Seismic vs. aseismic deformation in fault rocks and rock deformation experiments

Cristiano Collettini

European Research Council
SEVENTH FRAMEWORK PROGRAMME
"Ideas" Starting Grant
GLASS: 259256
Our understanding of the mechanics of earthquakes and faulting
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**Remote techniques**

Fault rocks? |
Deformation mech? |
Evolution with time?

**Experimentalists**
Our understanding of the mechanics of earthquakes and faulting

**Seismologists/Geophysicists**

- Seismological and geodetic data
- Fast (s) and slow (d-y) deformation
- “Normal” Earthquakes
- Afterslip
- VLF events
- Slow earthquakes
- Creep
- Remote techniques
- Fault rocks ?
- Deformation mech?
- Evolution with time?

**Geologists**

- Study of ancient and exhumed faults
- Long-term deformation (up to Ma)
- Textural evolution
- Mineralogical evolution
- Fluid involvement
- No seismic signals
- Normal earthquakes ?
- Afterslip ?
- Creep ?
- LFE ?

**Experimentalists**

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### Experimentalists

**Test physical properties of fault rocks**

**Reproduce the physics of faulting**

- Friction, velocity dependence of friction, fluid flow, microEQs
- Scaling problem between experimental (mm-cm) faults and natural (km) faults
### Our understanding of the mechanics of earthquakes and faulting

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**Remote techniques**
- Fault rocks?
- Deformation mech?
- Evolution with time?

**Experimentalists**
- Test physical properties of fault rocks
- Reproduce the physics of faulting

- Friction, velocity dependence of friction, fluid flow, microEQs

**Scaling problem between experimental (mm-cm) faults and natural (km) faults**
The spectrum of fault slip-behavior documented during this week is the result of different slip processes occurring along faults. These processes produce fault rocks.

Saffer et al., 2009
Introduction

Natural fault rocks and microstructures
Lab. experiments for slip behavior and microstructures

1) Fault structure, frictional properties and mixed-mode fault slip behavior of LANF

2) Heterogeneous strength and fault zone complexity of carbonate-bearing thrusts

3) Fault structure and slip localization in carbonate-bearing normal faults

Future directions

Experiments on the role of fluid pressure in fault stability
Heterogeneous faults in the lab
Fault zone structure

**Fault core:**
Is the structural, lithologic, morphologic portion of the fault zone where most of the displacement is accumulated

**Damage zone:**
Is the network of subsidiary structures that bound the fault core

Chester et al., JGR, 93;
Median Tectonic Line, Japan

(Wibberley & Shimamoto JSG 03)
Median Tectonic Line, Japan

(Wibberley & Shimamoto JSG 03)
Carboneras fault, Spain

Location Map

- Study area
- Alicante
- Almería
- Mediterranean Sea

Fractured lens of dolomite

Phyllosilicate-rich fault gouge bands
Carboneras fault, Spain

Faulkner & Rutter 01, Geology
Faulkner et al., 03, Tectonophysics
Along the fault zones, fault rocks are the result of different deformation processes.
## Fault rocks and Fault Mechanisms

**R.H. Sibson**

*Geol. Soc. Lond. vol 133, 1977, p.191-213 1480 citations*

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Fault gouge formed at 3 km of depth along the Bosman fault (South Africa) during a M=3.7 earthquake in 1997.
Cataclasite formed by grain size reduction, grain rotation and translation + cementation.
Pseudotachylyte: solidified frictional melt (amorphous material, no crystalline structure) formed by temperature rise during fast slip.
Mylonites: foliated rocks produced by “plastic” processes

Berthé et al., 1979, JSG
Lister and Snoke, 1984, JGG
R. H. Sibson

2: Fault rocks and style of faulting in the Outer Hebrides Thrust zone

Style of Faulting

Brittle shearing of intact rock
Sliding on existing planes
Cataclastic crush zones
Crush Melange

Fault Rocks

Pseudotachylyte
Cataclasite-Ultracataclasite (& some pseudotachylyte)
Crush breccias, microbrec & protocataclasite
Phyllonitic mylonites & ultramylonites
Protomylonites

Stress

Depth

1977

Gradiante geotermico
30°C/km

10-15 km

V
Fault rocks and Fault Mechanisms  
R.H. Sibson  
Geol. Soc. Lond. vol 133, 1977, p.191-213 1480 citations

From 1977 we have improved our understanding of fault rocks and deformation mechanisms

Methods

Laboratory analyses: MO, SEM, TEM, XRD.
Letter Section

Foliated Cataclasites

F.M. CHESTER, M. FRIEDMAN and J.M. LOGAN

Center for Tectonophysics and Departments of Geology and Geophysics, Texas A&M University, College Station, TX 77843 (U.S.A.)

