Macroscopic Source Properties from Dynamic Rupture Simulations with Off-fault Plasticity

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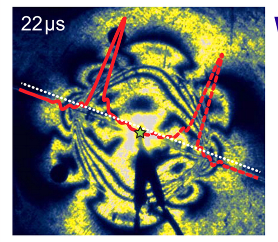
We apply the 2D spectral element method (SEM2DPACK of Ampuero, 2008) to model spontaneous rupture under strong velocity-and-state-dependent friction with off-fault Coulomb plasticity in a 2D in-plane model . Depending on initial parametrization and nucleation procedure the generated ruptures approach distinct zones of stable self-similar behavior: decaying, steady-state, growing pulse-like and crack-like ruptures, in both, sub- and super-shear regimes, bordered by sensitive transitional zones. The introduction of off-fault inelasticity quantitatively modifies the conditions to obtain each rupture mode, depending on the angle of maximum compressive initial stress and background shear stress level. Additionally, the considerable amount of induced off-fault energy dissipation alters macroscopic source properties, e.g. leads to slower rupture velocities, lower peak slip rates and lower shear stress levels on the fault with respect to the purely elastic case. The interaction between rupture modes and the induced off-fault energy dissipation contributes to the rupture energy balance of the earthquake, which is relevant for prediction of observable earthquake source parameters and strong ground motion.

Motivation



Lu,Lapusta,Rosakis,2007

Why study Rupture modes?

→ Crack- vs. pulse-like rupture (short rise times)

→ Sub- vs. supersonic rupture speeds

What controls initiation and transition of rupture modes?

What controls the dynamics of rupture pulses ?

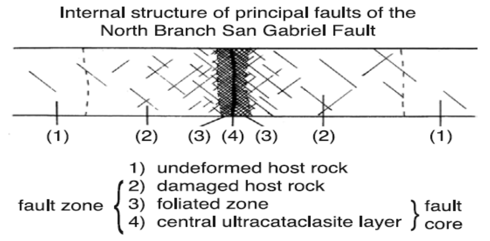
Why study Off-fault Plasticity ?

→ Field observations: Limited off-fault plasticity surrounding natural faults

→ LEFM: High stress concentrations at rupture front generate anelastic material response and energy dissipation

How are macroscopic source properties altered ?

What are physical limits of extreme ground motion ?



Chester,1993

Friction Law

→ **Rate-and-state dependent friction law with fast velocity-weakening** as in Ampuero and Ben-Zion (2008)

$$\mu_f = \mu_s + a\frac{V}{V+V_c} - b\frac{\theta}{\theta + D_c} \qquad \dot{\theta} = V - \frac{\theta\ V_c}{D_c} \qquad \mu_d = \mu_s + (a-b)$$

μ_f=friction coefficient, μ_s= static friction coefficient, μ_d= dynamic friction coefficient, V = slip velocity, V_c= characteristic velocity scale, a = direct effect coefficient, b = evolution effect coefficient, θ = state variable, D_c=characteristic slip scale

Plasticity

→ **Perfect plasticity with Coulomb yield function for 2D plane strain** as in Andrews (2005)

→ **Visco-plasticity** as in classical Duvaut-Lions

$$\epsilon = \epsilon^e + \epsilon^p \qquad \tau_{max} = \sqrt{\sigma_{xy}^2 + \frac{(\sigma_{xx}-\sigma_{zz})^2}{4}}$$

$$\dot{\epsilon}_{ij}^p = \frac{1}{2\mu T_v}\langle \tau_{max} - Y\rangle \frac{\tau_{ij}}{\tau_{max}} \qquad \tau_{ij} = \sigma_{ij} - \frac{1}{3}\sigma_{kk}\delta_{ij} \qquad Y = c\cos(\Psi) - (\sigma_{xx}+\sigma_{zz})\sin\frac{\psi}{2}$$

τ_{max}= maximum shear stress, σ_{ij}= stress tensor, c = cohesion, Ψ= internal friction angle, Y = yield strength, ε = total strain, ε^p = plastic strain, ε^e = elastic strain, T_v= visco-plastic relaxation time, <x> = ramp function, τ_{ij} = deviatoric part of stress tensor

