Rock tribology: Understanding earthquakes

Guilhem Mollon[1]

[1]LaMCoS
INSA LYON
Villeurbanne, France

TRAMME, July 2023

Preliminary remarks – Outline

Rocks

Faults

Earthquakes

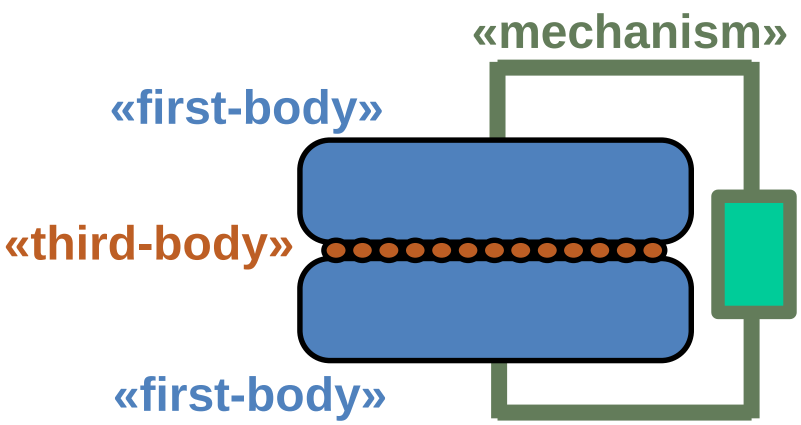
Friction

Case studies #1, #2

Preliminary remarks – Tribological framework

-In what follows, we will consider earthquakes as a friction instability problem.

-The most comprehensive framework for contact problems is the tribological triplet *(Godet 1984)*.



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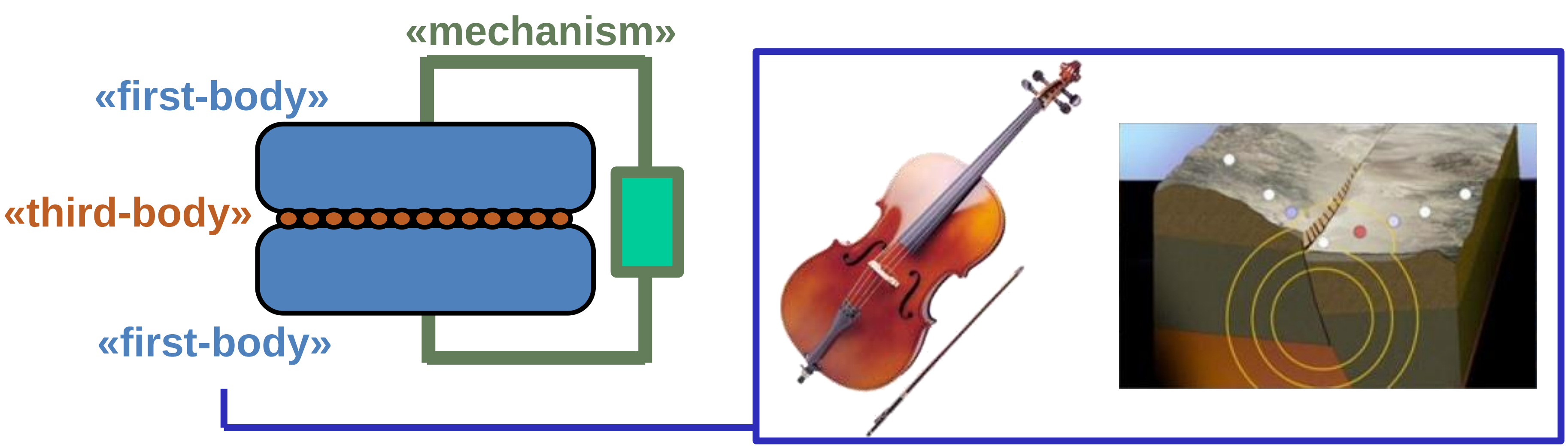

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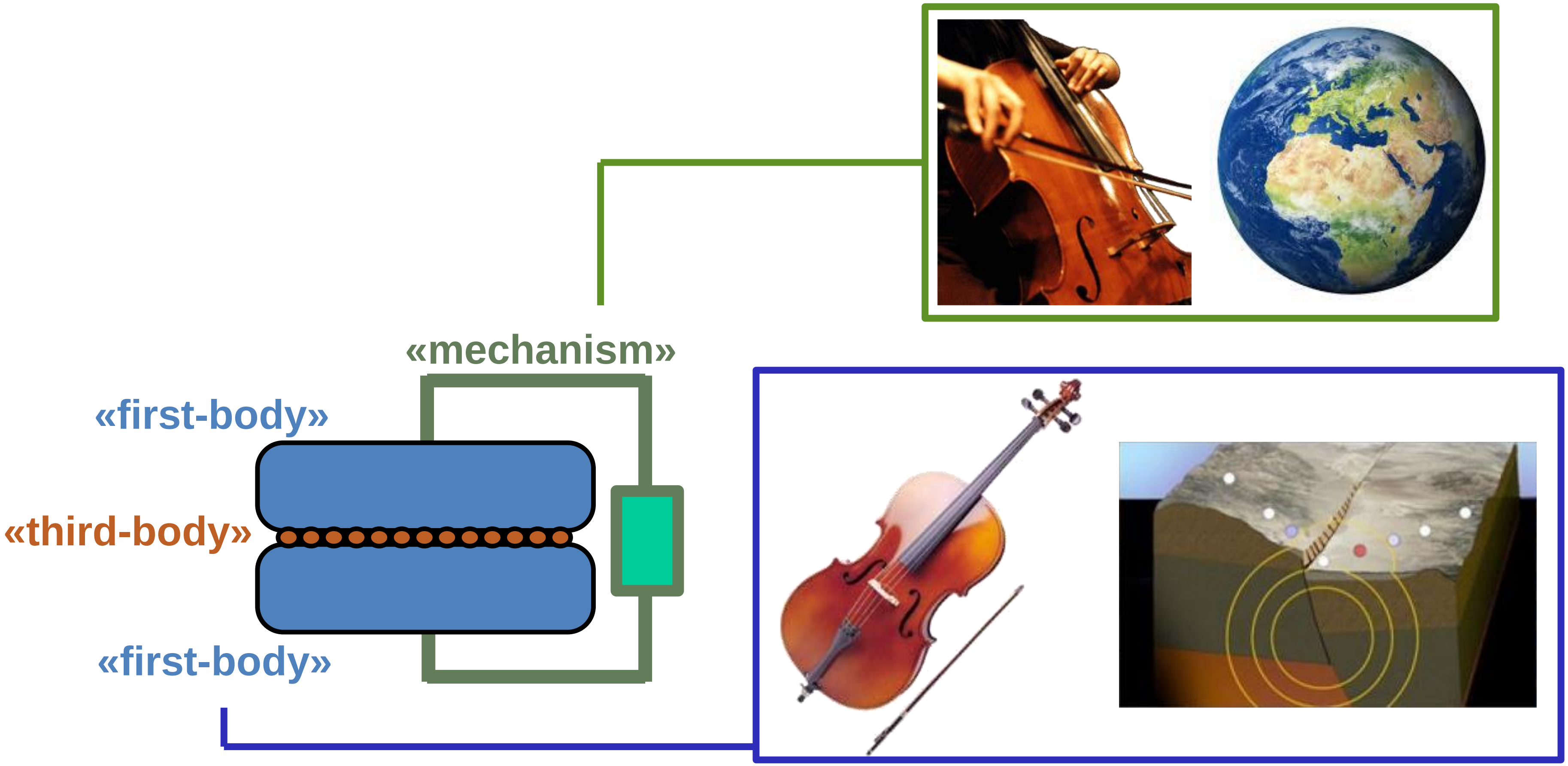

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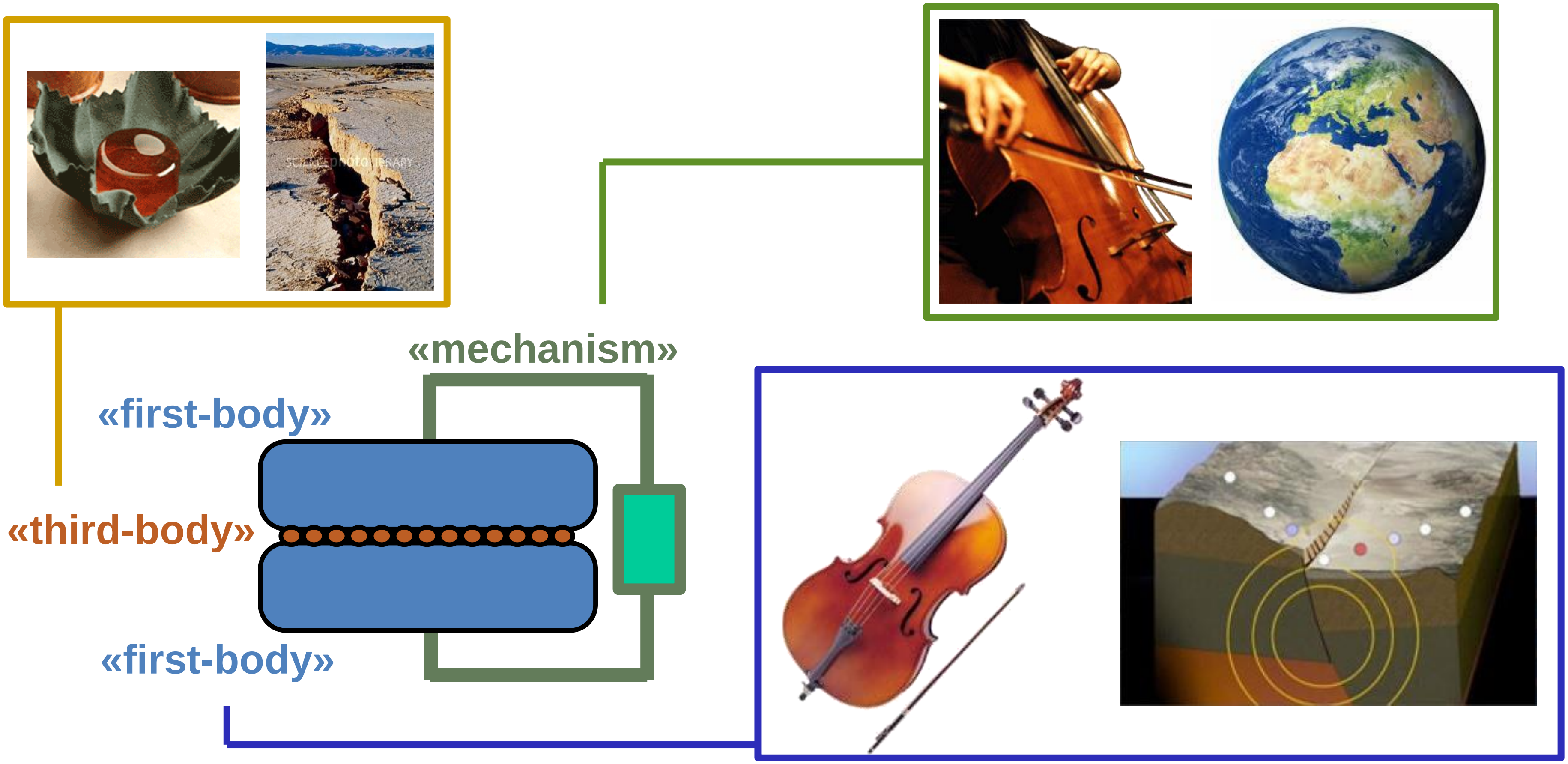

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Rocks

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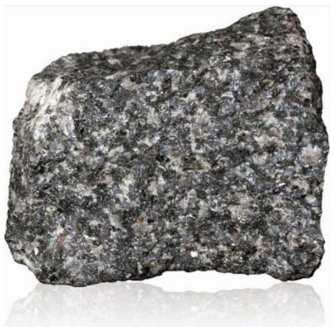
Rocks, faults, earthquakes – What is a rock?

-A rock is a naturally occurring aggregate of minerals.

Sandstone

Basalt

Gabbro



Gneiss

Granite

Marble

Limestone

Peridotite

Rocks, faults, earthquakes – What is a rock?

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Formed in various ways

Igneous rocks: formed by slow or quick cooling of magma or lava (i.e. molten rock)

Peridotite

Rocks, faults, earthquakes – What is a rock?

-A rock is a naturally occurring aggregate of minerals.

Sandstone

Formed in various ways

Sedimentary rocks: formed by slow deposition, compaction and cementation of small pieces of other rocks.

Limestone

Rocks, faults, earthquakes – What is a rock?

-A rock is a naturally occurring aggregate of minerals.

Formed in various ways

Metamorphic rocks: formed by slow physico-chemical transformation of other rocks under high pressures and/or temperature

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Rocks, faults, earthquakes – What is a rock?

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Found in various places

Mantle rocks: Typical of Earth mantle, submitted to slow solid-state convective flow, rarely found at the surface.

Peridotite

Rocks, faults, earthquakes – What is a rock?

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Gabbro

Found in various places

Oceanic rocks: Found in oceanic crust, formed at mid-ocean ridges.

Rocks, faults, earthquakes – What is a rock?

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Sandstone

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Granite

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Found in various places

Continental rocks: Found in continental crust, wide variety of mechanical, physical, and chemical history and properties.

Rocks, faults, earthquakes – What is a rock?

-A rock is a naturally occurring aggregate of minerals.

-Hence, rocks are essentially polycristalline composite materials made of mineral “grains”

- A mineral is a solid compound (almost 6000 kinds):

    -> with a clear chemical composition

    -> with a clear crystalline structures

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- Mohs scale of mineral hardness:

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- Mohs scale of mineral hardness:

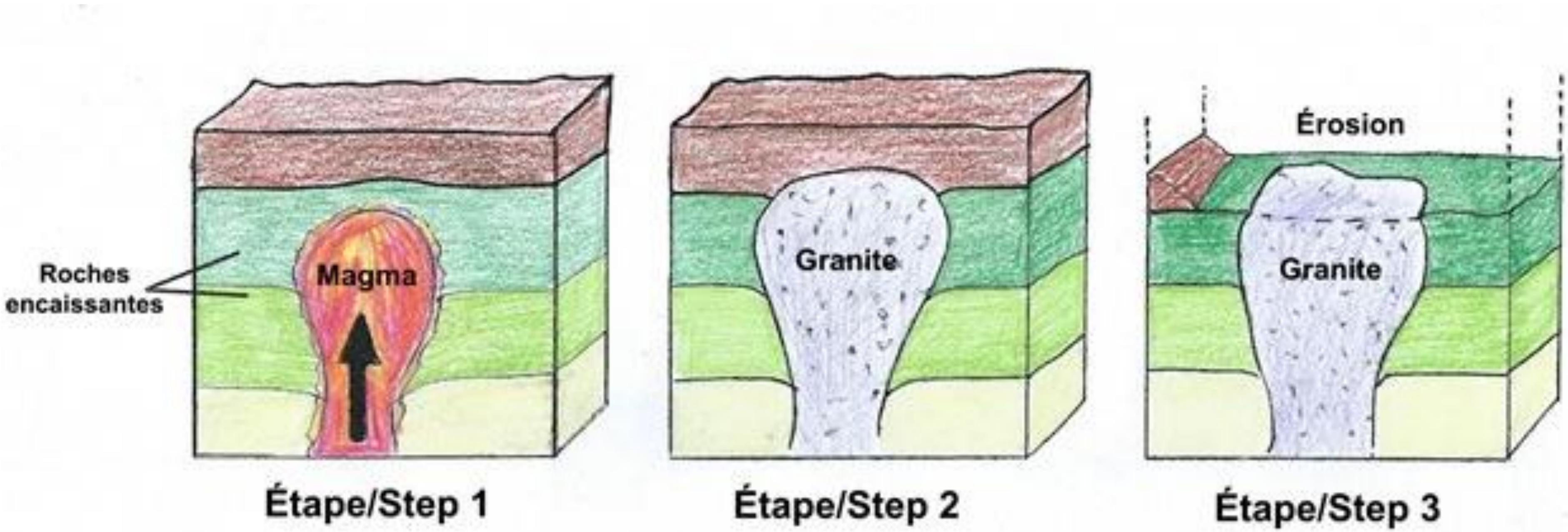
1. Talc — 3. Calcite — 6. Quartz — 10. Diamond

Rocks, faults, earthquakes – What is a rock?

-A typical rock: the granite

Formation

Igneous intrusive rock: Formed by the intrusion of magma, slow solidification, followed by erosion.



Rocks, faults, earthquakes – What is a rock?

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Location

Continental rock: Extremely common as a crustal basement rock in continental regions.

Half-Dome, Yosemite, CA, USA

Rocks, faults, earthquakes – What is a rock?

-A typical rock: the granite

Composition

Three main minerals: Quartz (~30%), Feldspar (~65%), Mica (~5%)

(typically, but extremely large variability of these percentages)

Fig. 2

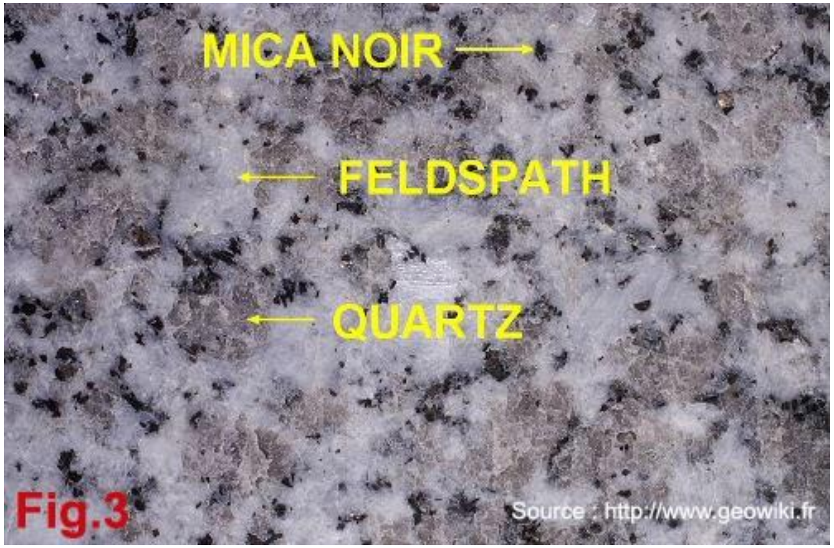


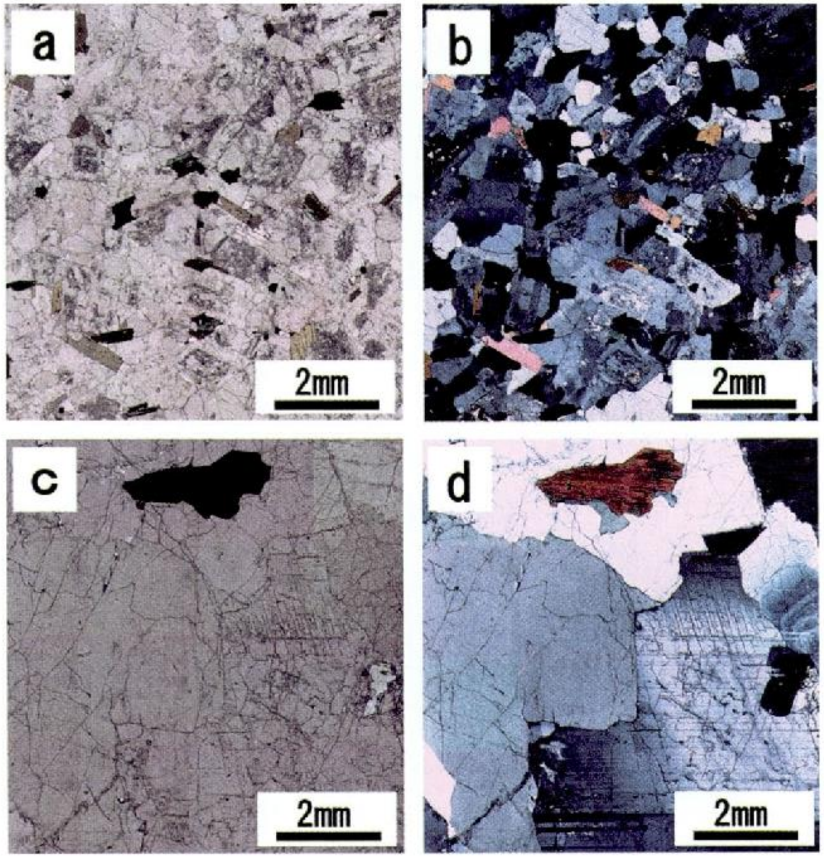
Fig.3

Rocks, faults, earthquakes – What is a rock?

-A typical rock: the granite

Microstructure

Coarse-grained: Typical size of the grains ~1 mm (with a huge variability) because of its slow cooling.



Rocks, faults, earthquakes – What is a rock?

-A typical rock: the granite

Typical physical properties

Density: ~2700 kg/m3

Compressive strength: ~200 MPa

Tensile strength: ~10 MPa

Young's modulus: ~70 GPa

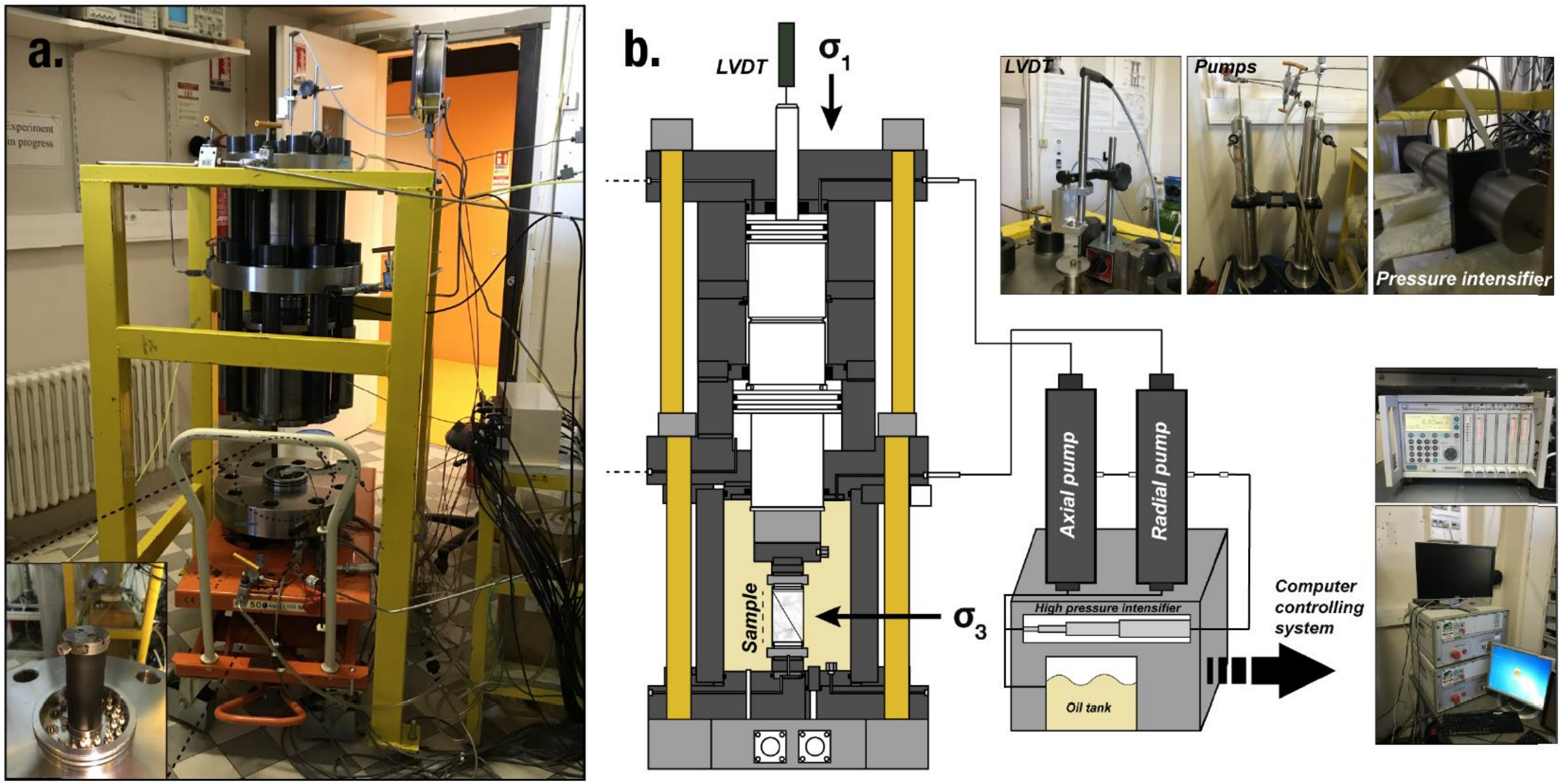
Poisson Ratio: ~0.25

Thermal conductivity: ~2.7 W/(mK)

Melting point: 800-1400 °C

Rocks, faults, earthquakes – What is a rock?

-Mechanical behavior of rocks



Typical rock mechanics experiment

Triaxial press: Samples of a few centimeters, submitted to radial confining pressure (up to 300 Mpa here) and axial driven strain.

J. Aubry (2019), Séismes de laboratoire : friction, plasticité, et bilan énergétique, *PhD Thesis, ENS Paris*

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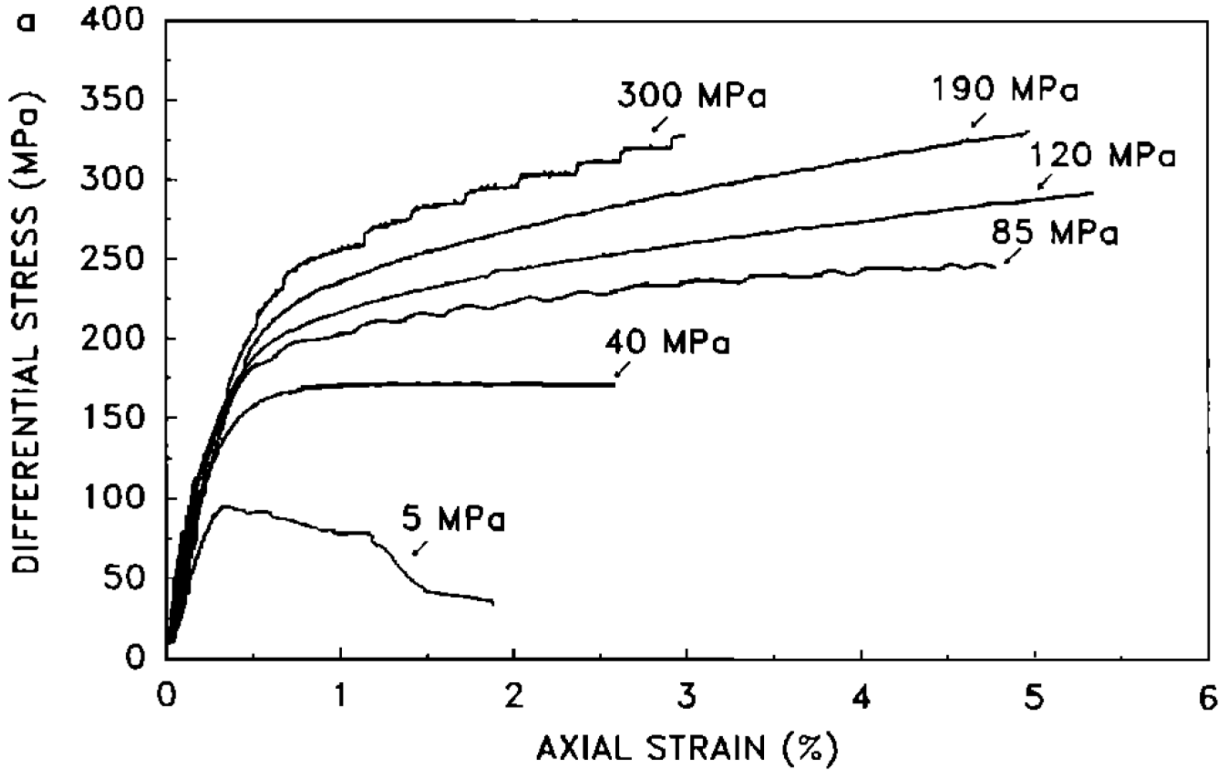

Scholz 2002

The example of marble

Behavior: Extremely brittle at low confining stress. Ductile under high pressure and/or high temperature. Details depend on rock type.

Friedrich et al. (1989), Micromechanics of the brittle to ductile transition in Carrara marble, *Journal of Geophysical Research, 94, B4*

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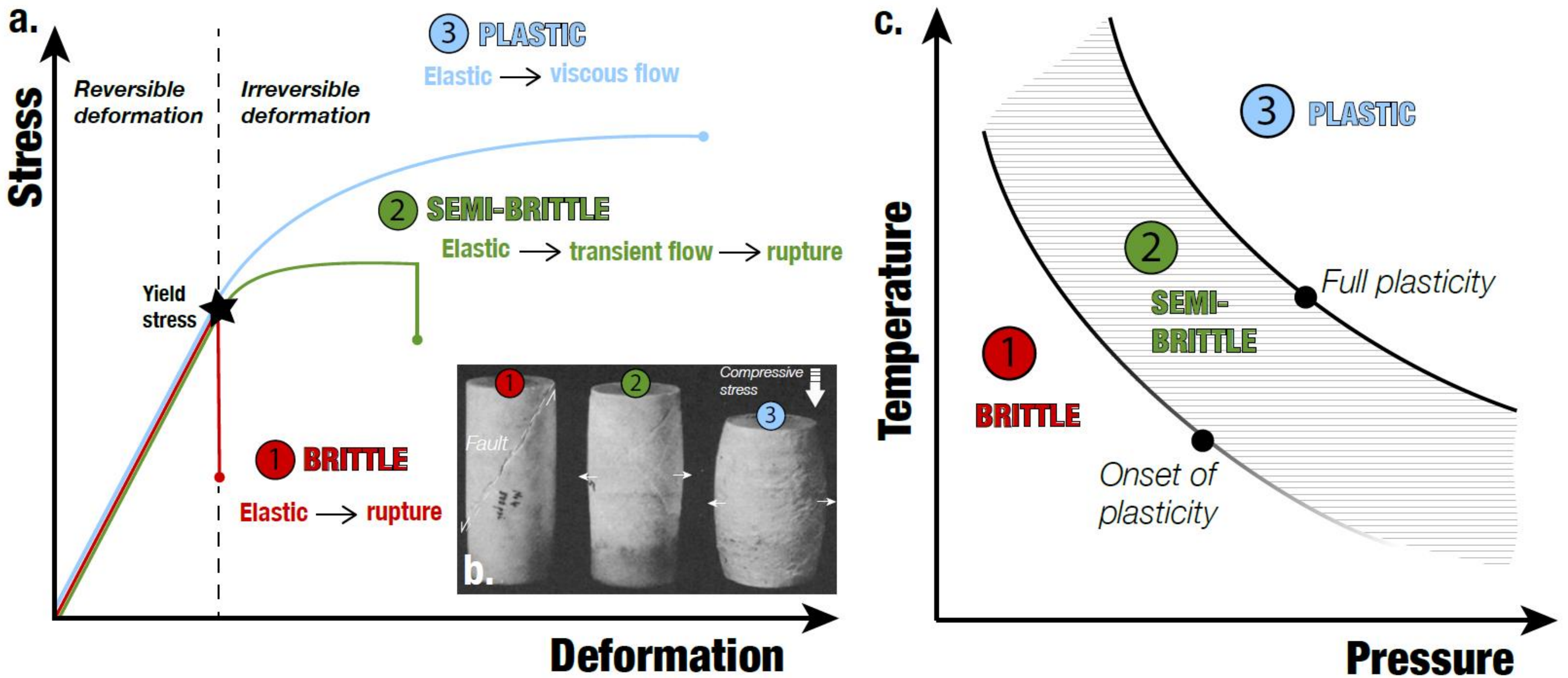

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Rocks, faults, earthquakes – What is a rock?

-Mechanical behavior of rocks

Brittle failure: Occurs by strong localization of the relative motion, either in tension (cracks, joints) or in shearing (fault).

Implies dilatancy (i.e. increase of volume of the rock) and frictional work (within cracks and faults)

-> Thermodynamically restricted at high pressure

Ductile deformation: Occurs by continuous strain of rocks without discontinuity, typically as folds and shear zones.

Relies on dislocation glides and diffusion creep, which are both insensitive to pressure but are thermally activated.

-> Thermodynamically promoted at large pressures and temperatures

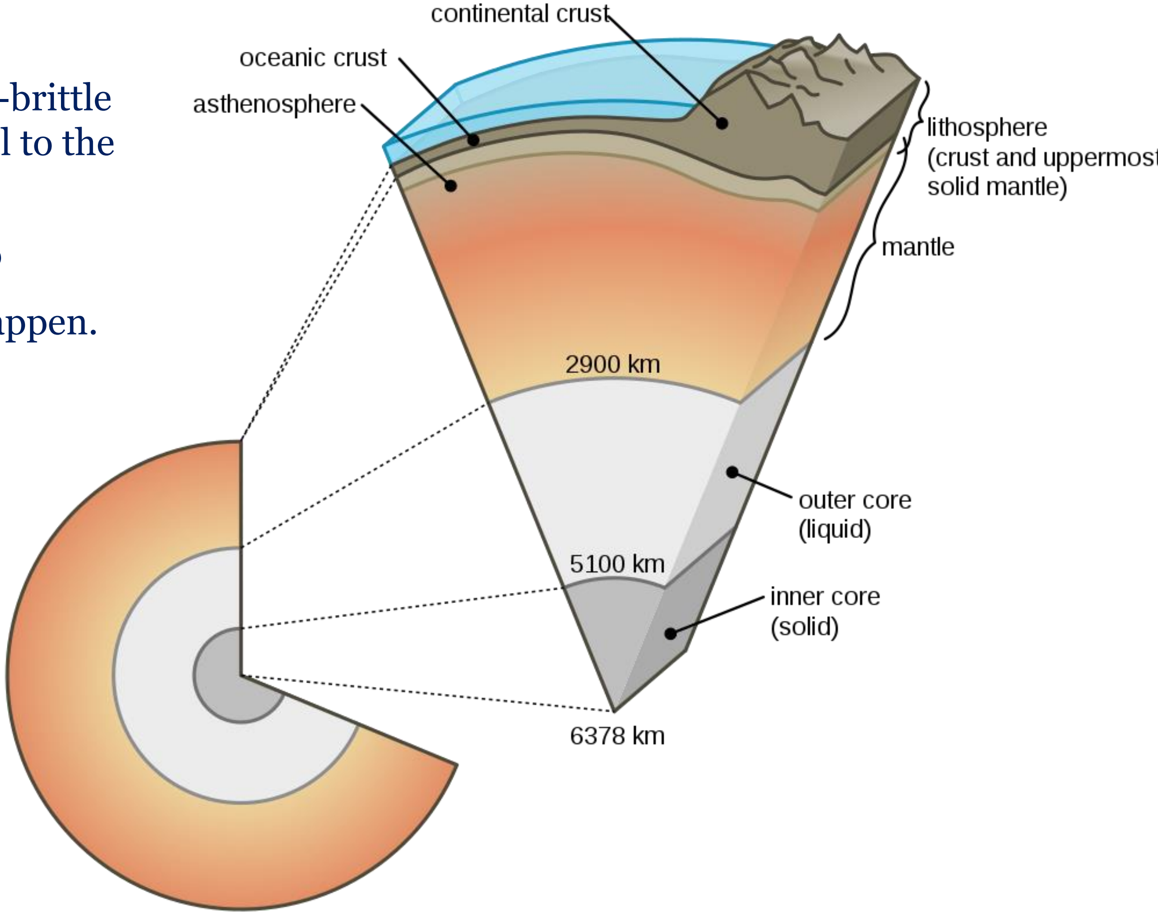
Rocks, faults, earthquakes – What is a rock?

-Consequences on the structure of the Earth

Lithosphere: outer layer with an elastic-brittle mechanical response (not exactly identical to the crust).

It is typically a few tens of km deep

The only place where earthquakes can happen.



Asthenosphere: inner layer with a (viscoplastic) ductile mechanical response (not exactly identical to the mantle).

Extends until outer core.

No earthquake can generally happen.

Faults

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Rocks, faults, earthquakes – What is a fault?

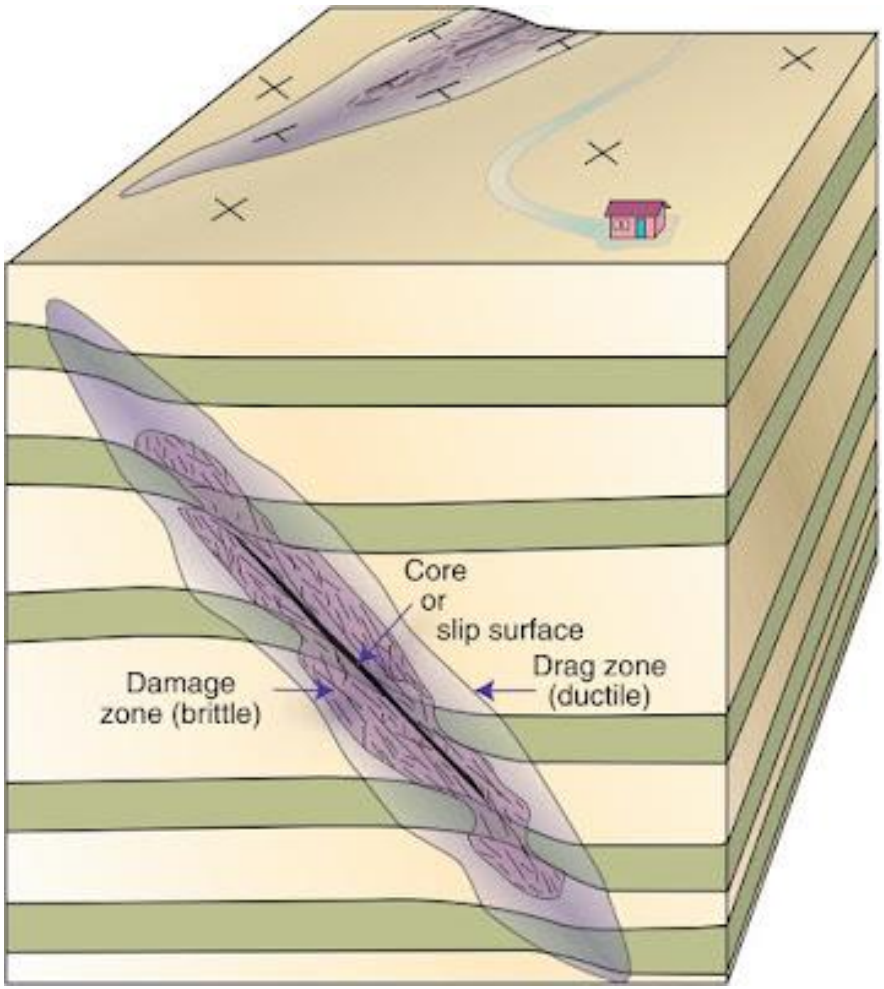
-A fault is a localized, thin, generally planar, zone of weakness in the lithosphere.

A segment of San Andreas fault system, CA, USA

Rocks, faults, earthquakes – What is a fault?

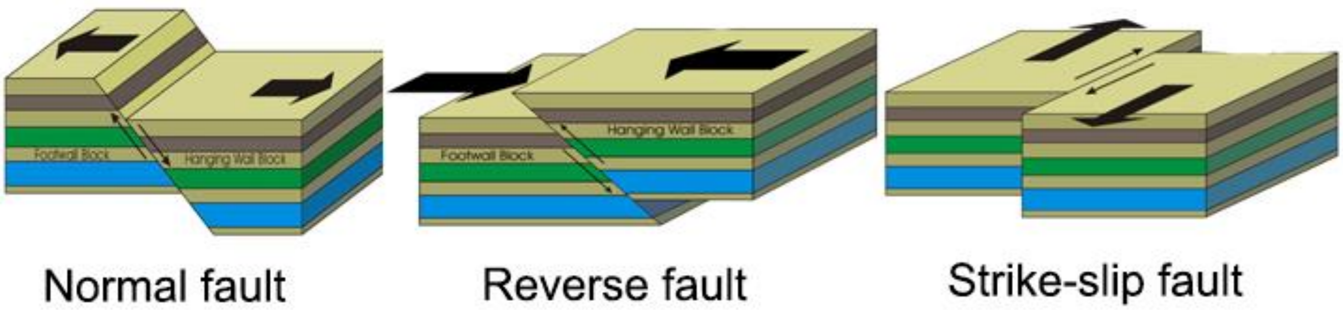
-A fault is a localized, thin, generally planar, zone of weakness in the lithosphere.

-It can reach the surface, but generally remains hidden at seismogenic depths (1-15 km, typically)



Rocks, faults, earthquakes – What is a fault?

-There are three main types of faults, depending of the tectonic context and of the stress state.



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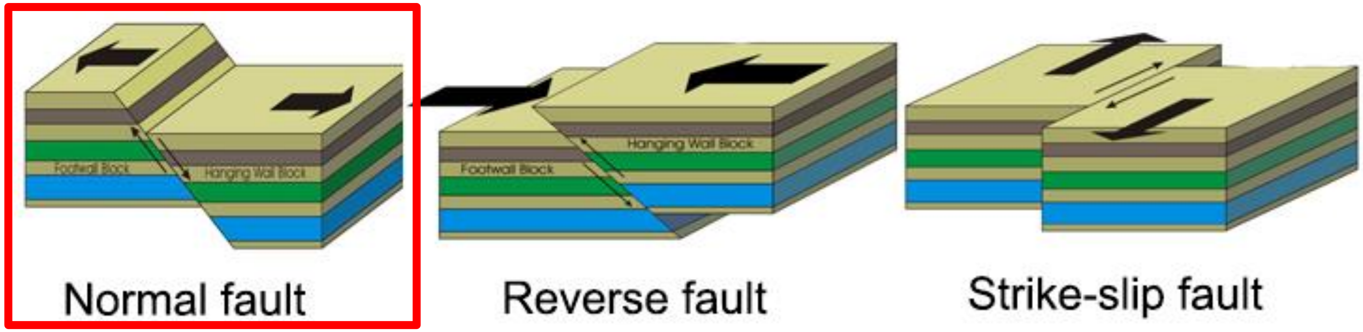
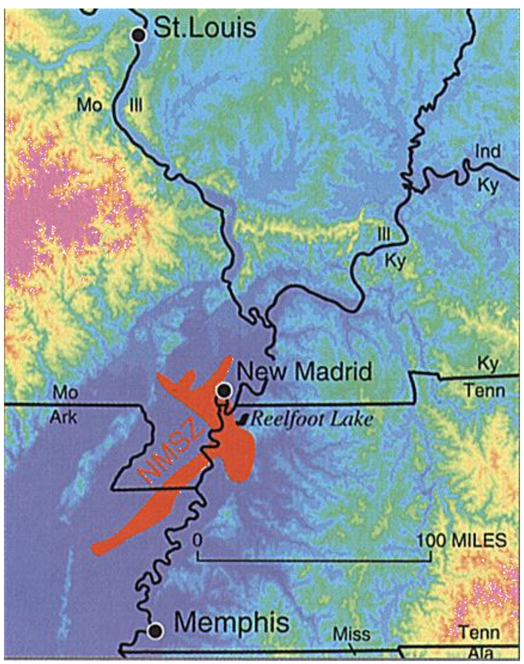
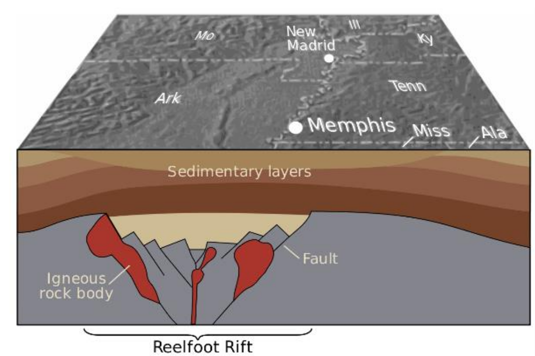




Normal faults: They correspond to an extensional tectonic context, which is quite rare on continental curst. Mostly occurs as “intraplate” features.

Typical example : New Madrid fault zone (Missouri, USA), responsible for 4 earthquakes of magnitudes 7 to 8 in 3 months, in 1811.



New Madrid fault zone, USA

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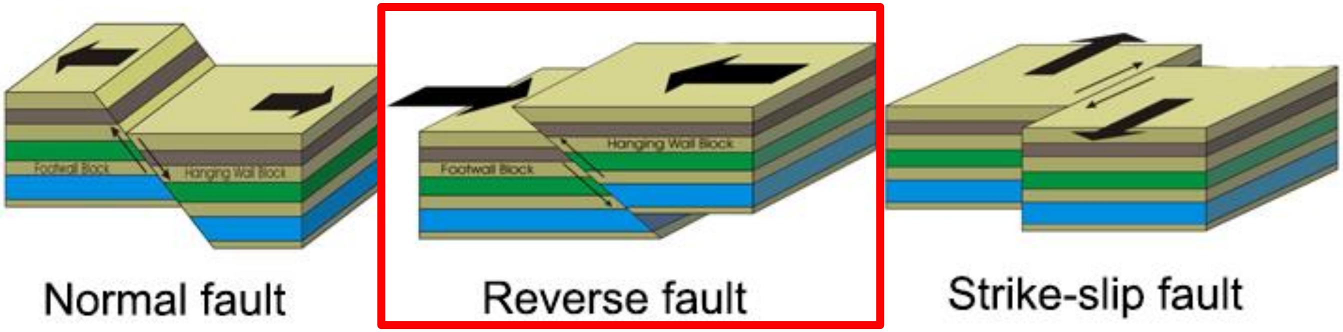
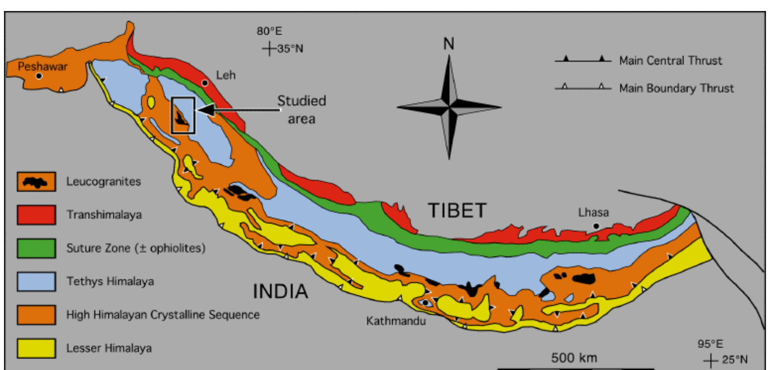
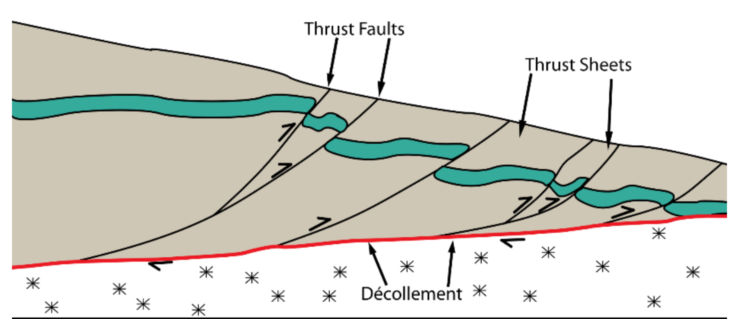


Reverse faults: Also called "thrust faults". They correspond to a compressional tectonic context, typical of subduction zones (but not only).

An example : Main Himalayan thrust (although a bit special). Responsible for the 2015 (M_w 7.8) Nepal earthquake (9,000 casualties)





Main Himalayan Thrust (Nepal, India, China, Pakistan, Buthan)

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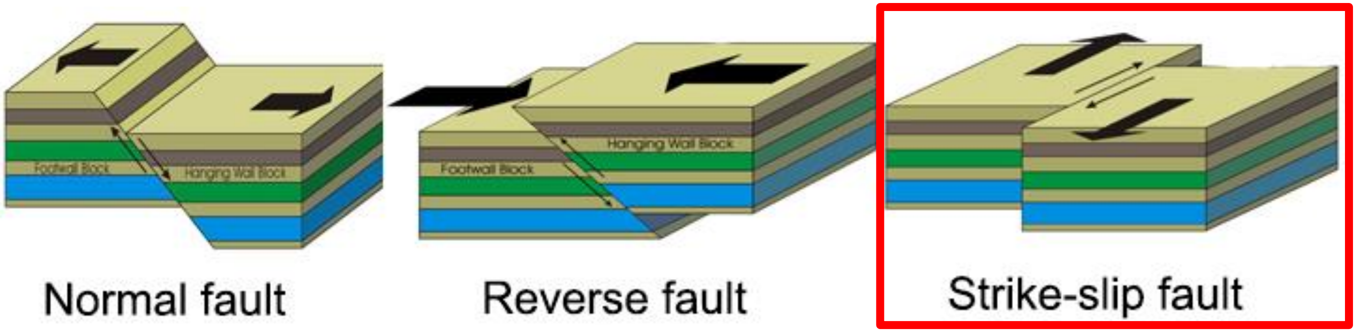
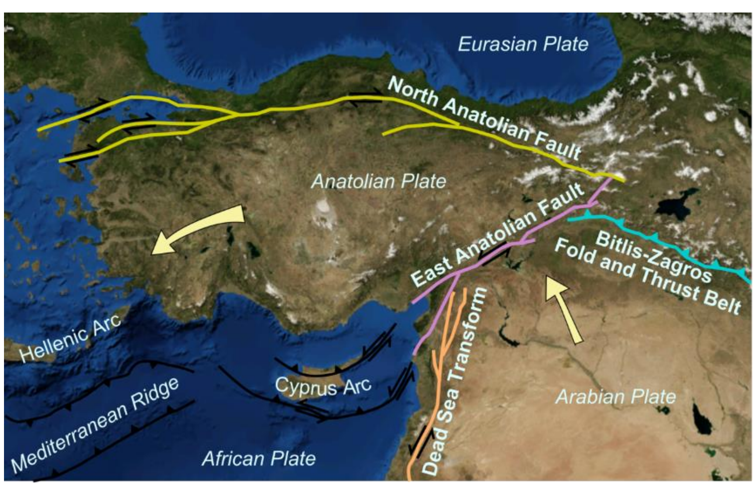


Strike-slip faults: Also called "transform faults", they correspond to a lateral sliding along a vertical plane.

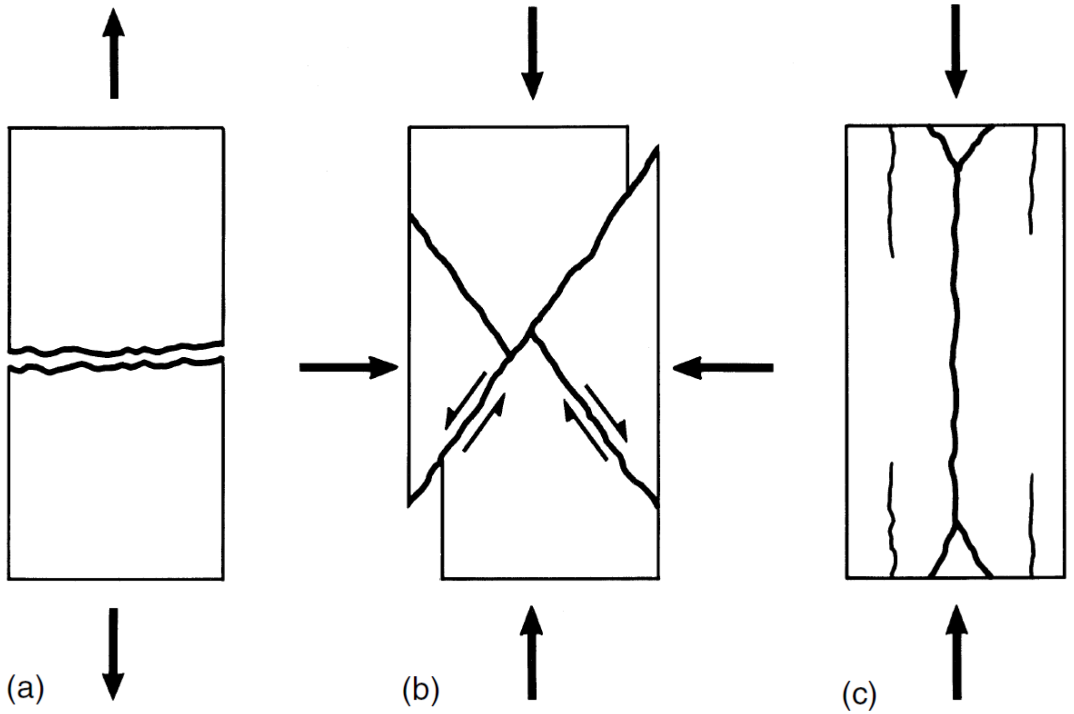
An example : North Anatolian fault. Responsible for the 1999 (M_w 7.6) Izmit earthquake (17,000 casualties). Threatens Istanbul.



North Anatolian Fault, Turkey

Rocks, faults, earthquakes – What is a fault?

-Where do faults come from? From lithosphere fracturing. But how does brittle rock fracture?



Scholz 2002

Lab evidence: Three main fracture geometries are observed, but only one is relevant to lithospheric conditions:

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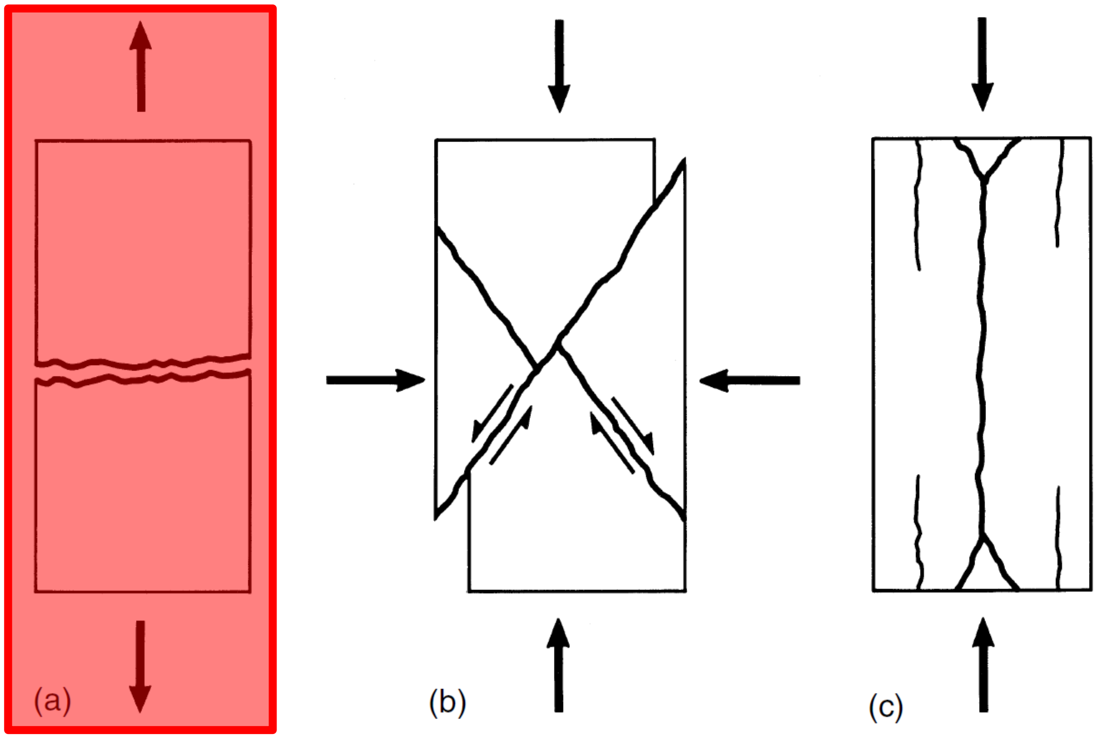

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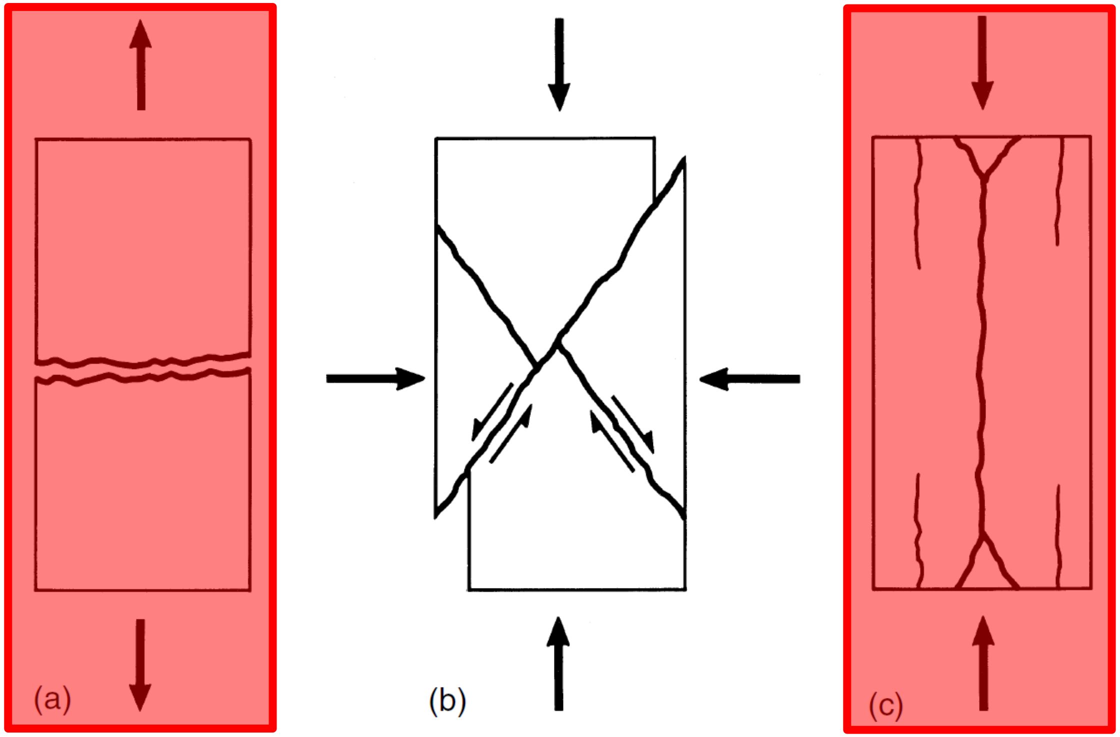

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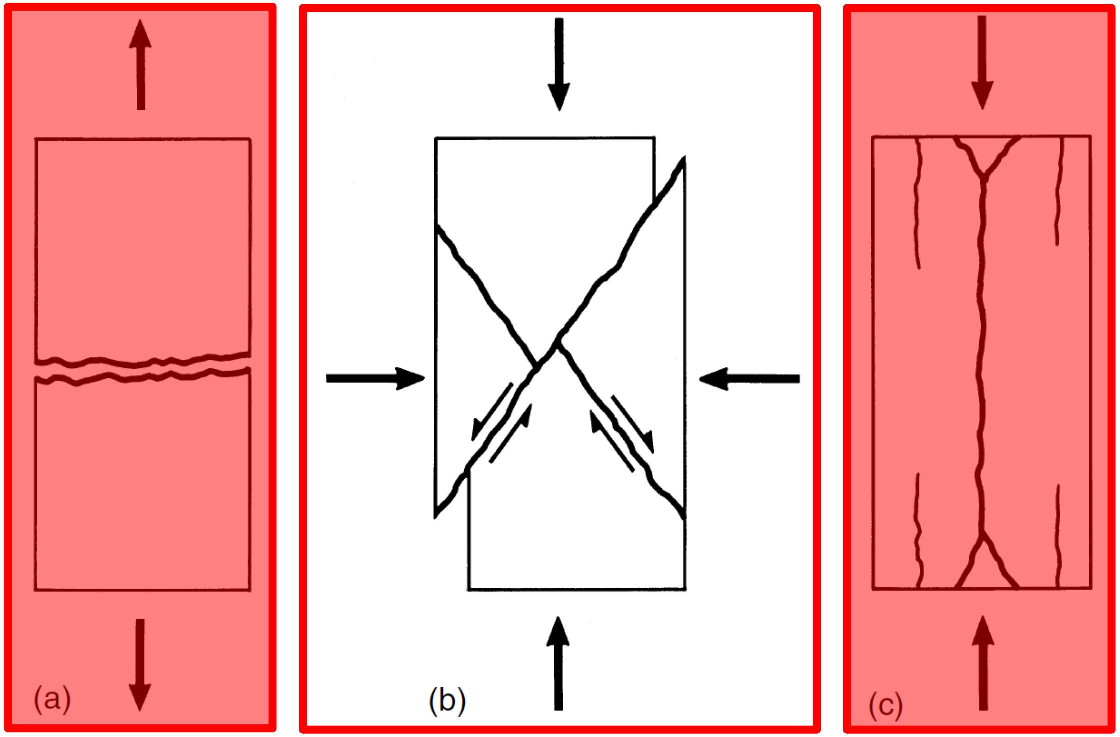

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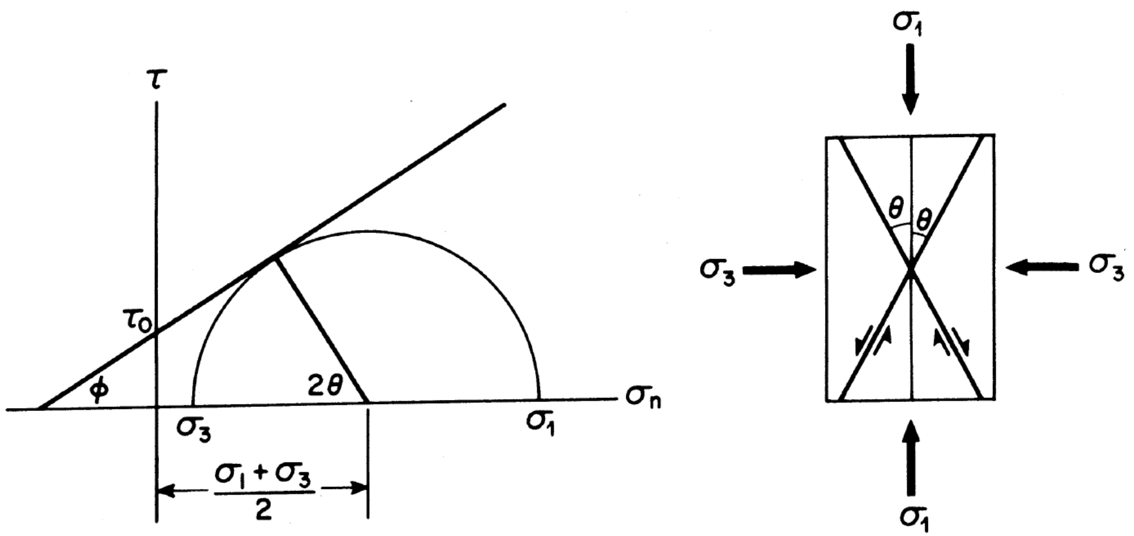
-Case (c) is an artefact of the friction on the loading surfaces

-Case (b) is relevant, as an oblique sliding with respect to the direction of maximum compression

Rocks, faults, earthquakes – What is a fault?

-The most widespread model (and that which reproduces best measurements and observations) to predict brittle fracture is the Mohr-Coulomb criterion.



Scholz 2002

Mohr-Coulomb criterion for rock brittle failure: Failure will occur if there is a certain plane in the rock for which the normal and tangential stresses reach this condition:

$$\tau = c + \sigma \cdot tan\varphi$$

Where c is the "internal cohesion" and φ is the "internal friction angle"

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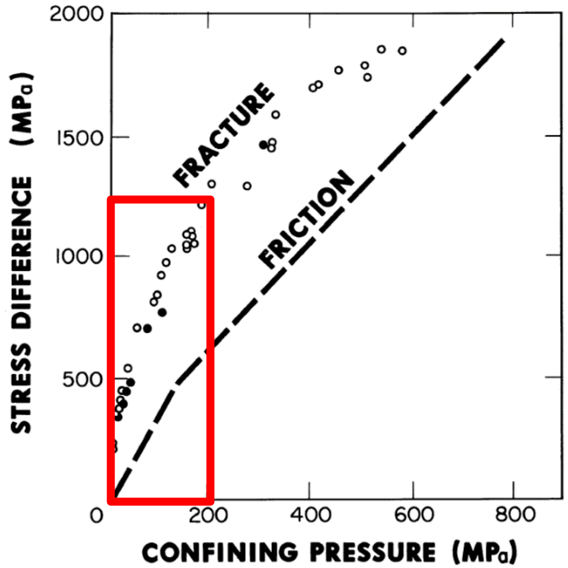

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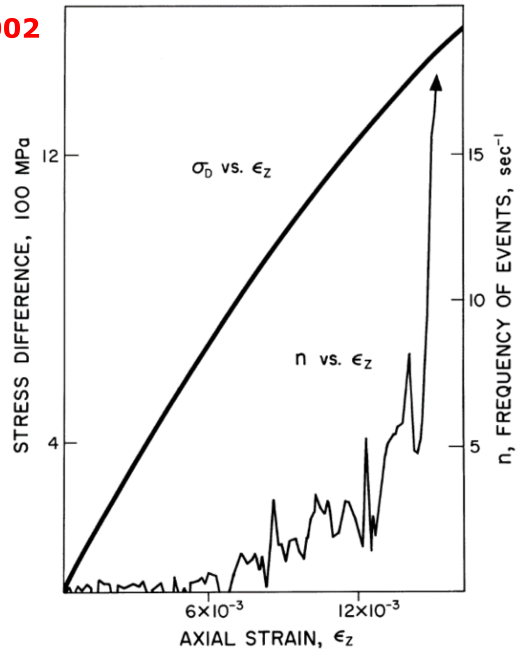
Mohr-Coulomb criterion is only valid for moderate confining pressures.

Fracture strength is highly pressure-dependent: looks pretty much like friction!

Rocks, faults, earthquakes – What is a fault?

-The brittle failure process is not sudden, it develops progressively and this can be followed by tracking acoustic emissions, also called Acoustic Events (AE)

Scholz 2002



Brittle failure process: The frequency of AE is very low in the perfect elastic zone, but starts to increase way before failure. When approaching fracturing, this frequency increases dramatically.

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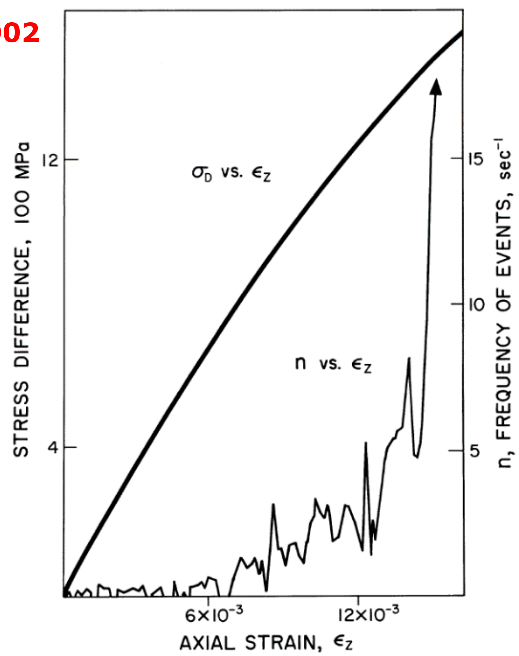
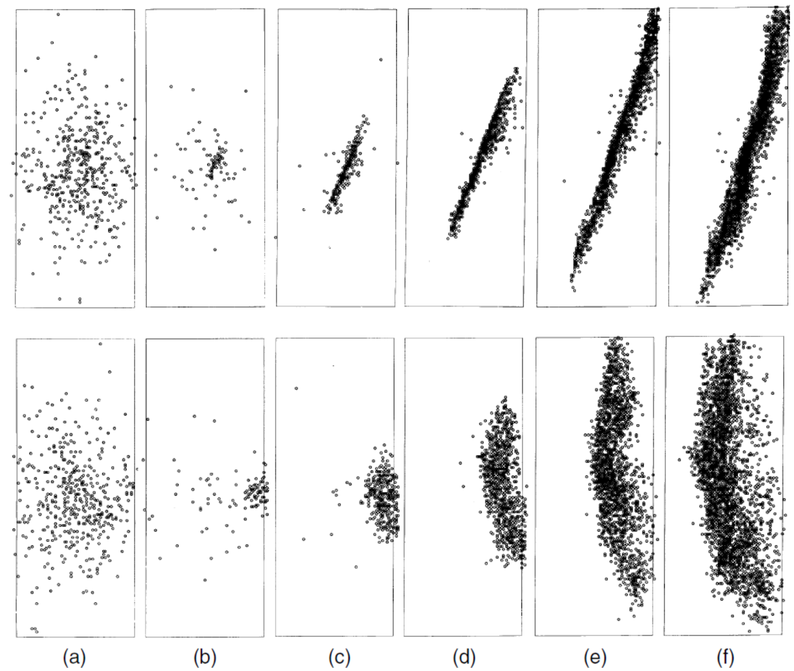


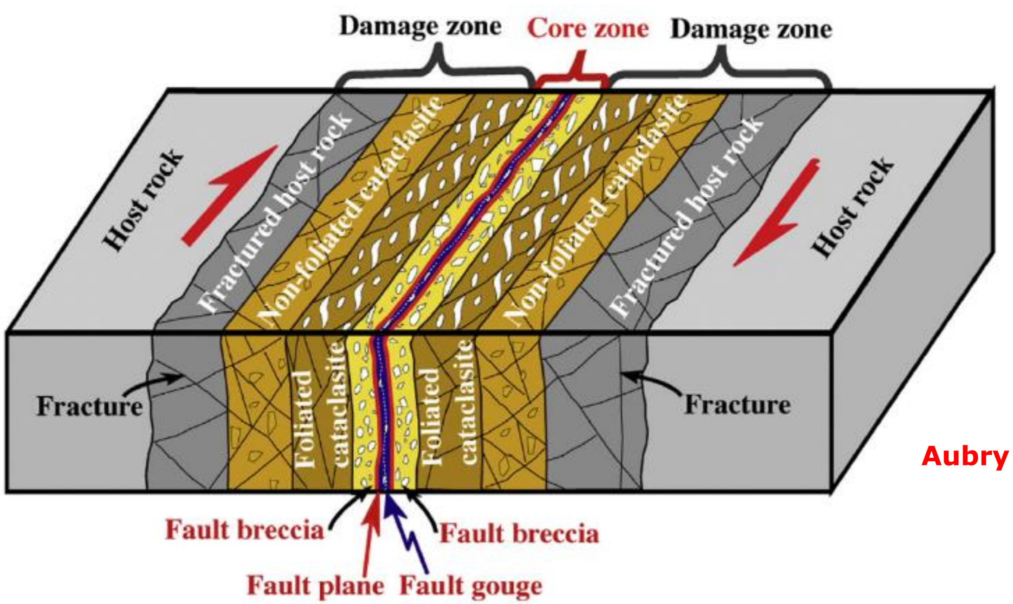


Brittle failure process: The frequency of AE is very low in the perfect elastic zone, but starts to increase way before failure. When approaching fracturing, this frequency increases dramatically.

The spatial location of these events (located by triangulation from several acoustic sensors) is first very widespread, and then localizes by coalescence around a nucleation zone. This zone extends progressively along an inclined plane until it totally crosses the sample, which finally fractures.

Rocks, faults, earthquakes – What is a fault?

-The structure of faults is generally summarized in the following regions:



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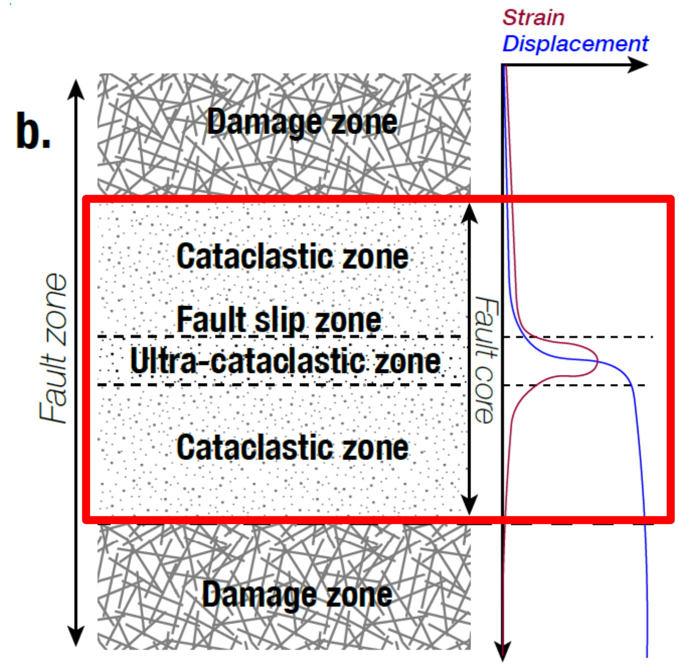

The core zone: This is where most of the differential motion is accommodated. It consists on a Principal Shear Zone (PSS) of finely crushed grains, and of a surrounding cataclastic zone which accommodates less shear but is also pulverized.

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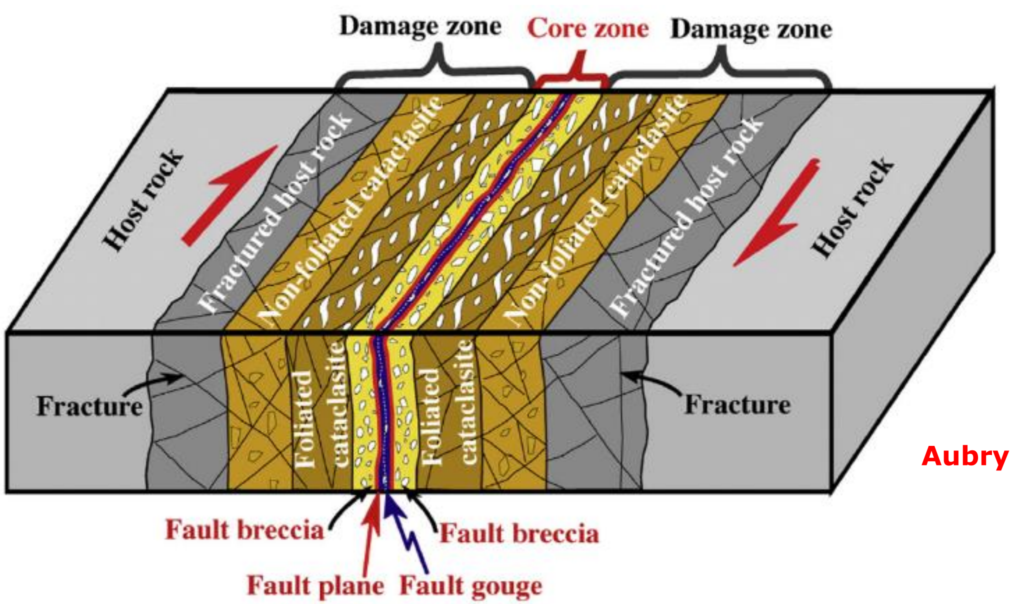

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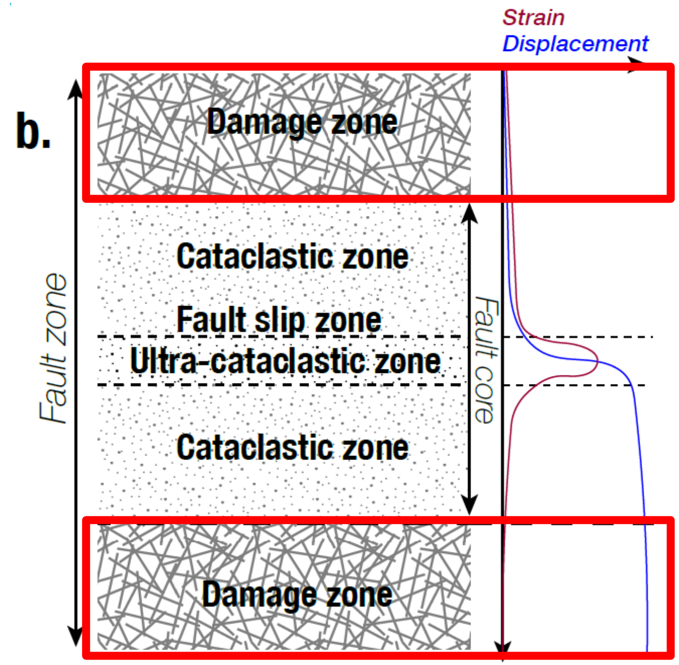

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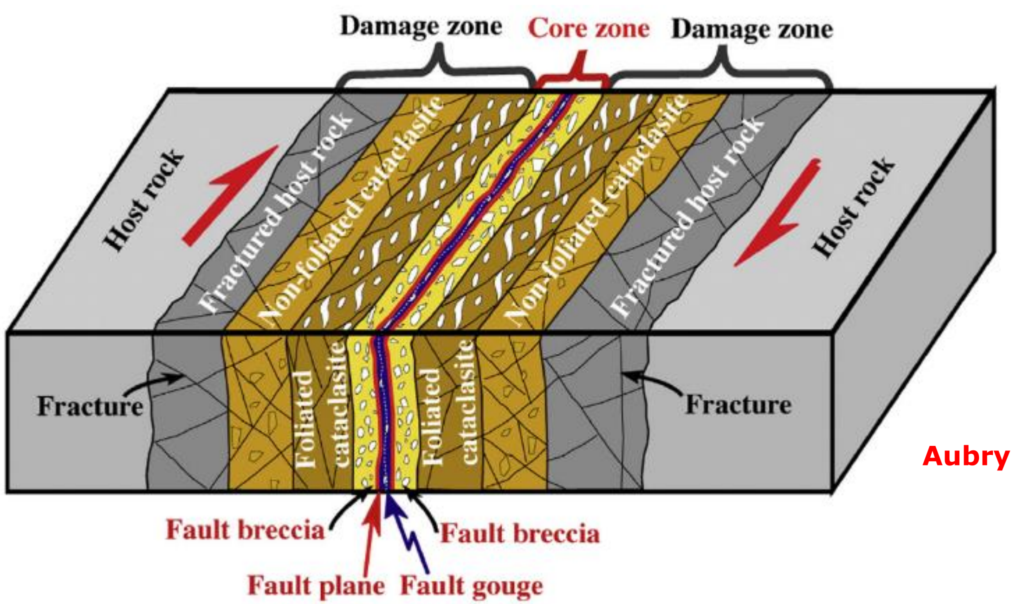

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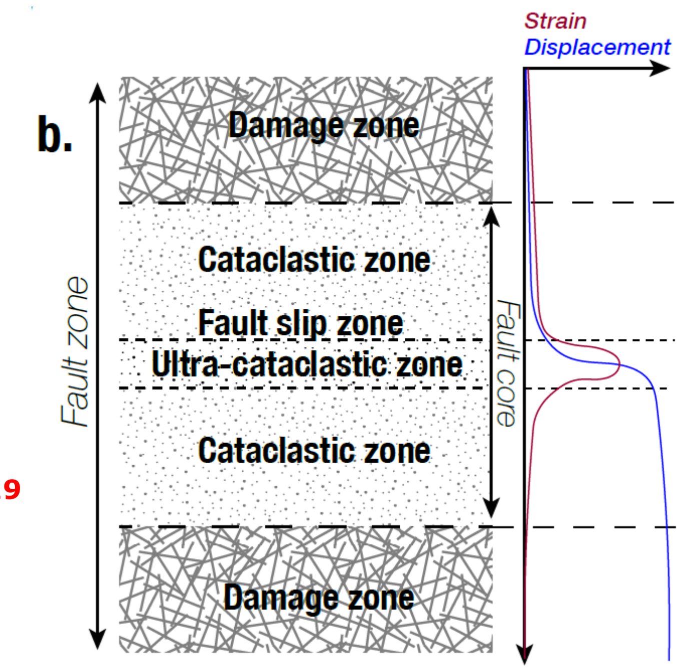

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The host rock: This area is elastic and undamaged, it transmits the tectonic loading to the fault

Rocks, faults, earthquakes – What is a fault?

-Real faults are more complex and inherently multiscale.

J. Muto et al. (2015), *Geophysical Research Letters*, 42.

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Rocks, faults, earthquakes – What is a fault?

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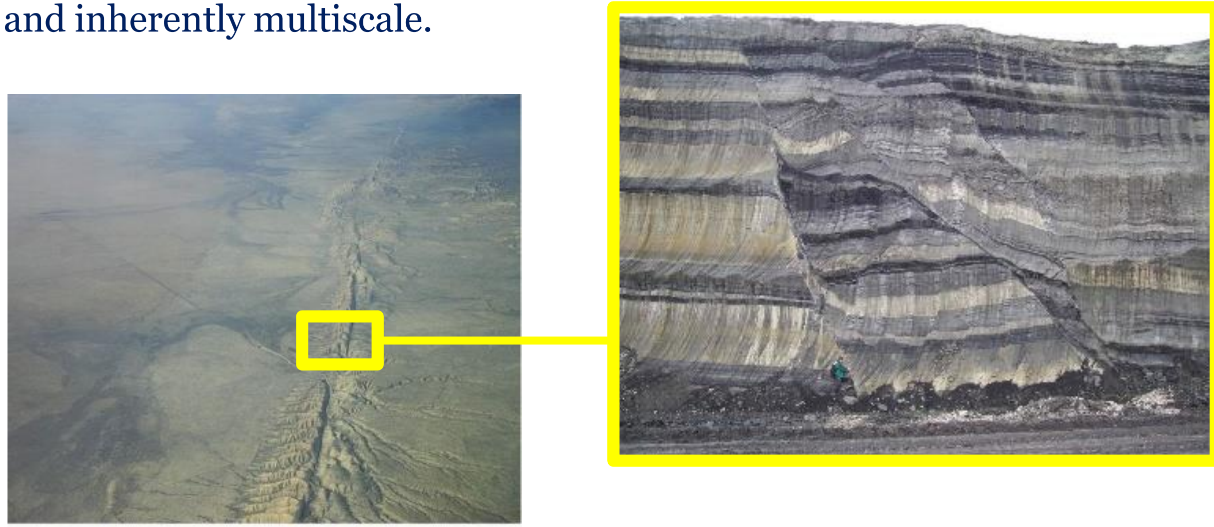

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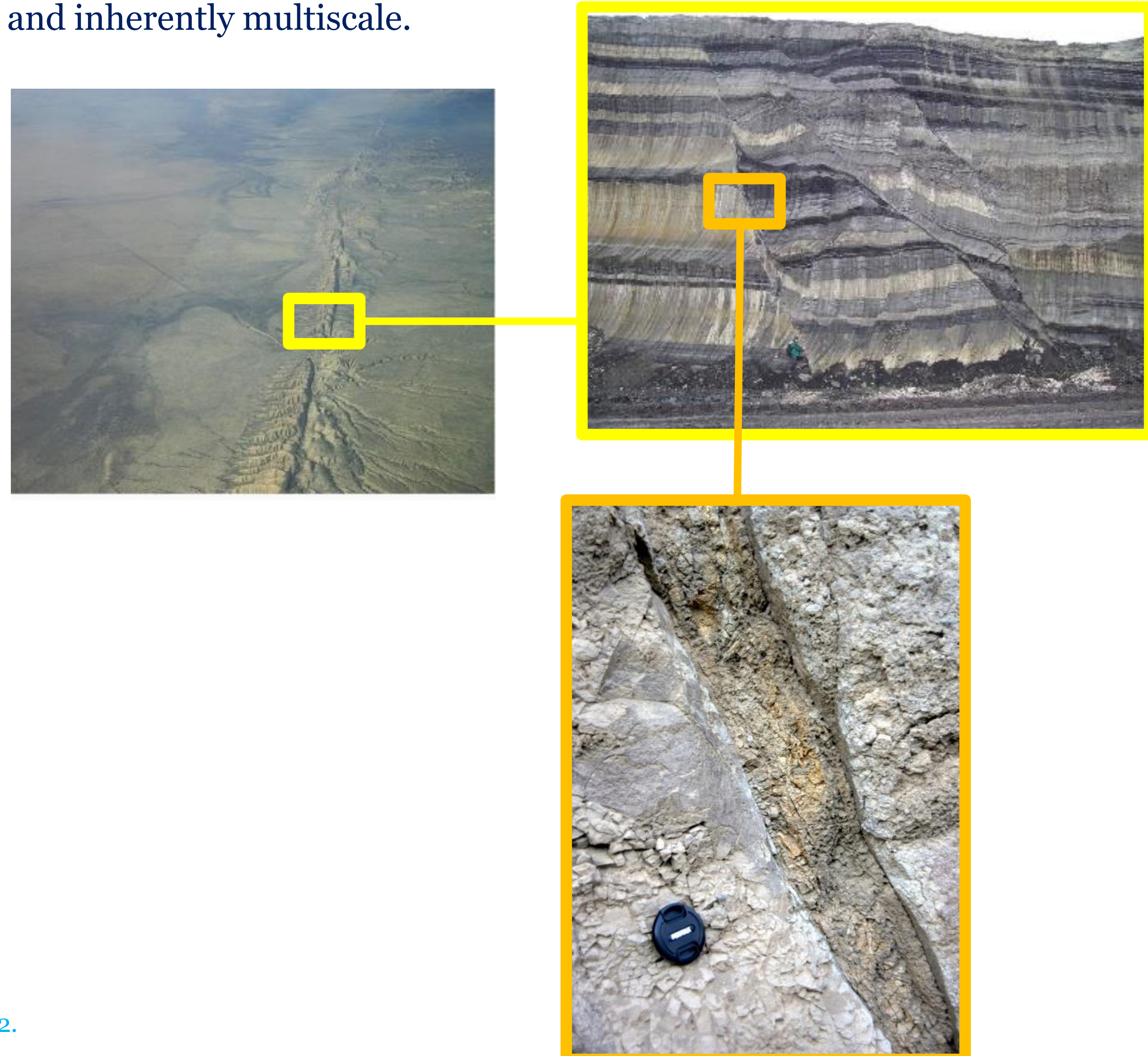

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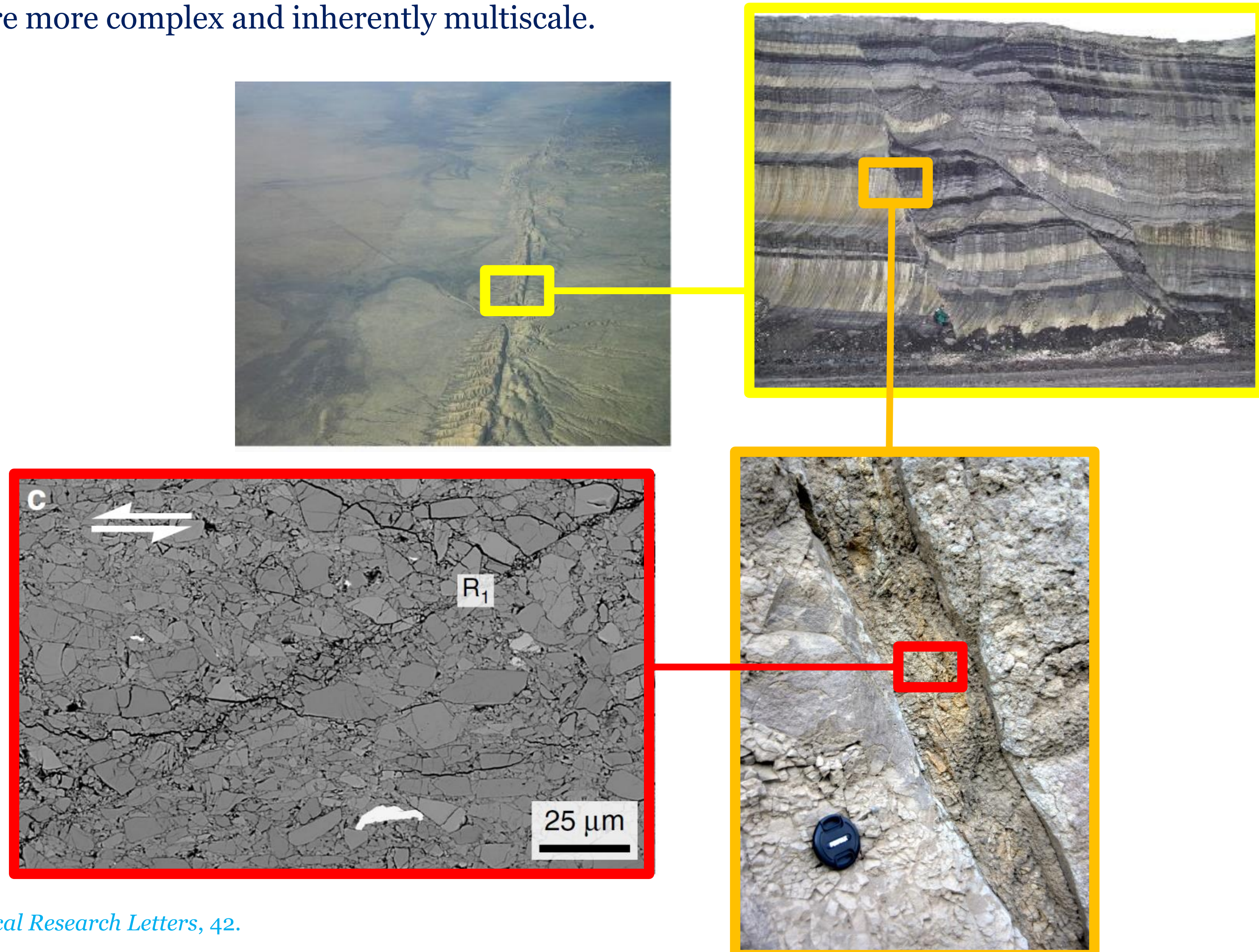

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Rocks, faults, earthquakes – What is a fault?