(Received September 28, 1984)

ABSTRACT


Contrary to recently proposed classifications of fault-related rocks (esp. Wise et al., 1984), cataclasis associated with brittle faulting can produce well-foliated fault gouge. Naturally foliated gouge associated with the Punchbowl fault, Los Angeles Co., California is reproduced in experiments in which only brittle conditions and cataclastic deformation mechanisms prevailed. Moreover, only a brittle regime of physical conditions is inferred for the Punchbowl faulting. Classifications of fault-related rocks must accommodate foliated cataclasites.
Letter Section

Foliated Cataclasites

F. M. CHESTER, M. FRIEDMAN and J. M. LOGAN

Center for Tectonophysics and Departments of Geology and Texas A&M University, College Station, TX 77843 (U.S.A.)

(Received September 28, 1984)
Olivine deformed at 1200°C
Strong lattice preferred orientation with deformation
Experimental investigation into the microstructural and mechanical evolution of phyllosilicate-bearing fault rock under conditions favouring pressure solution

B. Bos*, C.J. Spiers

HPT Laboratory, Institute of Earth Sciences, Utrecht University, PO Box 80021, 3508 TA Utrecht, the Netherlands

Received 1 June 2000; accepted 21 November 2000

Abstract

Mature crustal fault zones are known to be zones of persistent weakness. This weakness is believed to result from microstructural modifications during deformation, such as grain-size reduction and foliation development. Around the brittle–ductile transition, phyllosilicates are expected to have a significant effect on fault strength, in particular under conditions favouring pressure solution. To study such effects, we performed rotary shear experiments on brine-saturated halite/kaolinite mixtures, aimed at investigating the relation between microstructural and mechanical evolution in a system where pressure solution and cataclasis dominate. The results show significant strain weakening, and a transition with progressive strain towards more rate-sensitive and less normal stress-sensitive behaviour. This was accompanied by a microstructural evolution from a purely cataclastic microstructure to a mylonitic microstructure consisting of elongate, asymmetric clasts in a fine-grained, foliated matrix. The results demonstrate that strain weakening and the development of a typical ‘mylonitic’ microstructure can occur as a consequence of grain-size reduction by cataclasis, and a transition to pressure solution accommodated deformation, even in the absence of dislocation creep. The data raise questions regarding the reliability of microstructures as rheology indicators, as well as on the use of low strain, monomineralic flow laws for modelling crustal dynamics. © 2001 Elsevier Science Ltd. All rights reserved.
Experimental investigation into the microstructural and mechanical evolution of phyllosilicate-bearing fault rock under conditions favouring pressure solution

B. Bos*, C.J. Spiers
Foliated Fault rocks formed by:

- **Cataclasis**
- **Intracrys. plasticity**
- **Pressure soltion**
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Future directions

Experiments on the role of fluid pressure in fault stability
Heterogeneous faults in the lab
Frictional properties

Triaxial
- downstream pore pressure
- upstream pore pressure
- top seal
- spacer
- sample
- confining pressure $\sigma_2 = \sigma_3$
- jacket
- applied $\sigma_1$

Biaxial
- Load cell
- Gouge layer

Rotary-shear
- Thin section orientation
- Axial Load (air actuator)
- Simulated Fault
- Stationary Side
- Rotational Side
- 20 mm
Frictional properties

\[ \text{Friction, } \mu = \frac{\tau}{\sigma_n} \]

\( \sigma_n = 75 \text{ MPa} \)

\( 100 \text{ MPa} \)

\( 150 \text{ MPa} \)
EQ nucleation phase

Velocity dependence of friction

The velocity dependence of sliding friction is given by \((a-b) = \Delta u/\Delta \ln V\)

- **a**: Direct effect always of the same sign of the velocity change.
- **b**: Evolution effect, the coefficient of friction decay to a steady state for the new sliding velocity.
EQ nucleation phase

Velocity dependence of friction
**EQ nucleation phase**

Velocity weakening behavior seems to occur along sharp slip surfaces promoted by grain-size reduction and localization.
EQ nucleation phase

