Slow and Fast Slip Dynamics due to Fault and Fracture Networks

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Complex fault and crack networks at all scales

Fletcher et al. 2014
Sowers et al. 1994
Mitchell & Faulkner 2009
Hurst exponent with the azimuthal direction of profile extraction (q), as pointed by Renard et al. [2006] and Candela et al. [2009] using different statistical tools. When departing a few degrees from the direction of the smallest exponent, i.e., the slip direction, the Hurst exponent sampled is already very close to the largest exponent, i.e., the direction normal to slip. In contrast, the pre-factor linearly evolves with q.

In Figure 14b, we estimate the Hurst exponents and the pre-factors of composite synthetic profiles formed by the association of two profiles with a roughness root-mean square standard deviation that scales respectively as \( \text{RMS} = 0.005 \ L^{0.6} \) and \( \text{RMS} = 0.015 \ L^{0.8} \). In this way, the effect of sampling a combination of slip-parallel and slip-perpendicular topography along the rupture trace is reproduced, as it could be the case due to the landscape topography and/or some local vertical slip. As observed previously, the Hurst exponent and the pre-factor increase respectively nonlinearly and linearly with the increase of the percentage of the composite profile scaling as \( \text{RMS} = 0.015 \ L^{0.8} \).

Figure 13. Comparison of the roughness of the earthquakes surface ruptures with that of the exhumed fault surfaces. The global spectra of the exhumed fault surfaces for the (top) along and (bottom) normal slip direction are plotted on a log-log graph together with those obtained for the thirteen continental earthquake surface rupture traces. The exhumed fault data are identical to those plotted on Figure 9, and those of the surface ruptures correspond to that of Figure 12. Power law fits with a Hurst exponent of 0.8 and 0.6 are shown (gray lines). For the sake of comparison with previous studies, power law fits for three self-similar rough surfaces (i.e., \( H = 1 \)) with various pre-factors (RMS = 0.1 L, RMS = 0.01 L, and RMS = 0.001 L), are displayed (dashed dark lines).

2.2. Scanner Devices and Digital Elevation Models

Fault surface topography was scanned in the field using five different types of 3-D portable LiDAR laser scanners (see Table 1b) that use the time of flight of a light beam to accurately measure distances. The laser scanner records the topography of each exposed fault surface by collecting a cloud of points whose three dimensional coordinates correspond to points on the fault surface [Renard et al., 2006; Sagy et al., 2007; Candela et al., 2009; Resor and Mee, 2009; Wei et al., 2010]. The actual point spacing...
What mechanical models exist that explain these range of slip dynamics?
Two Broad Themes

- How do complex fault networks interact over long time scales (multiple seismic cycles)?
- How do complex fault and off-fault fracture networks interact during an earthquake rupture (using homogenisation and explicit modelling of off-fault fracture networks)?

Missing ingredients (in this talk):
- Mechanical/Rheological Complexity
- Chemical & Mineralogical Complexity
- Thermal Constraints
- Hydrological Structure
- Far-field loading complexity


**Broad ingredients in seismic cycle models**

![Diagram showing friction laws, loading, and brittle/plastic medium.](image)

- **Friction laws**
  - Resistance to movement

- **Brittle/Plastic Medium**
  - Strain rate: $10^{-15}/s$ (between earthquakes)
  - Strain rate: $10^3/s$ (during earthquakes)

- **Loading**

Mathematical expression:

$$\tau^f(s) = \tau^el_t(s) + \tau^{load}(s) + \tau^{rad}(s)$$
**Rate and state friction law**

Experiment

- **V₁ > V₂**

From Dieterich and Kilgore 1994

*Dieterich, 1979*  
*Ruina, 1983*

- **Granite**  
  #60 surface  
  15 MPa normal stress

- **Granite**  
  #60 surface, 1mm gouge  
  10 MPa normal stress

- **Soda-lime glass**  
  #60 surface  
  5 MPa normal stress

- **Lucite plastic**  
  #60 surface  
  2.5 MPa normal stress
Rate and state friction law

\[ f = \frac{\tau}{\sigma - p} = \frac{\tau}{\sigma} \]

\[ V = \text{slip rate} \]

\[ a = \left[ \frac{\partial f}{\partial \ln(V)} \right] \text{instantaneous} > 0 \text{ always} \]

\[ a - b = \left[ \frac{df}{d \ln(V)} \right] \text{steady-state} \] can be < 0 (potentially unstable), or > 0 (stable).