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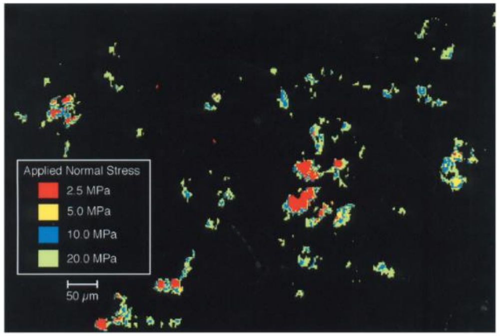

Dieterich and Kilgore (Pure and Appl. Geophys. 1994)

Rocks, faults, earthquakes – What is a fault?

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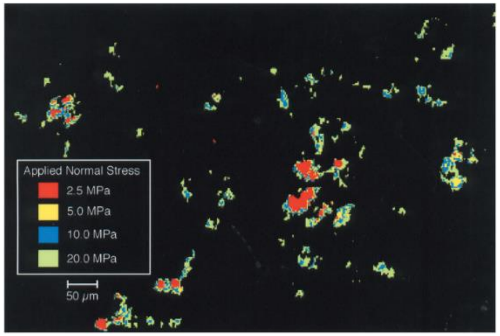

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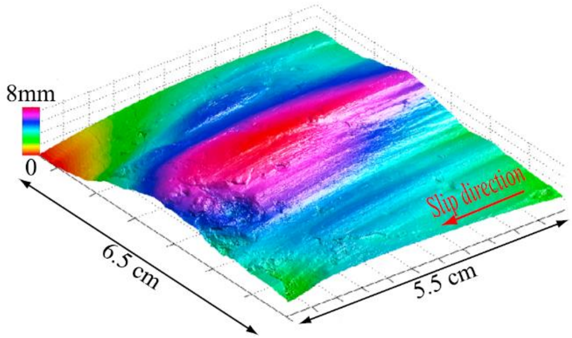

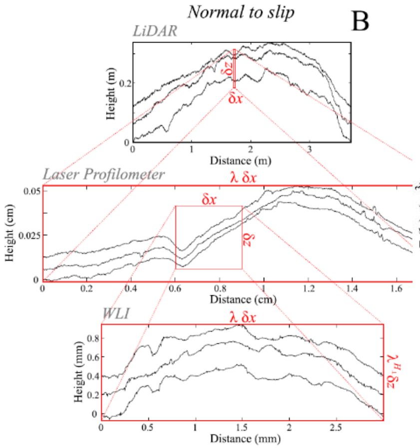

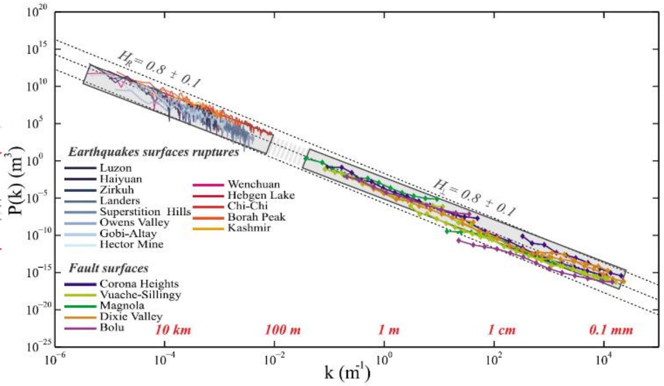

Candela et al. (JGR 2012)

Rocks, faults, earthquakes – What is a fault?

- All surfaces are rough.
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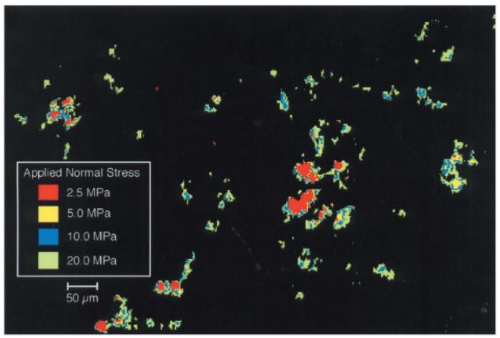
- Natural surfaces are found to be self-affine at all scales.
- This is also true for sand grains.



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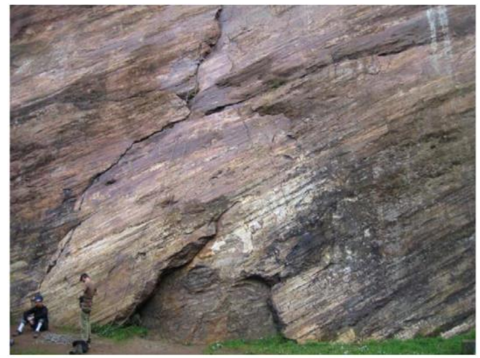

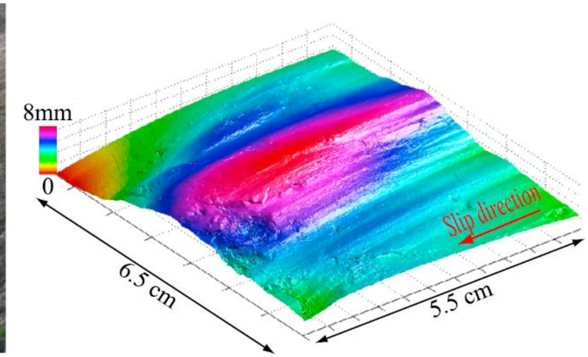

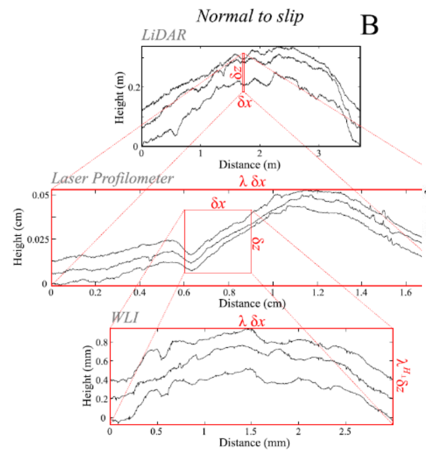

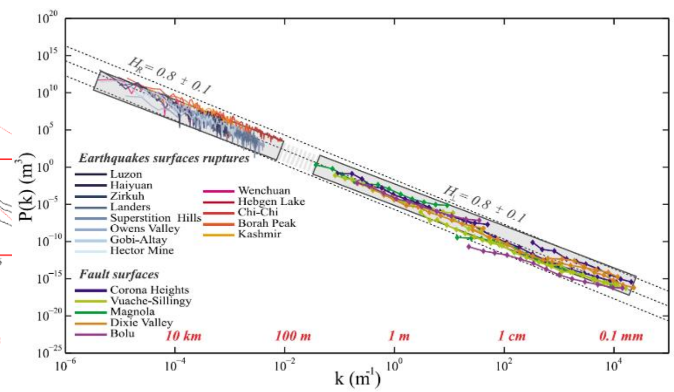

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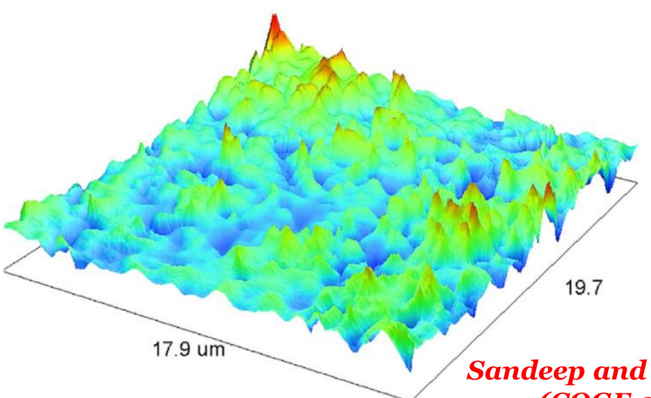
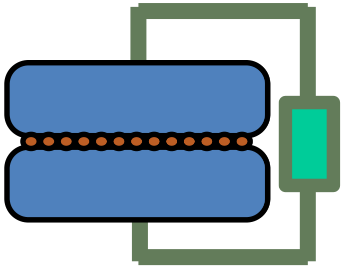
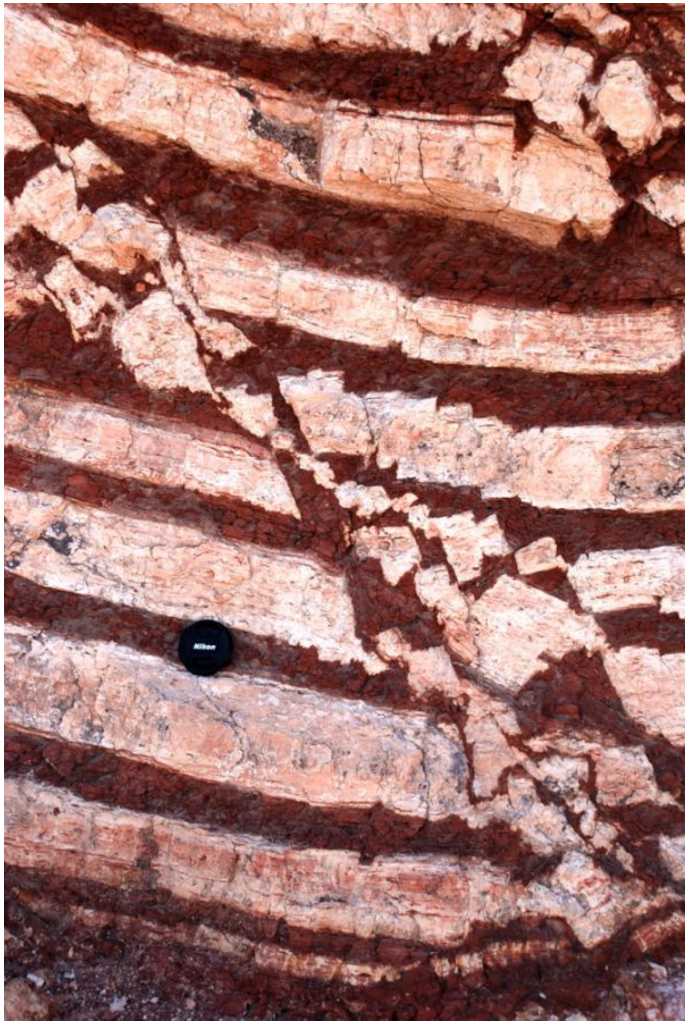


Sandeep and Senetakis (COGE 2019)

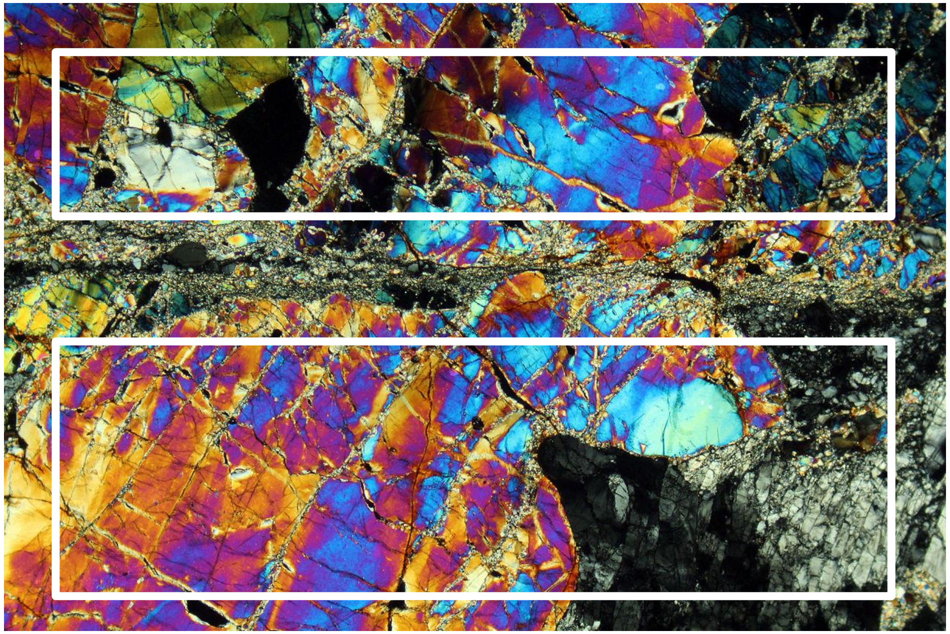
Rocks, faults, earthquakes – What is a fault?

- What is inside the fault core? Geological third bodies!





Early life of the fault: Large fragments of rock getting more and more fractured and pulverized as slip accumulates during several seismic events. This is often called a **Breccia**, i.e. a mixture of large and small pieces of fractured rock.



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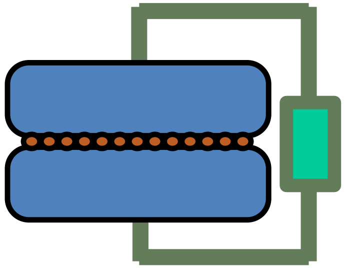

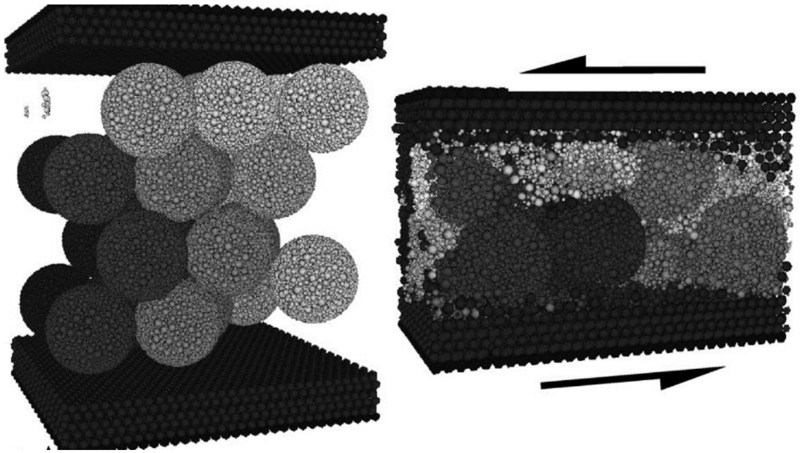

Mair and Abe 2008

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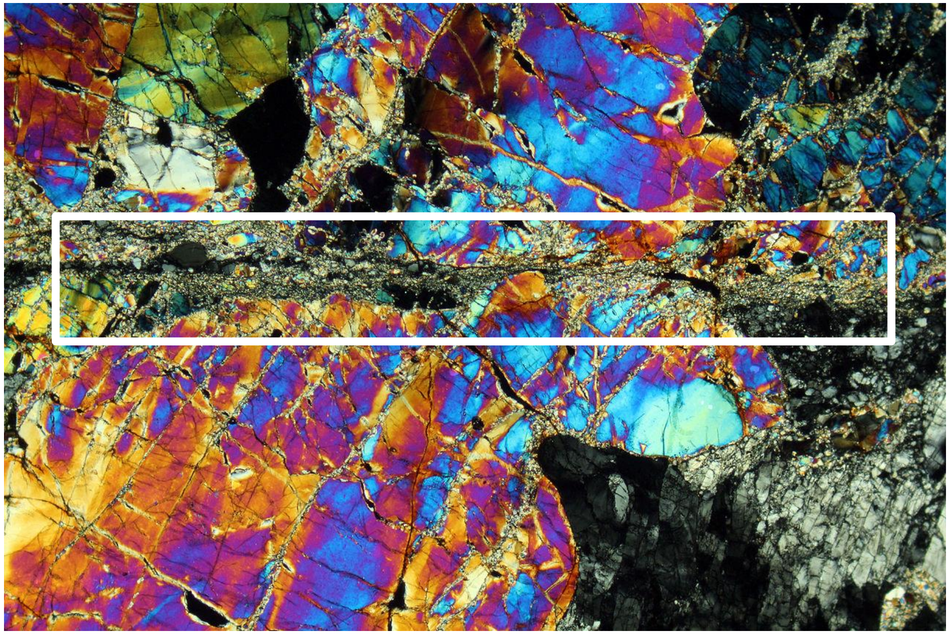
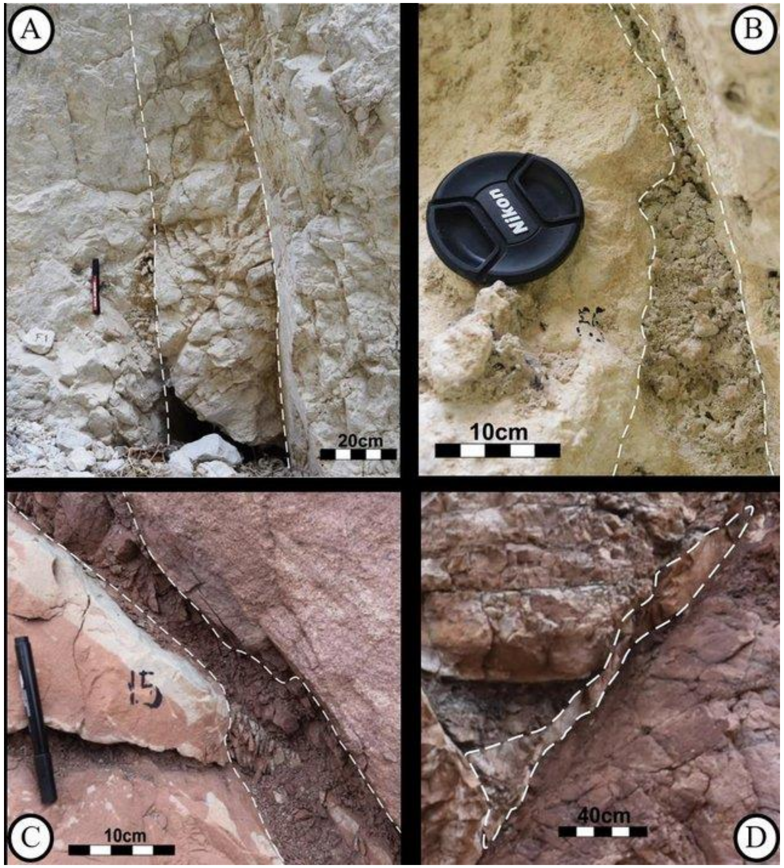


As slip accumulates: Grain size distribution tends towards a self-affine (i.e. fractal) law, which minimizes internal stresses in the grains.

This was demonstrated experimentally and numerically.

Rocks, faults, earthquakes – What is a fault?

- What is inside the fault core? Geological third bodies!



In a mature fault: The fault core gets filled with a very fine-grained powdery material : the **fault gouge**.

The thickness of this layer tends to increase as the fault gets more and more mature (i.e. as roughness gets more and more abraded and transformed into powder).

Rocks, faults, earthquakes – What is a fault?

- What is inside the fault core? Geological third bodies!

In a mature fault: If the fault gets smooth enough (in order to accommodate slip more easily) and long enough (in order to have large seismic events), frictional heating can result into melting of the gouge.

Rocks, faults, earthquakes – What is a fault?

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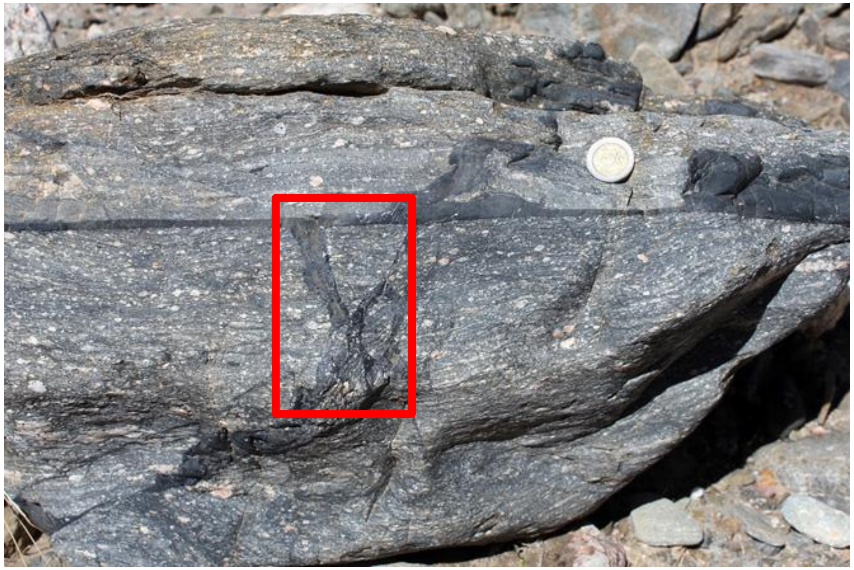
This type of rock is called "**pseudotachylites**". It is amorphous, rarely observed (because easily degraded), and can be located thanks to transversal injection veins.



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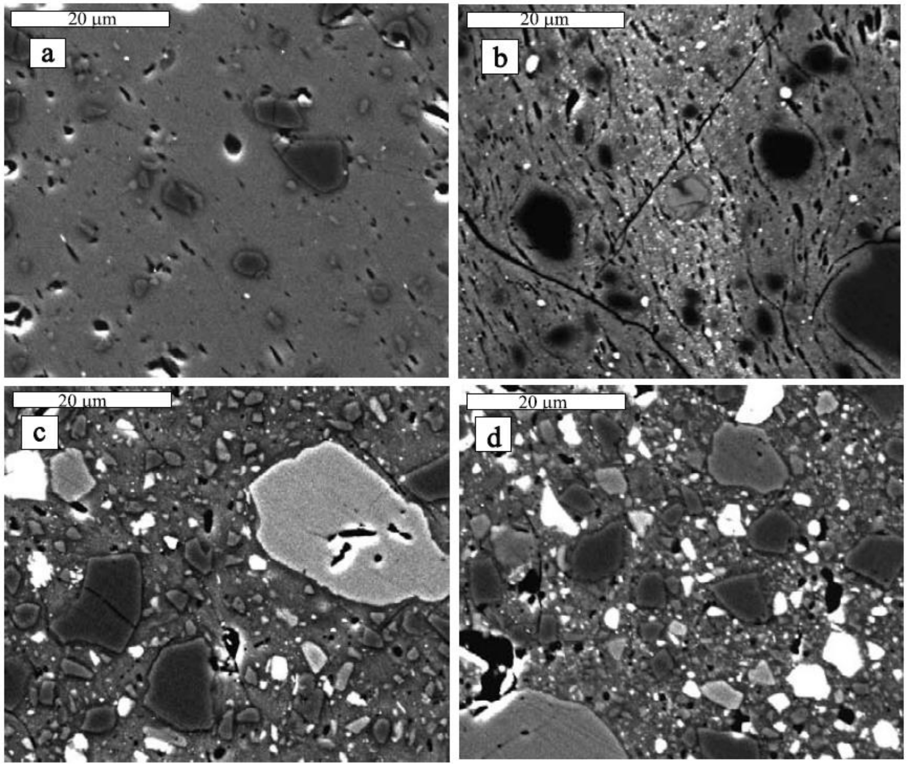

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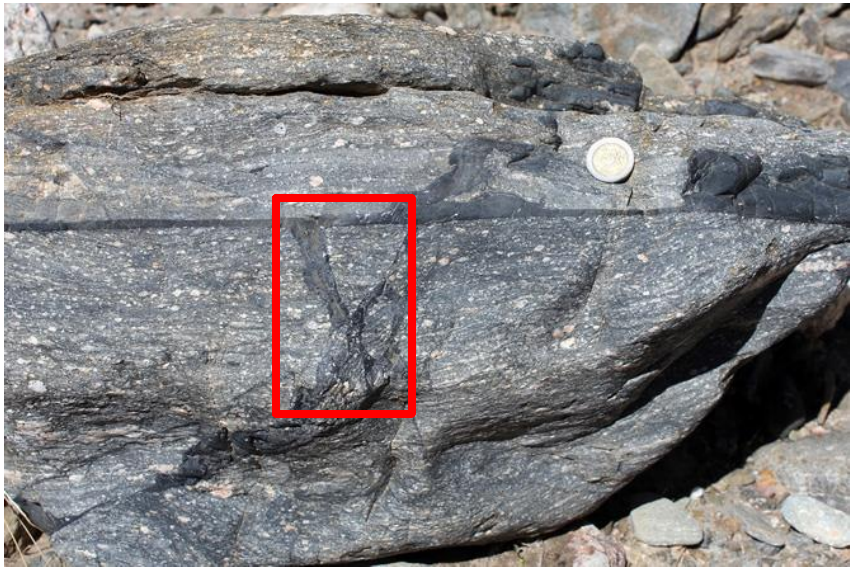


Partial melting: Most often, gouge melting is not complete, which gives rise to complex rheologies.

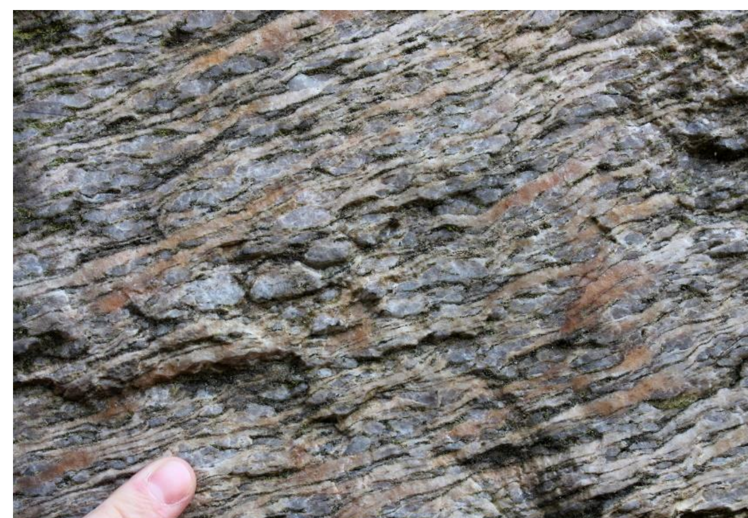
Rocks, faults, earthquakes – What is a fault?

- What is inside the fault core? Geological third bodies!

Deep faults: If the fault is sufficiently deep, it can accommodate slip by brittle-ductile mechanisms : this kind of fault rock is called “**Mylonites**”.

It is an extremely fined-grained rock, which exhibits lateral structuration and flow patterns.

Much closer to a plastic flow than to contact friction



Rocks, faults, earthquakes – What is a fault?

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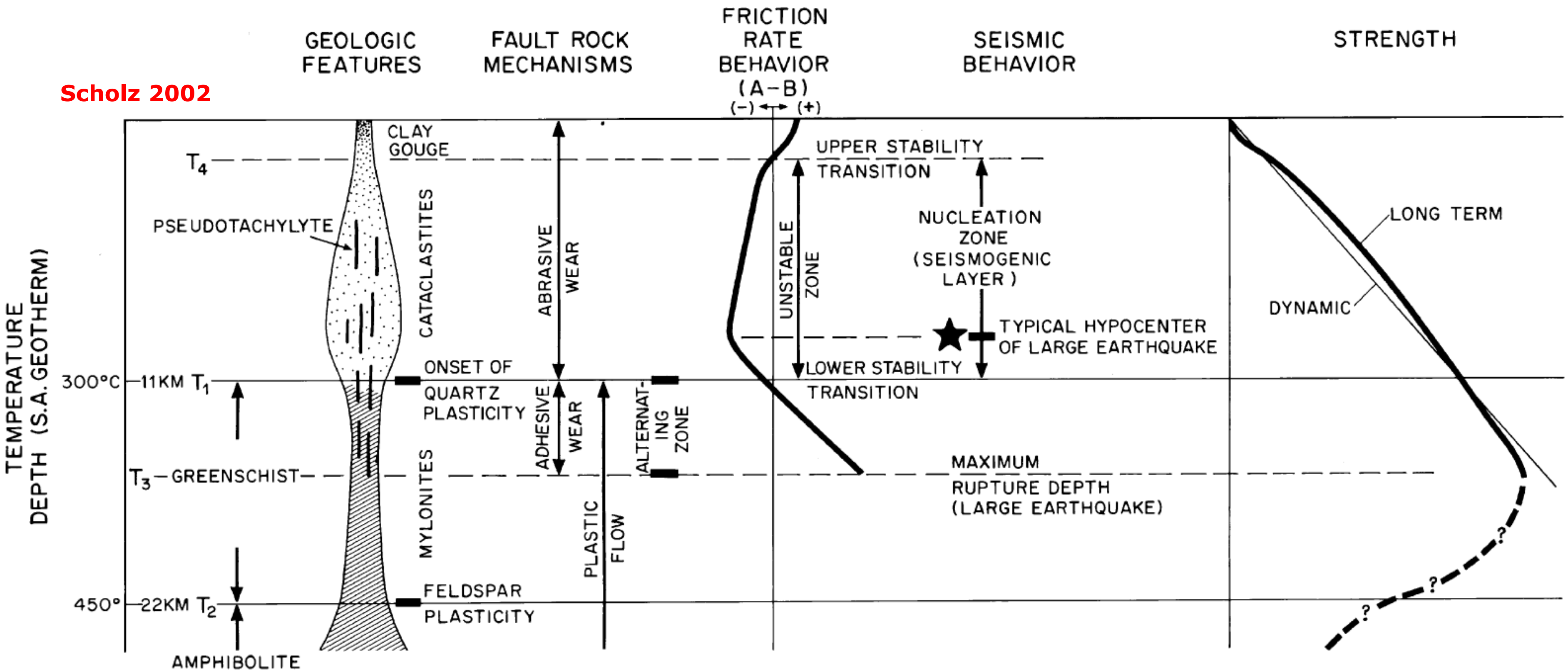
Scholz 2002



Fault structure: The same fault can have different sections with different levels of maturity, pressure, temperature, etc. Breccias, gouges, mylonites and pseudotachylites lead to a variety of frictional responses which complicate prediction and analysis.

Earthquakes

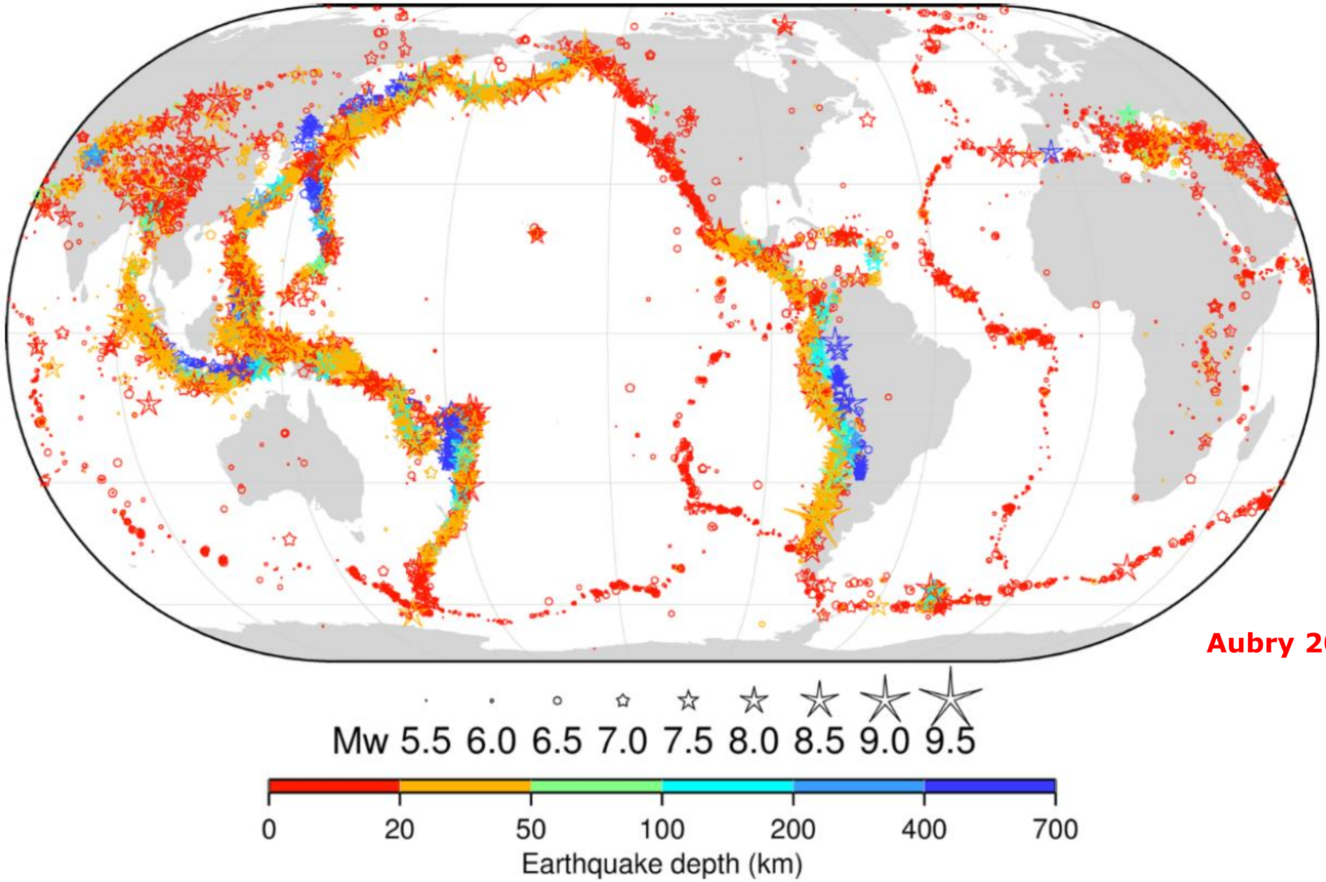
Guilhem Mollon[1]

[1]LaMCoS
INSA LYON
Villeurbanne, France

TRAMME, July 2023

Rocks, faults, earthquakes – What is an earthquake?

- Where do they happen?



Aubry 2019

Not everywhere! Most earthquakes happen on plate boundaries, and are driven by plates relative motions (up to a few centimeters per year). Intraplate earthquakes are also possible.

Rocks, faults, earthquakes – What is an earthquake?

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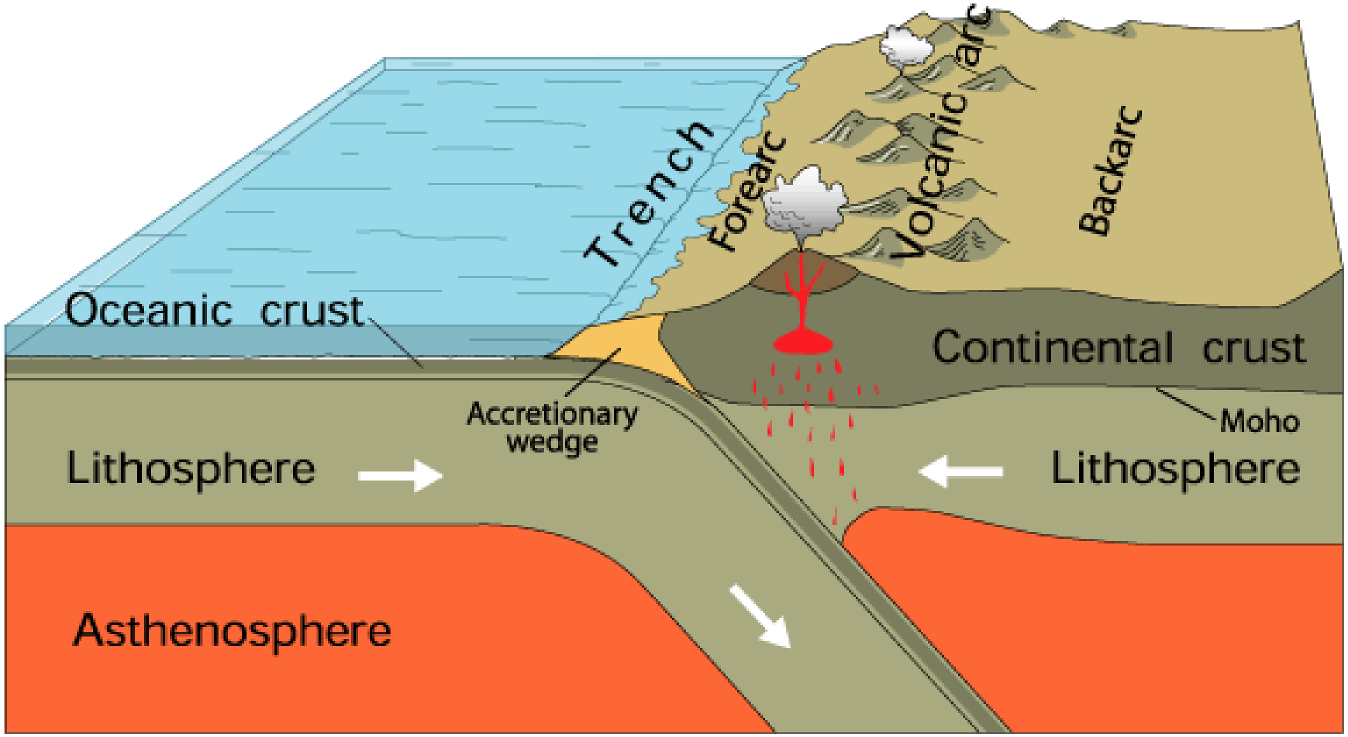

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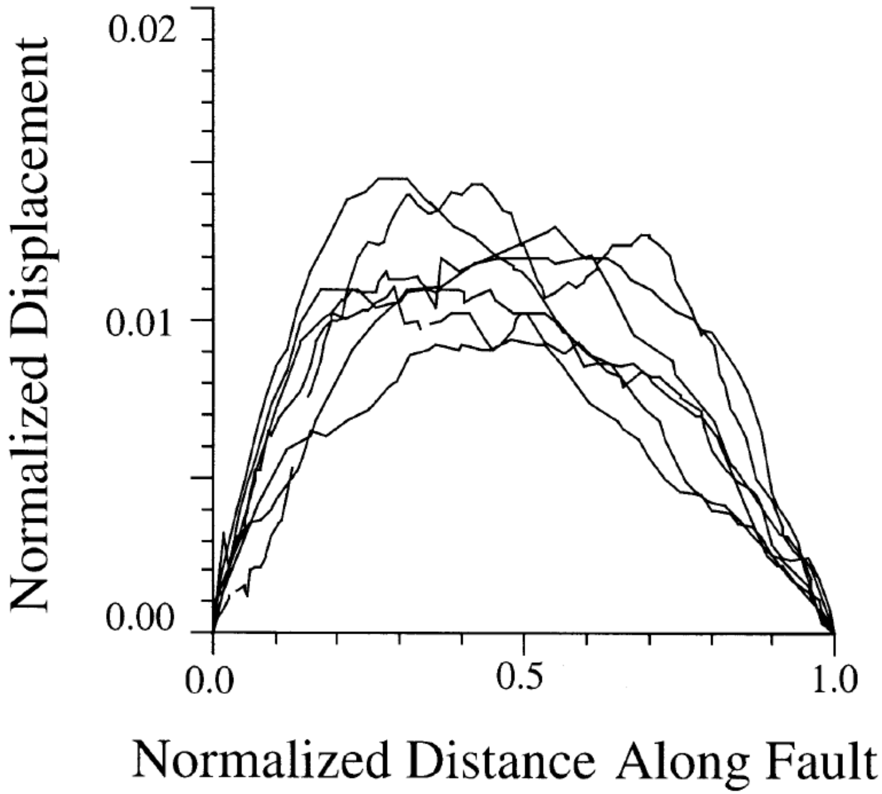
Largest earthquakes happen on large subduction zones (called "megathrust earthquakes")

Rocks, faults, earthquakes – What is an earthquake?

- An earthquake is a **sliding event** on a pre-existing fault.



Scholz 2002

Slip profiles on faults: all faults approximately follow the same slip profile, with a somewhat elliptical distribution of the total cumulated slip. Maximum slip is close to 1% of fault length.

An earthquake is only one small sliding event contributing to this general slip motion.

Rocks, faults, earthquakes – What is an earthquake?

- Sizes of earthquakes are extremely diverse.

Sliding distance : **1 mm**	Rupture size : **30*30 m**	Moment magnitude : **1**
Sliding distance : **3 mm**	Rupture size : **100*100 m**	Moment magnitude : **2**
Sliding distance : **1 cm**	Rupture size : **300*300 m**	Moment magnitude : **3**
Sliding distance : **3 cm**	Rupture size : **1*1 km**	Moment magnitude : **4**
Sliding distance : **10 cm**	Rupture size : **3*3 km**	Moment magnitude : **5**
Sliding distance : **30 cm**	Rupture size : **10*10 km**	Moment magnitude : **6**
Sliding distance : **1 m**	Rupture size : **15*60 km**	Moment magnitude : **7**
Sliding distance : **3 m**	Rupture size : **15*650 km**	Moment magnitude : **8**

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Seismic moment: amount of energy released by the earthquake:

$$M_0 = G \cdot A \cdot \Delta u$$

With G the elastic shear modulus, A the ruptured area, Δu the sliding distance. Generally Δu is heterogeneous (measured by geodetic and seismological methods), and an integral is used.

Moment magnitude: empirical formula to express seismic moment on the old Richter magnitude scale:

$$M_w = \frac{2}{3} log_{10}(M_0) - 10.7$$

Rocks, faults, earthquakes – What is an earthquake?

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Laboratory earthquakes

Sliding distance : **1 mm**	Rupture size : **30*30 m**	Moment magnitude : **1**
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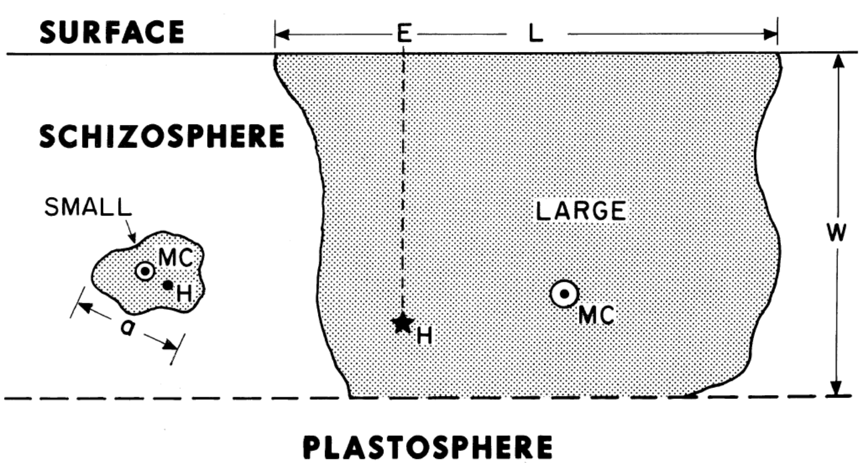
Energy*32

Energy*1000

Megathrust earthquakes



Scholz 2002

Rocks, faults, earthquakes – What is an earthquake?

- Largest earthquakes in history:

Rank	Date	Location	Event	Magnitude
1	May 22, 1960	Valdivia, Chile	1960 Valdivia earthquake	9.4–9.6
2	March 27, 1964	Prince William Sound, Alaska, United States	1964 Alaska earthquake	9.2
3	December 26, 2004	Indian Ocean, Sumatra, Indonesia	2004 Indian Ocean earthquake	9.1–9.3
4	March 11, 2011	Pacific Ocean, Tōhoku region, Japan	2011 Tōhoku earthquake	9.1[22]
5	June 11, 1585	Pacific Ocean, Aleutian Islands (now Alaska, United States)	1585 Aleutian Islands earthquake	9.25 (est.)
6	July 8, 1730	Valparaiso, Chile (then part of the Spanish Empire)	1730 Valparaiso earthquake	9.1–9.3 (est.)[23]
7	November 4, 1952	Kamchatka, Russian SFSR, Soviet Union	1952 Kamchatka earthquakes	9.0[24]
8	August 13, 1868	Arica, Chile (then Peru)	1868 Arica earthquake	8.5–9.0 (est.)
9	January 26, 1700	Pacific Ocean, US and Canada (then claimed by the Spanish Empire and the British Empire)	1700 Cascadia earthquake	8.7–9.2 (est.)
11	April 2, 1762	Chittagong, Bangladesh (then Kingdom of Mrauk U)	1762 Arakan earthquake	8.8 (est.)
11	November 25, 1833	Sumatra, Indonesia (then part of the Dutch East Indies)	1833 Sumatra earthquake	8.8 (est.)
12	November 26, 1852	Banda Islands, Indonesia (then part of the Dutch East Indies)	1852 Banda Sea earthquake	8.8 (est.)[25]
13	January 31, 1906	Ecuador – Colombia	1906 Ecuador–Colombia earthquake	8.8[26]
14	February 27, 2010	Offshore Maule, Chile	2010 Chile earthquake	8.8[26]
15	August 15, 1950	Assam, India – Tibet, China	1950 Assam–Tibet earthquake	8.7
16	October 28, 1707	Pacific Ocean, Shikoku region, Japan	1707 Hōei earthquake	8.7–9.3 (est.)
17	November 1, 1755	Atlantic Ocean, Lisbon, Portugal	1755 Lisbon earthquake	8.5–9.0
18	February 4, 1965	Rat Islands, Alaska, United States	1965 Rat Islands earthquake	8.7
19	October 28, 1746	Lima, Peru (then part of the Spanish Empire)	1746 Lima–Callao earthquake	8.6 (est.)
20	March 28, 1787	Oaxaca, Mexico (then part of the Spanish Empire)	1787 Mexico earthquake	8.6 (est.)
21	March 9, 1957	Andreanof Islands, Alaska, United States	1957 Andreanof Islands earthquake	8.6[26]
22	March 28, 2005	[Sumatra]], Indonesia	2005 Nias–Simeulue earthquake	8.6[26]
23	April 11, 2012	Indian Ocean, Sumatra, Indonesia	2012 Aceh earthquake	8.6
24	December 16, 1575	Valdivia, Chile (then part of the Spanish Empire)	1575 Valdivia earthquake	8.5 (est.)
25	November 24, 1604	Arica, Chile (then part of the Spanish Empire)	1604 Arica earthquake	8.5 (est.)
26	May 13, 1647	Santiago, Chile (then part of the Spanish Empire)	1647 Santiago earthquake	8.5 (est.)
27	May 24, 1751	Concepción, Chile (then part of the Spanish Empire)	1751 Concepción earthquake	8.5 (est.)
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Rocks, faults, earthquakes – What is an earthquake?

- Deadliest earthquakes in history:

Rank	Event	Date	Location	Fatalities	Magnitude	Notes
1	1556 Shaanxi earthquake	January 23, 1556	Shaanxi, China	820,000–830,000[132]	8.0	Estimated death toll in Shaanxi, China
2	1976 Tangshan earthquake	July 28, 1976	Hebei, China	242,769–700,000+ [133][134][135]	7.8	
3	1920 Haiyuan earthquake	December 16, 1920	Ningxia–Gansu, China	273,400[133][136]	7.8	Major fractures, landslides.
4	526 Antioch earthquake	May 21, 526	Antioch, Byzantine Empire (modern-day Turkey)	250,000[137]	7.0[138]	Procopius (II.14.6), sources based on John of Ephesus.
5	2004 Indian Ocean earthquake and tsunami	December 26, 2004	Indian Ocean, Sumatra, Indonesia	227,898	9.1–9.3	Became the deadliest tsunami on record, causing nearly 240,000 deaths from the earthquake and resulting tsunami across 14 countries.
6	1138 Aleppo earthquake	October 11, 1138	Aleppo, Syria	130,000–230,000[139]	7.1[139]	The figure of 230,000 dead is based on a historical conflation of this earthquake with earthquakes in November 1137 on the Jazira plain and on September 30, 1139 in the Azerbaijani city of Ganja. The first mention of a 230,000 death toll was by Ibn Taghribirdi in the fifteenth century.[140]
7	2010 Haiti earthquake	January 12, 2010	Haiti	100,000-316,000 (estimates)	7.0	Estimates vary from 316,000 (Haitian government) to 222,570 (UN OCHA estimate)[141] to 158,000 (*Medicine, Conflict and Survival*) to between 85,000 and 46,000 (report commissioned by USAID).[142][143]
8	1303 Hongdong earthquake	July 25, 1303	Shanxi, China	200,000[144]	8.0	Taiyuan and Pingyang were leveled.
9	856 Damghan earthquake	December 22, 856	Damghan, Iran	200,000	7.9 M_s	
10	893 Ardabil earthquake	March 22, 893	Ardabil, Iran	150,000	Unknown	Reports probably relate to the 893 Dvin earthquake, due to misreading of the Arabic word for Dvin, 'Dabil' as 'Ardabil'.[145] This is regarded as a 'fake earthquake'.[146]
11	533 Aleppo earthquake	November 29, 533	Syria	130,000[147]	Unknown	
12	1908 Messina earthquake	December 28, 1908	Messina, Italy	123,000[148]	7.1	The ground shook for 30 to 40 seconds around 5:20 am, and destruction occurred within a 300 km radius. 91% of structures in Messina were destroyed and ~70,000 residents died. Rescuers searched for weeks, and whole families were pulled out alive days later. A 40-foot (12 m) tsunami struck nearby coasts. Reggio Calabria on the Italian mainland also suffered heavy damage.
13	1948 Ashgabat earthquake	October 6, 1948	Ashgabat, Turkmen SSR (modern-day Turkmenistan)	10,000–110,000	7.3 M_s	

Rocks, faults, earthquakes – What is an earthquake?

- Deadliest earthquakes in history:

Rank	Event	Date	Location	Fatalities	Magnitude	Notes
1	1556 Shaanxi earthquake	January 23, 1556	Shaanxi, China	820,000–830,000[132]	8.0	Estimated death toll in Shaanxi, China
2	1976 Tangshan earthquake	July 28, 1976	Hebei, China	242,769–700,000+ [133][134][135]	7.8	
3	1920 Haiyuan earthquake	December 16, 1920	Ningxia–Gansu, China	273,400[133][136]	7.8	Major fractures, landslides.
4	526 Antioch earthquake	May 21, 526	Antioch, Byzantine Empire (modern-day Turkey)	250,000[137]	7.0[138]	Procopius (II.14.6), sources based on John of Ephesus.
5	2004 Indian Ocean earthquake and tsunami	December 26, 2004	Indian Ocean, Sumatra, Indonesia	227,898	9.1–9.3	Became the deadliest tsunami on record, causing nearly 240,000 deaths from the earthquake and resulting tsunami across 14 countries.
6	1138 Aleppo earthquake	October 11, 1138	Aleppo, Syria	130,000–230,000[139]	7.1[139]	The figure of 230,000 dead is based on a historical conflation of this earthquake with earthquakes in November 1137 on the Jazira plain and on September 30, 1139 in the Azerbaijani city of Ganja. The first mention of a 230,000 death toll was by Ibn Taghribirdi in the fifteenth century.[140]
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Correlation with size:

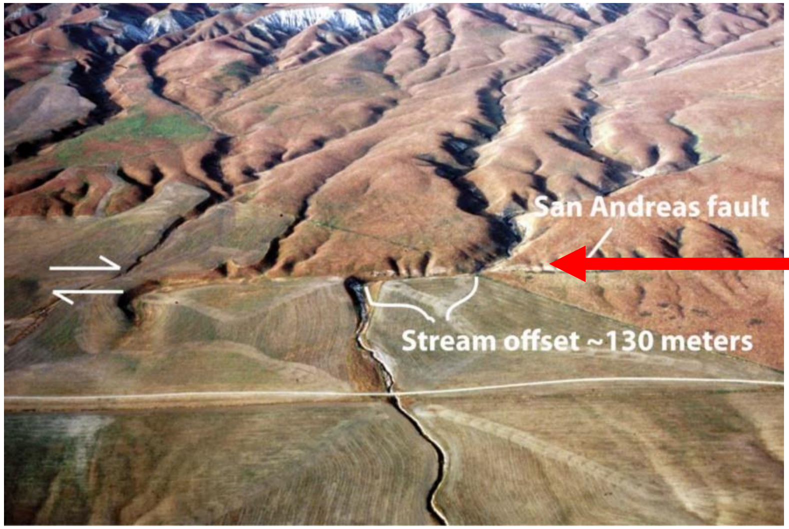
Big doesn't mean deadly, moderate doesn't mean harmless

Other important criteria: depth, rupture velocity, quality of infrastructures

Rocks, faults, earthquakes – What is an earthquake?

Contact instability in an interface called "Fault"

San-Andreas Fault



Cello, C-string

Loading system velocity: ~10^{-9} m/s

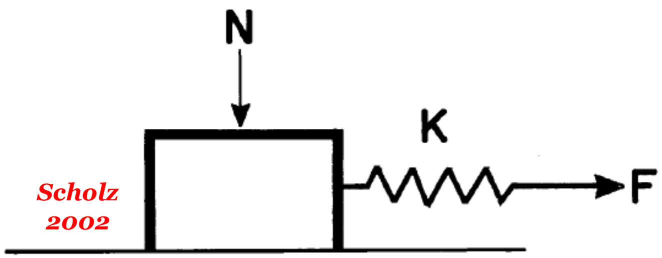
Frequency: ~10^{-9}-10^{-11} Hz

Loading system velocity: ~1 m/s

Frequency: 65 Hz

Rocks, faults, earthquakes – What is an earthquake?

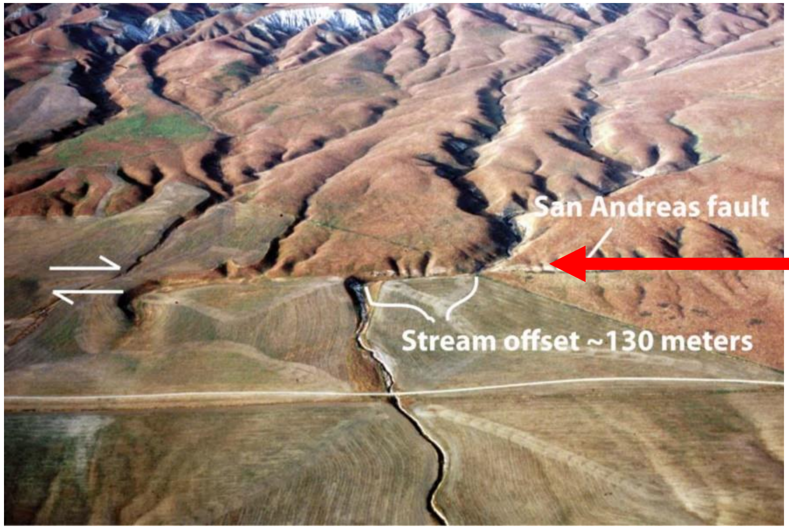
- A simple physical approach: the spring slider model



Scholz 2002

San-Andreas Fault

Cello, C-string



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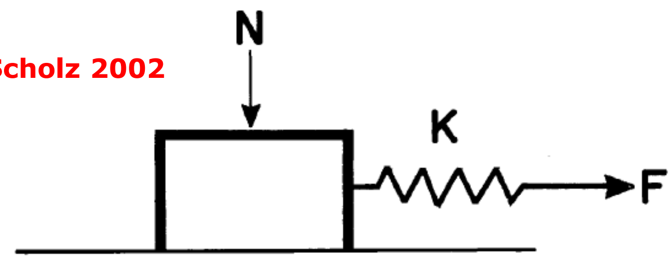
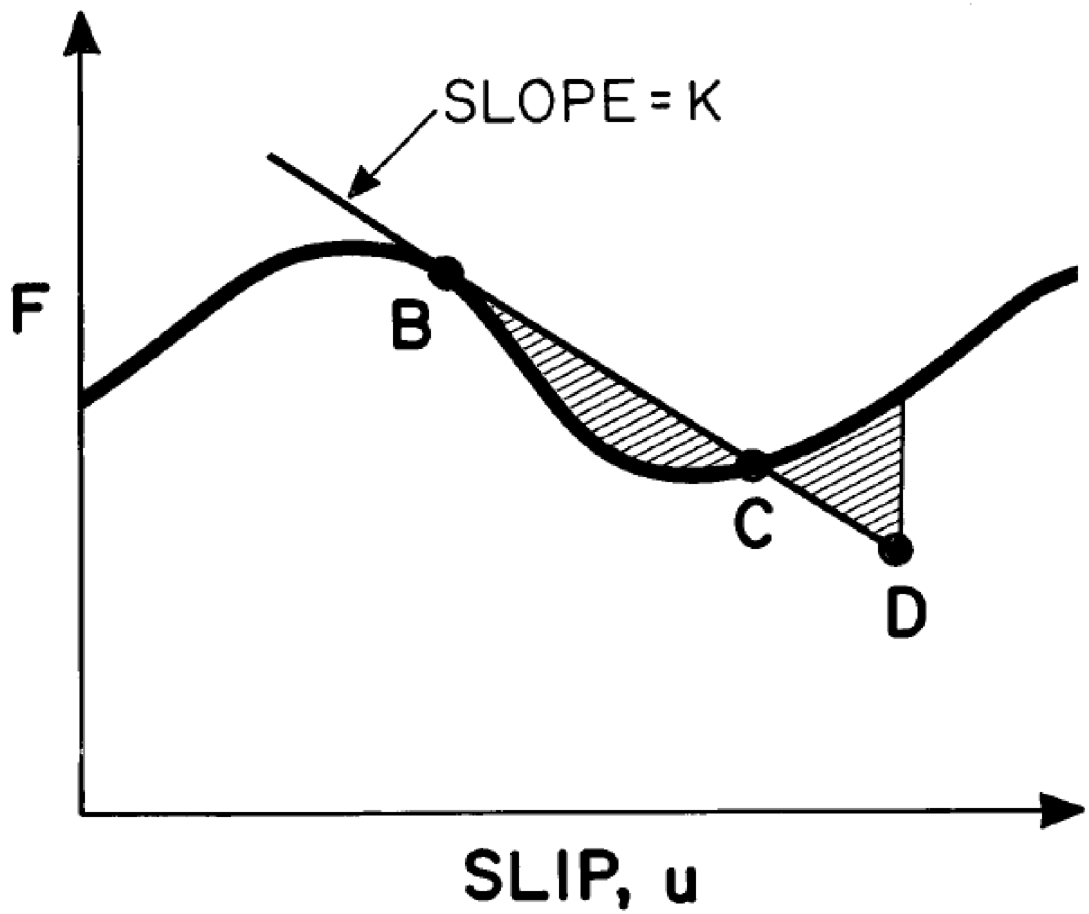
Scholz 2002

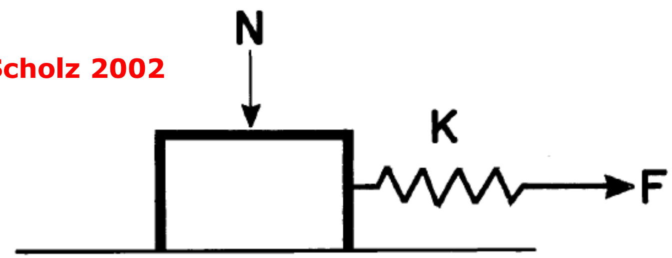




Rocks, faults, earthquakes – What is an earthquake?

- A simple physical approach: the spring slider model

Scholz 2002

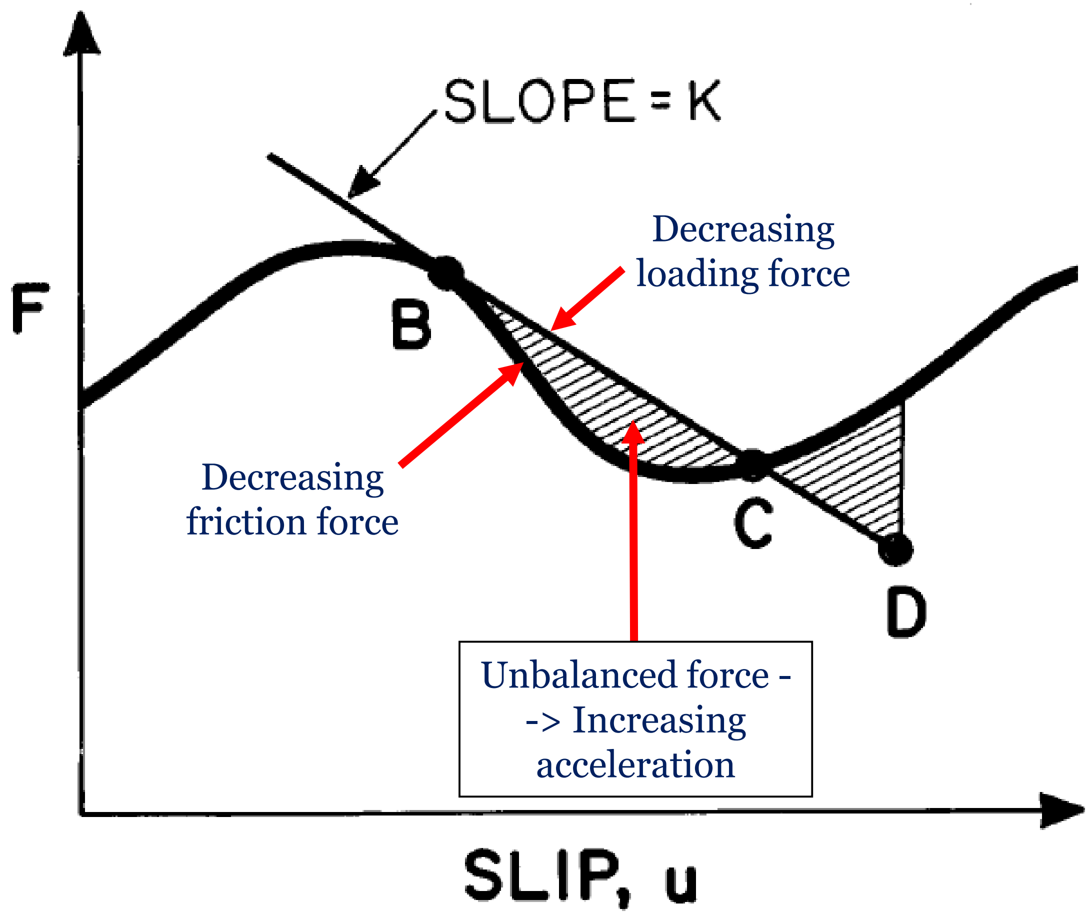


Contact instability:

If , at a certain time in the contact history, the friction force decreases with slip **faster** than the decrease of the elastic loading force,

Then there is a deficit of resisting force and a positive feedback to slip: sliding renders sliding easier.

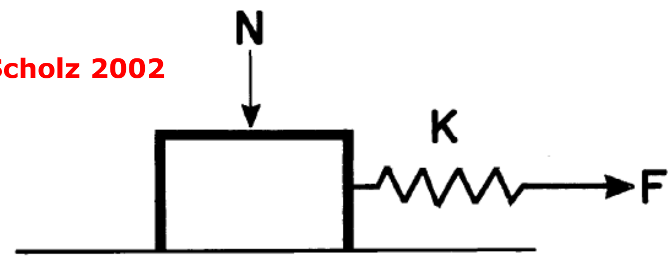
-> Dynamic instability!



Rocks, faults, earthquakes – What is an earthquake?

- A simple physical approach: the spring slider model

Scholz 2002



Hence instability requires:

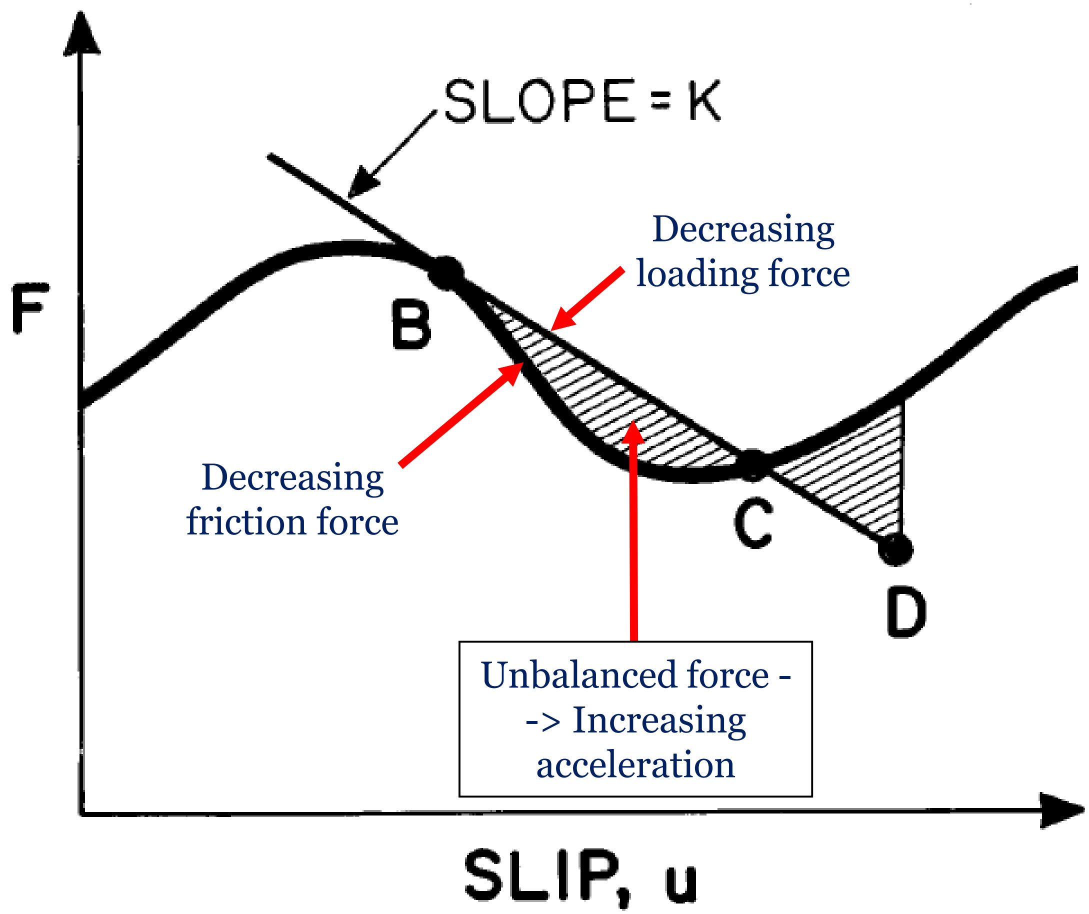
1. A weakening friction law
2. A sufficiently soft loading system

The value of the friction is irrelevant! Only its evolution with slip is important.

Instability occurs if:

$$\frac{(\mu_s - \mu_d) \cdot \sigma_n}{D_c} > K$$

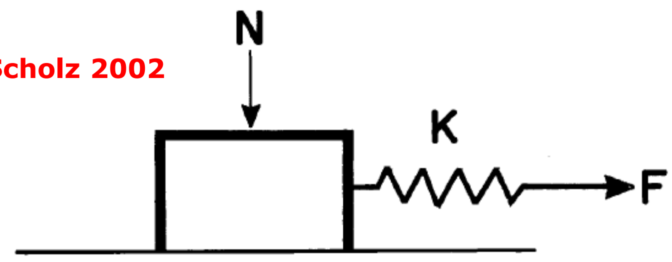
With μ_s the static friction, μ_d the dynamic friction, and D_c the weakening distance.



Rocks, faults, earthquakes – What is an earthquake?

- A simple physical approach: the spring slider model

Scholz 2002



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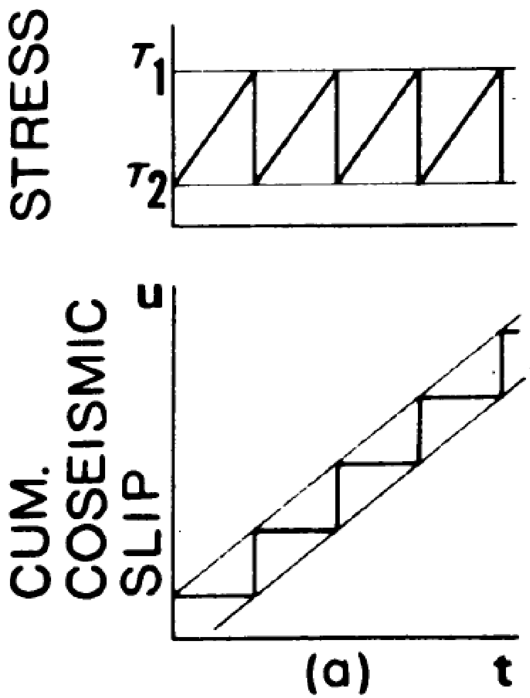
With μ_s the static friction, μ_d the dynamic friction, and D_c the weakening distance.

For a single slider:

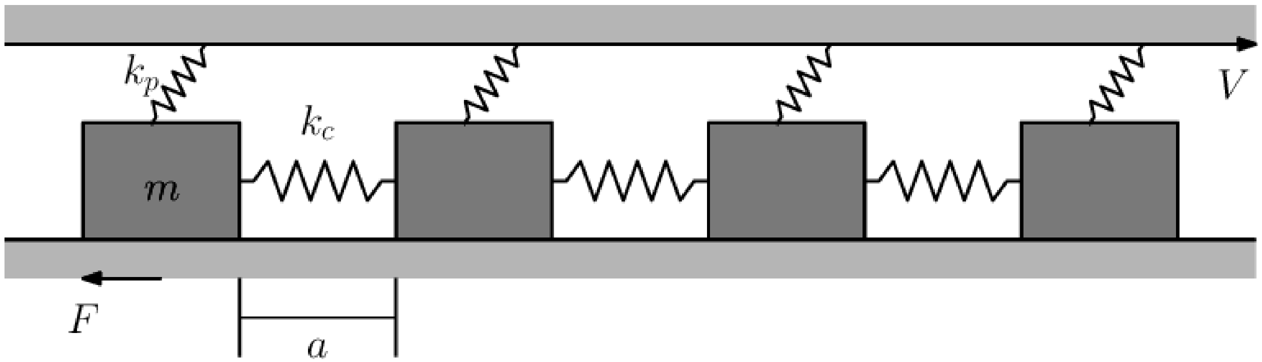
Periodic shift between "stuck" interseismic periods and "slipping" coeismic periods.



The so famous "Stick-slip"!

Rocks, faults, earthquakes – What is an earthquake?

- A more interesting case: the Burridge-Knopoff model



Several spring-slider models interacting with elastic springs:

If one slider slips, it is a small event.

If all sliders slip, it is a large event.

-> Possibility to account for all the spectrum of possible events on a theoretical fault.

Rocks, faults, earthquakes – What is an earthquake?

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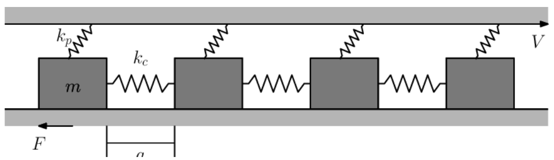

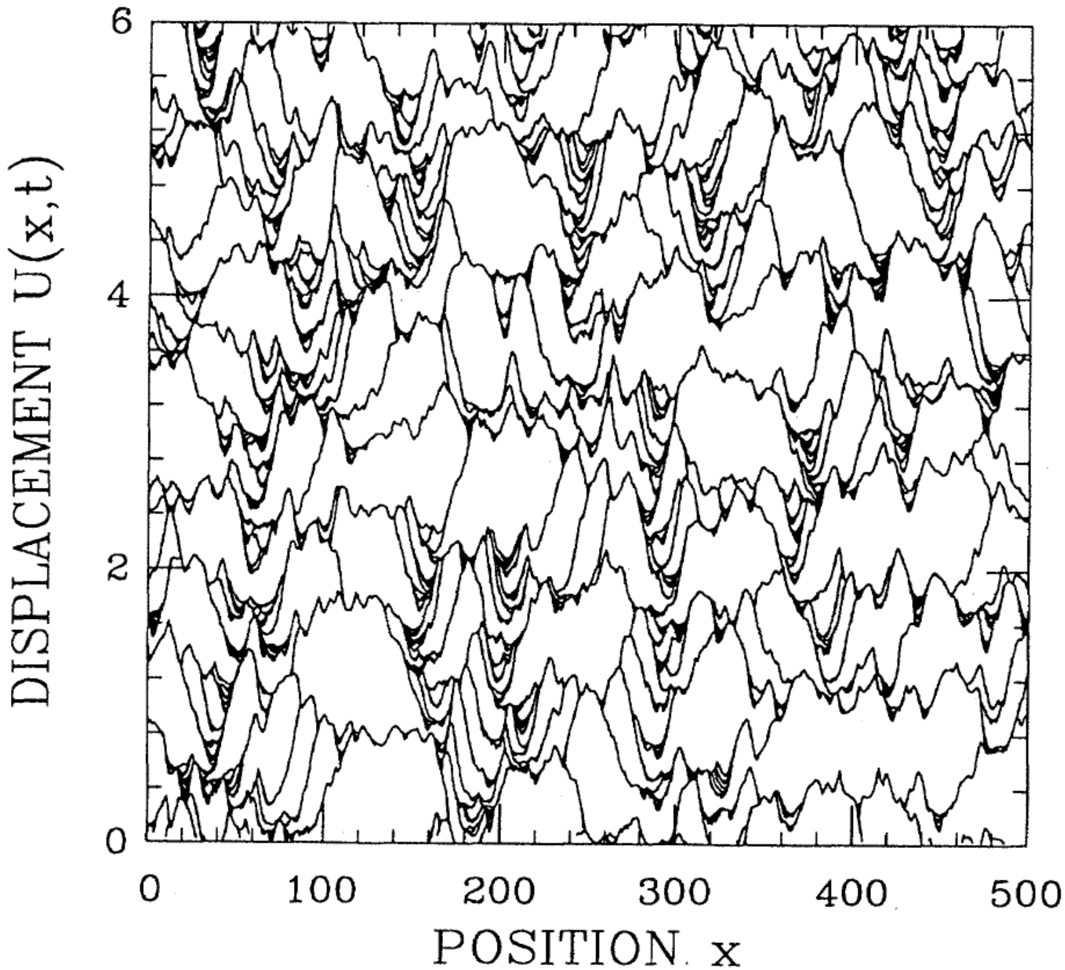

Carlson et al. 1992

Typical sliding history on such a complex fault: a deterministic but chaotic response!

Rocks, faults, earthquakes – What is an earthquake?

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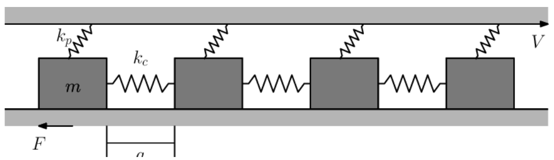

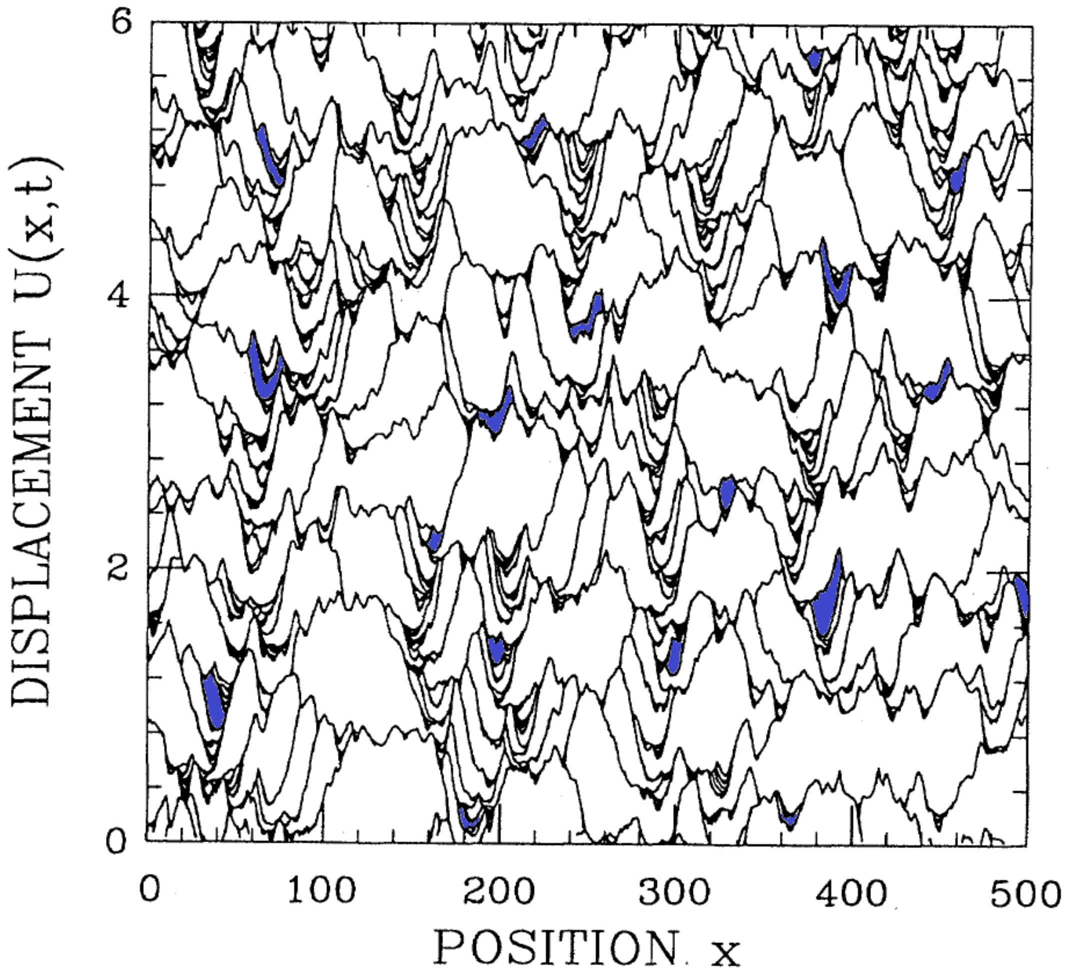

Small events:

-> frequent

-> limited size

-> limited slip

Carlson et al. 1992

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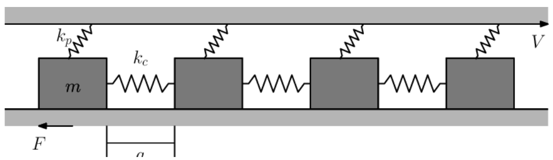

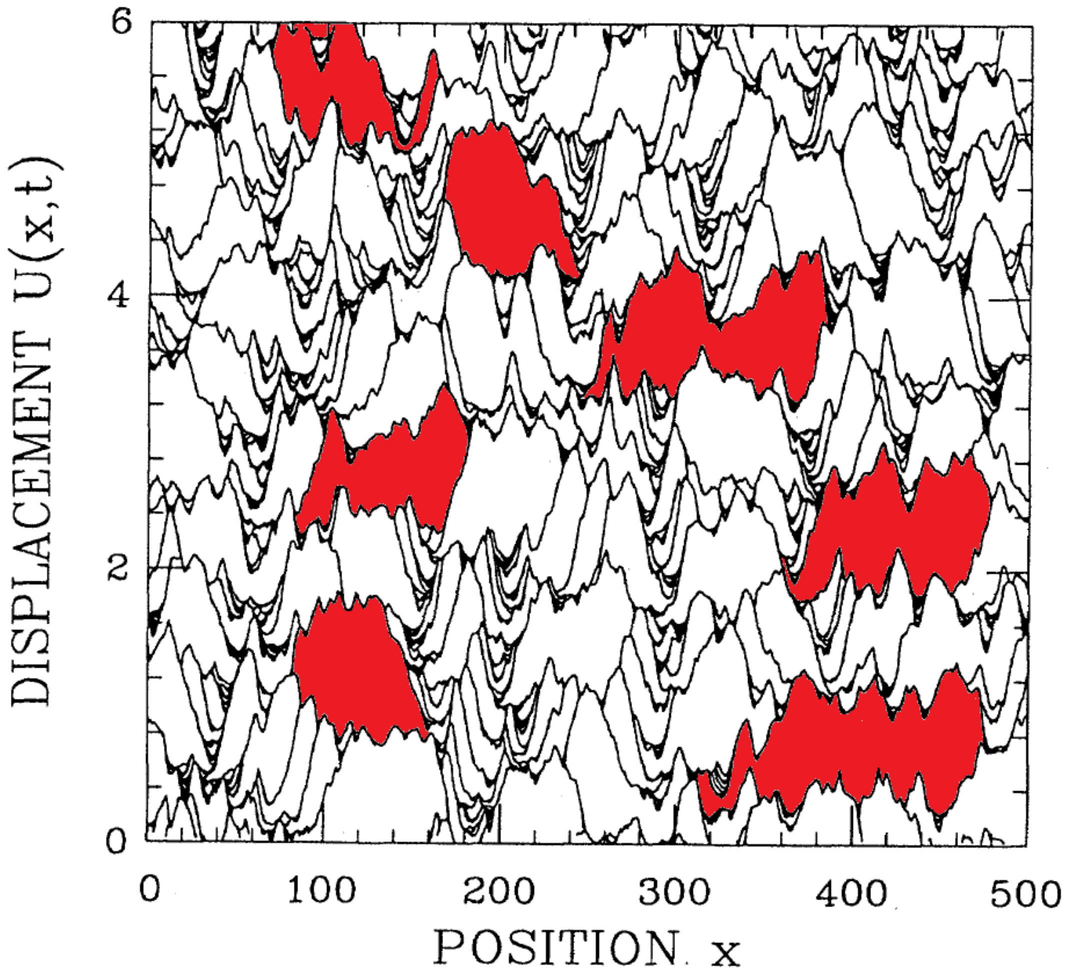

Large events:

-> rare

-> large size

-> large slip

Carlson et al. 1992

Typical sliding history on such a complex fault: a deterministic but chaotic response!

Rocks, faults, earthquakes – What is an earthquake?

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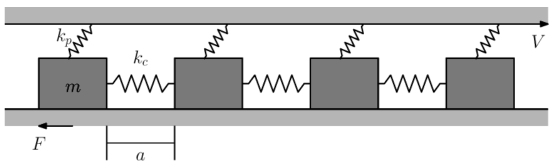
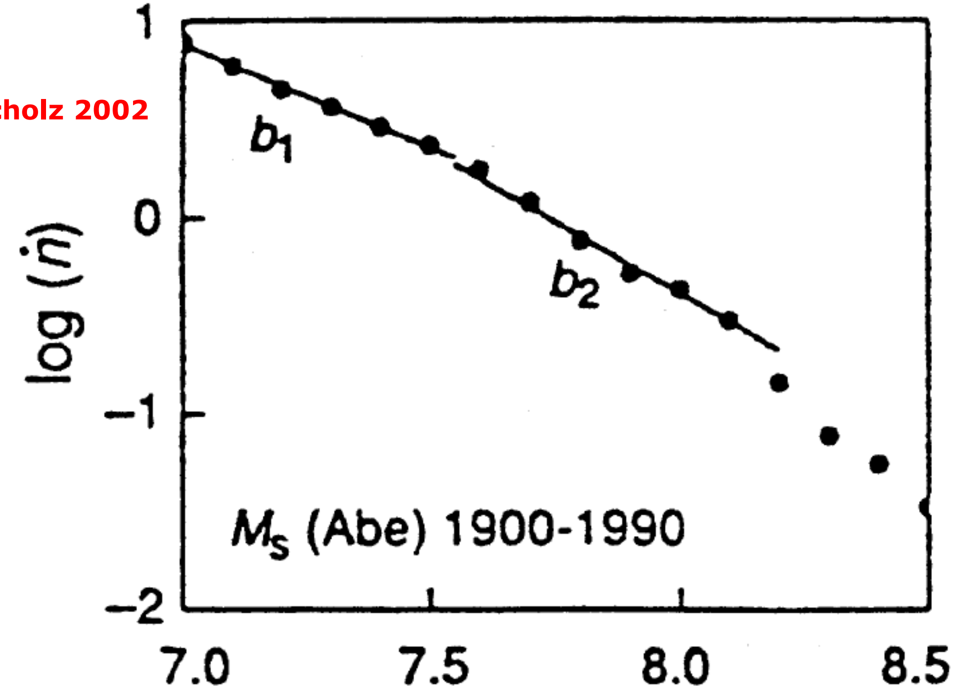


Scholz 2002



A very famous graph: the magnitude-frequency distribution.

Plotted on a log-log scale, we have a quasi-linear decay of the frequency of events as a function of their magnitude.

Rocks, faults, earthquakes – What is an earthquake?