Distributed deformation within cataclasites & phyllosilicate-rich fault rocks seem to favor velocity strengthening behavior.

\[ \text{Friction} \]

\[ a \ln(V/V_0) \]

\[ b \ln(V/V_0) \]

\[ V_0 = 30 \mu m/s \]
\[ V = 100 \mu m/s \]
\[ a = 0.007715 \]
\[ b = 0.001776 \]
\[ d_c = 33.61 \]
\[ a - b = 0.005939 \]
Dynamic weakening in High-Velocity Friction Experiments, HVFE
In granites and in the absence of water it has been shown that friction-induced melts can lubricate faults

Di Toro et al., Science 2006
In calcite-rich fault rocks thermal decomposition produces nanoparticles of calcite and lime that cause ultralow friction.

Han et al., Science 2007
In calcite-rich fault rocks the on-set of dynamic weakening seems to be associated with the development of plastic deformations.

HVFE halted at different displacement:
- green: at peak stress before weakening
- blue: soon after dynamic weakening

De Paola et al., in prep.

Dislocations and dislocation walls (DW) separate subgrains

Stacked & striated slip surfaces composed of compact polygonal nanostructures suggesting SP deformation
From HVFE (and also from some natural faults) it seems that plastic deformation plays a key-role in the dynamic weakening of some faults. Plastic deformation is present also within the elastico-frictional regime (random fabric).
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The LANF mechanical paradox

Frictional Fault Mechanics under Byerlee’s friction predicts no-slip on normal faults dipping less than 30°.
The LANF mechanical paradox

Frictional Fault Mechanics prediction is consistent with the absence of moderate-to-large earthquakes occurring on normal faults dipping less then 30° worldwide.

No M > 5.5 on LANF on positively discriminated rupture planes worldwide

Collettini & Sibson, Geology, 2001
However geological records show that LANF seem to be important structures for accommodating crustal extension.

Death valley detachment (Hayman et al., Geology, 2003)
However geological records show that LANF seem to be important structures for accommodating crustal extension.

A: Gulf of Corinth

B: Mykonos detachment

Detachment in the Gulf of Corinth and Cyclades (Sorel, Geology 2000; Jolivet et al., EPSL, 2010).
The CROP03 deep seismic reflection profile showed that significant extension in the Northern Apennines occurs on LANFs.
CROP03 Seismic Profiles + commercial seismic profiles

Barchi et al., 1998, MSGI;
Boncio et al., 2000, Tectonics;
Collettini and Barchi 2002, Tectonophysics;

displacement 6-8 km
slip-rate 1-2 mm/a
In 2000-2001, during 8 months, more than 2,000 earthquakes with ML<3.2 have been recorded by a dense temporary seismic network.

F1 & F2 hangingwall normal faults that sole into the detachment

Chiaraluce et al. JGR 2007
Map view of the 621 events located at <500 m from the detachment

A) A constant seismicity rate 3.5 event/d, $M_L < 2.3$, that cannot explain 1-2 mm/yr

B) Composite focal mechanisms with a gently E-dipping plane

C) Multiple events with highly correlated waveforms

Chiaraluce et al. JGR 2007
From 2010
TABOO infrastructure

50 permanent seismic stations covering an area of $120 \times 120$ km$^2$

24 continuous geodetic GPS stations

3 down-hole seismometers (GLASS ERC)

In 36 months TABOO recorded 19,422 events with $ML \leq 3.8$
Seismic images of an Active LANF.

Ancient exhumed faults to study fault zone structure and collect fault rocks for laboratory studies & rock deformation exp.
The Zuccale Fault:
- Displacement: 6-8 km
- Fault exhumation: 3-6 km

Smith et al., JSG, 2008.
Collettini et al., Geology 2009.
Low-strain domains
Low-strain domains

Calcite concentration along major fractures and syn-tectonic precipitation of calcite and talc along veins
Low-strain domains

Silica-rich fluid circulation
High-strain domains: interconnected talc rich network
High-strain domains: interconnected talc rich network

Fluid assisted dissolution and precipitation processes

\[
\text{DOLOMITE} + \text{SILICA} + \text{H}_2\text{O} = \text{TALC} + \text{CALCITE} + \text{CO}_2
\]

\[
3 \text{MgCa(CO}_3\text{)}_2 + 4 \text{SiO}_2 + \text{H}_2\text{O} = \text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2 + 3 \text{CaCO}_3 + 3 \text{CO}_2
\]
High-strain domains: interconnected talc rich network

Talc lamellae are oriented parallel to the foliation and are affected by rotation of the (001) talc layers.
Interlayer delaminations widespread resulting in talc grain-size reduction, down to 30 nm, and providing an infinite number of possible slipping planes.

