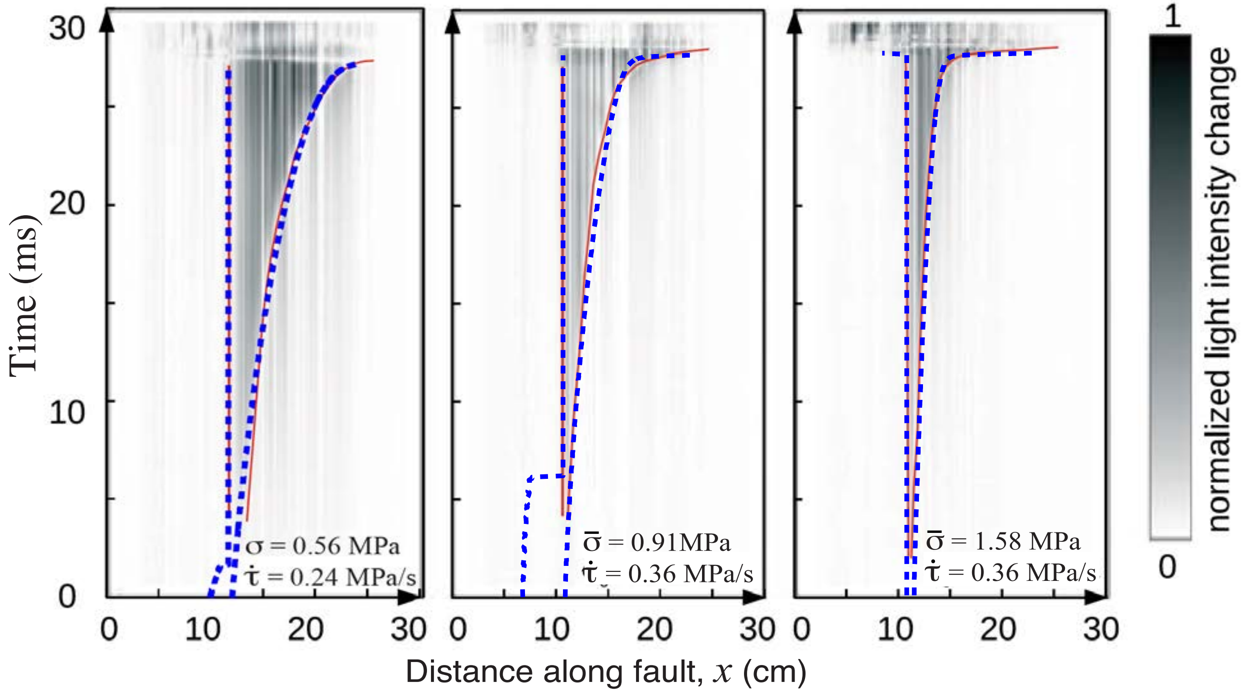
Modeling of the nucleation process of laboratory and crustal earthquakes



Yoshihiro Kaneko, GNS Science

Collaborators:

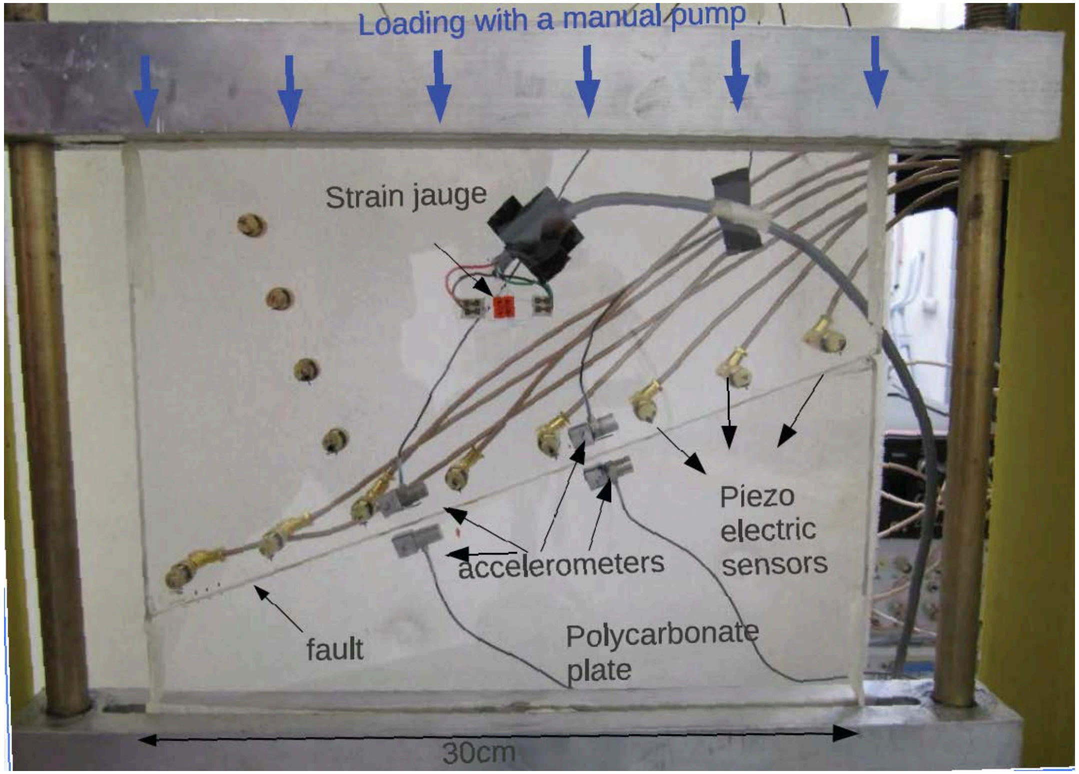
Stefan Nielsen, Durham University

Brett Carpenter, U. of Oklahoma

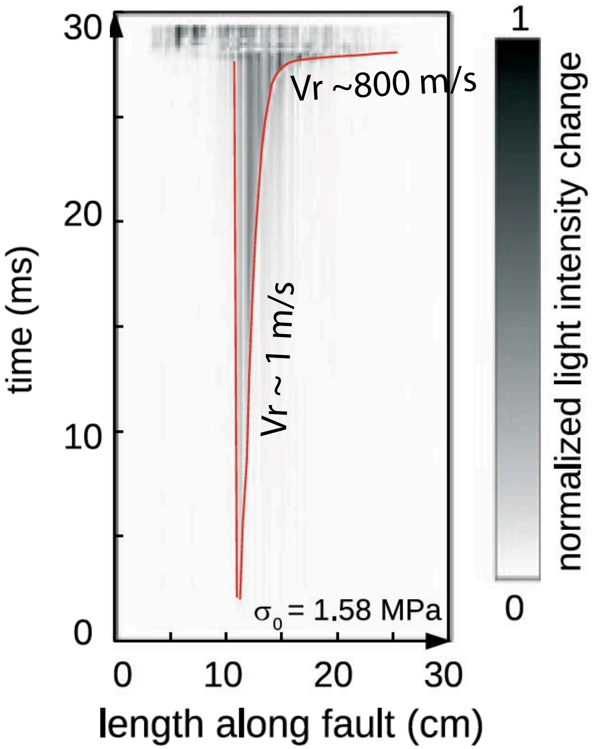
SCEC SEAS workshop, April 2018

Objective: To understand the mechanism of precursory slow slip

Evidence for precursory slow slip leading to the onset of an earthquake (e.g., Dodge et al. 1996; McGuire et al. 2005; Bouchon et al. 2011; Tape et al. 2013; Schurr et al. 2014)