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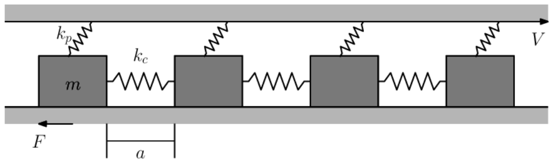

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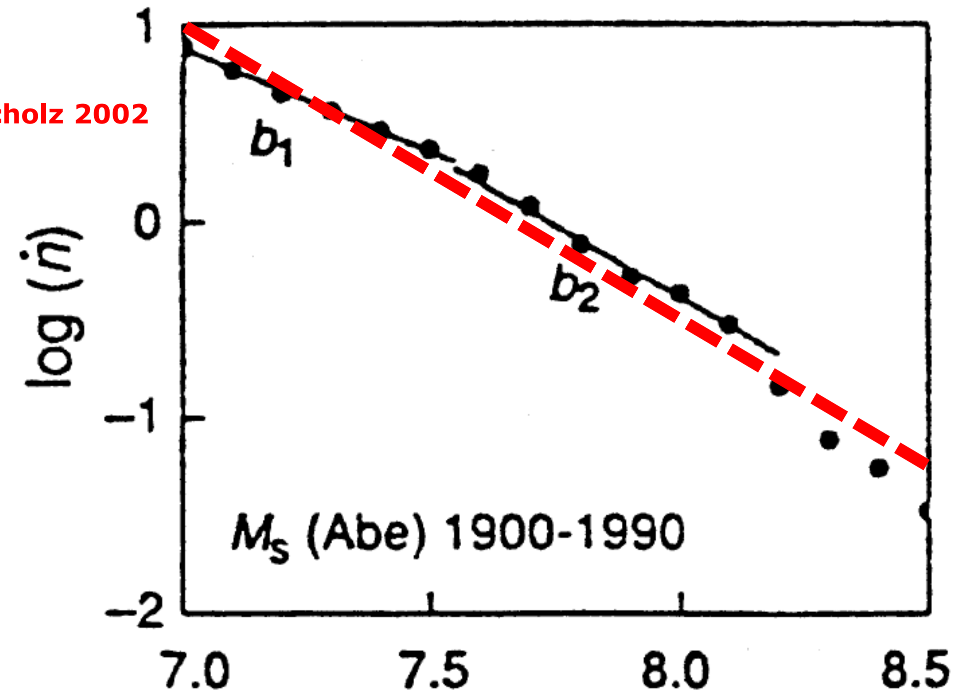


A very famous graph: the magnitude-frequency distribution.

Plotted on a log-log scale, we have a quasi-linear decay of the frequency of events as a function of their magnitude.

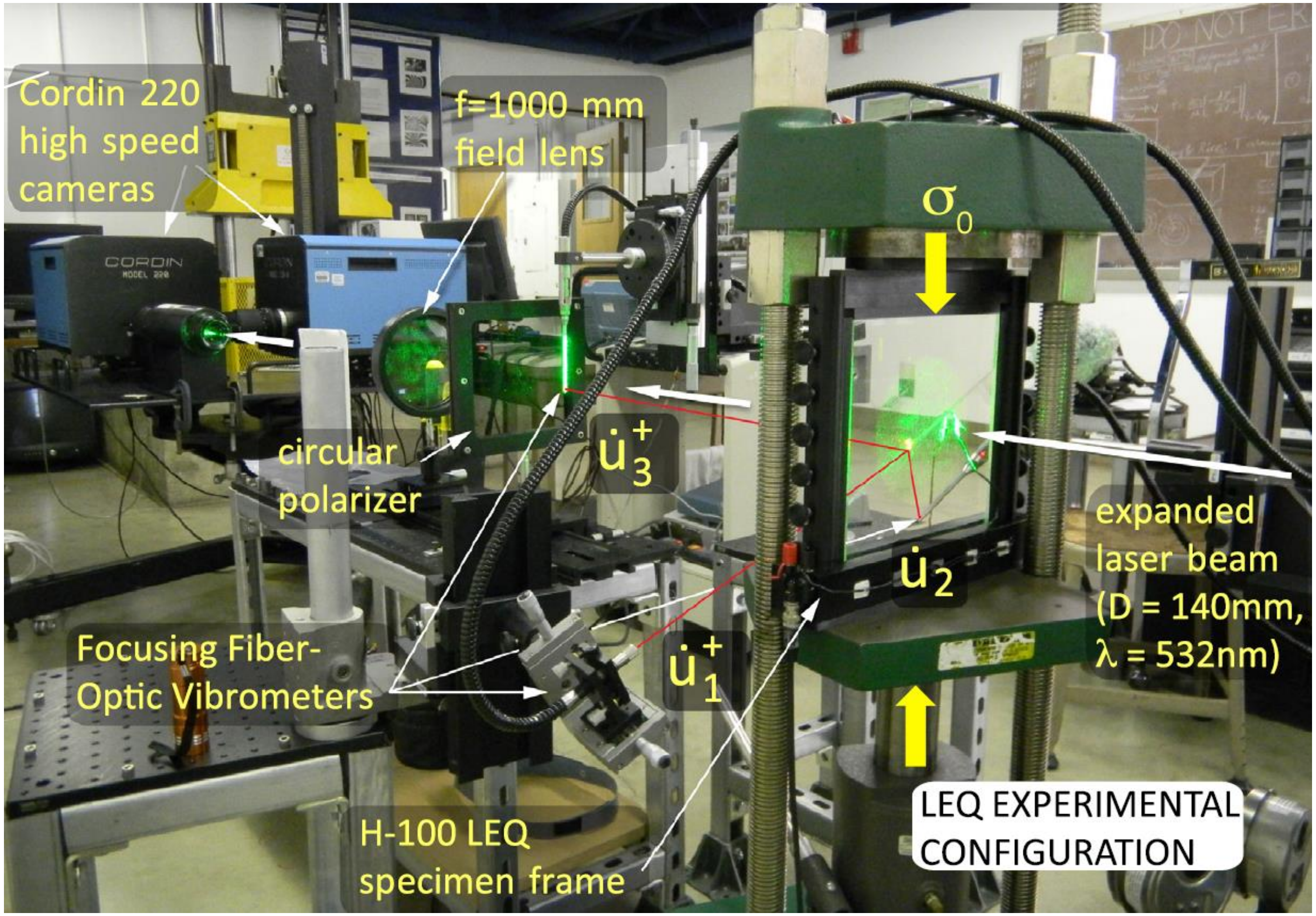
Formalized as a fundamental law of earthquake statistics: the Gutemberg-Richter law.

$$\boldsymbol{log_{10}(f) = a - b \cdot M_w}$$

Where $\boldsymbol{f}$ is the frequency of occurrence of events with a magnitude larger than $\boldsymbol{M_w}$, and $\boldsymbol{a}$ and $\boldsymbol{b}$ are fault-related constants

Rocks, faults, earthquakes – What is an earthquake?

- What does an earthquake look like? A lab view.



Mello et al. (2016)

Laboratory earthquake experiments on analog materials: how does slip start?

Precut polycarbonate plates with a polarized lazer beam and high-frequency acquisition.

Rocks, faults, earthquakes – What is an earthquake?

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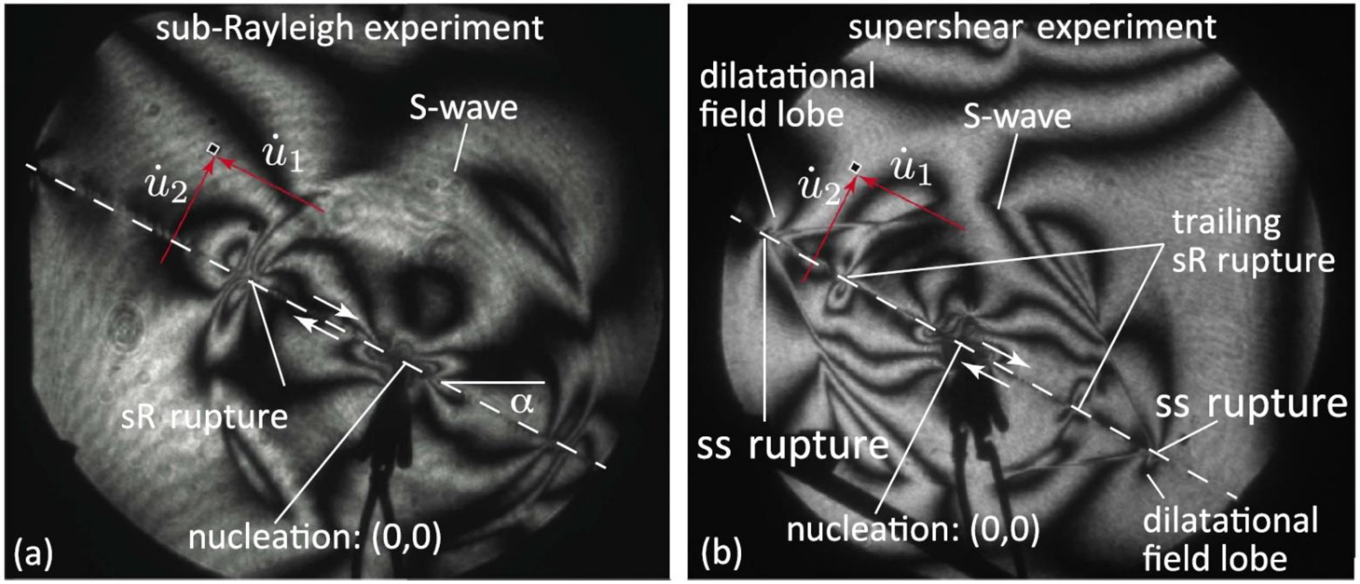

Mello et al. (2016)

Two main types of slip initiation:

Rocks, faults, earthquakes – What is an earthquake?

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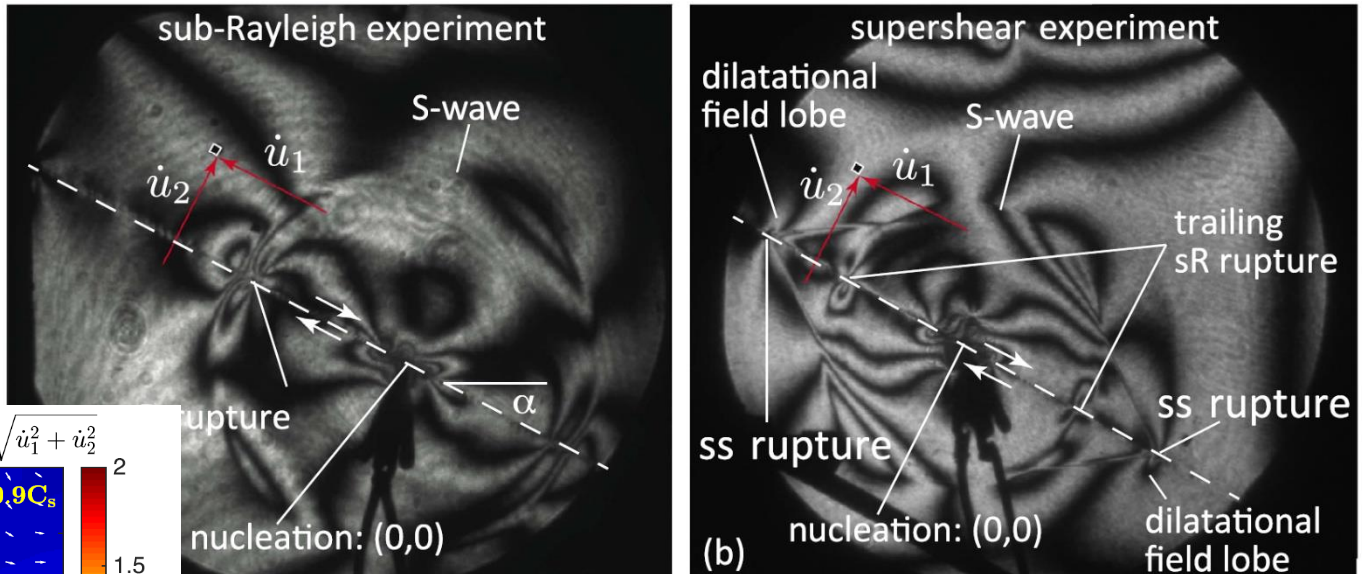

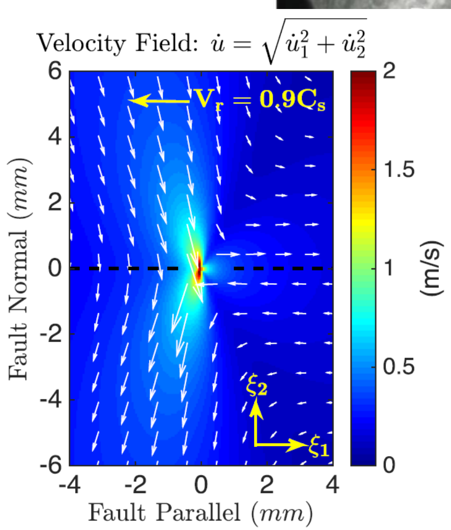

Mello et al. (2016)

Two main types of slip initiation:

"sub-Rayleigh" ruptures, propagating below the Rayleigh wave velocity in the medium, with a diffuse associated acoustic wave.

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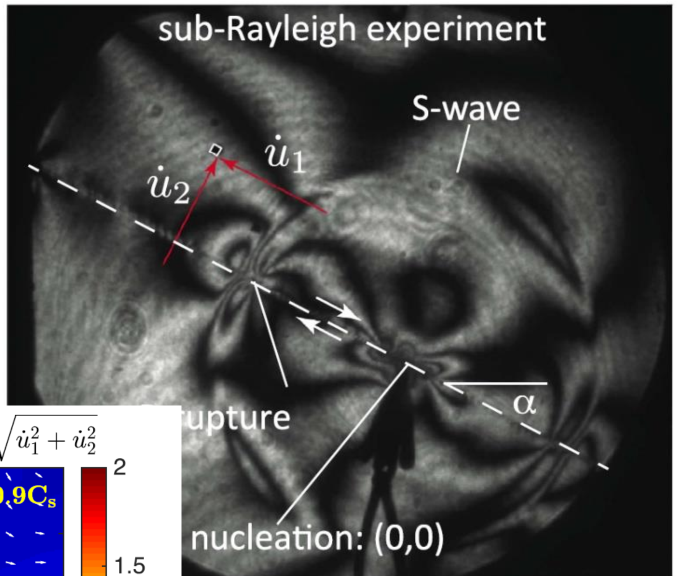

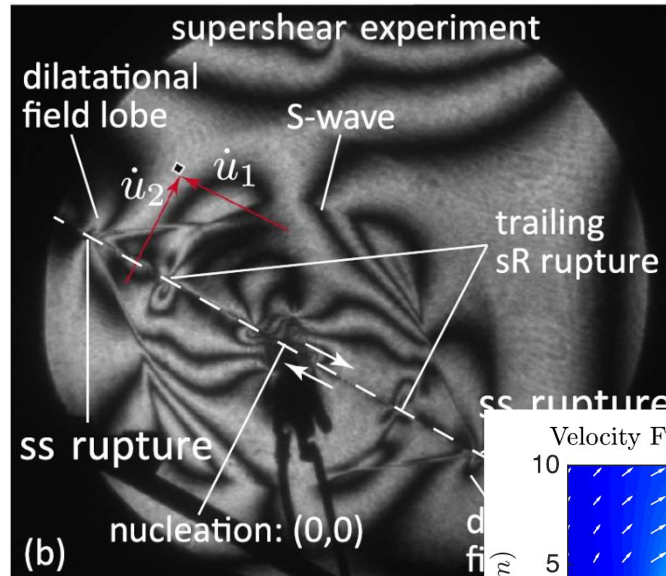

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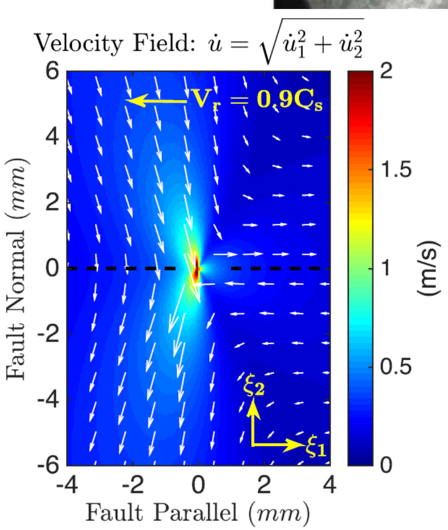
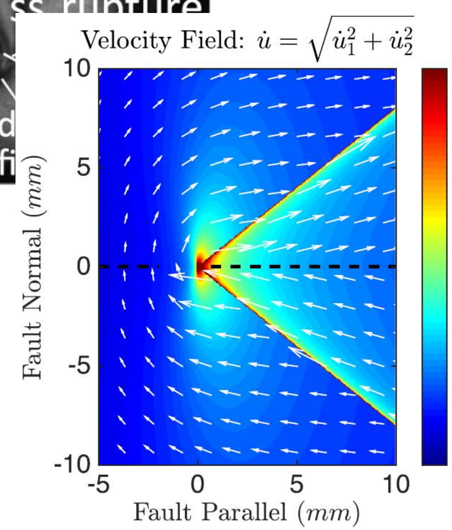


Two main types of slip initiation:

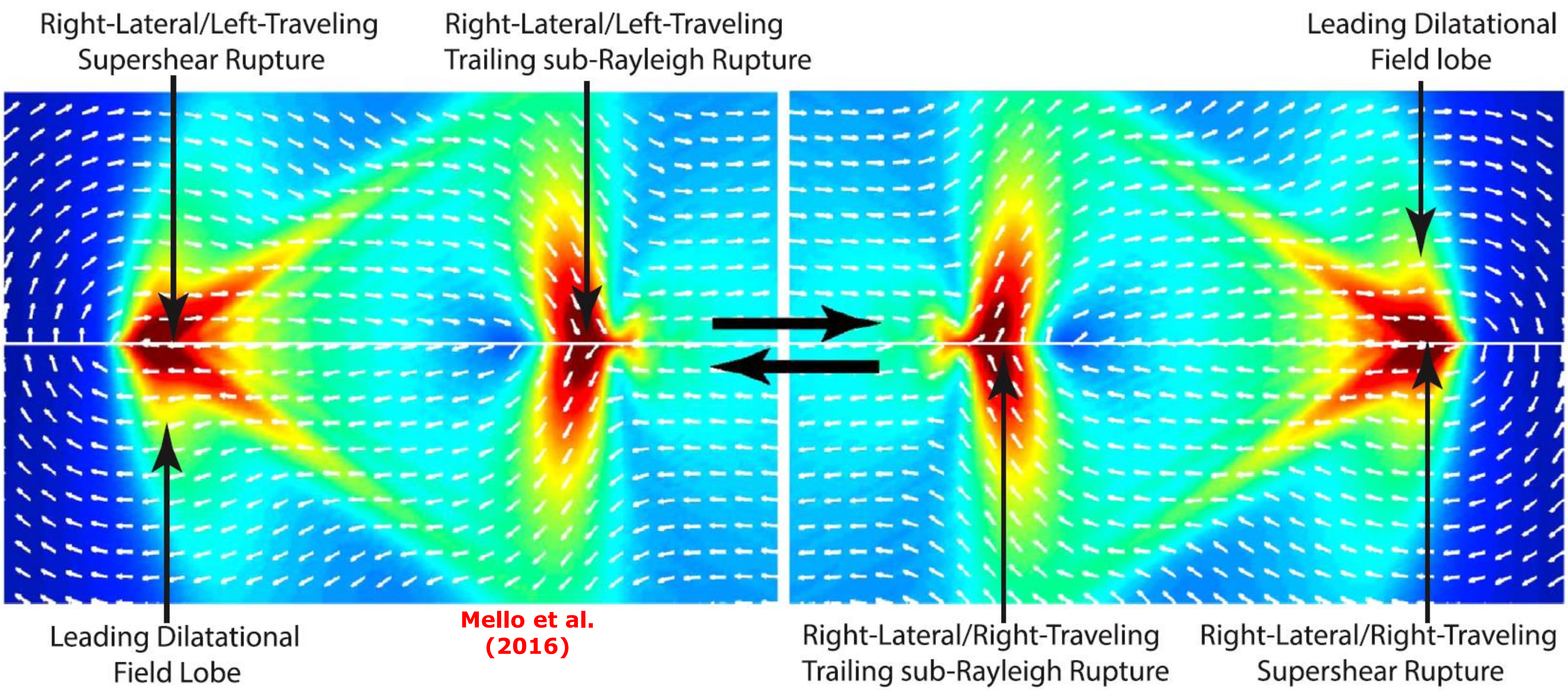
”sub-Rayleigh” ruptures, propagating below the Rayleigh wave velocity in the medium, with a diffuse associated acoustic wave.

”Supershear” ruptures, propagating at the speed of the shear waves in the medium, with a sharp and concentrated acoustic wave (Mach cone)



Rocks, faults, earthquakes – What is an earthquake?

- What does an earthquake look like? A lab view.



Sub-Rayleigh ruptures are the most natural and common, and supershear can arise from a stress concentration at the rupture tip if the stress drop is large enough. Such more destructive events are very rare, but were identified in the field on past and recent earthquakes.

Rocks, faults, earthquakes – What is an earthquake?

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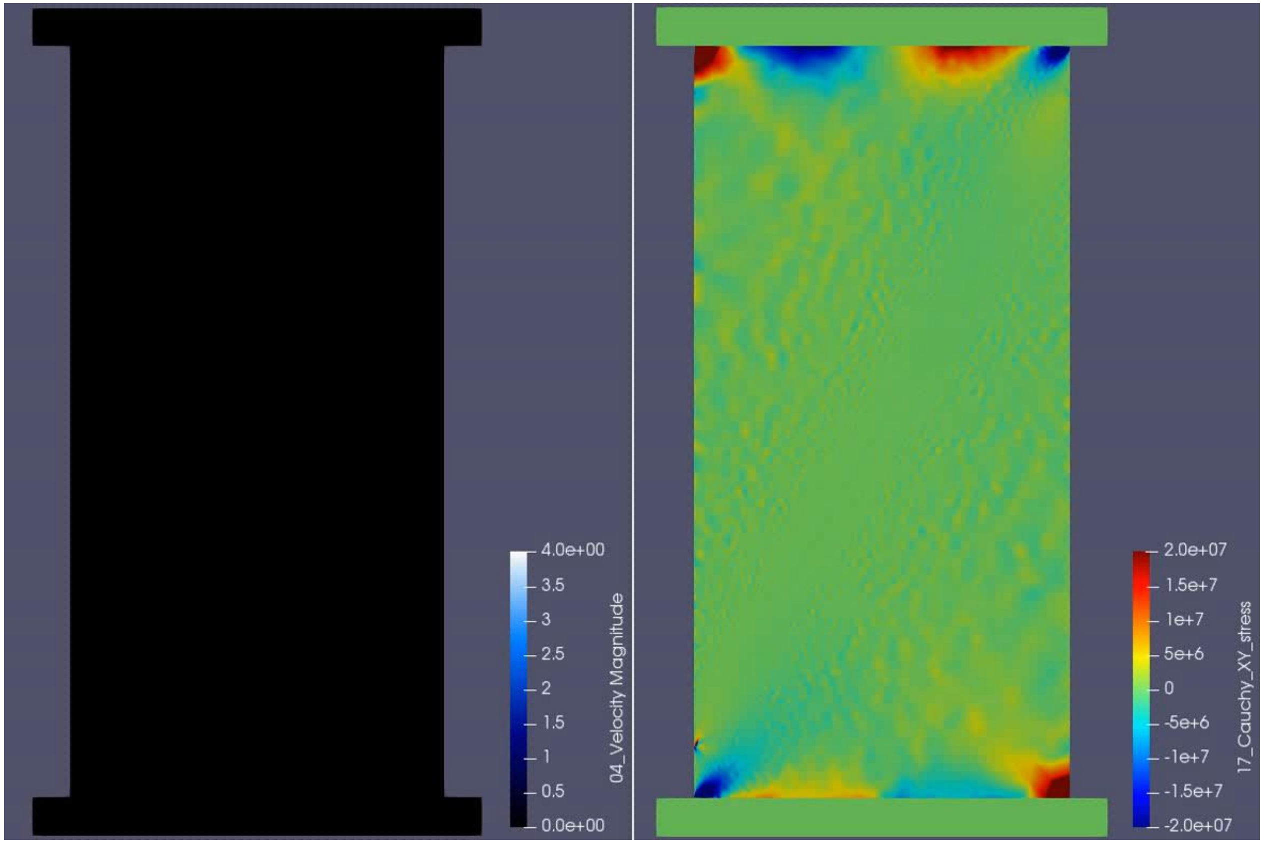


Velocity **Shear stress**

A simple and artificial numerical model:

Slip initiates on an existing fault in the lower left corner, as a sub-Rayleigh event.

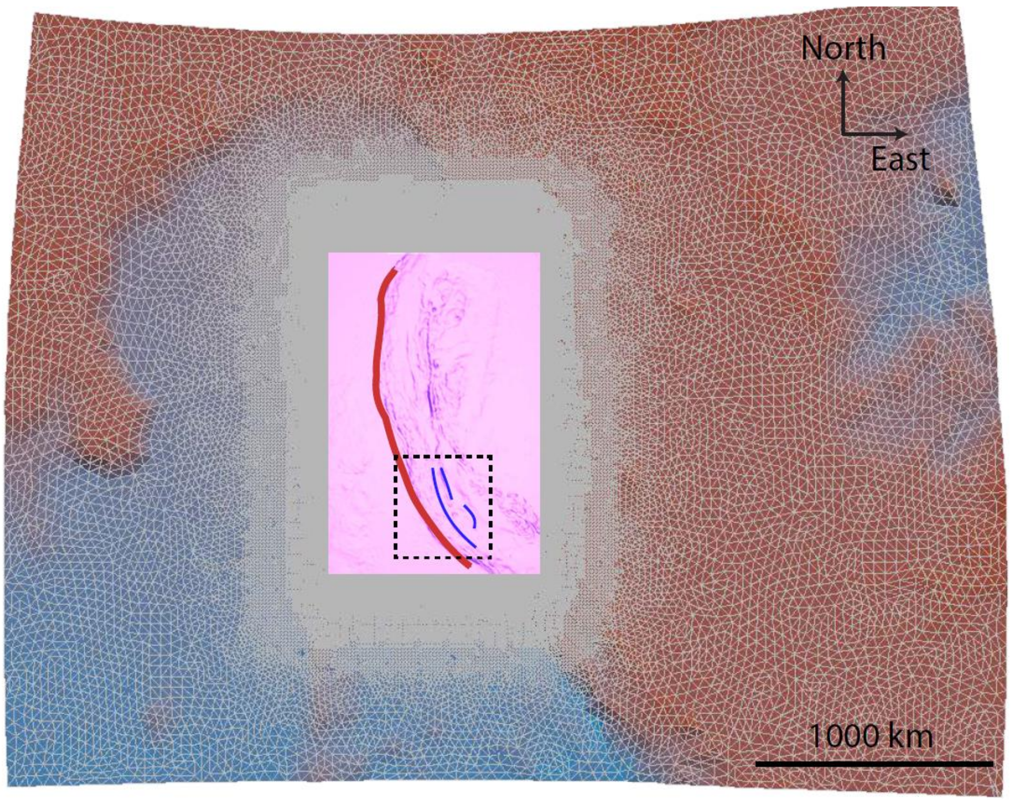
A supershear cone arises at one third of the fault, and accelerates past the initial rupture front.

Both fronts advance at a few km/s

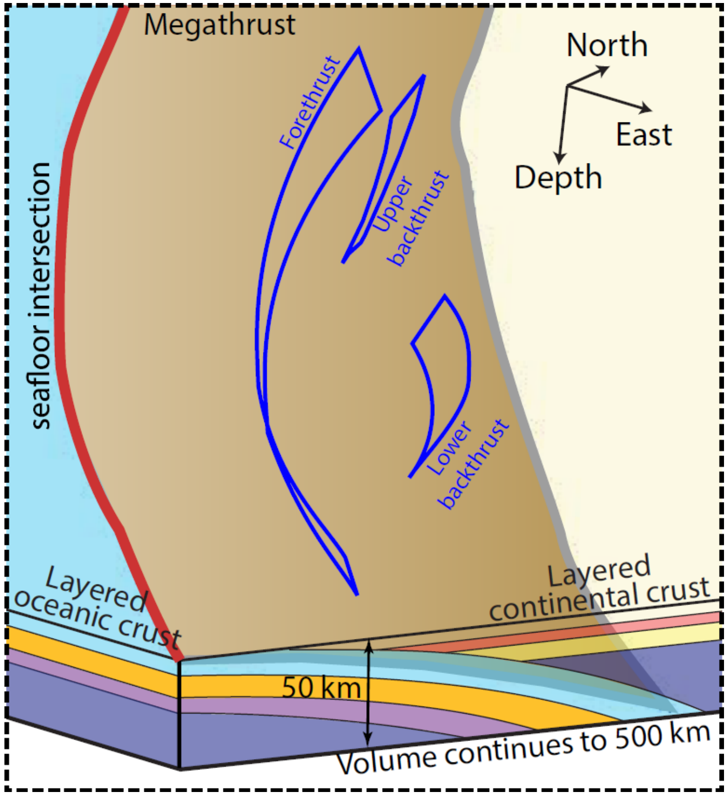
Fronts advance until complete sliding of the fault.

Rocks, faults, earthquakes – What is an earthquake?

- What does an earthquake look like? A numerical view.



Uphoff et al. (2017)

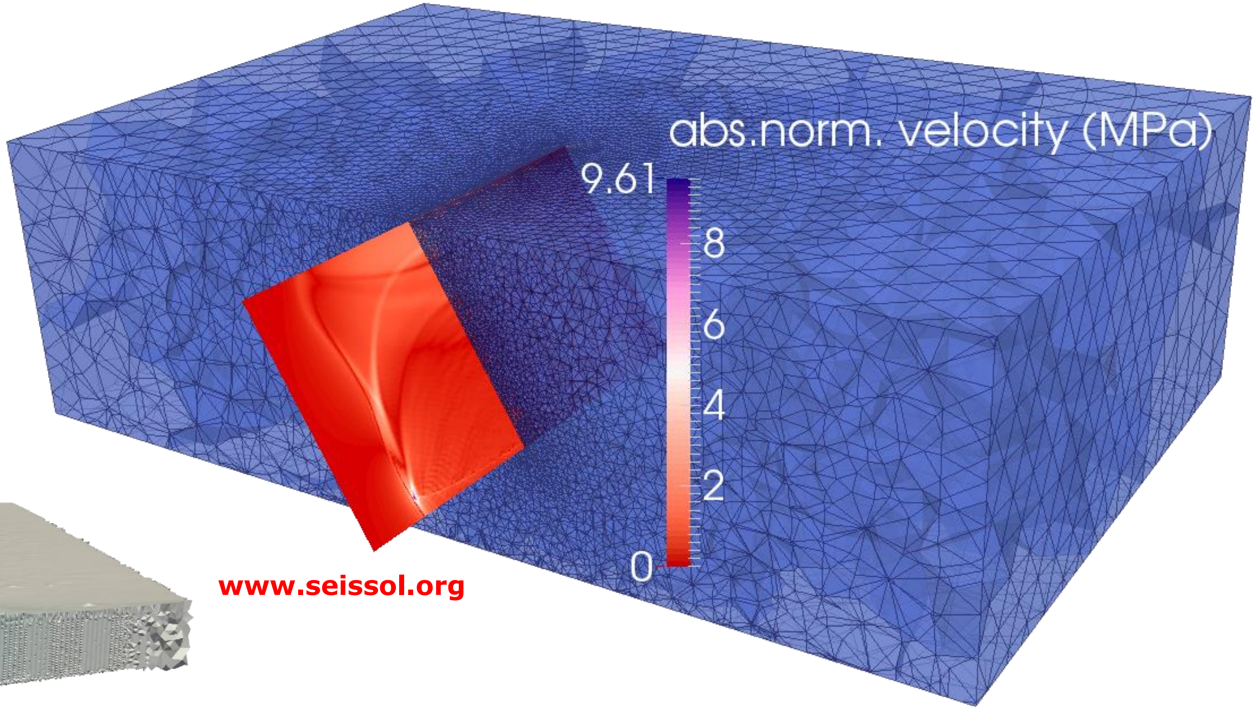


Modern computational means (both hardware and software) now allow simulating a whole fault system.

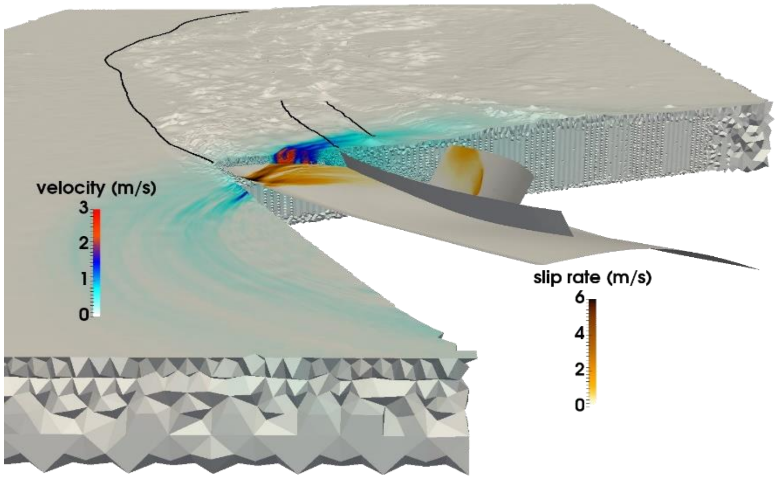
It requires an extremely extensive mesh (fine in the neighborhood of fault, but extended enough for seismic waves travel), and adaptive time steps (for both geological and dynamic time scales).

Rocks, faults, earthquakes – What is an earthquake?

- What does an earthquake look like? A numerical view.



www.seissol.org



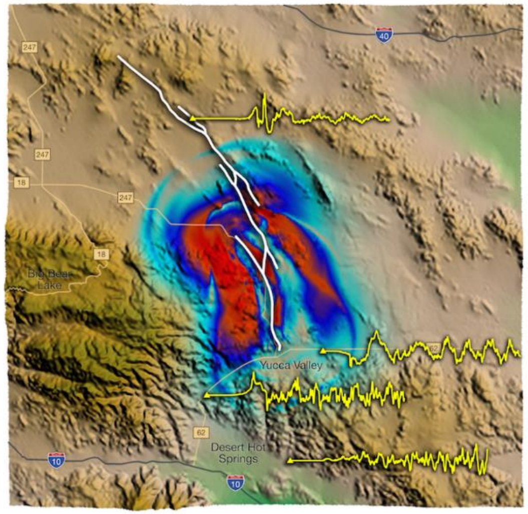
Simulations need calibration

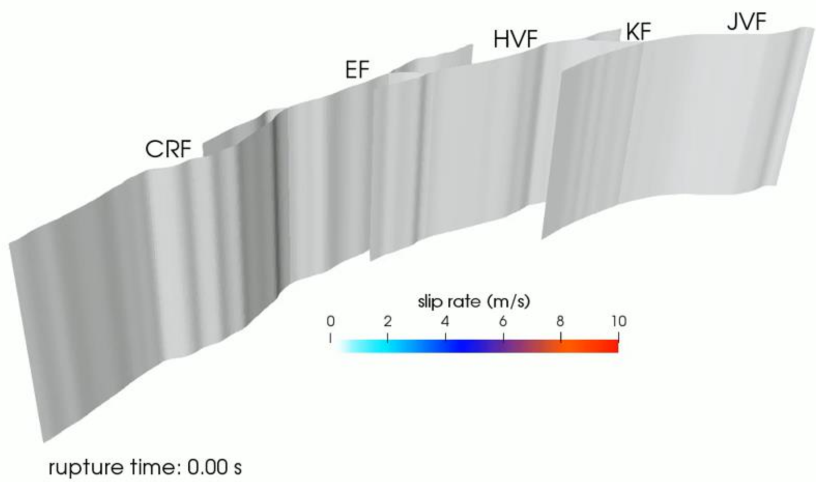
-on geodetic measurements (ground motion)

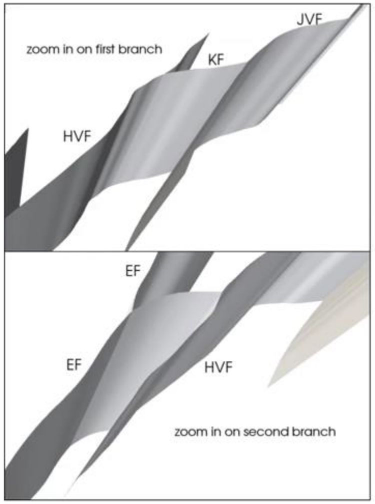
-on seismological measurements (acoustic waves)

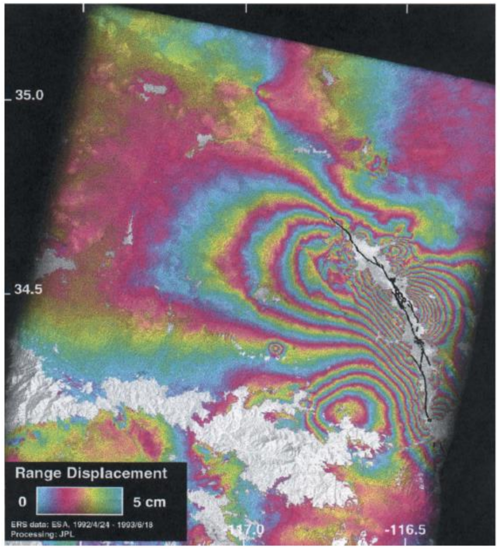
Rocks, faults, earthquakes – What is an earthquake?

- What does an earthquake look like? A numerical view.









www.seissol.org

An illustrative simulation: the Landers Earthquake

Occured in 1992 in California, one of the most studied earthquakes at its time, because of large amount of observational data.

Ruptured on several parallel fault segments, Magnitude of 7.3

Rocks, faults, earthquakes – What is an earthquake?

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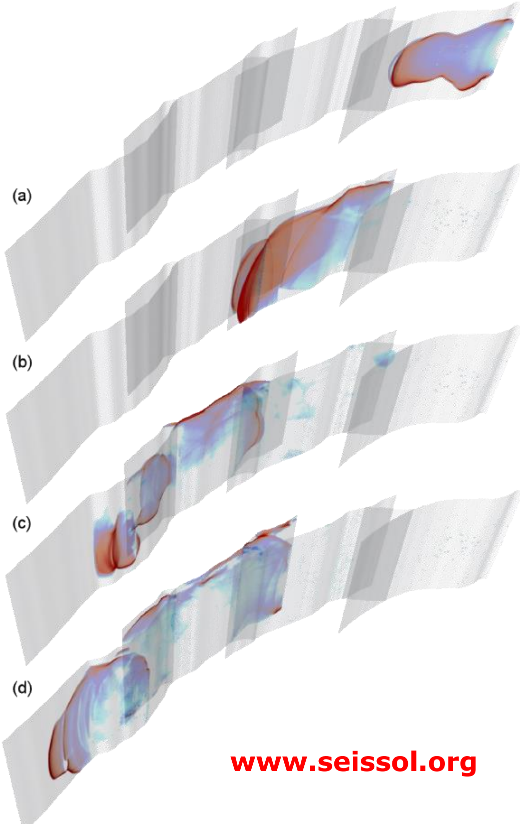
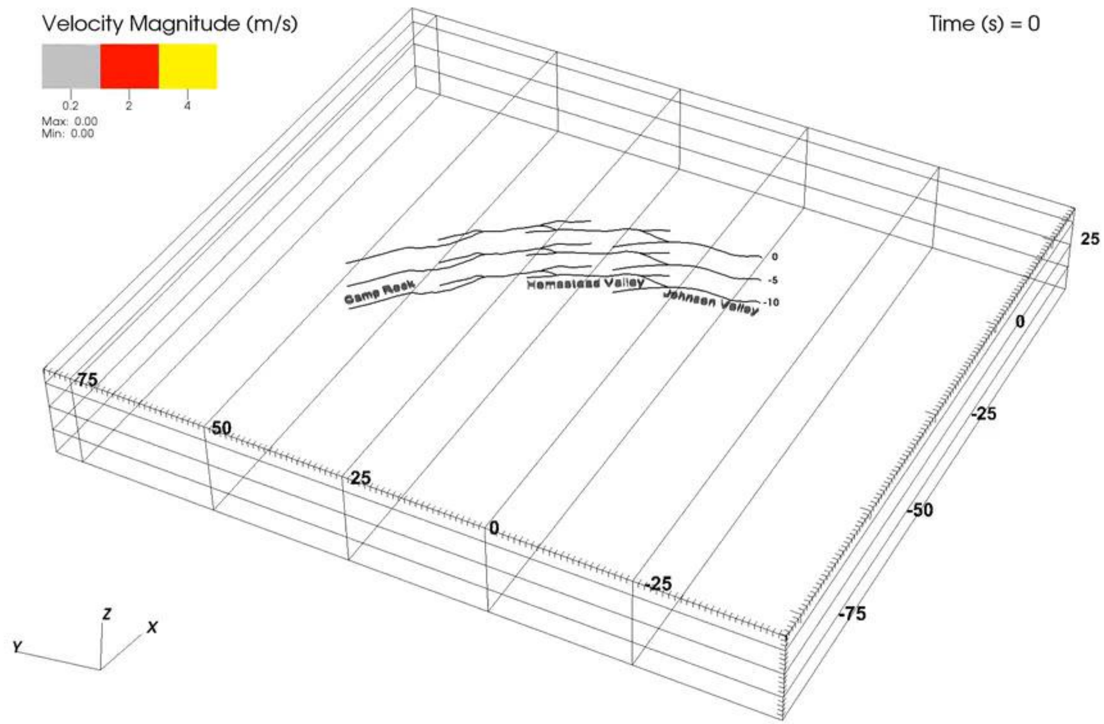




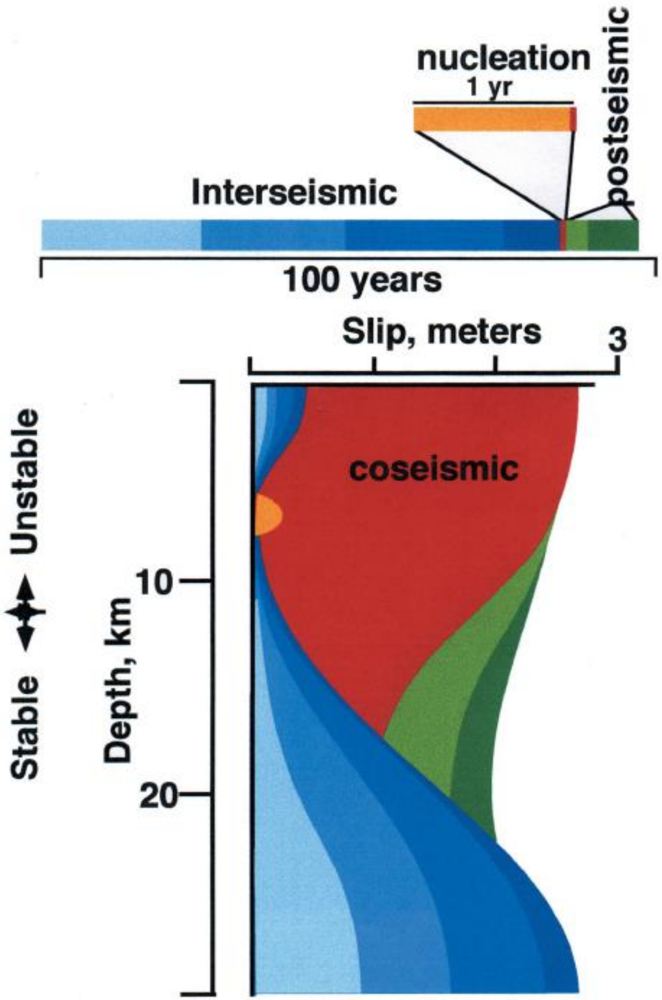
An illustrative simulation: the Landers Earthquake

Ground motion and acoustic waves are in accordance with observations, but is the model correct anyway? Yes, if the implemented physics are meaningful.

-> We need to pay attention to friction laws in rocks!

Rocks, faults, earthquakes – What is an earthquake?

- When it gets more complicated: the seismic cycle



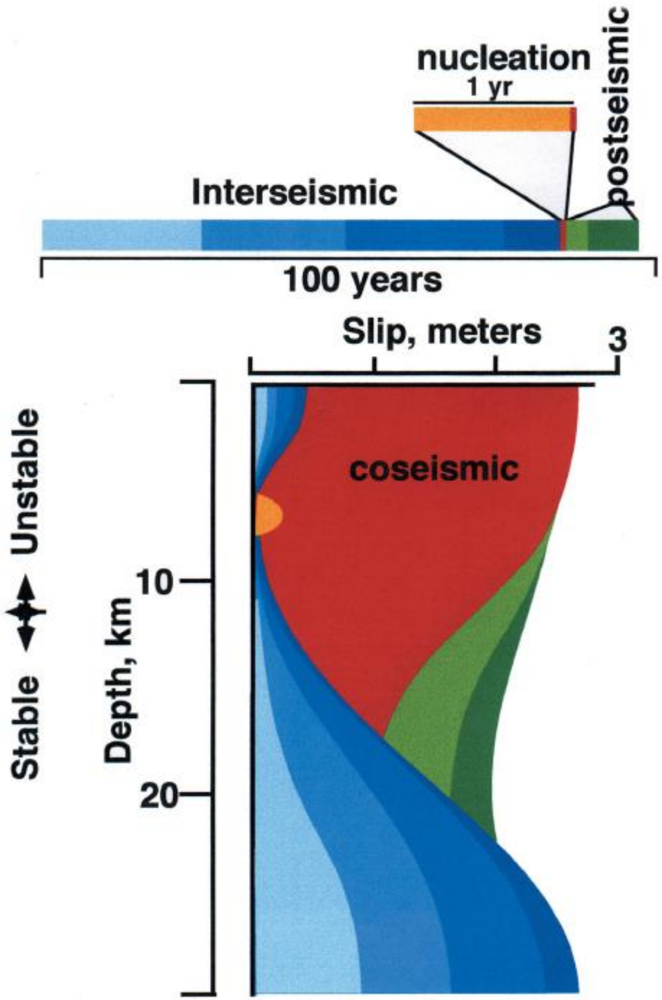
Scholz 2002

A general view of the seismic cycle.

Four important phases:

Rocks, faults, earthquakes – What is an earthquake?

- When it gets more complicated: the seismic cycle



Scholz 2002

A general view of the seismic cycle.

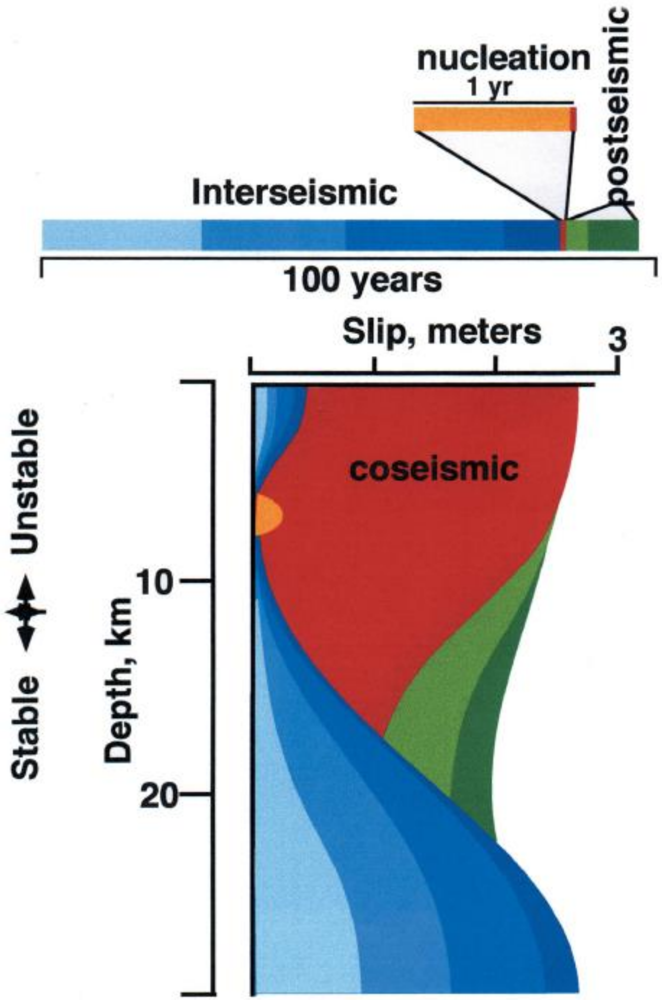
Four important phases:

-**preseismic**: local nucleation and increase of the slip rate

Sliding rate: $10^{-8} – 10^{-6}$ m/s ; Duration : a few months

Rocks, faults, earthquakes – What is an earthquake?

- When it gets more complicated: the seismic cycle



Scholz 2002

A general view of the seismic cycle.

Four important phases:

-**preseismic**: local nucleation and increase of the slip rate

Sliding rate: $10^{-8} – 10^{-6}$ m/s ; Duration : a few months

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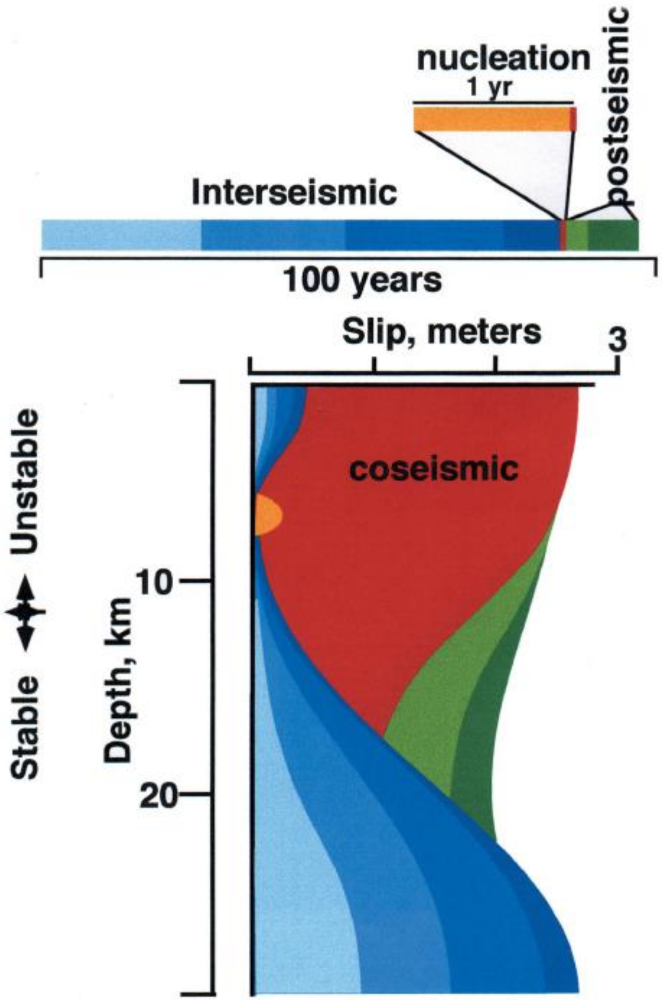

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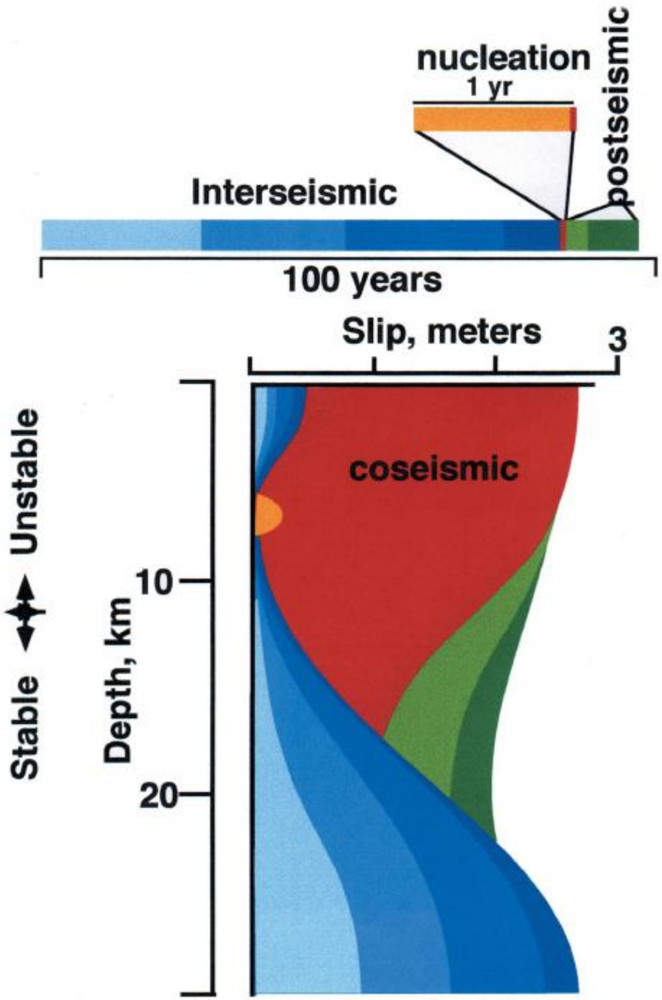

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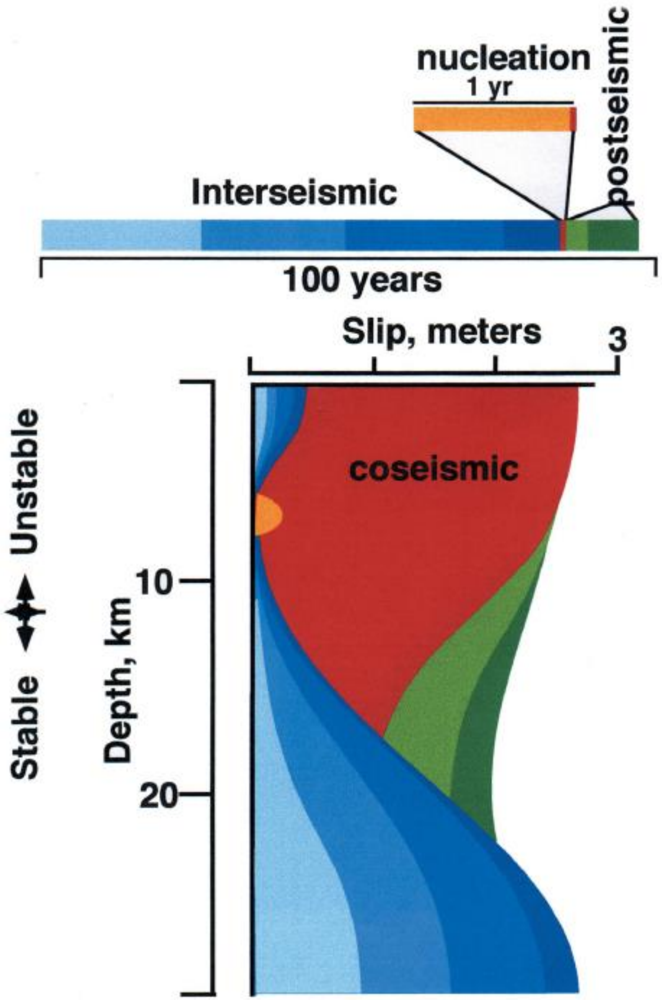

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Wide variety in lithologies, pressures, temperatures, velocities, durations…

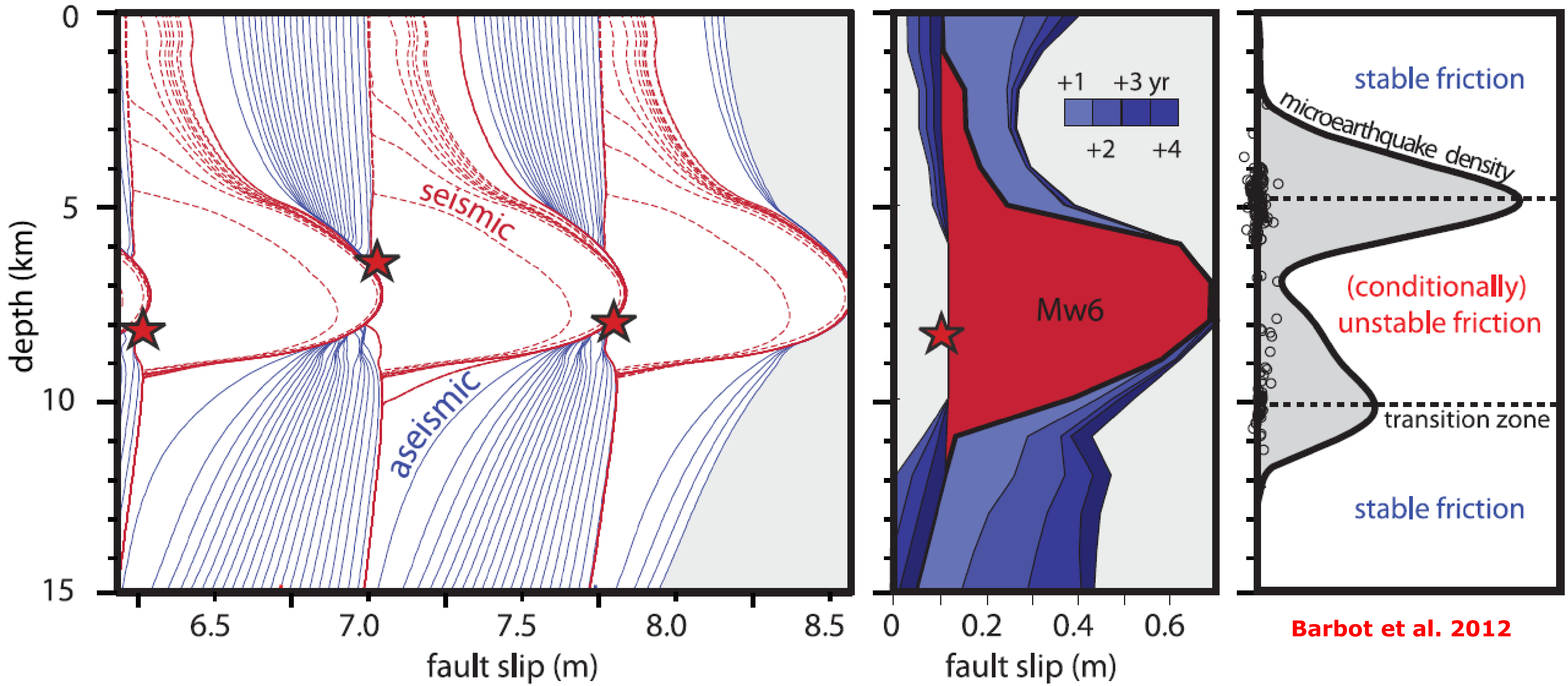
Obviously, one simple friction law is not sufficient!

Rocks, faults, earthquakes – What is an earthquake?

- When it gets more complicated: the seismic cycle.

A numerical view of the seismic cycle.

With ad-hoc weakening and strengthening friction laws and a good deal of calibration.



Barbot et al. 2012

Rocks, faults, earthquakes – What is an earthquake?

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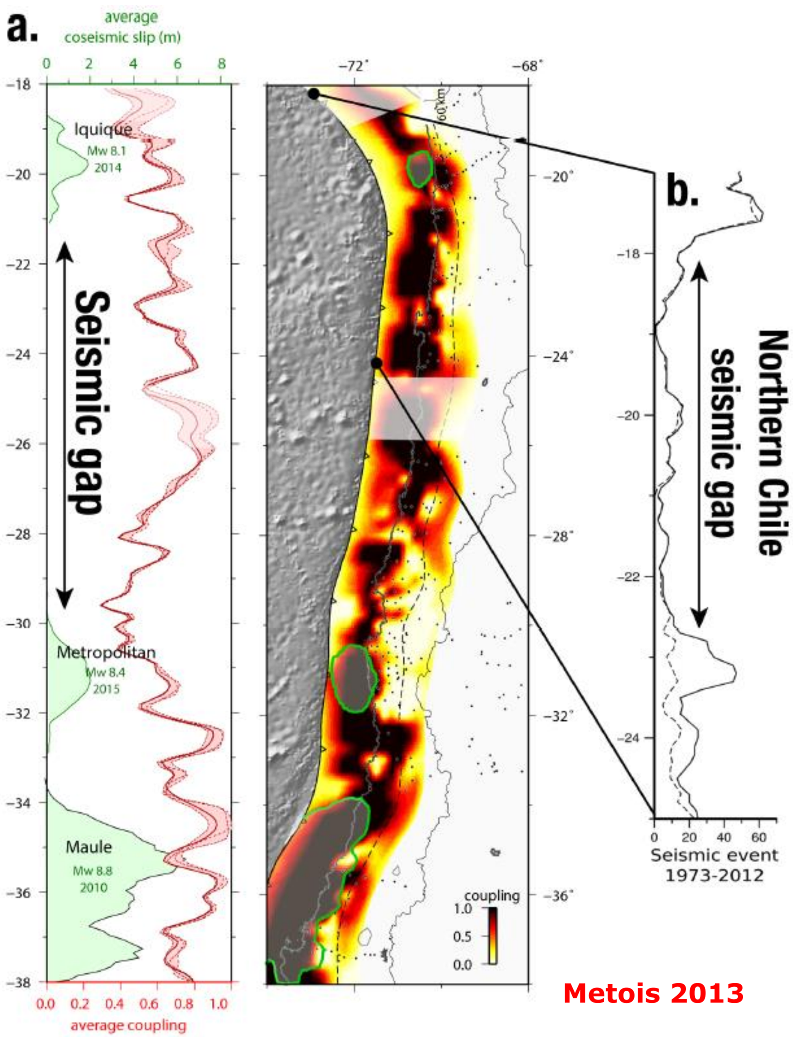

Metois 2013

On a same fault, many different possible behaviors

Rocks, faults, earthquakes – What is an earthquake?

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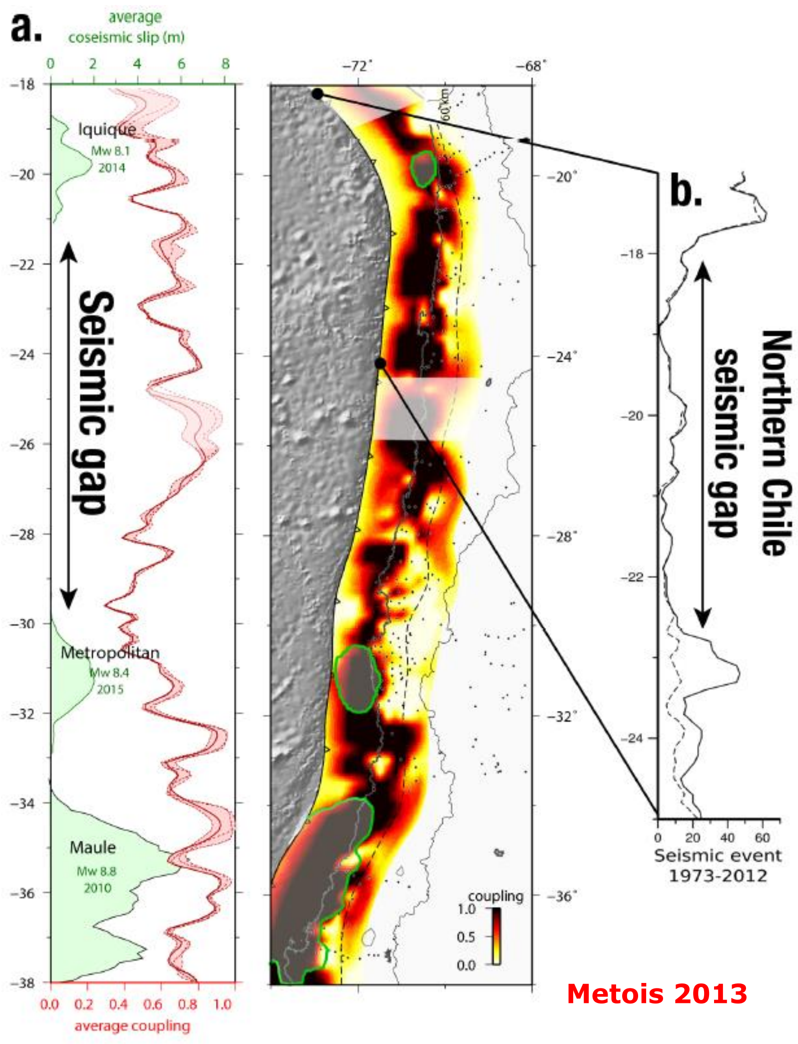

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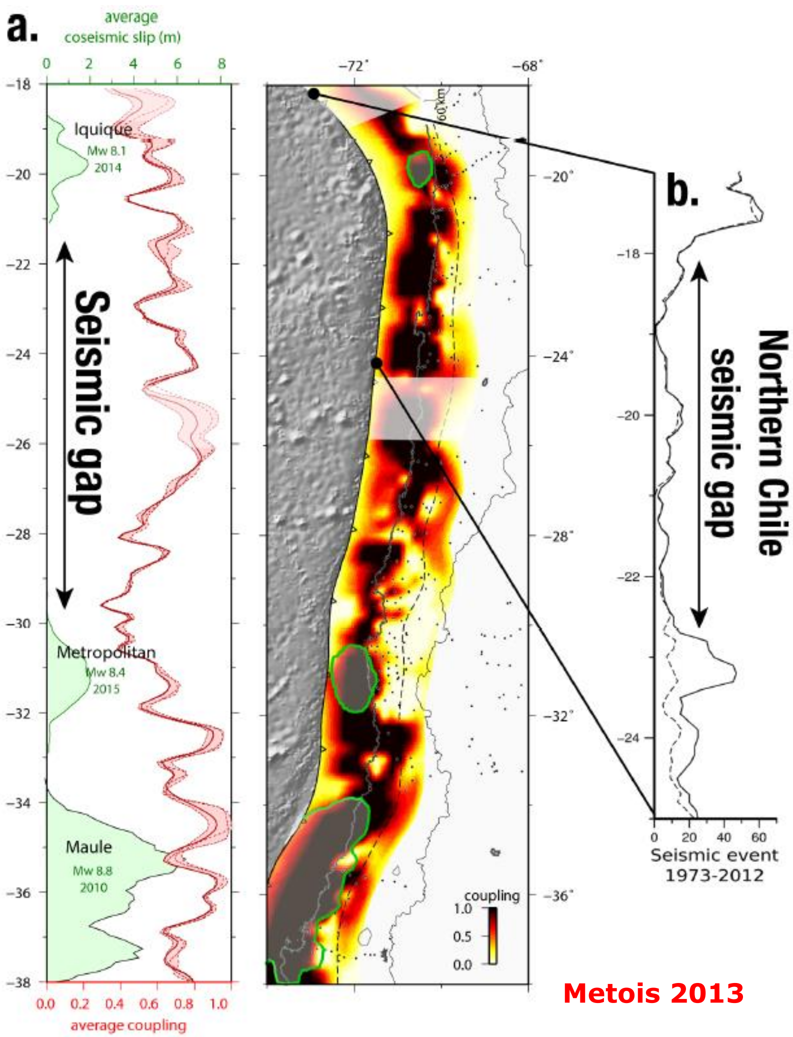

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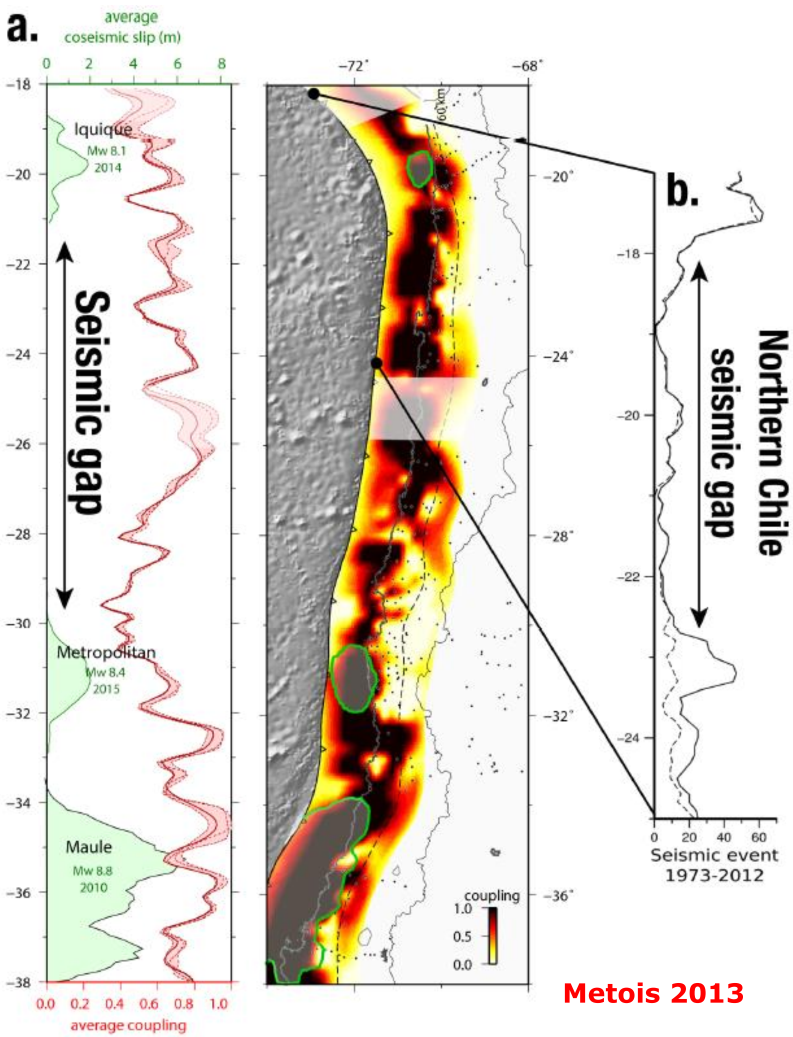

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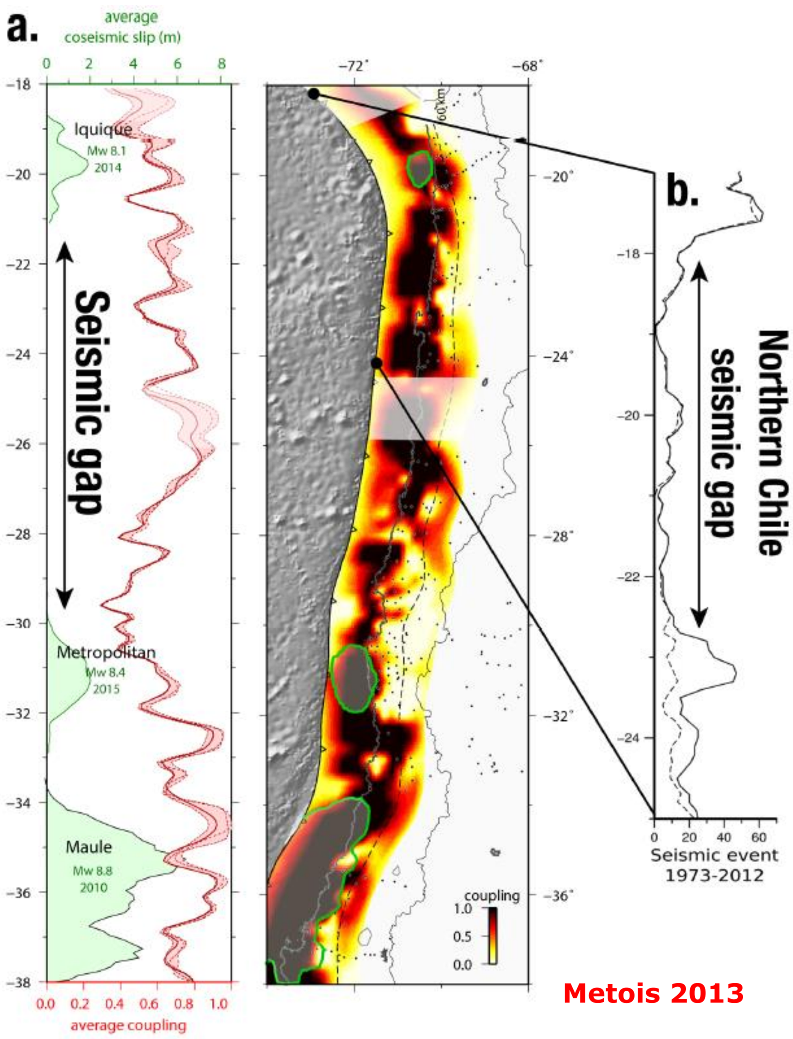

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Seismic gaps (where no earthquake has been recorded for a long time) -> seismic or aseismic?

Rocks, faults, earthquakes – What is an earthquake?

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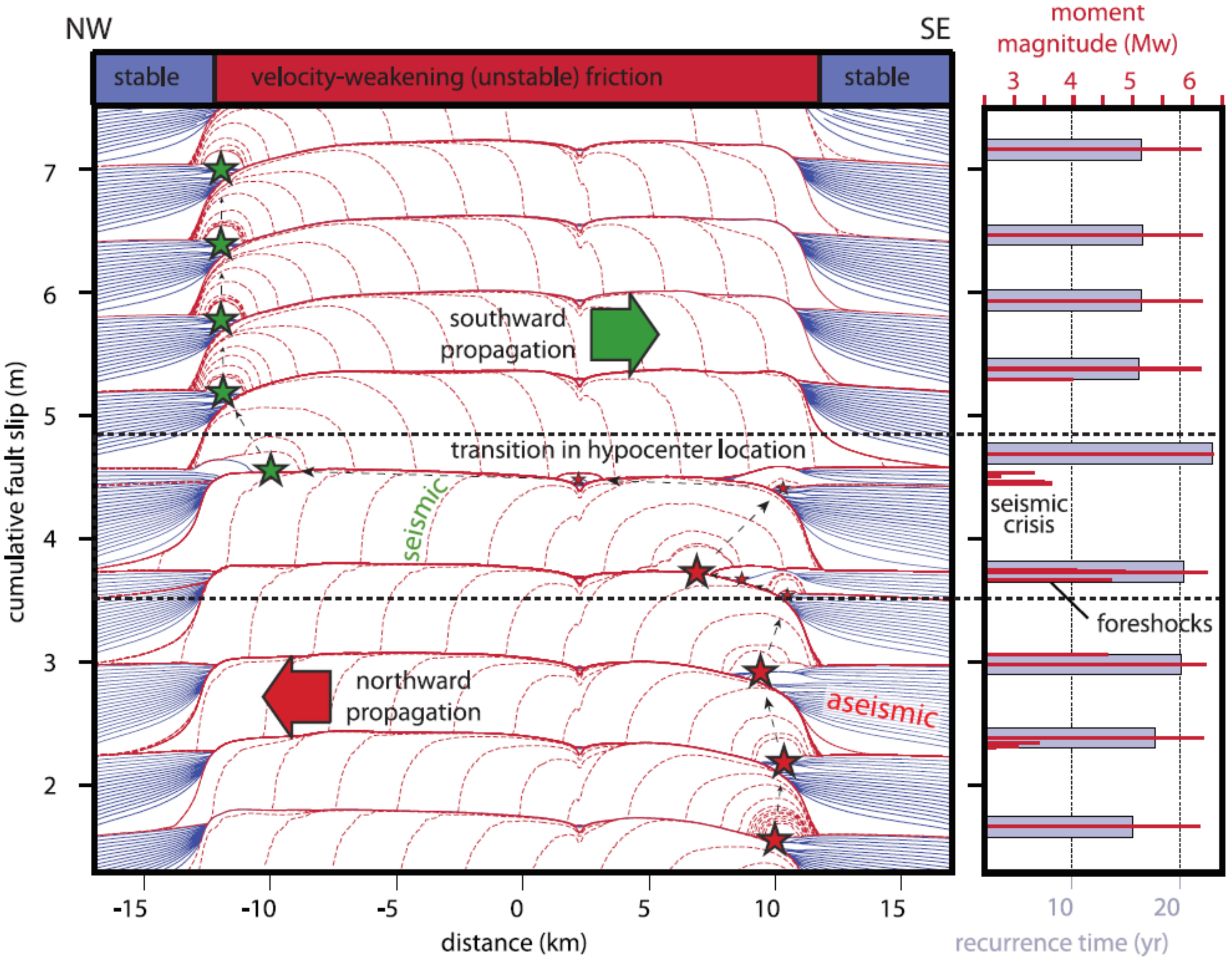

An example of seismic cycle predicted by a model for a coupled area surrounded by creeping segments.

Barbot et al. 2012

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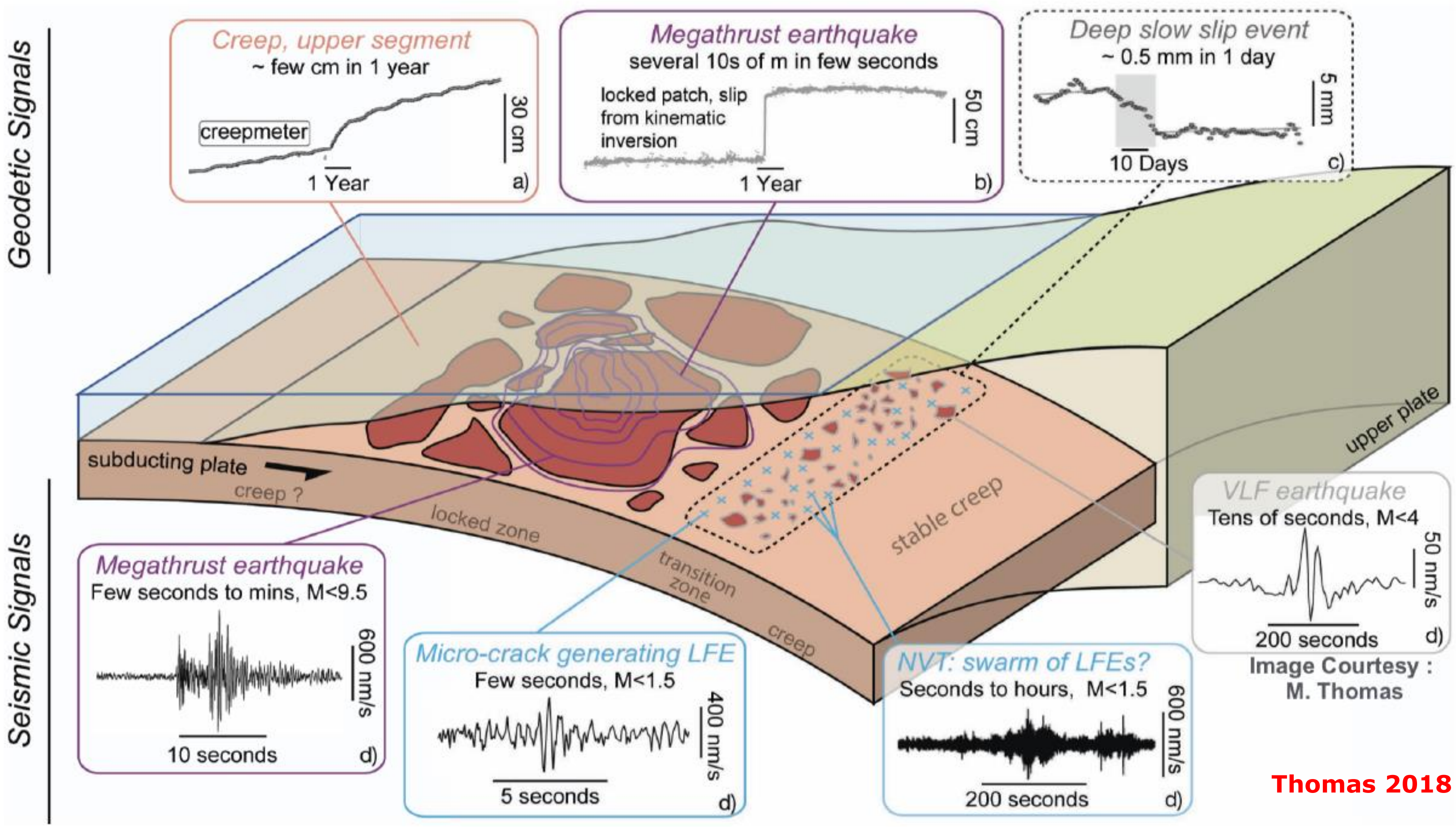


Thomas 2018

A wide variety of unknown slow-slip earthquake types were detected in the last 10 years.

It complexifies our view and our understanding on the dynamics of the lithosphere at seismogenic depths.