Nucleation procedures

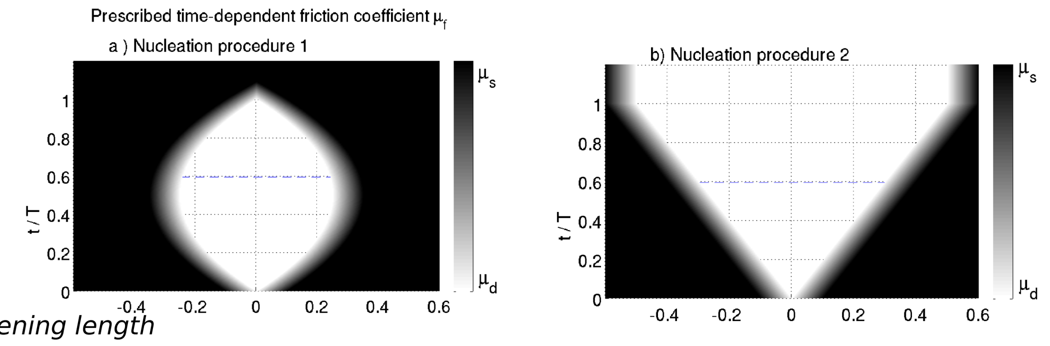
→ **Self-healing time-weakening** as in Andrews and Ben-Zion (1997)

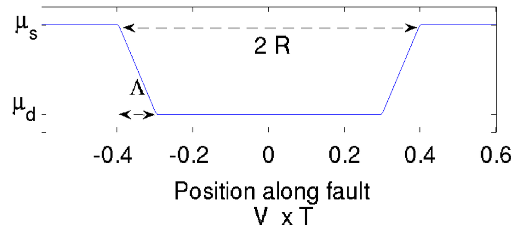
$$R = V_n t\left(1 - \frac{t}{T}\right)$$

→ **Non-healing time-weakening**

$$R = V_n t$$

$$\mu_f = \begin{cases} \mu_s - \frac{(R-x)}{\Lambda}(\mu_s - \mu_d) & \text{for } x > (R-\Lambda) \\ \mu_d & \text{for } x < (R-\Lambda) \end{cases}$$





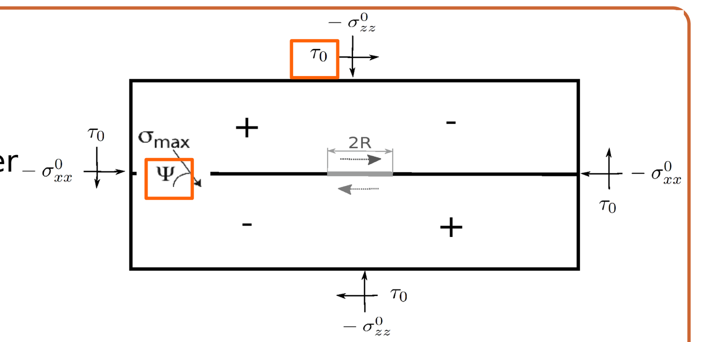
R = Boundary of source region, V_n= Rupture propagation speed, T= Total duration of nucleation, Λ= Weakening length

Numerical Method

→ SEM2DPACK (Ampuero, 2008) - a **Spectral Element Method (SEM)** in space discretization and a second-order explicit scheme in time discretization

→ All simulation in- and outputs are **non-dimensional**

$$S = \frac{\tau_s - \tau_0}{\tau_0 - \tau_d} \qquad \boxed{S = 2.5...0.666}$$



$$\boxed{\Psi = 10; 20; 29.52; 40; 45; 50; 60}$$

Simulation Parameters

ρ	Density	1	μ_d	Dynamic friction coefficient	0.1
c_s	Shear wave speed	1	D_c	Characteristic slip scale	1
ν	Poisson's ratio	0.25	σ_0	Background normal stress	2
μ_s	Static friction coefficient	0.6	τ_0	Background shear stress	0.5-1.0
a	Direct effect coefficient	0.005	T	Duration of Nucleation	0.001-1000
b	Evolution effect coefficient	0.505	T_v	visco-plastic relaxation time	0.017
μ	Shear modulus	1	c	Cohesion	0
v_c	Characteristic velocity scale	0.07			

ρ	Density	2738 $\frac{kg}{m^3}$
c_s	Shear wave speed	2826.1 $\frac{m}{s}$
μ	Shear modulus	21.87 GPa
D_c	Characteristic slip scale	0.744 mm
σ_n	Background normal stress	130 MPa
s_{xz}	Background shear stress	0.5-45.5MPa
c	Cohesion	0

