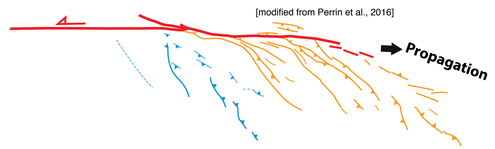
Seismic rupture on propagating faults: Off-fault fan, splay faults and wing cracks

Simon Preuss[1], Jean Paul Ampuero[2], Taras Gerya[1], **Ylona van Dinther**[3]
[1]**Institute of Geophysics, ETH Zurich** - [2]Géoazur - Université Nice Sophia Antipolis - [3]Utrecht University

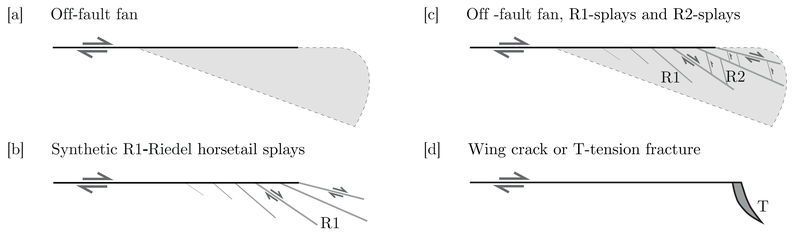
1 Introduction

natural examples → **conceptual model**

[modified from Perrin et al., 2016]



Mature North Anatolian Fault System



Objective: investigate incipient secondary faulting due to the propagation of a dynamic earthquake rupture on a mature fault

2 Seismo-Thermo-Mechanical Modeling

Van Dinther et al., (JGR, 2013b) extended to seismic time scales with adaptive time stepping and rate-and-state friction (Herrendoerfer et al., JGR, 2018) for evolving faults (Preuss et al., JGR, 2019) and novelties *

τ_{II} - second invariant of stress tensor
P - pressure
V_p - plastic slip rate
V_0 - reference slip rate
μ_s - static friction coefficient
θ - state
L - characteristic slip distance

Conservation

$$\frac{\partial v_x}{\partial x}+\frac{\partial v_y}{\partial y}=0$$
$$\frac{\partial \sigma'_{xx}}{\partial x}+\frac{\partial \sigma'_{xy}}{\partial y}-\frac{\partial P}{\partial x}=\rho\frac{Dv_x}{Dt}$$
$$\frac{\partial \sigma'_{yx}}{\partial x}+\frac{\partial \sigma'_{yy}}{\partial y}-\frac{\partial P}{\partial y}=\rho\frac{Dv_y}{Dt}$$

Rheology

$$\dot{\epsilon}'_{ij}=\frac{1}{2\eta}\sigma'_{ij}+\frac{1}{2G}\frac{D\sigma'_{ij}}{Dt}+\begin{cases}0 & for\ \sigma'_{II}<\sigma_{yield}\\ \chi\frac{\partial g_{pl}}{\partial \sigma'_{ij}} & for\ \sigma'_{II}=\sigma_{yield}\end{cases}$$
$$\sigma'_{ij}=2\eta_{vp}\dot{\epsilon}'_{ij}Z+\sigma'^{0}_{ij}(1-Z) \qquad Z=\frac{G\Delta t_{comp}}{G\Delta t_{comp}+\eta_{vp}}$$

Plastic strength with Invariant regularized RSF formulation

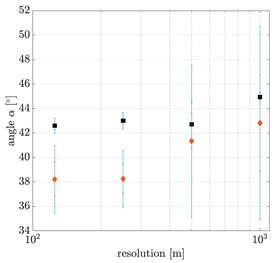
$$\sigma_{yield}=C+\mu_{eff}\cdot P$$
$$\tau_{II}=\sigma_{\text{yield}}=a\,P\,\text{arcsinh}\left[\frac{V_p}{2V_0}\exp\left(\frac{\mu_0+b\ln\left(\frac{\theta V_0}{L}\right)}{a}\right)\right]$$
$$V_p=2\dot{\varepsilon}'_{II(\text{p})}\,D \qquad \frac{d\theta}{dt}=1-\frac{V_p\,\theta}{L}$$

3 Model extension and setup

* Preuss et al. (JGR, 2019) extended with:
- Grid size convergence evolving faults due to slip rate dependent fault width formulation

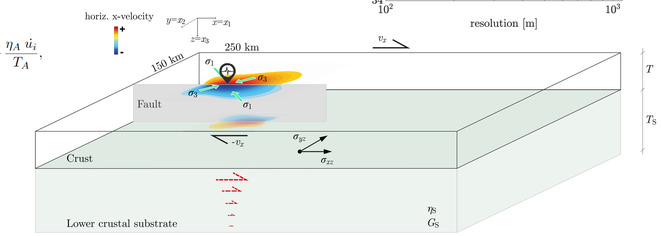
$$V_\text{p}=2\dot{\varepsilon}'_{II(p)}W.$$

$$W=\begin{cases}W_{\max}, & \text{if } W_{V_p}\geq W_{\max}\\ W_{V_p}, & \text{if } W_{\max}\geq W_{V_p}\geq\Delta x \quad \text{with} \quad W_{V_p}=W_{\max}\log\left(1+K\frac{V_0}{V_p}\right)\\ \Delta x, & \text{if } W_{V_p}\leq\Delta x\end{cases}$$



