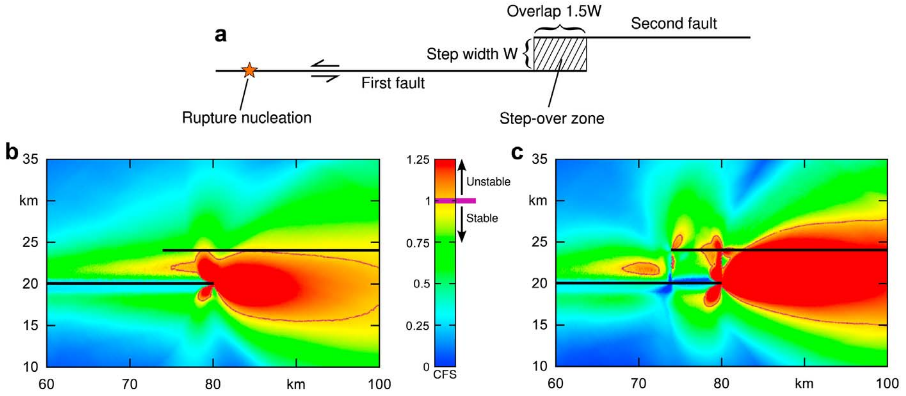

Figure 1. Model configuration and stress interactions along a segmented fault. (a) Model configuration used in our simulations, showing the two faults and step-over ($W = 1.5 - 10$ km). (b) Dynamic stress patterns at the vicinity of an undamaged step-over ($\alpha = 0$). The Contour CFS = 1 indicates the stresses required to enable a rupture jump of 4 km (i.e., for rupture on the first fault to trigger nucleation on the second fault). (c) Dynamic stress patterns at the vicinity of a damaged step-over ($\alpha = 0.35$). Significantly enhanced stresses are observed along the bi-material interfaces that bound the step-over and radiating from the tip of the ruptured fault (labeled 'First fault' in Figure 1a).

loading phase is initiated with homogeneous stress representing a relaxed fault zone (excluding stress build-up from previous earthquake cycles). The loaded stress field (with stress concentration at damaged step-overs) provides the initial conditions for the dynamic phase in which rupture is initiated (in a nucleation zone) and propagates into the step-over zone (Figure 1; auxiliary material, sections A3–A4).

[6] Our simulations consist of two parallel faults (60 km and 40 km long) separated by a step-over zone (1,500–10,000 m wide), as shown in Figure 1a. The step-over geometry in our simulations (width: overlap ratio of 1:1.5) is comparable to previous work [*Harris et al.*, 1991; *Harris and Day*, 1993], and conforms with field observations [*Kim et al.*, 2004]. The faults are embedded in a homogeneous material with a constant, uniform damage level prescribed within the step-over zone to represent weakened material. Application of non-evolving damage is appropriate for our simulations of large off-fault damage zones at seismogenic depth, as these zones are not expected to significantly heal after the post-seismic stage [*Finzi et al.*, 2011; *Ben-Zion and Sammis*, 2003] nor are they expected to accumulate much damage in a single earthquake [*Finzi et al.*, 2009; *Ben-Zion and Sammis*, 2003].

[7] A triangular element mesh is constructed using Gmsh [*Geuzaine and Remacle*, 2009] with a grid step size of Δx = 100 m along the faults. The penalty method is used to enforce the contact boundary conditions [*Olsen-Kettle et al.*, 2008]. In addition, a buffer zone, 2 km wide, is set along the model boundaries with absorbing boundary conditions [*Olsen-Kettle et al.*, 2008]. Our model applies a rupture nucleation procedure, velocity-weakening friction law and fault parameters that follow widely used numerical techniques [*Langer et al.*, 2012; *Ampuero and Ben-Zion*, 2008; *Olsen-Kettle et al.*, 2008] (see auxiliary material for overview of procedures), and it yields a magnitude 7 earthquake with a subshear, pulse-like rupture. The simulated time histories of fault slip and seismic waves are used to calculate the Coulomb Failure Stress (CFS) ($\sigma_{CFS} = \mu'\sigma_N + |\tau|$, where the effective coefficient of friction is $\mu' = \mu(1 - B)$, B is Skempton's coefficient [*Harris and Day*, 1993]), and σ_N and τ are the normal and shear stresses, respectively). The CFS levels reported in our analysis represent the highest CFS recorded during the co-seismic stage.