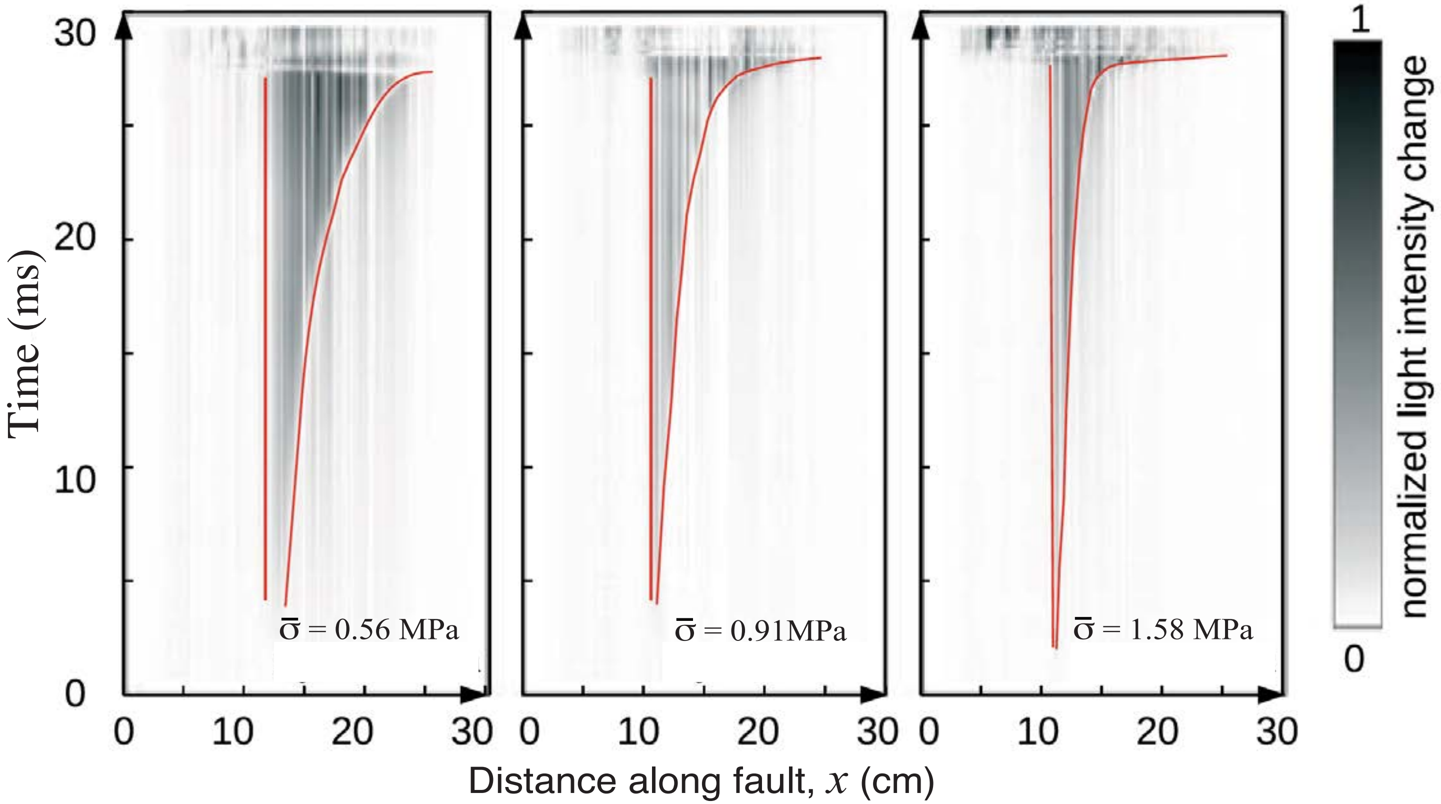
(Latour et al., 2013)



In the experiments of Latour et al. (2013):

- Dynamic shear rupture is spontaneously nucleated under slow applied loading
- Photo-elasticity technique is used to identify the evolution of rupture front (red curve)
- Initial slow rupture propagation and its acceleration to sub-shear speeds is observed

Precursory slow slip in laboratory experiments



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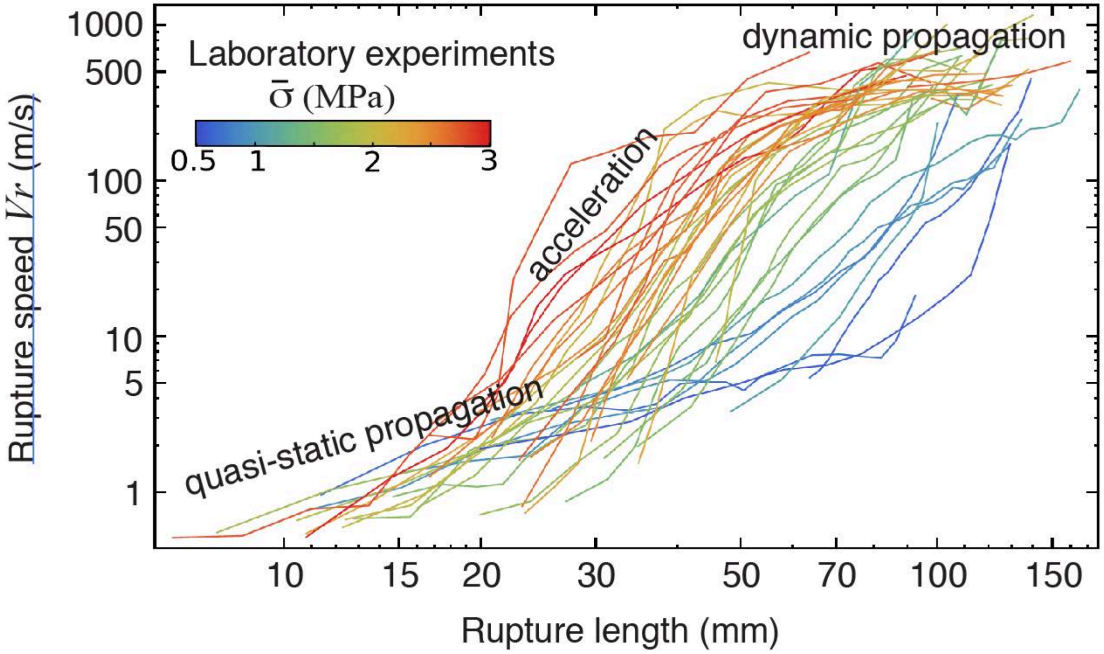
In the experiments of Latour et al. (2013):

- Length scale of slow rupture propagation decreases with increasing normal stress

Characteristics of precursory slow slip in lab experiments



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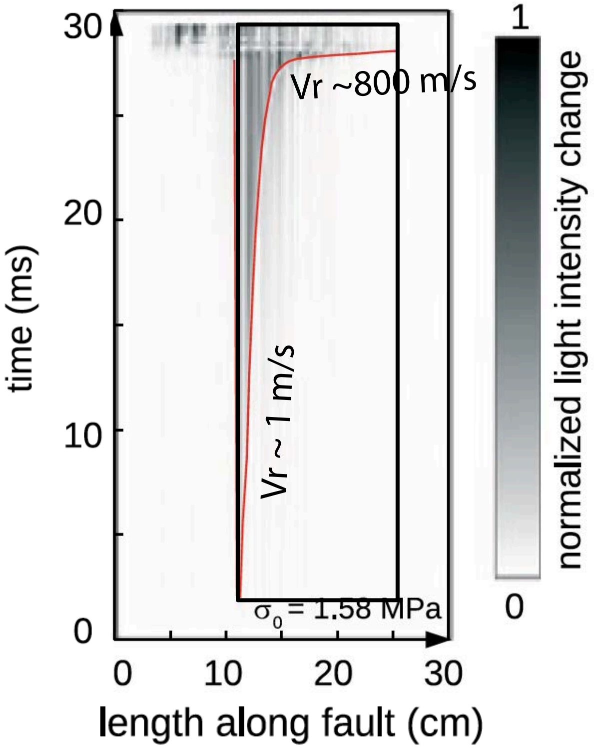
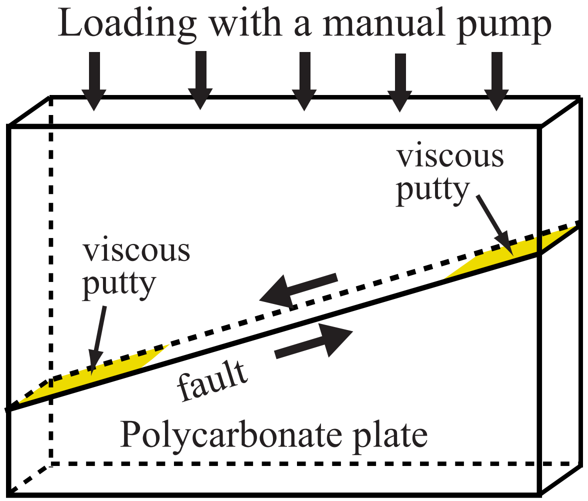


