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## Characteristics of episodic fault growth and off-fault deformation structures

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Natural fault networks are geometrically complex systems that evolve through time. The growth and evolution of faults and their off-fault damage pattern are influenced by both dynamic earthquake ruptures and aseismic deformation during the interseismic period. To better understand each of their contributions to faulting we simulate both earthquake rupture dynamics and long-term deformation in a visco-elasto-plastic crust subjected to rate-and-state-dependent friction [1,2]. The continuum mechanics-based numerical model presented here includes three new features. First, a 2.5-D approximation to incorporate effects of a viscoelastic lower crustal substrate below a finite depth. Second, we introduce a dynamically adaptive (slip-velocity-dependent) measure of fault width to ensure grid size convergence of fault angles for evolving faults. Third, fault localisation is facilitated by plastic strain weakening of bulk rate-and-state friction parameters as motivated by laboratory experiments. This allows us to for the first time simulate sequences of episodic fault growth due to earthquakes and aseismic creep. Localized fault growth is simulated for four bulk rheologies ranging from persistent velocity-weakening to velocity-strengthening. Yet, episodic fault growth is only obtained for a bulk rheology that transitions from velocity-strengthening friction to velocity-weakening friction. Interestingly, in each of these bulk rheologies, faults predominantly localise [LDZ1] and grow in the inter-seismic period due to aseismic deformation. However, [LDZ2] off-fault deformation - both distributed and localised - is typically formed during dynamic earthquake ruptures. Simulated off-fault deformation structures range from fan-shaped distributed deformation to localized Riedel splay faults and antithetic conjugate [LDZ3] Riedel shear faults [LDZ4] and towards wing cracks. We observe that the fault-normal width of the outer damage zone saturates with increasing fault length due to the finite depth of the seismogenic zone. We also observe that dynamically and statically evolving stress fields from neighbouring fault strands affects first and secondary fault growth. Finally, we find that the amount of off-fault deformation distinctly depends on the degree of optimality of a fault with respect to the prevailing but dynamically changing stress field. Typically, we simulate off-fault deformation on faults parallel to the loading direction. This produces a 6.5-fold higher off-fault energy dissipation than on an optimally oriented fault, which in turn has a 1.5-fold larger stress drop. The misalignment of the fault with respect to the static stress field thus facilitates off-fault deformation. These results imply that fault geometries bend

[2], individual fault strands interact and that optimal orientations and off-fault deformation vary through space and time. With our work we establish the basis for simulations and analyses of complex evolving fault networks subject to both long-term and short-term dynamics. Currently, we are using this basis to simulate and explain orthogonal faulting observed in the 2019 M6.4-M7.1 Ridgecrest earthquake sequence.