Unstable slip patch size \( \approx 4h^* \);

\[ h^* = 2\mu L / [\pi (1 - \nu)(b - a)_{\text{max}} \sigma] \]

\[ 4h^* \approx 1.0 \text{ km} \times L^{40} \mu m \times 1.0 \text{ MPa} \sigma_{273 \degree C} \]

\( \delta/L \) (slip/L)

\[ a/b > 1 : \text{ rate strengthening} ; \] \( 0 < a/b < 1 : \text{ rate weakening} \)

\[ \text{Dieterich, 1979} \]

\[ \text{Ruina, 1983} \]

\[ \text{Theory:} \]

\[ a = kBT / \sigma \Omega \]

\[ \text{Dieterich, 1979} \]

\[ \text{Ruina, 1983} \]

\[ \text{Rate and state friction law} \]

\[ \text{Allows for restrengthening of the fault} \]
Seismic (m/s & km/s) and Aseismic (μm/s & km/day) transients with R&S friction on planar faults

- Spatially heterogeneous a/b
- Newtonian viscous rheology + asperities
- Periodic normal stress perturbations → “Aseismic” Stick Slip
- Static stress perturbations from neighbouring faults
- ‘Tuning’ fault length: Failed nucleation
- Trade-off between dilatant strengthening/thermal pressurisation

Perfettini et al. [2001], Liu and Rice [2005], Liu and Rice [2007], Rubin [2008], Segall and Rice [1995], Segall et al. [2010], Segall and Bradley [2012], Ando et al. [2012] and many others.
Can geometry control the observed complexity of the seismic cycle?

**However...**

Real world
- Complex fault network
- Non-planar geometry of faults
- Interaction between faults
- Diversity of observed signals

Dominant modelling philosophy
- Single planar fault
- Linear elastic rheology
- Complexities coming from rheological variations

Can geometry control the observed complexity of the seismic cycle?
(Fast) Seismic cycle models

Rate and state friction
Ageing state evolution

Friction laws
Elastic Medium

Loading

Quasi-dynamic:
boundary element
method with
radiation damping
Convolution accelerated
Using H-Matrices
Romanet [2017]

Global constant
stress rate

\[
\tau_f = \sigma_n \left( f_0 + a \log \left( \frac{V}{V_0} \right) + b \log \left( \frac{V_0 \theta}{D_c} \right) \right) \quad \dot{\theta} = 1 - \frac{\theta V}{D_c}
\]

\[
\tau_f(s) = \tau_{el}^f(s) + \tau_{load}^f(s) + \tau_{rad}^f(s)
\]
Single rate weakening fault

\[ \frac{L}{L_{\text{nuc}}} = 2 \]

Dynamic instability when

\[ L > L_{\text{nuc}}(a/b) \]

\[
L_{\text{nuc}} = 2 \times 1.3774 \frac{\mu D_c}{\sigma_n b} \quad ; \quad 0 < a/b < 0.3781
\]

\[
L_{\text{nuc}} = 2 \times 1.3774 \frac{\mu D_c}{\pi \sigma_n b(1 - a/b)^2} \quad ; \quad a/b \to 1
\]

Rubin and Ampuero [2005] and Viesca [2016 a, b]

1- Periodic events
2- Only dynamic events
Simplest “Conceptual” Model of Fault Geometric Complexity

- Non-Dimensionalise length scales by $L_{nuc}(a/b)$
- Keep loading rate constant
- Keep $a/b$ constant and rate-weakening ($0 < a/b < 1$)
- Anti-plane sense of motion $\Rightarrow$ No normal traction change

Do spontaneously emerging “stress” heterogeneities produce slow and fast dynamics?
Geometry induced fault dynamics

Fault 1

Fault 2

L = 2L_{nuc}  

W = 0.1L_{nuc}  

L_{nuc}
Geometry induced fault dynamics

Fault 1

Fault 2

$L = 2L_{\text{nuc}}$  

$D = 0.1L_{\text{nuc}}$  

$F_{\text{ault}}$ 1  

$F_{\text{ault}}$ 2
Geometry induced fault dynamics

Fault 1

Fault 2

\[ L = 2L_{\text{nuc}} \]

\[ W = L_{\text{nuc}} \]

\[ D = 0.1L_{\text{nuc}} \]
‘Phase Diagram’ (for fixed overlap distance)

Scaled distance between the faults, $D/L_{nuc}$

- **Damped Domain**
- **SSE & EQ**
- **Complex EQ**
- **Periodic EQ**
- **Slip Bursts**

```
0.1 0.5 1.0
```

```
0.1 0.5 1.0
```

```
0.1 0.5 1.0
```

```
W/L = 0.5  D/L_{nuc}
```

```
L/L_{nuc}
```

```
L/L_{nuc}
```