Key observations:

- There are three stages of the rupture evolution: (i) slow quasi-static propagation, (ii) faster acceleration and (iii) rapid dynamic rupture propagation
- Length scale of quasi-static rupture decreases with increasing normal stress
- Dynamic propagation phase does not occur under small normal stresses (< 0.5 MPa)

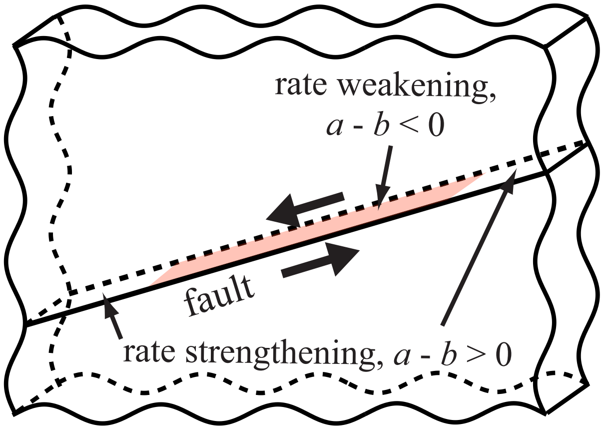
Fault model

Laboratory experiment



(Latour et al., GRL, 2013)

Fault model

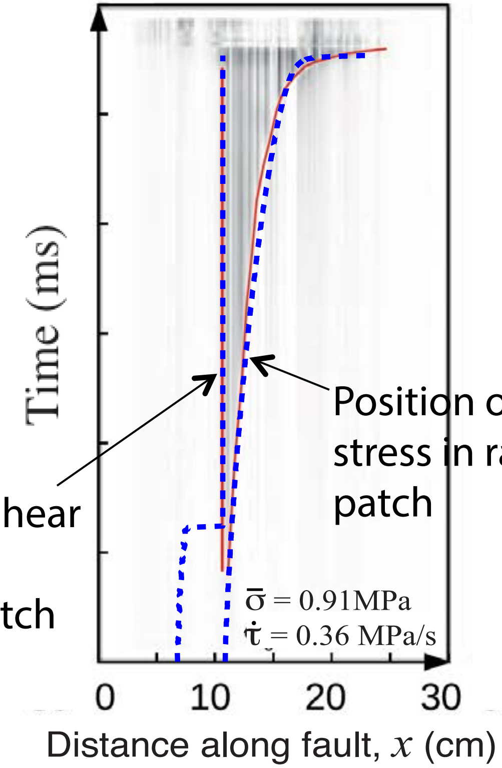


(Lapusta and Liu, 2009; Kaneko et al., 2010)

- 2D dynamic model (in-plane) with a fault embedded into a polycarbonate medium
- Fault response is governed by rate-and-state friction with the slip law
- Set-up of the model is motivated by that of the laboratory experiments (e.g., rate-strengthening segments mimic coating of viscous patches)
- Dynamic shear ruptures nucleate spontaneously under slow background loading
- We vary parameters not well constrained from lab experiments: a - b, D_c and $\dot{\tau}$

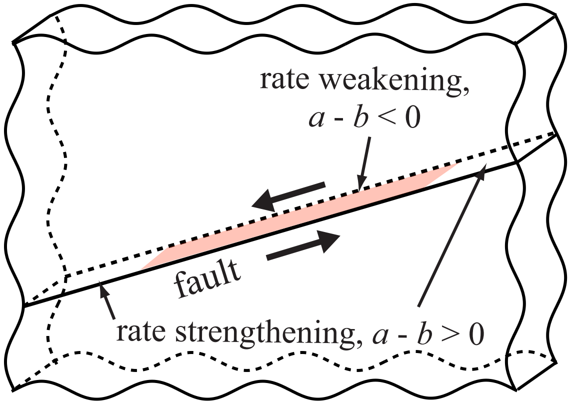
Modeled nucleation agrees well with lab observations

Red: laboratory; Blue: simulation



Position of peak shear stress in rate-weakening patch

Position of peak shear stress in rate-strengthening patch



- The asymmetry of the rupture behavior is reproduced by different lengths of the rate-strengthening (creeping) patches (Also the characteristics of slip-law nucleation)

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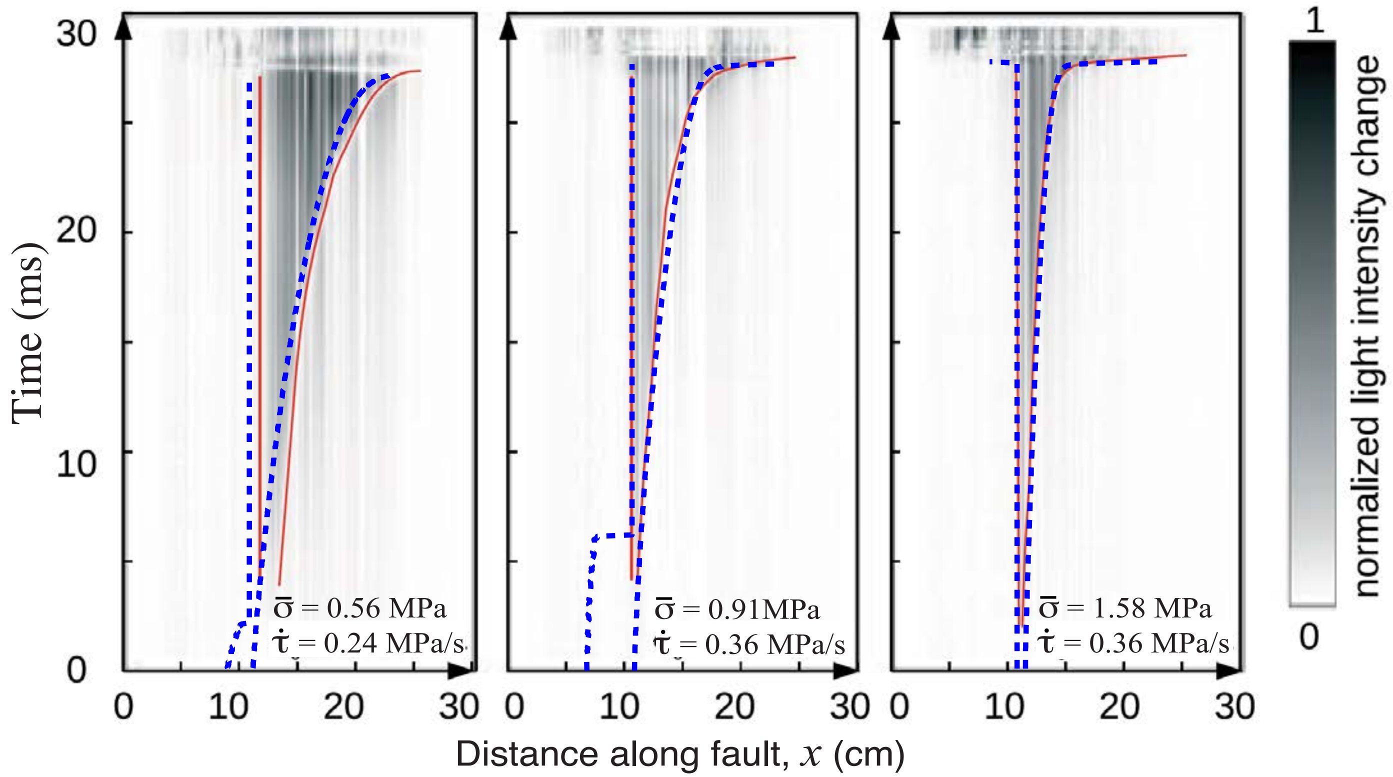

- The asymmetry of the rupture behavior is reproduced by different lengths of the rate-strengthening (creeping) patches (Also the characteristics of slip-law nucleation)
- There is a slight mismatch for σ = 0.56 MPa likely due to stress inhomogeneity in this particular experimental run