Collettini et al., Geology, 2009
Viti & Collettini, CMP, 2009
Influx of silica-rich fluids
Dissolution of dolomite (Dol) and precipitation of calcite (Cal)
Interconnected talc-rich foliation affected by frictional slip
Low strain
Brittle dilatancy & increase of permeability
Influx of silica-rich fluids
Dissolution of dolomite (Dol) and precipitation of calcite (Cal)
High strain
Interconnected talc-rich foliation affected by frictional slip
Which are the frictional properties of these fault rocks?

Talc grain-size reduction, down to 30 nm providing an infinite number of possible slipping planes.
2008 ICDP workshop to drill across the active LANF in the Apennines
Let’s rock on!

Do not worry Cristiano, we will survive!

Are we doing the right thing going in the field with kids?

NSF: discoveries
Faults Family and Friction by Marone & Collettini, 2010
http://www.nsf.gov/discoveries/
Let’s rock on!

**NSF**: discoveries
Faults Family and Friction by Marone & Collettini, 2010
http://www.nsf.gov/discoveries/
Let’s rock on!

Dad! Is this foliated fault rock OK for the experiments?

NSF: discoveries
Faults Family and Friction by Marone & Collettini, 2010
http://www.nsf.gov/discoveries/
6 years later
Differential thermal analysis coupled with mass spectrometer; XRPD on bulk starting sample; XRPD on the fine fraction (< 2 µm).

Collettini, Niemeijer, Viti, Marone, Nature 2009
Double direct biaxial loading apparatus at Penn State University
Each rock-type plots along a line consistent with a brittle failure envelope, **BUT** the foliated solid wafers are much weaker than their powdered analogues.

Powders show a friction close to Byerlee’s values whereas the foliated rocks posses values significantly lower, 0.45-0.23, and for each normal stress solid rocks have a friction coefficient 0.2-0.3 lower than powders.

Collettini, Niemeijer, Viti, Marone, Nature 2009
**Powders:** Deformation occurs along a zone characterised by cataclasis with grain-size reduction and affected by shear localization along R1, Y, B shears (e.g. Logan, 1978; Beeler et al., 1996; Marone et al., 1998).

\[
\sigma_n = 50 \text{ MPa}; \text{ displacement} = 3.0 \text{ cm}; \mu = 0.52.
\]
Solid-foliated sliding surfaces located along the pre-existing very fine grained, <2mm.

Microstructures
solid-foliated vs. powdered

\[ \sigma_n = 50 \text{ MPa}; \text{ displacement} = 3.0 \text{ cm}; \mu = 0.32 \]
Frictional sliding along phyllosilicates: friction 0.2-0.3, well below Byerlee’s range.
Heterogeneous fault zone structure and frictional properties

<table>
<thead>
<tr>
<th>Rock-Type</th>
<th>Friction</th>
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<tr>
<td>Foliated Phyll.</td>
<td>0.3</td>
</tr>
<tr>
<td>Foliated Phyll.</td>
<td>0.25</td>
</tr>
<tr>
<td>Dolostone</td>
<td>0.7</td>
</tr>
<tr>
<td>Mafic</td>
<td>0.7</td>
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![Fault zone structure and frictional properties image]
The velocity dependence of sliding friction is given by \( (a-b) = \frac{\Delta u}{\Delta \ln V} \).

Negative values of \( (a-b) \) reflect velocity weakening behaviour, positive \( (a-b) \) reflect velocity strengthening, which results in stable sliding.
Heterogeneous fault zone structure and frictional properties
Mixed-mode slip behaviour: creep + microseismicity

Collettini et al., EPSL, 2011.
Mixed-mode slip behaviour: creep + microseismicity
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Heterogeneous faults in the lab
Bonini et al., 2014
Field studies of regional thrusts that represent exhumed analogues of the active faults responsible for the seismicity in the Emilia region.