Friction

Guilhem Mollon[1]

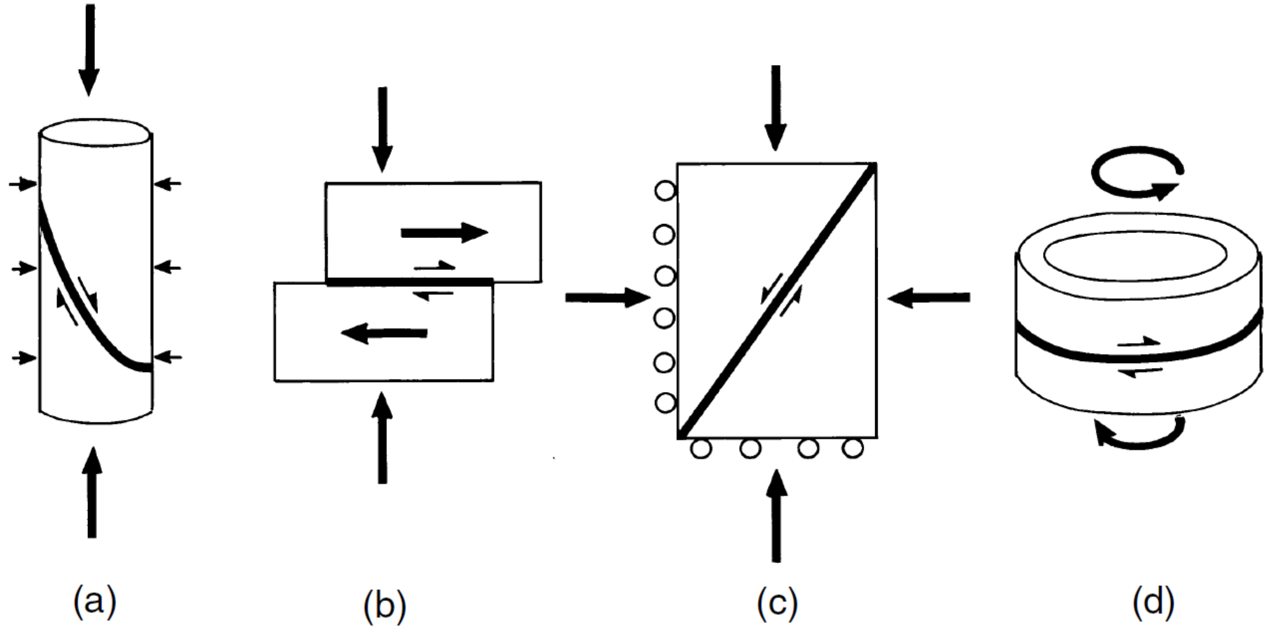
[1]LaMCoS
INSA LYON
Villeurbanne, France

TRAMME, July 2023

Rocks friction laws

- Typical experimental systems for rock friction measurements:

Scholz 2002



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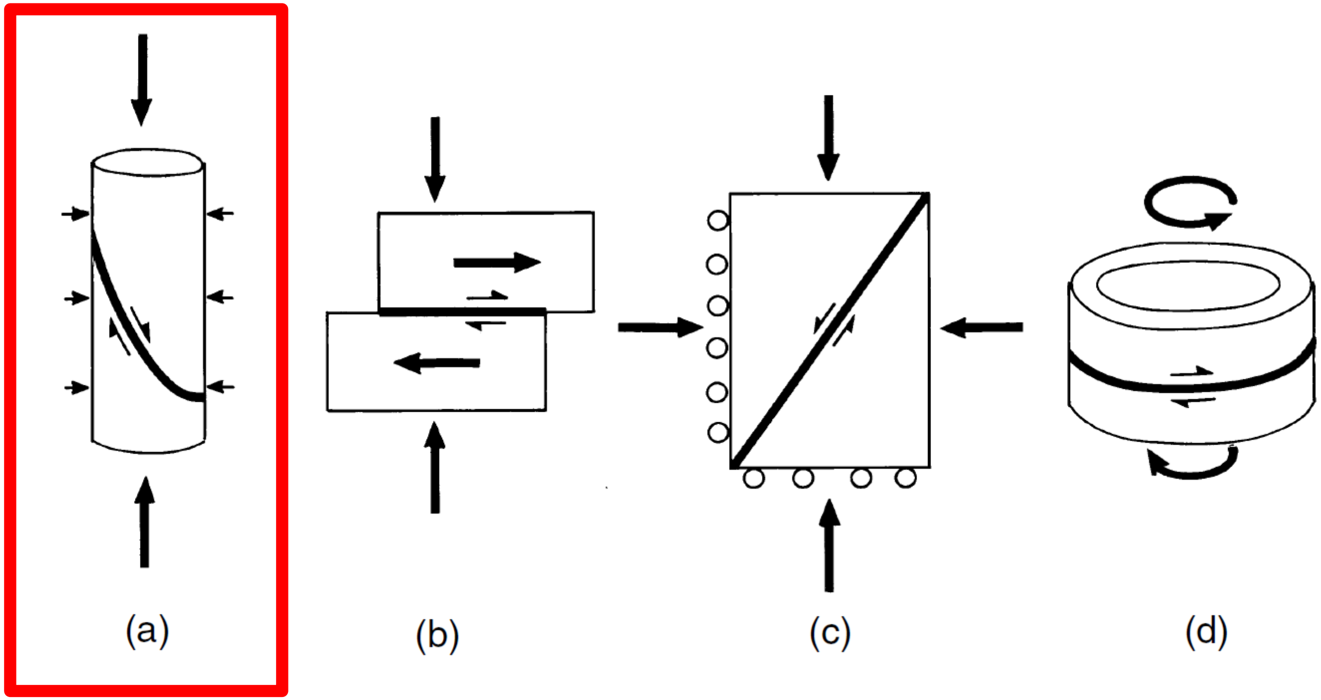

Triaxial pressure vessel on precut samples

-> Allows for large stress levels, consistent with seismogenic depths

-> Spontaneous occurrence of stable or unstable sliding, can generate lab earthquakes

Rocks friction laws

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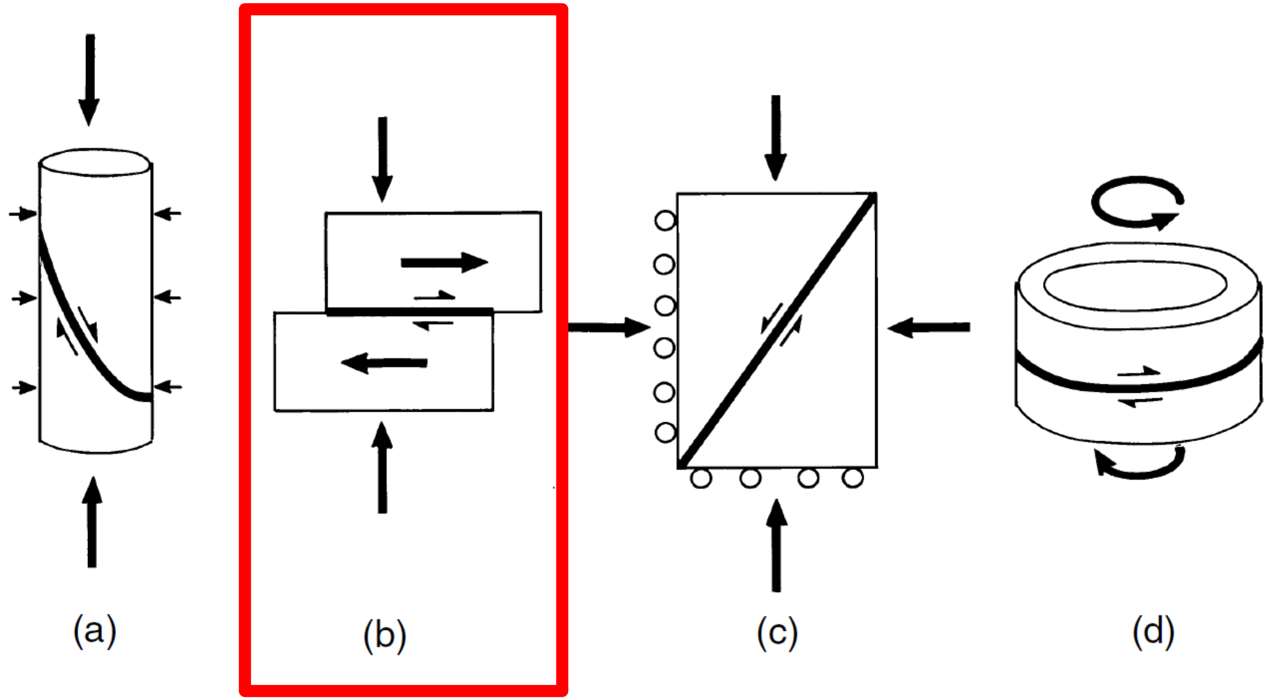
Scholz 2002



Direct shear tests on bare rock or gouge samples

-> Excellent control of the relative displacement and relative velocity

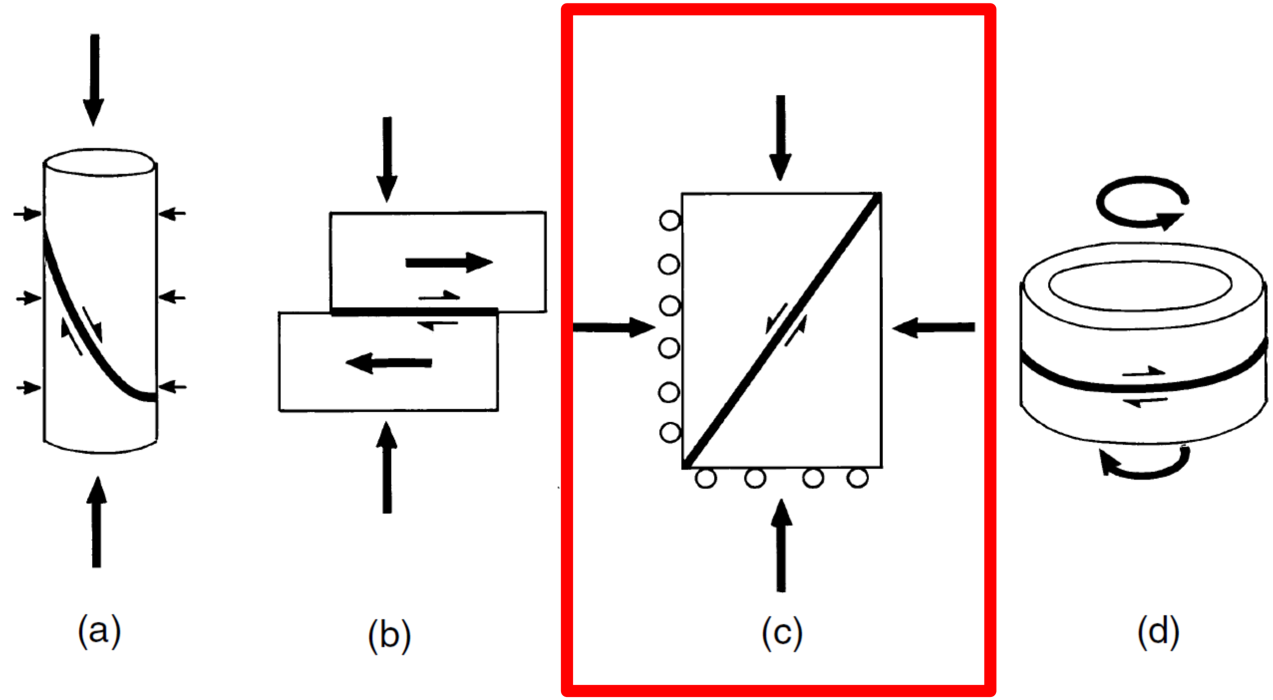
-> Moderate stress levels

-> Appropriate for very slow sliding velocities, i.e. slip nucleation

Rocks friction laws

- Typical experimental systems for rock friction measurements:

Scholz 2002



Precut plane-stress biaxial tests

-> Very limited in stress levels, usually used on model materials (e.g. polycarbonates)

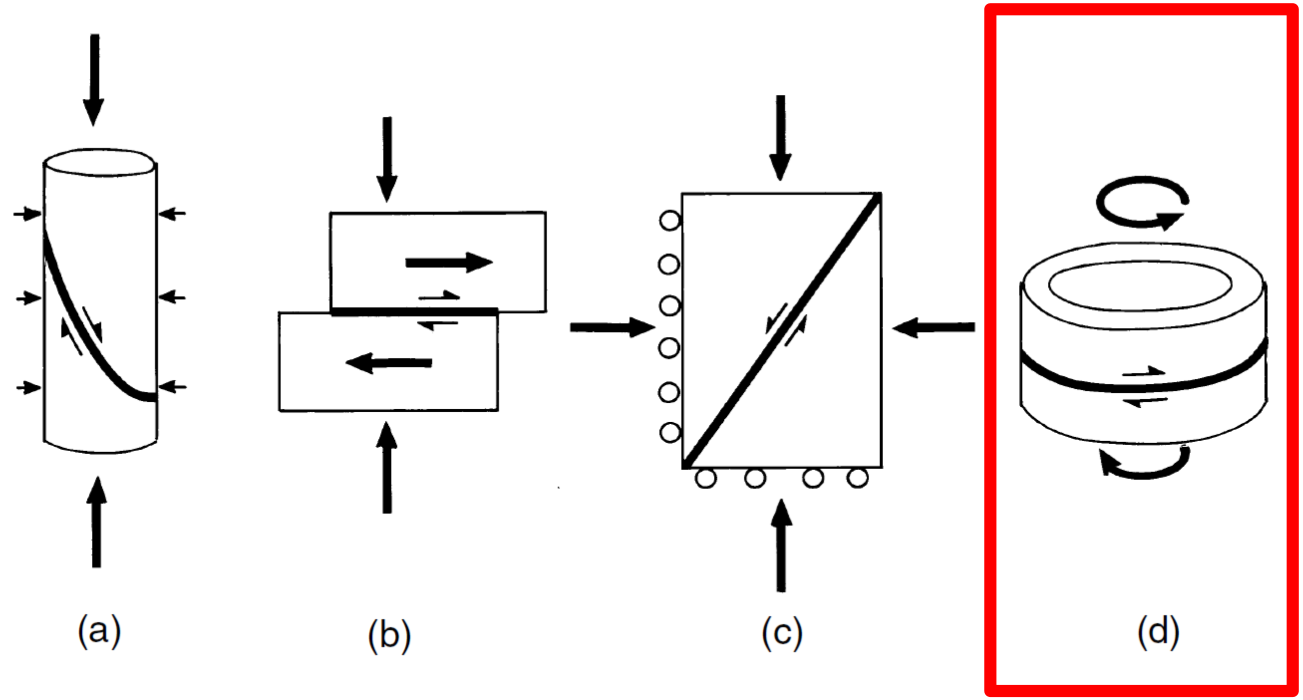
-> Can spontaneously nucleate lab earthquakes

-> Appropriate for imaging rupture, not for accurate measurement

Rocks friction laws

- Typical experimental systems for rock friction measurements:

Scholz 2002



Rotary shear tests

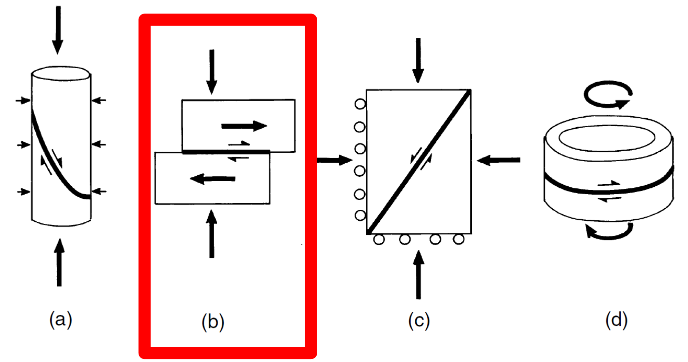
-> Limited stress levels, but very high sliding velocities (up to 1 m/s)

-> Very energetic contacts, can reproduce shear heating in real faults

-> Appropriate for measurement of friction dynamic weakening

Rocks friction laws

- Elementary friction law: **Amontons-Coulomb**



Amontons-Coulomb friction law:

Shear stress in a sliding contact is proportional to normal stress, whatever everything (velocity, roughness, etc.)

$$\tau = \mu \cdot \sigma$$

Typical values of the friction coefficient μ in rocks: 0.6 - 0.85

Rocks friction laws

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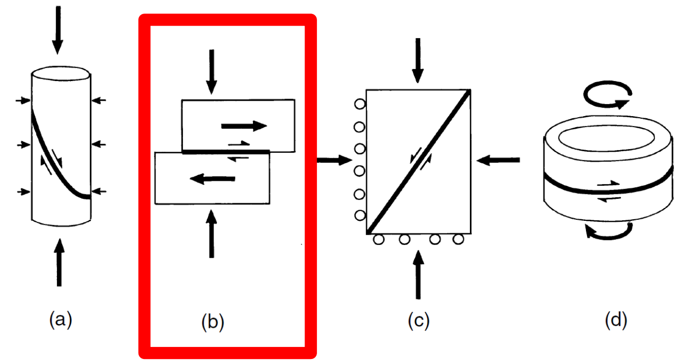

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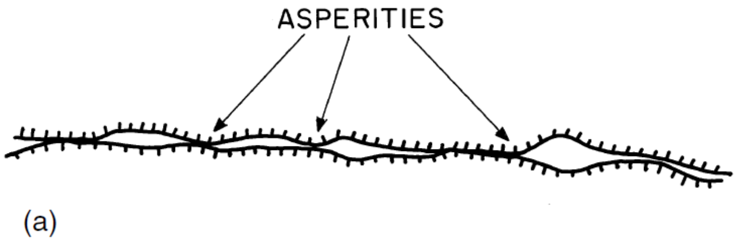
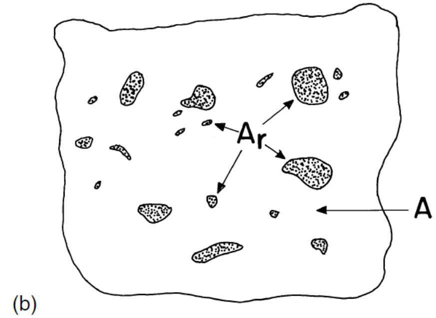
Typical values of the friction coefficient μ in rocks: 0.6 - 0.85

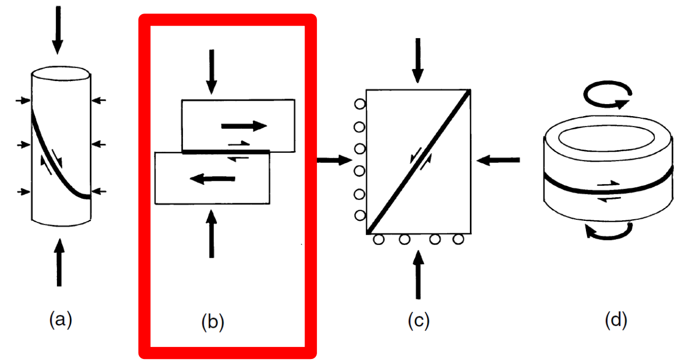
Acceptable as a first approximation, widely used in theoretical and numerical modelling. Based on an ideal model of rough surface with asperities, and a “real contact area” much smaller than the apparent one.





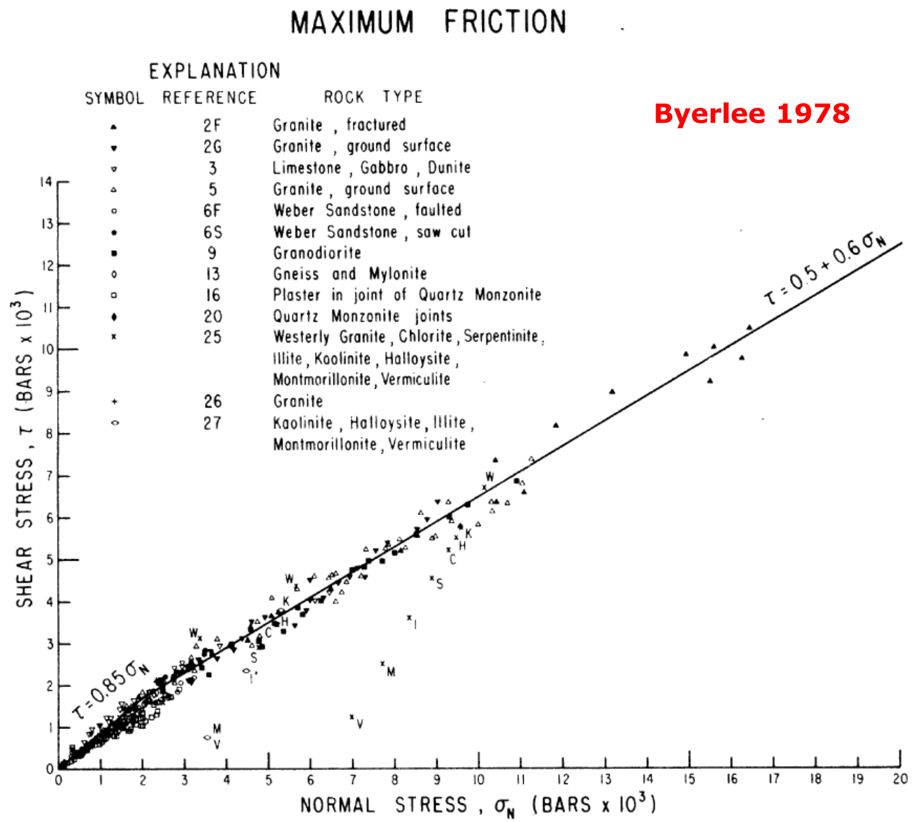
Rocks friction laws

- A closer look: the Byerlee friction law.



An empirical friction law:

Based on a large number of measurements on various rocks, Byerlee proposed the following law:



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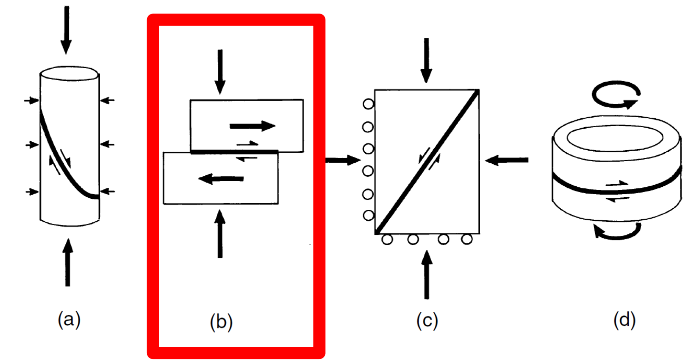

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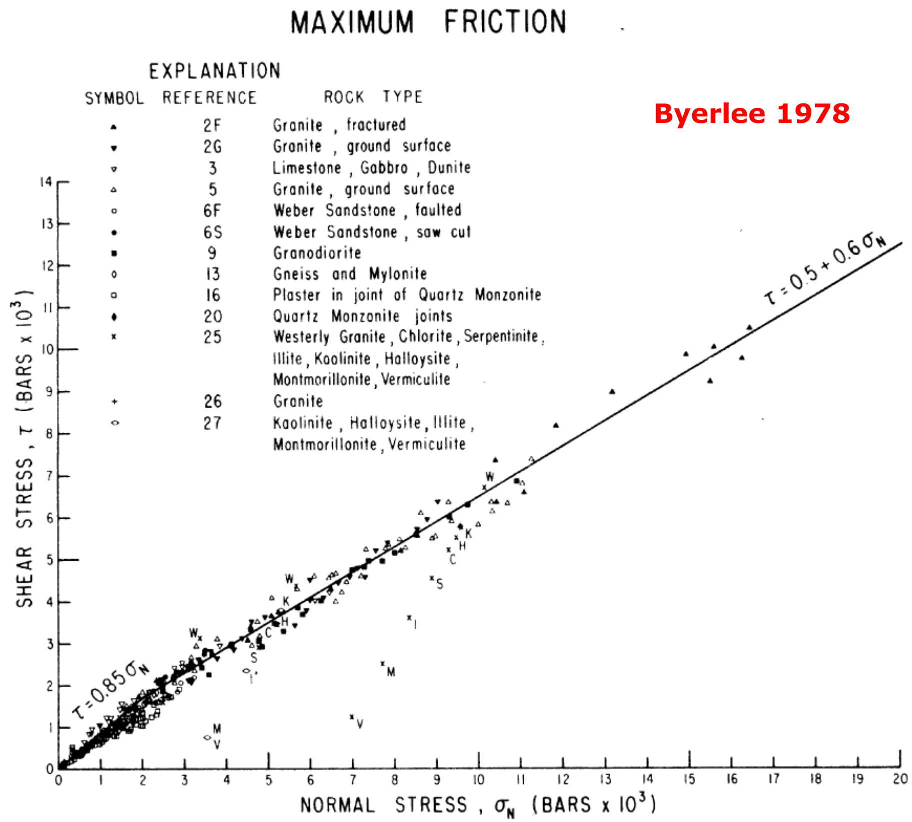
$$\tau = 0.85 \cdot \sigma \qquad for\ \sigma < 200\ MPa$$
$$\tau = 50 + 0.6 \cdot \sigma \quad for\ \sigma > 200\ MPa$$

A bilinear law, with no theoretical justification, but with robust experimental validation.

At large stresses, it looks very much like the Mohr-Coulomb brittle failure criterion -> Friction and fracture follow a common phenomenology.



Byerlee 1978

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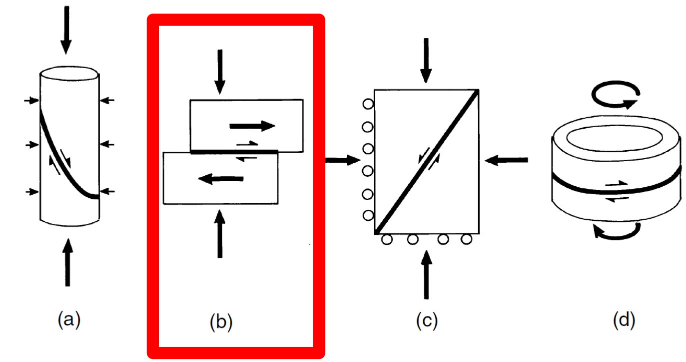

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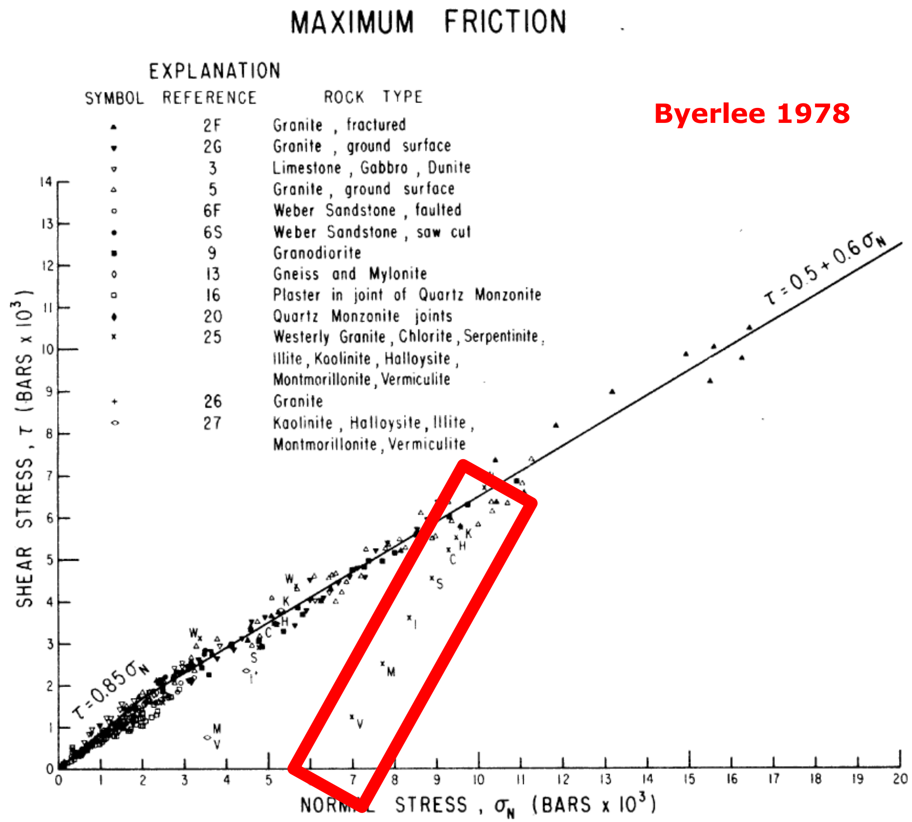
Several important exceptions: clay minerals, which are abundant in fault gouge.



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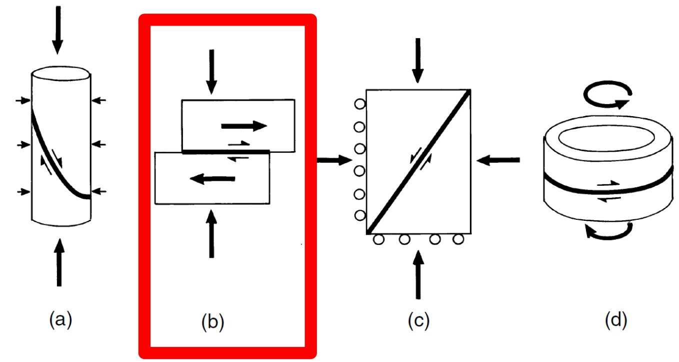
Rocks friction laws

- An even closer look: Rate and State Friction.

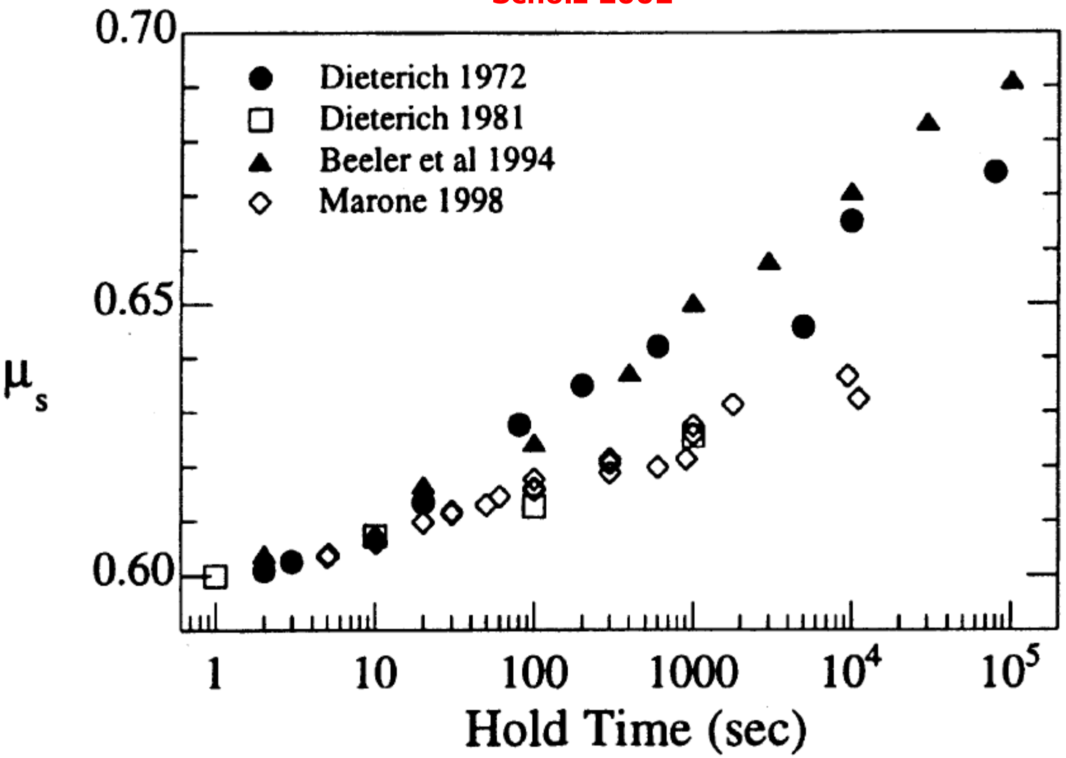


Some experimental evidences:

The strength of a contact between rocks increases with time, in a somewhat logarithmic way.

This is attributed to physico-chemical effects -> Contact ageing.

Scholz 2002



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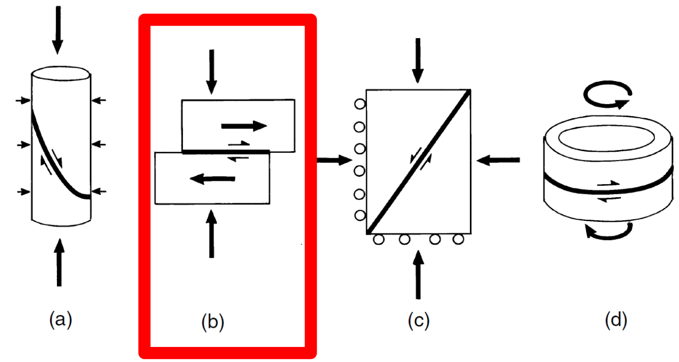
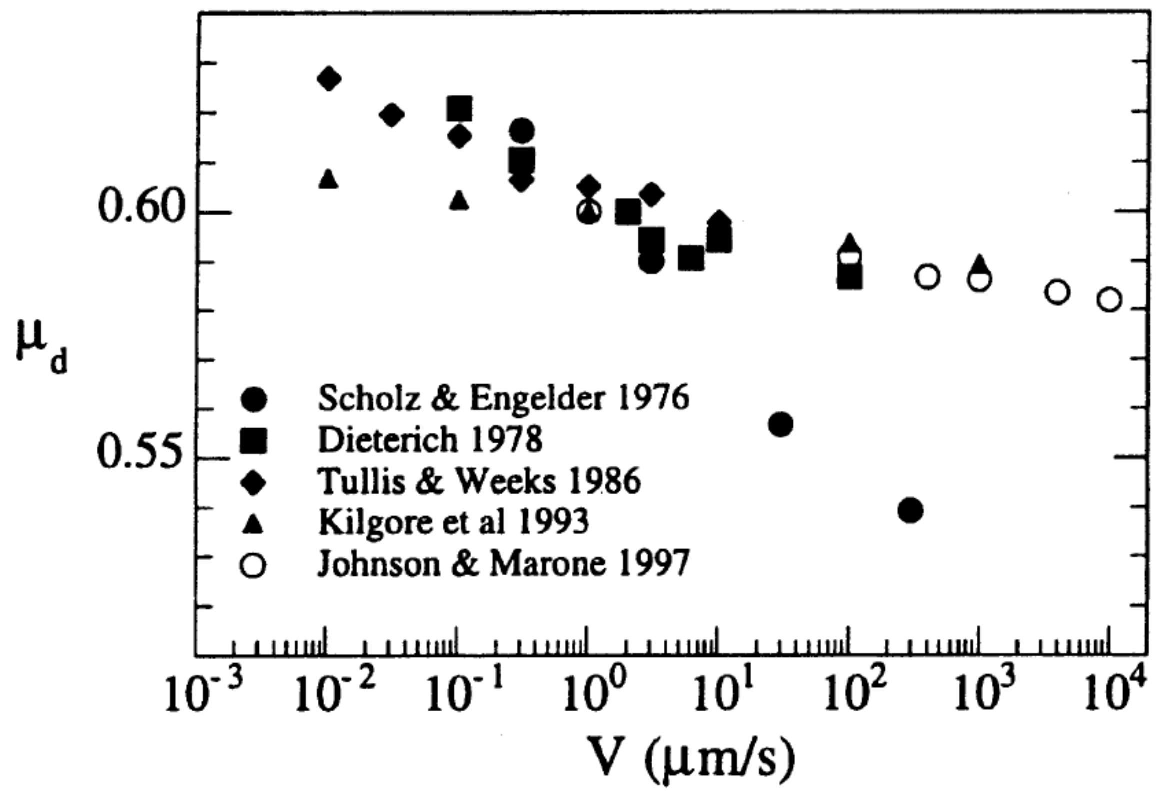


Scholz 2002

Some experimental evidences:

The strength of a contact between rocks decreases with sliding velocity, also in a somewhat logarithmic way.



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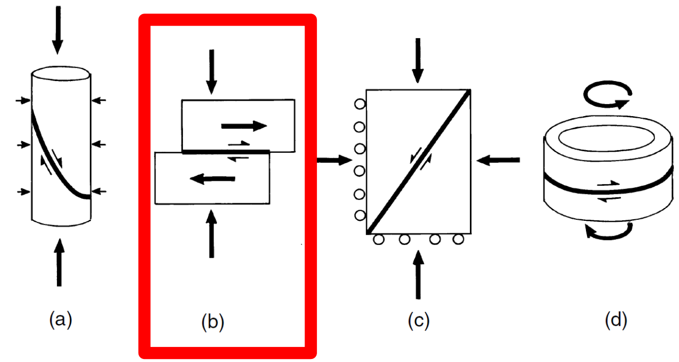

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-> Two competing effects!

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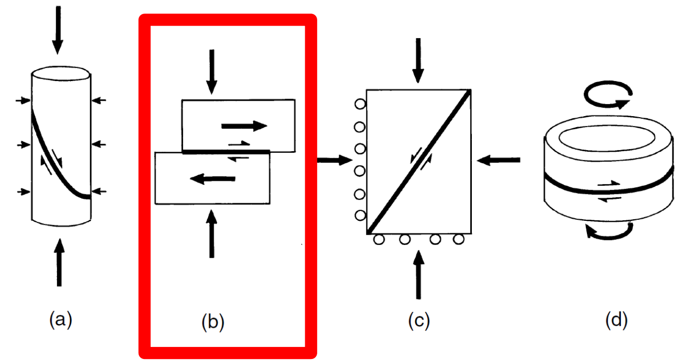

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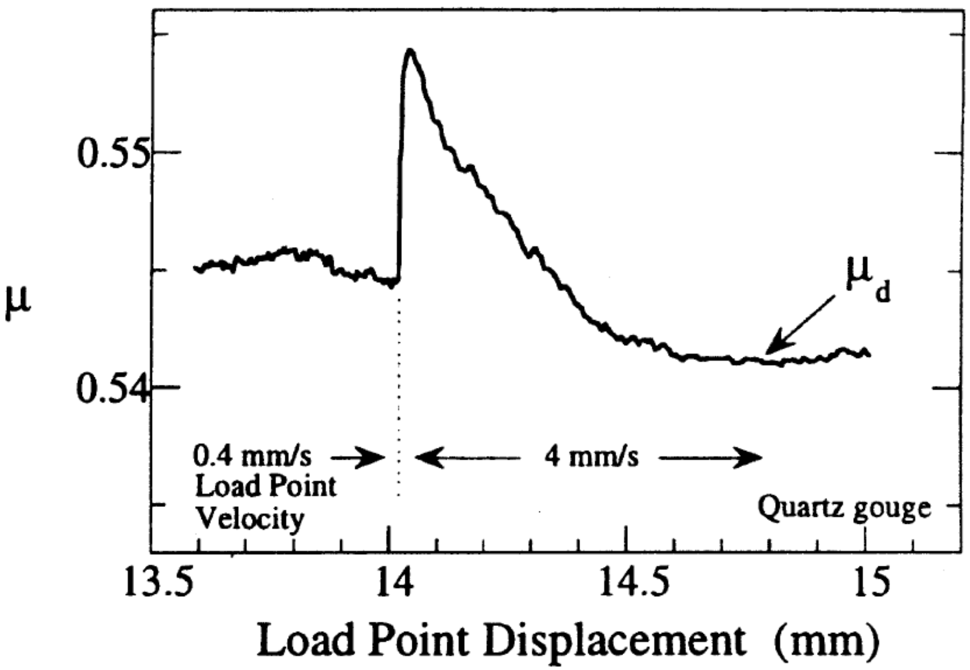
Marone 1998



-> Two competing effects!

They lead to a complex response of the contact, for example in the case of a change in the sliding velocity:

-A direct effect

-A stabilization towards a different value

Rocks friction laws

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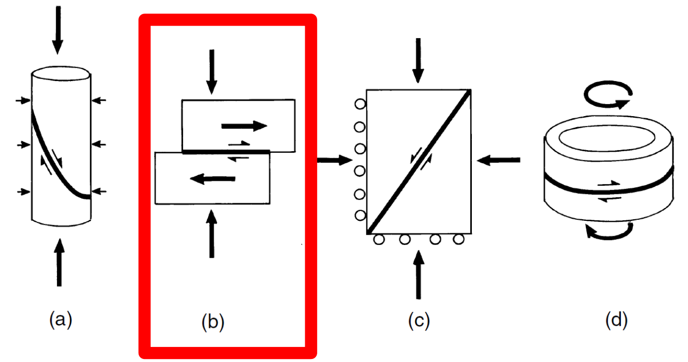

This was formalized in a formula:

The **Rate and State** Friction (RSF) law, which depends on two variables : the sliding velocity and a certain state parameter, with an uncertain physical meaning.

$$\mu(V,\theta) = \mu_0 + a \cdot ln\left(\frac{V}{V_0}\right) + b \cdot ln\left(\frac{V_0\theta}{D_c}\right)$$

Where μ_0 is the measured friction for a given velocity of reference V_0, D_c is a characteristic distance, and a and b are material constants.

Rocks friction laws

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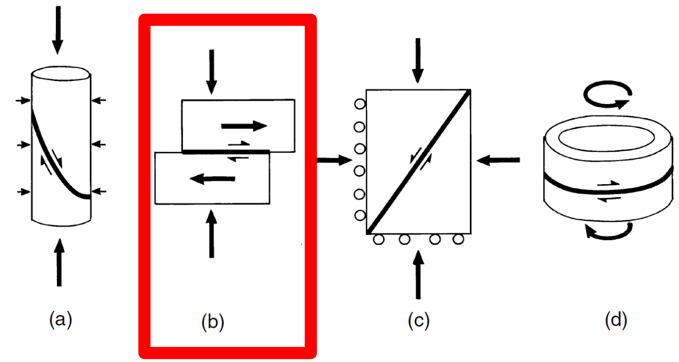

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This law must be completed by an evolution law for θ, for example the Ruina “slowness” law:

$$\dot{\theta} = 1 - \frac{V_0\theta}{D_c}$$

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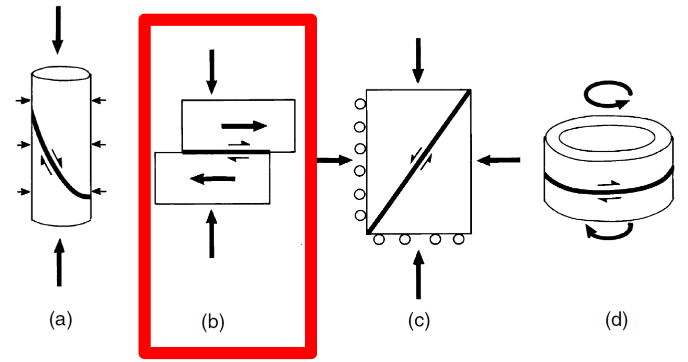

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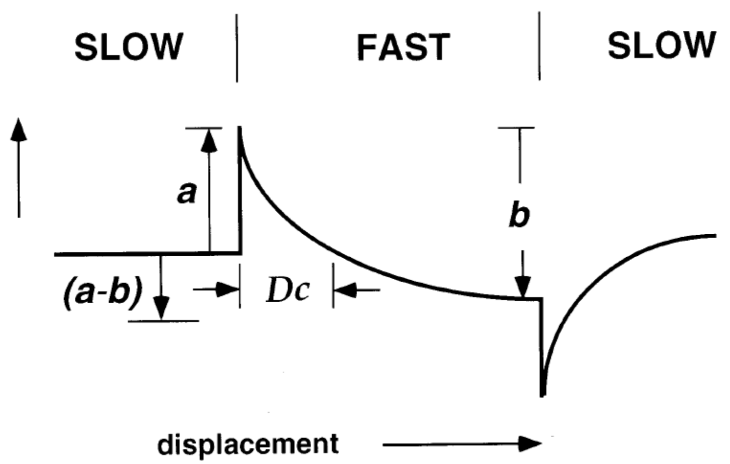

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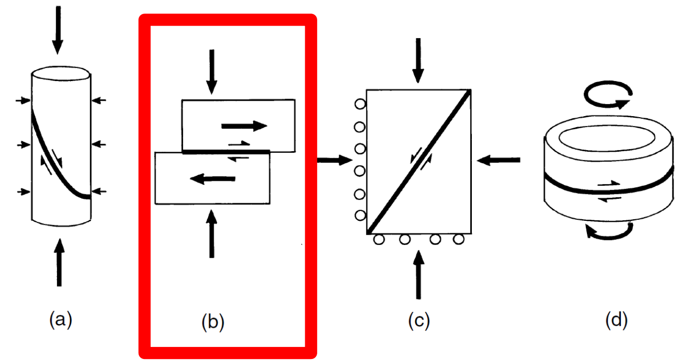

For a steady-state sliding, RSF predicts:

$$\mu_{ss} = \mu_0 + (a - b) \cdot ln \frac{V}{V_0}$$

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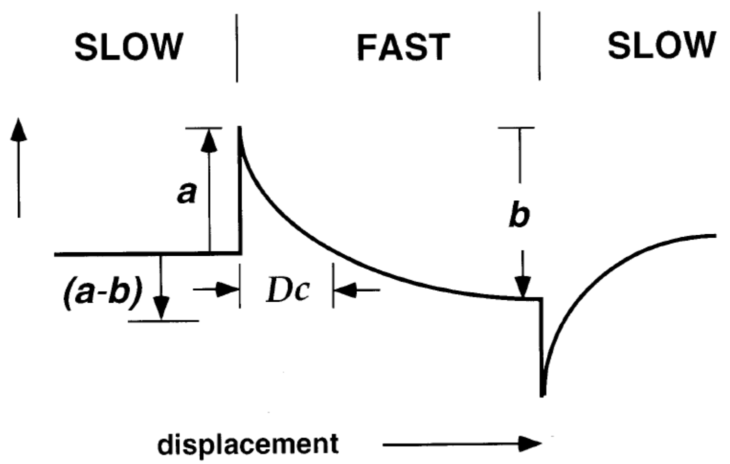

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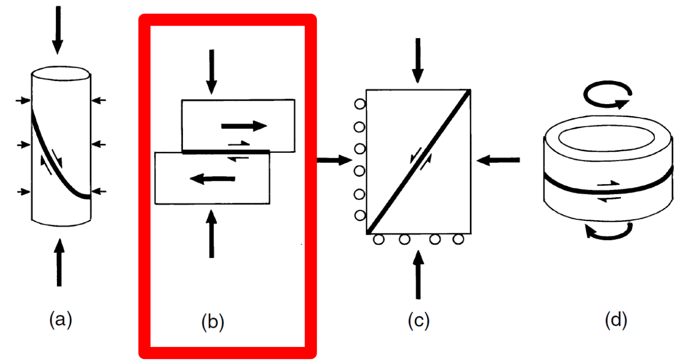

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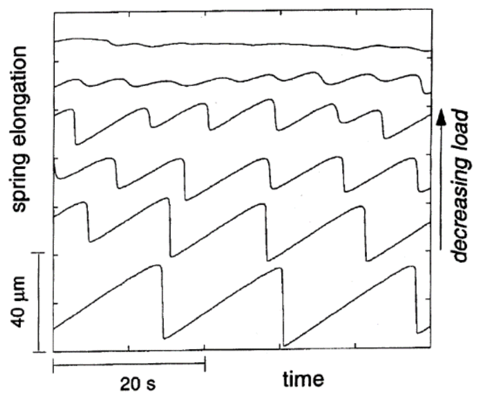
Hence, the quantity $(a - b)$ controls the steady-state dependency of friction to sliding velocity:

If $(a - b) > 0$ -> Velocity strengthening (stable)

If $(a - b) < 0$ -> Velocity weakening (unstable)



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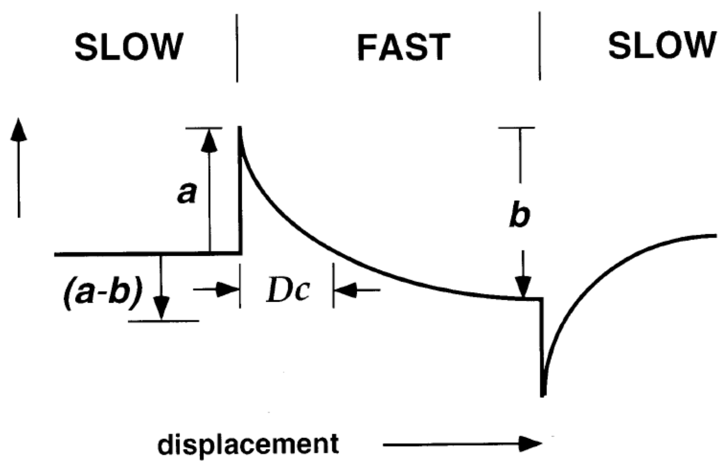

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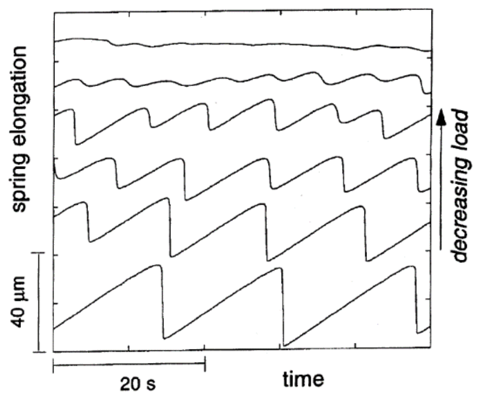
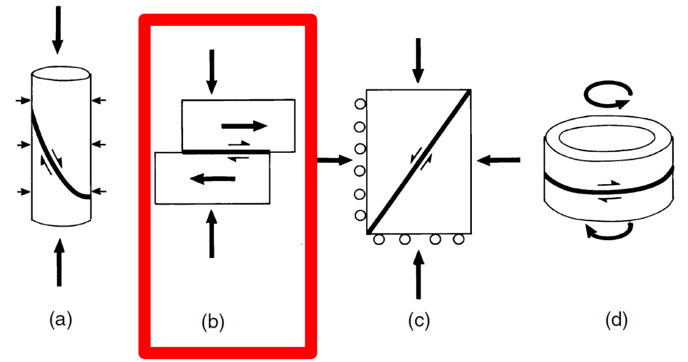
If $(a - b) < 0$ -> Velocity weakening (unstable)





-> Widely used for the modelling of earthquake nucleation, because in the right order of magnitude for sliding velocities.

-> Lack of theoretical foundation (although some explanations were proposed based on plastic flow laws of asperities).

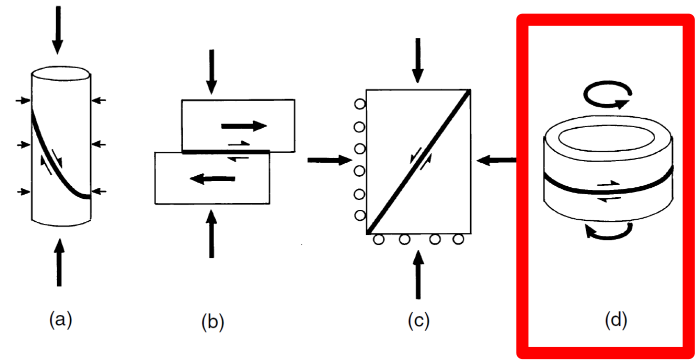
-> $(a - b)$ can only be calibrated based on experimental results, but not predicted theoretically.

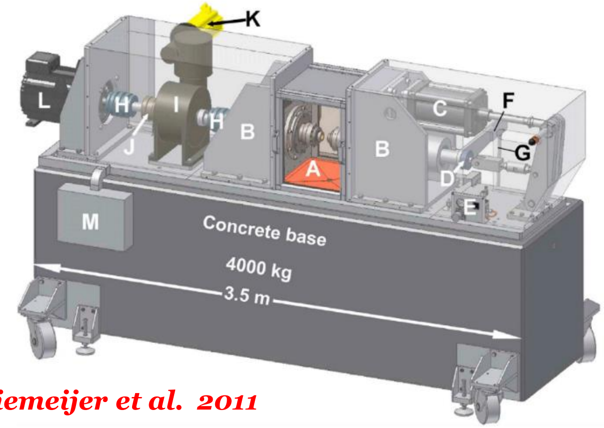
-> Breaks down at coseismic slip rates.

Rocks friction laws

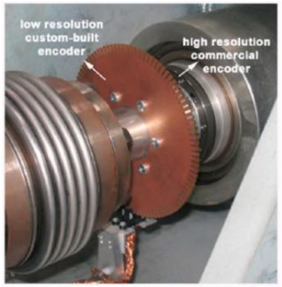
- Dynamic weakening.

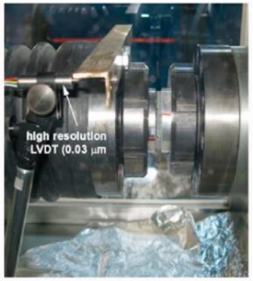
Experiments dedicated to high-energy sliding:



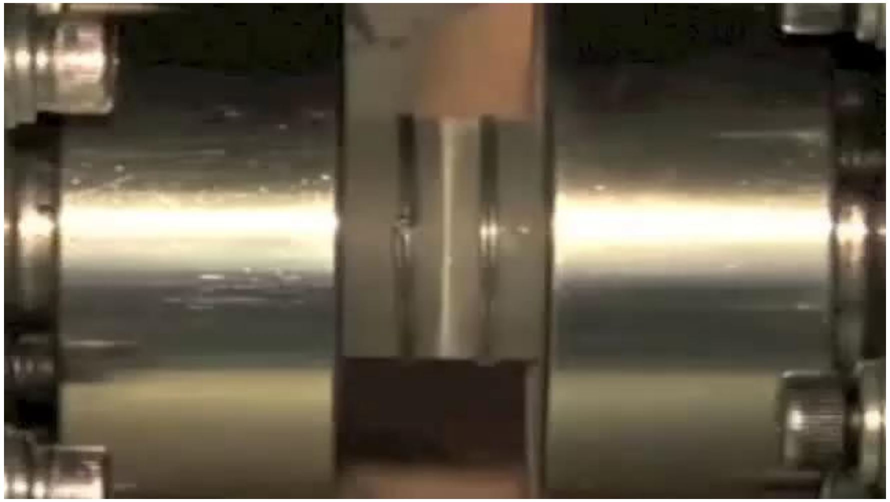


Niemeijer et al. 2011





Rotary shear apparatus

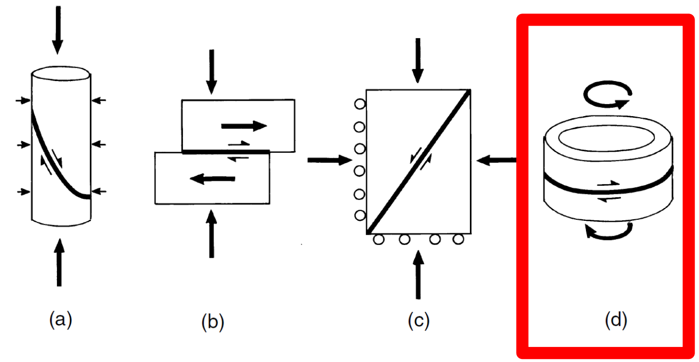


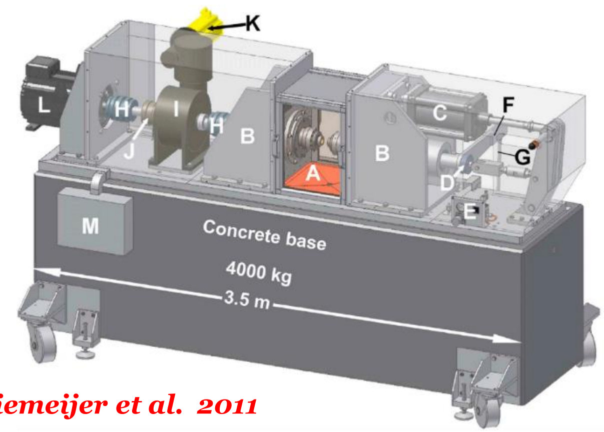
Rocks friction laws

- Dynamic weakening.

Experiments dedicated to high-energy sliding:

They reveal a systematic and dramatic velocity weakening





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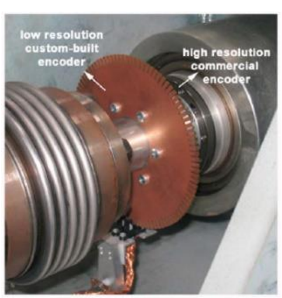

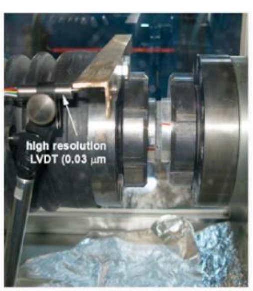

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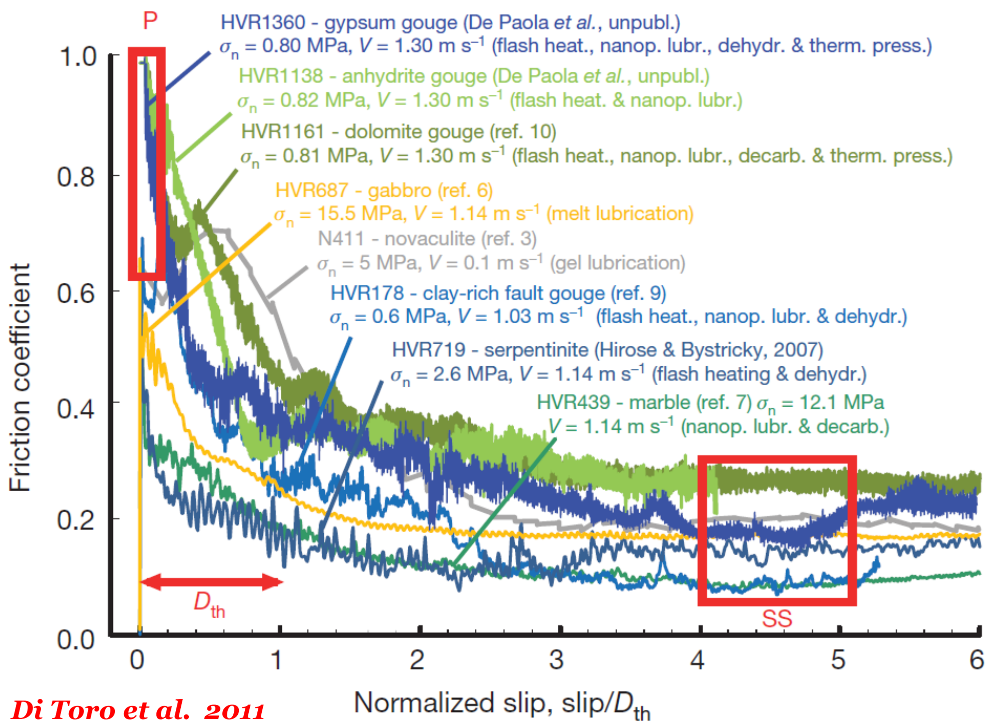


Di Toro et al. 2011

Rocks friction laws

- Dynamic weakening.

These observations are at the basis of the "Flash Heating" theory.

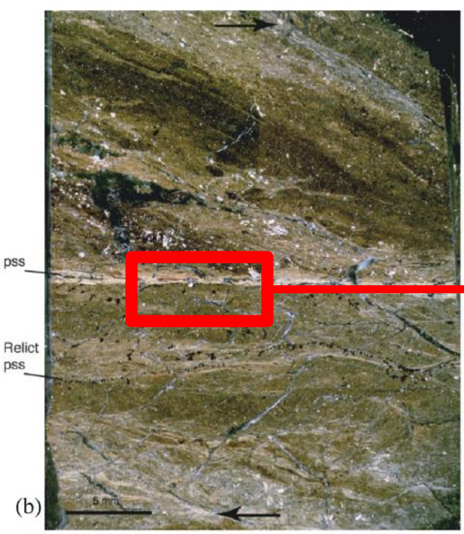
-> Since heat creation is restricted to very small areas, temperature increase is very quick.

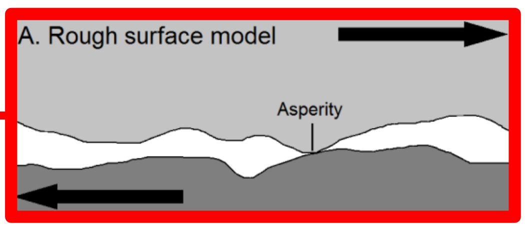
-> Asperities weaken because of local softening or melting, in quasi-adiabatic conditions.

-> Fault friction is controlled by the proportion of weakened asperities.

$$f = (f_o - f_w)\frac{V_w}{V} + f_w \text{ when } V > V_w$$

Rice 2006





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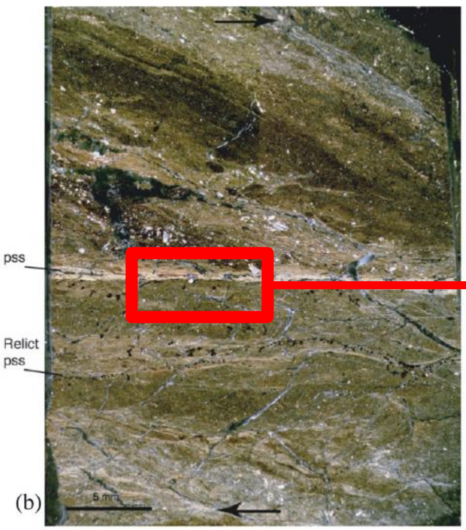
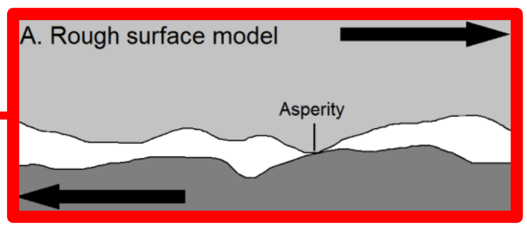
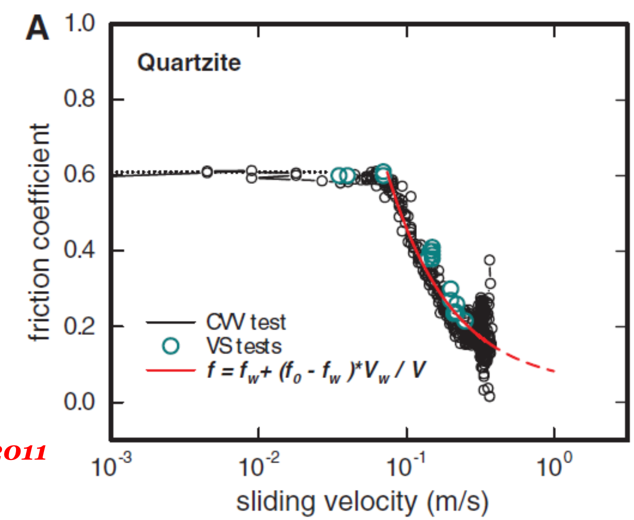


Di Toro et al. 2011





Goldsby and Tullis 2011

Rocks friction laws

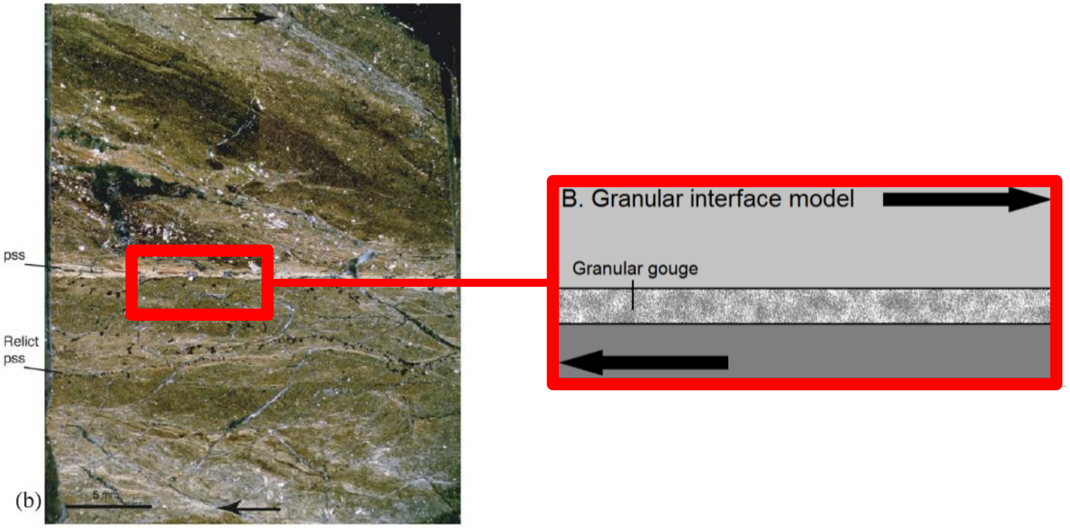
- Dynamic weakening.

But how do we deal with fault gouge, in this view?

-> Fault sliding is rarely on bare rock.

-> Most of the time, it is more accurate to qualify it as the shearing of a gouge layer, not sliding.

-> Is there weakening in a gouge layer, in the absence of geometric asperities?



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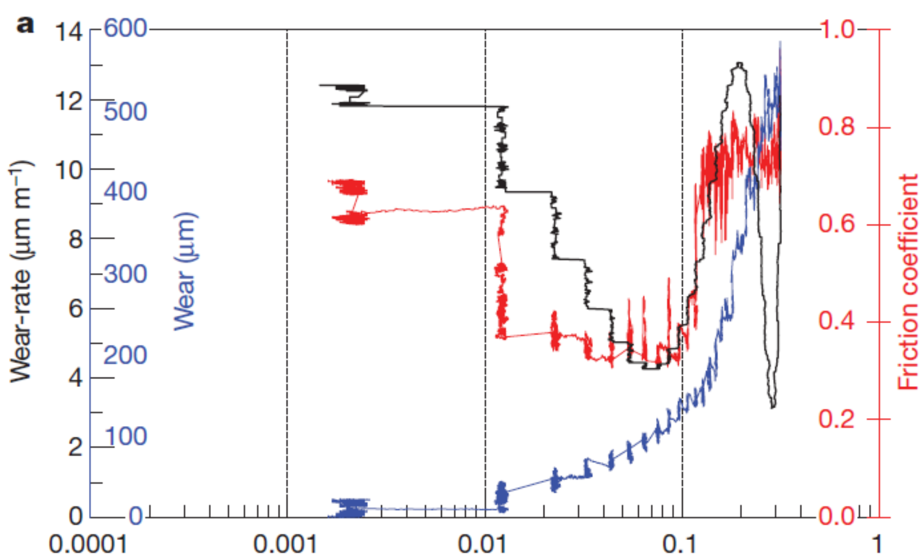
-> Fault sliding is rarely on bare rock.

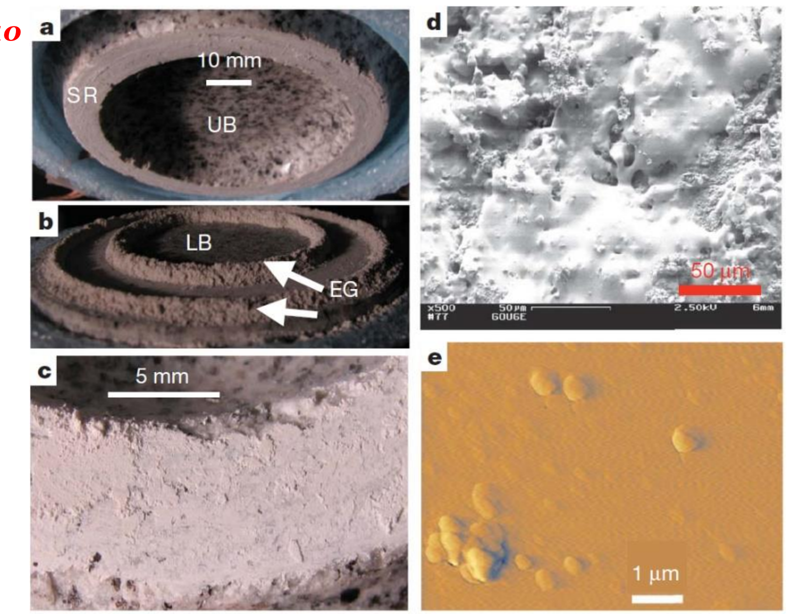
-> Most of the time, it is more accurate to qualify it as the shearing of a gouge layer, not sliding.

-> Is there weakening in a gouge layer, in the absence of geometric asperities?

-> Yes! We even have evidences of melting in the gouge interface.

Reches and Lockner 2010

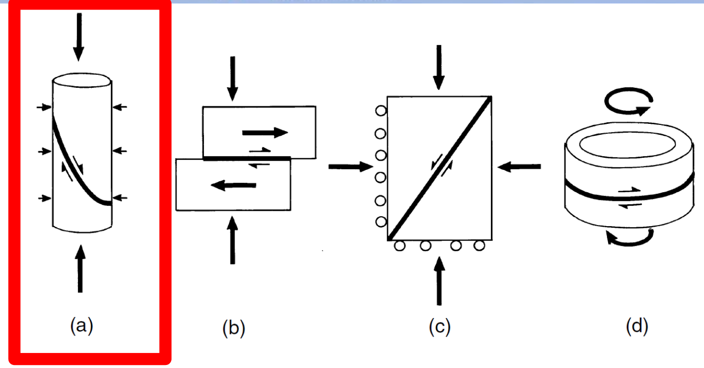


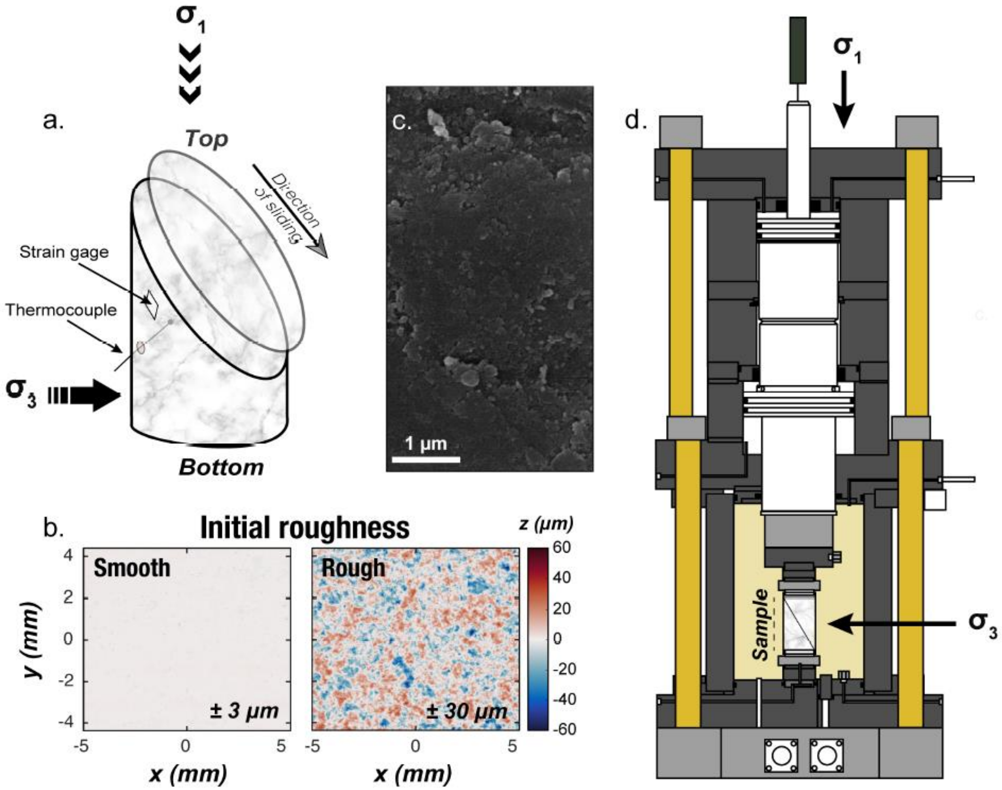


Friction weakening in the presence of gouge

Rocks friction laws

- Saw-cut triaxial experiments on Westerley granite under σ_3=45-180MPa (Aubry 2020)





Saw-cut triaxial experiment

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- Saw-cut triaxial experiments on Westerley granite under σ_3=45-180MPa (Aubry 2020)
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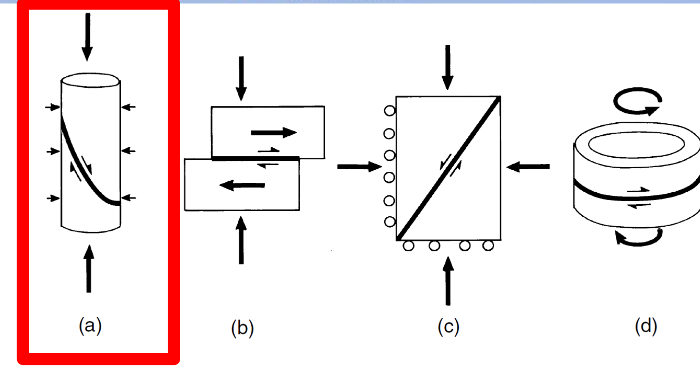
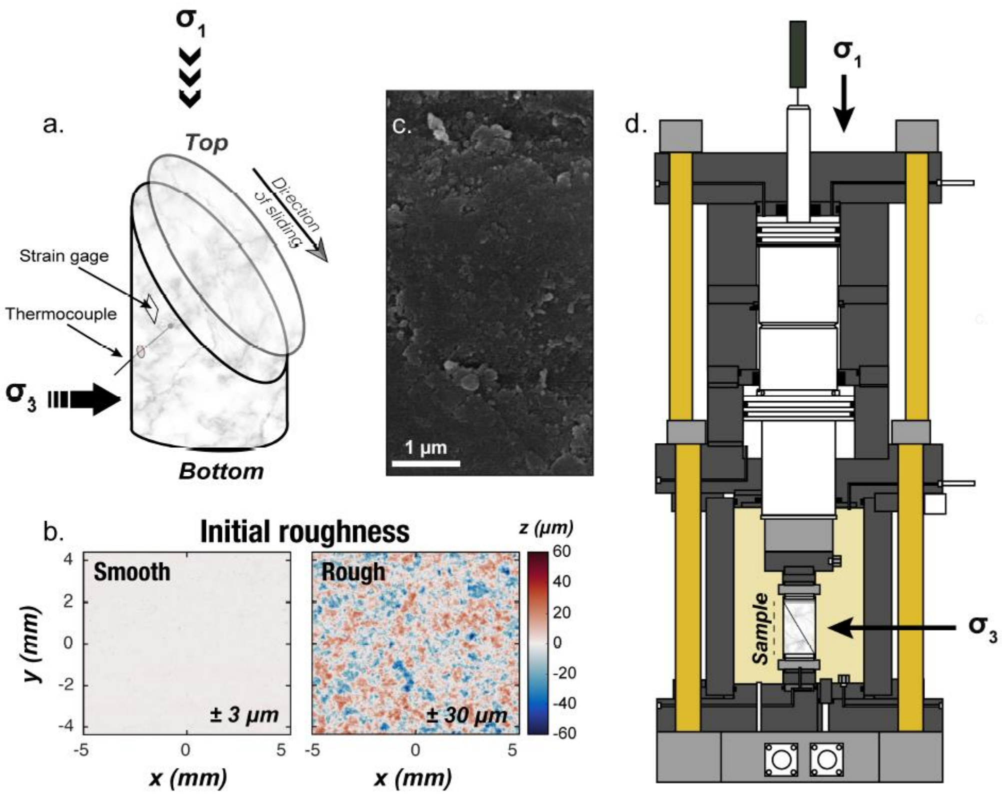
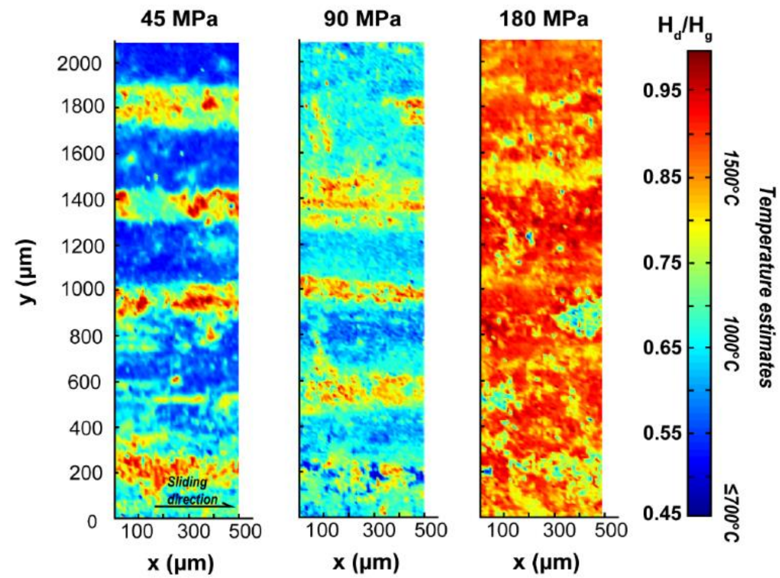




Saw-cut triaxial experiment

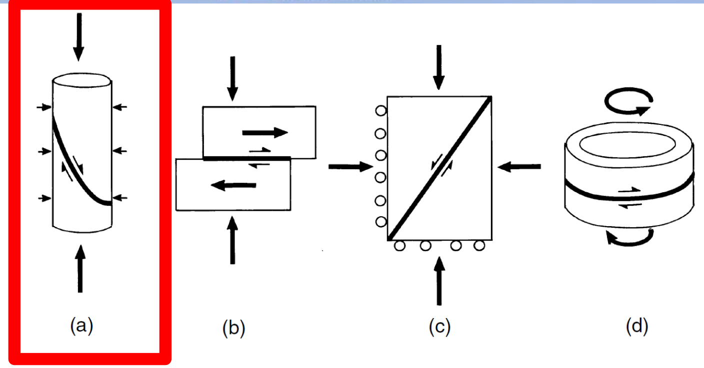
Local temperature increase mapped by carbon deposition technique



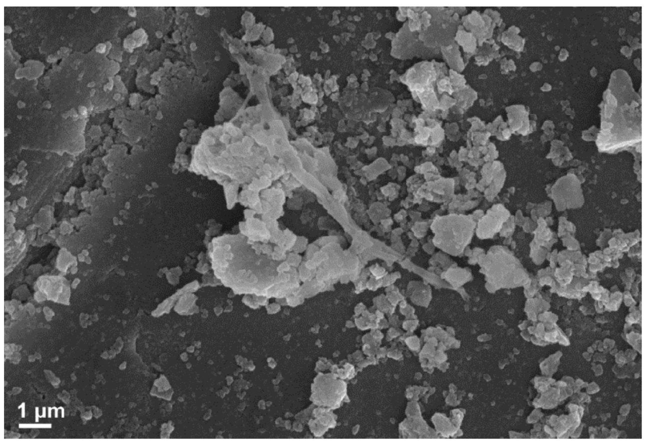
Aubry et al. 2019

Rocks friction laws

- Saw-cut triaxial experiments on Westerley granite under σ_3=45-180MPa (Aubry 2020)
- Temperature trackers (amorphous carbon layer) showed clear evidences of flash heating
- SEM–TEM observation showed partial or total melting of the gouge layer.

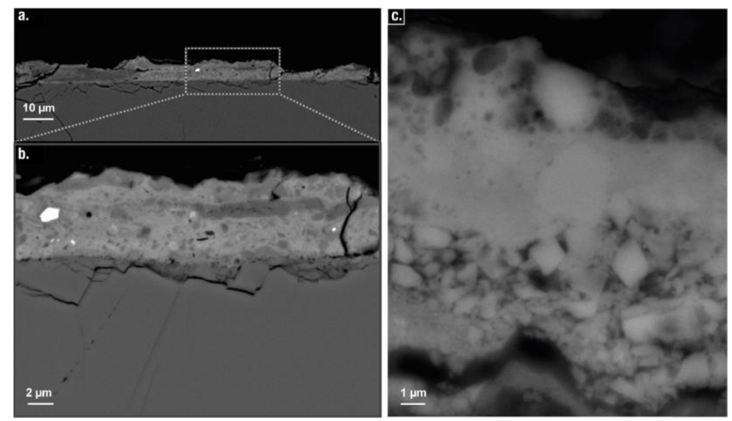


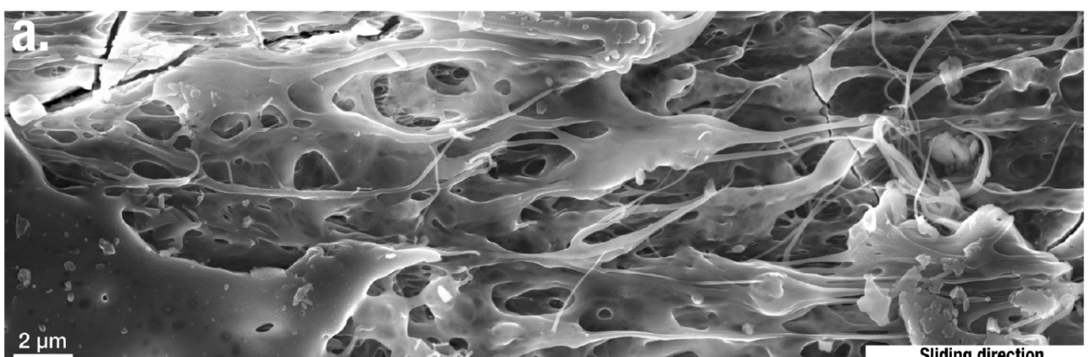
Aubry et al. 2019



Initial gouge particles
Size ~ 1 µm

Cross section of amorphous melt layer with micro/nanometric gouge particles





Completely established layer of melt

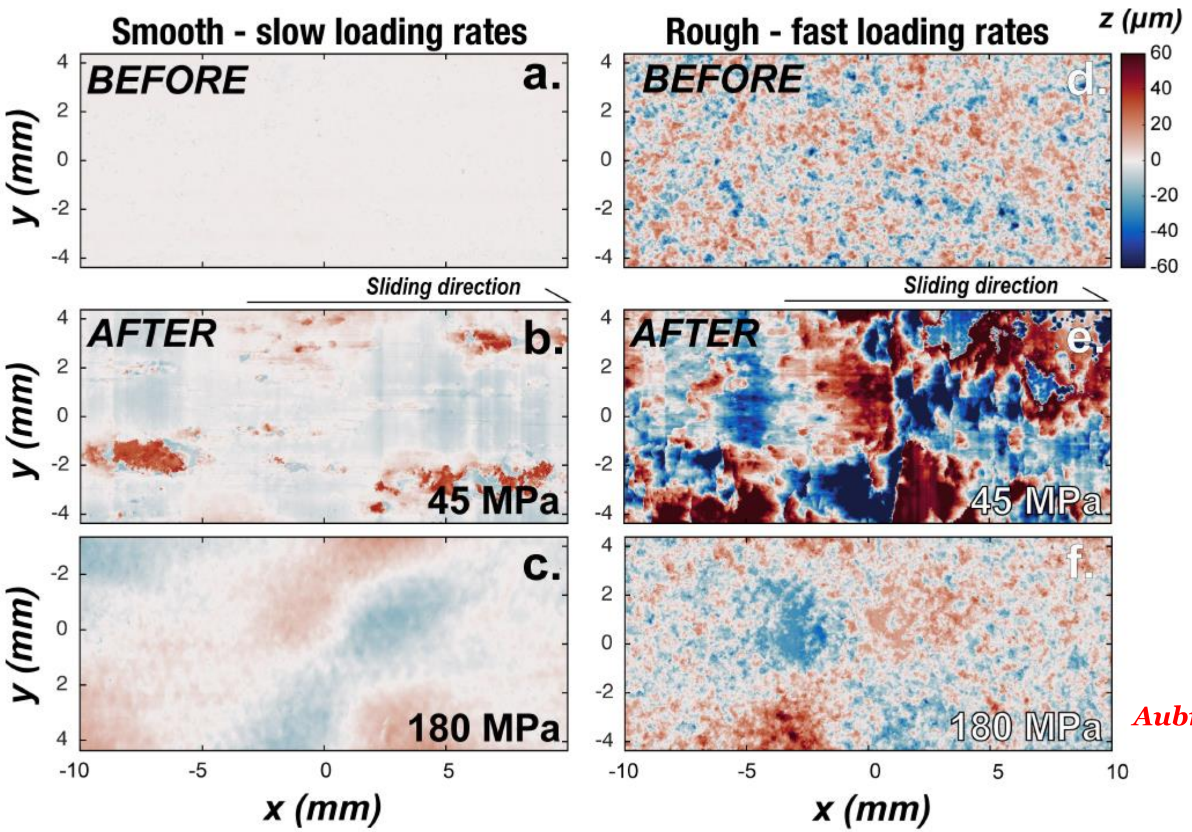
Rocks friction laws

- What happens in the interface?

Evolution of the roughness: several possible behaviors

-> Initially smooth laboratory fault may become rough

-> Initially rough laboratory fault may become smooth



Aubry et al. 2019

Rocks friction laws

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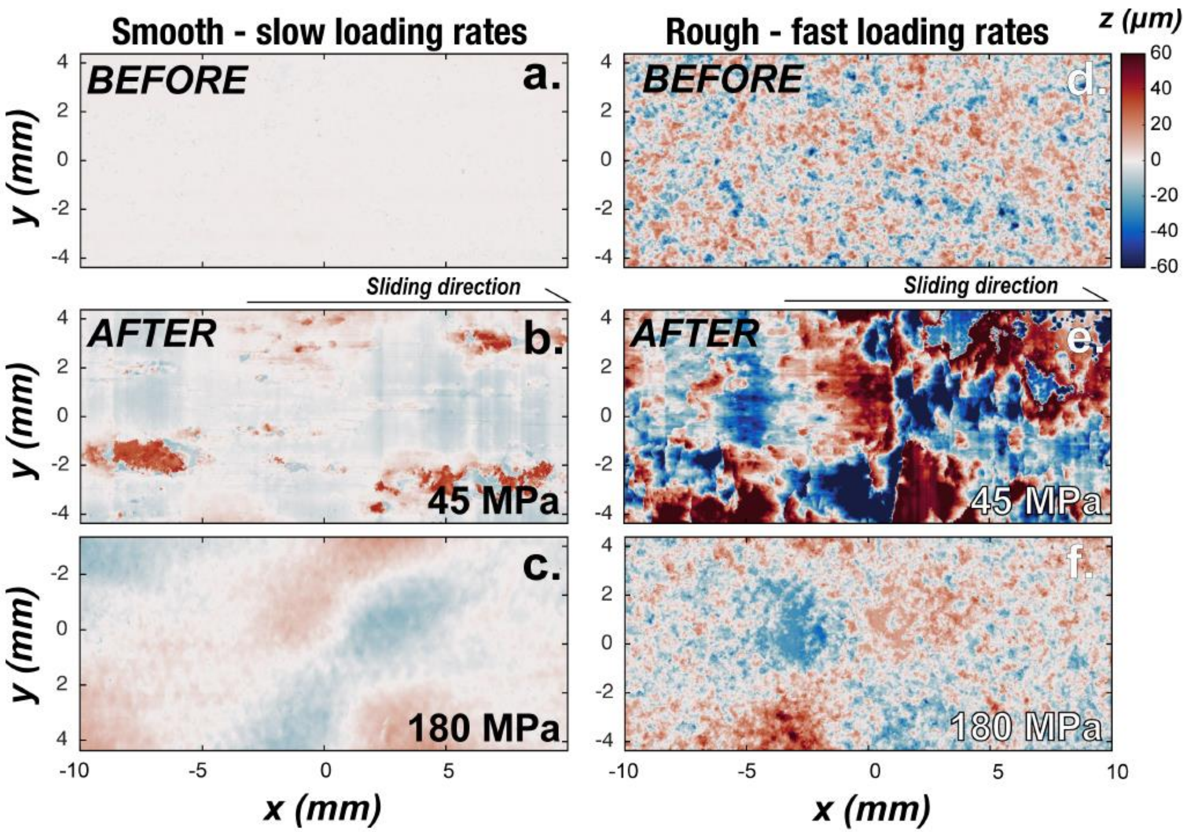


Roughness increase can be related to:

-Renewal of asperities in the case of abrasive or adhesive wear

-Accumulation and compaction of third body (gouge)

-Plastic deformation of the bulk rock underneath

Roughness decrease can be related to:

-Mating of the asperities

-Plastic shearing of the asperities

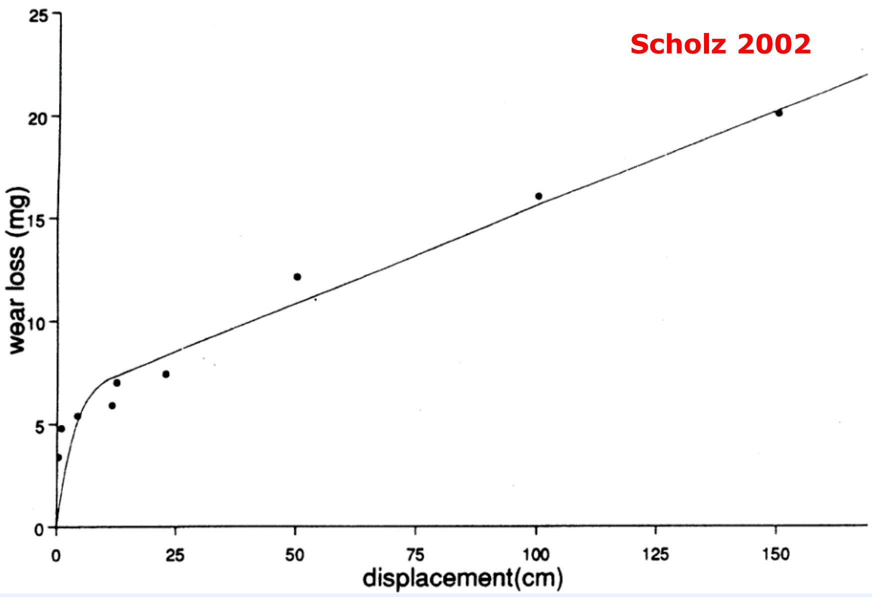
-Melting and quenching

Rocks friction laws

- What happens in the interface?

Wear of the surfaces and gouge formation

-> Experimental wear rate usually consists in a running-in period of asperity-related fast wear, followed by a lower steady-state wear rate (related to an established gouge layer)



Rocks friction laws

- What happens in the interface?

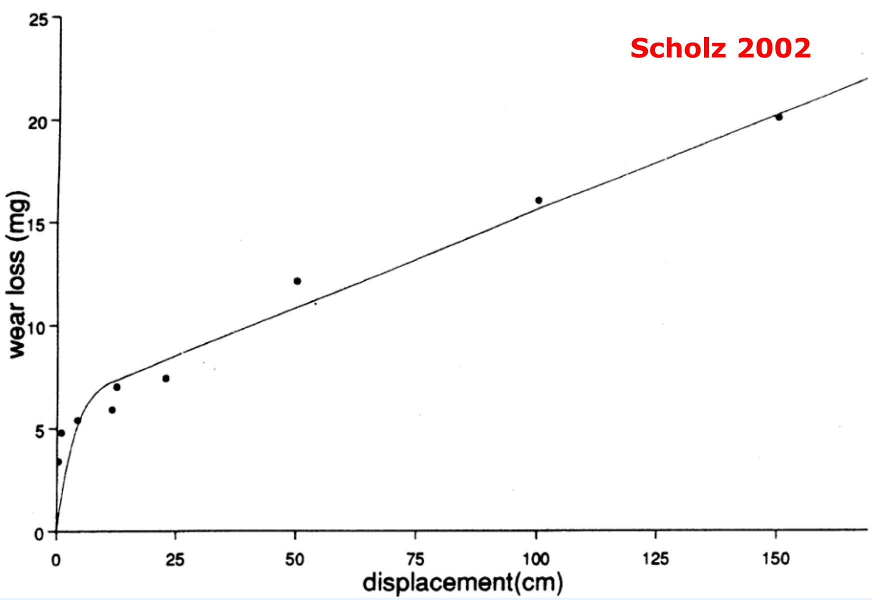
Wear of the surfaces and gouge formation

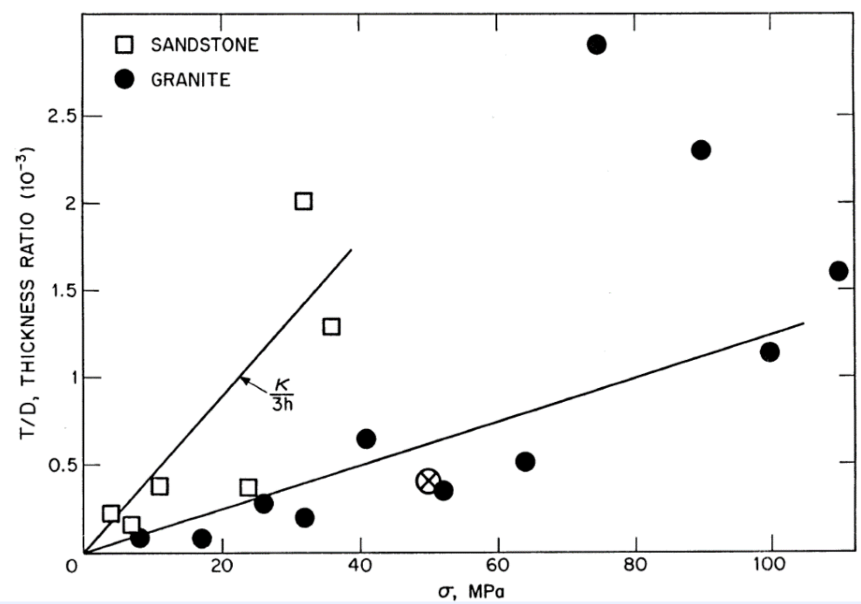
-> Experimental wear rate usually consists in a running-in period of asperity-related fast wear, followed by a lower steady-state wear rate (related to an established gouge layer)

-> This rate is extremely dependent on the lithology (i.e. rock type): Sandstone (a cemented aggregate of large grains with a very large porosity) wears much faster than granite (a solid cristallized rock obtained by magma cooling).

-> It seems to follow a Archard-like phenomenology (i.e. proportional to normal stress).

Scholz 2002





Rocks friction laws

- What happens in the interface?