Scaling: stresses by strength drop: $\tau_D=\sigma_n(\mu_s-\mu_d)$, strains by τ_D/μ, slip & displacements by D_c, distances by $X=\mu D_c/(1-\nu)\tau_D$, time by X/c_s

Realistic scaling example: stress by τ_D=65 Mpa, distance by X=1916.59m, time by X/c_s=0.68s

General Rupture Modes

(see also EGU2011-11910 for details)

→ **In elastic and plastic media ruptures approach distinct stable, assumedly self-similar rupture regimes bordered by highly sensitive transitional modes**

→ **Nucleation and pre-stress level determine rupture style**

→ **Transitions between decaying pulses, growing pulses and crack-like rupture (compare Nielsen & Madariaga 2003; Festa & Vilotte 2006; Shi et al. 2008; Ampuero and Ben-Zion 2008)**

→ **Phase transitions** of steady-state and pulse-crack superposition **shift** with varied nucleation and pre-stress

→ **Supershear transition is independent of nucleation and rupture mode**

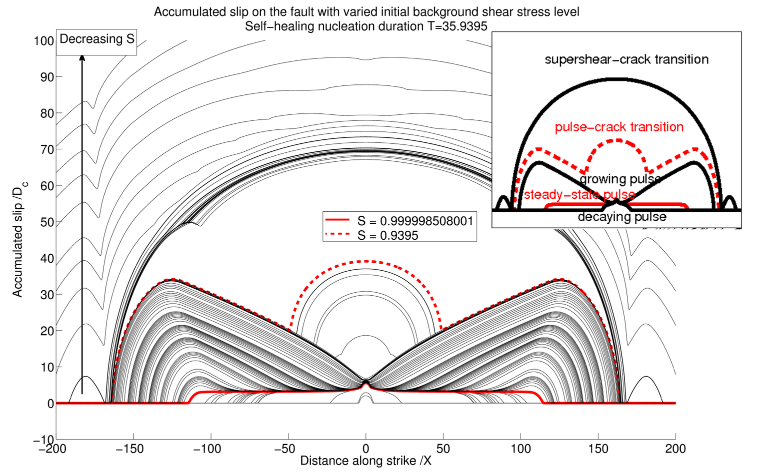
→ **Off-fault plasticity shifts transformational modes** in the respective parameter space

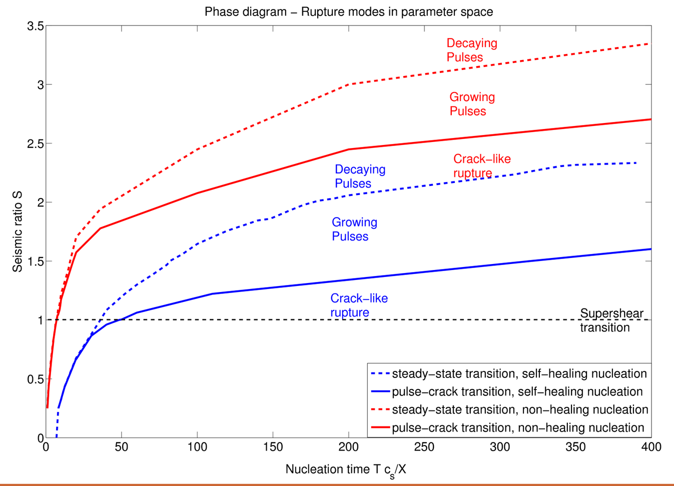
→ **Qualitatively unaltered** rupture modes

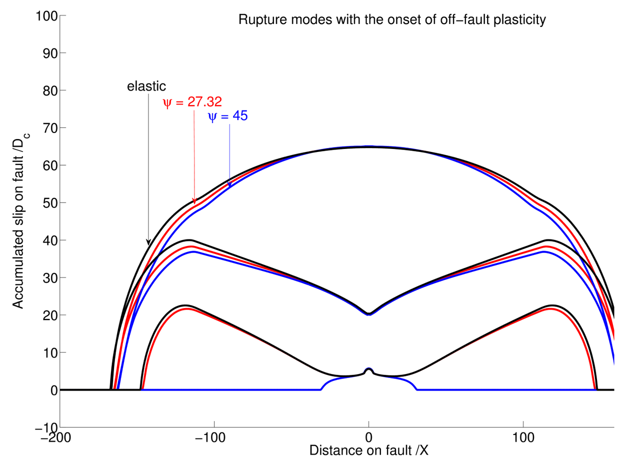
→ **Increasing** plasticity level (Ψ) **: shorter** range of growing pulses