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L/L_{nuc}
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L/L_{nuc}
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L/L_{nuc}
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L/L_{nuc}
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L/L_{nuc}
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L/L_{nuc}
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L/L_{nuc}
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L/L_{nuc}
```

```
L/L_{nuc}
```
Can we reproduce the observed scaling laws?

\[ M_0 \propto T \]
**Slow events**

\[ M_0 \propto T^3 \]
**Classic 3D earthquakes**

\[ M_0 \propto T^2 \]
**Classic 2D earthquakes**

- Slow events
  - Rupture Velocity < 0.01 \( V_s \) &
  - 1 \( \mu \)m/s < Slip Velocity < 1 mm/s

- Earthquakes
  - Rupture Velocity > 0.01 \( V_s \) &
  - Slip Velocity > 1 mm/s

Observations

- Moment, \( M \), (N-m)
- Duration, \( T \), (s)

- Cascadia
- Mexico
- Eastern Shikoku
- North Eastern Kii
- Tokai
- Western Shikoku
- Denolle & Shearer (2016)

-Ide et al., 2007
-Sekine et al., 2010
-Gomberg et al., 2016
-Gao et al., 2012
-Denolle and Shearer, 2016
Can we reproduce the observed scaling laws?

Observations

Moment, \( M \), (N-m)
Duration, \( T \), (s)

<table>
<thead>
<tr>
<th>Location</th>
<th>Moment, ( M )</th>
<th>Duration, ( T )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cascadia</td>
<td>10^{16}</td>
<td>10^{12}</td>
</tr>
<tr>
<td>Mexico</td>
<td>10^{17}</td>
<td>10^{13}</td>
</tr>
<tr>
<td>Eastern Shikoku</td>
<td>10^{18}</td>
<td>10^{14}</td>
</tr>
<tr>
<td>North Eastern Kii</td>
<td>10^{19}</td>
<td>10^{15}</td>
</tr>
<tr>
<td>Tokai</td>
<td>10^{20}</td>
<td>10^{16}</td>
</tr>
<tr>
<td>Western Shikoku</td>
<td>10^{21}</td>
<td>10^{17}</td>
</tr>
<tr>
<td>Denolle &amp; Shearer (2016)</td>
<td>10^{22}</td>
<td>10^{18}</td>
</tr>
</tbody>
</table>

Physics based multi-scale model of a fault network

\( M \propto T \)
\( M \propto T^3 \)

\( L/L_{nuc} \)
\( D/L_{nuc} \)
Conclusion

Most basic geometrical fault complexity can give rise to both slow and fast dynamics on purely rate weakening faults.

Scaling laws arise from simple fault networks in rate and state framework.
A real world application

<table>
<thead>
<tr>
<th>Date</th>
<th>M</th>
<th>Event</th>
<th># Faults</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>7.2</td>
<td>El Mayor-Cucapah</td>
<td>≥6</td>
</tr>
<tr>
<td>1999</td>
<td>7.1</td>
<td>Hector Mine</td>
<td>≥4</td>
</tr>
<tr>
<td>1992</td>
<td>7.3</td>
<td>Landers</td>
<td>≥5</td>
</tr>
<tr>
<td>1987</td>
<td>6.6</td>
<td>Superstition Hills</td>
<td>≥2</td>
</tr>
<tr>
<td>1987</td>
<td>6.2</td>
<td>Elmore Ranch</td>
<td>≥6</td>
</tr>
<tr>
<td>1979</td>
<td>6.4</td>
<td>Imperial Valley</td>
<td>≥3</td>
</tr>
<tr>
<td>1971</td>
<td>6.6</td>
<td>San Fernando</td>
<td>≥2</td>
</tr>
<tr>
<td>1968</td>
<td>6.5</td>
<td>Borrego Mtn.</td>
<td>≥2</td>
</tr>
<tr>
<td>1956</td>
<td>6.8</td>
<td>San Miguel</td>
<td>≥2</td>
</tr>
<tr>
<td>1940</td>
<td>6.9</td>
<td>Imperial Valley</td>
<td>≥2</td>
</tr>
<tr>
<td>1934</td>
<td>~7.1</td>
<td>Cerro Prieto</td>
<td>≥1</td>
</tr>
<tr>
<td>1892</td>
<td>~7.2</td>
<td>Laguna Salada</td>
<td>≥3</td>
</tr>
<tr>
<td>1857</td>
<td>~7.9</td>
<td>Fort Tejon</td>
<td>≥1</td>
</tr>
</tbody>
</table>
Aseismic Event #06

$\delta_{\text{max}} \sim 10.7 \text{ cm}$
$L_{\text{rup}} \sim 2.2 \text{ km}$
$M_w \sim 5.0$
$T \sim 02d \ 00h \ 00m \ 02s$

Previous Event: 61Y 07M 27d 05h 00m

Aseismic Event #07

$\delta_{\text{max}} \sim 15.6 \text{ cm}$
$L_{\text{rup}} \sim 3.6 \text{ km}$
$M_w \sim 5.2$