Wear of the surfaces and gouge formation

Wear is associated with a large number of complex phenomena in the interface:

Rocks friction laws

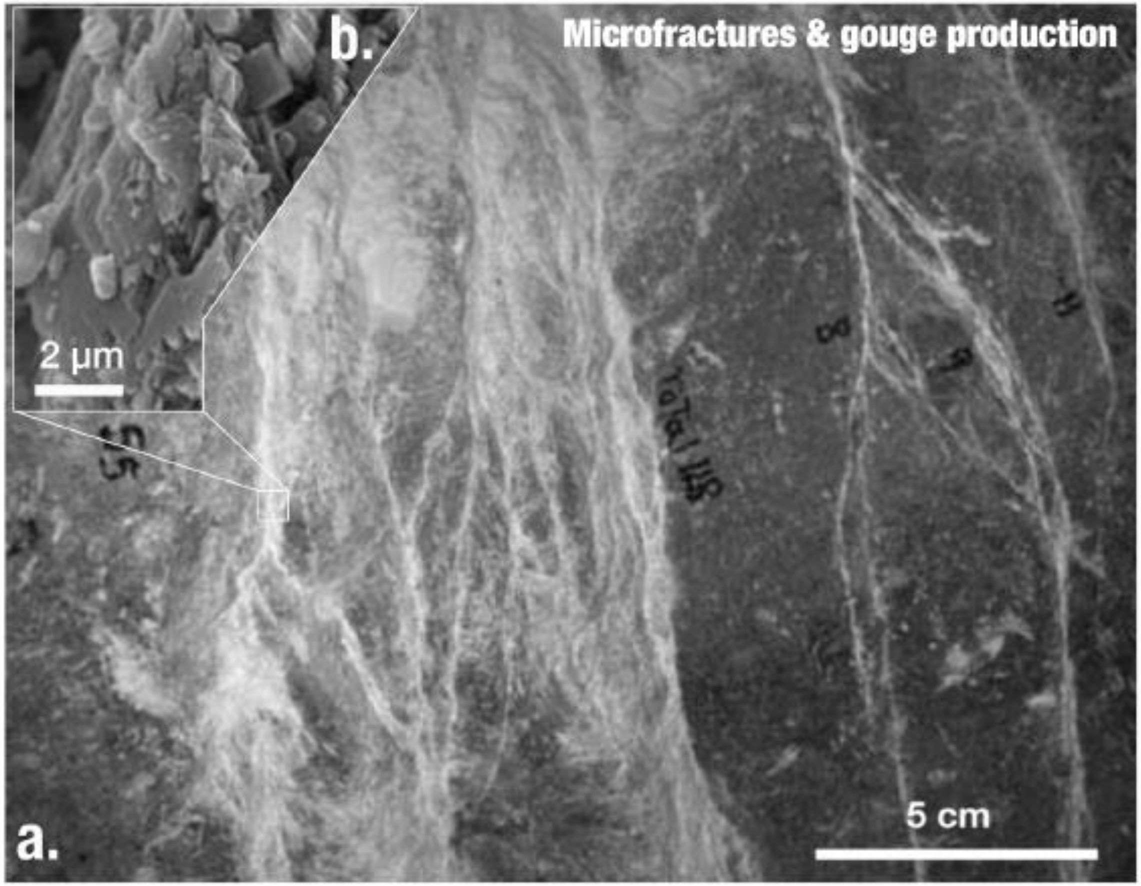
- What happens in the interface?

Wear of the surfaces and gouge formation

Wear is associated with a large number of complex phenomena in the interface:

Aubry 2019

-> Microfracturing



Rocks friction laws

- What happens in the interface?

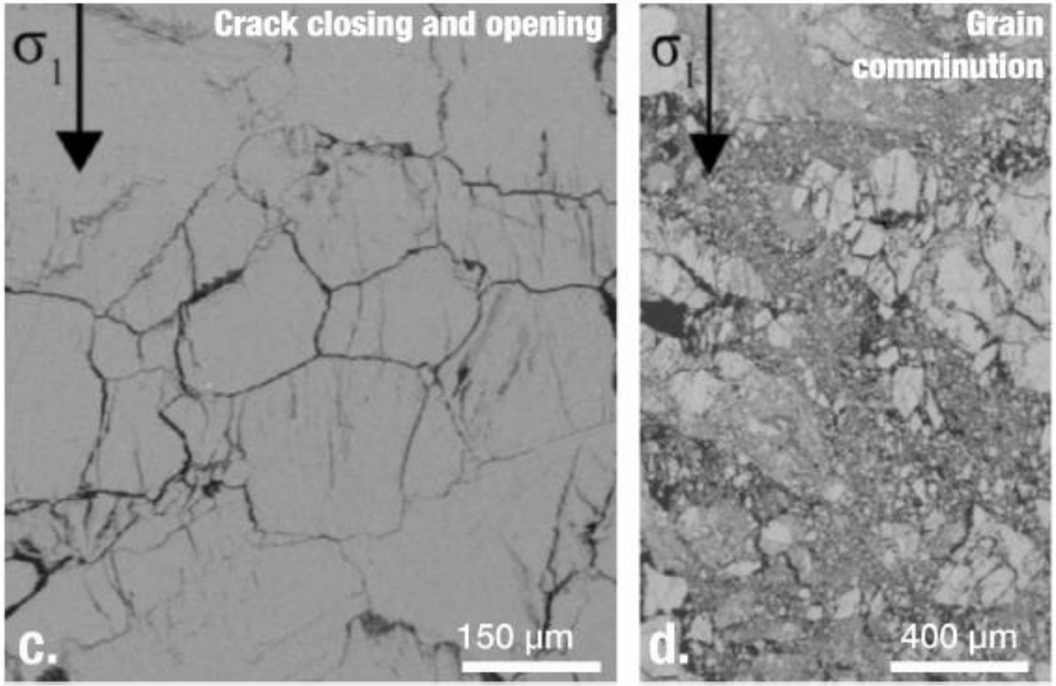
Wear of the surfaces and gouge formation

Wear is associated with a large number of complex phenomena in the interface:

-> Microfracturing

-> Cracks and grains comminution

Aubry 2019



Rocks friction laws

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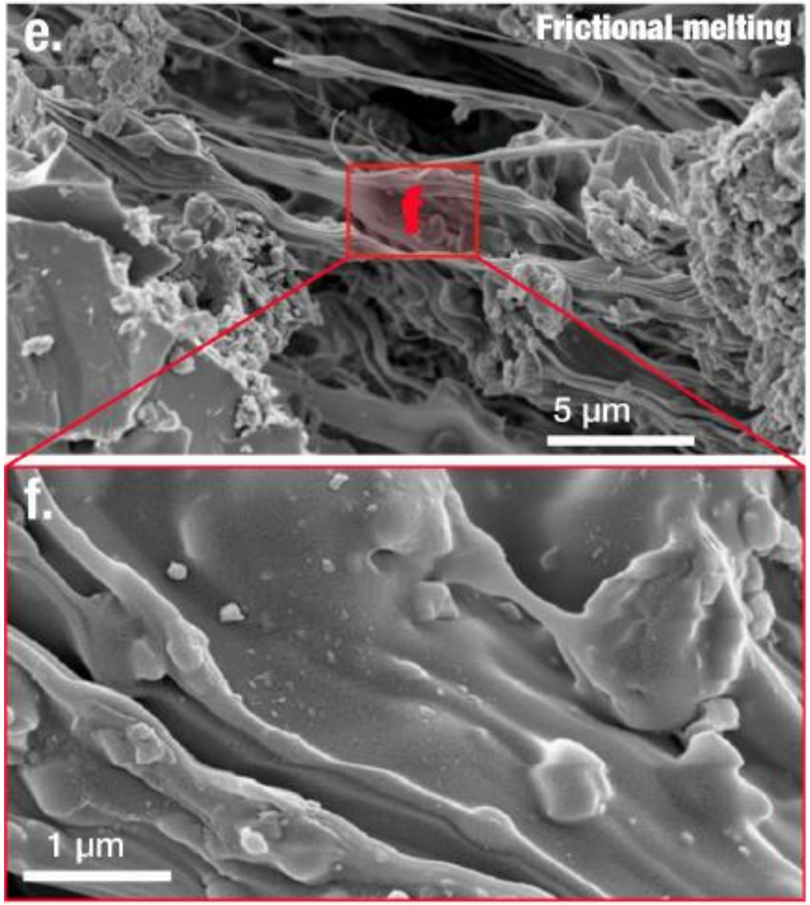
Aubry 2019



-> Microfracturing

-> Cracks and grains comminution

-> Frictional melting

Rocks friction laws

- What happens in the interface?

Wear of the surfaces and gouge formation

Wear is associated with a large number of complex phenomena in the interface:

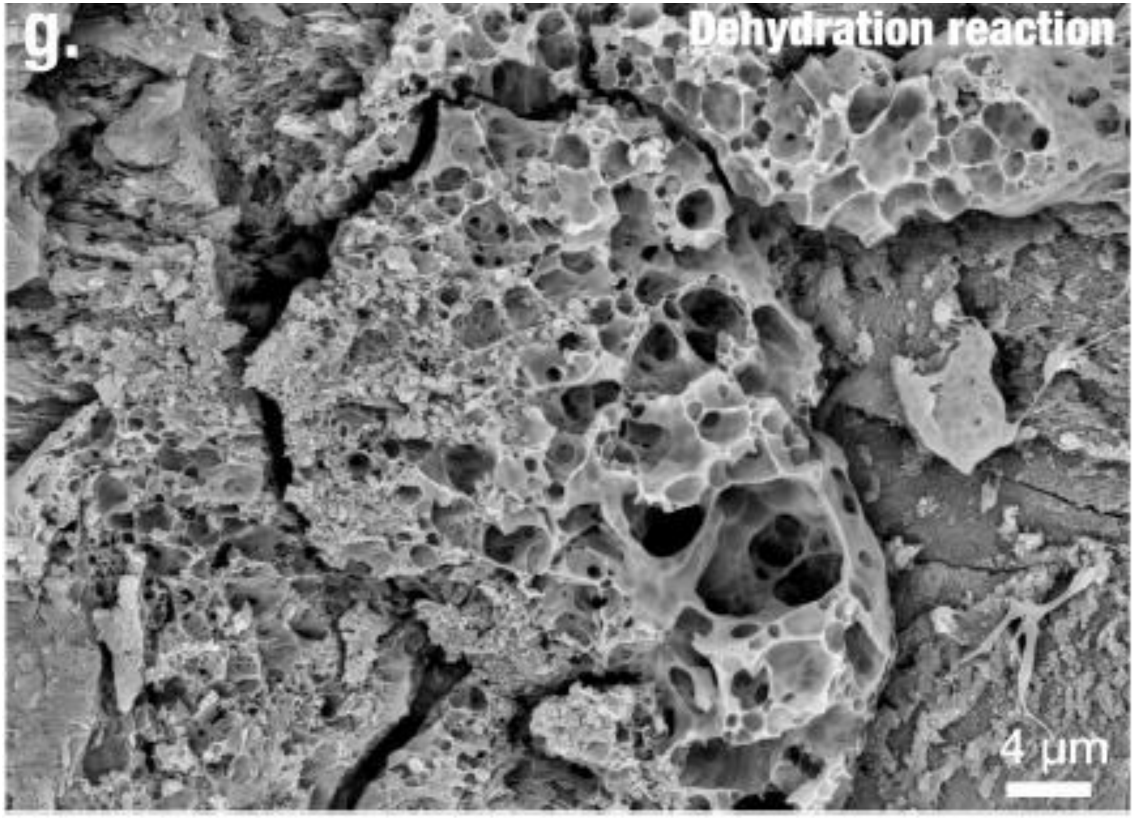
-> Microfracturing

-> Cracks and grains comminution

-> Frictional melting

-> Chemical reactions

Aubry 2019



Simulations – Case study #1

Guilhem Mollon[1]

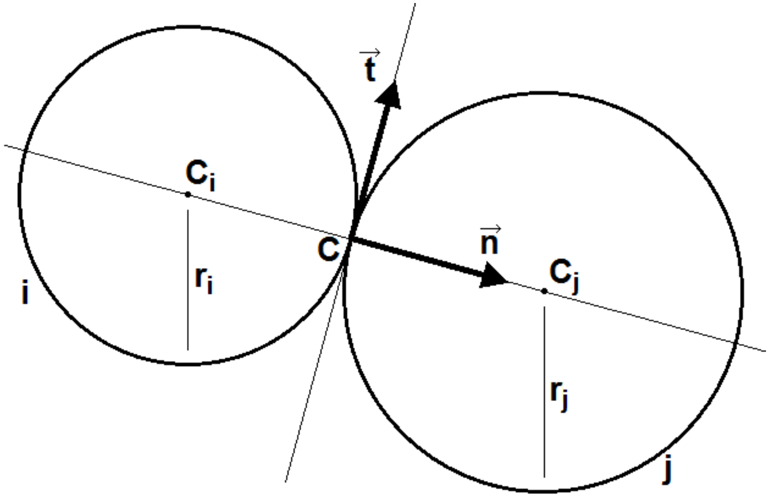
[1]LaMCoS
INSA LYON
Villeurbanne, France

TRAMME, July 2023

DEM simulation protocol:

- Discrete Element Modelling (DEM) is a numerical method dedicated to granular materials.
- Each grain is represented explicitly as a rigid body subjected to Newtonian dynamics.

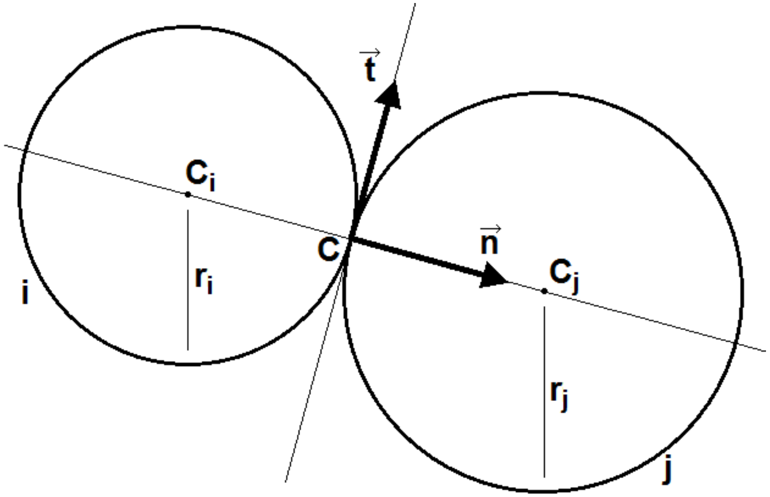
$$m_i \frac{d^2\overrightarrow{x_i}}{dt^2} = \sum \overrightarrow{F_i}$$



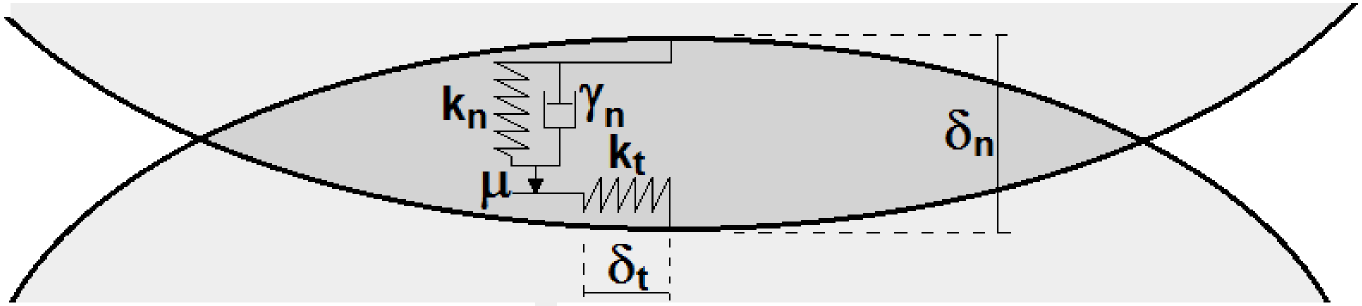
DEM simulation protocol:

- Discrete Element Modelling (DEM) is a numerical method dedicated to granular materials.
- Each grain is represented explicitly as a rigid body subjected to Newtonian dynamics.
- Bodies interact through a standard contact model with friction and damping.
- Discs in the historical method, but can be extended to arbitrary shapes.

$$m_i \frac{d^2\vec{x_i}}{dt^2} = \sum \vec{F_i}$$



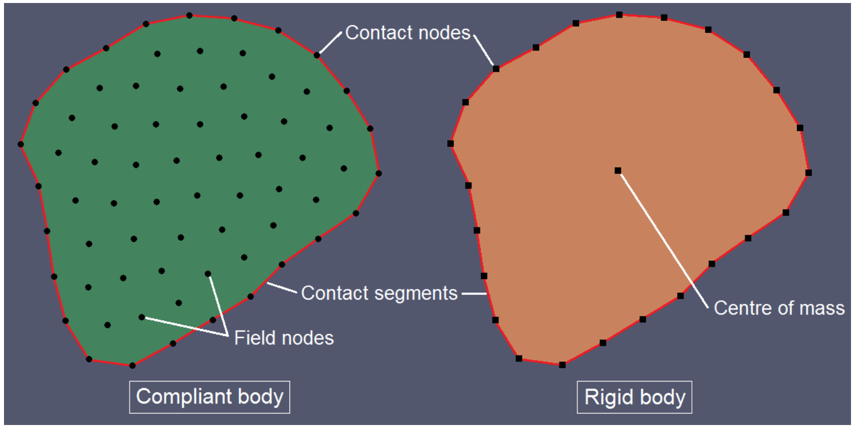
$$\vec{F_{ij}} = F_n \vec{n} + F_t \vec{t}$$

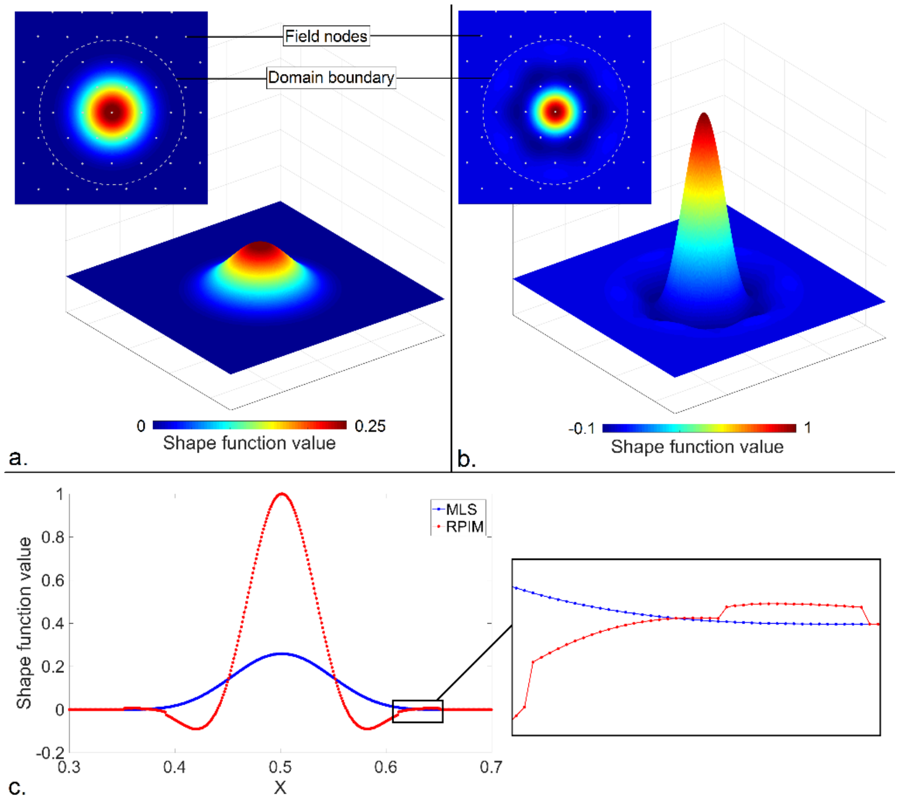


Numerical method

Classical DEM deals with the interaction of **rigid bodies**, but we often need to go beyond.

A compliant body (e.g. a grain) is represented by a discrete set of nodes, which carry the degrees of freedom in displacements.





Between the nodes, continuous fields are interpolated using Moving Least Square (MLS) shape functions.

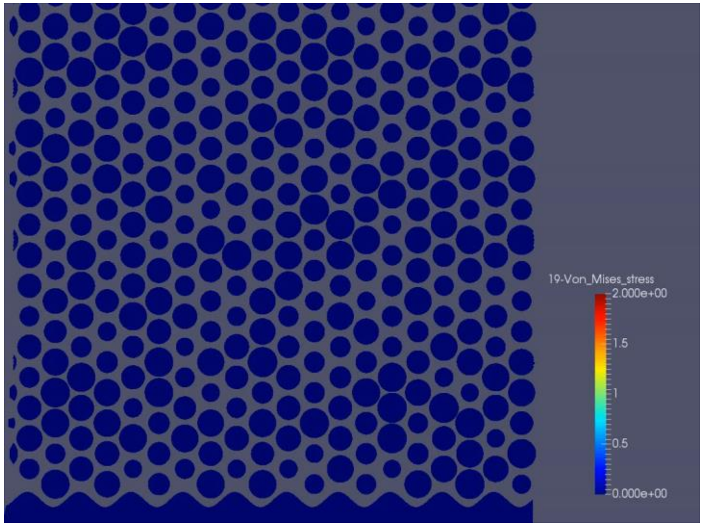
MLS provides a better accuracy than FEM for a given number of degrees of freedom, and a **dramatic improvement in robustness**.

All implemented in an open-source code : MELODY (*Mollon 2018*).

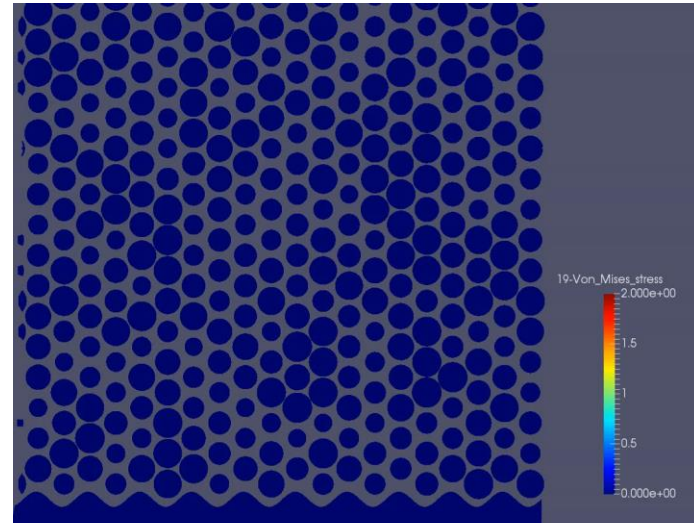
Mollon, G. (2018). "A unified numerical framework for rigid and compliant granular materials", Computational Particle Mechanics, 5, 517-527

Rheology of mixtures of soft and rigid grains

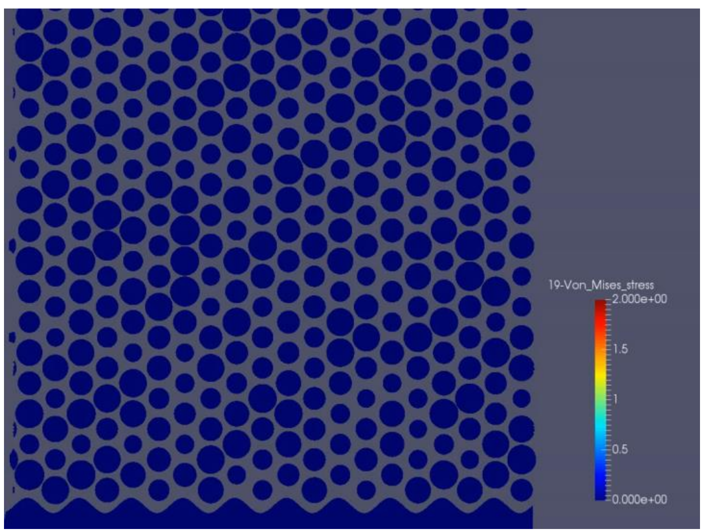
20% soft



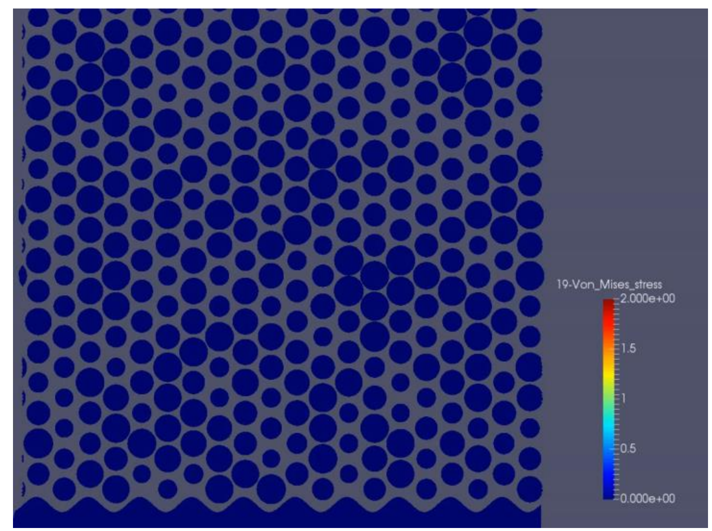
40% soft



60% soft

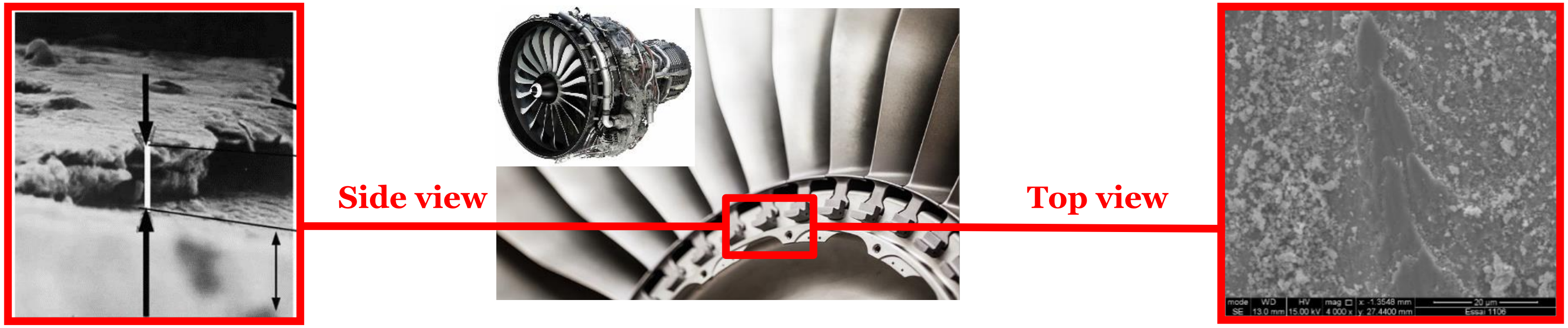


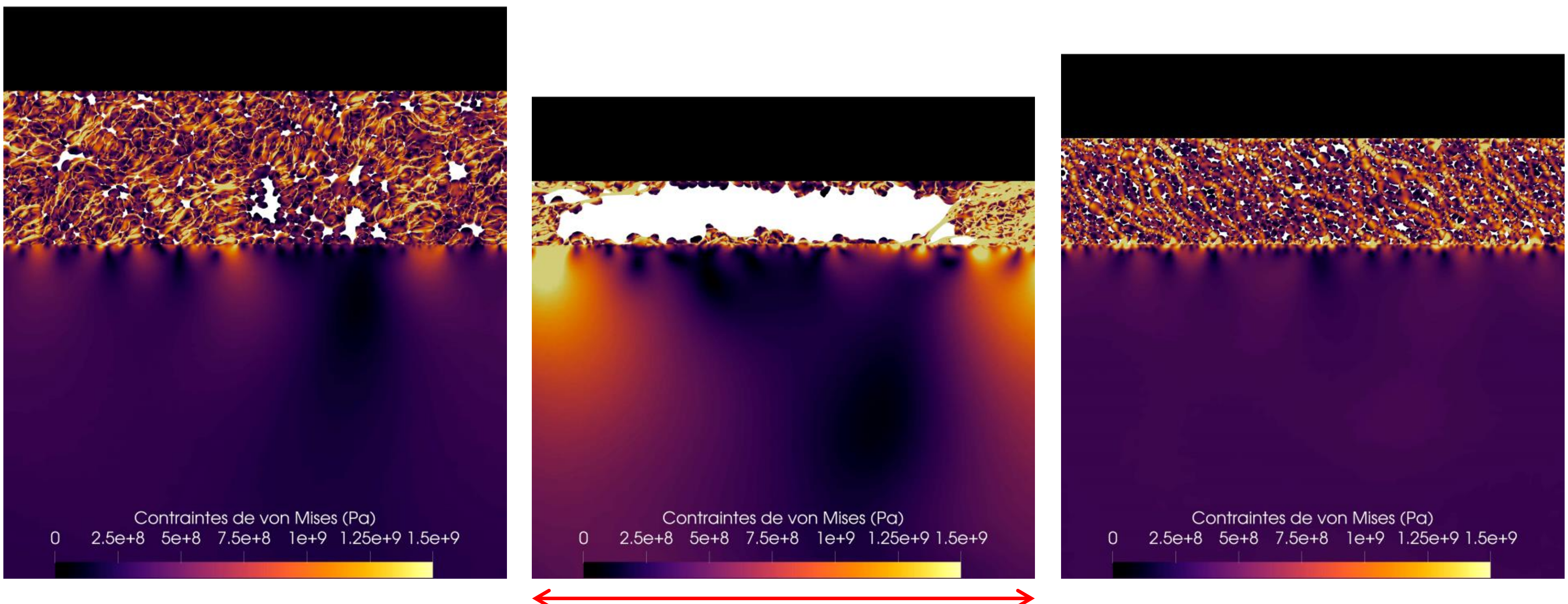
80% soft



Mollon, G. (2018). "Mixtures of hard and soft grains: micromechanical behavior at large strains", Granular Matter, 20, 39

Solid flow regimes and stress concentrations in industrial contacts

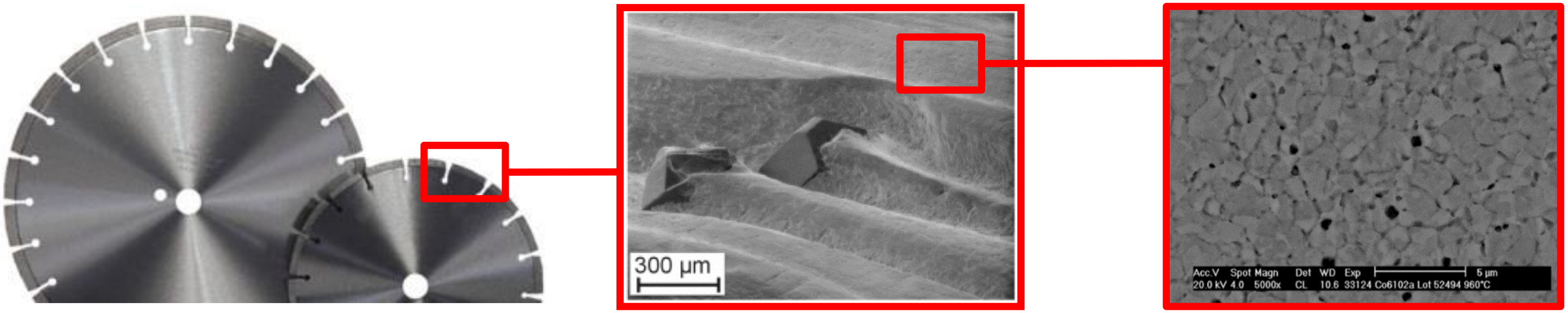


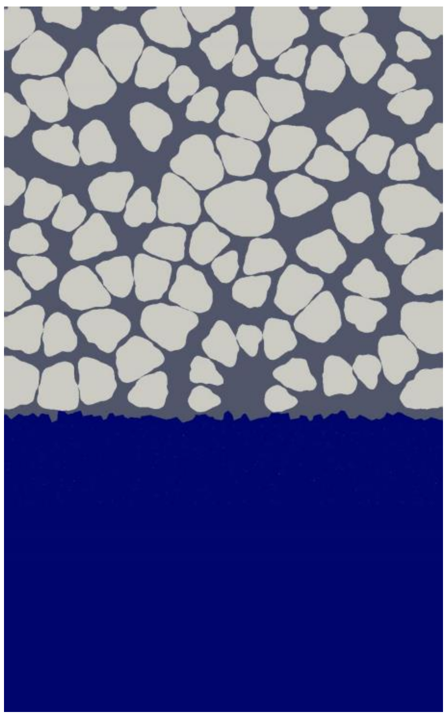


A few µm

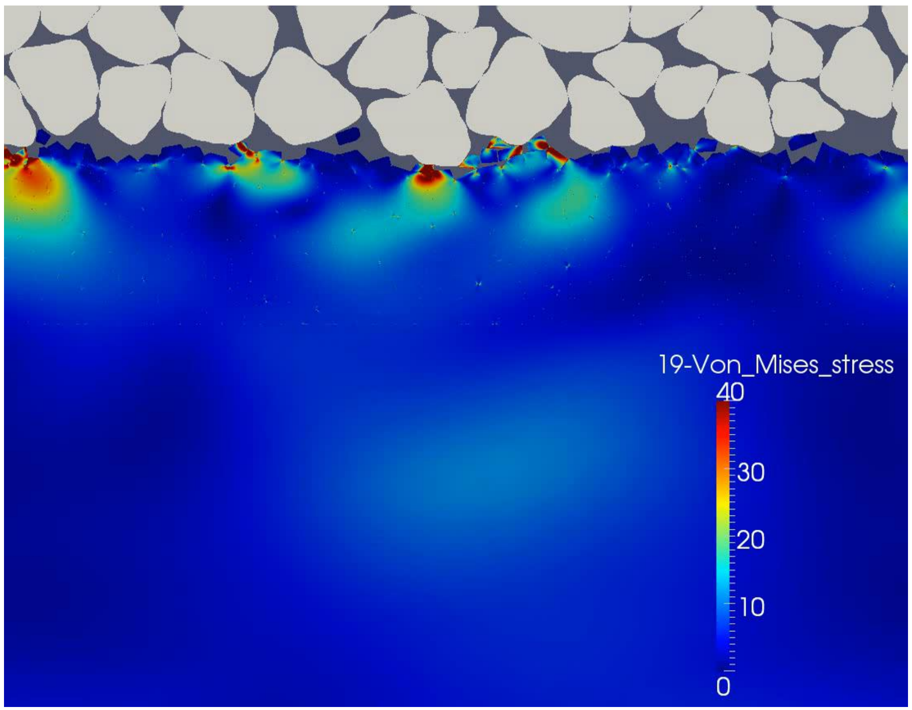
Bouillanne, O., et al. (2023), in prep.

Abrasive wear of diamond tools during rock cutting



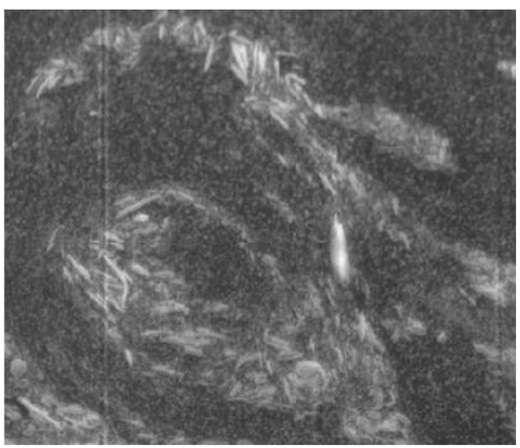


A few µm

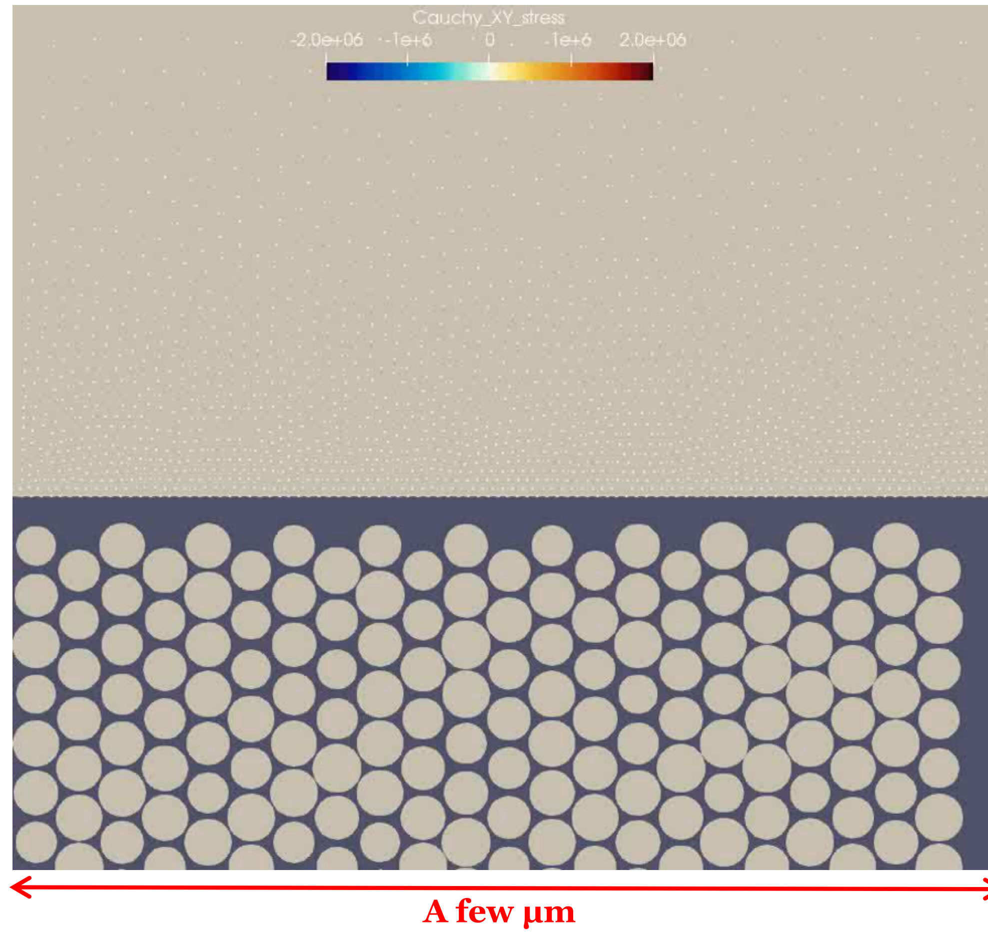


Quacquarelli, A., Mollon, G., Commeau, T., and Fillot, N. (2021). "A dual numerical-experimental approach for modeling wear of Diamond Impregnated Tools", Wear, 478–479, 203763

Wear particle creation and ejection in the tire-road contact



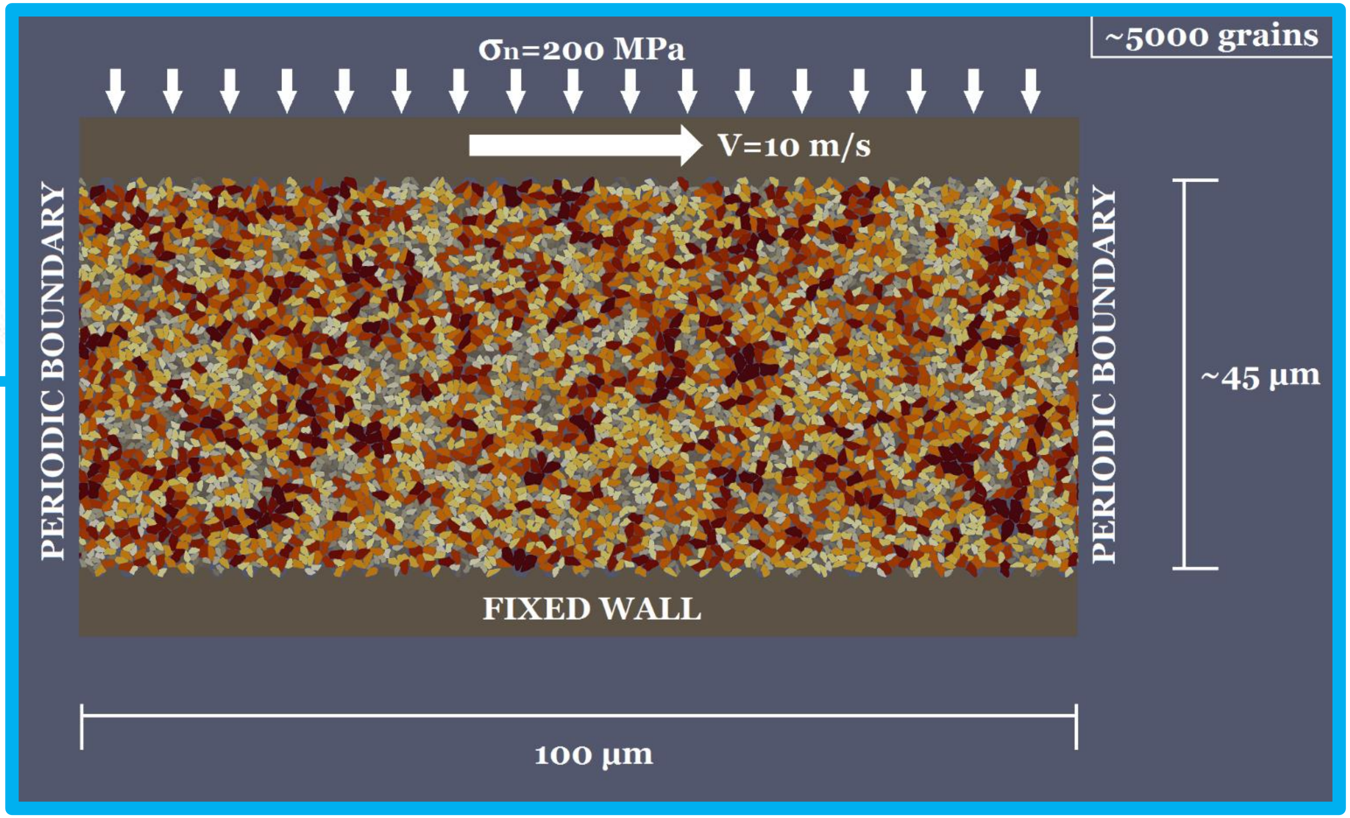
Interactions between worn elastomer and road mineral particles modify surface properties.



Daigne, K., et al. (2023), in prep.

DEM simulation protocol:

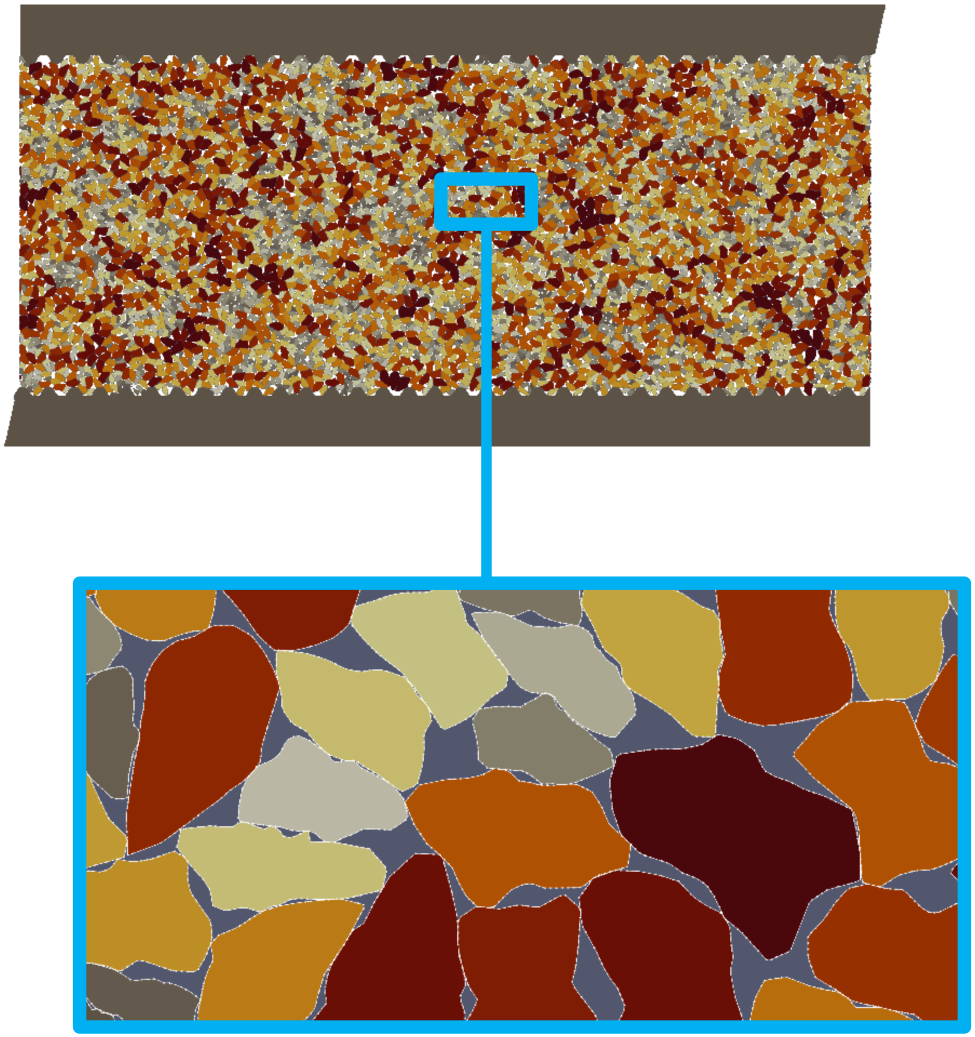
- We assume a perfectly established comminuted gouge with ~1µm angular grains.
- Sample width of 100µm, thickness can vary.
- Normal stress s_n=200 Mpa, sliding velocity V=10m/s, periodic lateral boundaries.
- Code MELODY2D (Mollon 2018); plane strain; Simulated time: 20-50 µs; time step ~1ps.



Local contact conditions:

- Contour of the particles described by a piecewise linear function. Two-pass node-to-segment algorithm.

- Angular shapes and penalized frictional contact between gouge particles, μ=0.8 (calibrated in Mollon et al. 2020).



Angular grains

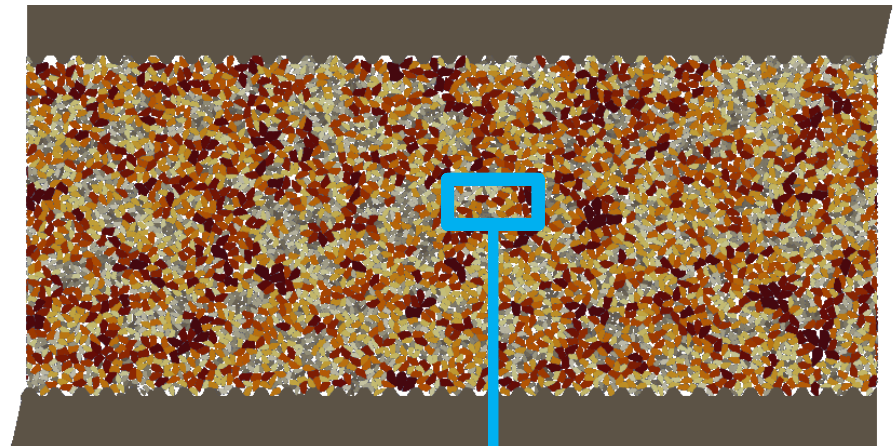
Local contact conditions:

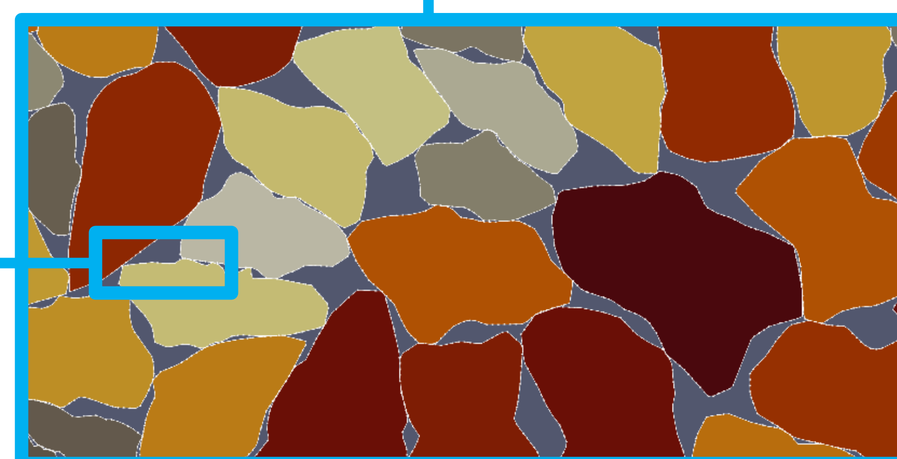
- Contour of the particles described by a piecewise linear function. Two-pass node-to-segment algorithm.

- Angular shapes and penalized frictional contact between gouge particles, μ=0.8 (calibrated in Mollon et al. 2020).

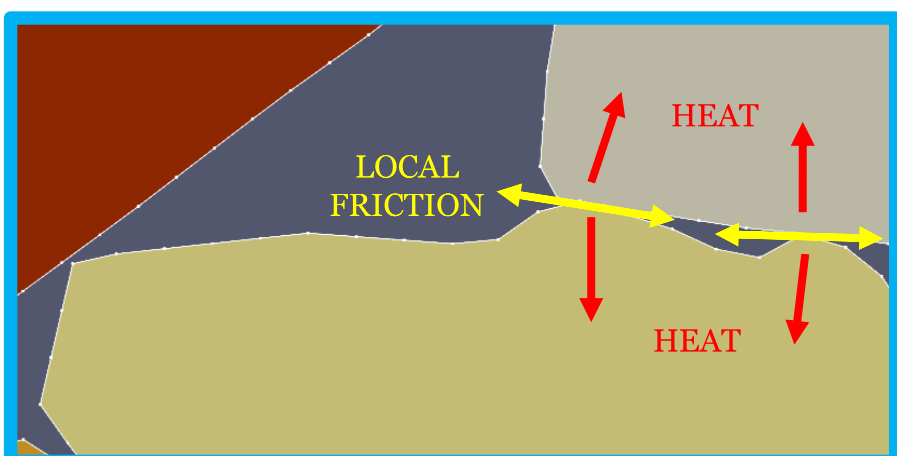
- Any mechanical energy dissipated by intergranular friction is converted in heat and shared between the contacting grains.

- Temperature of each grain increases. No heat diffusion through contacts (yet).





Angular grains

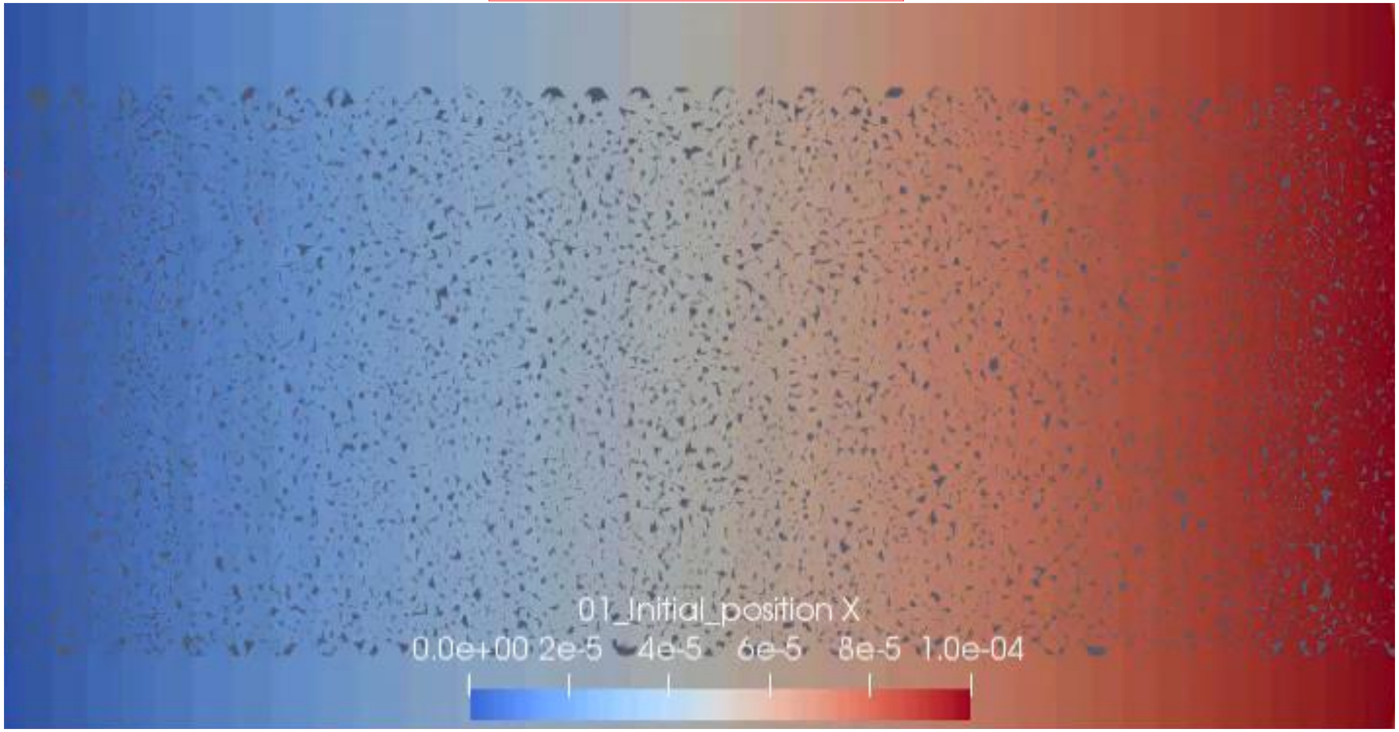


Node-to-segment contact

We first vary the thickness of the gouge layer, from ~9µm to ~90µm.

- A typical sheared granular flow, as commonly simulated in tribological models.

Sliding side of the fault

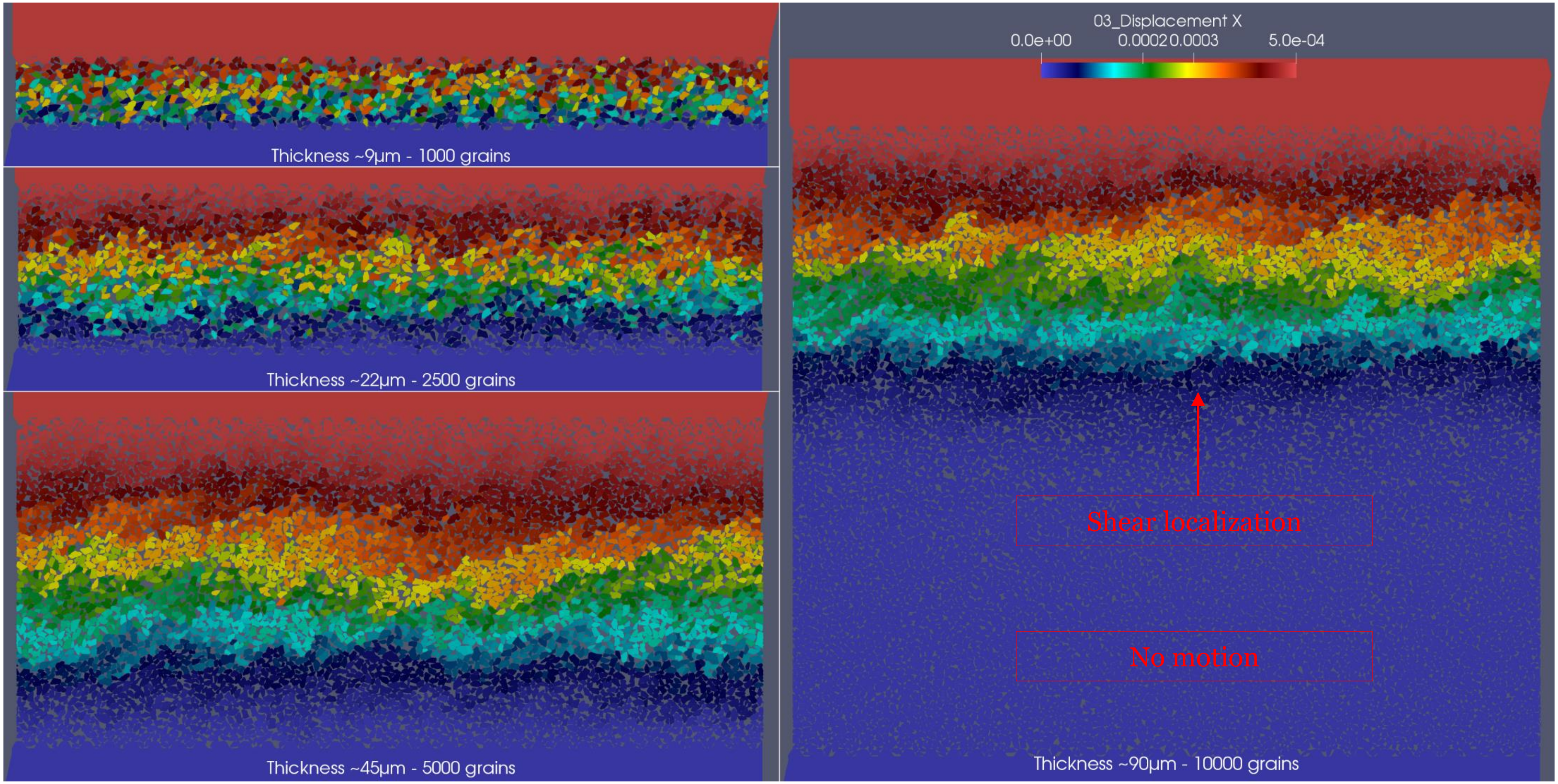


Fixed side of the fault

We first vary the thickness of the gouge layer, from ~9µm to ~90µm.

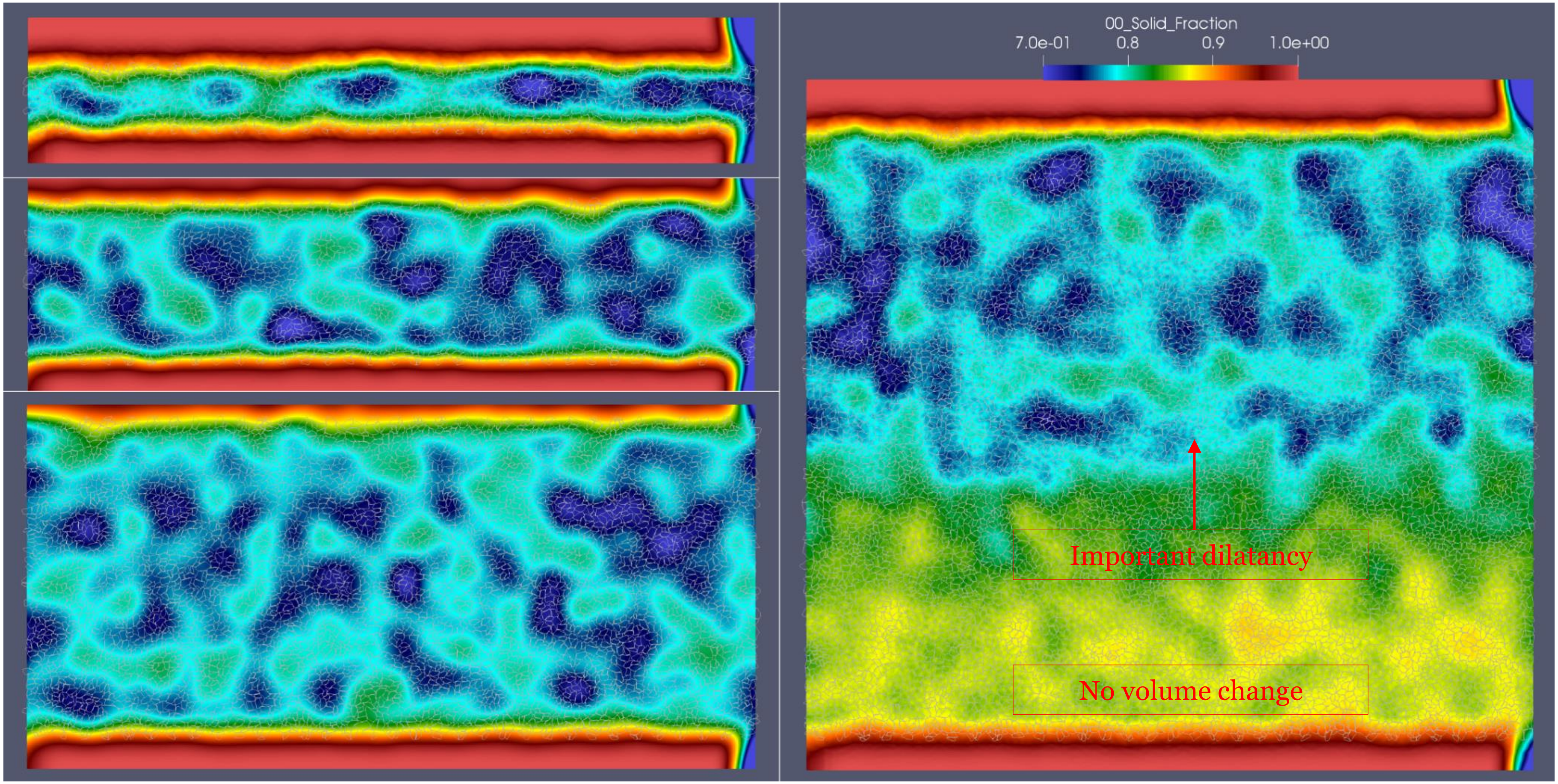
- A typical sheared granular flow, as commonly simulated in tribological models.
- Shear distributed in the whole thickness for 9µm, 22µm, and 45µm, but localized for 90µm.

Final X-displacement after 50µs shearing



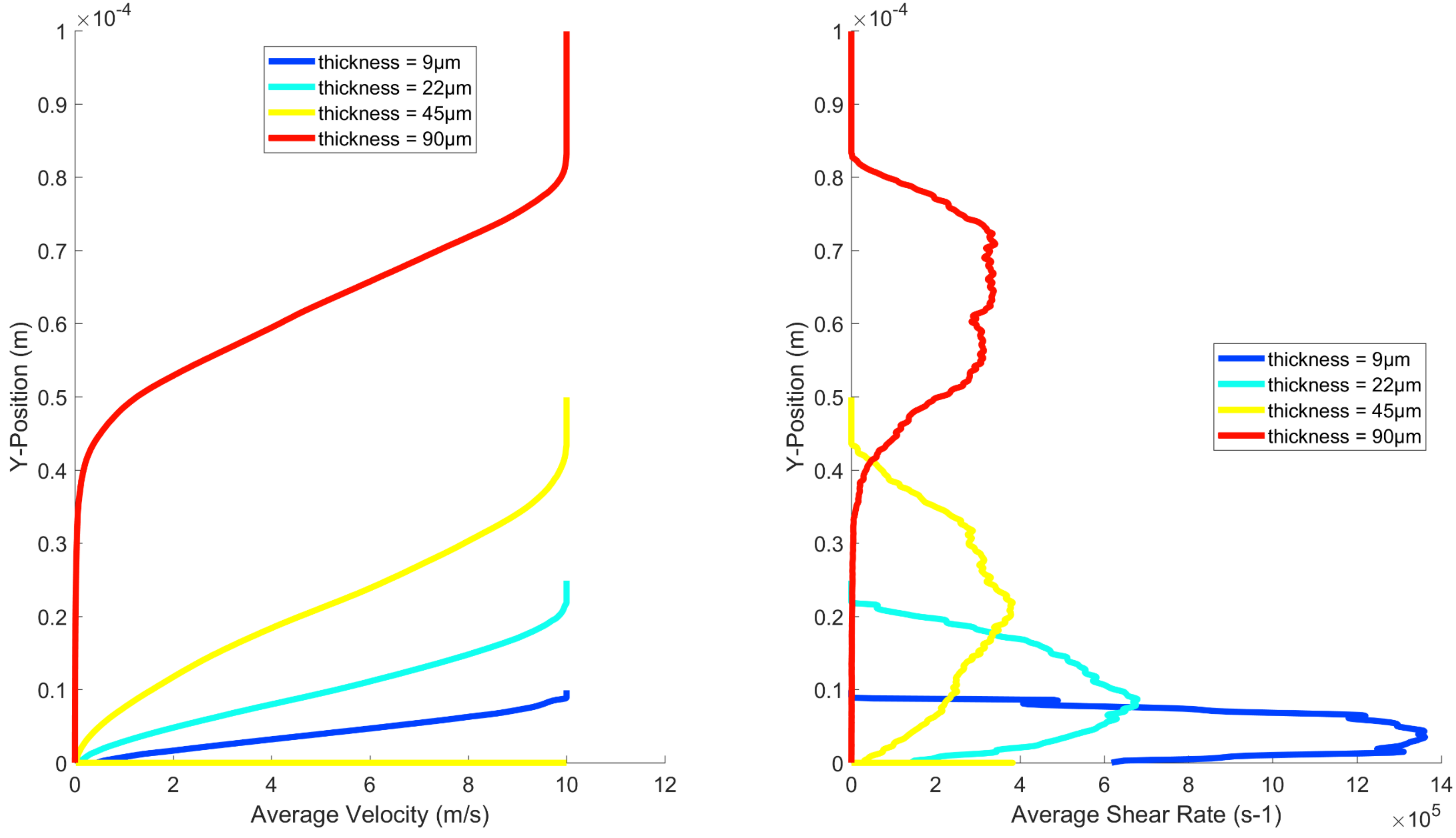
We first vary the thickness of the gouge layer, from ~9µm to ~90µm.

- A typical sheared granular flow, as commonly simulated in tribological models.
- Shear distributed in the whole thickness for 9µm, 22µm, and 45µm, but localized for 90µm.
- Confirmed by final distribution of the Volume Fraction of the granular packing



We first vary the thickness of the gouge layer, from ~9µm to ~90µm.

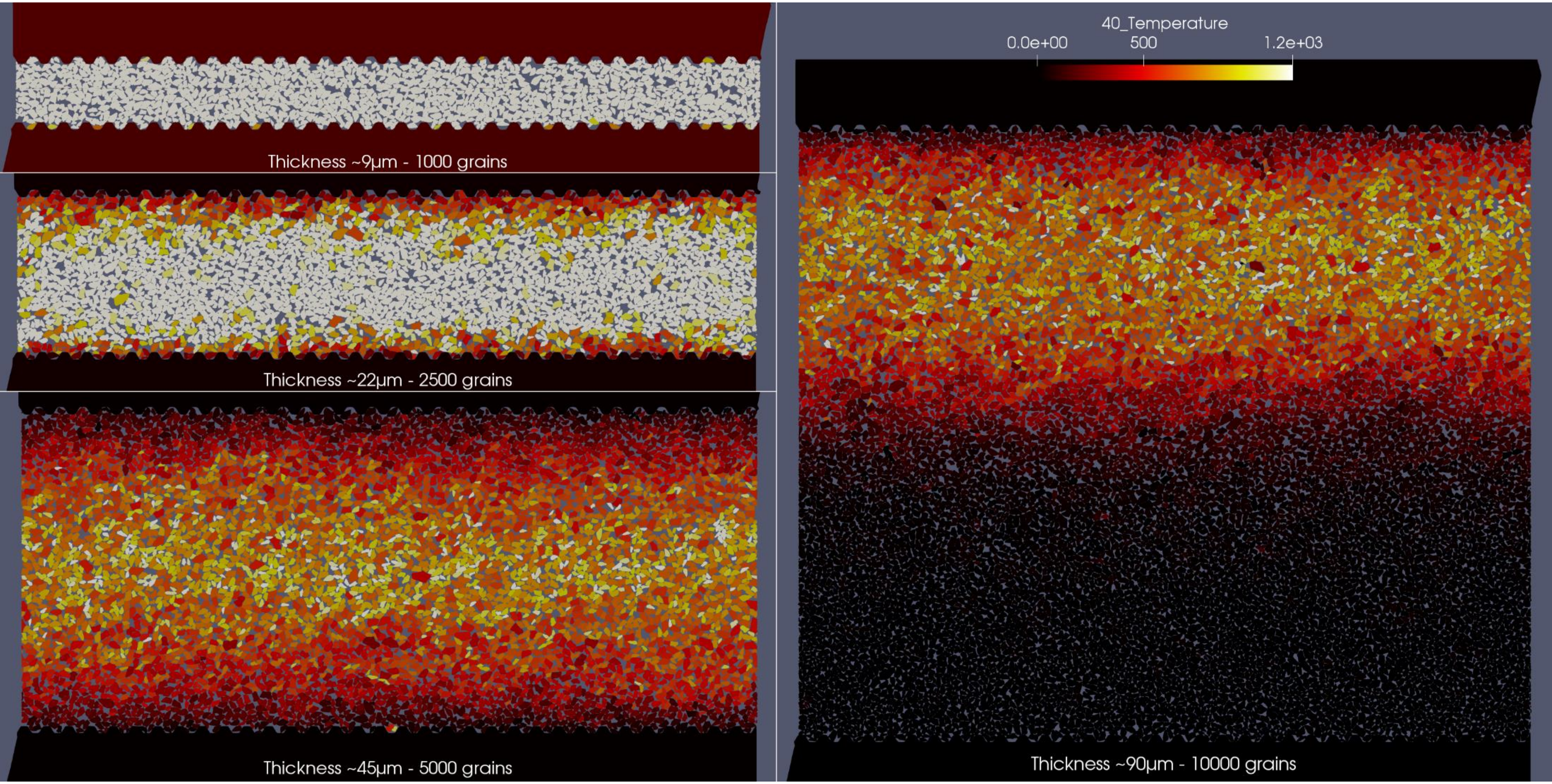
- Shear-rate is thus very high for small layer thickness, but stabilizes above a thickness of 45µm.



Heat creation in the sample.

- Heat creation is expressed as a temperature increase (in K) in adiabatic conditions (no diffusion).

- Heating sites follow shear localization sites. Temperature increase is much larger in thin layers, and stabilizes for large thicknesses.

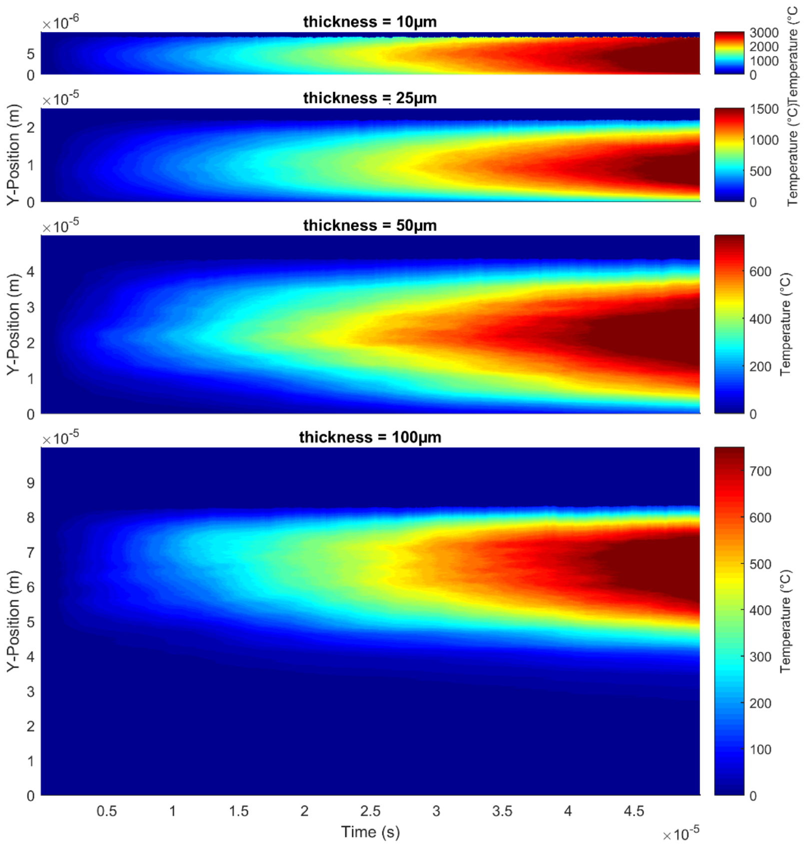


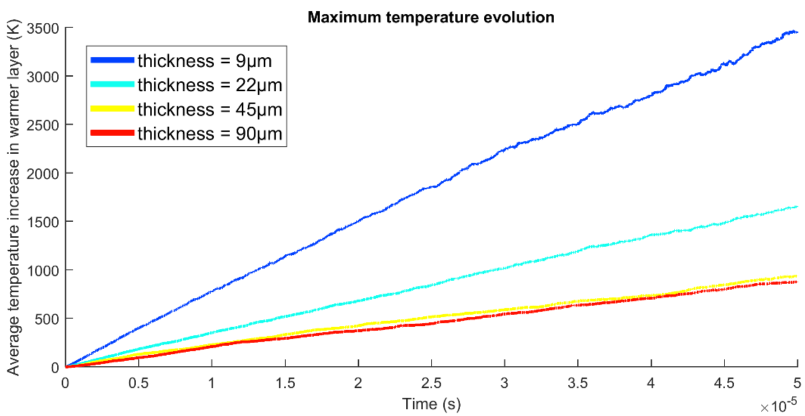
Heat creation in the sample.

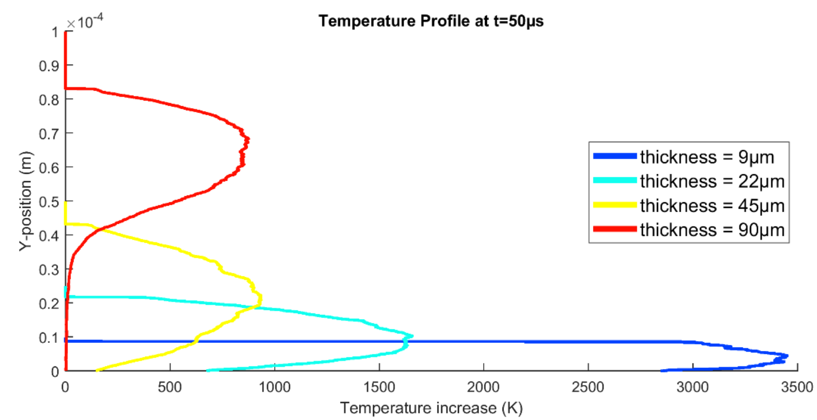
- Heat creation is expressed as a temperature increase (in K) in adiabatic conditions (no diffusion).

- Heating sites follow shear localization sites. Temperature increase is much larger in thin layers, and stabilizes for large thicknesses.

- Temperature maps show a linear increase with time, with a maximum value at the center of the sheared layer.

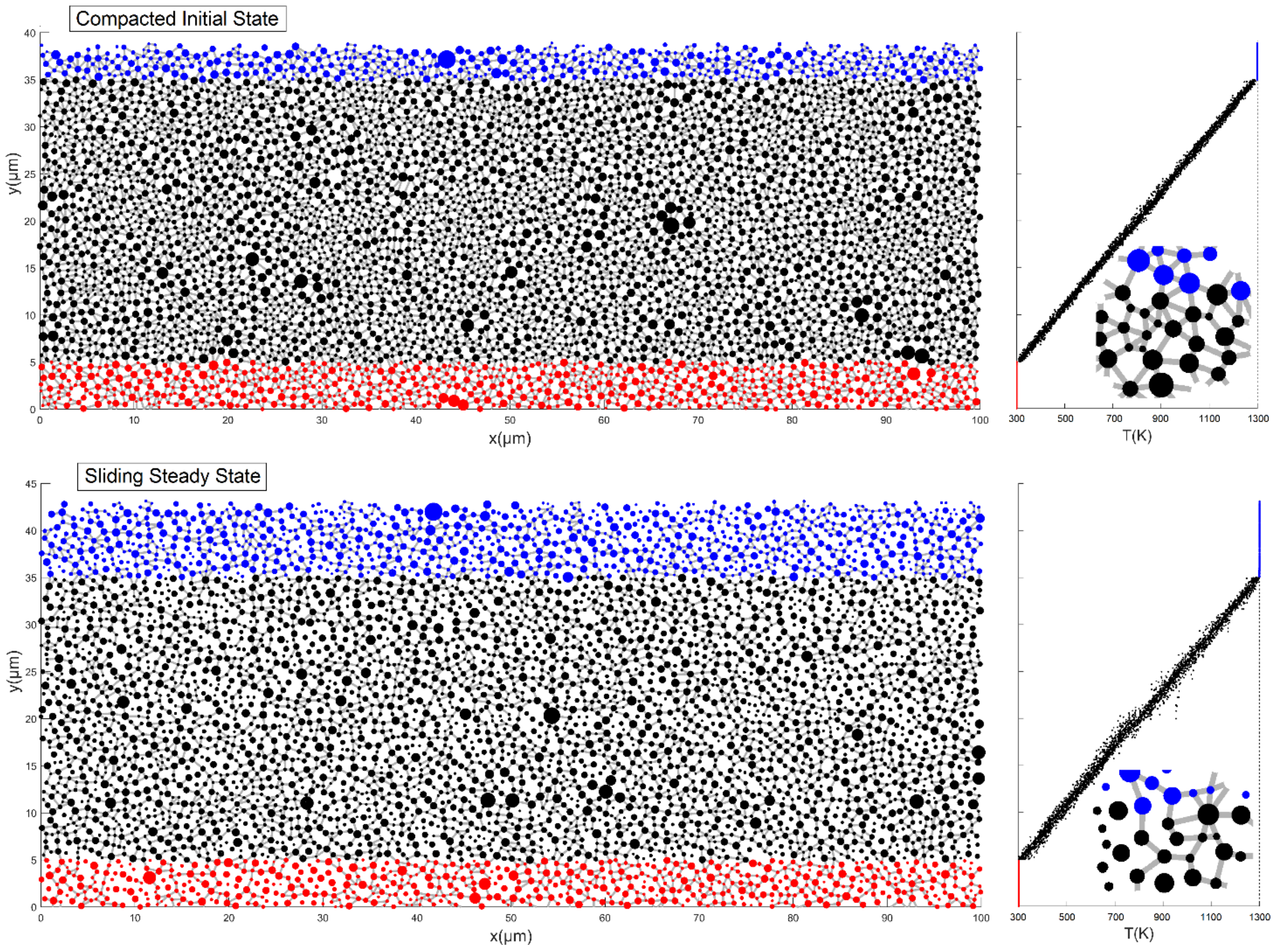






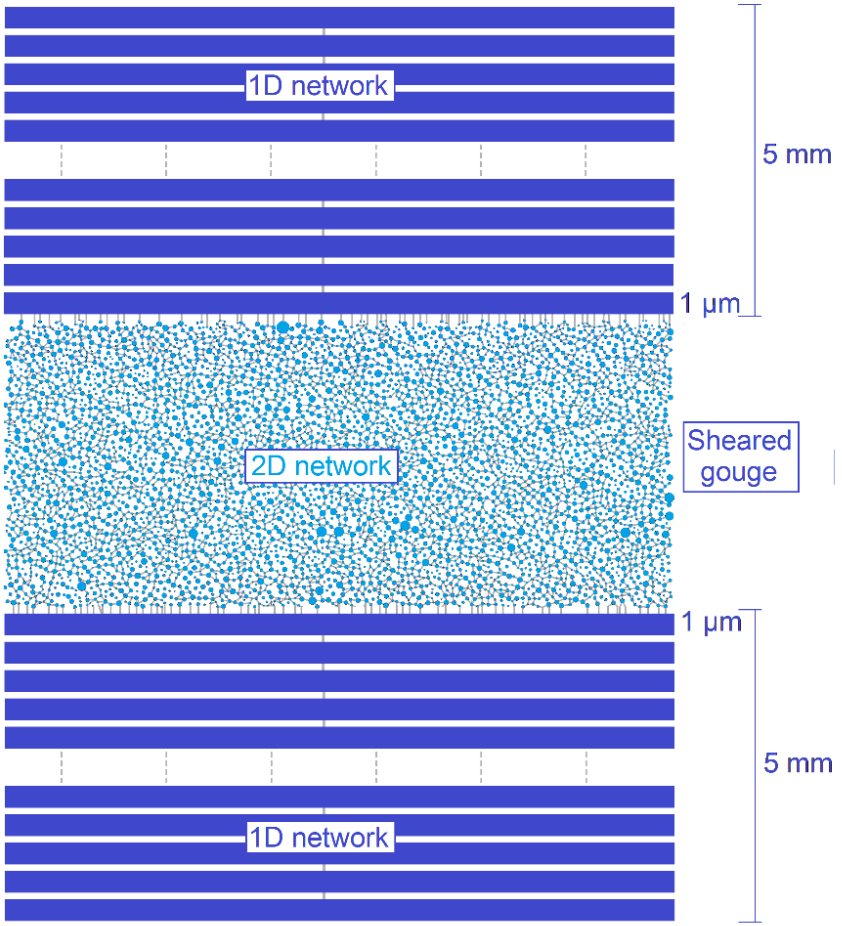
Heat diffusion

- Thermal model based on the contact network, calibrated on bulk conductivity of intact gouge.
- Interestingly, heat conductivity is divided by 2.5 after shearing.



Heat diffusion

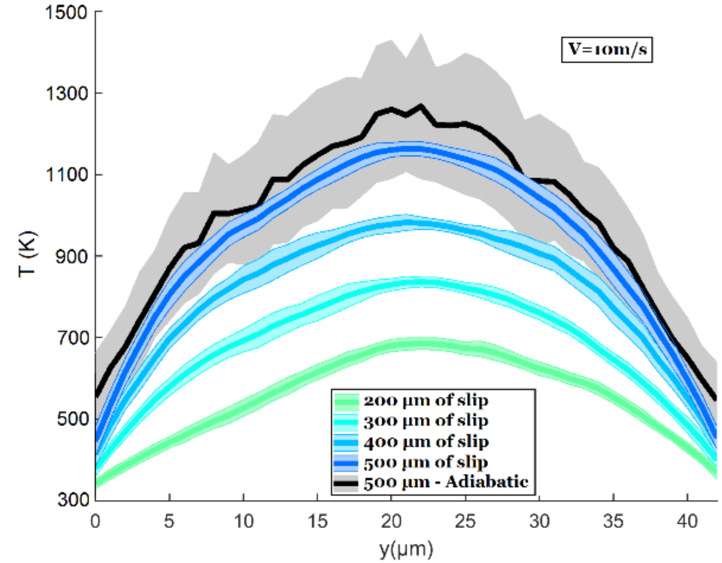
- Thermal model based on the contact network, calibrated on bulk conductivity of intact gouge.
- Interestingly, heat conductivity is divided by 2.5 after shearing.
- After calibration, second pass on mechanical stored results with an evolving contact network.

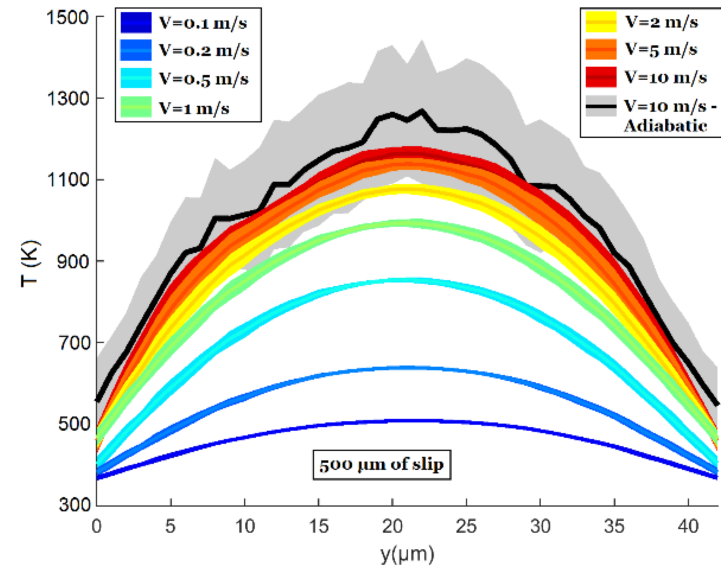


Heat diffusion

- Thermal results: Parabolic temperature profile, with an increasing amplitude along slip. Strong reduction of the temperature variability with respect to adiabatic case.

- Temperature increase in the middle of the layer after 500 µm of slip reaches 1000 K for a sliding velocity of 1 m/s.



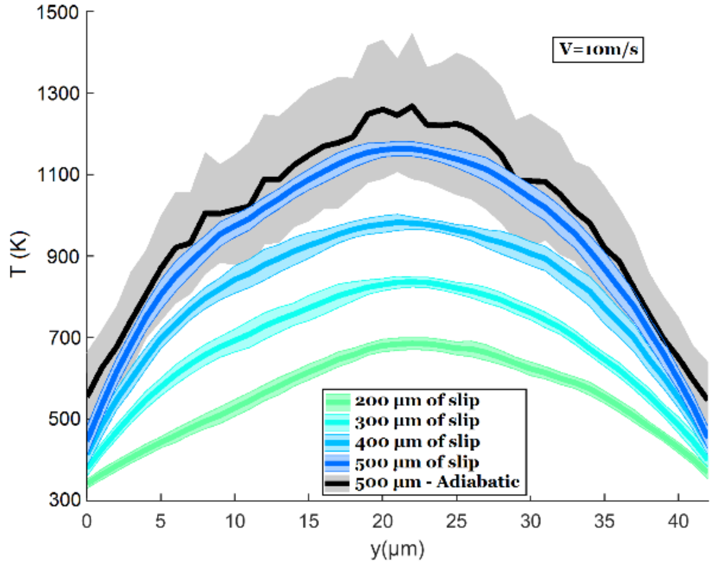


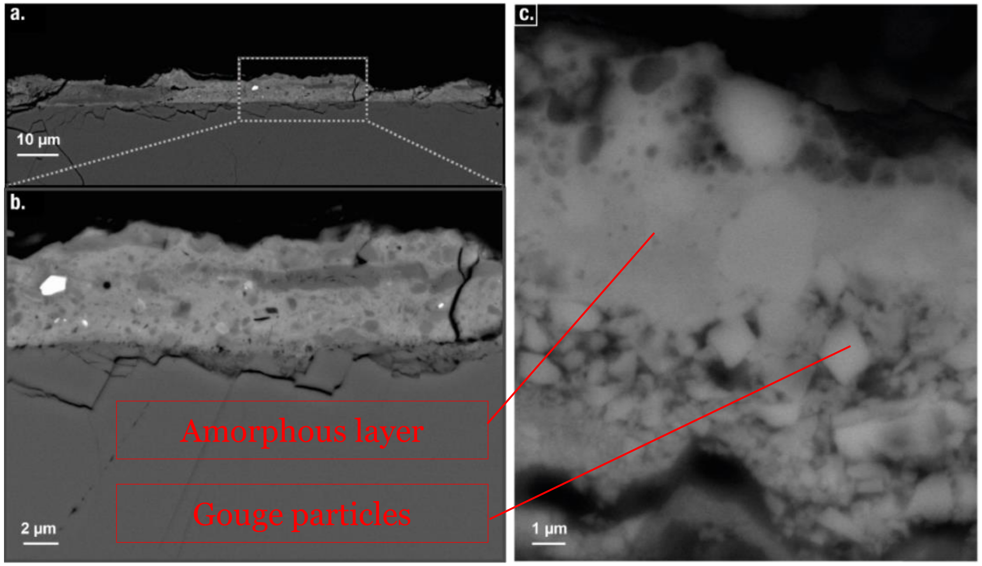
Heat diffusion

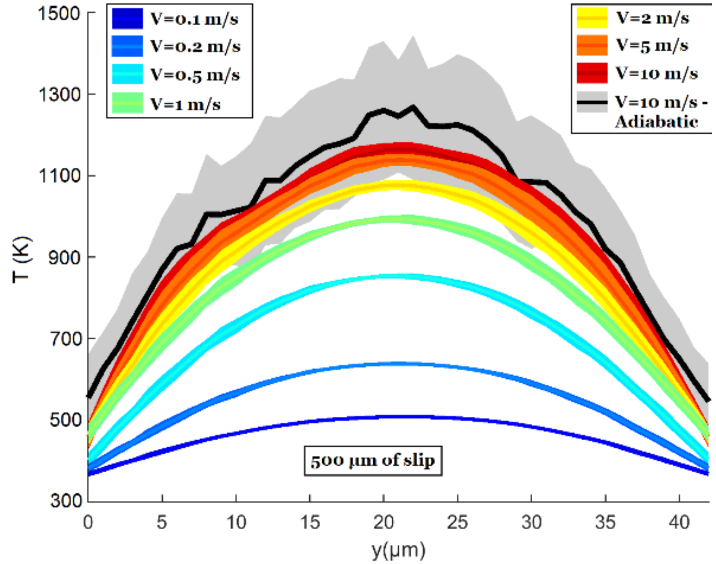
- Thermal results: Parabolic temperature profile, with an increasing amplitude along slip. Strong reduction of the temperature variability with respect to adiabatic case.

