A Heterogenous Model of Episodic Tremor and Slow-Slip Events with Spatio-temporal Variability

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In collaboration with Zhen Liu and Pablo Ampuero
New earthquake family

- Observation
- Rate-and-state
- Concept
- ETS with RTR
- ETS Variability
- Discussion

Ide et al. 2007
New earthquake family

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Ide et al. 2007
Slow to Fast Earthquakes

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Iide et al. 2007
Luo and Ampuero 2018
Episodic Tremor ands Slow-slip Events (ETS)

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Ide et al. 2007
Rogers and Dragert 2003
ETS Variability in Cascadia

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Luo and Liu
ETS Variability in Small Scale

Luo and Liu
Heterogenous Fault: Geology Study

Fagereng 2010
Heterogenous Fault: Geology Study

Increasing ratio of incompetent/competent material

Discontinuities dominant

Mixed continuous-discontinuous

Continuous deformation dominant

15 cm

10 cm

5 cm

Seismic slip at kilometer-scale possible in interacting clusters of competent bodies

< meter scale seismic slip possible

Microseismically active, flowing zone, large ruptures do not nucleate but may propagate through

High interaction through stress bridges

Moderate interaction between competent bodies

Low interaction between competent bodies

Localized peaks in shear strain rate

Fluctuating shear strain rates

Fairly uniform shear strain rates

Various ratio of competent - incompetent material

Fagereng and Sibson 2010
Heterogenous Fault: Lab Study

- Composite fault gouge of various ratio competent / incompetent material
- Slip / stress drop highly depends on the competent / incompetent ratio

Kocharyan and Novikov 2016
Differential Pore-Pressure

Pore-space reduction by solution and cementation:

Change of porosity results change in permeability and pore pressure.

Rittenhouse 1971
Differential Pore-Pressure: Large Scale

Permeability difference cause different pore pressure via sealing:

- Zero permeability: perfect seal, Aqua-thermal pressuring.
- Low but finite permeability: slow fluid leak, disequilibrium compaction, sub-parallel to Lithostatic.

Rittenhouse 1971
Differential Pore-Pressure: Small Scale

Fault valving action accompanying earthquake rupture (EQ).

Ruptures breach permeability barriers:
- Increasing local permeability
- Allowing discharge
- Decreasing fluid-pressure
- Increasing fault frictional strength

Differential pore pressure at small time scale
Differential Pore-Pressure: Small Scale

Pressure solution at seismogenic depth: more soluble elements dissolve first
=> Porosity differences between competent/incompetent materials
=> Differential pore pressure at small length scale

Fagereng and Hartog 2017
Heterogenous Fault: Gouging

- Fault zone with two rough surfaces and gouge or sediments in between.
- When pressed, surfaces make solid-solid contact at discrete asperities.
- Difference of compressibility and permeability between the asperities and gouge results in difference of effective normal stress.

Luo and Ampuero 2018
Rate-and-state Friction

Rate-and-State Friction
\[ \mu = \mu^* - a \ln \frac{V^*}{V} + b \ln \frac{V^* \theta}{D_c} \]

Evolution Law
\[ \dot{\theta} = -\frac{V \theta}{D_c} \ln \frac{V \theta}{D_c} \]

Stress Balance
\[ \tau(x, t) = \tau^\infty(x, t) + \frac{g}{2} H(\delta) - \frac{g}{2c_s} V \]
Rate-and-state Friction

\[ \mu = \mu^* - a \ln \frac{V^*}{V} + b \ln \frac{V^* \theta}{D_c} \]

- \( D_c \) characteristic slip distance
- \( a \) direct effect
- \( b \) evolitional effect
Asperity-in-Matrix Subduction Zone

Luo and Ampuero 2018
Asperity-in-Matrix Subduction Zone

SEVEN independent non-dimensional numbers
- VW/VS area ratio
- Relative Strength: ratio of \(|b-a|/\sigma\) of VW/VS patch
- Individual criticalness of VW patch \((L_w/L_{cw})\)
- ...

Luo and Liu

Luo and Ampuero 2018
Asperity-in-Matrix Subduction Zone

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- **Time:** Days
- **Stable**
- **VW Individual Criticalness**
- **T-instability**
- **P-instability**
- **Total-instability**
- **Partial-instability**

Luo and Ampuero 2018
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Stable T-instability
P-instability
Slow EQs with seismic slip
Tremor and SSE??
Slow EQs without seismic slip
Small EQs

Regular / Mega EQs

VW Individual Criticalness

Luo and Ampuero 2018
**Observation**

- Rate and state

**Concept**

- ETS with RTR
- ETS Variability

**Discussion**

*Houston et al, 2011*
Asperity-in-Matrix ETS with RTR

- Well-organized tremor activity propagating at steady speed
- Hierarchical tremor migration
- Large portion of SSE (aseismic)
- Wide range of parametric space
Asperity-in-Matrix ETS with RTR

A

B

log10 ($V / V_{pl}$)

- $a_{fr}$ (KPa)
- $b_{fr}$ (KPa)
- $Dc$ ($\mu$m)

10$^1$ 10$^2$ 10$^3$

$X$ (km)

0 1 2 3 4 5 6 7

Time (year)

0 50 100

Tremor count

10$^1$ 10$^2$ 10$^3$

1 2 3 4 5 6 7

$X$ (km)

0 10 20 30 40

Tremor count

10$^1$ 10$^2$ 10$^3$

4.43 4.44 4.44 4.46 4.48

Time (year)

0 50 100

Tremor count

RTR

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ETS Variability: Observed

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Luo and Liu
ETS Variability: Observed

Tremor activity strongly correlated with tidal phase (stress)

Rubinstein et al. 2008
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ETS Variability: Modeled

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Luo and Liu
Asperity-in-matrix model incorporates heterogenous frictional properties and stress conditions, representing physically realistic subduction zone

A common mechanism of stress (pore-pressure) variations in a local region with multiple tremor asperities, the model is able to reproduce the broad spectrum of observed ETS variabilities: RTRs, ETS gap and halt

A potential way to probe fault zone properties and stressing conditions that are otherwise difficult to estimate