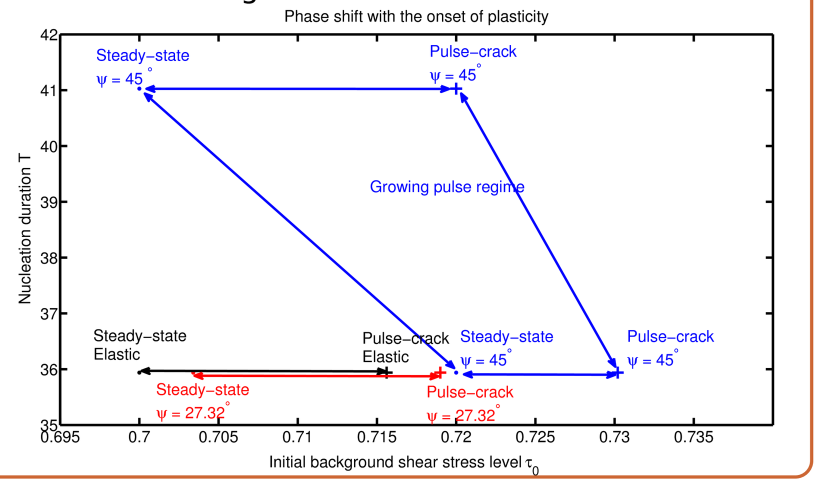
→ **Decreasing Ψ :** shift to **smaller** nucleation duration/background stresses

→ **Increasing** nucleation duration T **: spreading** the range of growing pulses to **lower** background shear stress levels







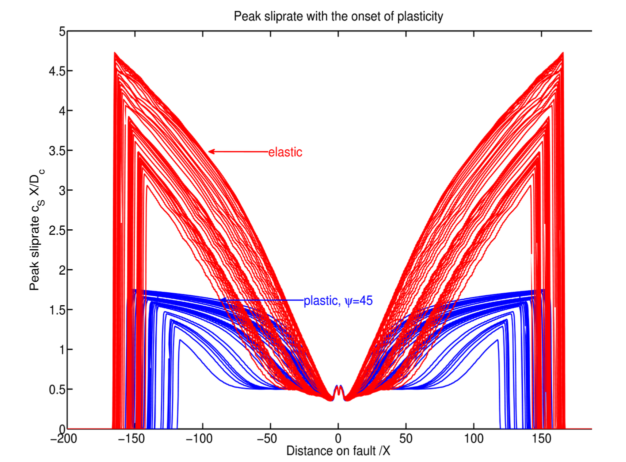


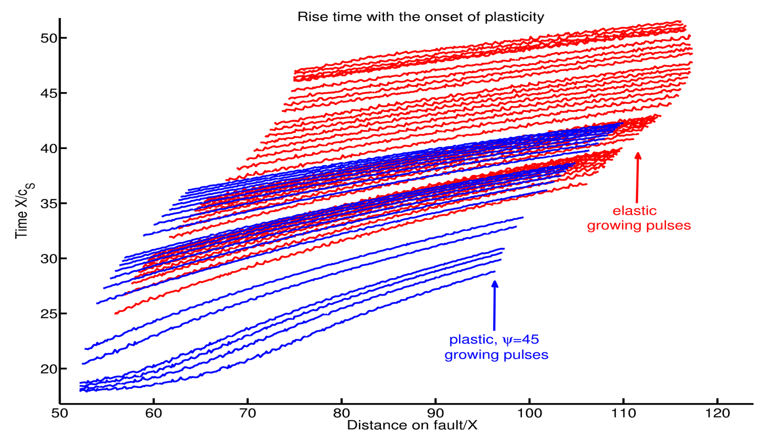
Macroscopic source properties in plastic media