- Temperature increase in the middle of the layer after 500 µm of slip reaches 1000 K for a sliding velocity of 1 m/s.

- Onset of melting likely to happen in the central 10 µm of the gouge layer, in good accordance with the Aubry 2019 experiments.



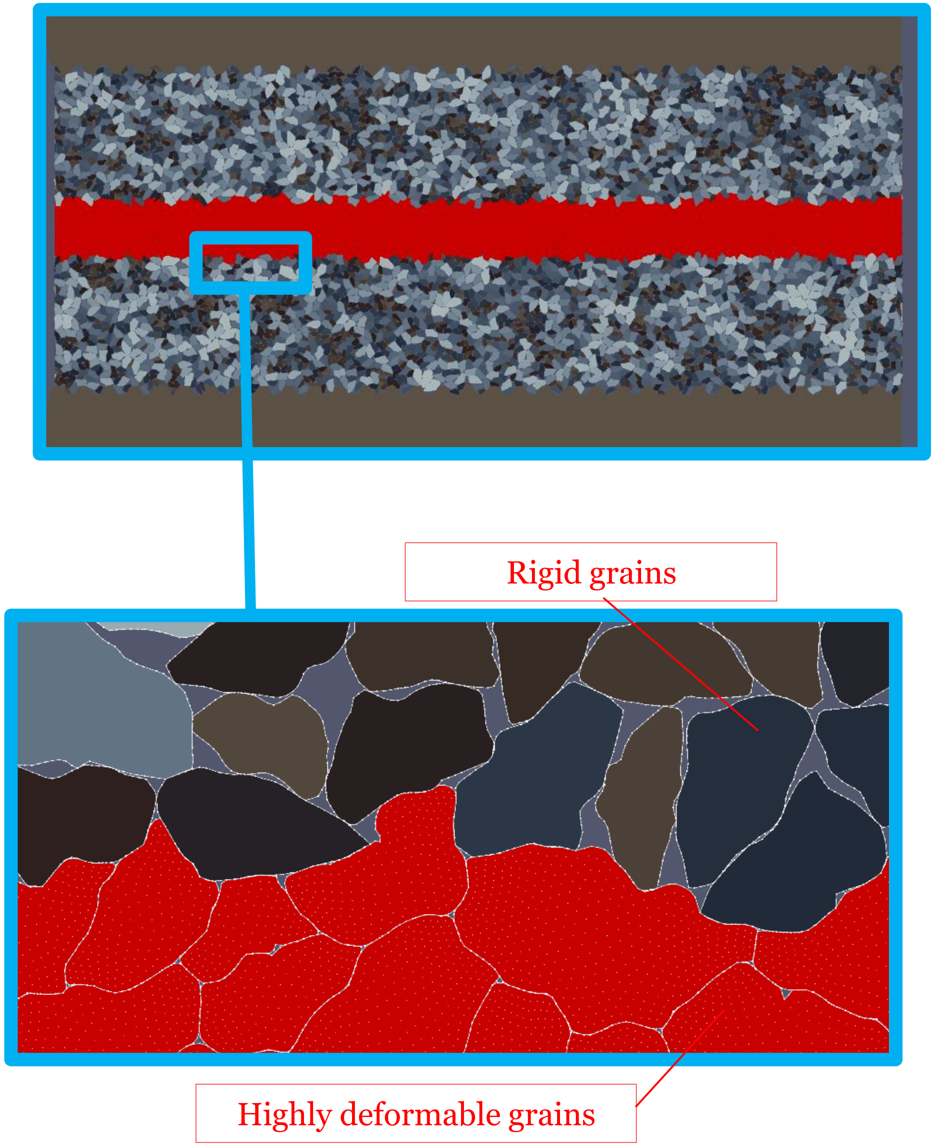




Simulation of a fully molten central layer

-Proxy for the melt rheology: highly deformable, incompressible, viscoelastic grains (Mollon 2018).

-Deformability simulated by a multibody meshfree method (DEM enriched with continuum mechanics), in the code MELODY2D



Simulation of a fully molten central layer

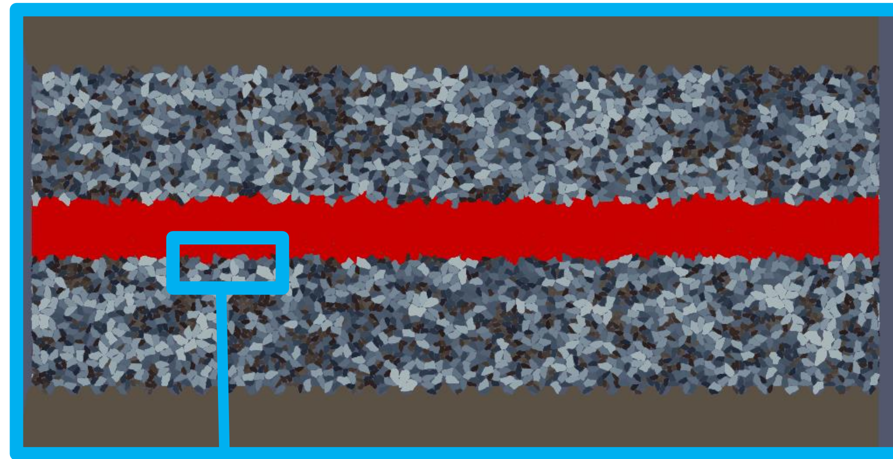
-Proxy for the melt rheology: highly deformable, incompressible, viscoelastic grains (Mollon 2018).

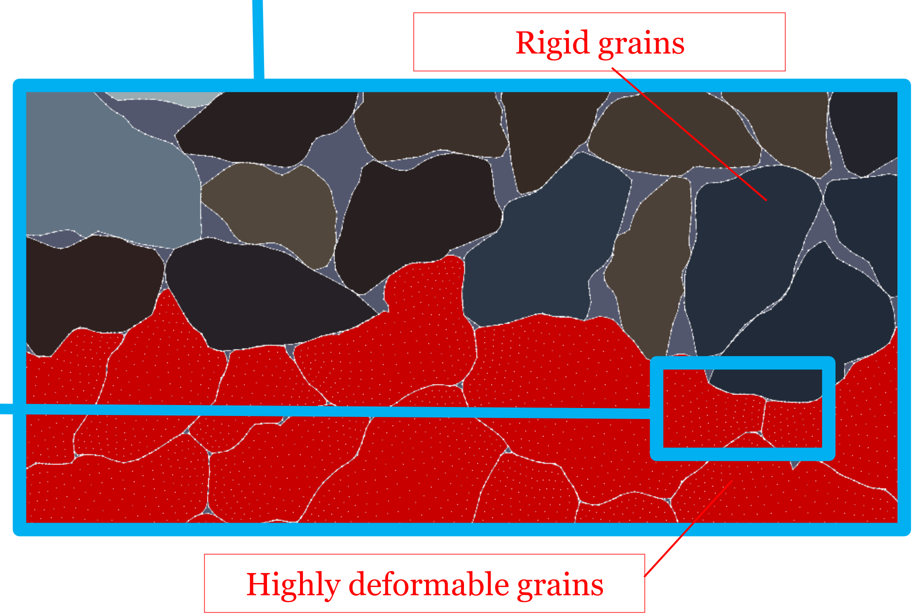
-Deformability simulated by a multibody meshfree method (DEM enriched with continuum mechanics), in the code MELODY2D

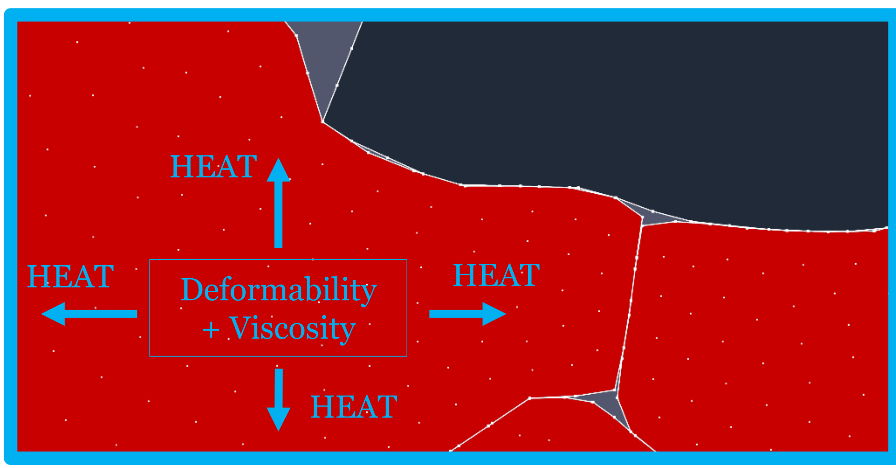
-No friction and no cohesion at contacts, but energy dissipation by internal viscosity and subsequent heat creation.

-Still no heat diffusion through contacts.

-Equivalent viscosity: ~10 Pa.s (in the low range for molten silicates, Wallace et al. 2019).







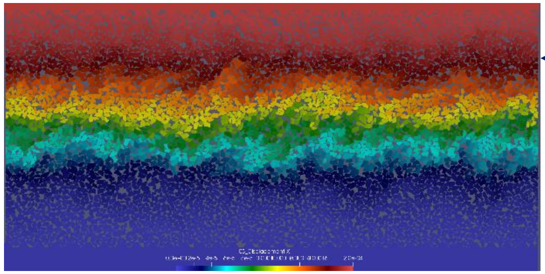
Simulations Results

X-displacement (μm)

200

0

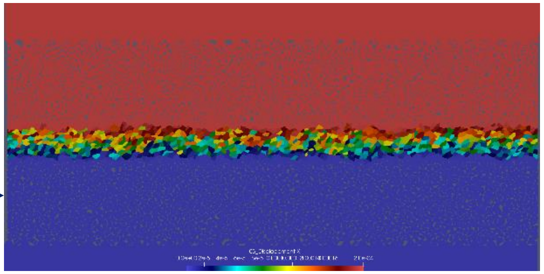
Only solid grains: **μ=0.48**



Distributed shear in the granular layer

Localized accommodation in the central melt layer, solid grains unaffected

Fully molten central layer: **μ=0.08**



Simulations Results

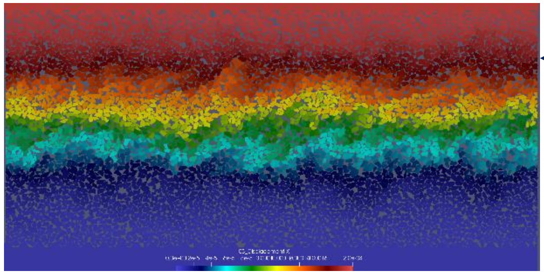
Only solid grains: **μ=0.48**

Fully molten central layer: **μ=0.08**

X-displacement (μm)

200

0



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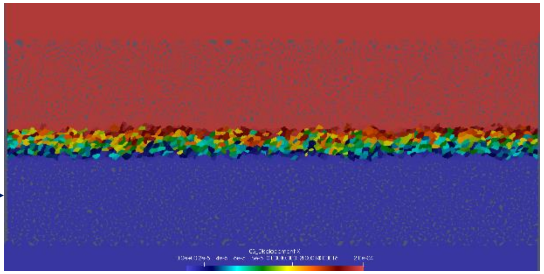
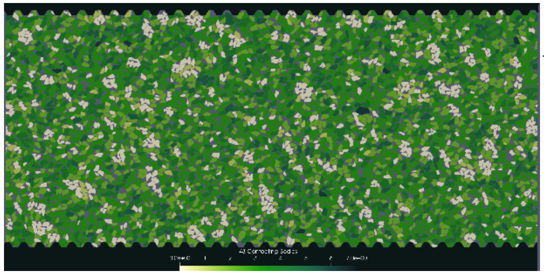


Number of contacting grains

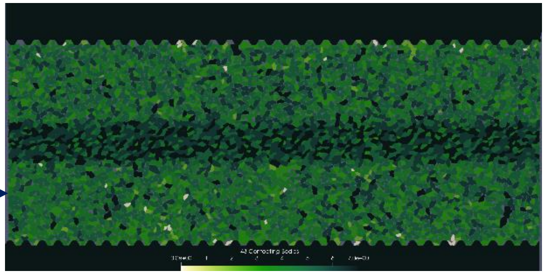
7

0



Low and heterogeneous connectivity

Large and homogeneous connectivity, especially in the melt layer



Simulations Results

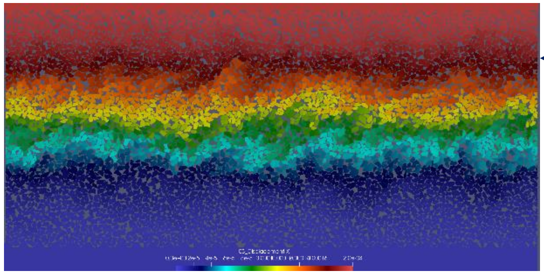
Only solid grains: **μ=0.48**

Fully molten central layer: **μ=0.08**

X-displacement (μm)

200

0



Distributed shear in the granular layer

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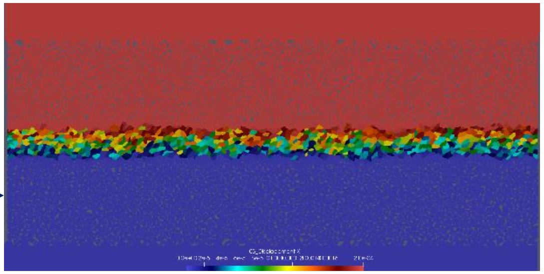
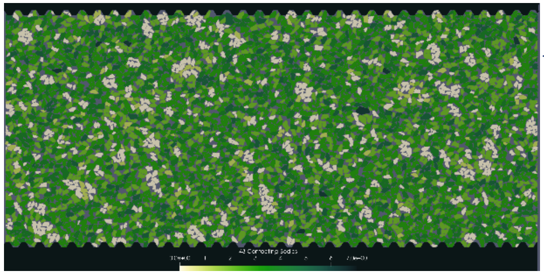


Number of contacting grains

7

0



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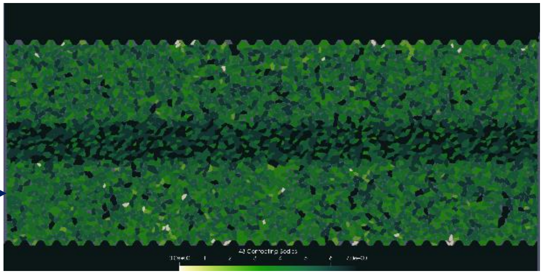
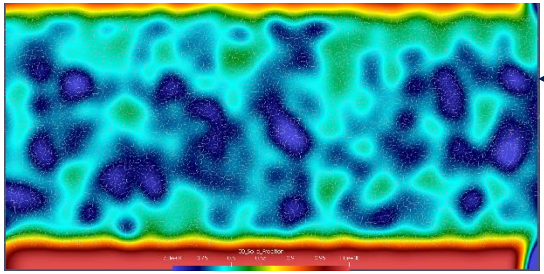


Volume fraction of the granular packing

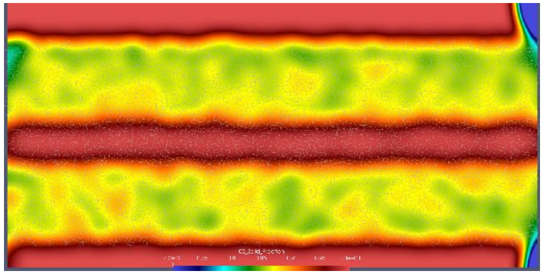
1

0.7



Important dilatancy

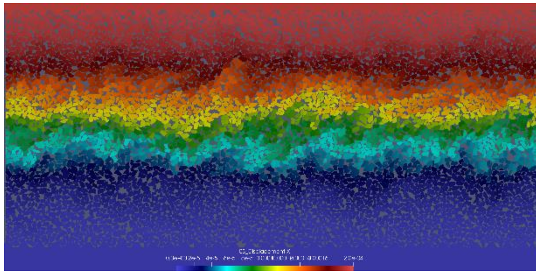
No volume change in solid grains, Volume Fraction close to 1 in the melt layer



Simulations Results

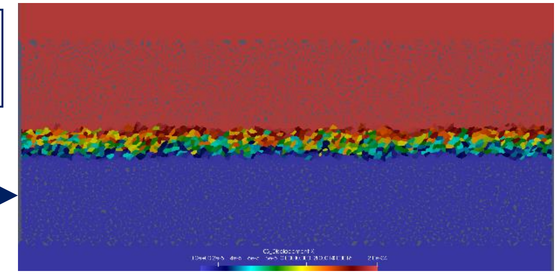
	Only solid grains: **μ=0.48**		Fully molten central layer: **μ=0.08**

X-displacement (μm) — 200 / 0

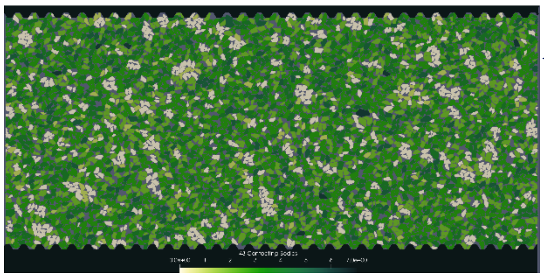


Distributed shear in the granular layer

Localized accommodation in the central melt layer, solid grains unaffected

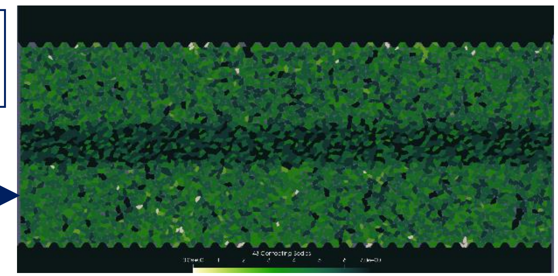


Number of contacting grains — 7 / 0

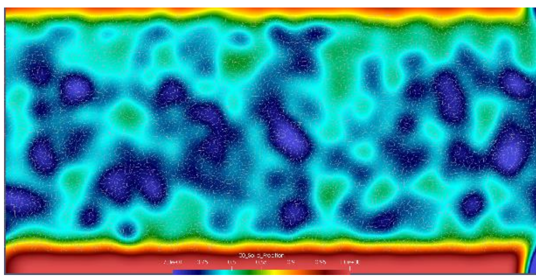


Low and heterogeneous connectivity

Large and homogeneous connectivity, especially in the melt layer



Volume fraction of the granular packing — 1 / 0.7



Important dilatancy

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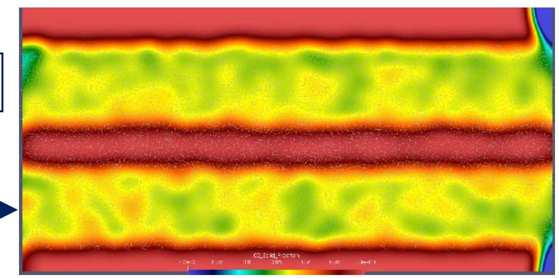
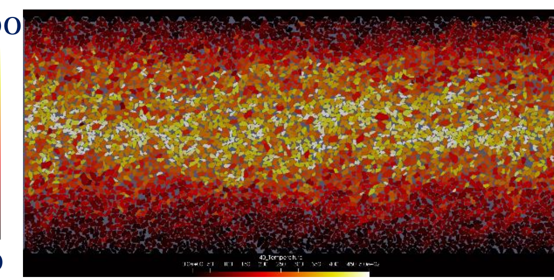
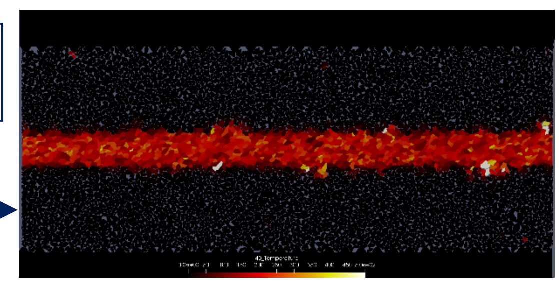


Temperature elevation (K) — 500 / 0



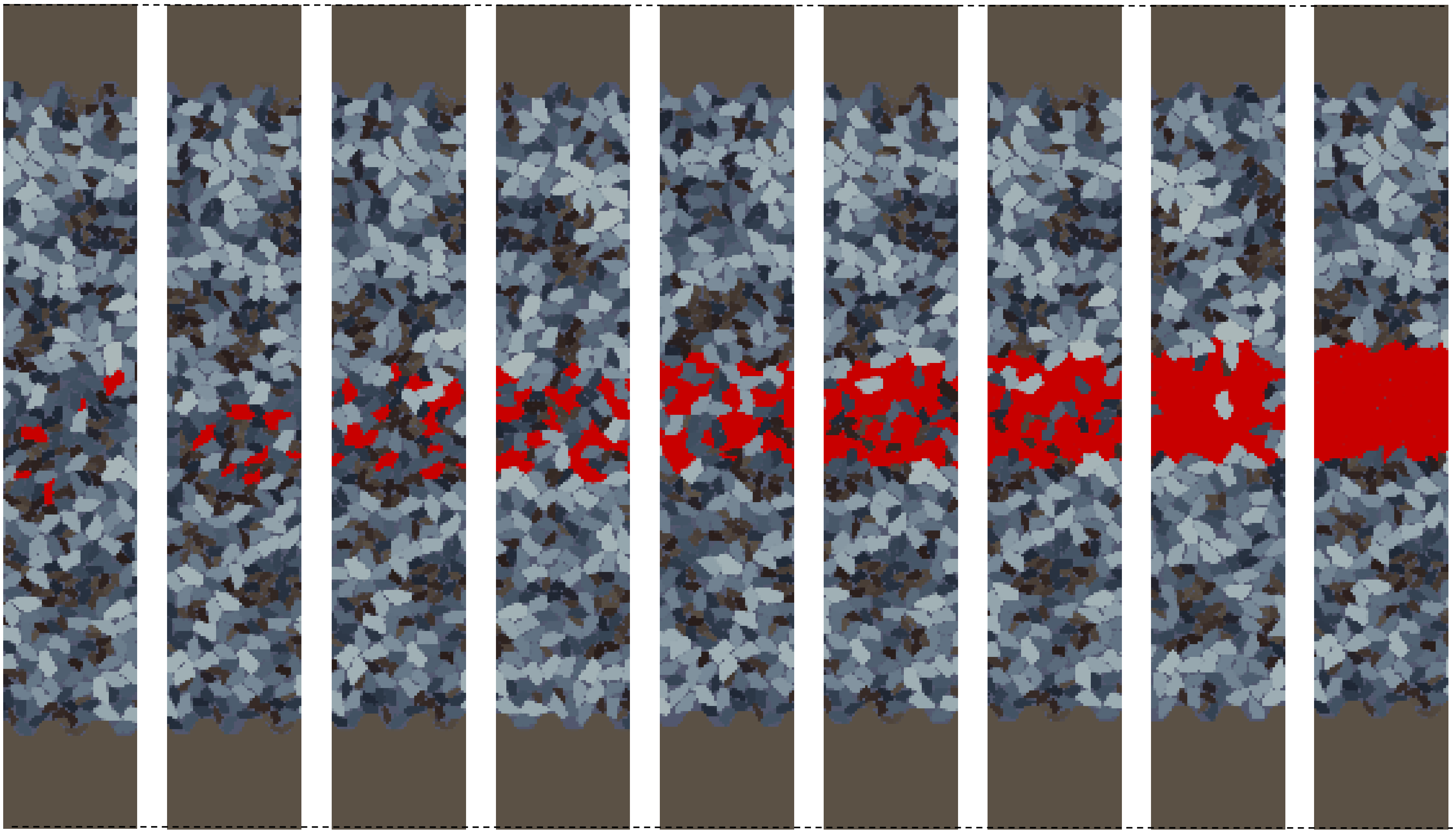
Distributed and important temperature elevation

Only moderate temperature elevation in the melt layer



Investigation of the progressive creation of the melt layer:

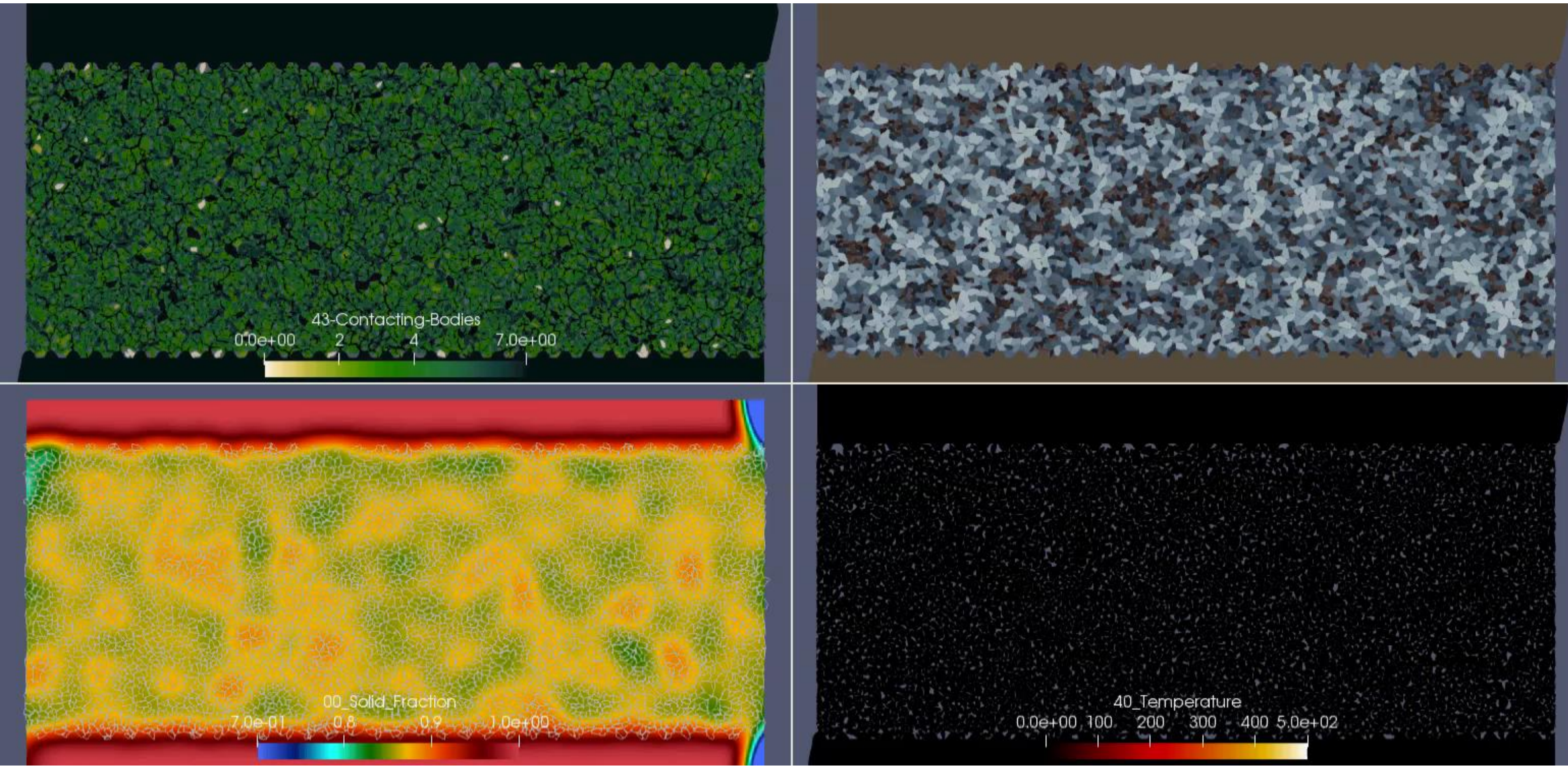
9 simulations with increasing proportions of melt Φ_M in the central layer (5% to 100%, partial views)



5%	10%	20%	30%	40%	50%	60%	80%	100%

Investigation of the progressive creation of the melt layer:

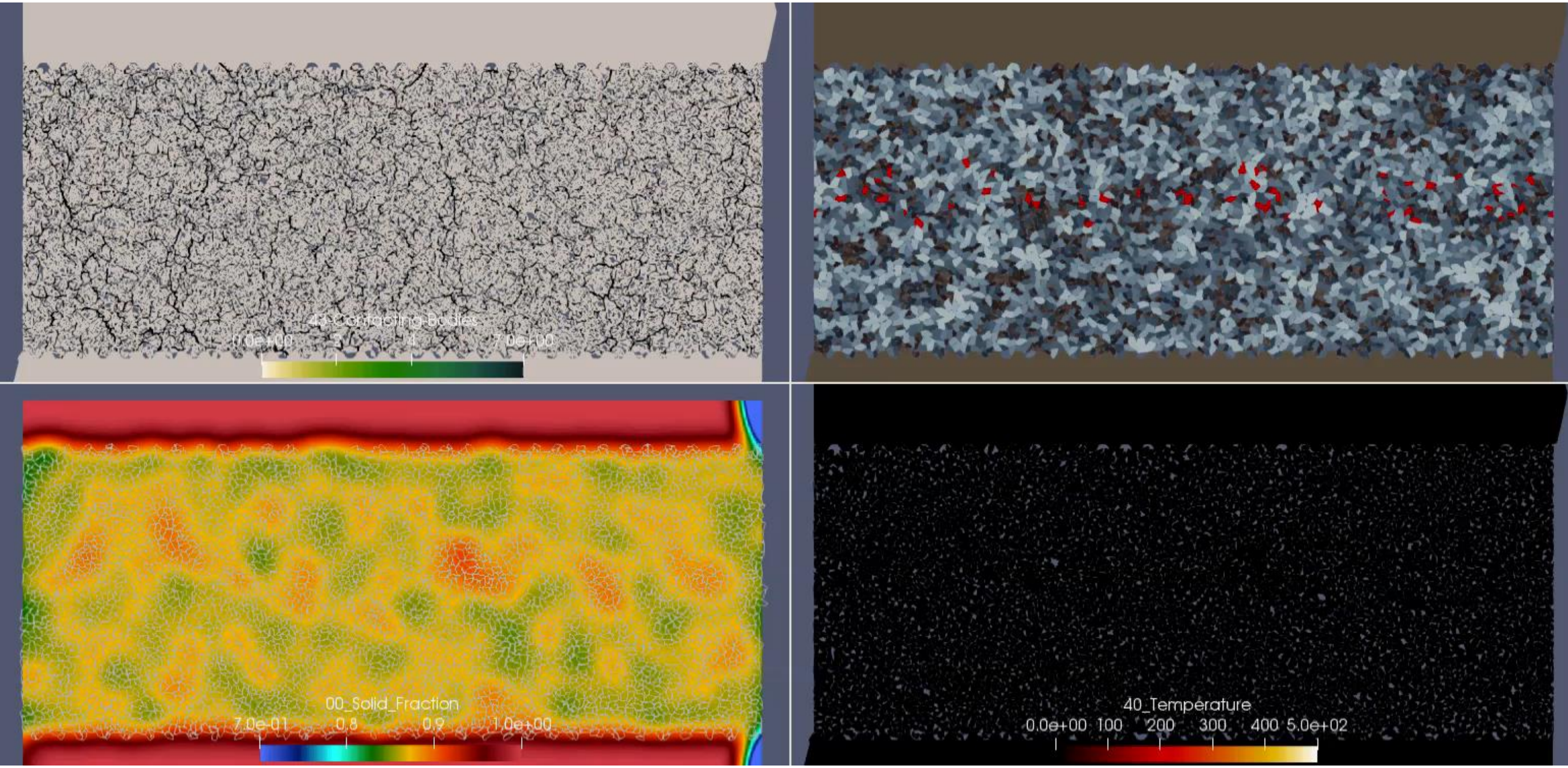
9 simulations with increasing proportions of melt Φ_M in the central layer (5% to 100%, partial views)



0%

Investigation of the progressive creation of the melt layer:

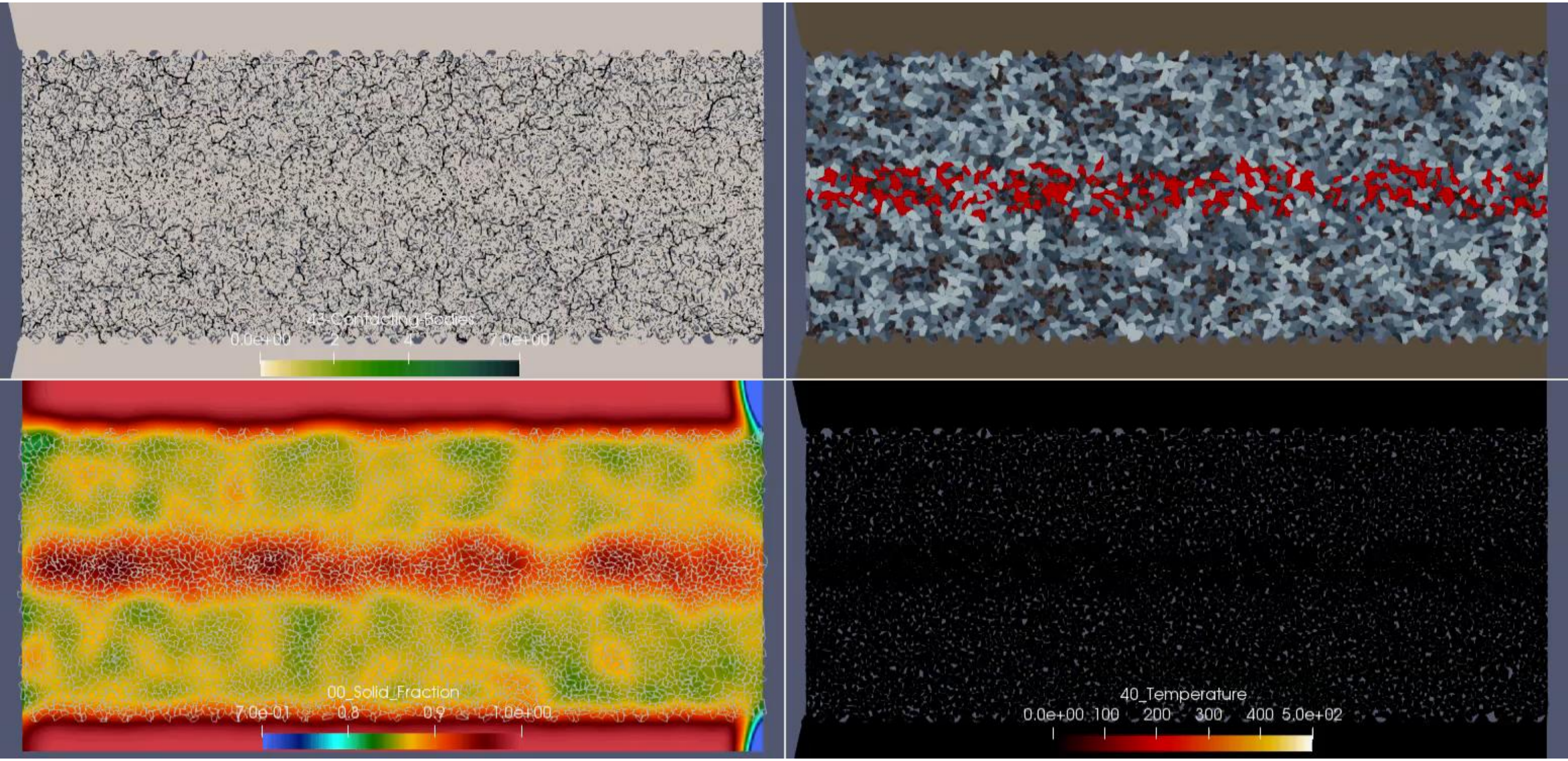
9 simulations with increasing proportions of melt Φ_M in the central layer (5% to 100%, partial views)



5%

Investigation of the progressive creation of the melt layer:

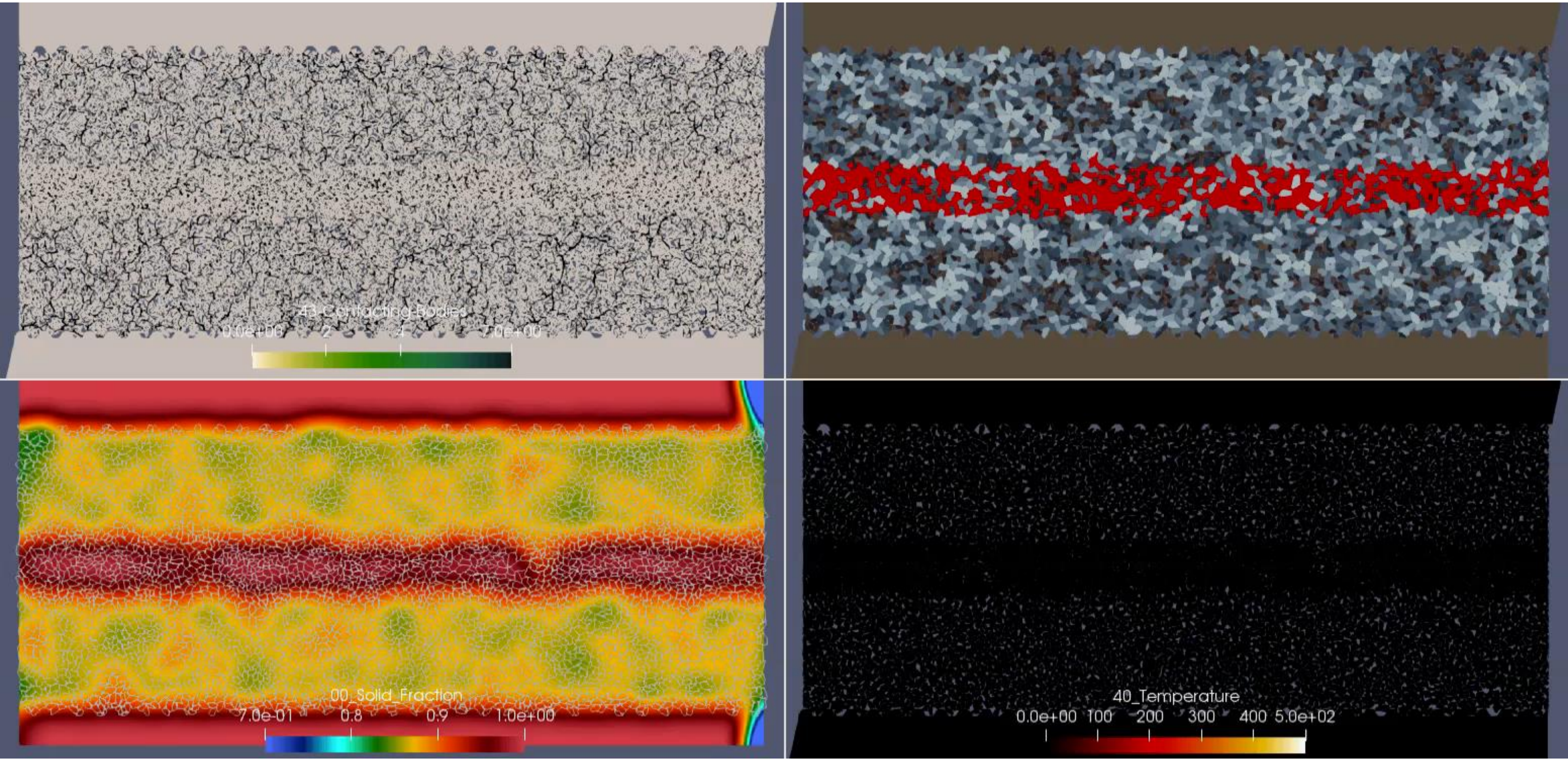
9 simulations with increasing proportions of melt Φ_M in the central layer (5% to 100%, partial views)



30%

Investigation of the progressive creation of the melt layer:

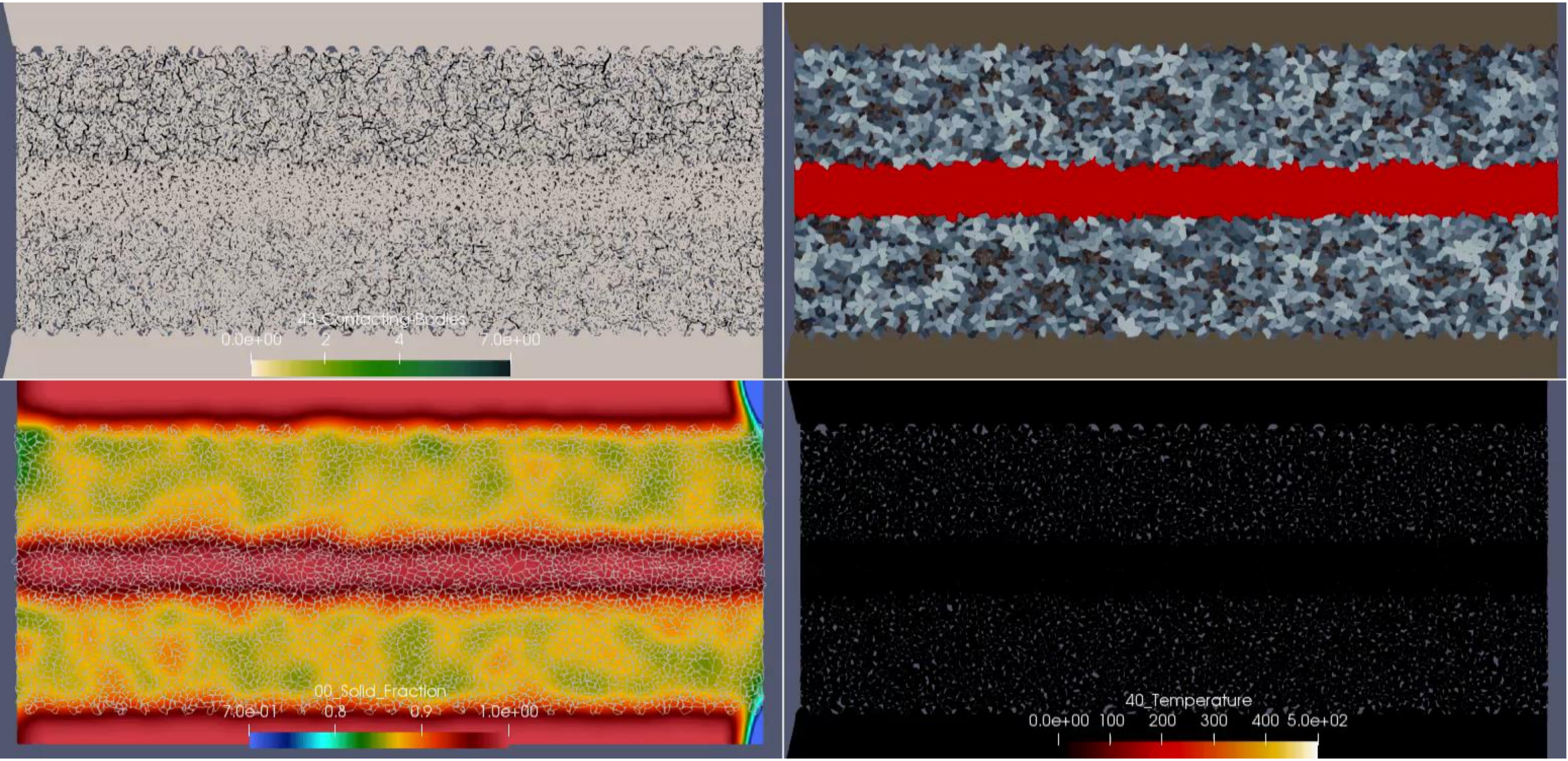
9 simulations with increasing proportions of melt Φ_M in the central layer (5% to 100%, partial views)



60%

Investigation of the progressive creation of the melt layer:

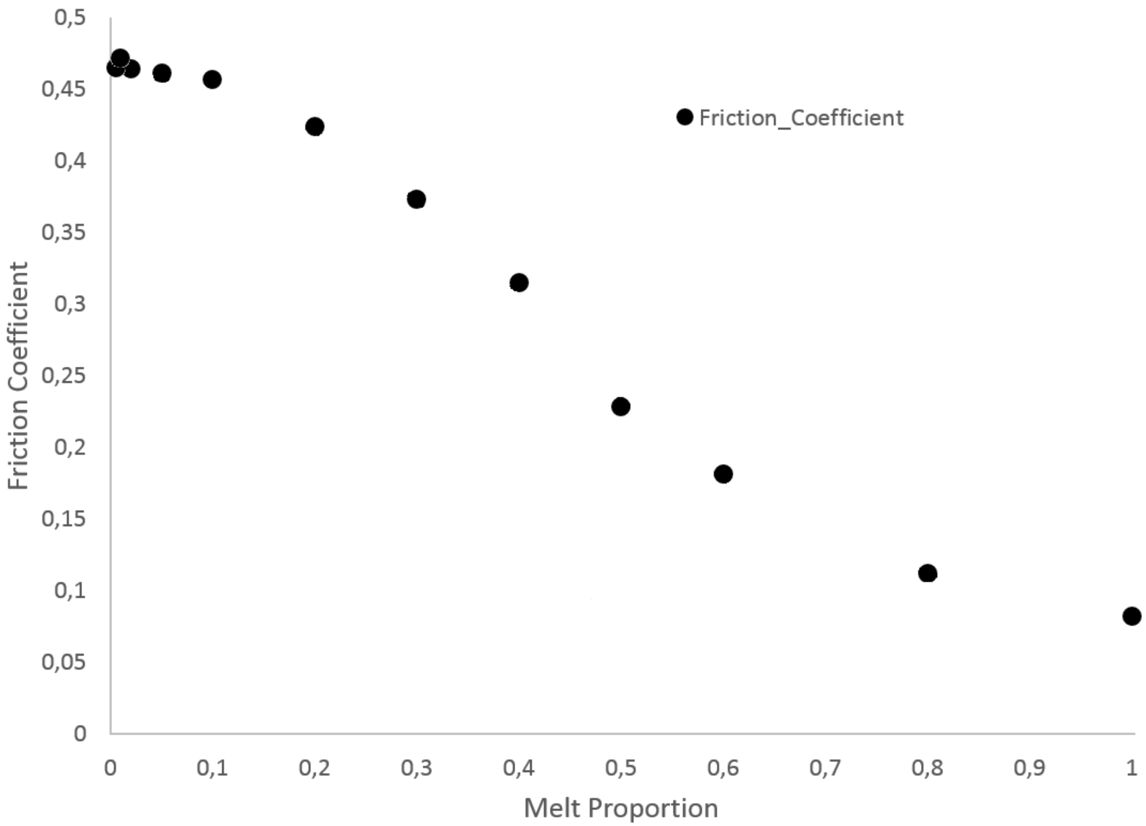
9 simulations with increasing proportions of melt Φ_M in the central layer (5% to 100%, partial views)



100%

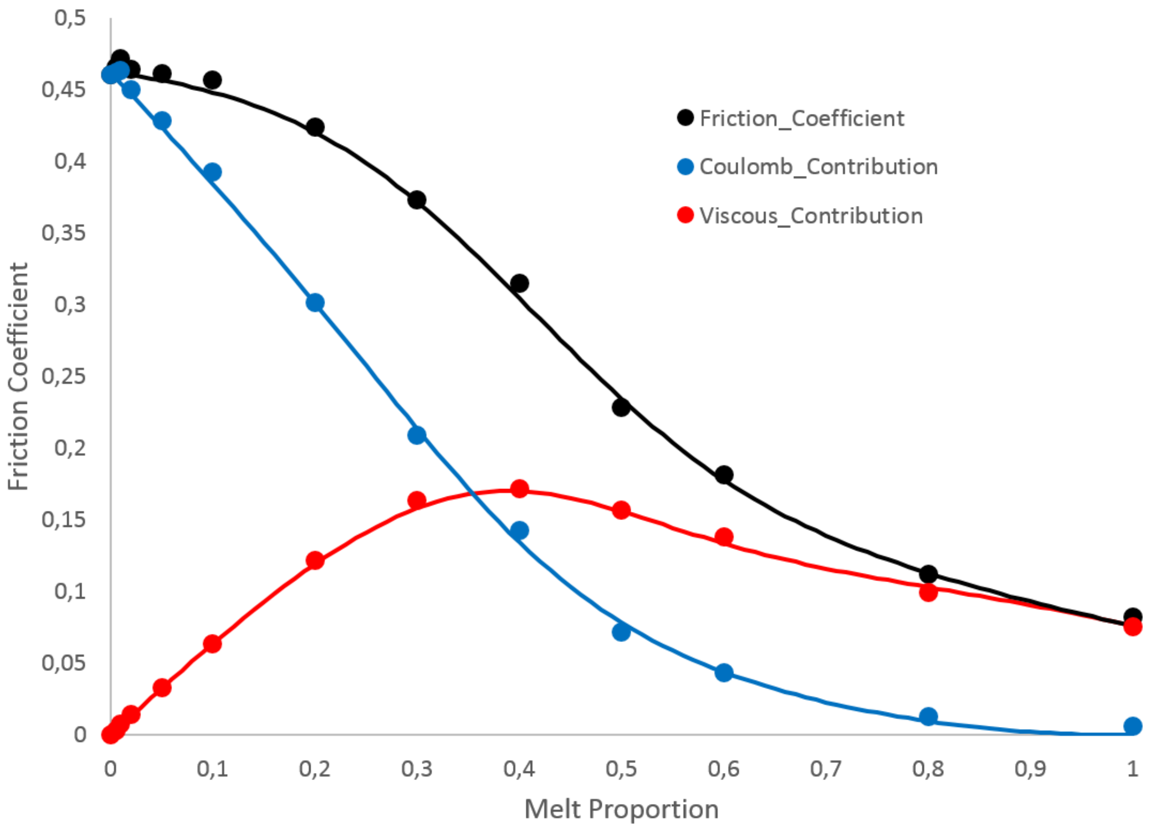
Friction and energetic budget

- Friction coefficient of the interface decreases non-linearly with Φ_M



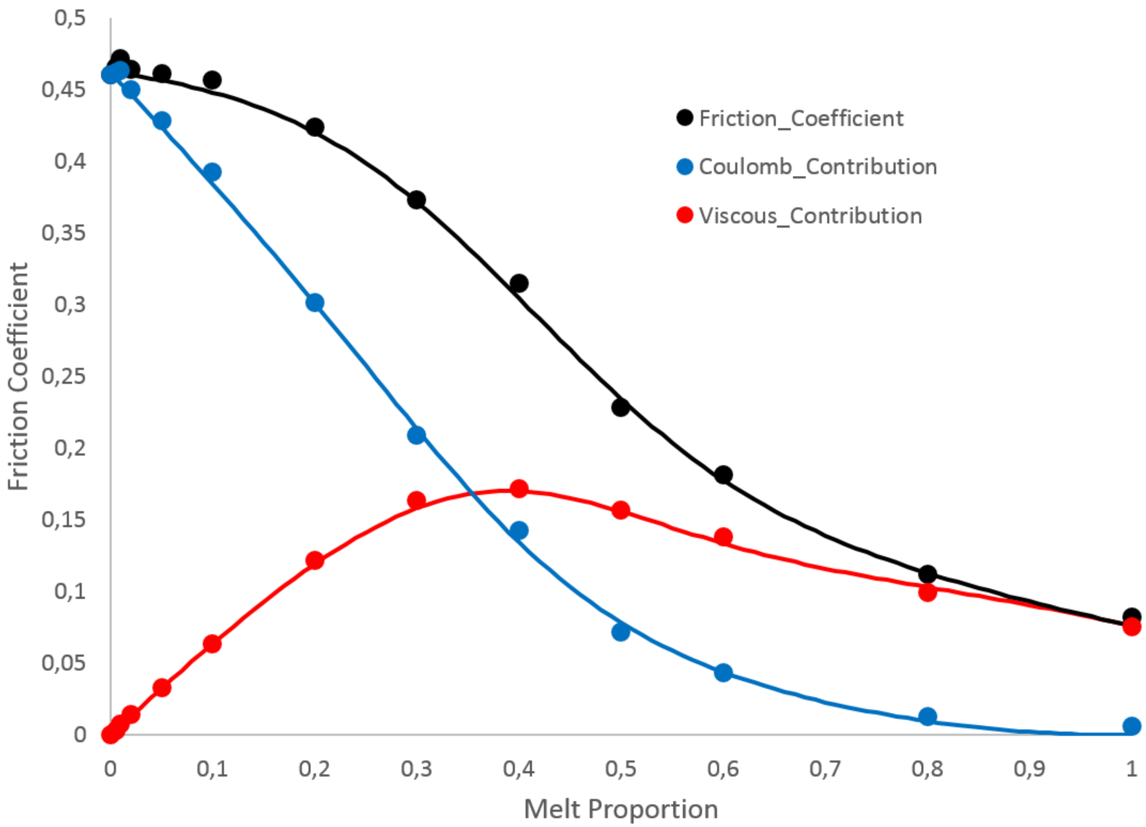
Friction and energetic budget

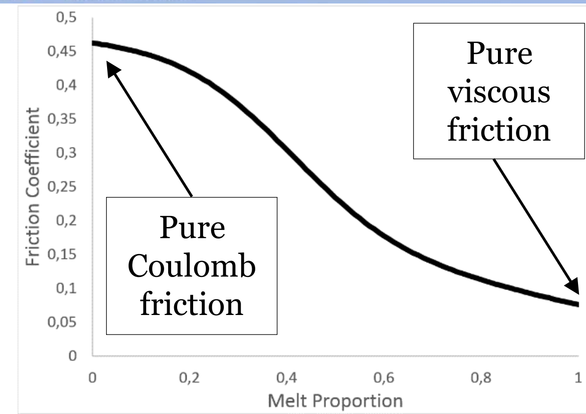
- Friction coefficient of the interface decreases non-linearly with Φ_M
- Based on the type of energy dissipation (solid or deformable grains), friction is decomposed into two contributions: a Coulomb term and a viscous term.

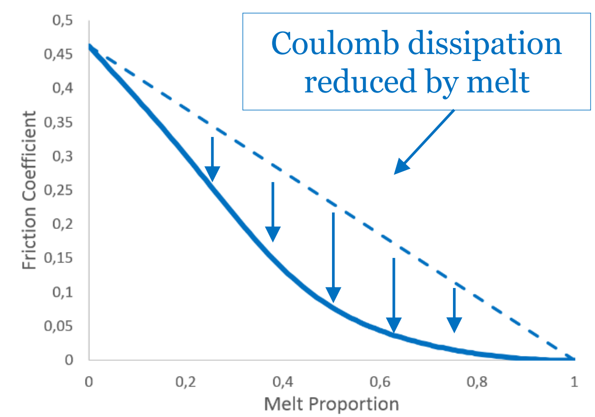


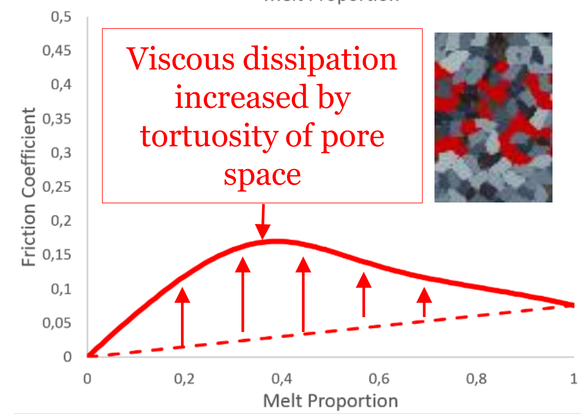
Friction and energetic budget

- Friction coefficient of the interface decreases non-linearly with Φ_M
- Based on the type of energy dissipation (solid or deformable grains), friction is decomposed into two contributions: a Coulomb term and a viscous term.
- These contributions do not evolve linearly with Φ_M









Friction and energetic budget

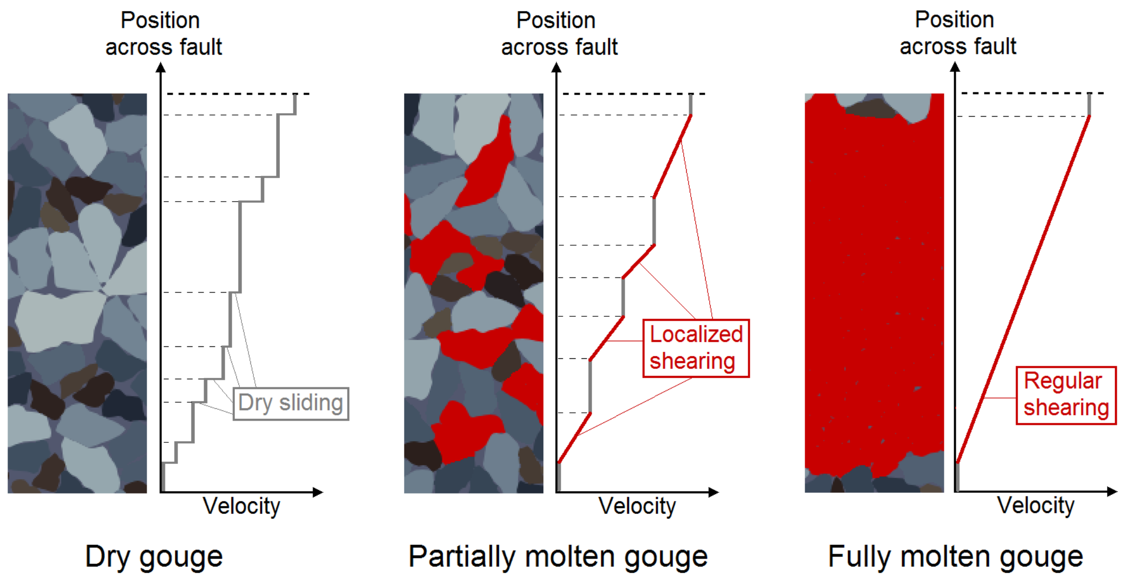
- Friction coefficient of the interface decreases non-linearly with Φ_M

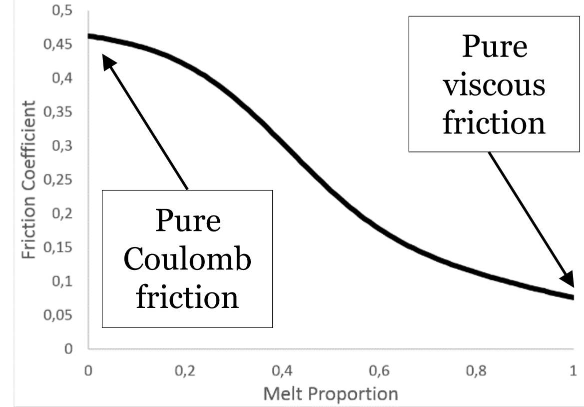
- Based on the type of energy dissipation (solid or deformable grains), friction is decomposed into two contributions: a Coulomb term and a viscous term.

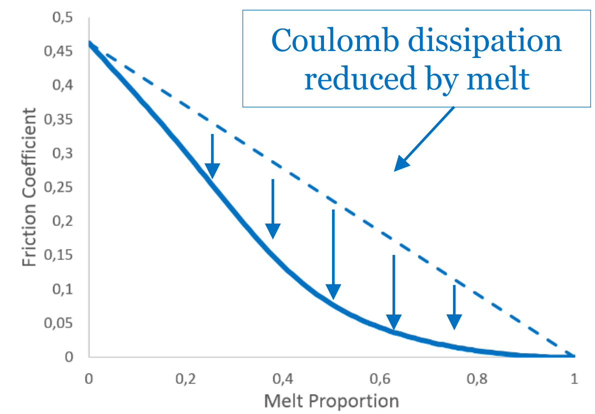
- These contributions do not evolve linearly with Φ_M

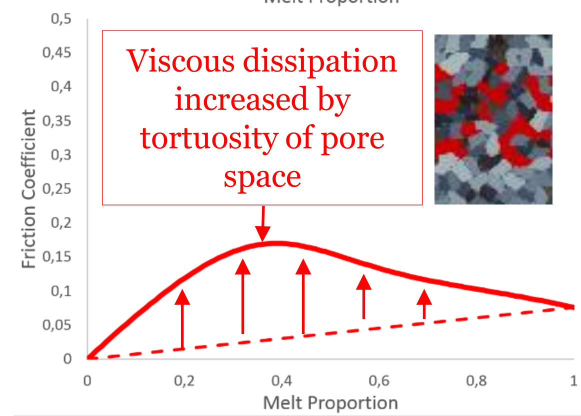
- Coulomb contribution is smaller than expected at partial melting
  -> Lubrication by the molten grains

- Viscous contribution is larger than expected at partial melting
  -> Localization of shearing in the “fluid” phase









Simulations – Case study #2

Guilhem Mollon[1]

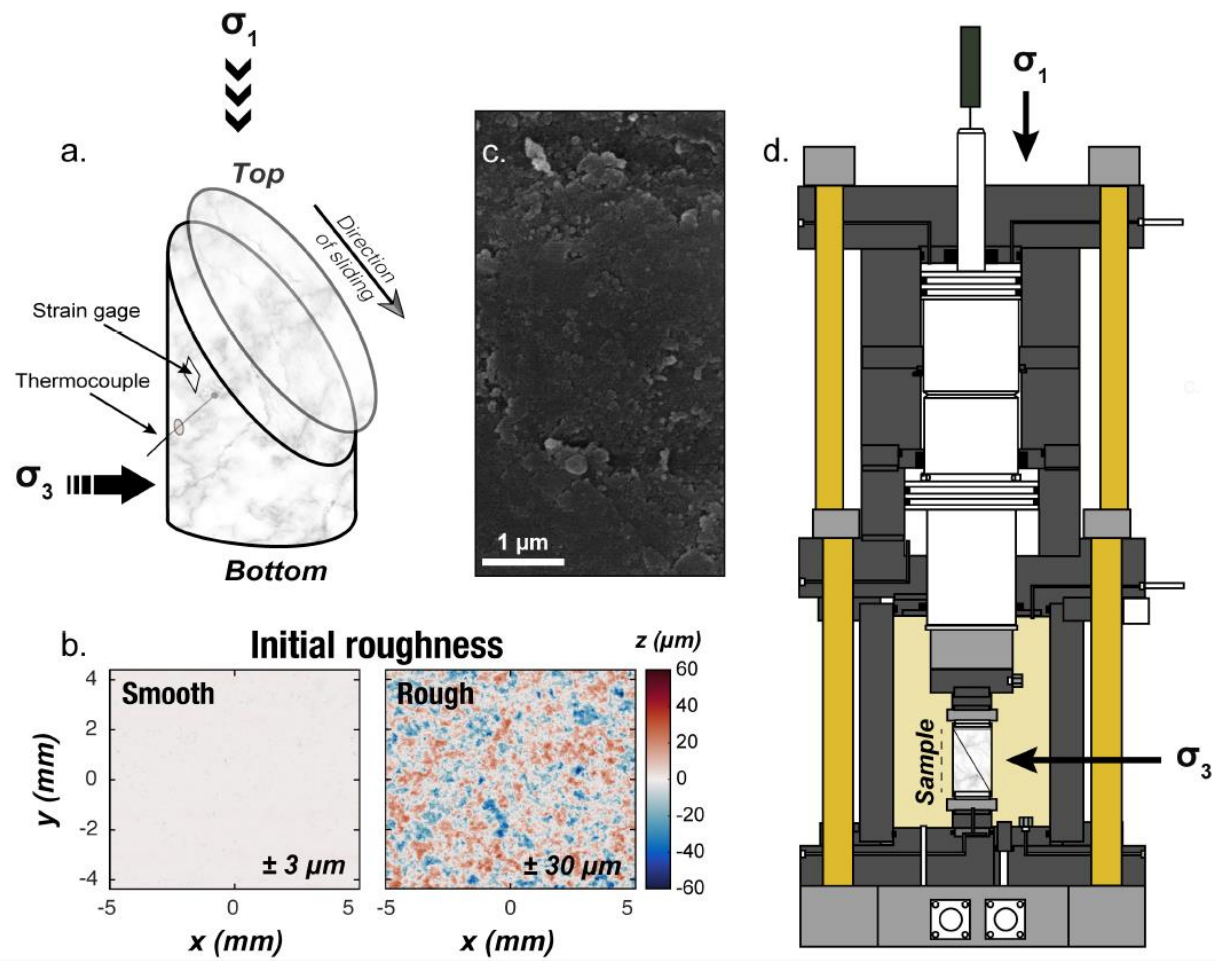
[1]LaMCoS
INSA LYON
Villeurbanne, France

TRAMME, July 2023

Motivation of the study

-We take inspiration from triaxial compression tests performed at ENS (*Aubry et al. 2020*)

Triaxial compression tests on sawcut marble samples, with a controlled roughness.

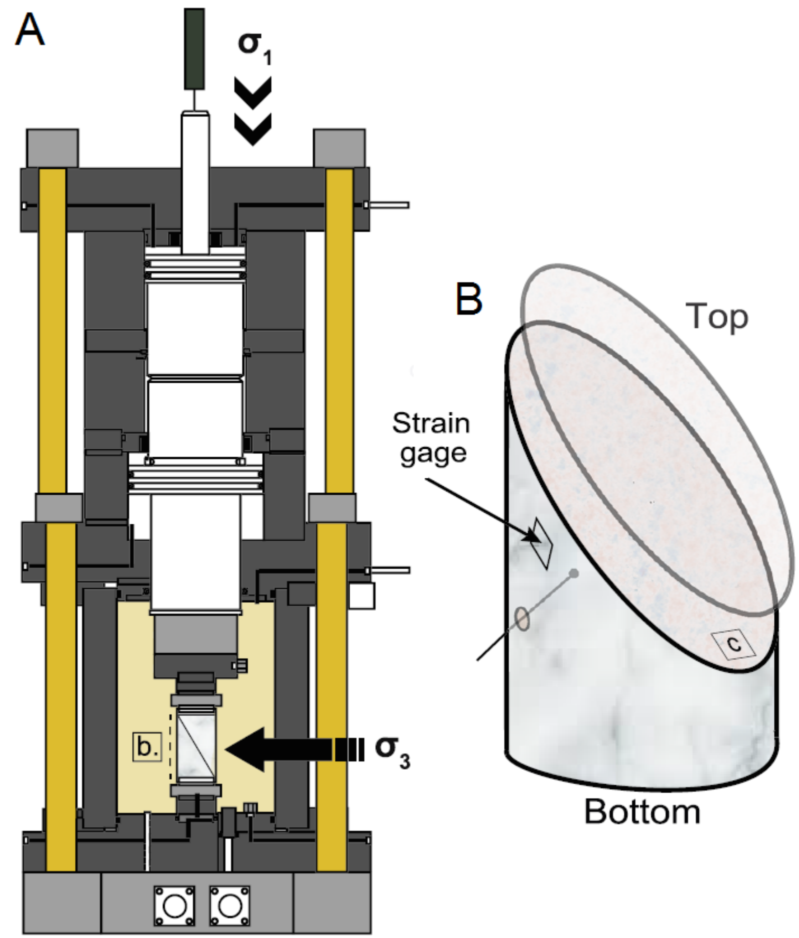


J Aubry, FX Passelègue, J Escartín, J Gasc, D Deldicque, A Schubnel (2020), Fault stability across the seismogenic zone, *JGR Solid Earth*, 125(8).

Motivation of the study

-We take inspiration from triaxial compression tests performed at ENS (*Aubry et al. 2020*)

-Precut and resurfaced marble samples

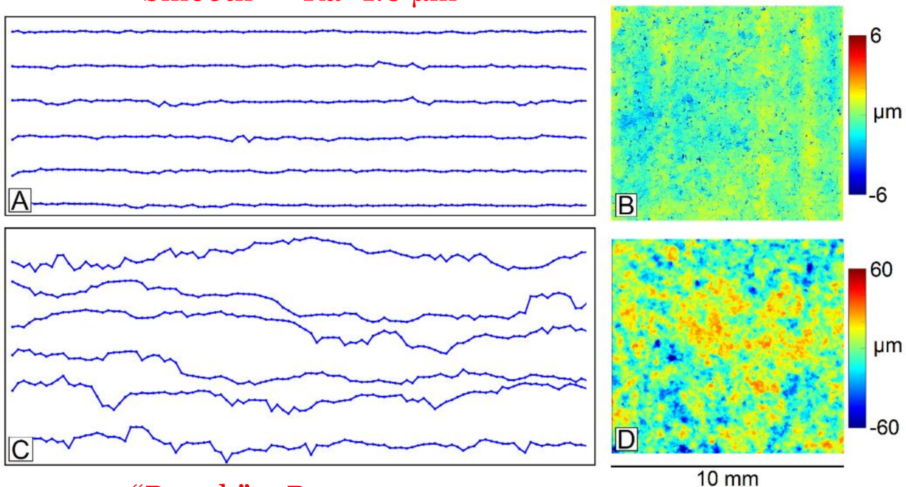


Motivation of the study

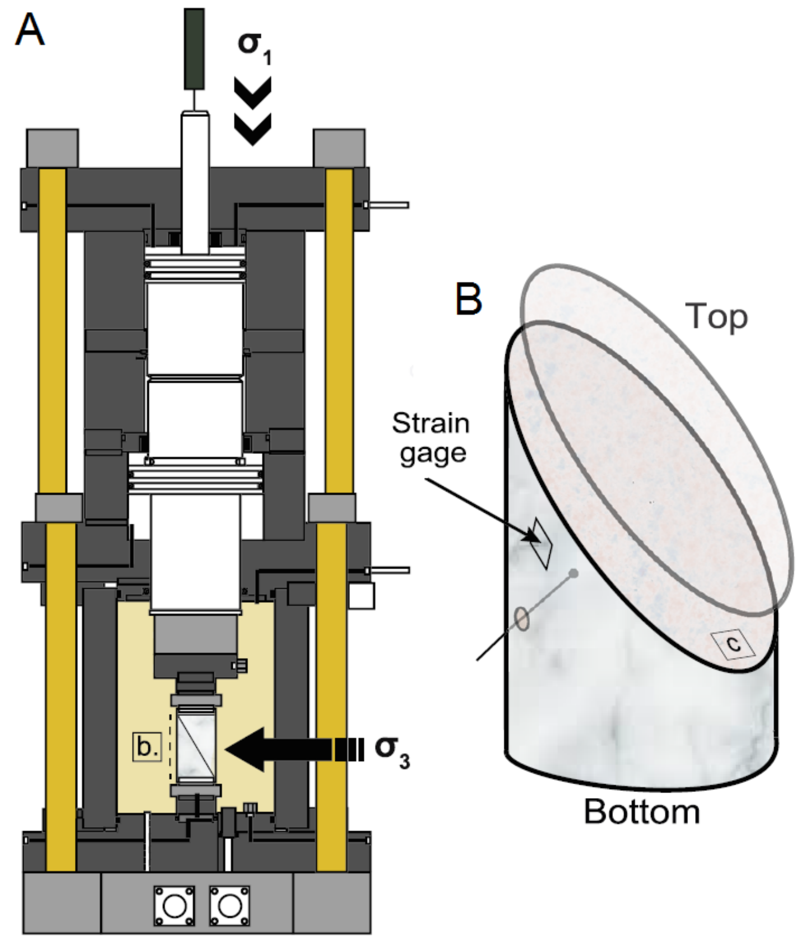
-We take inspiration from triaxial compression tests performed at ENS (*Aubry et al. 2020*)

-Precut and resurfaced marble samples – Surfaces are either “smooth” or “rough”

“Smooth” – Ra=1.0 µm



“Rough” – Ra=12.7 µm



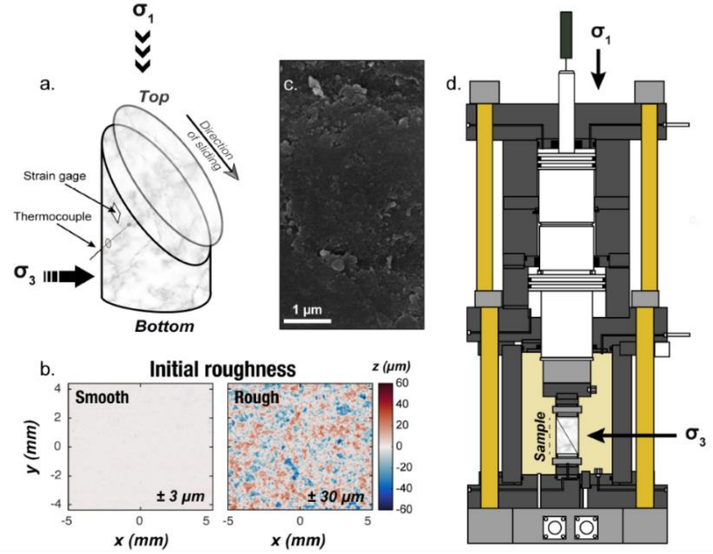
Motivation of the study

-We take inspiration from triaxial compression tests performed at ENS (*Aubry et al. 2020*)

-Precut and resurfaced marble samples – Surfaces are either “smooth” or “rough”

-Is it possible to build a numerical model to reproduce the earthquake cycle as observed in the lab?

Triaxial compression tests on sawcut marble samples, with a controlled roughness.



Motivation of the study

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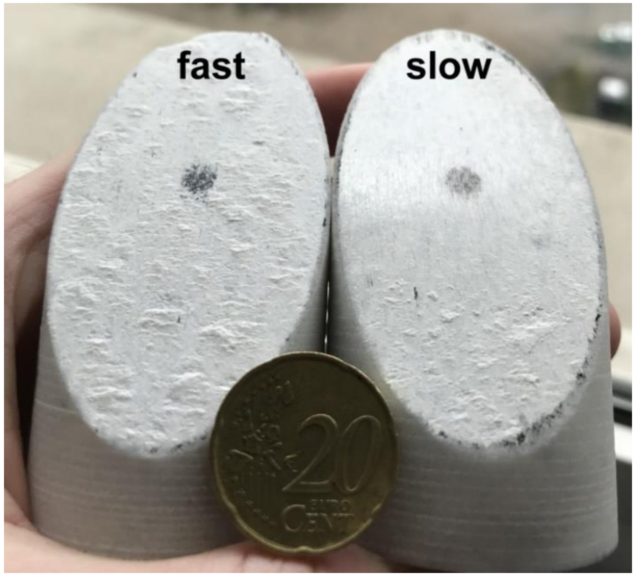


-To reproduce some of the experimental physics, the model should contain:

-> Elastic deformability of the two half samples (to store and restitute deformation energy)

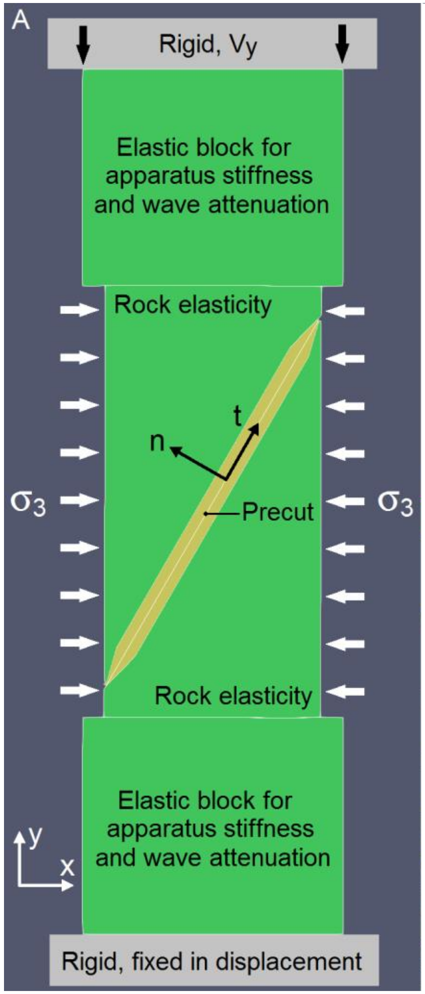
-> Degradable surface (to simulate rock damage)

-> Separable surface material (to reproduce gouge emission in the interface)

-> Deformable and dissipative boundary conditions (to simulate attenuation of acoustic waves)

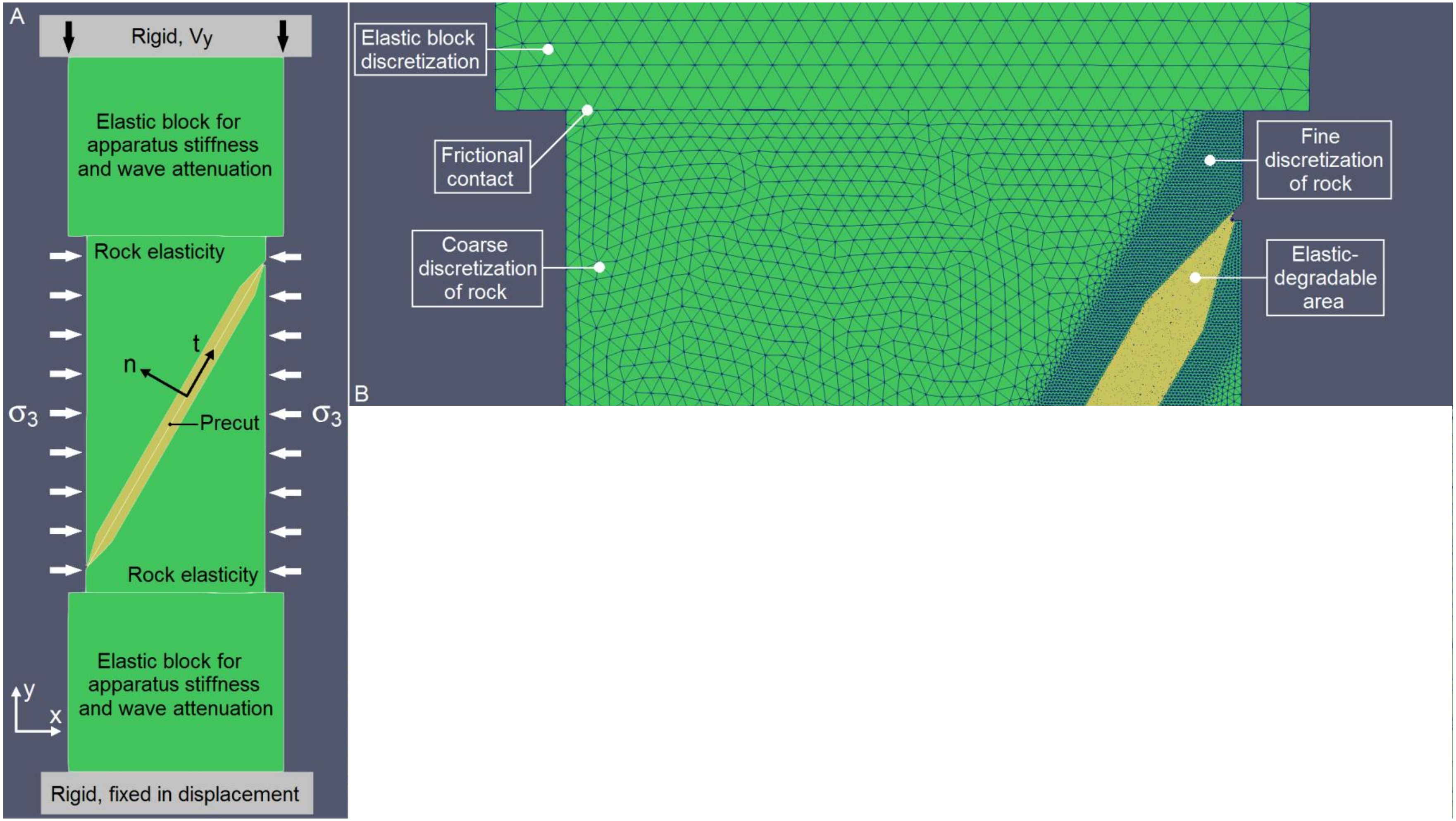
Layout of the model

-Continuous modelling (Meshfree approach) for elastic parts



Layout of the model

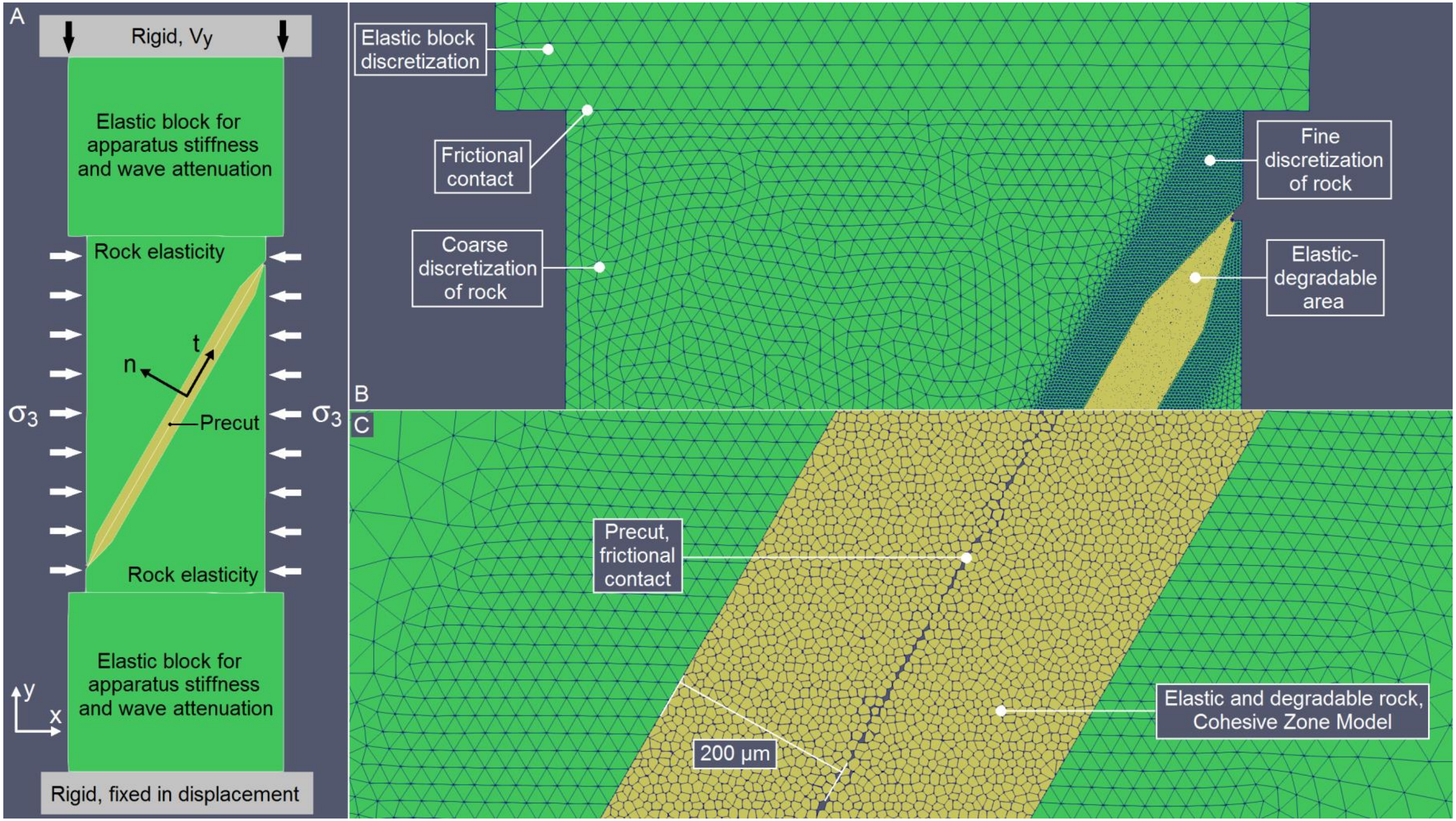
-Continuous modelling (Meshfree approach) for elastic parts



Layout of the model

-Continuous modelling (Meshfree approach) for elastic parts

-Discrete modelling (DEM) for elastic-damageable surfaces and to-be-released fault gouge



Model layout

-2D model combining continuous parts (bulk of half-samples, loading system) and discrete parts (first 200 µm of the surfaces into contact). Reduced scale (1/10th) with respect to experiments.

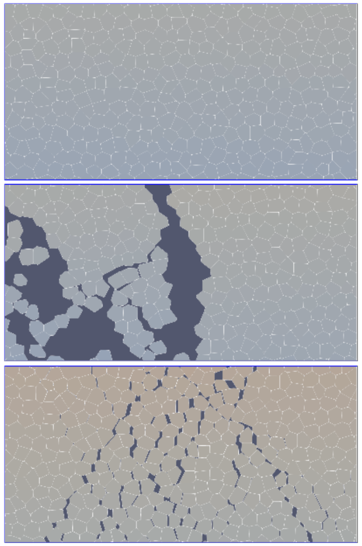
-Half-samples initially separated, put into contact, submitted to radial confining stress, and to vertical strain-driven loading through elastic loading blocks.

Model layout

-2D model combining continuous parts (bulk of half-samples, loading system) and discrete parts (first 200 μm of the surfaces into contact). Reduced scale (1/10th) with respect to experiments.

-Half-samples initially separated, put into contact, submitted to radial confining stress, and to vertical strain-driven loading through elastic loading blocks.