$T \sim 01d \ 16h \ 47m \ 24s$

Previous Event: 01Y 11M 28d 21h 26m
Seismic Event #05

\[ \delta_{\text{max}} \sim 82.4 \, \text{cm} \]
\[ L_{\text{rup}} \sim 7.1 \, \text{km} \]
\[ M_w \sim 6.1 \]
\[ T \sim 65.67 \, \text{s} \]

Source Time Function

Previous Event: 28Y 00M 17d 06h 22m

Seismic Event #06

\[ \delta_{\text{max}} \sim 97.1 \, \text{cm} \]
\[ L_{\text{rup}} \sim 7.6 \, \text{km} \]
\[ M_w \sim 6.1 \]
\[ T \sim 115.02 \, \text{s} \]

Source Time Function

Previous Event: 00Y 01M 09d 06h 46m
Complex off-fault crack networks


Complex fault network in kilometric scale to smaller scale off-fault crack network
Coseismic off-fault damage and radiation

Theoretical analysis

Observations

Experiments

Shaded region shows the area of potential shear cracks.

Enhanced High-frequency radiation in near field ground motion

Enhanced High-frequency radiation observed from laboratory experiments

Rice et al. (2005)

Dunham et al. (2011)

Passelegue et al. (2016); Marty, M2 thesis (2016)
Co-seismic dynamic damage generation

Dynamic earthquake rupture modelling with dynamic coseismic off-fault damage

- We use the Combined Finite-Discrete Element Method (FDEM) package, Hybrid Optimisation Software Suite (HOSS), developed by Los Alamos National Laboratory
Analysis of Acceleration amplitude spectrum in near-field ground motion

- Relatively high-frequency content (10 ~ Hz) is observed in near-field ground motion.
- Focus on the Maximum cut-off frequency in acceleration amplitude spectrum.

![Graph showing acceleration amplitude spectrum](image)

Lucerne Valley 1992 Landers earthquake

Dunham et al. (2011)
Damage evolution in depth

- Q. How does the damage zone width evolve in depth?
- Measure the damage zone width at every 1 km depth with Constant $D_c$ and Constant $G_{IIC}$ cases

"Flower-like structure"

The damage zone width decreases with depth.
Non dimensionalised damage zone width in depth

- Scaling the damage zone width $W$ by estimated process zone size $R_0$, $W/R_0$

- Damage zone width $W$ decreases in depth with both constant $D_c$ and constant $G_{IIc}$ cases.

- Non dimensionalised width, $W/R_0$, is independent of depth.

- Damage zone width decreases in depth with both constant $D_c$ and constant $G_{IIc}$ cases.
2016 Mw 7.8 Kaikoura Earthquake, NZ
Fault-parallel displacement (m)
Distance from rupture along profile (m)

Displacement profile J2 - localized slip

Displacement profile P2 - asymmetric and distributed deformation

Displacement profile P3 - slip quite localized
Dynamic earthquake rupture modelling with Off-fault damage
Jordan-Kekerengu-Papatea fault system, NZ

Tensile strength $C_1 = 8$ MPa
Shear Strength $C_{ij} = 48$ MPa

Time: 0.00 (s)
Combination of high-resolution deformation field and dynamic rupture modelling including off-fault damage

=> unambiguous evidence for rupture along Papatea F. triggering bilateral rupture along Jordan Thrust - Kekerengu Fault
Conclusion

- Secondary crack network can be generated by dynamic earthquake rupture. 2D distribution of frequency contents shows that the high frequency (10-100Hz) radiation is enhanced by the secondary crack network.

- Macroscopic shear wave velocity in the damage zone decreases by ~20%.

- Our case study shows the damage evolution in depth with more intricate crack networks in deeper cases.

- It shows that the width of damaged zone decreases in depth, forming "flower-like" structure as the characteristic slip distance in linear slip-weakening law or the fracture energy on the fault is kept constant with depth.

- This method has been applied to the complex fault system with the same framework.