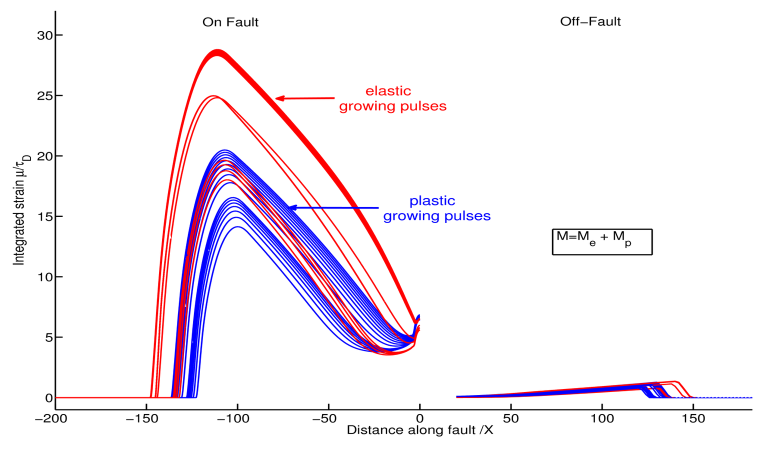
→ **Focus on (self-similar) growing pulses regime to study the interaction of pulse-like dynamics and off-fault plasticity**

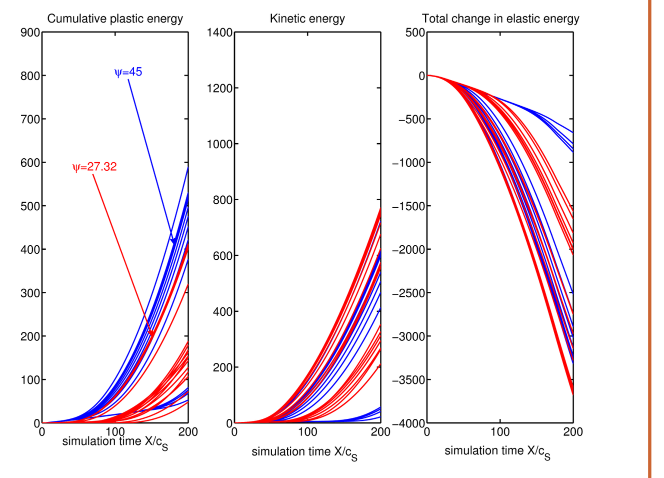
→ **The onset of plasticity leads to :**

- **Lower peak sliprates and faster saturation into self-similar behavior**
- **Shorter rise times**
- **Rise time is proportional to position as consequence of self-similarity**
- **Plastic component of seismic moment induced off-fault by plastic strain field**
- **Plastic dissipated energy dependent on Ψ**









→ **Amount of alteration is dependent on angle of max. compressive stress and pre-stress level**

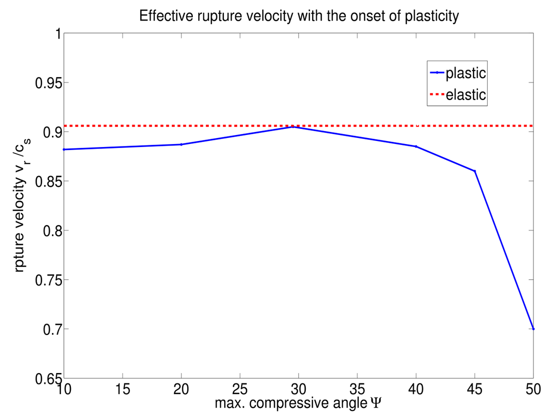
- **Lowered effective rupture velocity**

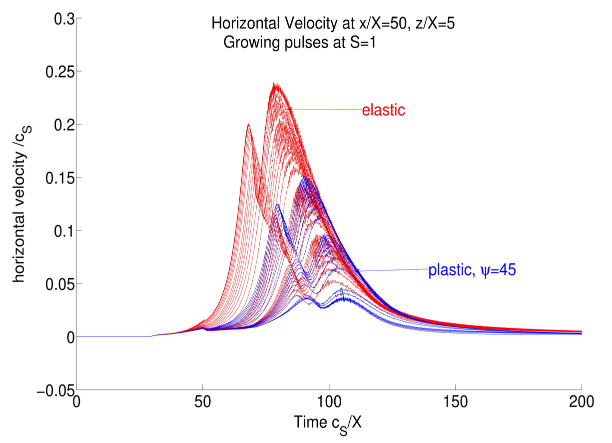
→ **Off-fault plasticity lowers effective rupture velocity dependent on Ψ**