[8] Damage affects fault stresses and rupture dynamics by reducing the shear strength (rigidity, G) of the material within step-overs ($G = G_0(1 - \alpha)$, where $0 < \alpha < 1$ is a damage variable that correlates with crack density). (For details and theoretical background of the applied damage rheology we refer to *Lyakhovsky et al.* [1997], *Hamiel et al.* [2006], *Finzi et al.* [2011], and to auxiliary material section A1). Systematically varying step-over size and damage level, we evaluate the maximum step-over width a rupture is expected to jump. To evaluate whether a rupture jumps over a step-over, we record the maximal co-seismic CFS along the second fault and compare it with a reference stressing level determined for a 4 km wide, undamaged, step-over (red contour in Figure 1b). This level represents an estimate of the stress increase required to enable the maximal rupture jump as predicted in homogeneous dynamic and static rupture studies [*Harris et al.*, 1991; *Harris and Day*, 1999; *Wesnousky*, 2006]. If, as in Figure 1b, the second fault experiences CFS > 1, then the earthquake rupture cascades to the second fault and the step-over is considered an ineffective barrier. Figures 1 and 2 show how damage changes the stability of step-overs and the width a rupture may jump.

3. Dynamic Rupture Propagation and Step-Over Stability

[9] Our simulations provide important insights into the mechanisms controlling rupture propagation and arrest. We find that damage greatly increases the step-over width an earthquake can jump (Figures 1 and 2). Our results indicate that significantly damaged step-overs are unstable and could enable large rupture jumps (e.g., with $B = 0.5$ and $\alpha = 0.3$, ruptures can jump over steps as wide as 8 km). As realistic damage levels at dilational step-overs may even be higher [*Finzi et al.*, 2011], rupture might jump step-overs wider

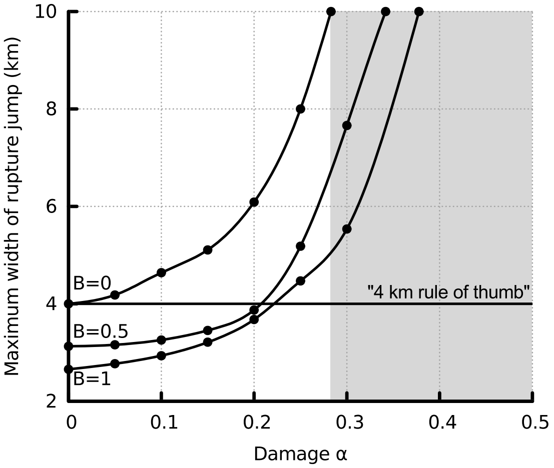

Figure 2. The maximum distance an earthquake is expected to jump as a function of damage in the step-over. Results are shown for simulations with damage dependent rigidity and Skempton's coefficients $B = 0, 0.5, 1$. The horizontal dashed line represents the damage-independent rule of thumb pertaining that ruptures cannot jump step-overs wider than 4 km [*Wesnousky*, 2006]. The shaded area ($\alpha \geq 03$) represents the range of conditions that may have enabled the 10 km rupture jump documented in the M7.8 Kunlun, China 2001 earthquake (assuming $B = 0$; whereas for $B = 0.5$ the range would be $\alpha \geq 0.35$).

than 10 km (Figure 2) and over larger discontinuities along-strike (Figure 1c).

[10] We identify rigidity reduction within the step-over zone and stress concentration along material interfaces as the main destabilizing mechanisms (Figure 1c; also see auxiliary material). Rigidity reduction leads to large co-seismic slip along the source fault and higher stresses on the receiver fault. Material contrast at the interface along step-bounding faults induces both static and dynamic stress concentrations. The static effect is related to asymmetric strain accumulation across the bimaterial faults (during tectonic loading), and the dynamic effect is induced by seismic waves traveling along the bimaterial interfaces. The destabilizing effect of bimaterial interfaces may prove to be particularly dominant in rupture processes along large strike-slip faults and subduction faults which juxtapose very different lithologies [*Ma and Beroza*, 2008].

[11] Finally, static stress concentration near highly damaged step-overs (Figure 3) may induce significant seismic and aseismic deformation during the inter-seismic stage, and may explain common observations of rupture nucleation at step-over zones. In fact, simulations with large step-overs and high damage levels ($\alpha > 0.4$, not shown here) exhibited spontaneous rupture nucleation at the step-over. Such inter-seismic deformation at highly stressed step-over zones could significantly relax local stress concentrations and stabilize the step-over zone. We therefore suggest that observations of crack density, seismic velocities at depth and enhanced inter-seismic strain induced by nearby earthquakes [e.g., *Hamiel et al.*, 2006; *Cochran et al.*, 2009] should be used to assess stress conditions and 'intrinsic stability' of segmented strike-slip faults. Furthermore, such observations are essential for constraining rupture models and improving assessments of seismic hazards.