Pondrelli et al., 2012

≈15 km

Massoli et al., 2006
Distributed deformation in marly limestones

Legend
- Scaglia Cinerea
- Scaglia Variegata
- Scaglia Group
- Marne a Fucoidi
- Maiolica
- Corniola + CD
- Calcare Massiccio
(No vertical exaggeration)

Tesei et al., JSG, 2013
Distributed deformation in marly limestones

Legend
- Scaglia Cinerea
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- Marne a Fucoidi
- Maiolica
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- Calcare Massiccio

(No vertical exaggeration)

Hangingwall

S-CC tectonite Shear Zone

≈20 m

Outcrop

Coscerno Thrust

≈500 m E

W

S

N
Viti et al., CMP, 2014

Deformation

protolith

early stylolite

mature stylolite

calcite
clay

30 nm
60 nm

Viti et al., CMP, 2014
Localized deformation in massive limestone

Calcare Massiccio, lower Jurassic

Age of activity, Mio-Plioc.
Displacement 5-10 km
Exhumation 2-3 km

Scaglia Rossa, upper Cretaceous

Collettini et al., Geology 2013
Amorphous-silicate material made of: relict calcite and clay, numerous vesicles, poorly crystalline/amorphous phases, and newly formed calcite skeletal.
Calcite crystal showing decarbonation.
Calcite crystal showing decarbonation.
Thermal decomposition of calcite initiates at about 600 °C, **BUT** the fault rock of the thrust formed at 2-3 km of depth, at temperature below 70° C.
Thermal decomposition of calcite initiates at about 600 °C, **BUT** the fault rock of the thrust formed at 2-3 km of depth, at temperature below 70° C.

EQ slip localized on a thin slip surface Temperature increase with Decarb + Dehyd. ....and the production of vesiculated material with skeletal crys.

Collettini et al., Geology 2013
Reproduce the heterogeneous fault rocks in the lab.

Collettini et al., IJRMMMS, 2014
ss friction  v. steps  slide-hold-slide

Displacement (mm)

Friction

Coefficient of Friction, $\mu$

Velocity Step (VS)

Slide-Hold-Slide (SHS)

Sample Layers

Frictional Healing, $\Delta \mu$

$\Delta \mu_c$, Creep Relaxation

Hold Time
Slide-hold-slide experiments: frictional healing $\Delta \mu$
Shear zones are weak, v. strengthening with no re-strengthening.

Tesei et al., EPSL, 2014
Shear zones are weak, v. strengthening with no re-strengthening.

Sharp slipping zones are strong, v. weakening with re-strengthening.

Tesei et al., EPSL, 2014
Decarbonated material is weaker than calcite and very velocity weakening in particular at low sliding velocities.

Carpenter et al., in review
Shear zones with pressure solution and sliding along phyllosilicates

Weak, $\mu = 0.2-0.3$

Velocity strengthening

No-healing

Long term creep

Localization with cataclasis and thermal decomposition

Strong, $\mu = 0.6-0.7$

Velocity neutral/weakening

Re-strengthening

Repeatable seismic slip

DC weak

Very velocity weakening
How can we extrapolate these two characterization to an entire fault plane?
Series of geological cross sections across the fault plane

Tesei et al., EPSL, 2014
Series of geological cross sections across the fault plane

Tesei et al., EPSL, 2014
Series of geological cross sections across the fault plane

Tesei et al., EPSL, 2014
Series of geological cross sections across the fault plane

Tesei et al., EPSL, 2014
Series of geological cross sections across the fault plane

Tesei et al., EPSL, 2014
Fault plane heterogeneities

Long term creep

Repeatable EQs
**Fault Zone**

- **Weak, ductile** (seismogenesis unlikely)
- **Strong, brittle** (potential seismogenesis)

**Tectonites**
- S-CC' tectonites

**Cataclasites and principal plane**

**Friction Properties**
- Low strength, no restrengthening, velocity strengthening
- High strength, fast restrengthening, velocity weakening

**Figure a**
- Footwall
- FLAT
- RAMP
- N
- ~10 km

**Figure b**
- FLAT
- Seismic
- Aseismic
- Mixed mode

**References**
- Tesei et al., EPSL, 2014
Introduction

Natural fault rocks and microstructures
Lab. experiments for slip behavior and microstructures

1) Fault structure, frictional properties and mixed-mode fault slip behavior of LANF

2) Heterogeneous strength and fault zone complexity of carbonate-bearing thrusts

3) Fault structure and slip localization in carbonate-bearing normal faults

Future directions

Experiments on the role of fluid pressure in fault stability
Heterogeneous faults in the lab
USGS Shake Map