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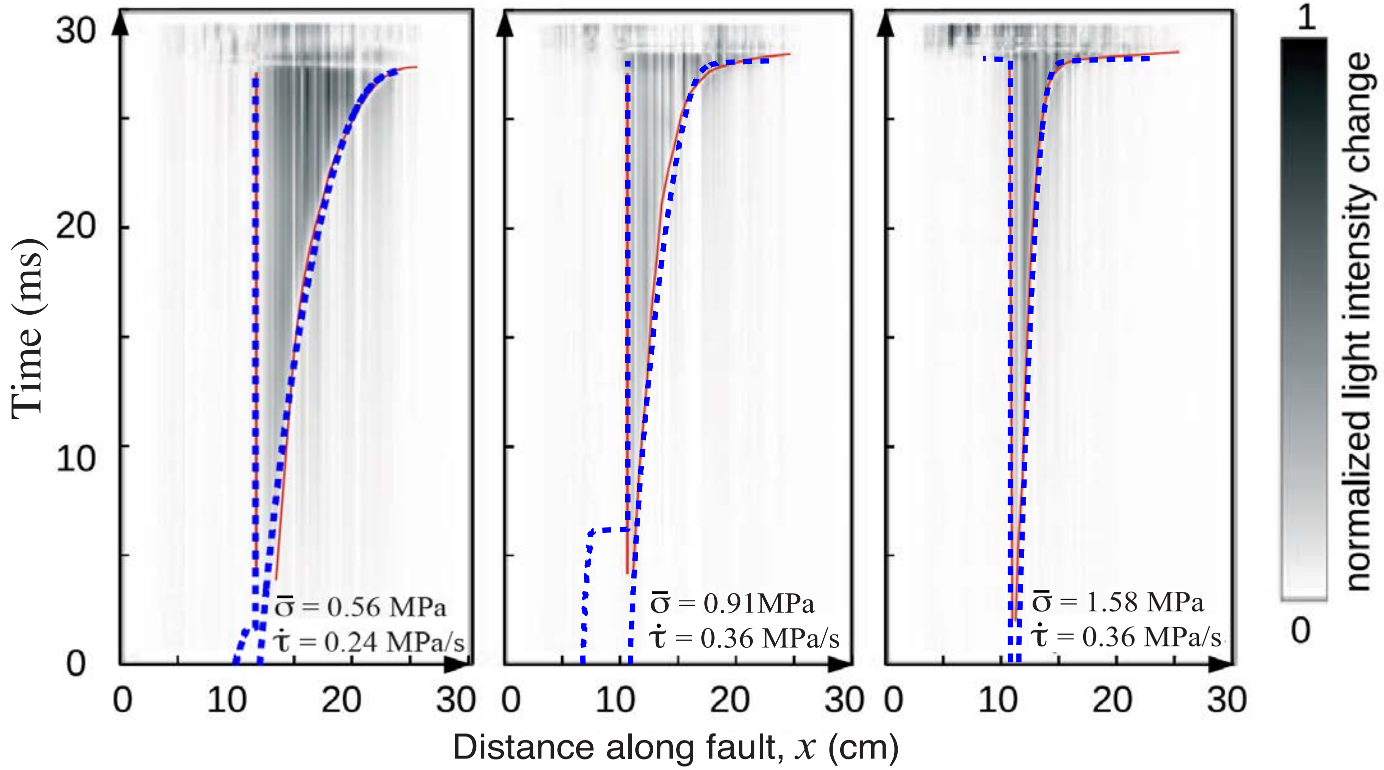
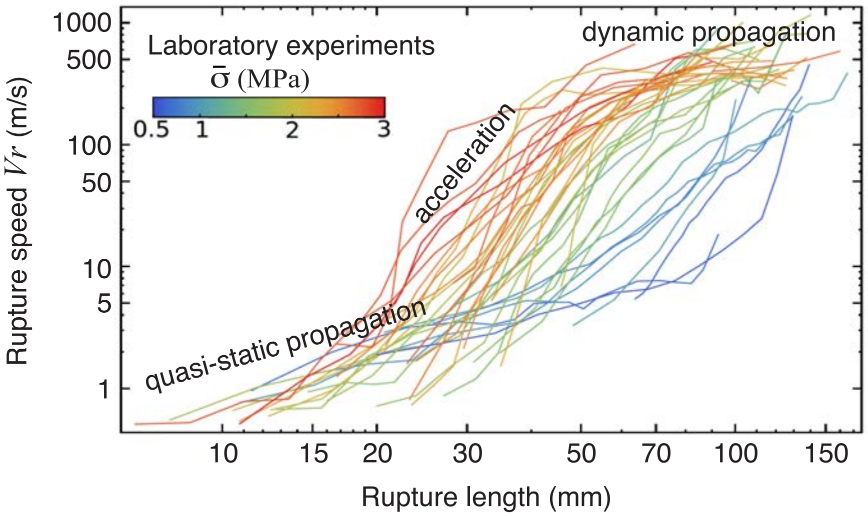


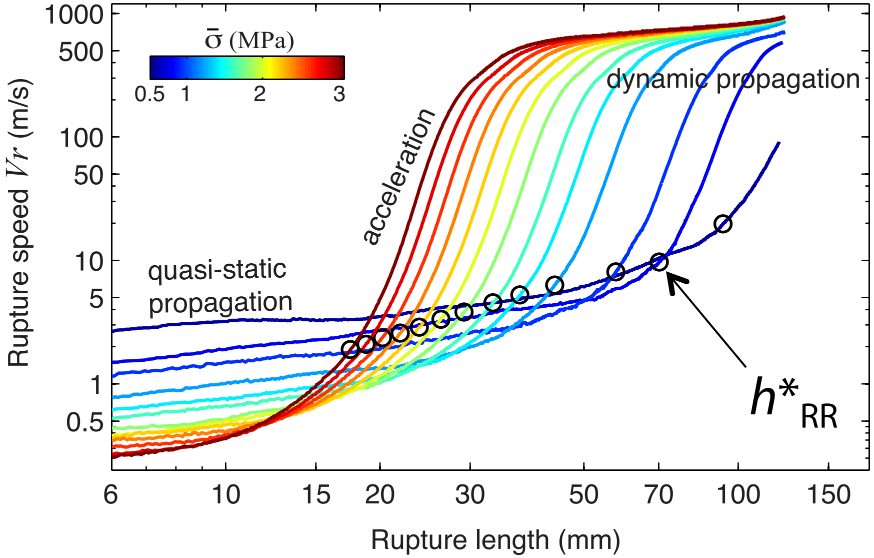
- The asymmetry of the rupture behavior is reproduced by different lengths of the rate-strengthening (creeping) patches (Also the characteristics of slip-law nucleation)
- There is a slight mismatch for $\sigma = 0.56$ MPa likely due to stress inhomogeneity in this particular experimental run
- Positions of the modeled and observed rupture fronts are in excellent agreement