4. Discussion and Conclusion

[12] The insights gained from our analysis are instructive in assessment of fault-system stability incorporating additional information on material properties. For example, damage-zone dilation [*Finzi et al.*, 2012] or porosity increase [*Hamiel et al.*, 2005] will reduce material-density within the step-over and velocity-contrast across step-bounding faults (resulting in a subtle stabilizing effect). In such conditions, pore-pressure changes would further stabilize a fault-system with releasing step-overs [*Harris and Day*, 1993; *Cocco and Rice*, 2002]. Figure 2 demonstrates the effect of dynamic pore-pressure changes, comparing the maximum rupture jump in simulations with Skempton's coefficients of $B = 0, 0.5, 1$. It also clearly shows that for high damage levels the destabilizing mechanisms dominate and enable very large rupture jumps. Another potentially important stabilizing mechanism involves energy dissipation and stress-relaxation due to enhanced inelastic deformation within damaged step-over zones [*Shipton et al.*, 2006; *Duan and Day*, 2008; *Ma and Andrews*, 2010; *Manighetti et al.*, 2009]. Accounting for inter-seismic strain and dynamic processes of dissipation would stabilize the simulated step-overs requiring higher damage levels or material contrasts to achieve the reported rupture jumps.

[13] Our work provides a physics-based explanation for outstanding observations of large rupture jumps, and it indicates that rupture predictions based on historic seismic records and simplified models are inadequate. Neglecting off-fault material properties, such models predict a maximum jump of 4–5 km [*Harris and Day*, 1999; *Wesnousky*, 2006]. To simulate the 10 km rupture jump documented in the 2001 Kunlun, China earthquake [*Xu et al.*, 2002; *Antolik et al.*, 2004; *Duan and Oglesby*, 2006], such models require either very large stress heterogeneities [*Duan and Oglesby*, 2005] or incorporation of unmapped linking faults [*Antolik*

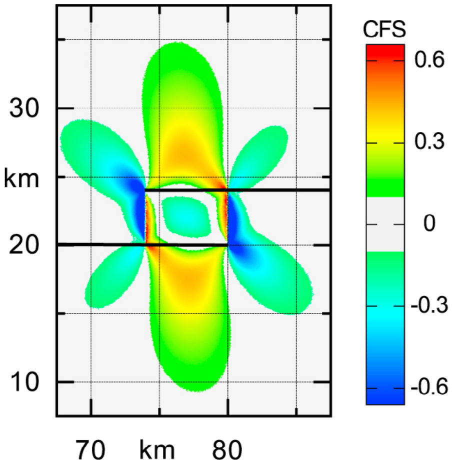

Figure 3. Inter-seismic stress patterns at the vicinity of a damaged step-over. CFS stress concentrations at a 4 km wide damaged step-over ($\alpha = 0.35$). Zero CFS corresponds to background stress and CFS = 1 is the reference stressing level as shown in Figure 1.

et al., 2004]. Based on observations of significant damage within the ruptured step-over [*Xu et al.*, 2002], we propose that damage enabled the large rupture jump. Specifically, we obtain comparable rupture jumps (≥10 km) in simulations with $\alpha \geq 0.3$ and $B = 0$ (and $\alpha \geq 0.35$ for $B = 0.5$; Figure 2).

[14] We note that the merits of physics-based, rupture models extend beyond the challenge of predicting earthquake magnitudes along segmented strike-slip faults. Our results suggest that rupture models could foresee remotely triggered seismicity along bi-material faults following large earthquakes (such as observed along terrain bounding faults following the Landers and Denali earthquakes [*Gomberg et al.*, 2004; *Hill et al.*, 1993]). In such locations, material contrasts could induce static stress concentrations and enhance dynamic stresses sufficiently to trigger seismicity from afar. Finally, extending our models to 3D would enable to predict rupture propagation along subduction zones where material heterogeneities have been shown to control the segmentation and magnitude of complex mega-thrust earthquakes [*Shen et al.*, 2009; *Sparkes et al.*, 2010]. This could help better predict the occurrence and magnitude of multi-segment earthquakes such as the 2004 India Ocean (M9.1) and 2011 Tohoku-oki, Japan (M9).

[15] Our work sheds light on the important role material properties play in rupture dynamics. We conclude that highly damaged step-overs induce stress and strain patterns that promote rupture jumps across large distances. Our analysis of damage-related destabilizing mechanisms suggests that faults along bimaterial interfaces are particularly susceptible to large cascading earthquakes with multi-segment ruptures. We call for re-evaluation of earthquake rupture models where off-fault damage and bimaterial faults are observed, and we provide practical guidelines for including such observations in improved seismic hazard analysis.

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