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)

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

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

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

(Latour et al., 2013)
Characteristics of precursory slow slip in lab experiments

- 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)

Key observations:

- \( V_r \approx 1 \text{ m/s} \) (Latour et al., 2013)
- \( V_r \approx 800 \text{ m/s} \) (Latour et al., 2013)
Fault model

- 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

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

\[
\sigma = 0.56 \text{ MPa} \\
\tau = 0.24 \text{ MPa/s}
\]

\[
\sigma = 0.91 \text{ MPa} \\
\tau = 0.36 \text{ MPa/s}
\]

\[
\sigma = 1.58 \text{ MPa} \\
\tau = 0.36 \text{ MPa/s}
\]
Modeled nucleation agrees well with lab observations

- 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
Modeled nucleation agrees well with lab observations

- 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

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

$\sigma$ (MPa)

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

Other findings not discussed today:

- The growth of rupture can be scaled by `breakdown power' $(G V_\tau / \ell)$ and $h^*$
- The acceleration phase occurs in equivalent quasi-static simulations, suggesting that the acceleration phase is an aseismic 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

- 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.
Predicting the nucleation process of SAFOD earthquakes

- 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).

$h^* \sim 60$ m
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 (with 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)
- Stage 1: localized slow-slip pulse emerges and triggers high-frequency foreshocks
- Stage 2: accelerating slow slip and high-frequency foreshocks
- Stage 3: earthquake rupture

Scenario II (small nucleation size)
- Slow slip event:
  - Stage 1: localized slow-slip pulse emerges and triggers high-frequency foreshocks
  - Stage 2: accelerating slow slip and high-frequency foreshocks
- Triggered mainshock:
  - Stage 3: earthquake rupture

Earthquake rupture initiates within a nucleation zone and then rapidly accelerates
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)

Scenario II (small nucleation size)

Earthquake rupture initiates within a nucleation zone and then rapidly accelerates
What controls the behavior of nucleating ruptures?

- The growth of rupture can be scaled by `breakdown power’ \( \frac{G V_r}{\ell} \) and \( h^* \) — individual curves collapse in a consistent way
- Critical nucleation size and breakdown power control the scaling of nucleating ruptures