Model agrees with experiments with different normal stresses

Laboratory experiments



Numerical models

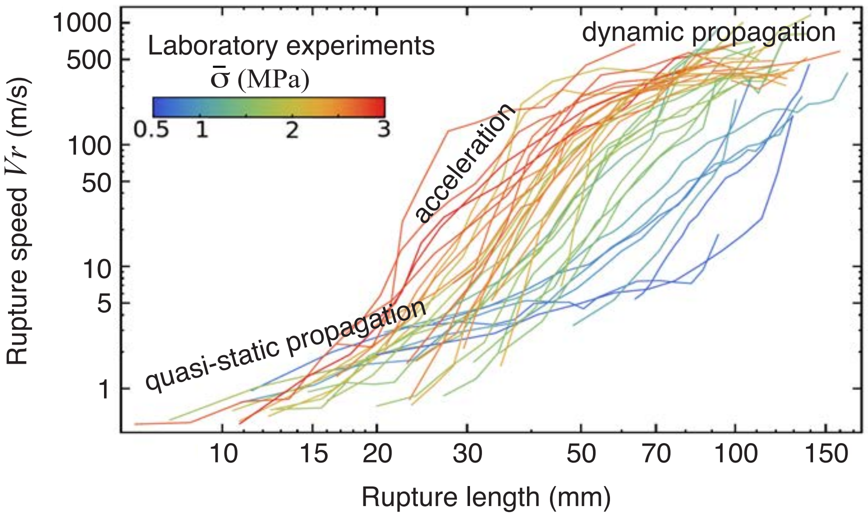


h^*_{RR} = Rice & Ruina theoretical estimate

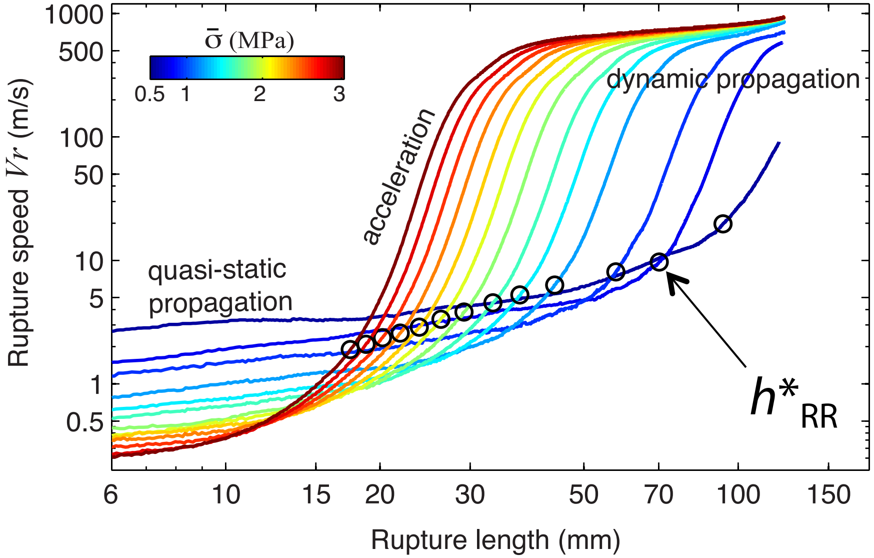
Model reproduces key observations:

- There are three stages of the rupture evolution: (i) slow quasi-static propagation, (ii) faster acceleration and (iii) rapid dynamic rupture propagation
- Length scale of quasi-static rupture decreases with increasing normal stress
- Dynamic propagation phase does not occur under small normal stresses (< 0.5 MPa)

Model agrees with experiments with different normal stresses



Laboratory experiments



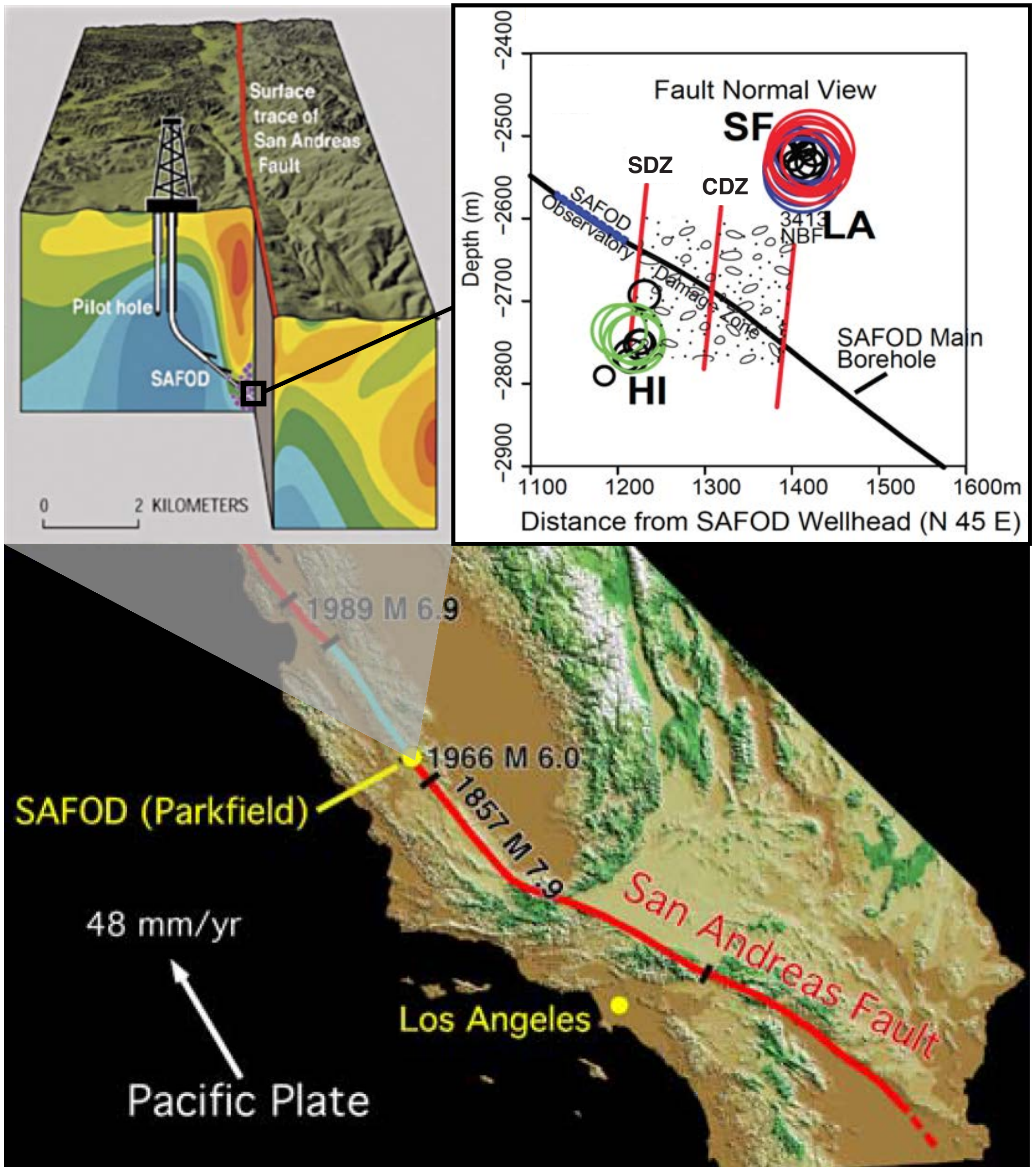
Numerical models

h^*_{RR} = Rice & Ruina theoretical estimate

Other findings not discussed today:

- The growth of rupture can be scaled by `breakdown power' (GV_r/ℓ) and h^*
- The acceleration phase occurs in equivalent **quasi-static** simulations, suggesting that the acceleration phase is an **asesimic** process
- **Background loading rate and loading configuration** significantly affect the **rupture propagation speeds** during nucleation

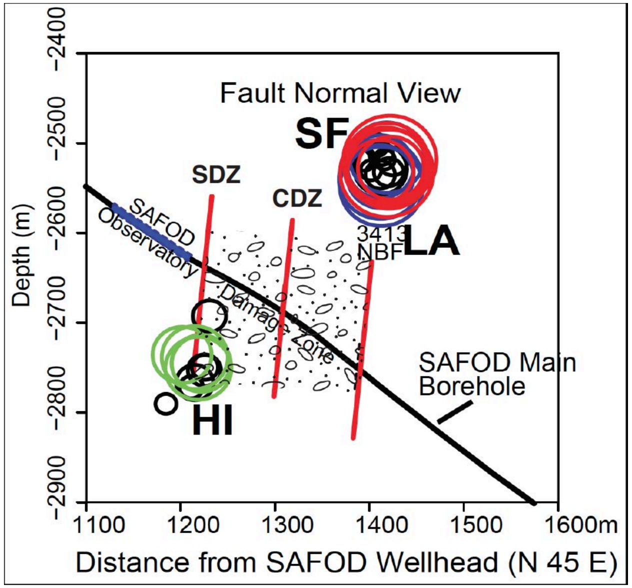
How do we test our model against real earthquakes?