-Calibration of the discrete part : Cohesive Zone Model (CZM) contact law between polygonal grains:

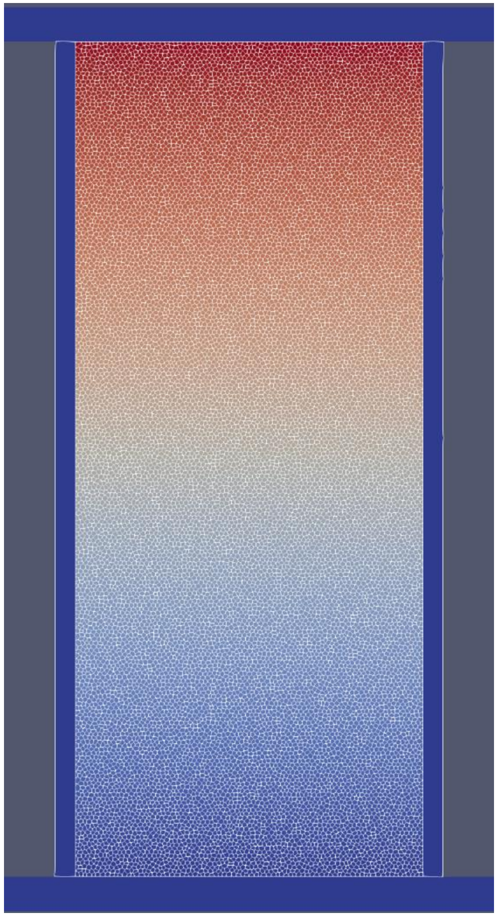


-> Elastic link if intact (damage=0)

-> Breaks if tensile or tangential strength threshold is reached (damage set to 1)

-> Frictional contact if broken (damage=1)

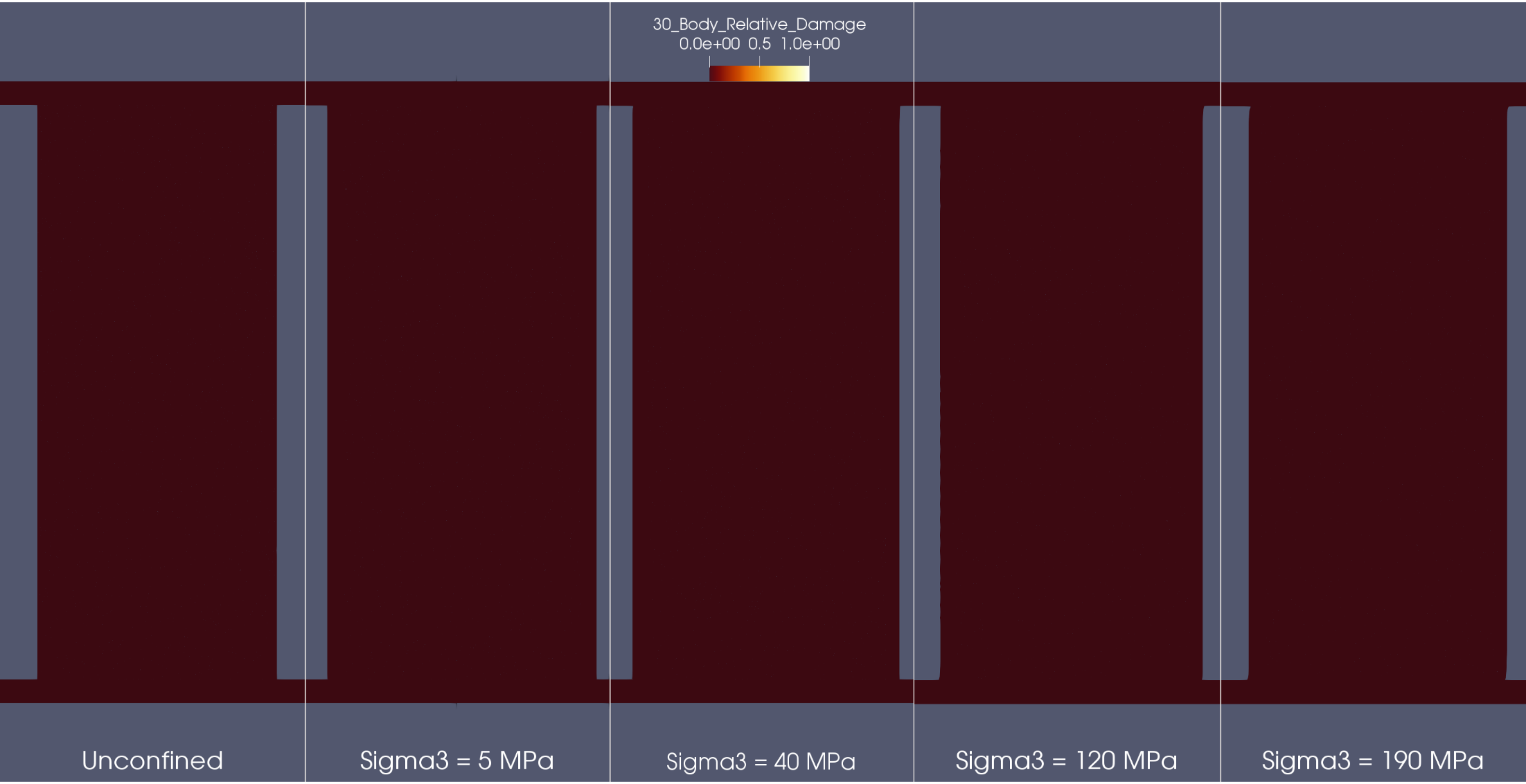
-Calibration performed with independent simulations in order to reproduce the strength properties of Marble, based on *Friedrich et al. 89*.



Simulation of biaxial compression on marble.

Fredrich, J. T.; Evans, B. & Wong, T.-F., (1989). "Micromechanics of the brittle to plastic transition in Carrara marble", *JGR: Solid Earth*, 94, 4129-4145

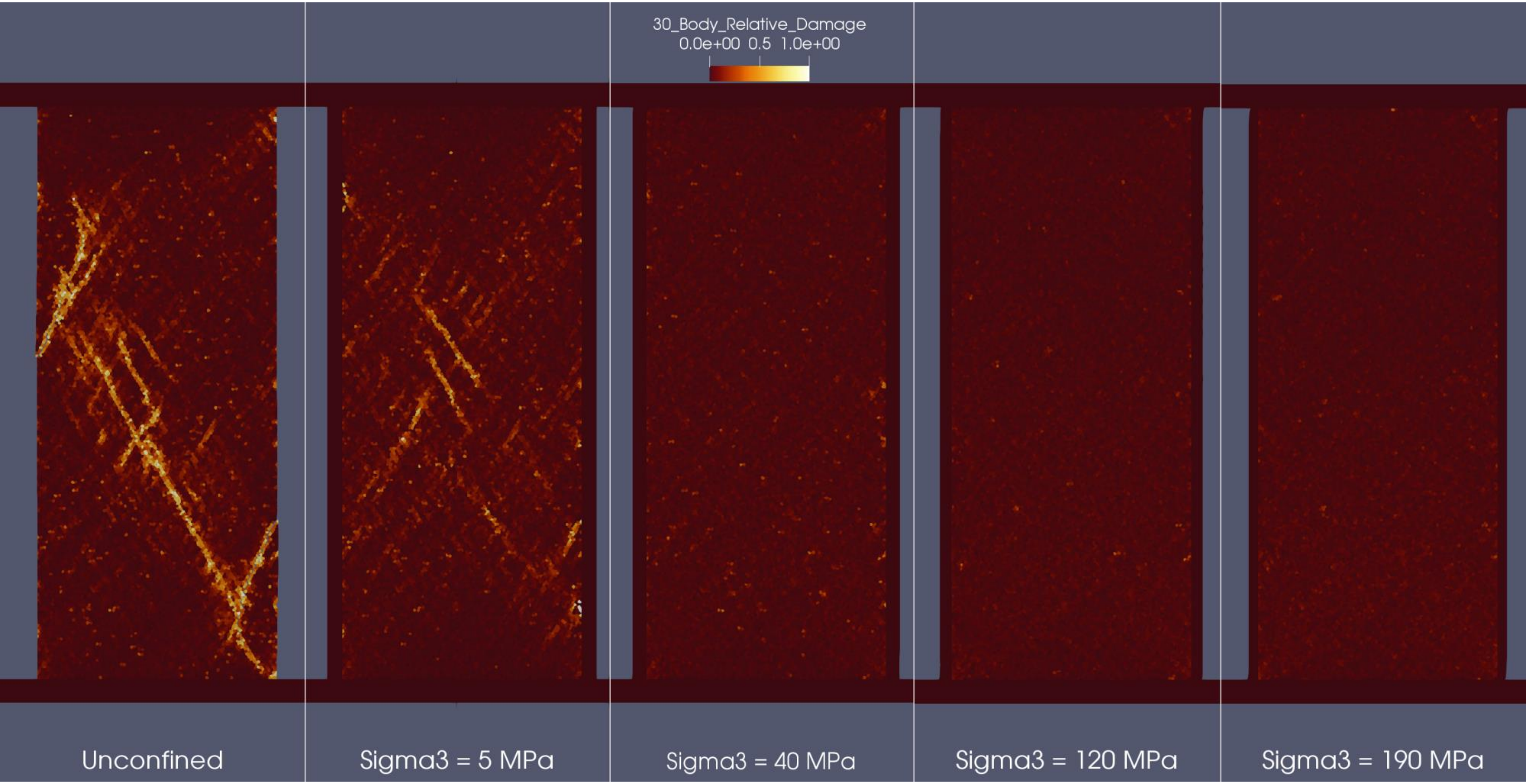
0% Shortening



Initial state of the calibration simulations, for different confining stresses.

Mollon, G., (2018). "A unified framework for rigid and compliant granular materials", *Comp. Part. Mech.*, 5, 517-527

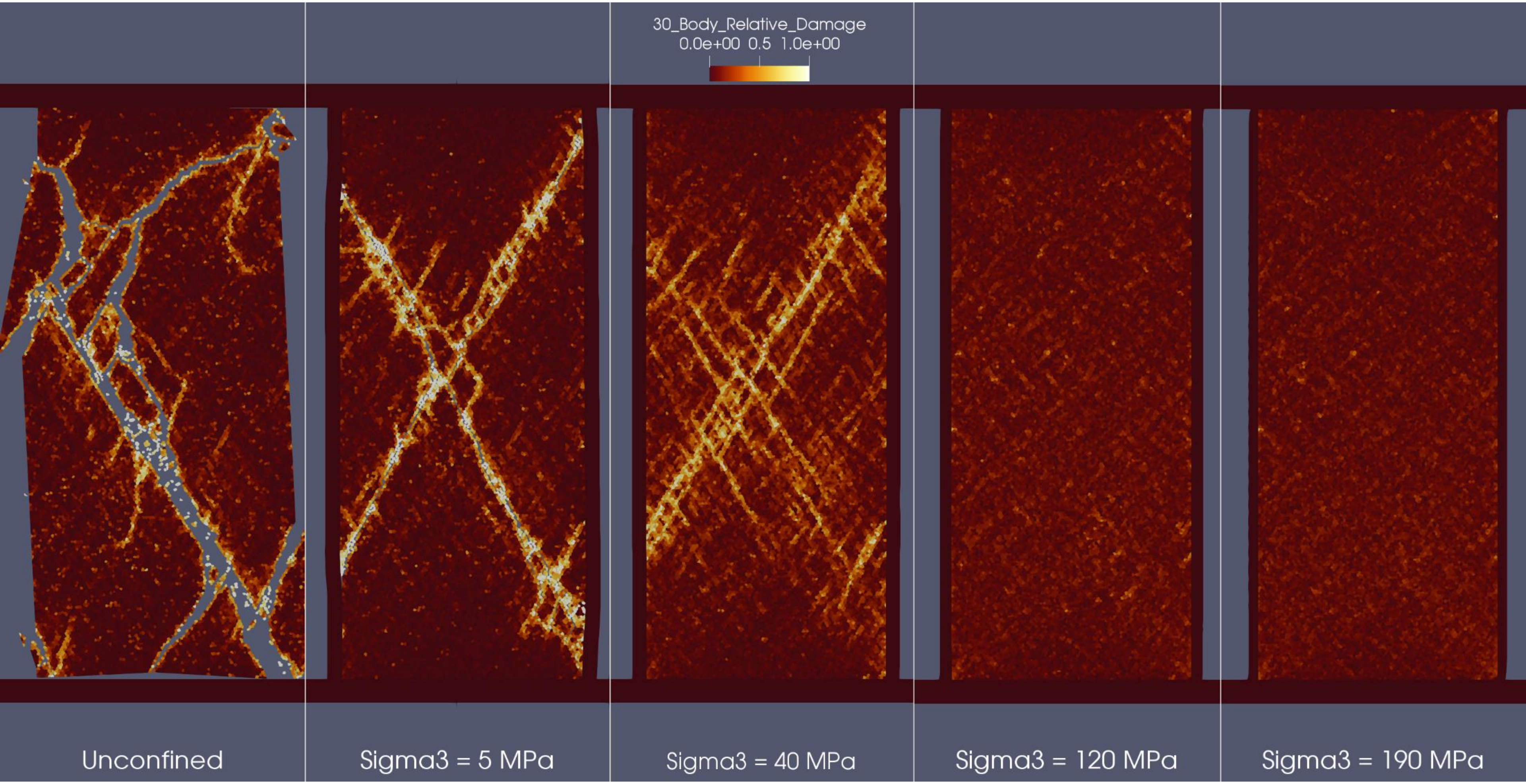
0.36% Shortening



Initiation of damage.

Mollon, G., (2018). “A unified framework for rigid and compliant granular materials”, *Comp. Part. Mech.*, 5, 517-527

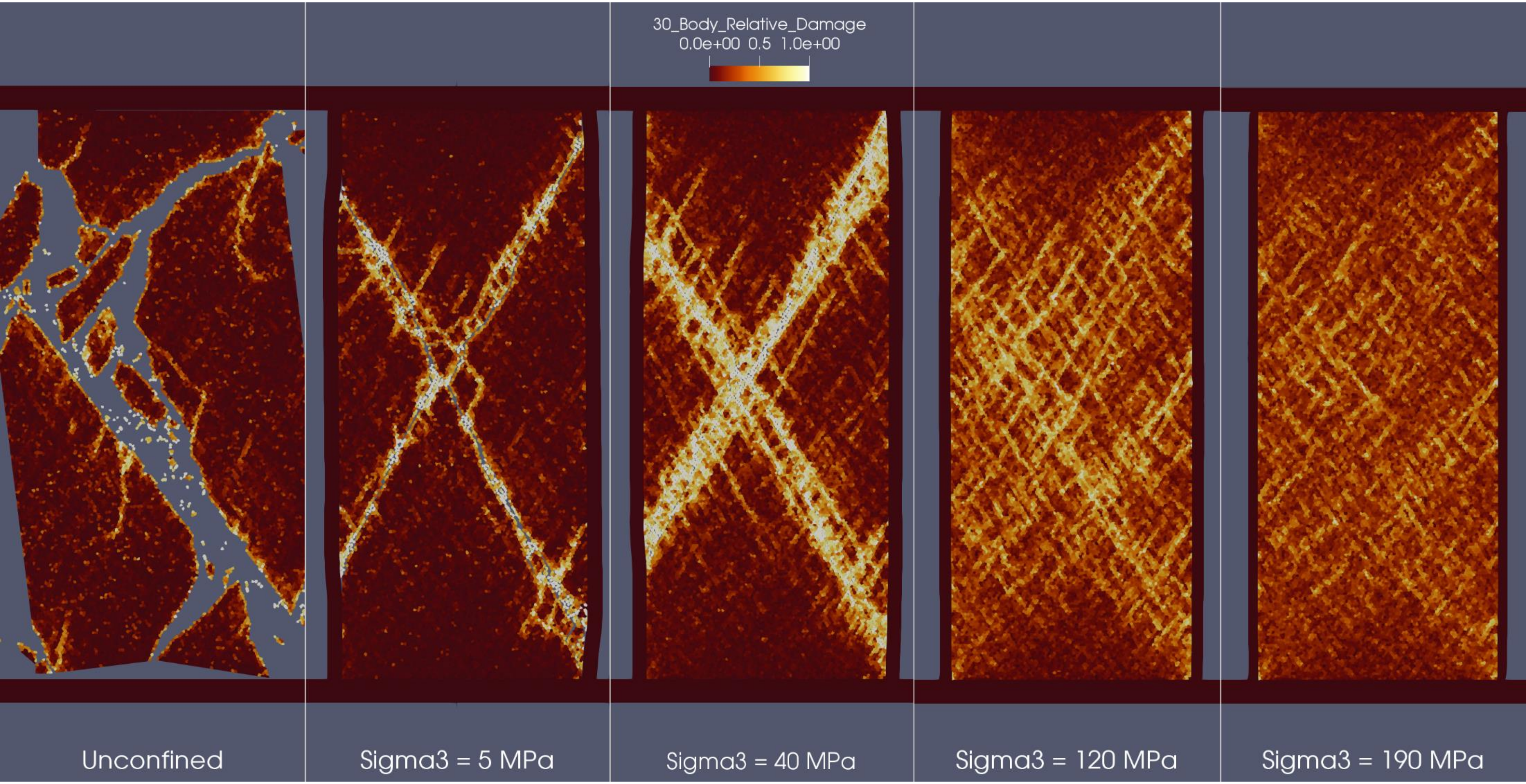
0.56% Shortening



Brittle fracture for 0 and 5 Mpa ; Shear bands for 40 Mpa ; Diffuse damage for 120 and 190 MPa

Mollon, G., (2018). “A unified framework for rigid and compliant granular materials”, *Comp. Part. Mech.*, 5, 517-527

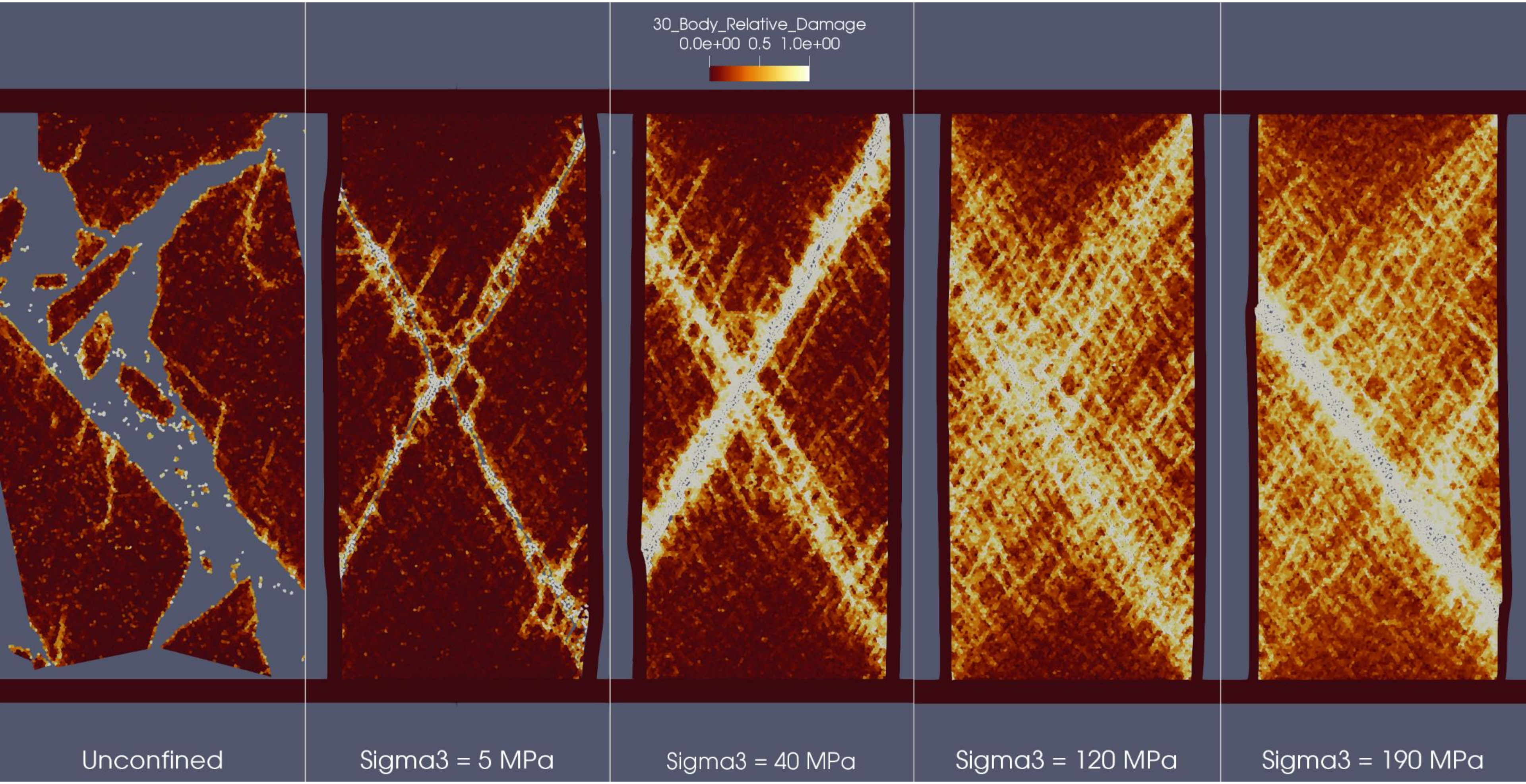
0.94% Shortening



Brittle fracture for 0 and 5 Mpa ; Shear bands for 40 Mpa ; Diffuse damage for 120 and 190 MPa

Mollon, G., (2018). "A unified framework for rigid and compliant granular materials", *Comp. Part. Mech.*, 5, 517-527

1.45% Shortening



Brittle fracture for 0 and 5 Mpa ; Shear bands for 40 Mpa, and also for 120 and 190 MPa

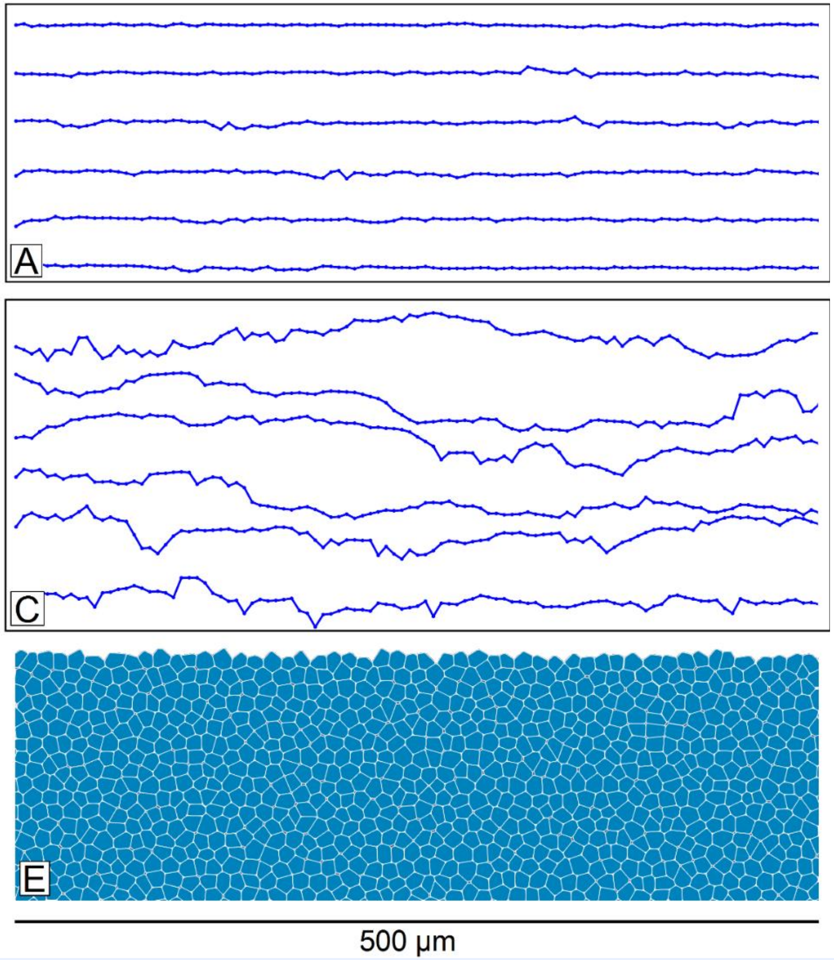
-> Nice qualitative agreement with experimental knowledge (sudden, localized and brittle fracture at low confinement, distributed and ductile failure at high confinement)

Layout of the model

-Continuous modelling (Meshfree approach) for elastic parts

-Discrete modelling (DEM) for elastic-damageable surfaces and to-be-released fault gouge

-Intermediate fault roughness

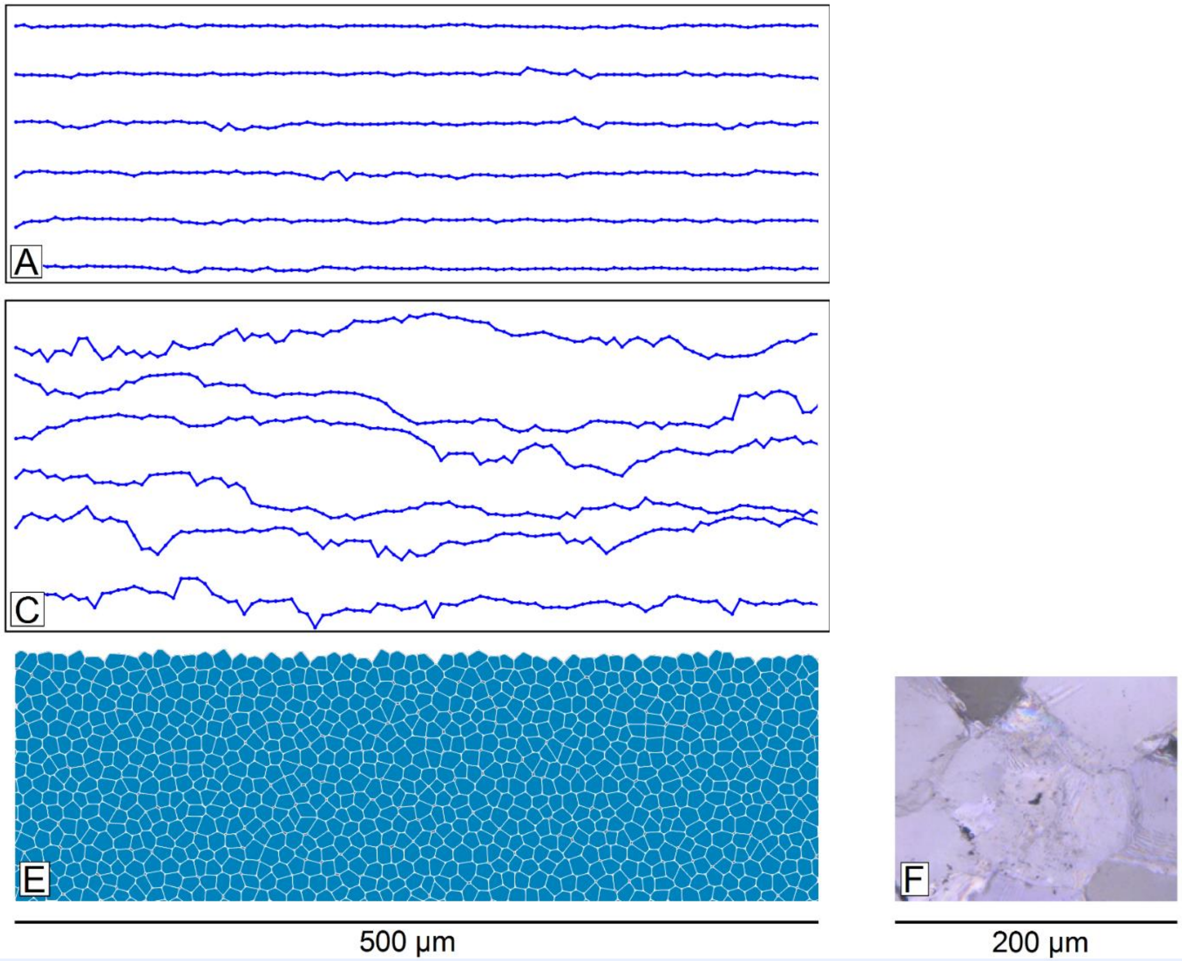


Layout of the model

-Continuous modelling (Meshfree approach) for elastic parts

-Discrete modelling (DEM) for elastic-damageable surfaces and to-be-released fault gouge

-Intermediate fault roughness – Small grain size

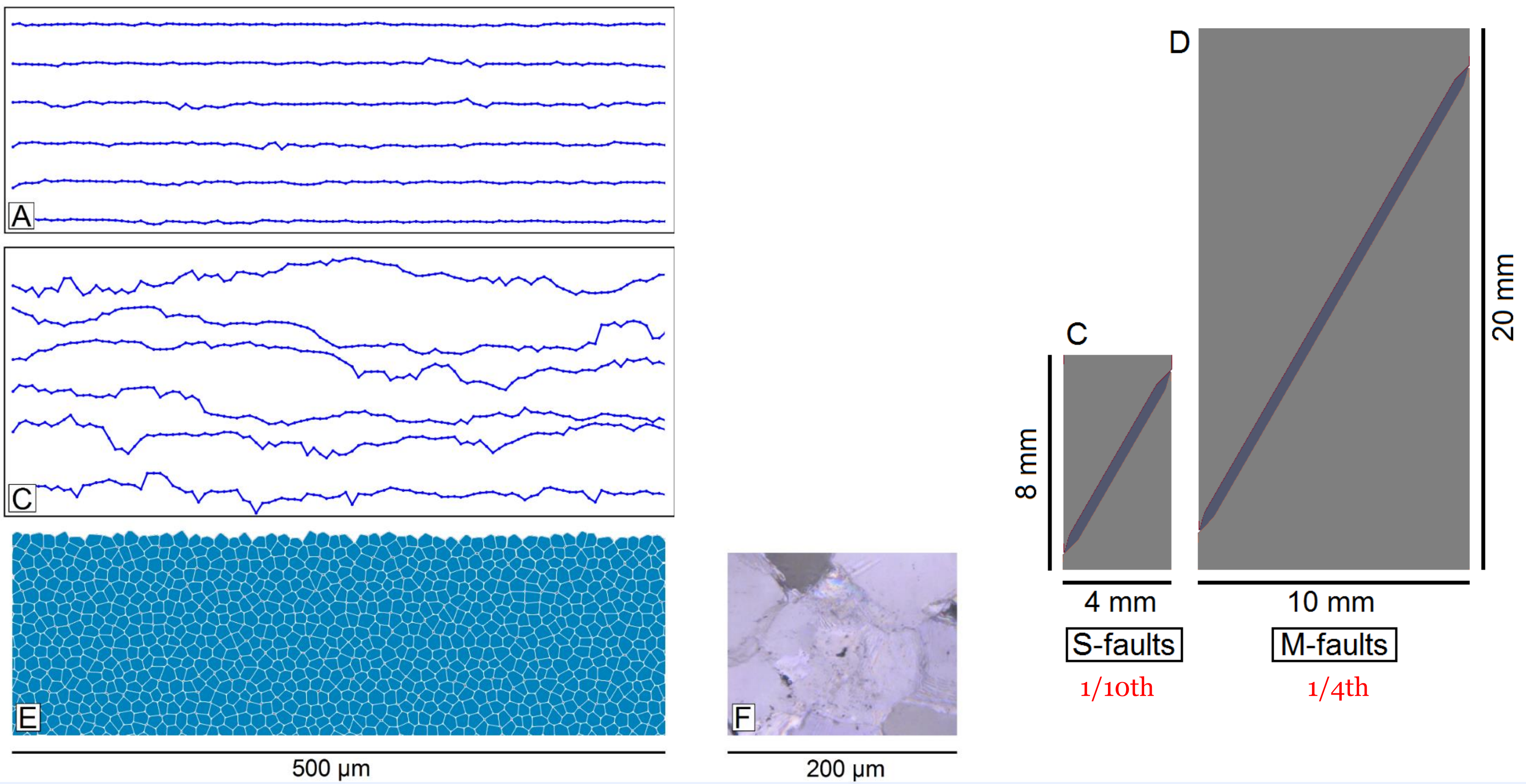


Layout of the model

-Continuous modelling (Meshfree approach) for elastic parts

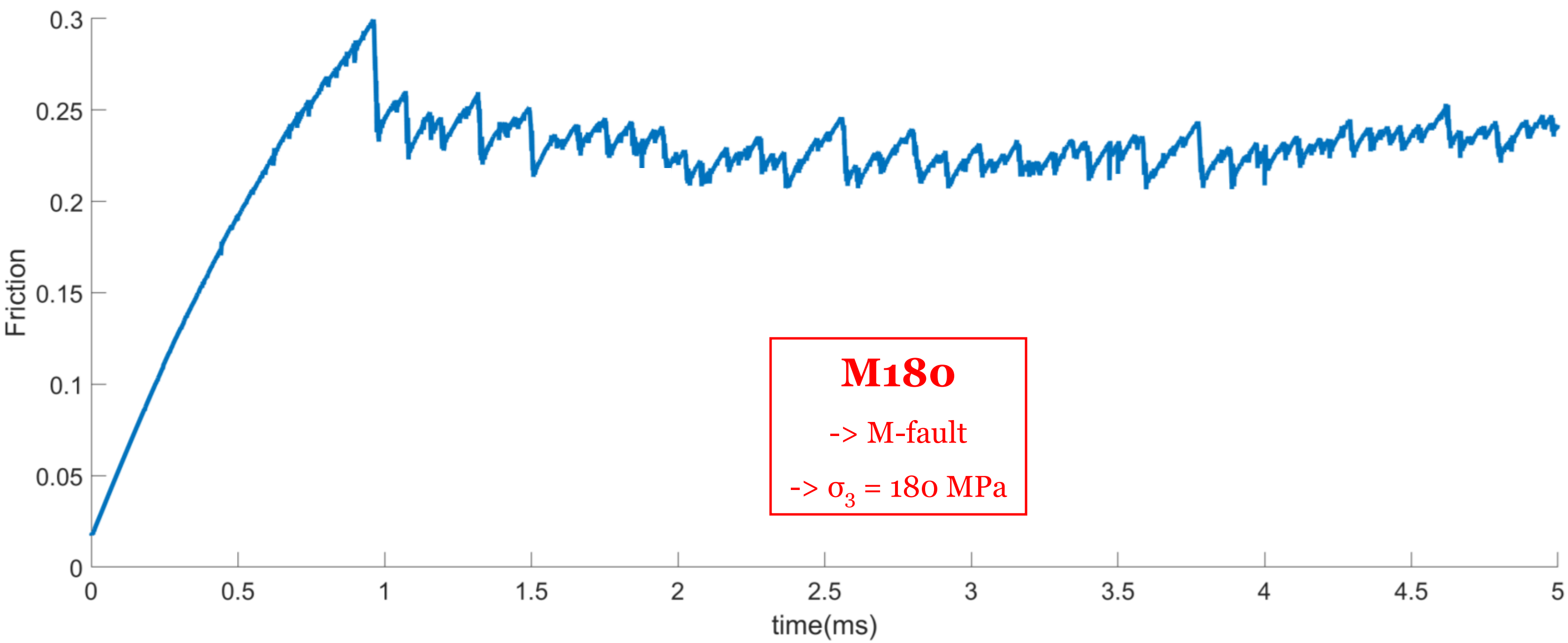
-Discrete modelling (DEM) for elastic-damageable surfaces and to-be-released fault gouge

-Intermediate fault roughness – Small grain size – Two scales of model



Some numerical results

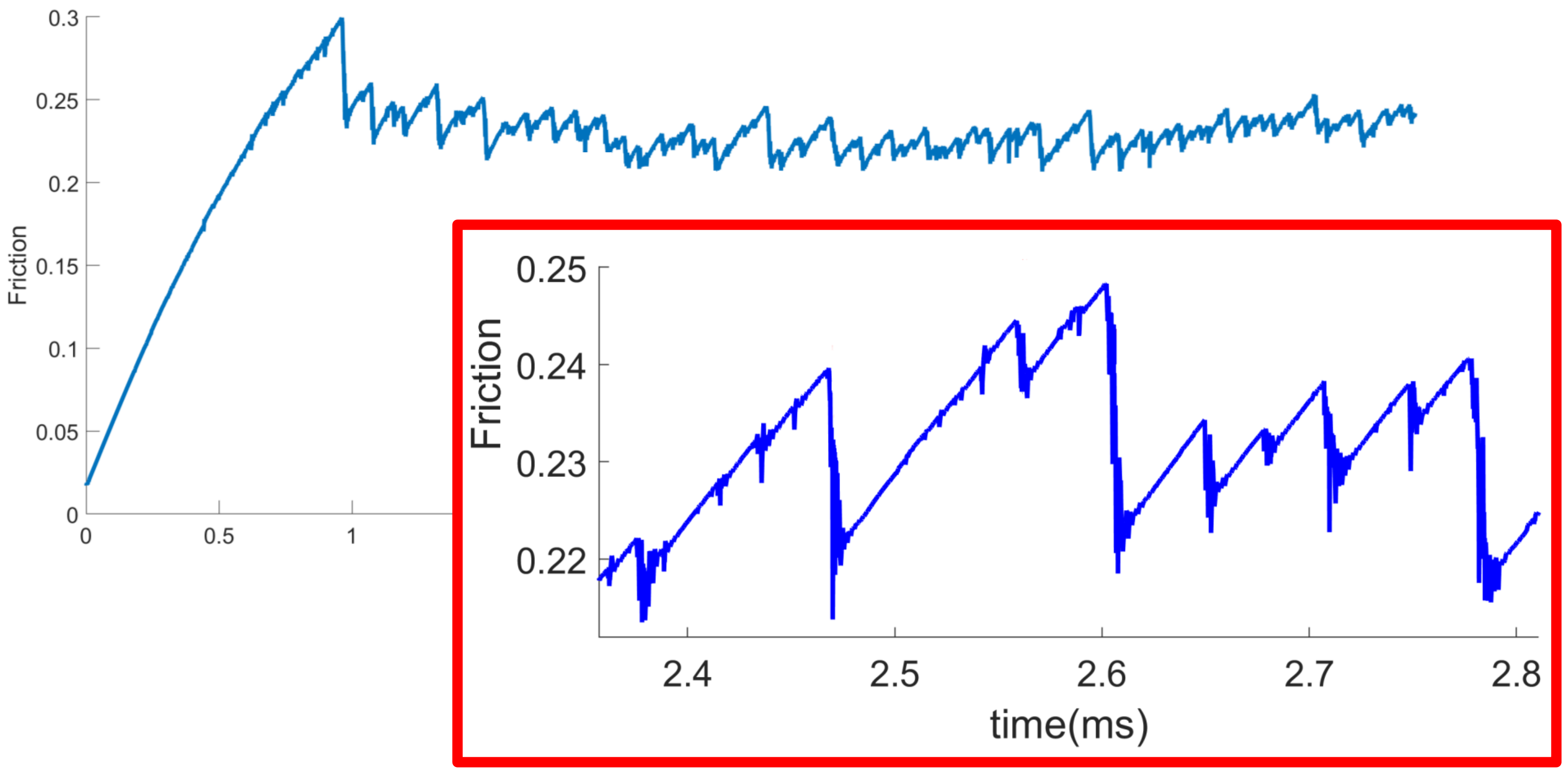
-Beautiful stick-slip patterns



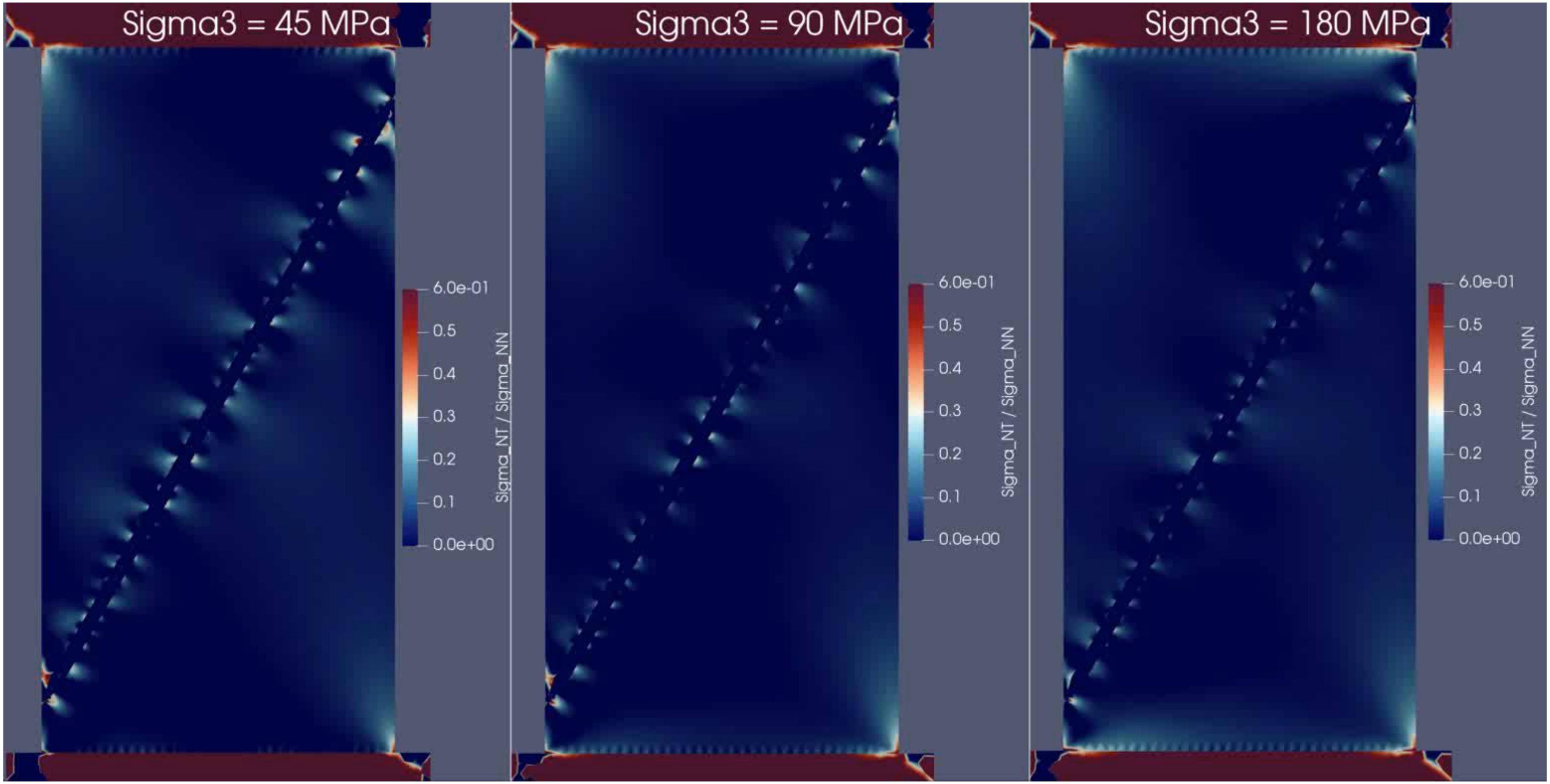
Some numerical results

-Beautiful stick-slip patterns

-Laboratory earthquakes reproduced without ad-hoc weakening friction law!



Stress field and local phenomena



Stress field and local phenomena

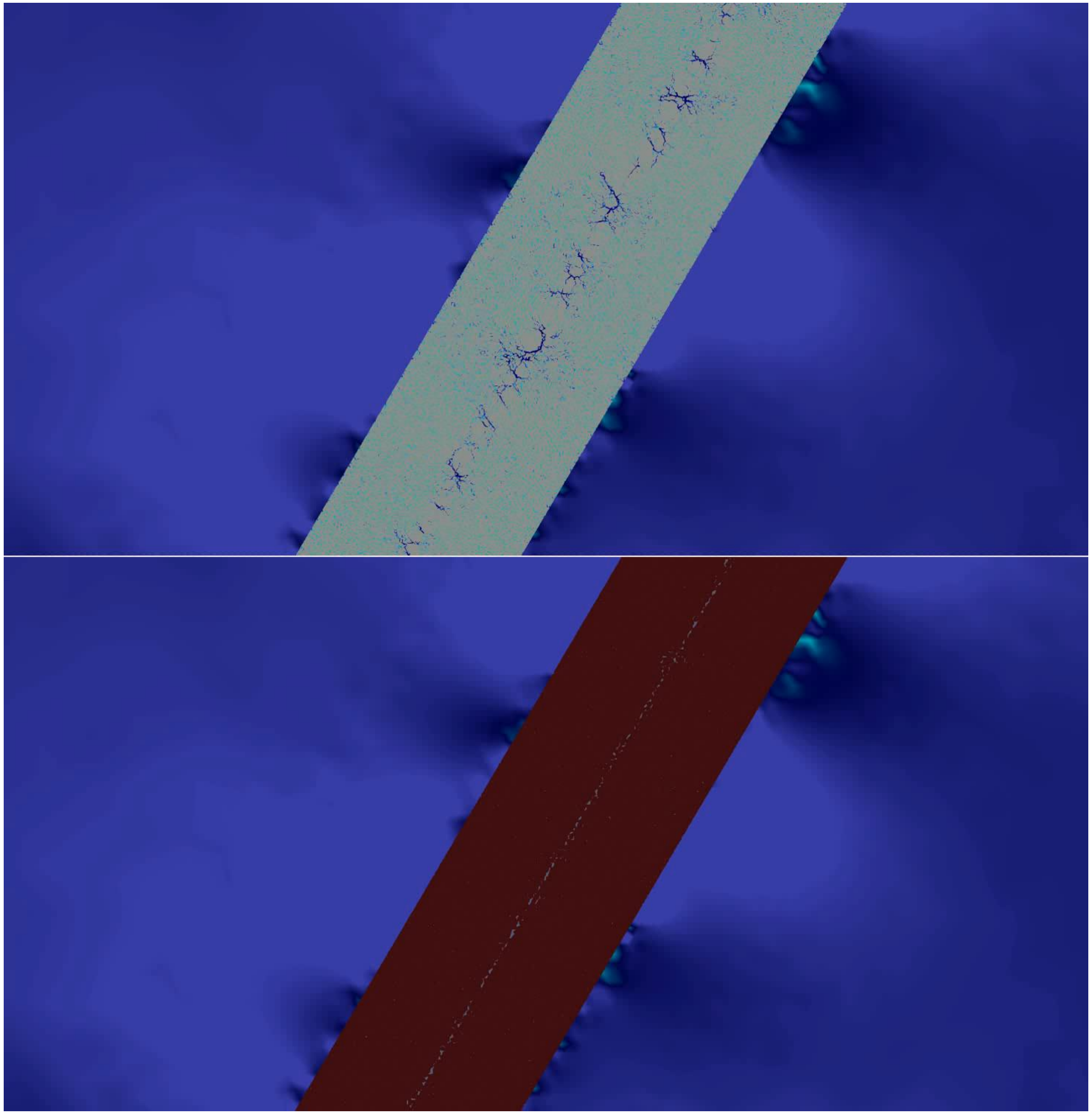
-Progressive damaging

-Sudden events

-Emission of gouge

-Stress concentration

-> Asperity without roughness!



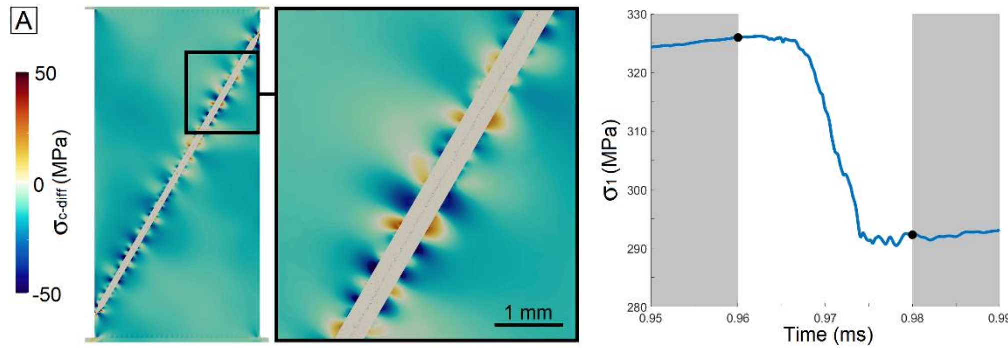
Differential stress for single events

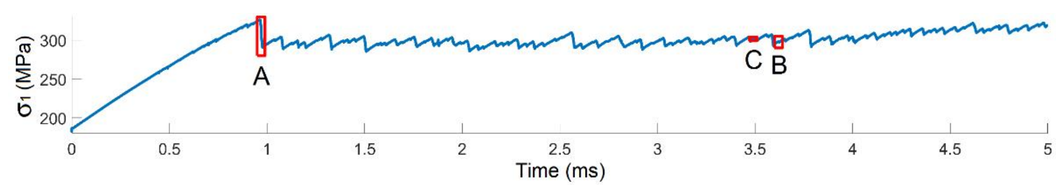
-Large event

-> Large σ_1 drop (~30 Mpa)

-> Complete sliding

-> Heterogeneity in the residual state





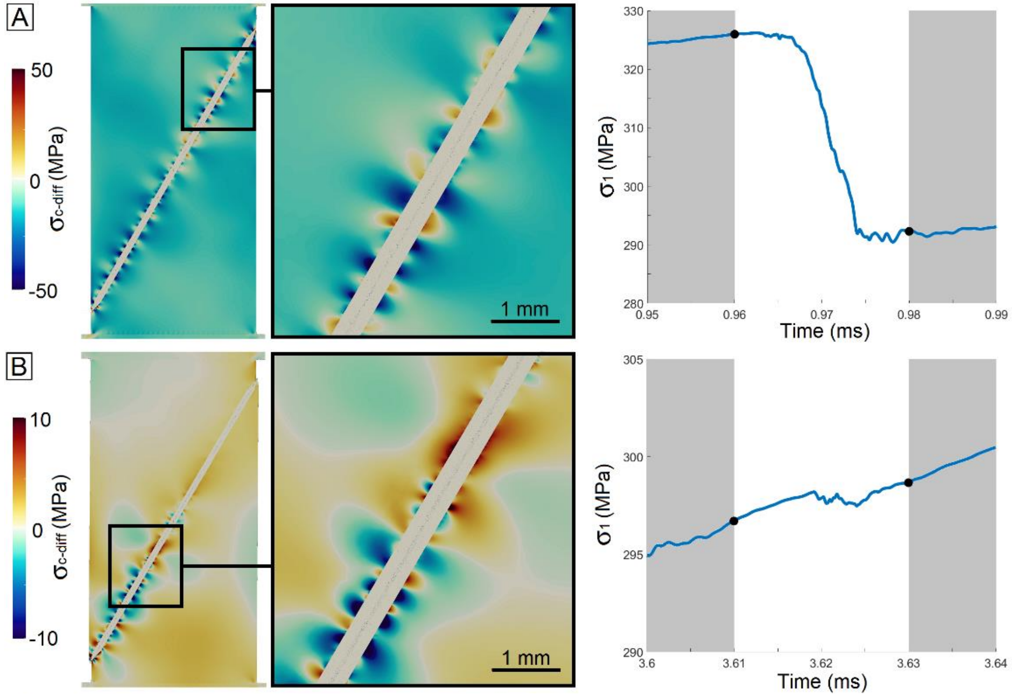
Differential stress for single events

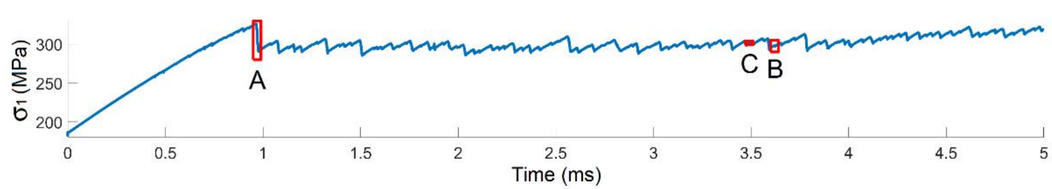
-Large event

- -> Large σ_1 drop (~30 Mpa)
- -> Complete sliding
- -> Heterogeneity in the residual state

-Intermediate event

- -> Barely noticeable at boundaries
- -> Lower half of the sample slipped
- -> Stress concentration at crack tip





Differential stress for single events

-Large event

-> Large σ_1 drop (~30 Mpa)

-> Complete sliding

-> Heterogeneity in the residual state

-Intermediate event

-> Barely noticeable at boundaries

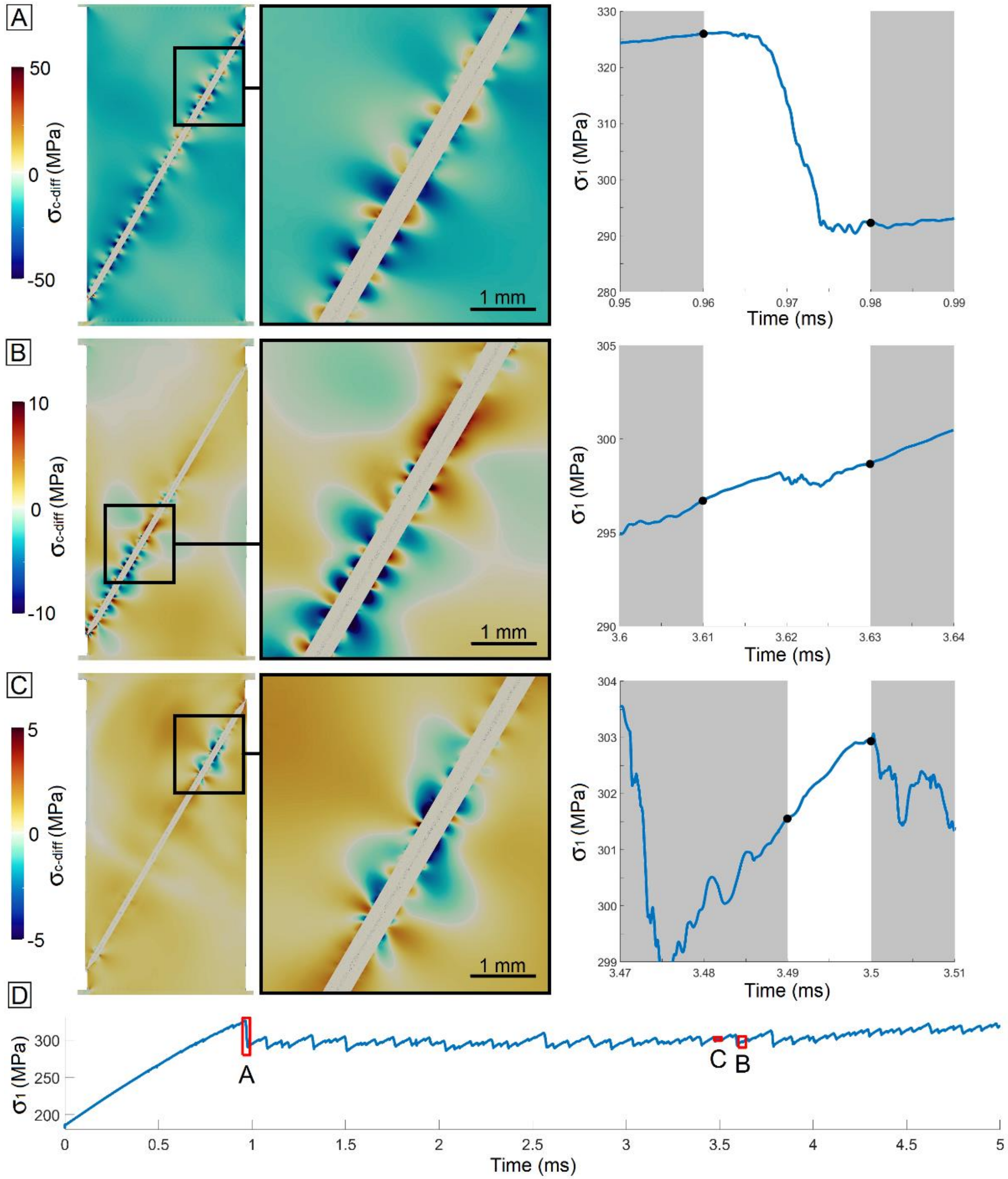
-> Lower half of the sample slipped

-> Stress concentration at crack tip

-Small event

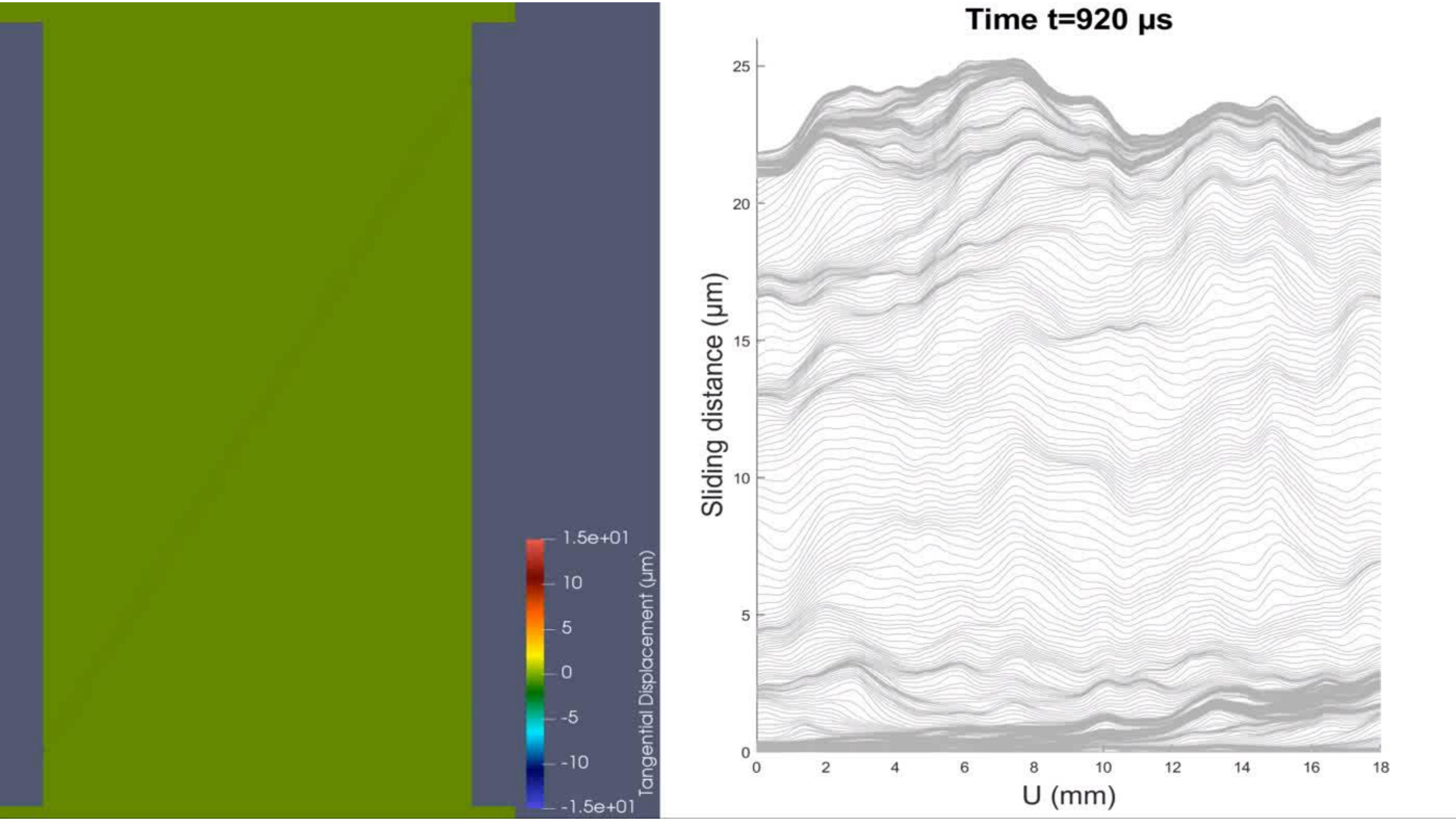
-> Unnoticed at boundaries

-> 15% of the sample slipped



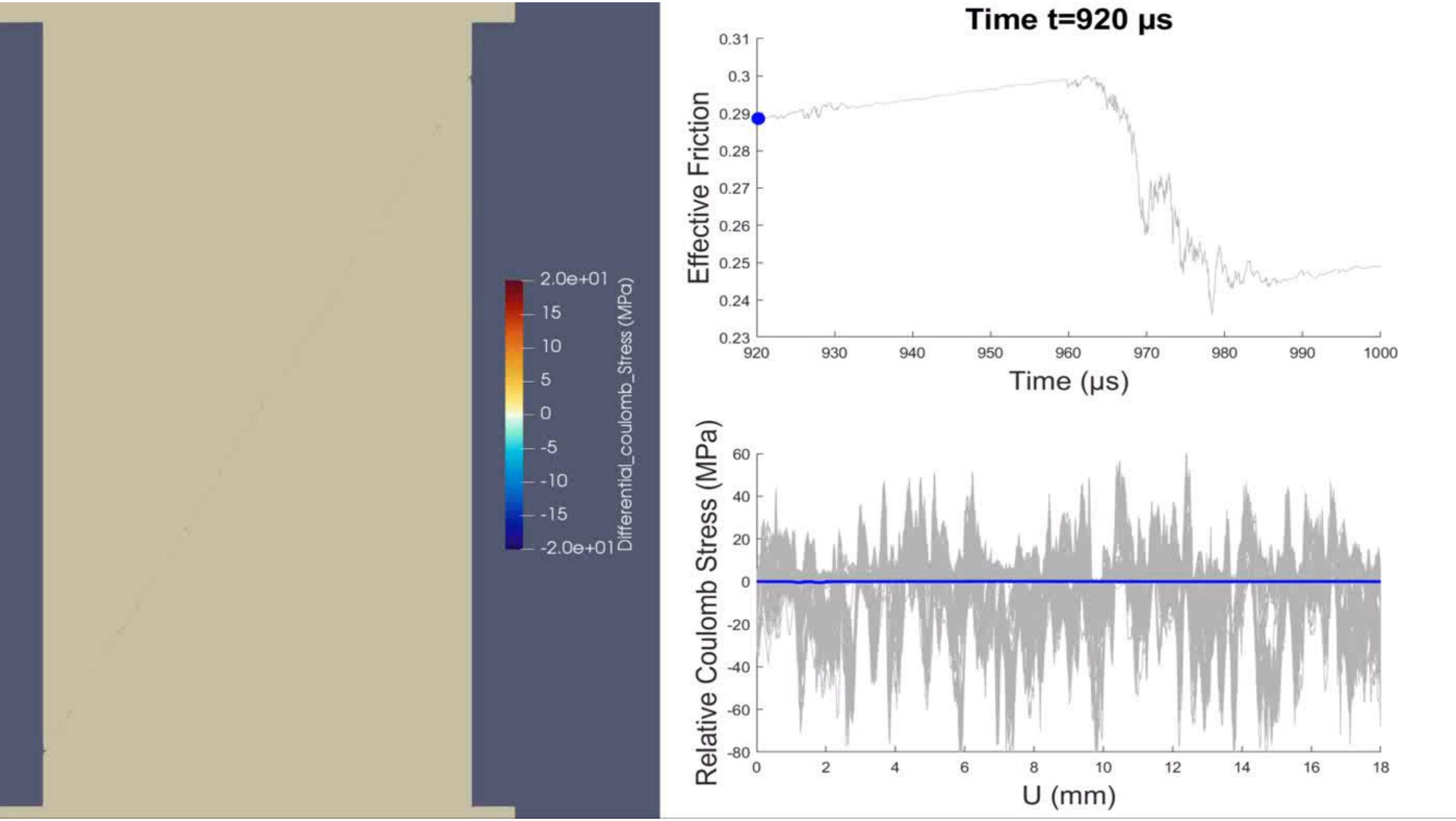
Sliding history during a large event

Sliding distance: ~25 µm; Sliding velocity: ~2-5 m/s; Stress drop: ~30 Mpa; Friction drop: ~0.05



Stress history during a large event

Sliding distance: ~25 µm; Sliding velocity: ~2-5 m/s; Stress drop: ~30 Mpa; Friction drop: ~0.05



Velocity history during a large event

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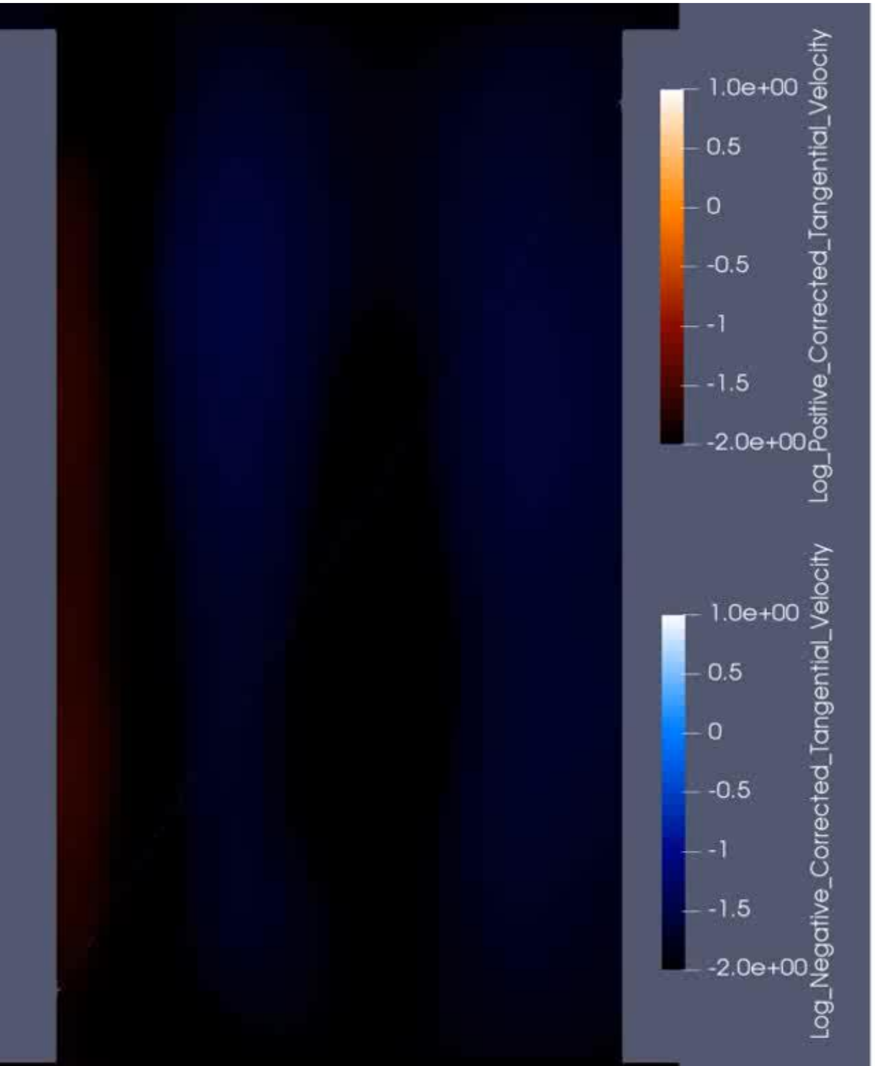
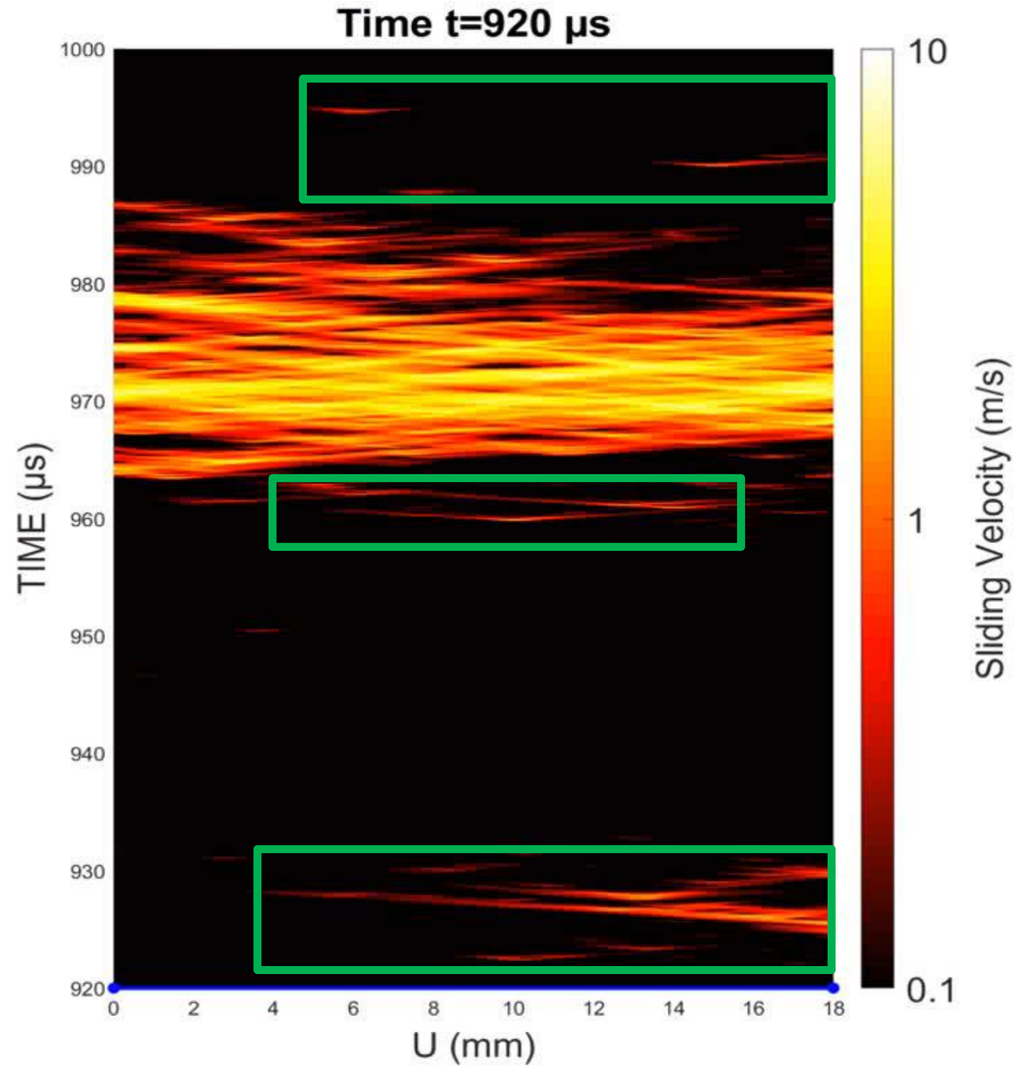


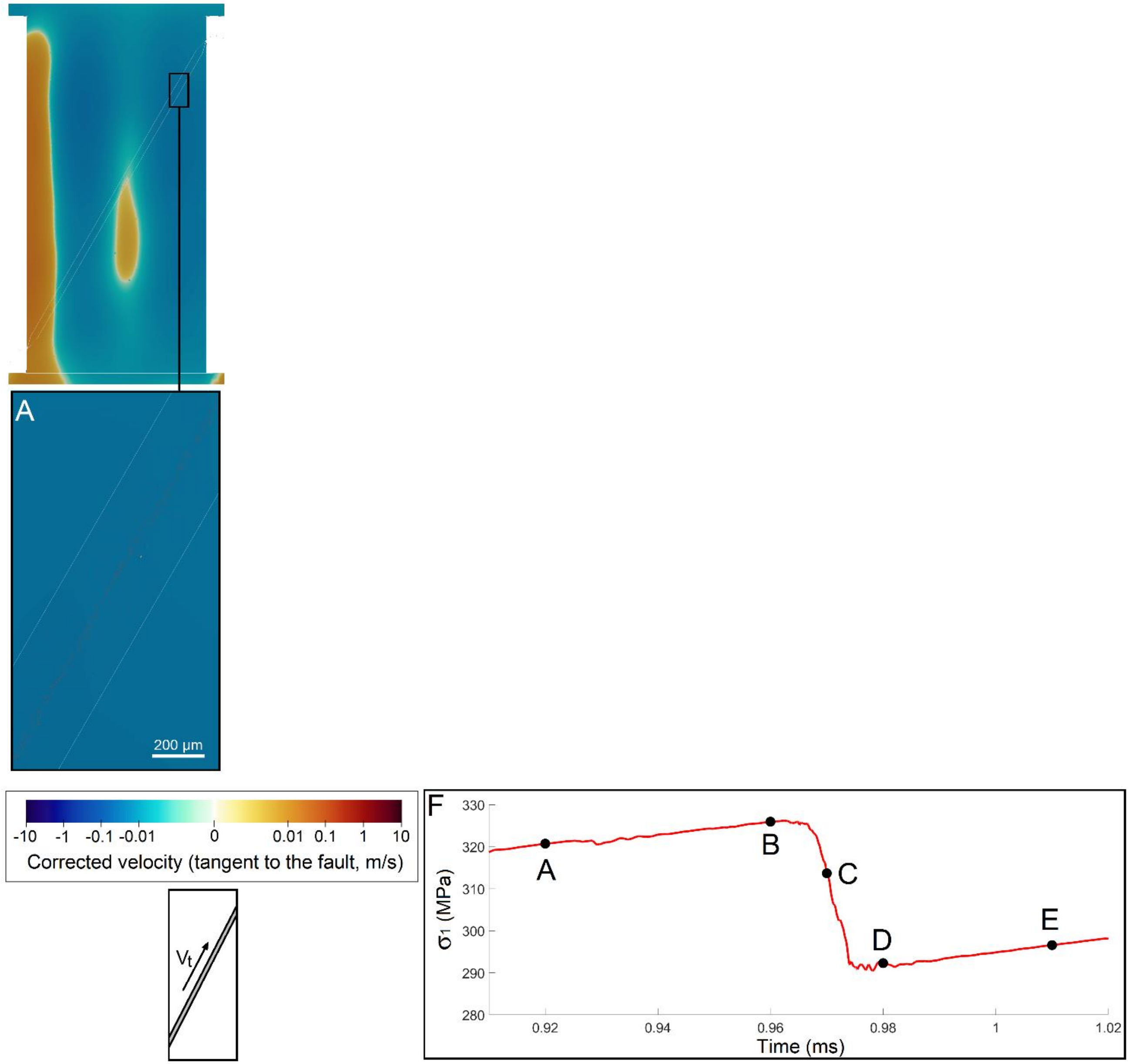


Velocity history

-50 µs before mainshock

-> Coupled fault

-> Residual elastic waves



Velocity history

-50 µs before mainshock

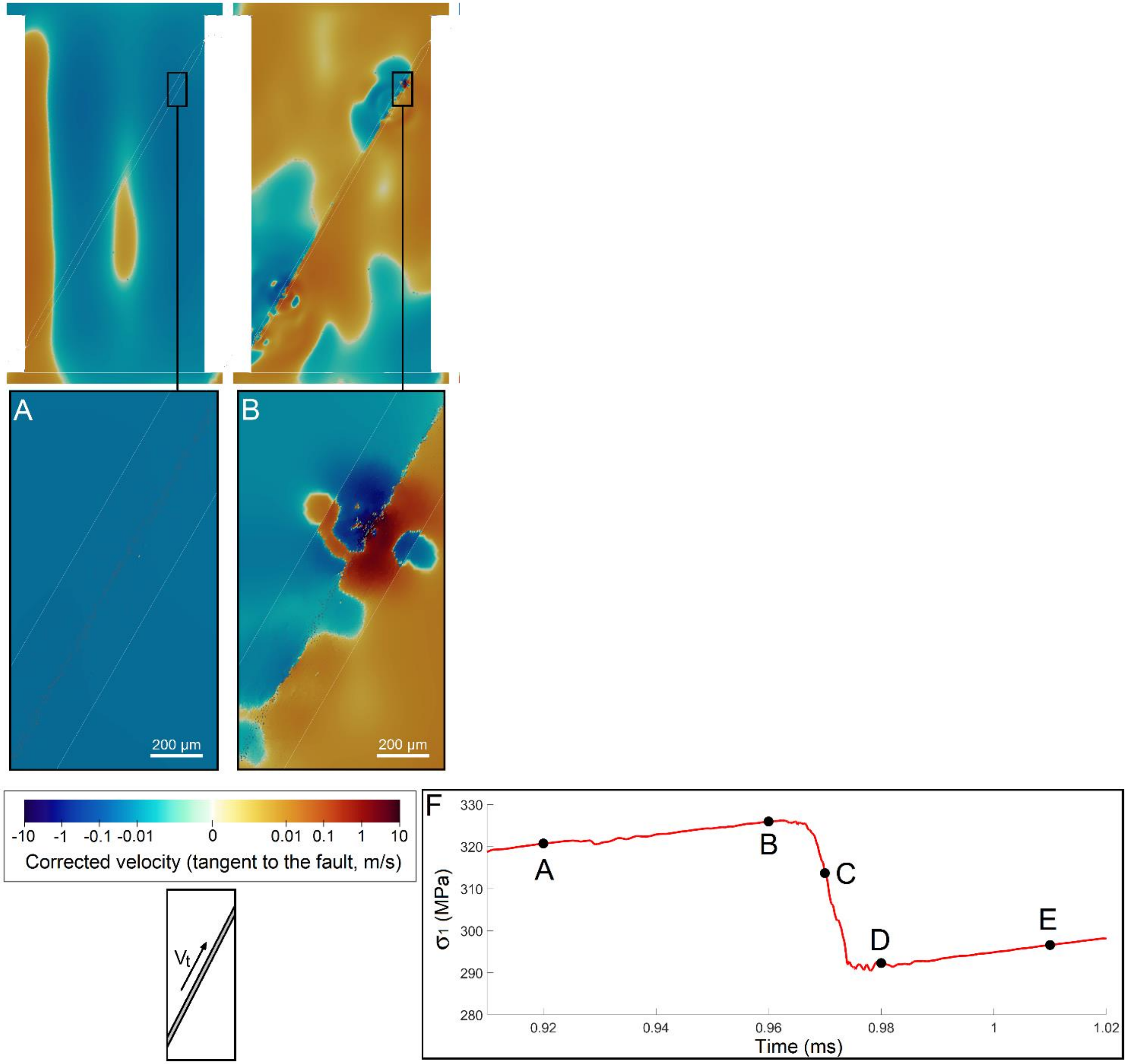
-> Coupled fault

-> Residual elastic waves

-3 µs before mainshock

-> Local uncoupling

-> Foreshocks?



Velocity history

-50 µs before mainshock

-> Coupled fault

-> Residual elastic waves

-3 µs before mainshock

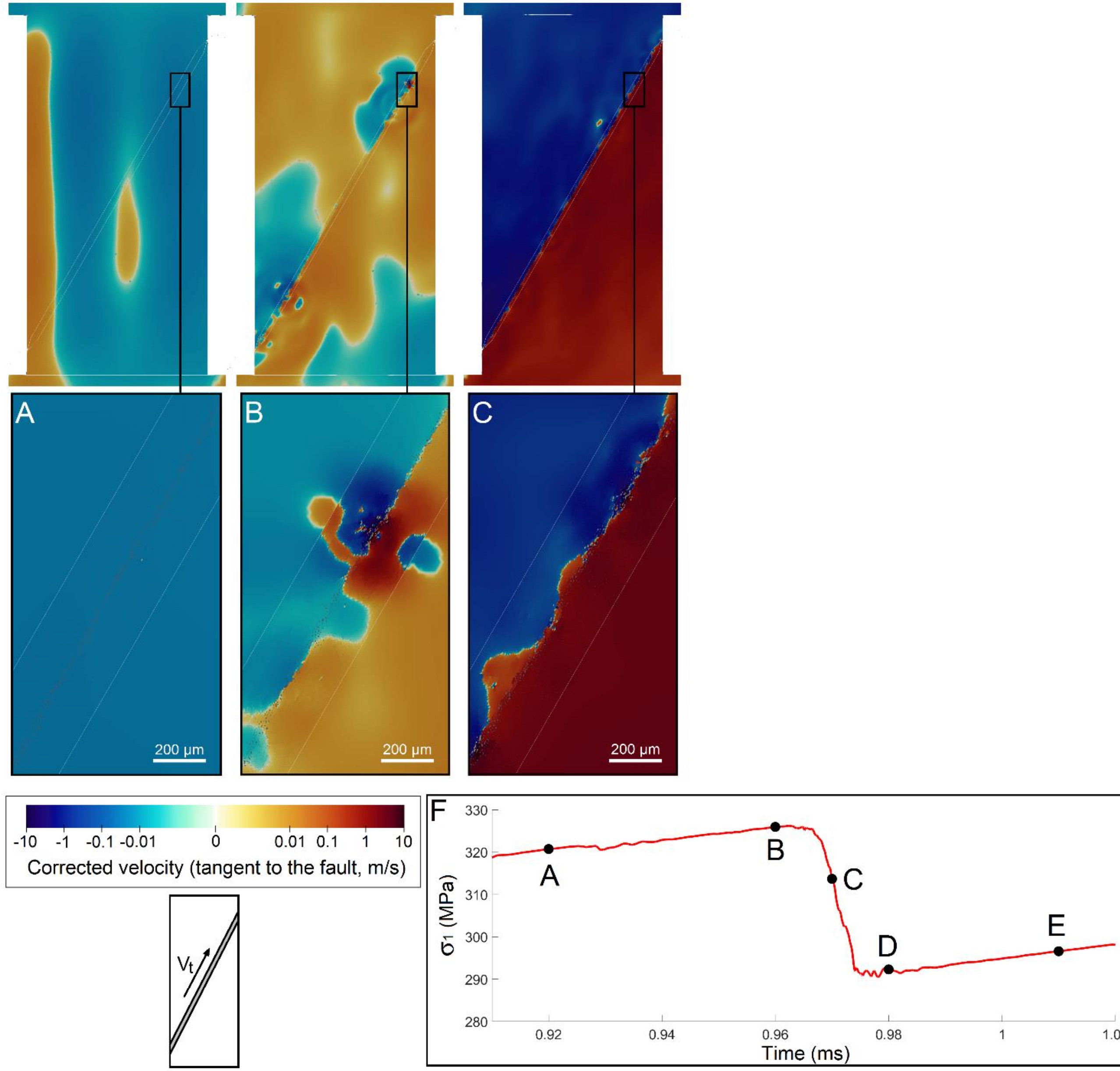
-> Local uncoupling

-> Foreshocks?

-Mainshock

-> Complete fast slip

-> Localized in gouge



Velocity history

-50 µs before mainshock

-> Coupled fault

-> Residual elastic waves

-3 µs before mainshock

-> Local uncoupling

-> Foreshocks?

-Mainshock

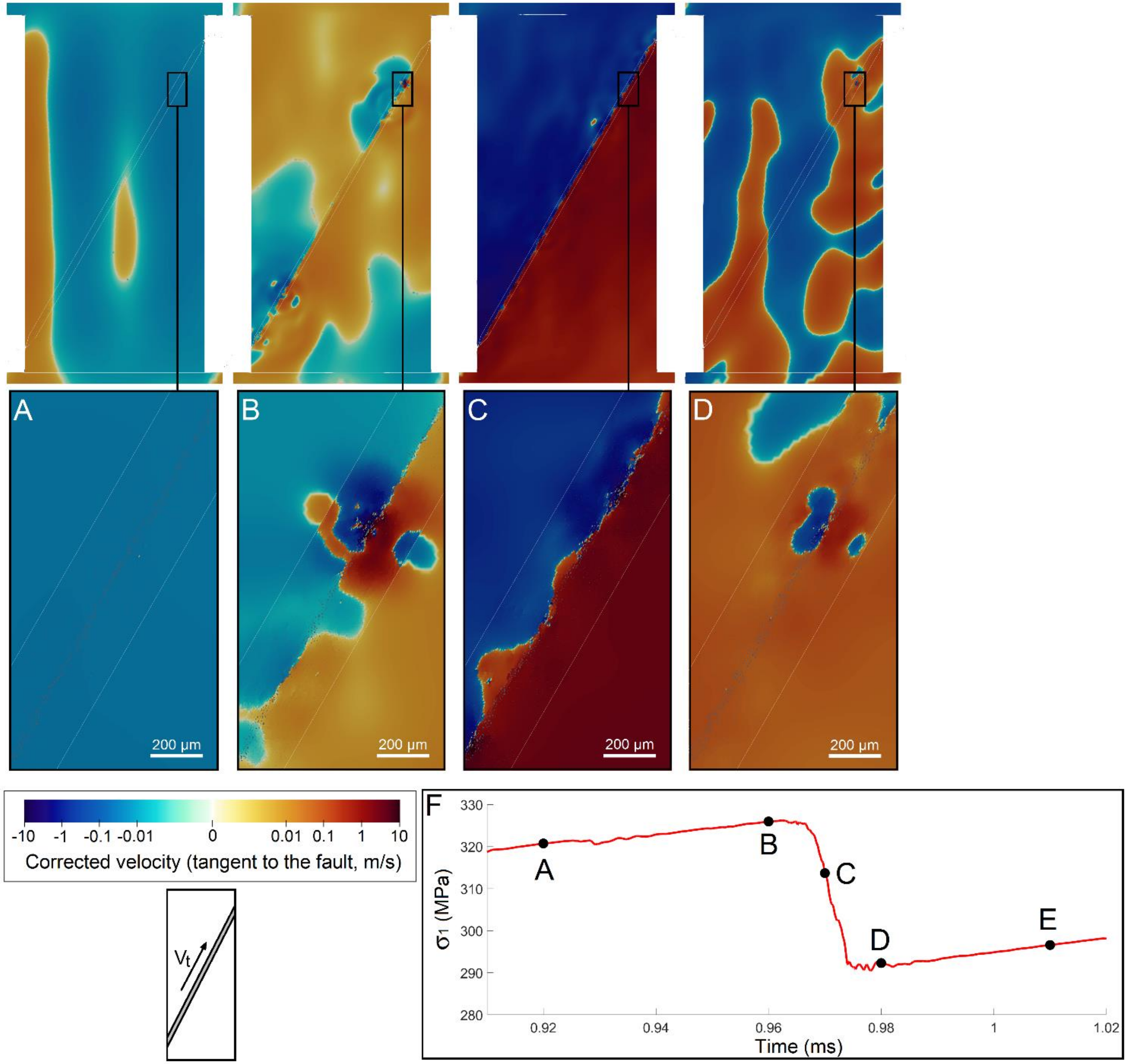
-> Complete fast slip

-> Localized in gouge

-4 µs after mainshock

-> Partially recoupled fault

-> Aftershocks



Velocity history

-50 µs before mainshock

-> Coupled fault

-> Residual elastic waves

-3 µs before mainshock

-> Local uncoupling

-> Foreshocks?