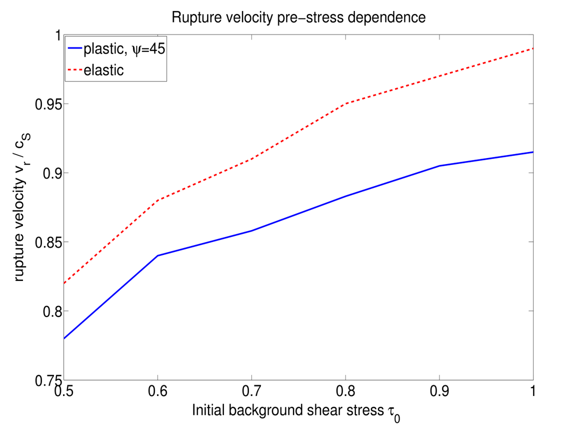
→ **Pre-stress dependence of rupture velocity is preserved**

→ **All rupture modes propagate at lower effective rupture velocities**

→ **Off-fault velocity field is as well damped**







- **Lowered dynamic seismic ratio (fault strength excess) for all transitional rupture modes**

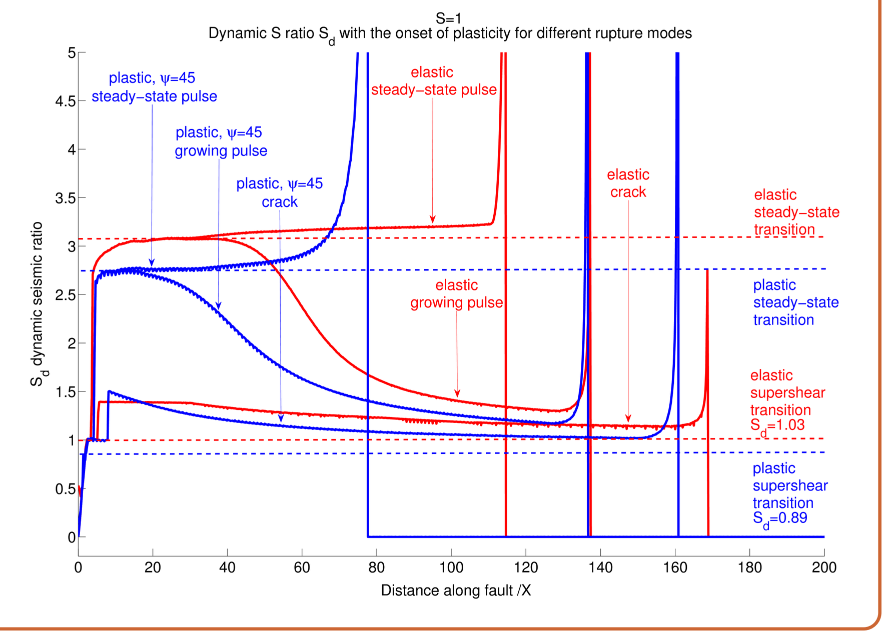
→ **Dynamic strength excess S_d as meassure of closeness of the fault to rupture mode transition**

→ **Off-fault plasticity lowers critical S_d for all rupture mode transitions, dependent on nucleation and pre-stress state of the fault**

→ **Supershear transition occurs at lowered S_d < 0.91, independent of nucleation and rupture mode**

$$S_d = \frac{\tau_{max} - \tau_0}{\tau_0 - \tau_{min}}$$

τ_{max}= maximum shear stress to initiate rupture, τ_{min}= minimum shear stress level during sliding



Conclusions and Outlook

We have explored, through numerical simulations, the interaction of rupture modes under velocity-weakening friction with off-fault plasticity. We especially focus on the growing pulse regime, which is considered to convergence into self-similar, nucleation-independent behavior. The onset of plasticity preserves qualitatively all elastically defined rupture modes, but shifts the sharply defined mode transitions in the respective initial parameter space. Initial conditions to allow rupture mode transition can be summarized in a dynamically defined strength excess parameter, the dynamic seismic ratio S_d . Macroscopic source properties are altered considerably by off-fault energy dissipation at the crack tip, to which amount is depending on the maximum compressive angle of initial stress and the overall pre-stress level of the fault. Future work will quantitatively relate various observable earthquake properties, as the apparent fracture energy (frictional plus plastic dissipation), rupture and healing front speed, peak slip and slip velocity, dynamic stress drop and size of the process and plastic zones, and draw the comparison to analytical solutions available for steady state-like rupture in elastic media (Zheng & Rice (1998), Rice (2005)) and self-similar growing pulses. Furthermore, we will endeavor to obtain parametrizations that mimic off-fault yielding to be implemented in pseudo-dynamic source characterizations.