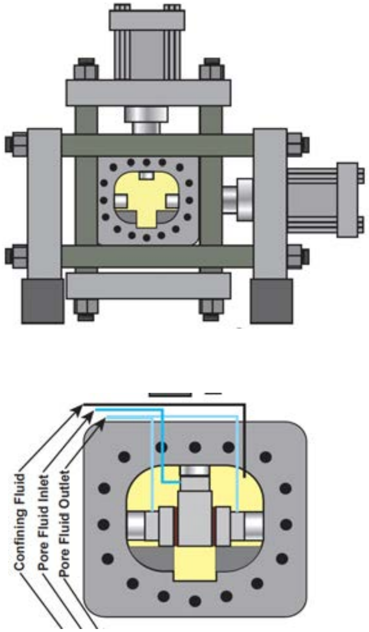


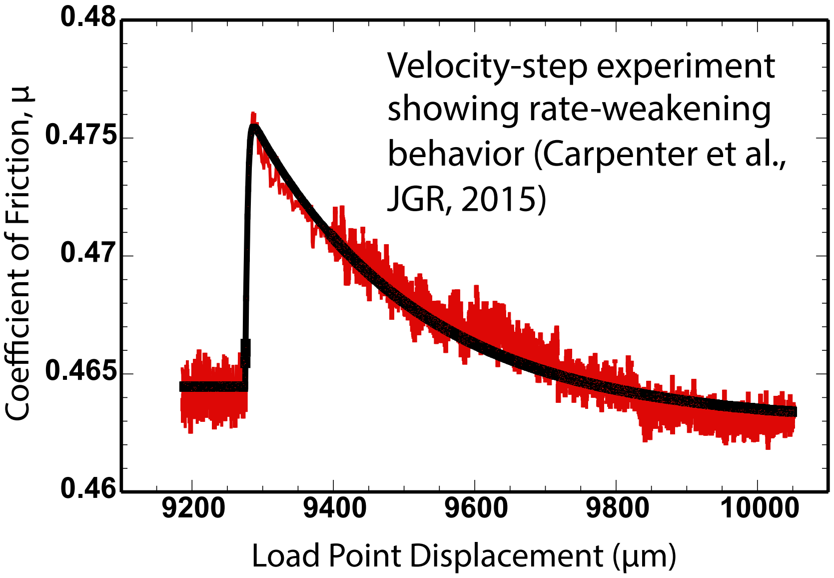
- SAFOD (San Andreas Fault Observatory at Depth) experiments
- `Hawaii' repeaters are located on the down-dip extension of the south deforming zone (SDZ)
- Repeating earthquakes are thought to rupture a rate-weakening patch surrounded by a creeping region (similar to our model)
- We apply our model to the nucleation of SAFOD repeaters

(Zoback et al., 2011)

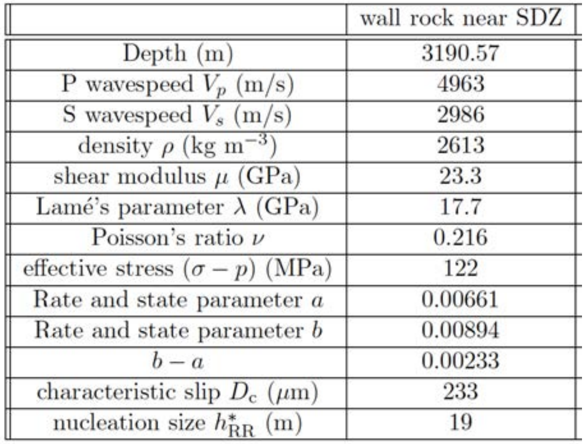
Measurements of the friction properties of SAFOD samples





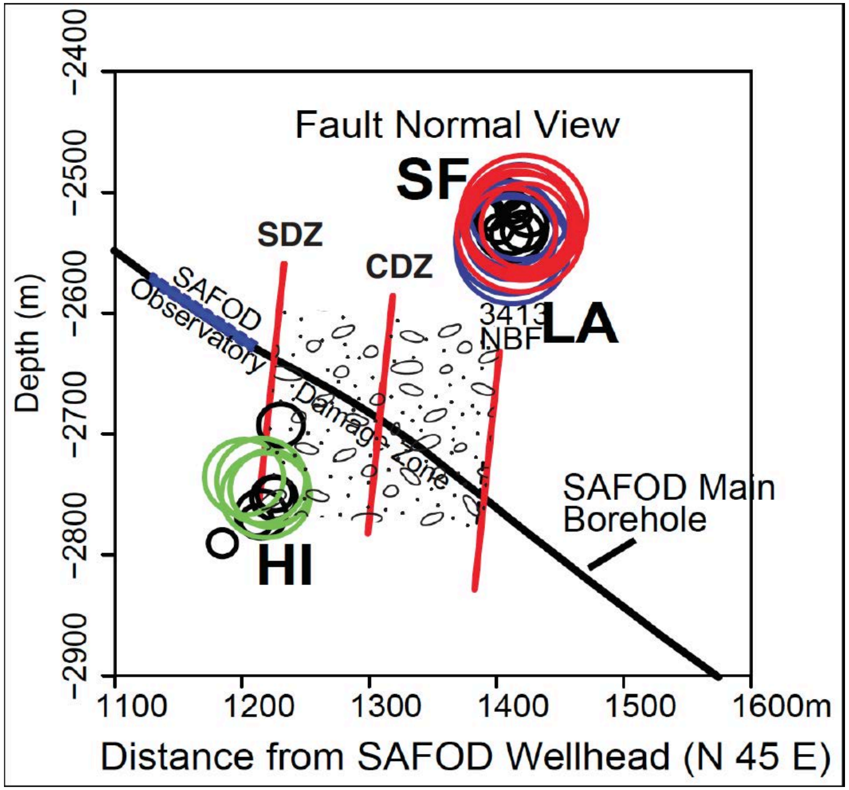

Velocity-step experiment showing rate-weakening behavior (Carpenter et al., JGR, 2015)

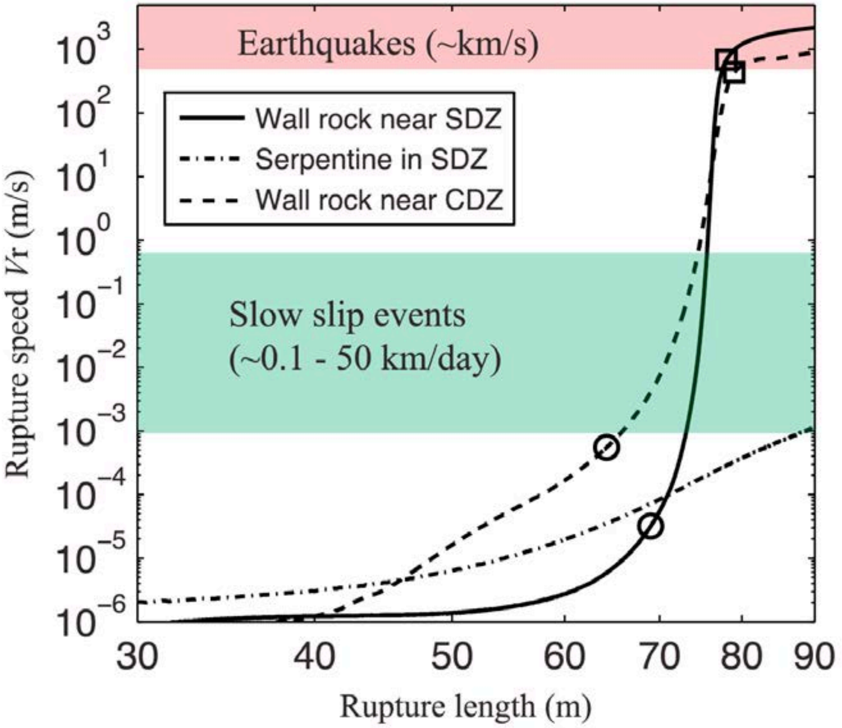
- Rocks near or within the SDZ and CDZ damage zones generally show rate-strengthening frictional behavior, consistent with the creeping segment of SAF
- However, three experimental runs (out of ~50) show rate-weakening behavior, indicating seismic rupture can nucleate for those cases
- SAFOD geophysical logs provide in-situ measurements of elastic properties; nearly all the parameters are constrained



	wall rock near SDZ
Depth (m)	3190.57
P wavespeed V_p (m/s)	4963
S wavespeed V_s (m/s)	2986
density ρ (kg m^{-3})	2613
shear modulus μ (GPa)	23.3
Lamé's parameter λ (GPa)	17.7
Poisson's ratio ν	0.216
effective stress $(\sigma - p)$ (MPa)	122
Rate and state parameter a	0.00661
Rate and state parameter b	0.00894
$b - a$	0.00233
characteristic slip D_c (μm)	233
nucleation size h^*_{RR} (m)	19