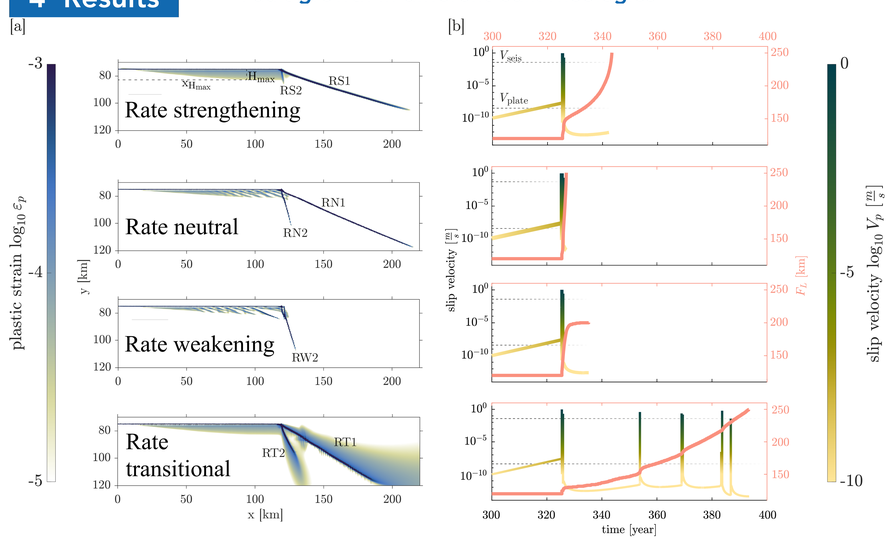
- 2.5-D model (gen. Elsasser approach; Lehner, JGR, 1981)

$$\tau_{i3}=\frac{G_A\,u_i}{b}+\frac{\eta_A\,\dot{u}_i}{T_A},$$



4 Results

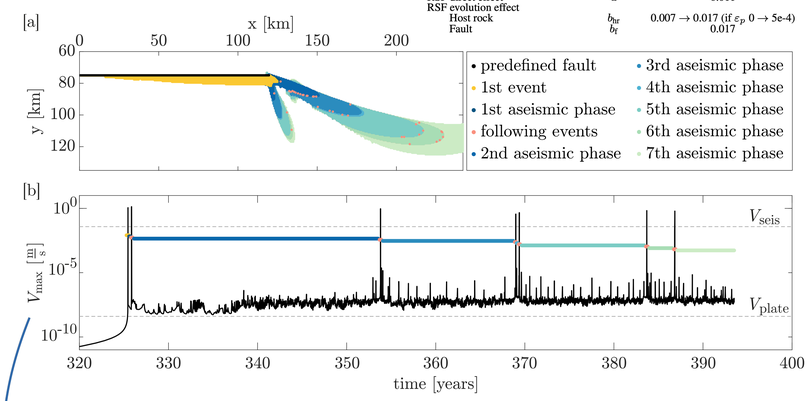
Fault growth in different bulk rheologies



Fault growth in rate transitional bulk

Rate-and-state friction parameters:

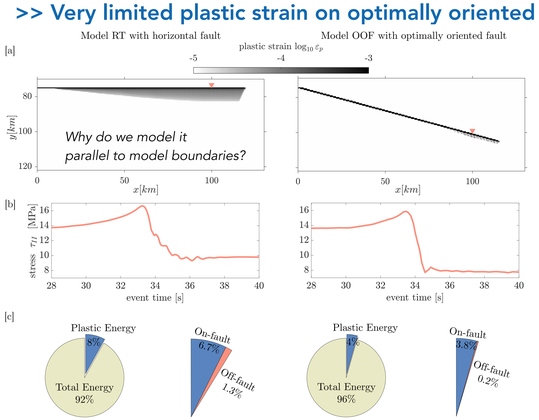
Characteristic slip distance		
Host rock	L_{hr}	1.0 → 0.01 m (if ε_p 0 → 5e-4)
Fault	L_f	0.01 m
RSF direct effect	a	0.011
RSF evolution effect		
Host rock	b_{hr}	0.007 → 0.017 (if ε_p 0 → 5e-4)
Fault	b_f	0.017



>> Fault growth occurs mainly aseismically
>> Structural complexity forms mainly seismically

5 On-fault vs- off-fault plastic strain

>> Very limited plastic strain on optimally oriented fault

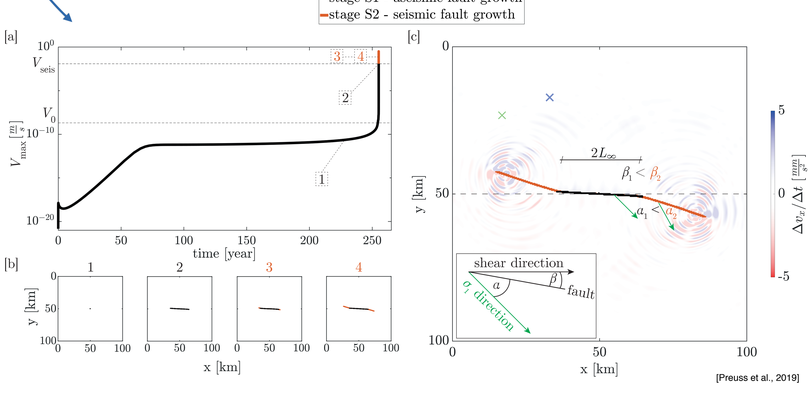


Conclusions

- Riedel and conjugate faults generated simultaneously at tip of a pre-existing fault
- Seismic fault growth is steeper than aseismic fault growth
- Faults dominantly extend aseismically
- Structural complexity is generated seismically
- Type of off-fault deformation (distributed vs. localized) depends on bulk properties
- Amount of off-fault deformation depends on the optimality of the predefined fault

Seismic fault growth is steeper than aseismic fault growth

Reminder from Preuss et al., JGR, 2019): fault growth in homogeneous, rate-weakening medium from a point defect



[Preuss et al., 2019]