<table>
<thead>
<tr>
<th>Perceived Shaking</th>
<th>Not Felt</th>
<th>Weak</th>
<th>Light</th>
<th>Moderate</th>
<th>Strong</th>
<th>Very Strong</th>
<th>Severe</th>
<th>Violent</th>
<th>Extreme</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potential Damage</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Peak Acc (g)</td>
<td>&lt;0.1</td>
<td>0.1-1.4</td>
<td>1.5-3.9</td>
<td>3.9-6.2</td>
<td>9.2-18</td>
<td>18-34</td>
<td>34-65</td>
<td>65-124</td>
<td>&gt;124</td>
</tr>
<tr>
<td>Peak Vel (cm/s)</td>
<td>0.1-0.6</td>
<td>0.05-1.0</td>
<td>1.0-2.5</td>
<td>2.5-4.0</td>
<td>4.0-8.0</td>
<td>8.0-16</td>
<td>16-32</td>
<td>32-64</td>
<td>&gt;64</td>
</tr>
<tr>
<td>Intensity</td>
<td>I</td>
<td>II</td>
<td>III</td>
<td>IV</td>
<td>V</td>
<td>VI</td>
<td>VII</td>
<td>VIII</td>
<td>IX</td>
</tr>
</tbody>
</table>

Emilia Earthquake 2012
$M_w = 6.1$

1997-1998 Umbria-Marche seismic sequence

L'Aquila Earthquake 2009
$M_w = 6.0$
$M_w = 6.3$

Tirrenian Sea
~19,000 high-resolution aftershock locations nucleated along causative fault of MW=6.1, 2009 L’Aquila earthquake.

Seismological fault zone structure characterization

Valoroso et al., Geology 2014
At the km scale

Along strike, fault length is ~10 km and the maximum width of the fault is ~1.5 km.

Some displacements are distorted and denote a degree of interaction.
At the outcrop scale

parallel slipping zones distributed over a width of about 50 m
Collecting rock samples for microstructural studies & experiments
At micron scale: thin Principal Slipping Zone with parallel slipping planes + disaggregation features pointing to decarbonation.
At the nanoscale: plastic deformation with twinning, nanograins & polygonal structures (with strain-free calcite crystals) similar to the one documented in HVFE at the early stage of dynamic weakening (De Paola et al., in prep.)
Very high healing rates in particular for CaCo$_3$ solutions

Carpenter et al., in prep.
Very high healing rates favored by dissolution and precipitation processes during hold periods. 

\[ \sigma_n = 50 \text{ MPa}, \text{ hold time } 3000 \text{ s} \]

Carpenter et al., in prep.
The common theme linking multiscale observations is the presence of multiple slipping planes.
These multiple slipping planes are the result of different deformation mechanisms including:

Fault growth & interaction

Collettini et al., JSG, 2014
These multiple slipping planes are the result of different deformation mechanisms including:

- Fault growth & interaction
- Strength evolution with cementation and healing

Collettini et al., JSG, 2014
These multiple slipping planes are the result of different deformation mechanisms including:

**Fault growth & interaction**

**Strength evolution with cementation and healing**

**Plastic deformation and decarbonation during co-seismic slip**
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Experiments on the role of fluid pressure in fault stability

R&S friction predicts a frictional instability when the stiffness of the fault ($K_c$) is greater than the stiffness of the loading system ($K$).

$$k < k_c = \frac{(\sigma_n - P_f)(b-a)}{D_c}$$
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Experiments on the role of fluid pressure in fault stability
Heterogeneous faults in the lab
Heterogeneous experimental faults

Tesei et al., in progress

20 cm
Interaction between EQ-like and creep like fault patches along a large (20 x 20 cm), fluid rich experimental fault.
Thank you
Slipping zone of no thickness (Rice, 2006):

\[
\Delta T = \frac{\tau_f}{\rho C_p} \sqrt{\frac{V s}{\pi \kappa}}
\]

\(\tau_f\) is the shear resistance of the fault; 
\(\rho = 2710 \text{ kg/m}^3\); 
\(C_p\) is the heat capacity (962 J/kgK); 
\(V = 1 \text{ ms}^{-1}\) is the constant slip velocity; 
\(s\) is the mean co-seismic slip; 
\(k\) is the thermal diffusivity.