Predicting the nucleation process of SAFOD earthquakes



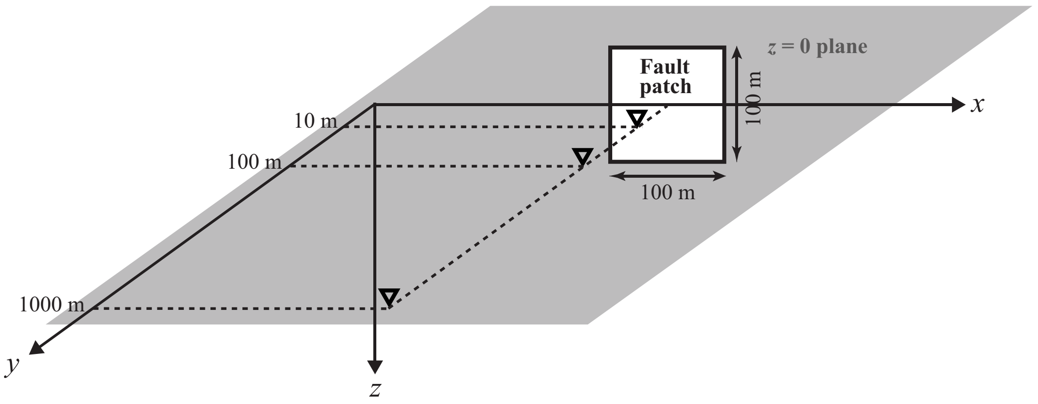


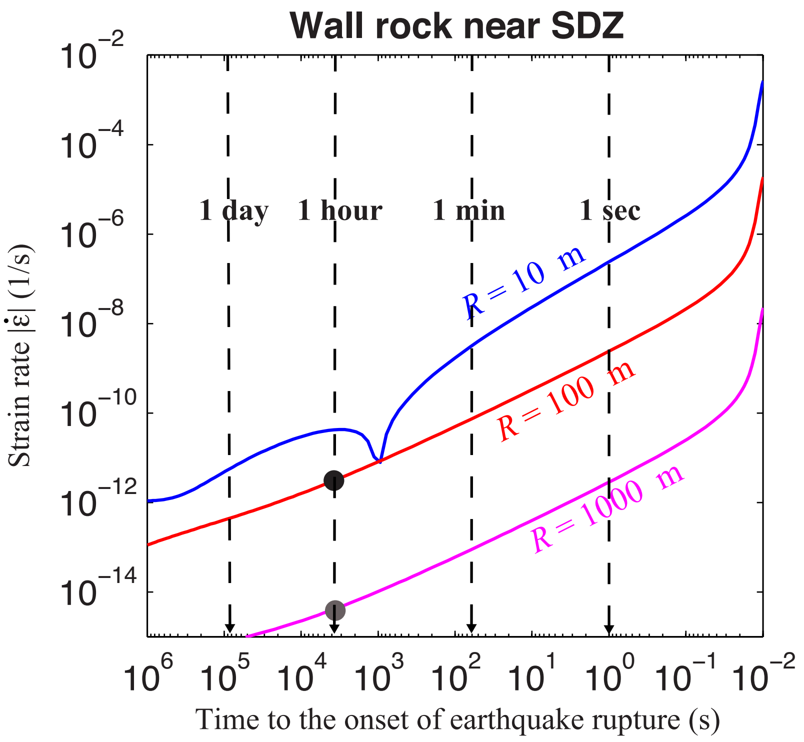
$h^{*} \sim 60$ m

- The behavior of the nucleation processes is qualitatively similar to that of laboratory ones (despite up to a factor of 10^{3} difference in model parameters)
- The length and time scales are orders of magnitude different
- The acceleration phase starts at ~1 day before the onset of dynamic rupture (as opposed to milliseconds)

Can the nucleation phase of SAFOD earthquakes be detected?

- Assume M2 repeaters rupture a square fault
- Compute strain rate changes due to slip evolution on the fault with a correction factor that approximates 3D nucleation





- Compare predicted strain changes with detection threshold of strainmeter
- Preseismic strain changes may be large enough to be detected by borehole strainmeters situated within ~100 m from the hypocenter (but not at 1 km away)

  → Testable with future deployment of strainmeters at the existing SAFOD observatory

Conclusions

- Relatively simple model incorporating rate-and-state friction (w/ the slip law) and elastic continuum can quantitatively reproduce the evolution of rupture nucleation observed in laboratory experiments.
- In both laboratory and numerical experiments *with a range of normal stresses*, the nucleation proceeds in two distinct phases: initial slow quasi-static propagation phase and faster acceleration phase.
- The nucleation process of SAFOD M2 repeaters may also consist of two distinct phases, with the nucleation size of ~60 m.
- The nucleation phase of SAFOD repeaters may be observable *in the hours before* the occurrence of seismic rupture by strainmeters located close (~100 m) to the hypocenter, in a position that can be reached by the *existing* borehole.

Kaneko et al. (JGR, 2016; GRL, 2017)

Main question: How do earthquake ruptures nucleate?

Evidence for precursory slow slip leading to the onset of an earthquake (e.g., Dodge et al. 1996; McGuire et al. 2005; Bouchon et al. 2011; Tape et al. 2013; Schurr et al. 2014)

Two possible interpretations of precursory slow slip

Scenario I (large nucleation size)

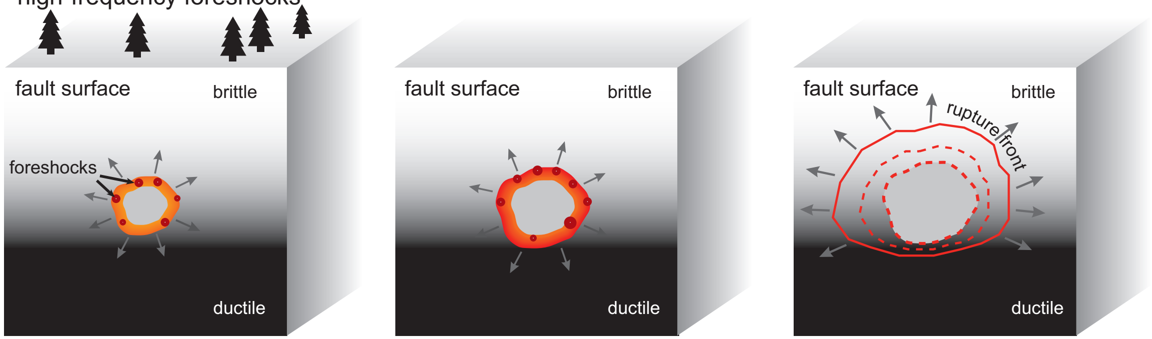
Nucleation

stage 1:
localized slow-slip pulse
emerges and triggers
high-frequency foreshocks

stage 2:
accelerating slow slip and
high-frequency foreshocks

Mainshock

stage 3:
earthquake rupture



Scenario II (small nucleation size)

Slow slip event

stage 1:
localized slow-slip pulse
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high-frequency foreshocks

stage 2:
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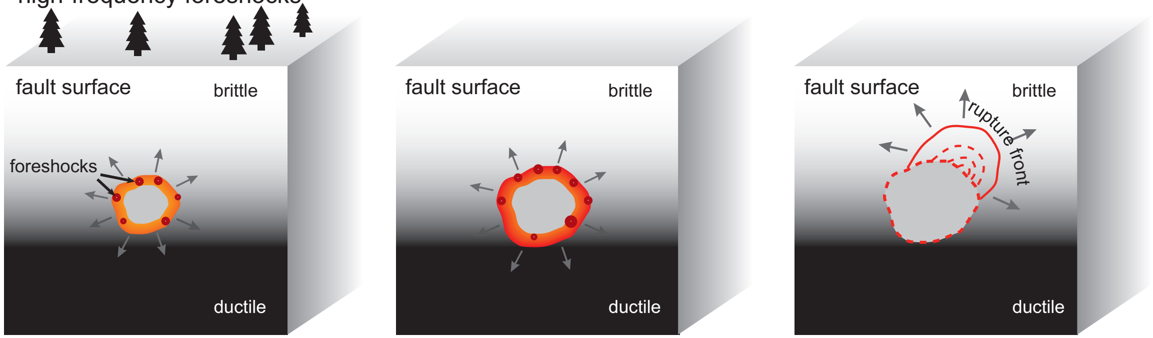
high-frequency foreshocks

Triggered mainshock

stage 3:
earthquake rupture



Earthquake rupture initiates within a nucleation zone and then rapidly accelerates

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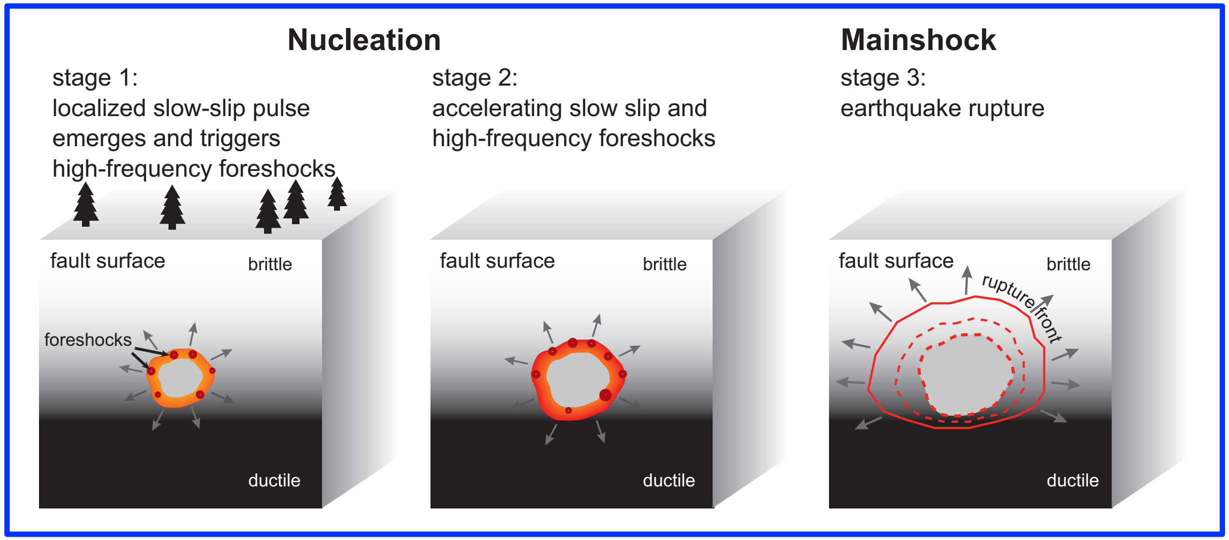

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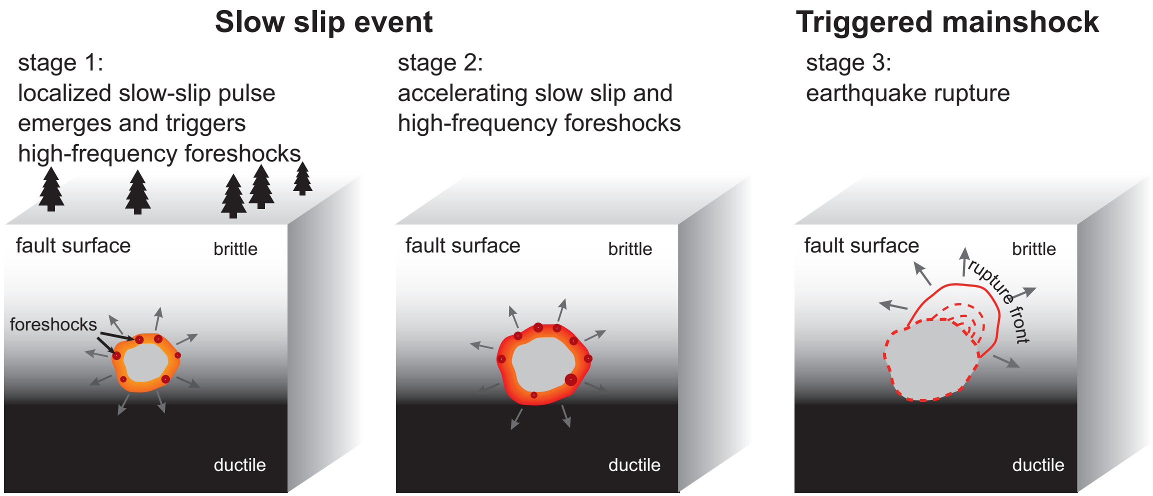

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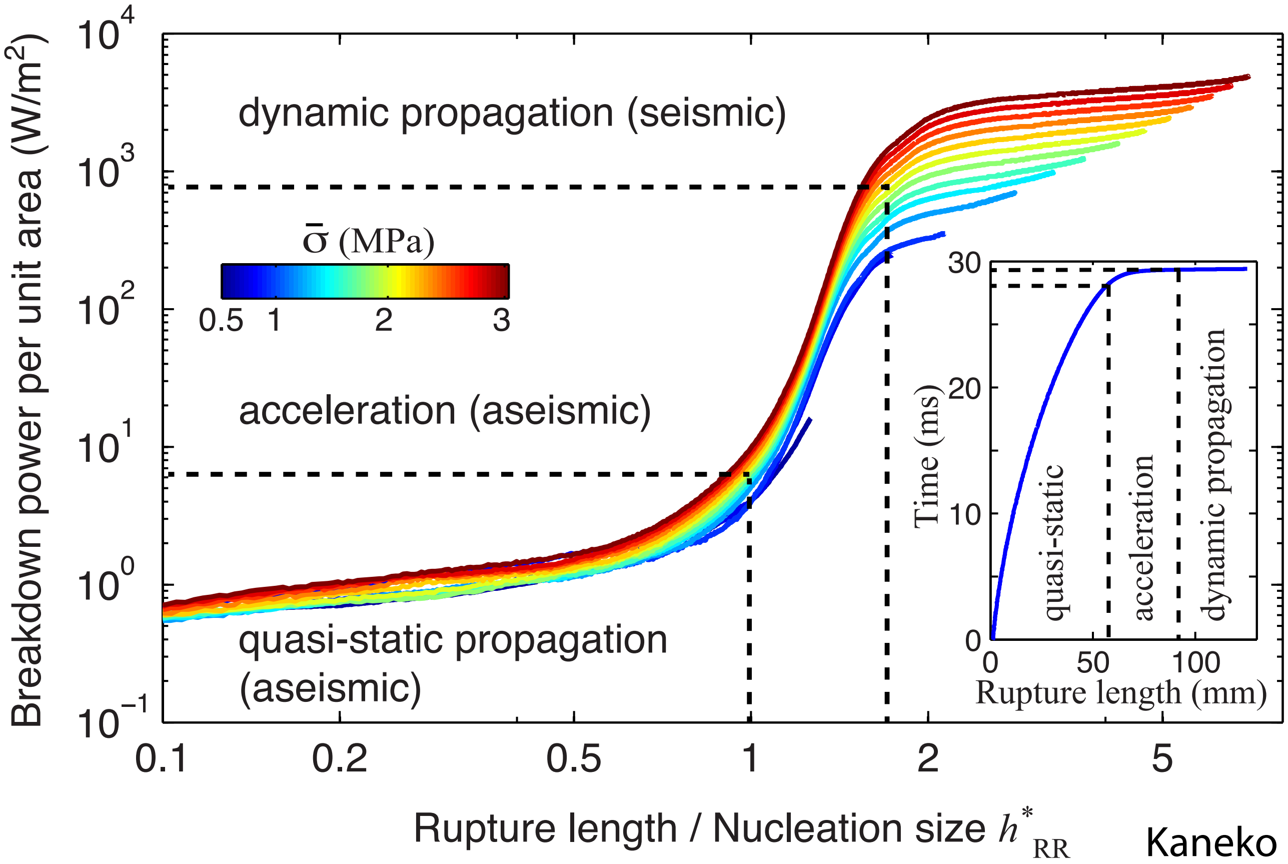
What controls the behavior of nucleating ruptures?



Kaneko et al. (JGR, 2016)

- The growth of rupture can be scaled by `breakdown power' (GV_{r}/ℓ) and h^* $\longrightarrow$ individual curves collapse in a consistent way
- Critical nucleation size and breakdown power control the scaling of nucleating ruptures