-Mainshock

-> Complete fast slip

-> Localized in gouge

-4 µs after mainshock

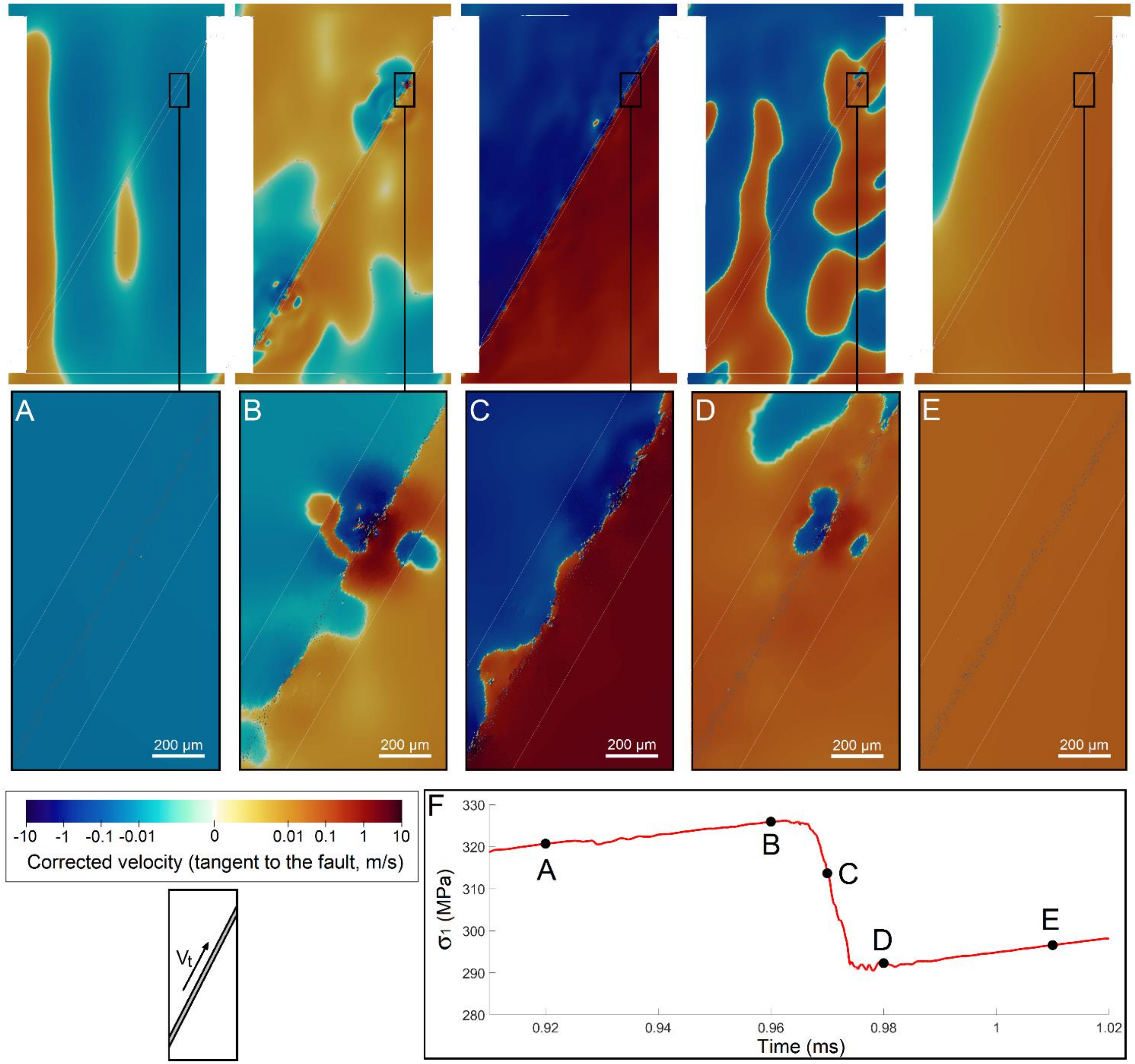
-> Partially recoupled fault

-> Aftershocks

-40 µs after mainshock

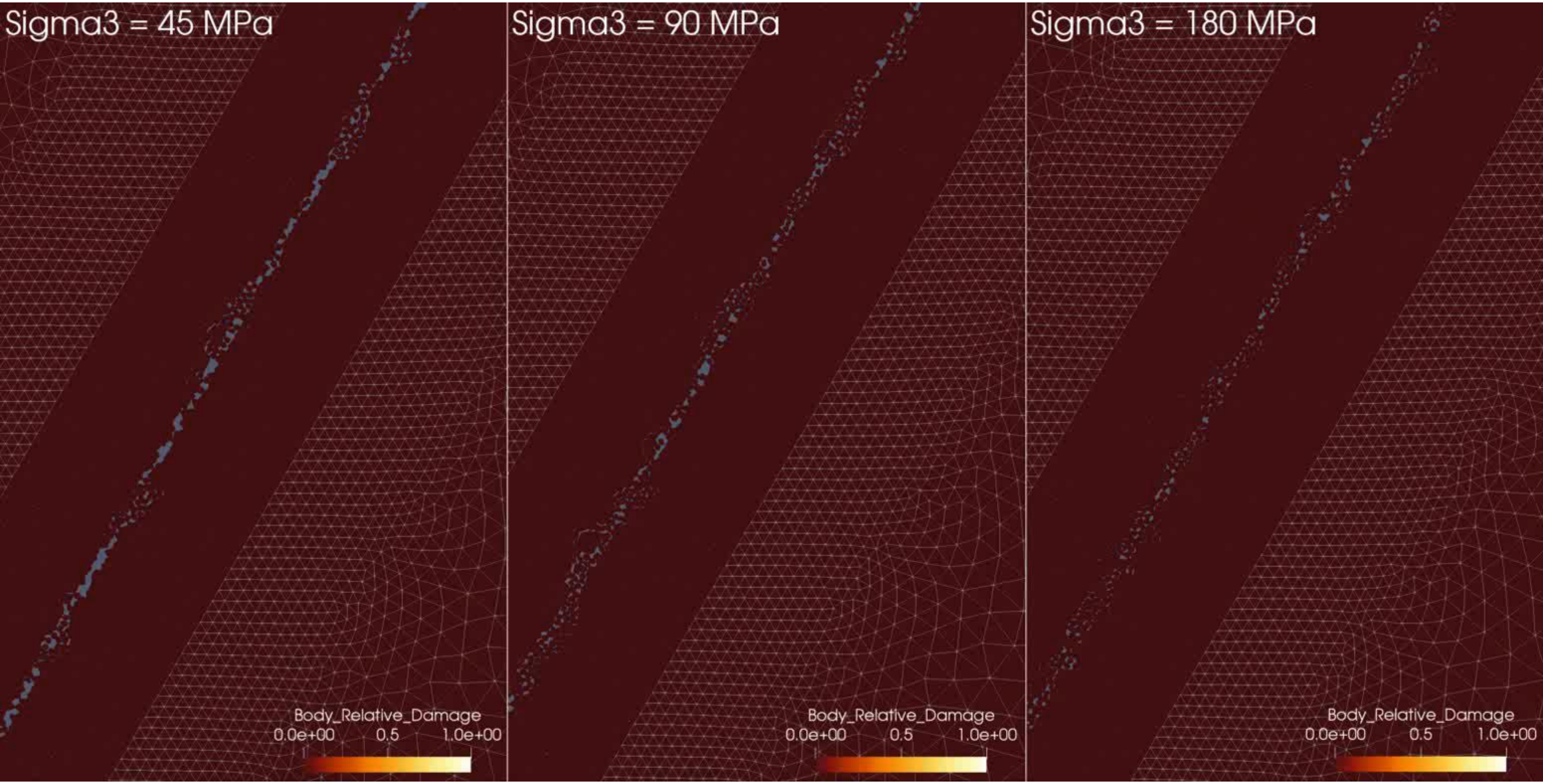
-> Recoupled fault

-> Residual elastic waves

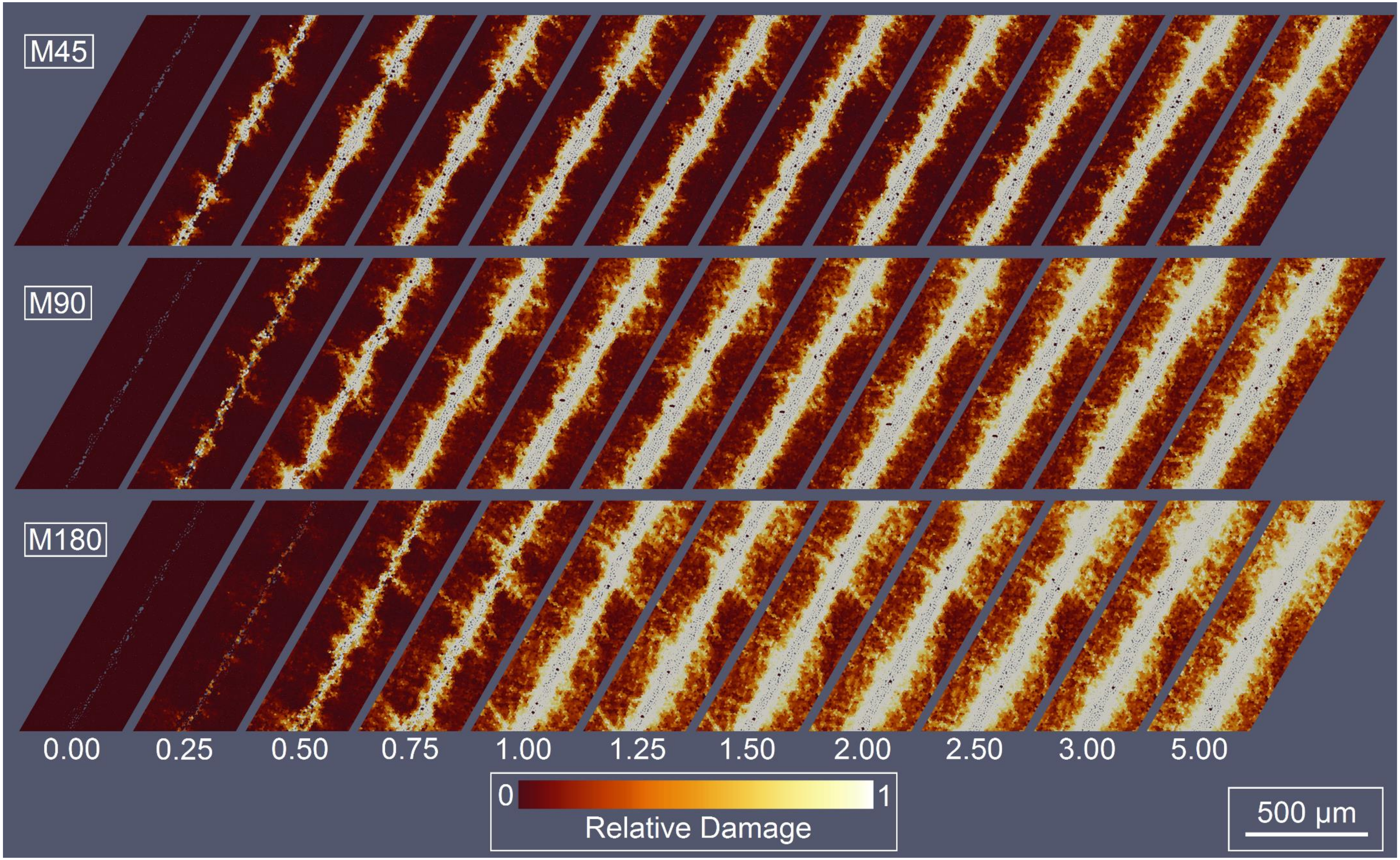


Damage and gouge production

Progressive development of a damage front and of an accommodating gouge layer

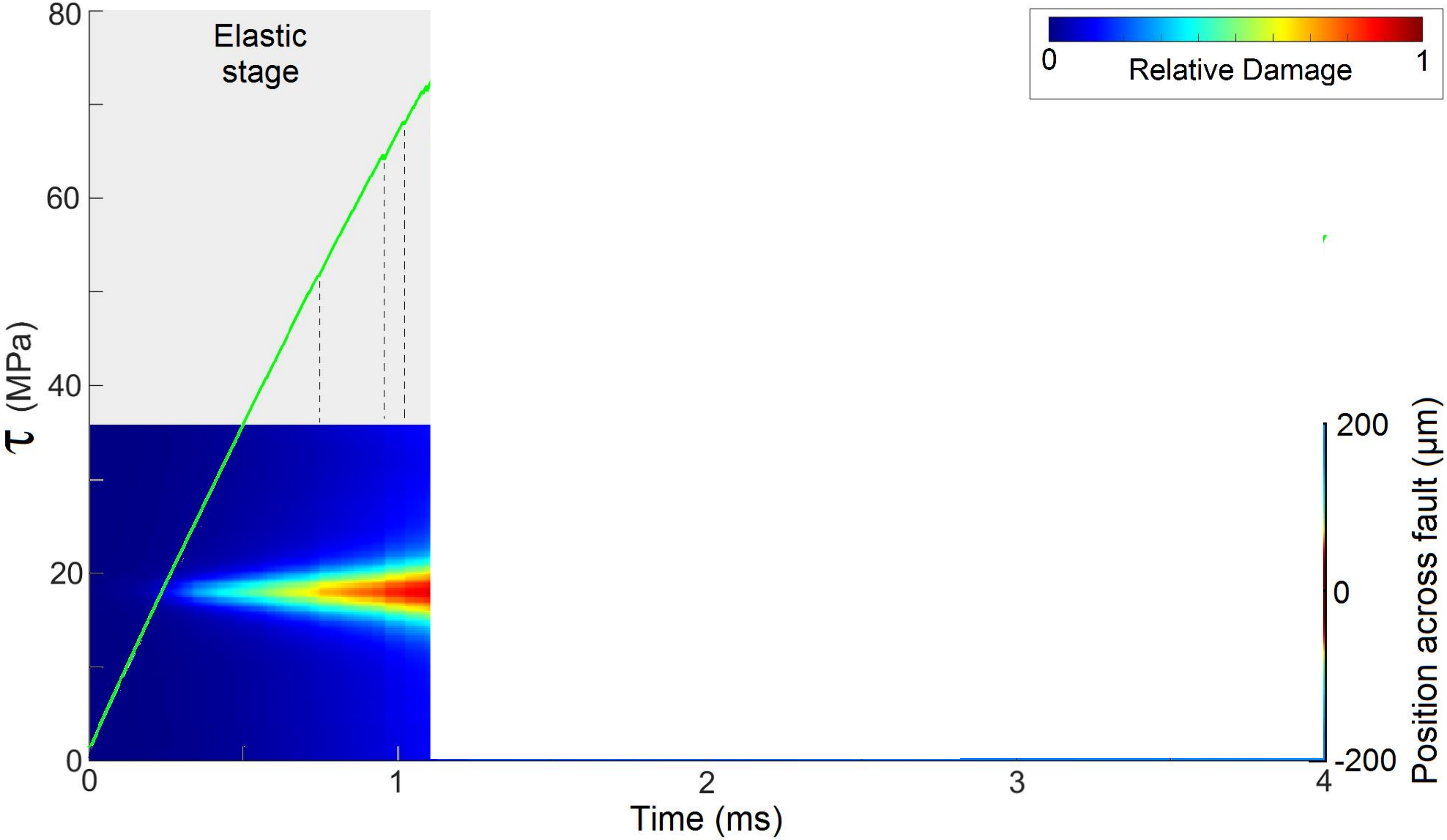


Damage and gouge production



Damage and gouge production

Sliding events and damage progress are first concomitant, but uncouple after a certain sliding distance



Damage and gouge production

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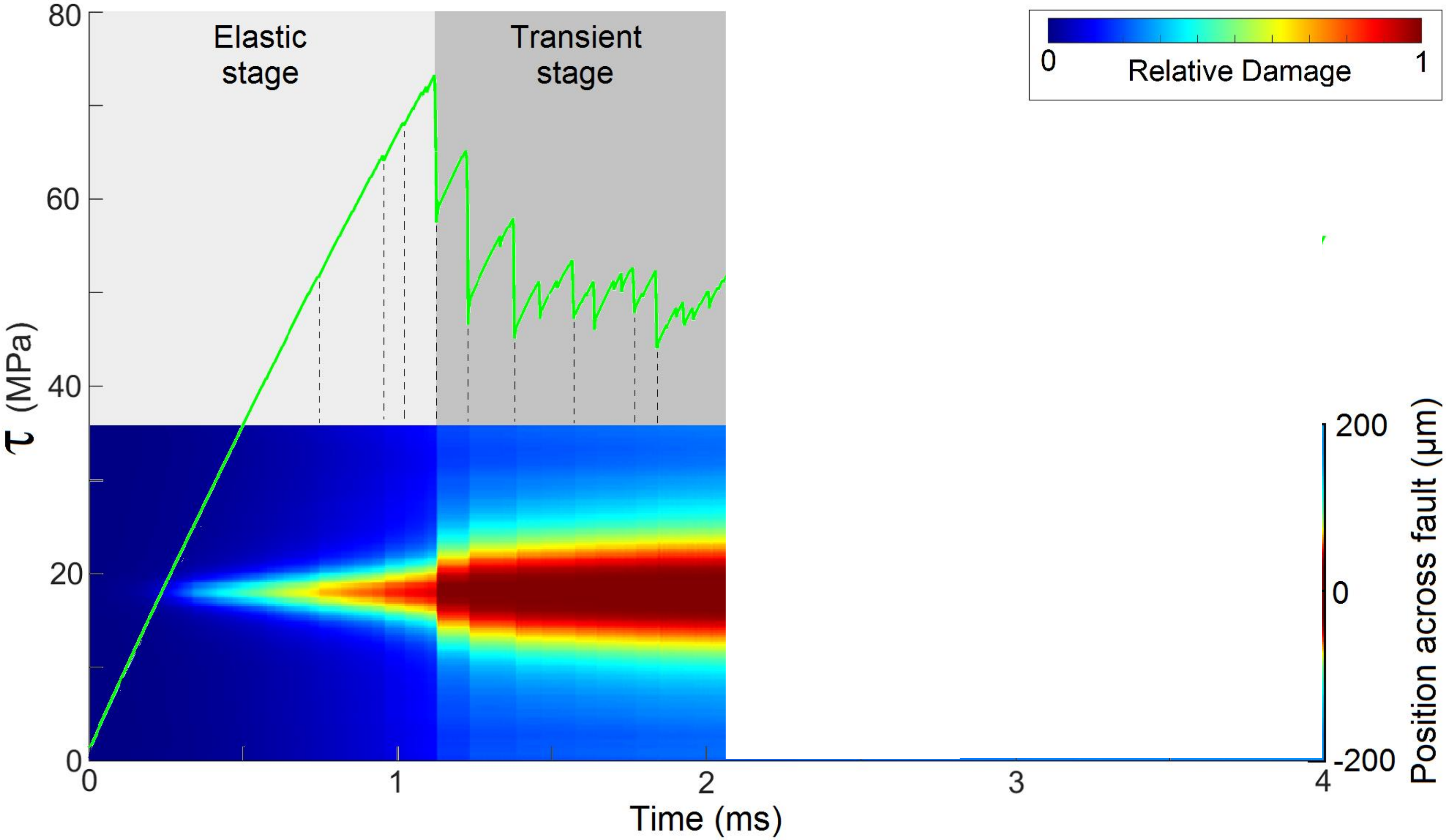

Damage and gouge production

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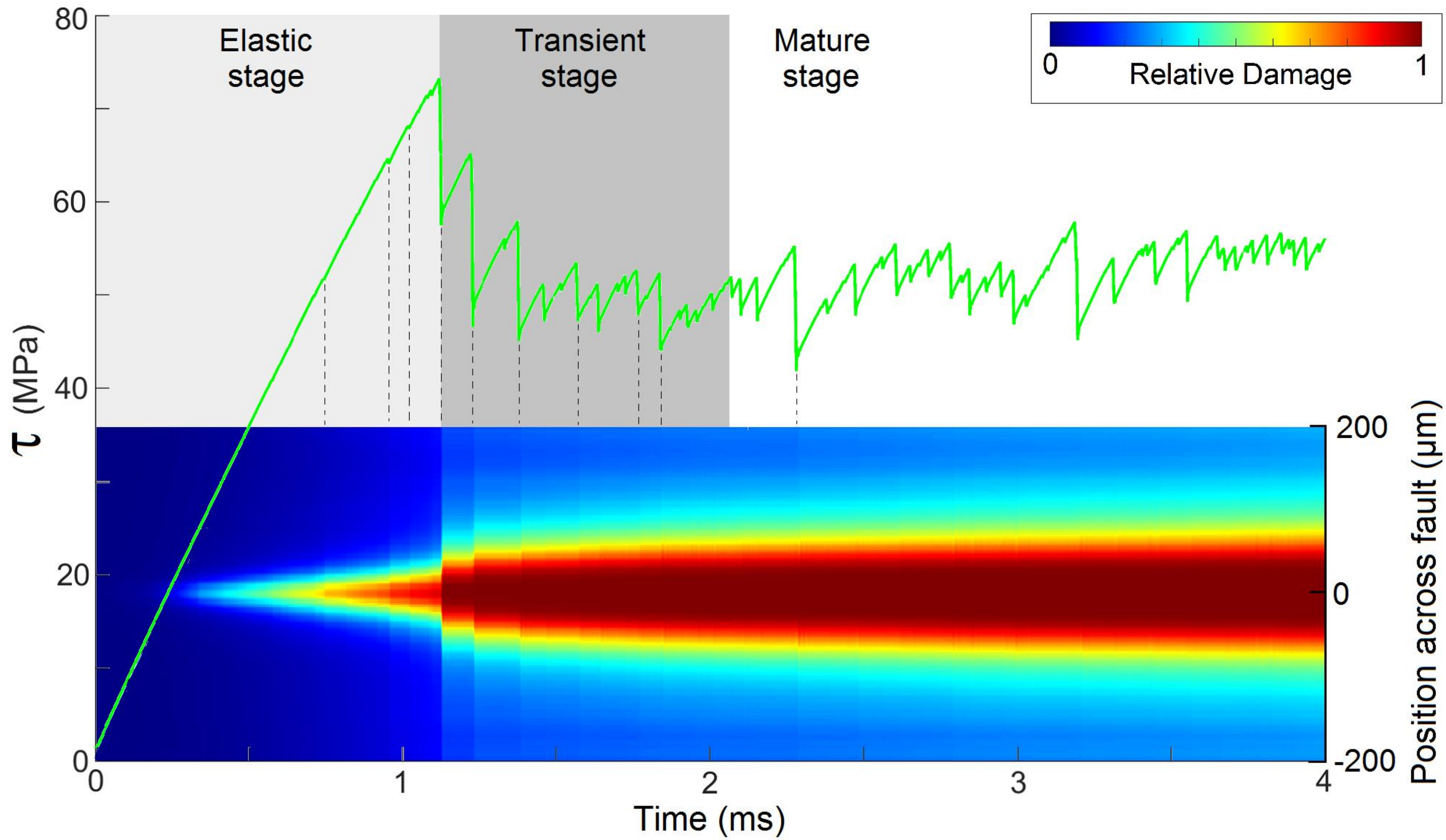
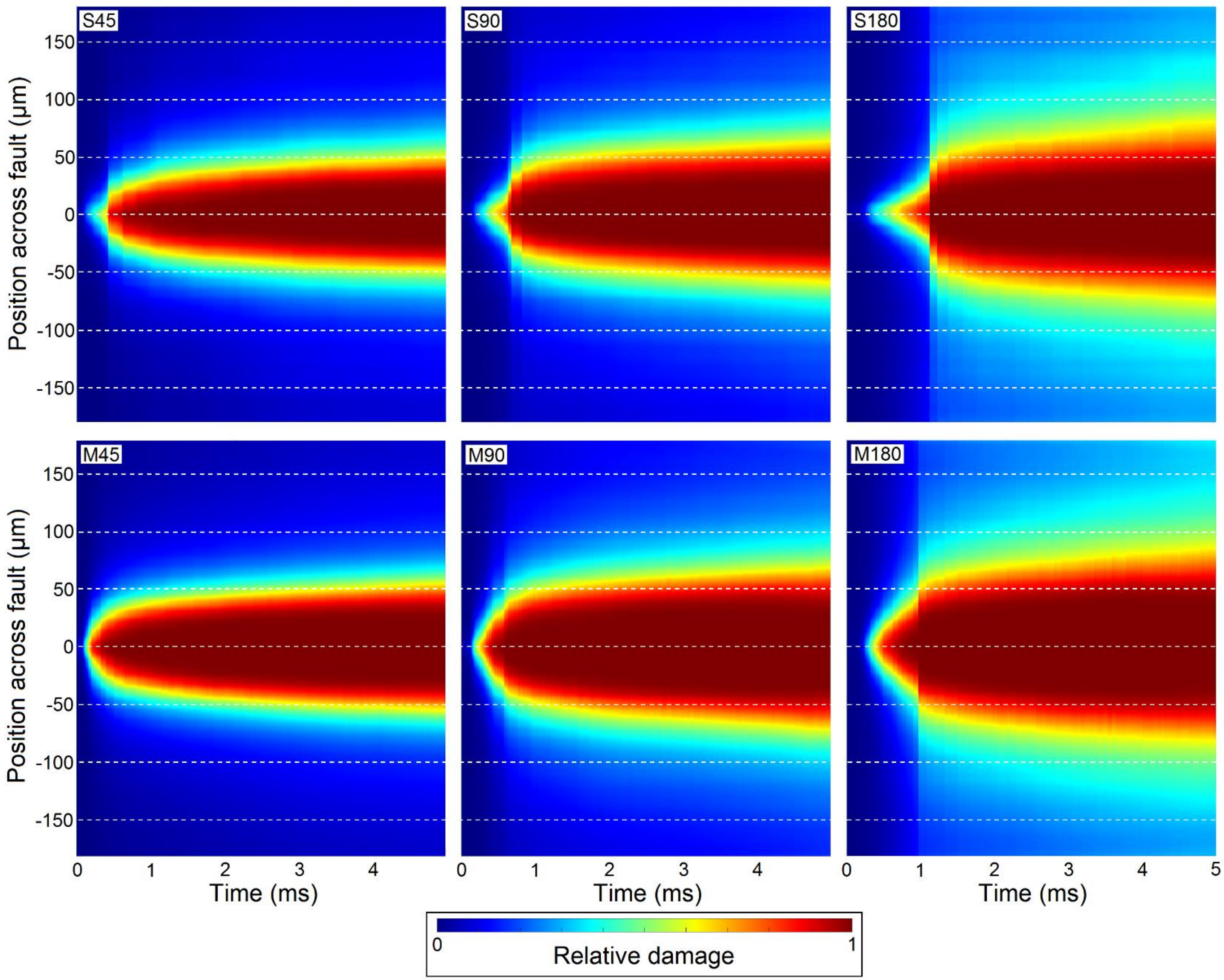
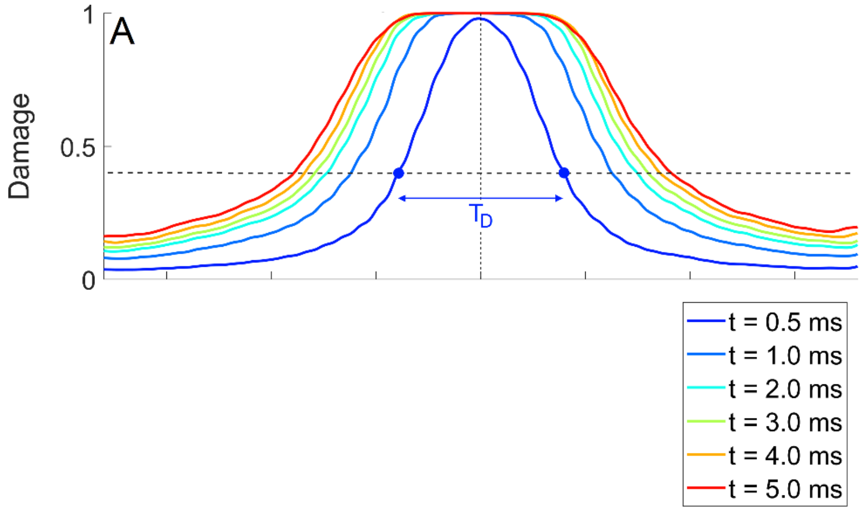


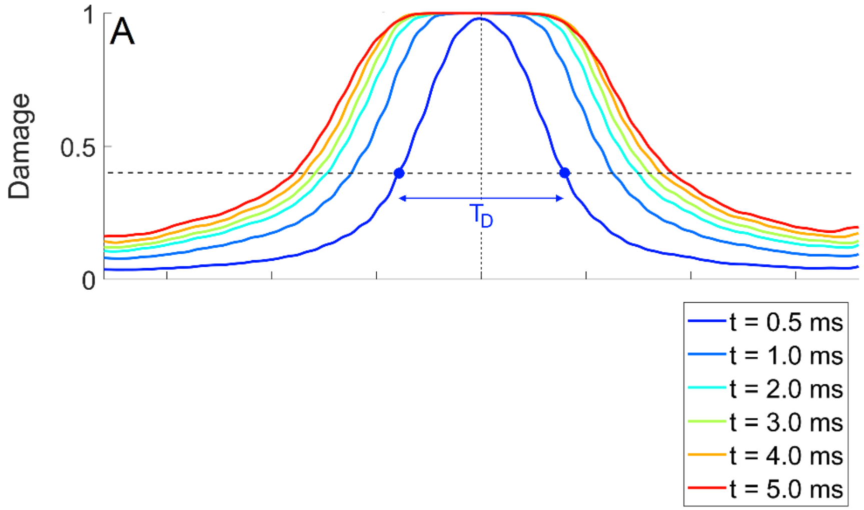
Damage and gouge production

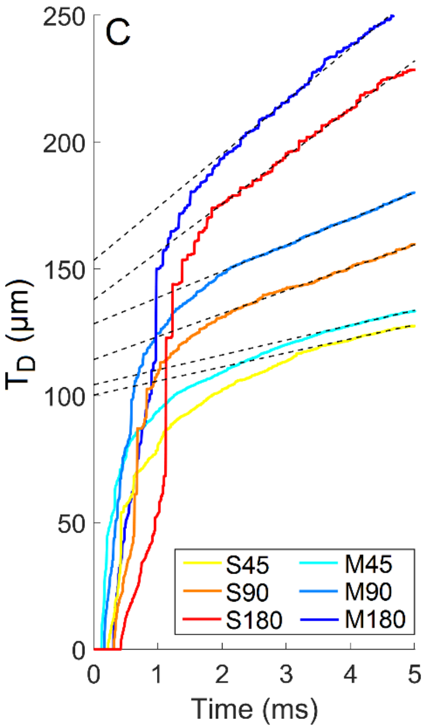


Damage and gouge production

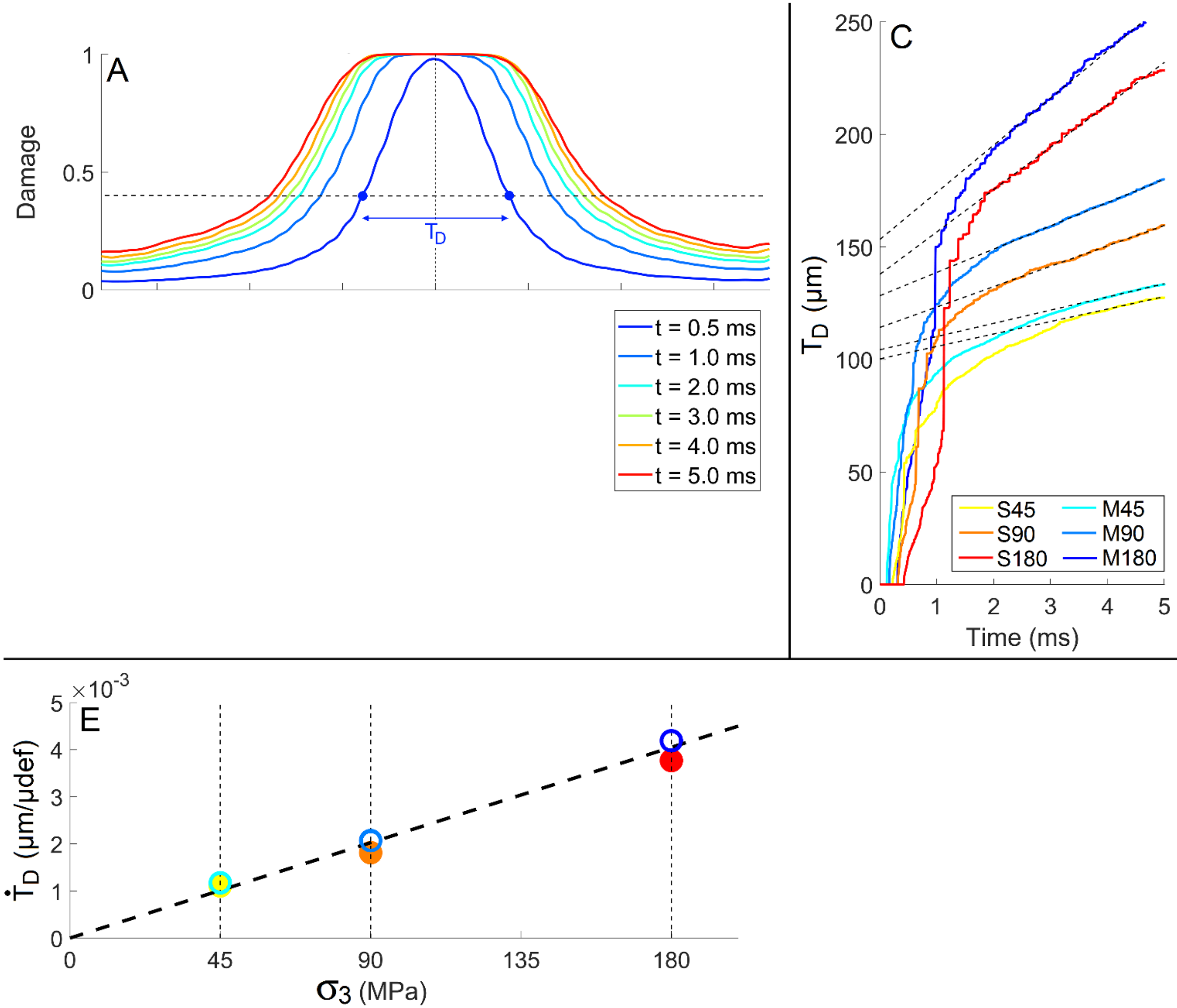


Damage and gouge production

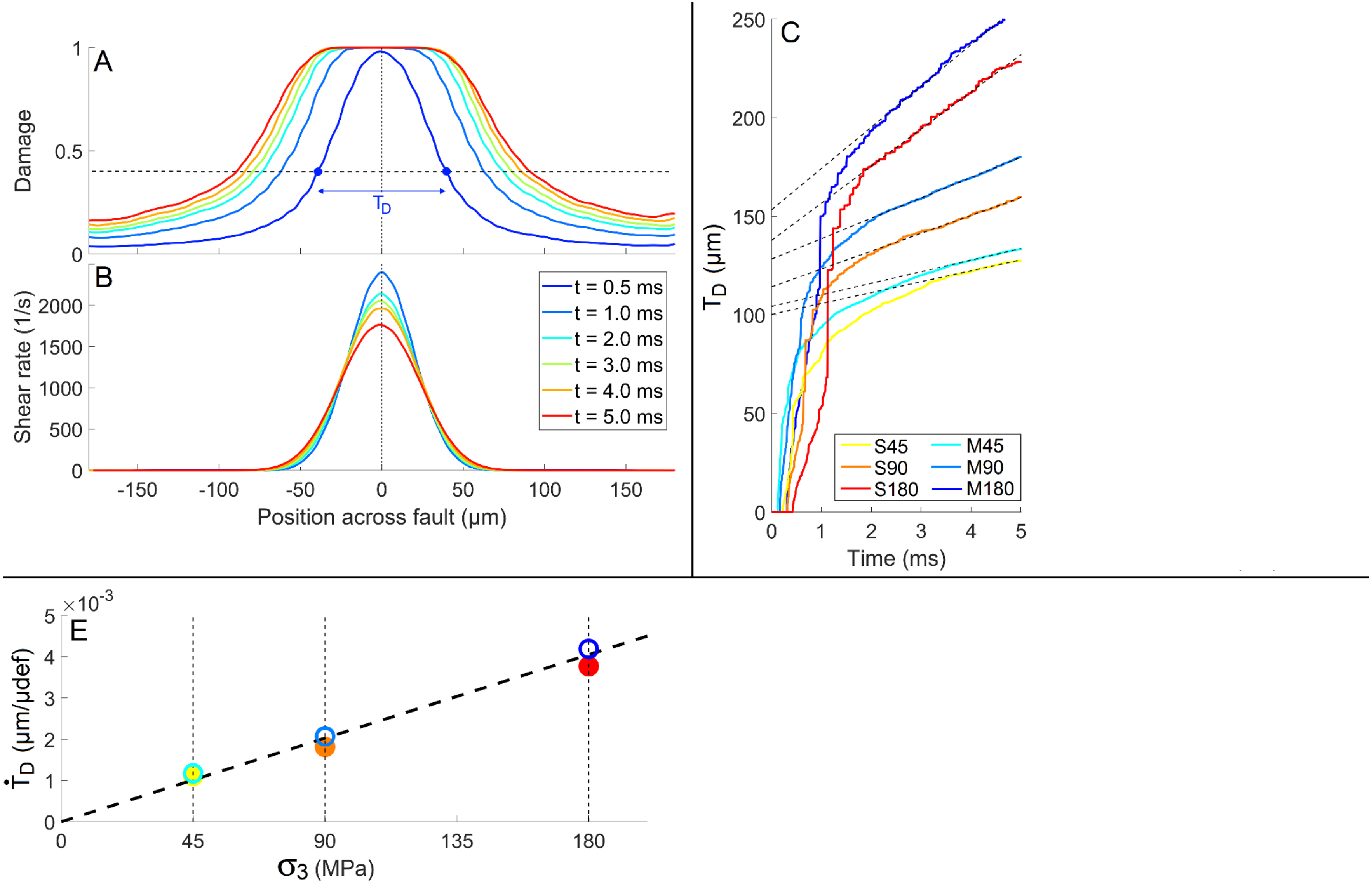




Damage and gouge production



Damage and gouge production



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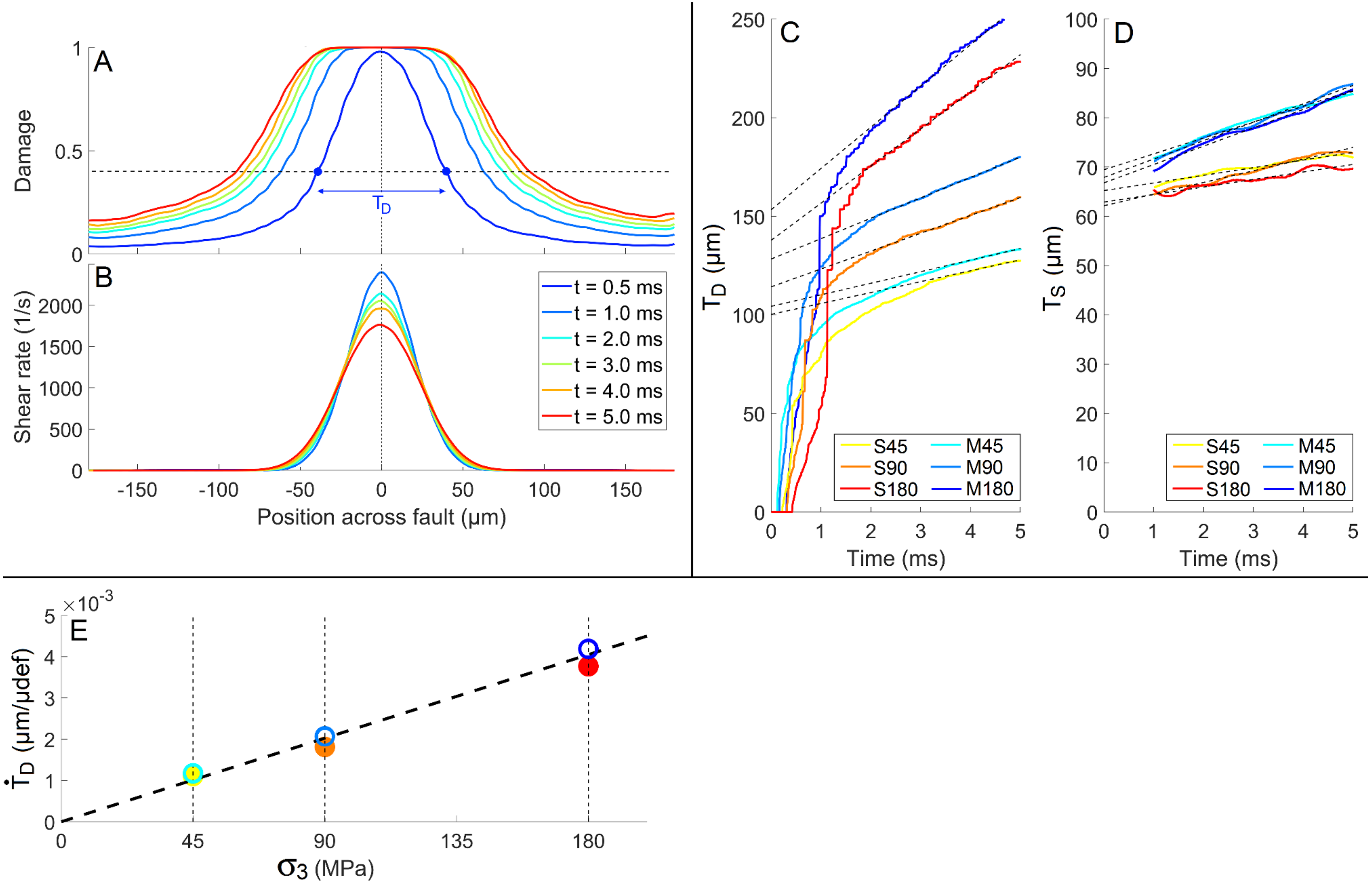
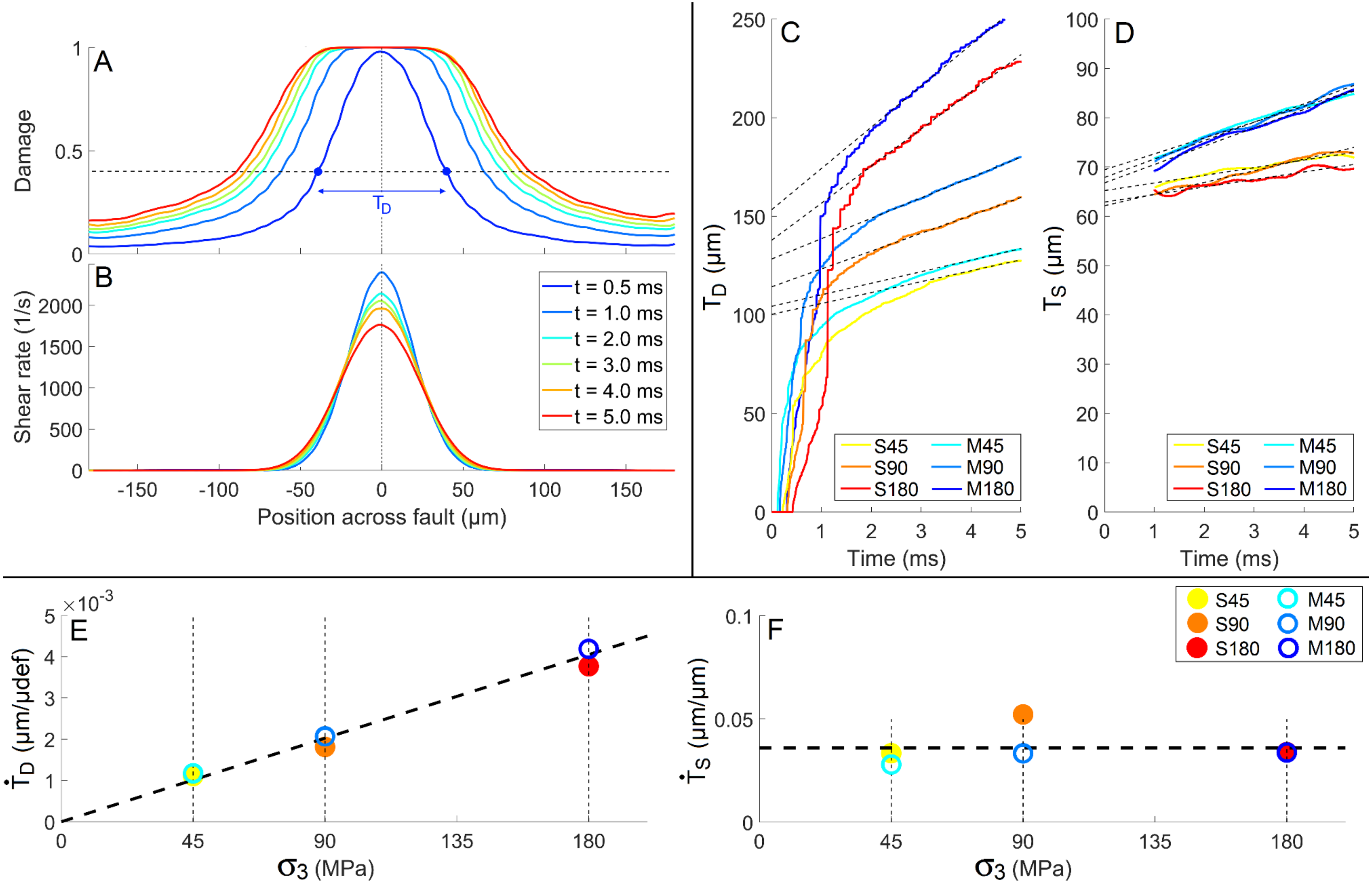
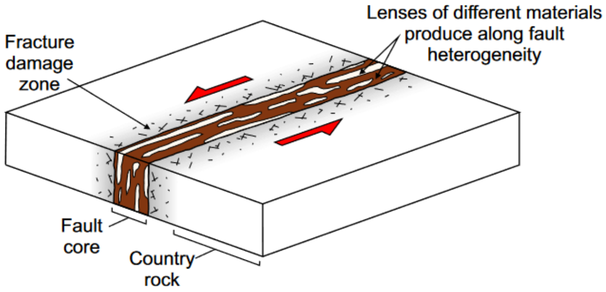
Damage and gouge production

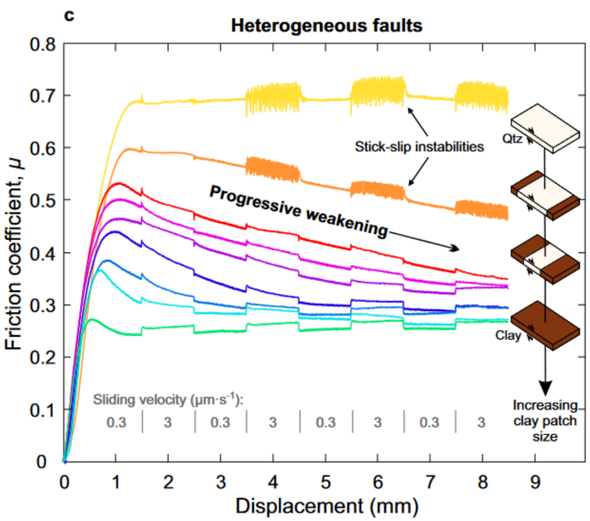


Damage and gouge production



Fault complexity: a hot topic



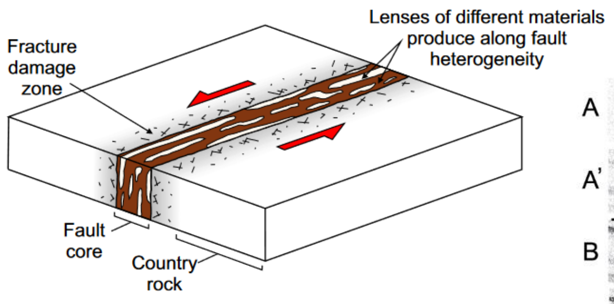


Bedford et al. 2022

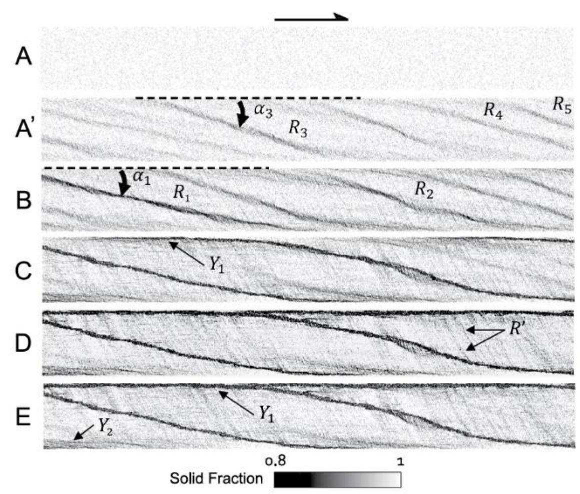
The average frictional strength of a heterogeneous fault is not just an average of the respective frictional properties of each site.

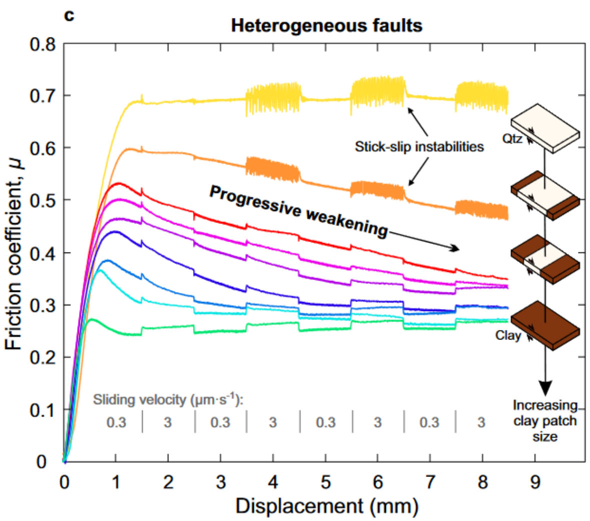
Bedford JD, Faulkner DR, Lapusta N (2022), Fault rock heterogeneity can produce fault weakness and reduce fault stability, Nature Comm., 13:326.

Fault complexity: a hot topic



Casas et al. 2023



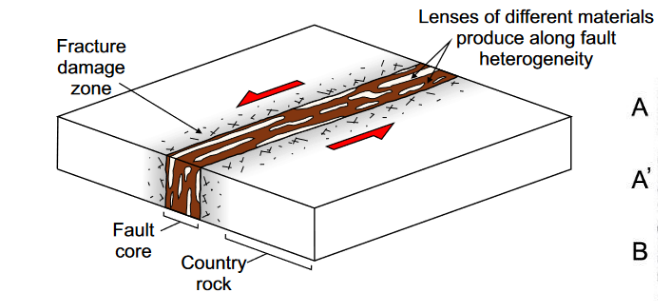


Bedford et al. 2022

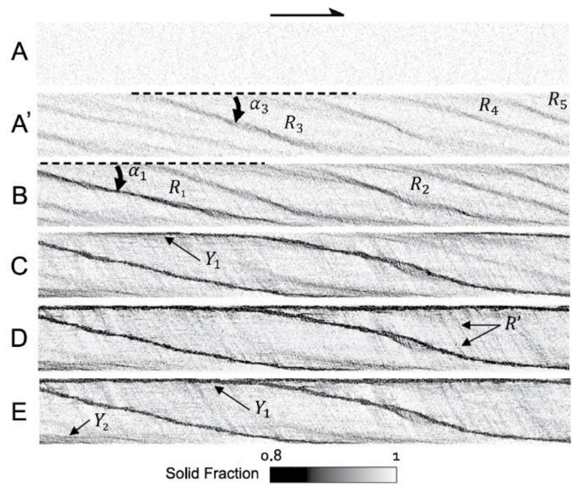
Complexity arises spontaneously from a homogeneous gouge layer because of shear localization patterns.

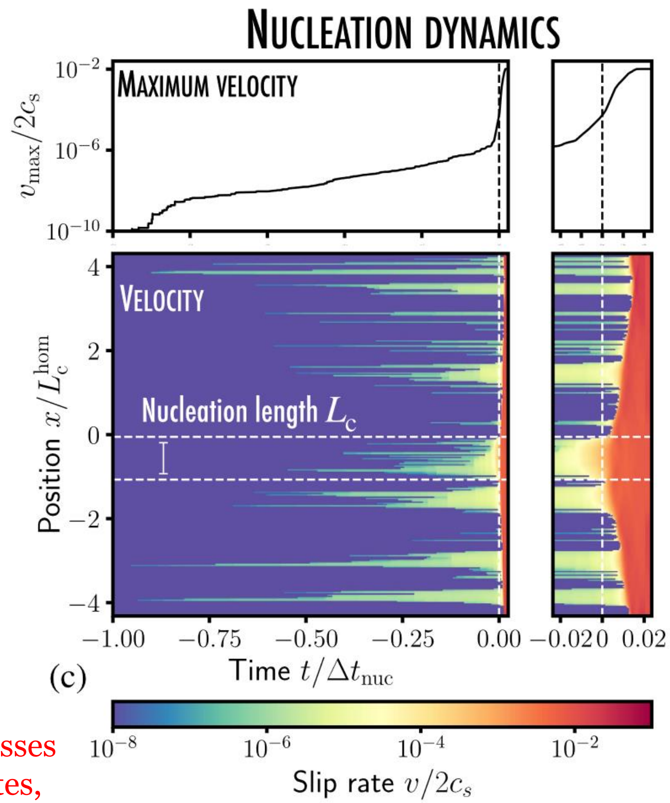
Casas N, Mollon G, Daouadji A (2023), Influence of grain-scale properties on localization patterns and slip weakening within dense granular fault gouge, JGR: Solid Earth., 128, e2022JB025666

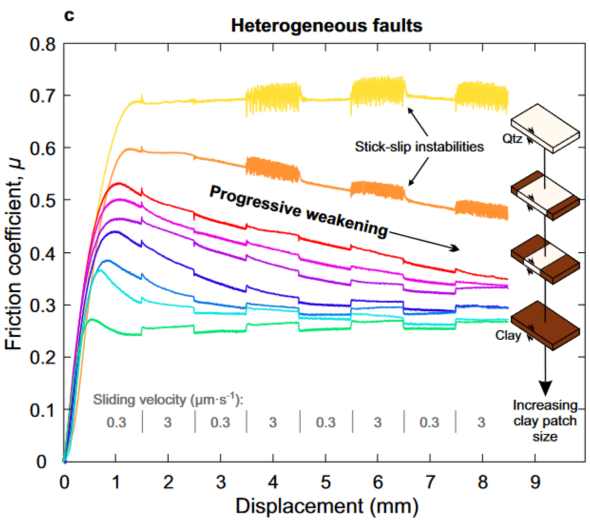
Fault complexity: a hot topic



Casas et al. 2023







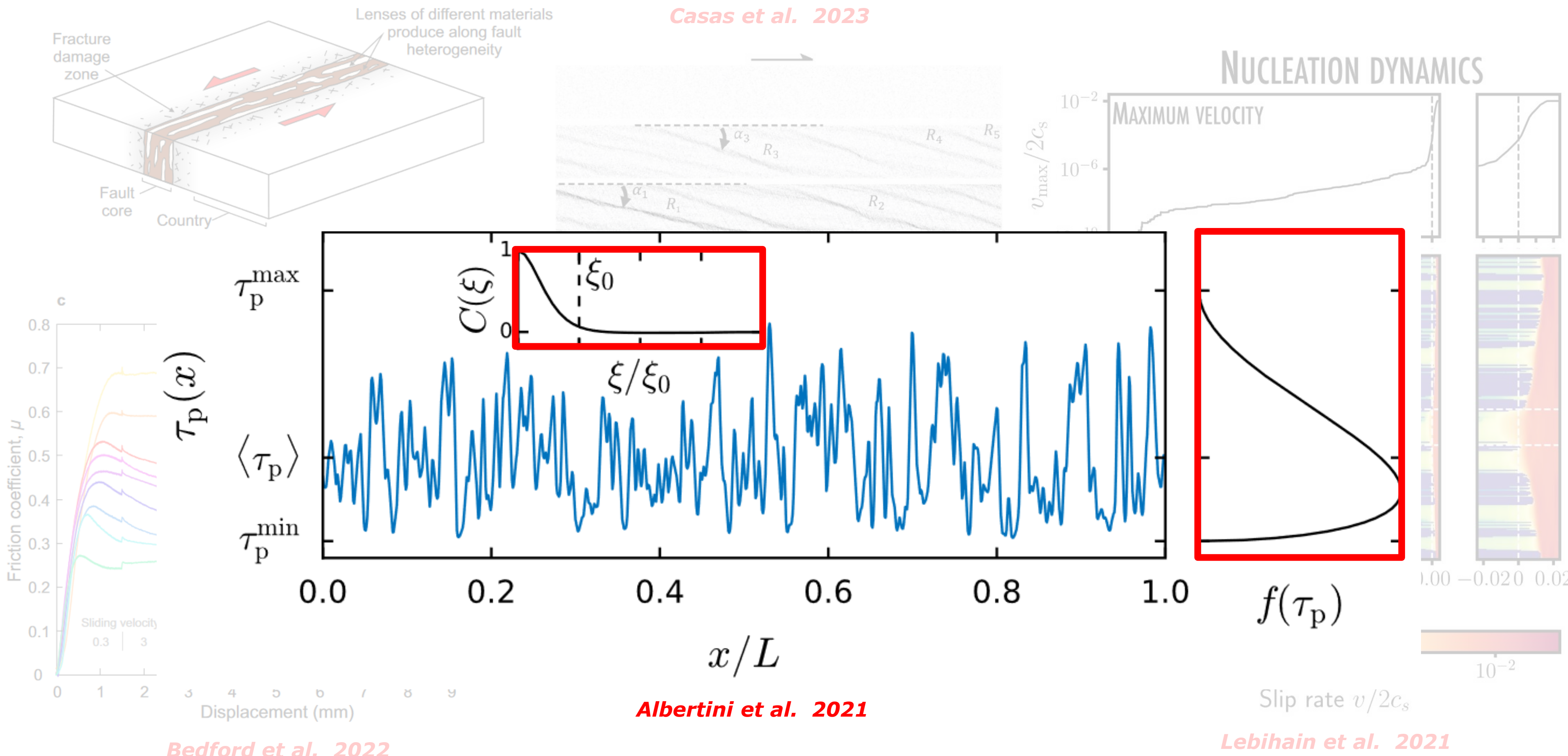
Bedford et al. 2022

Complex nucleation processes at multiple concurrent sites, interplay between nucleation length and fluctuation length.

Lebihain et al. 2021

Lebihain M, Roch T, Violay M, Molinari JF (2021), Earthquake nucleation along faults with heterogeneous weakening rate, Geophys. Res. Lett., 48(21)

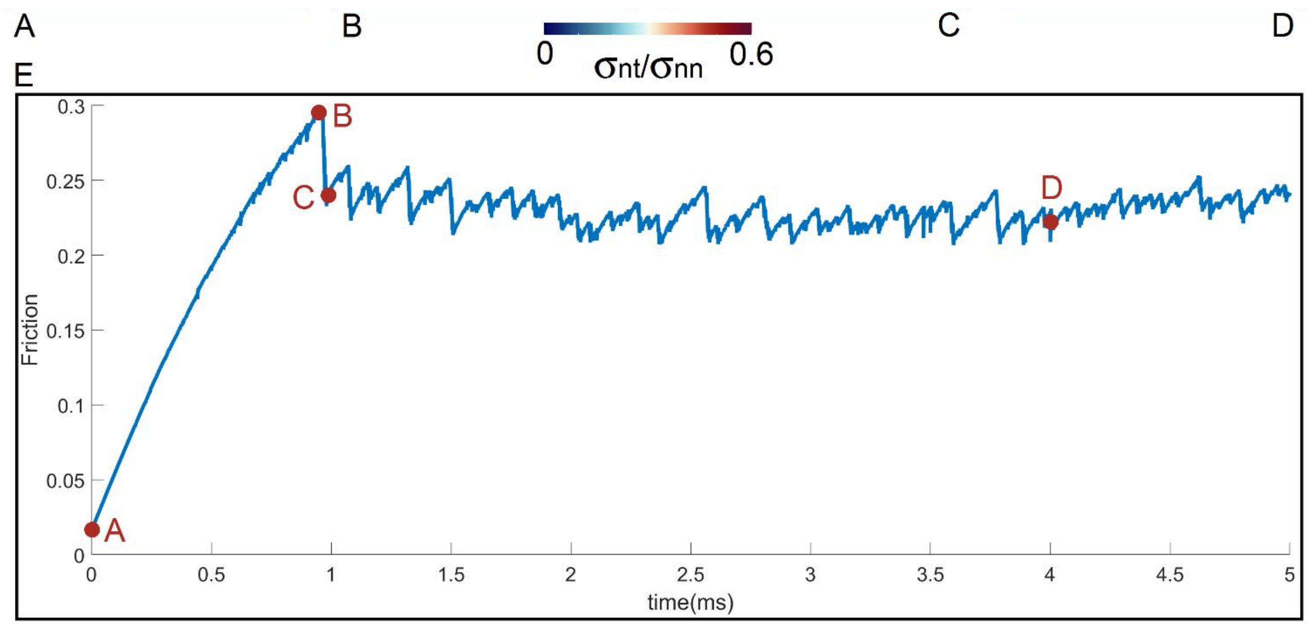
Fault complexity: a hot topic



We need more understanding on the origins and the statistical properties of fault heterogeneity.

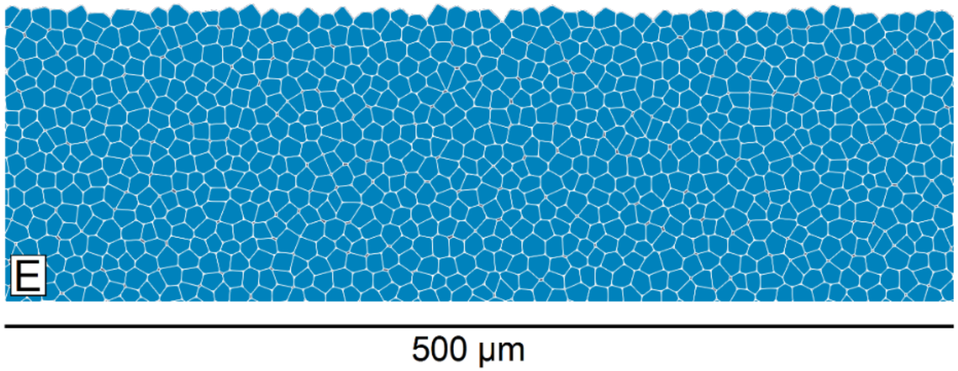
Albertini G, Karrer S, Grigoriu MD, Kammer DS (2021), Stochastic properties of static friction, J. Mech. Phys. Solids, 147, 104242

Stress heterogeneities



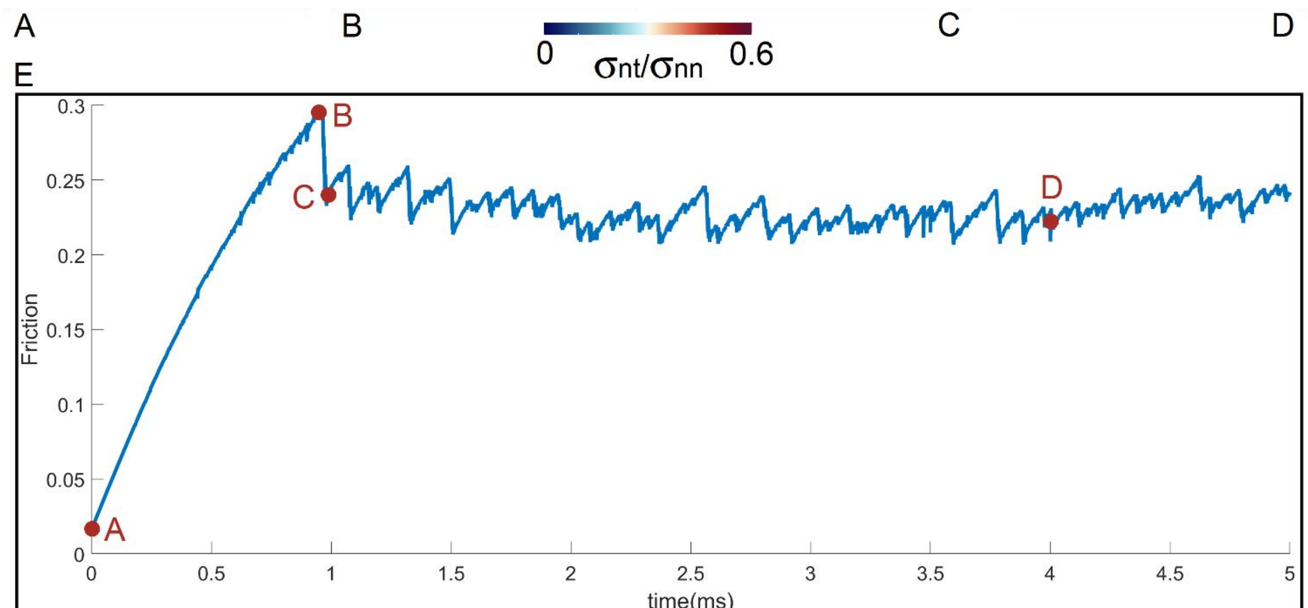
Spontaneous appearance of stick-slip patterns without *ad-hoc* weakening law.

Stress heterogeneities



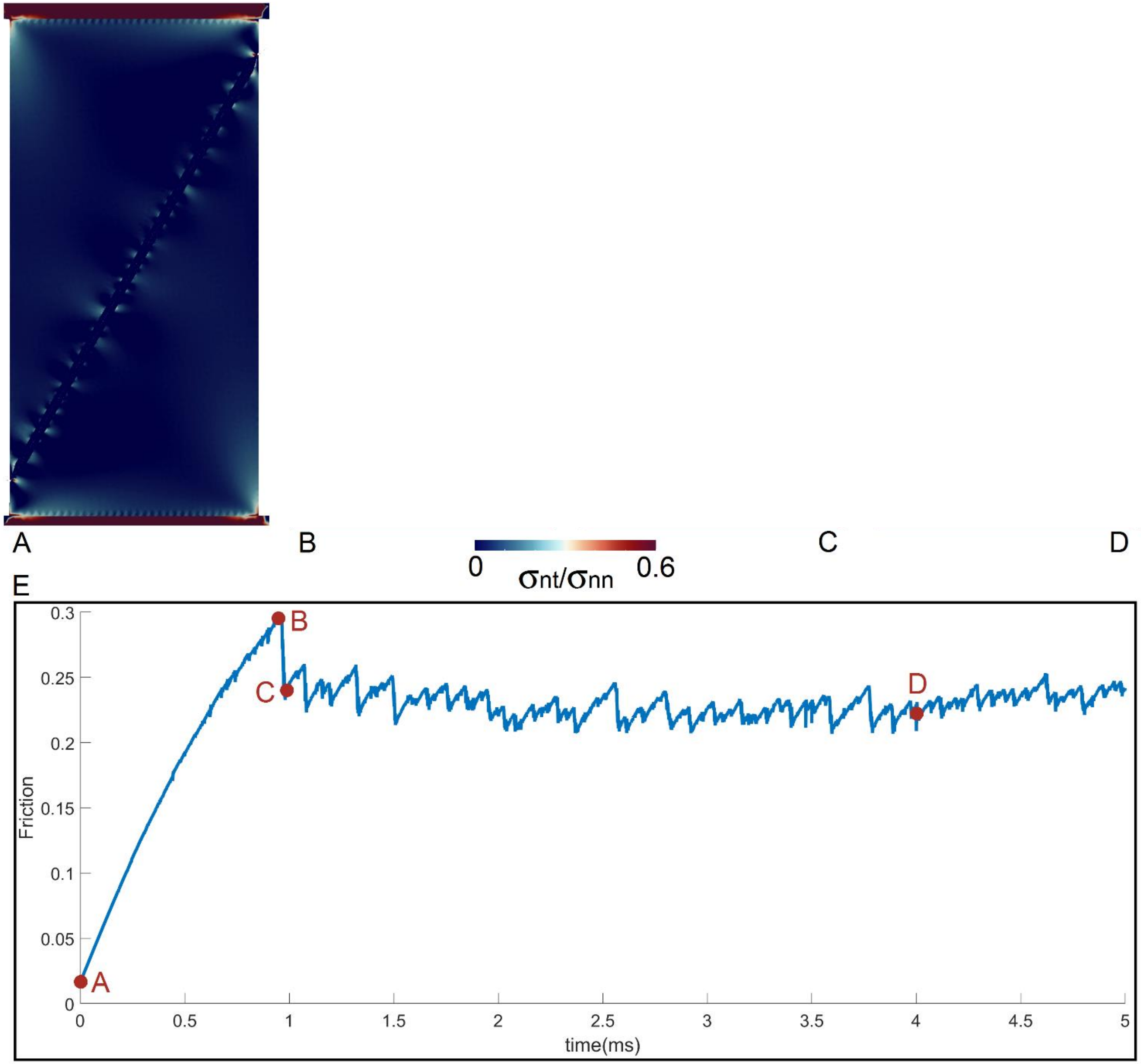
Nominally flat initial surfaces and homogeneous microstructure.

Spontaneous appearance of stick-slip patterns without *ad-hoc* weakening law.



Stress heterogeneities

-Homogeneous initial state

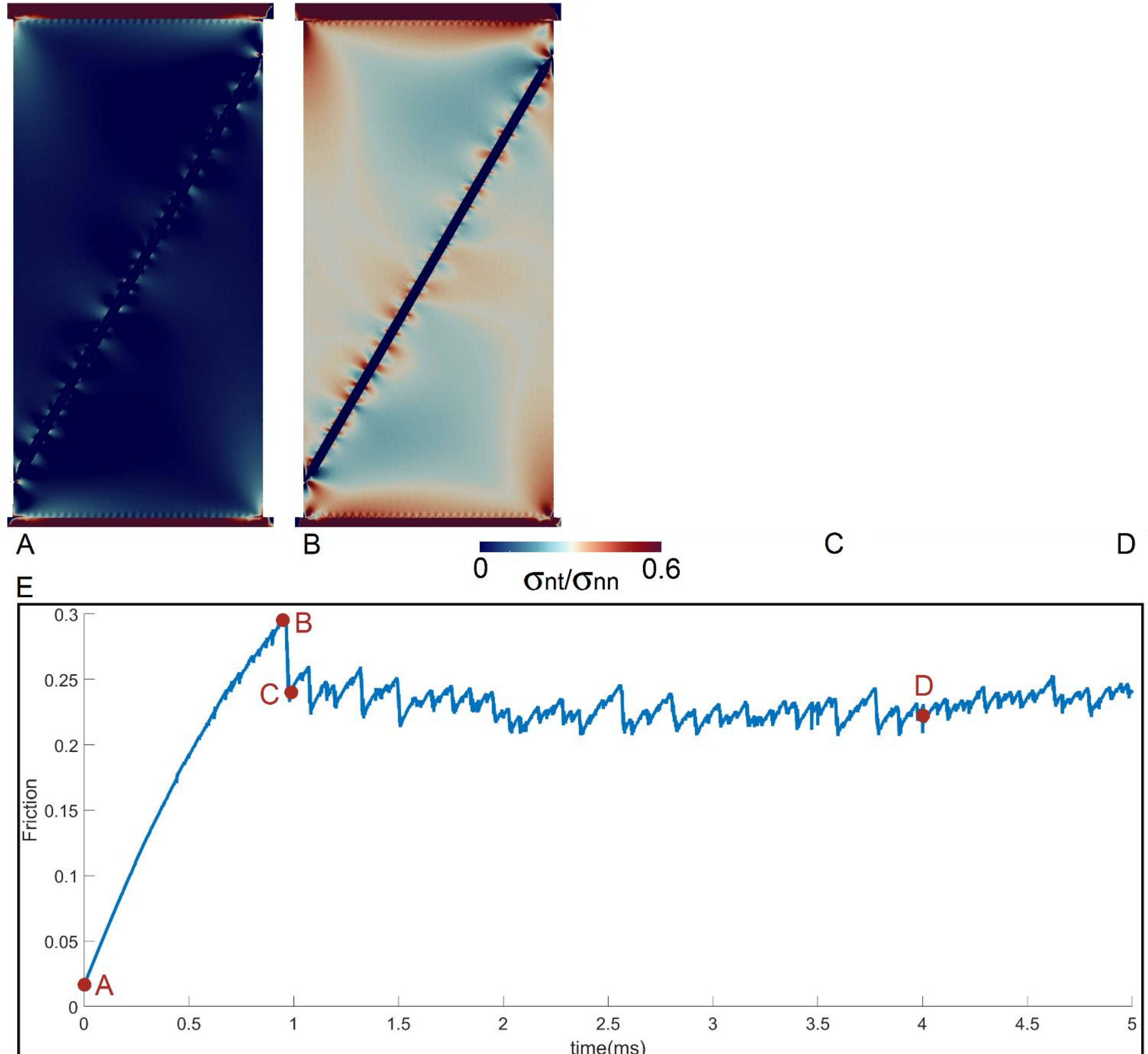


Spontaneous appearance of stick-slip patterns without *ad-hoc* weakening law.

Stress heterogeneities

-Homogeneous initial state

-Elastic heterogeneities



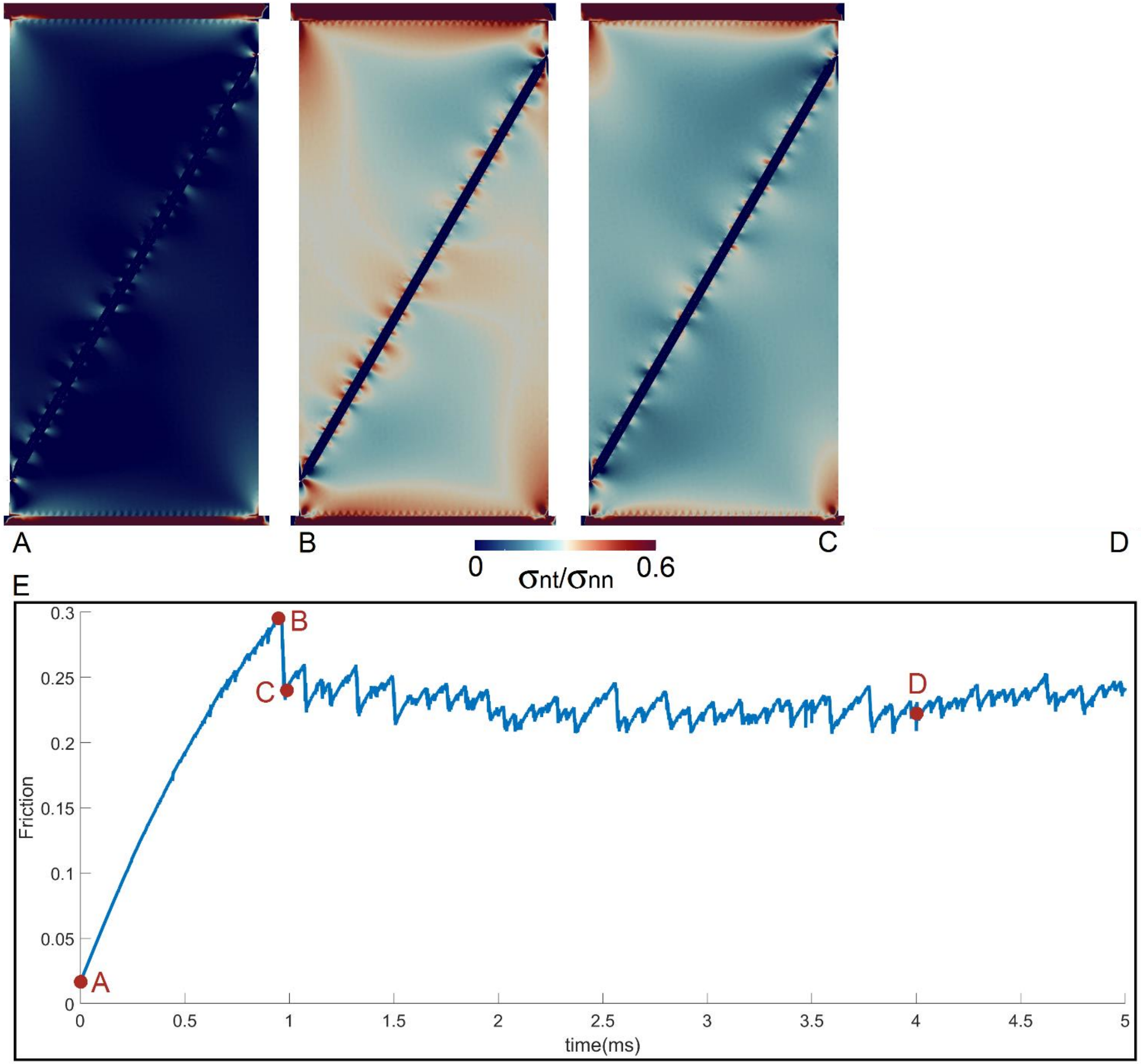
Spontaneous appearance of stick-slip patterns without *ad-hoc* weakening law.

Stress heterogeneities

-Homogeneous initial state

-Elastic heterogeneities

-Single-sliding heterogeneities



Spontaneous appearance of stick-slip patterns without *ad-hoc* weakening law.

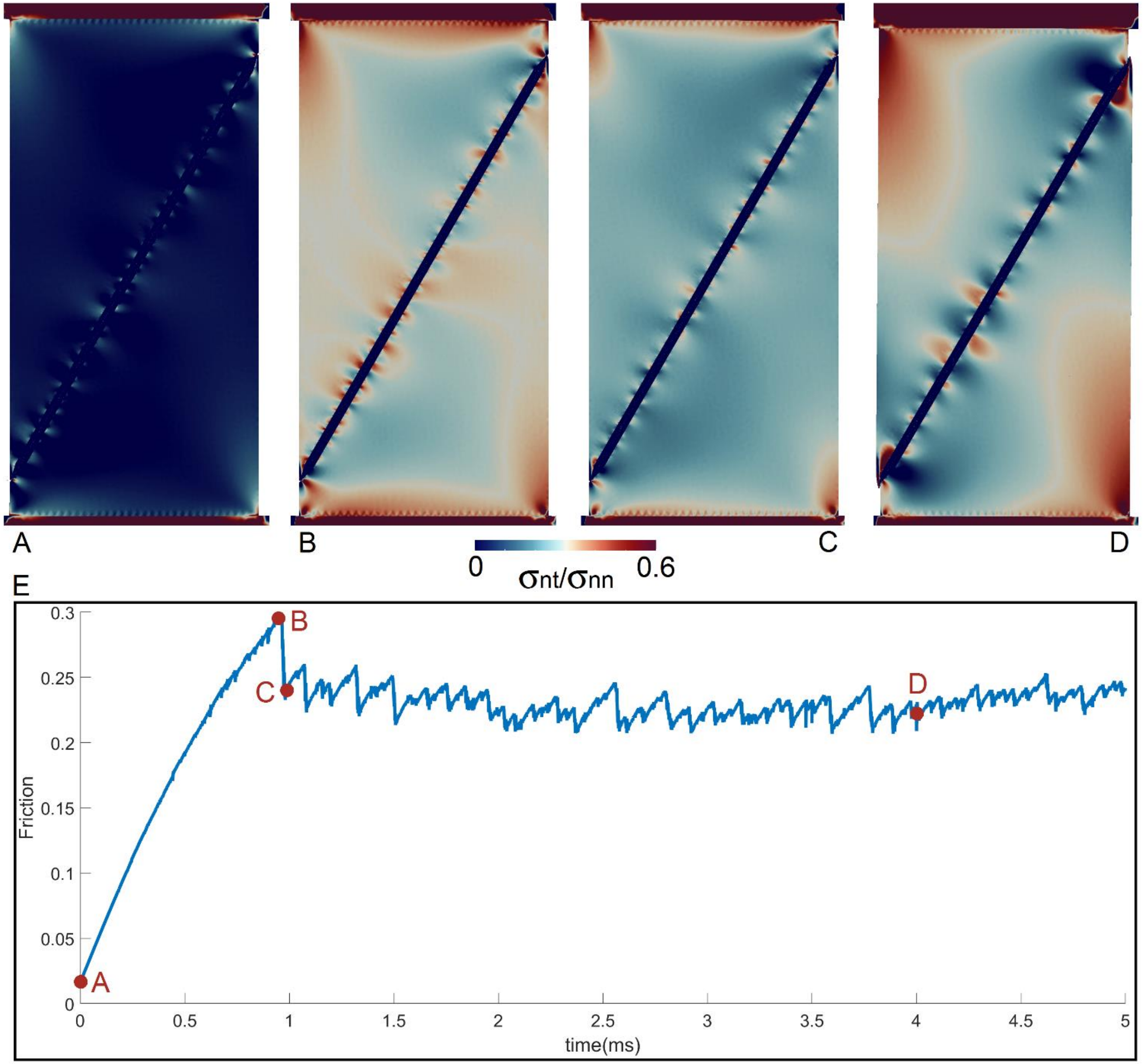
Stress heterogeneities

-Homogeneous initial state

-Elastic heterogeneities

-Single-sliding heterogeneities

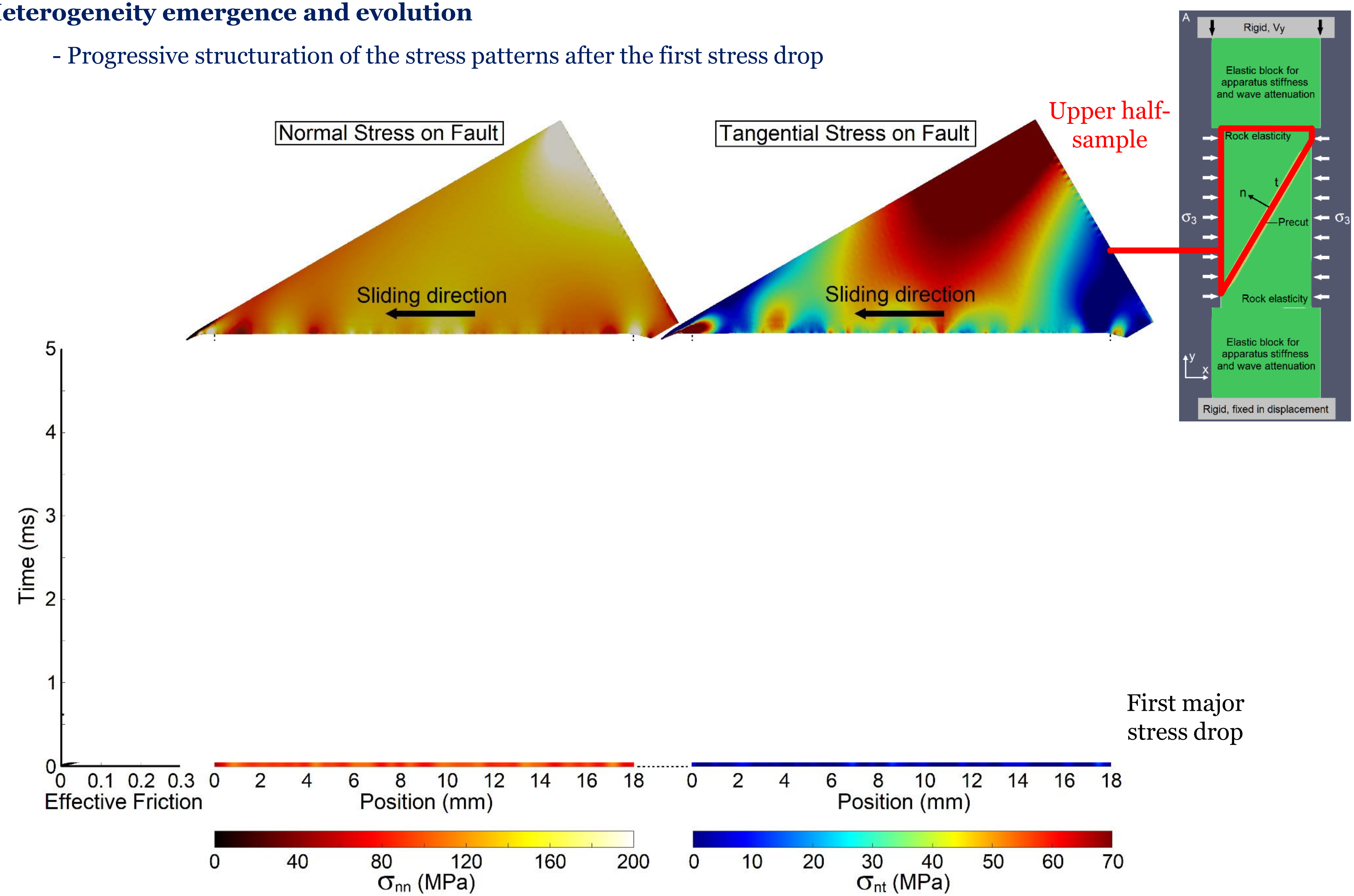
-Cumulated heterogeneities



Spontaneous appearance of stick-slip patterns without *ad-hoc* weakening law.

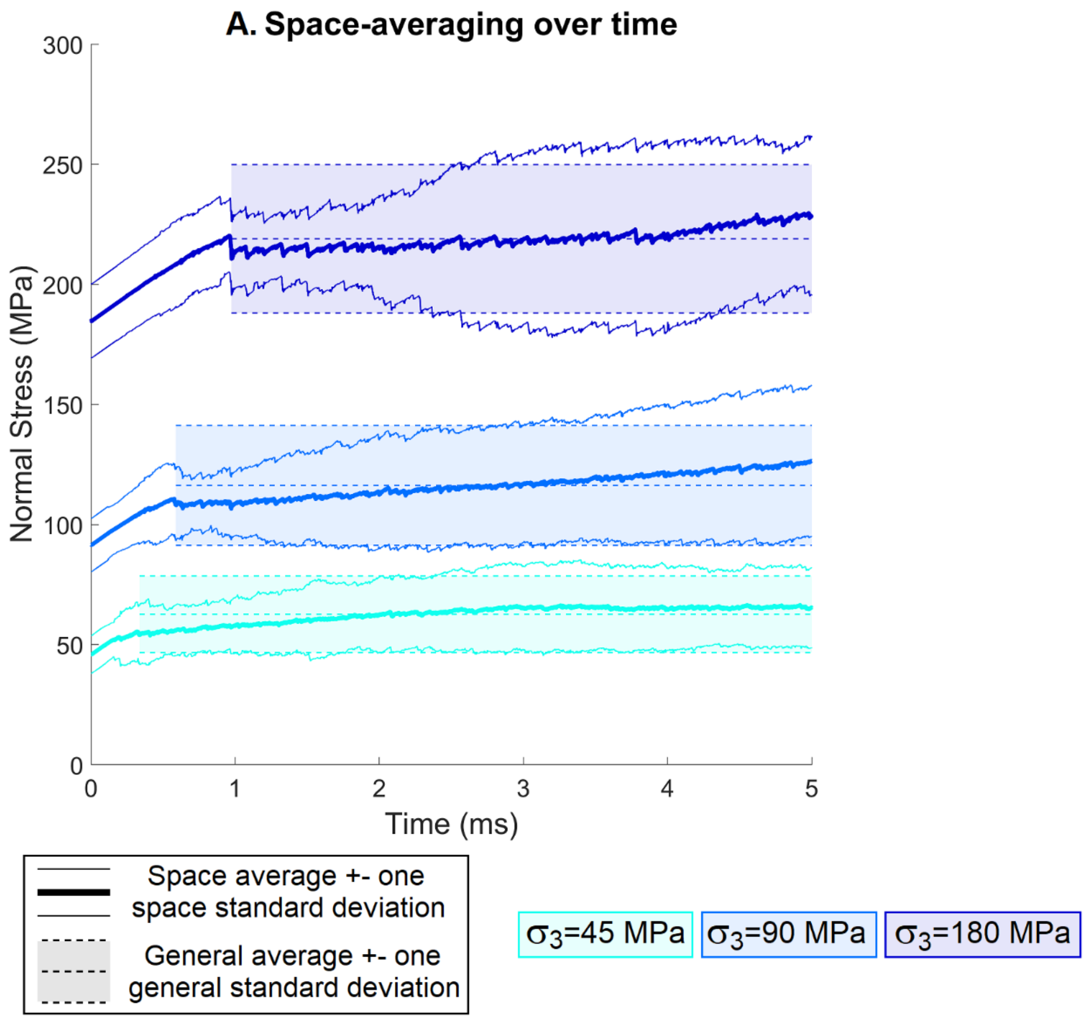
Heterogeneity emergence and evolution

- Progressive structuration of the stress patterns after the first stress drop



Heterogeneity emergence and evolution

- Progressive structuration of the stress patterns after the first stress drop
- Moderate variations in time, large variations in space



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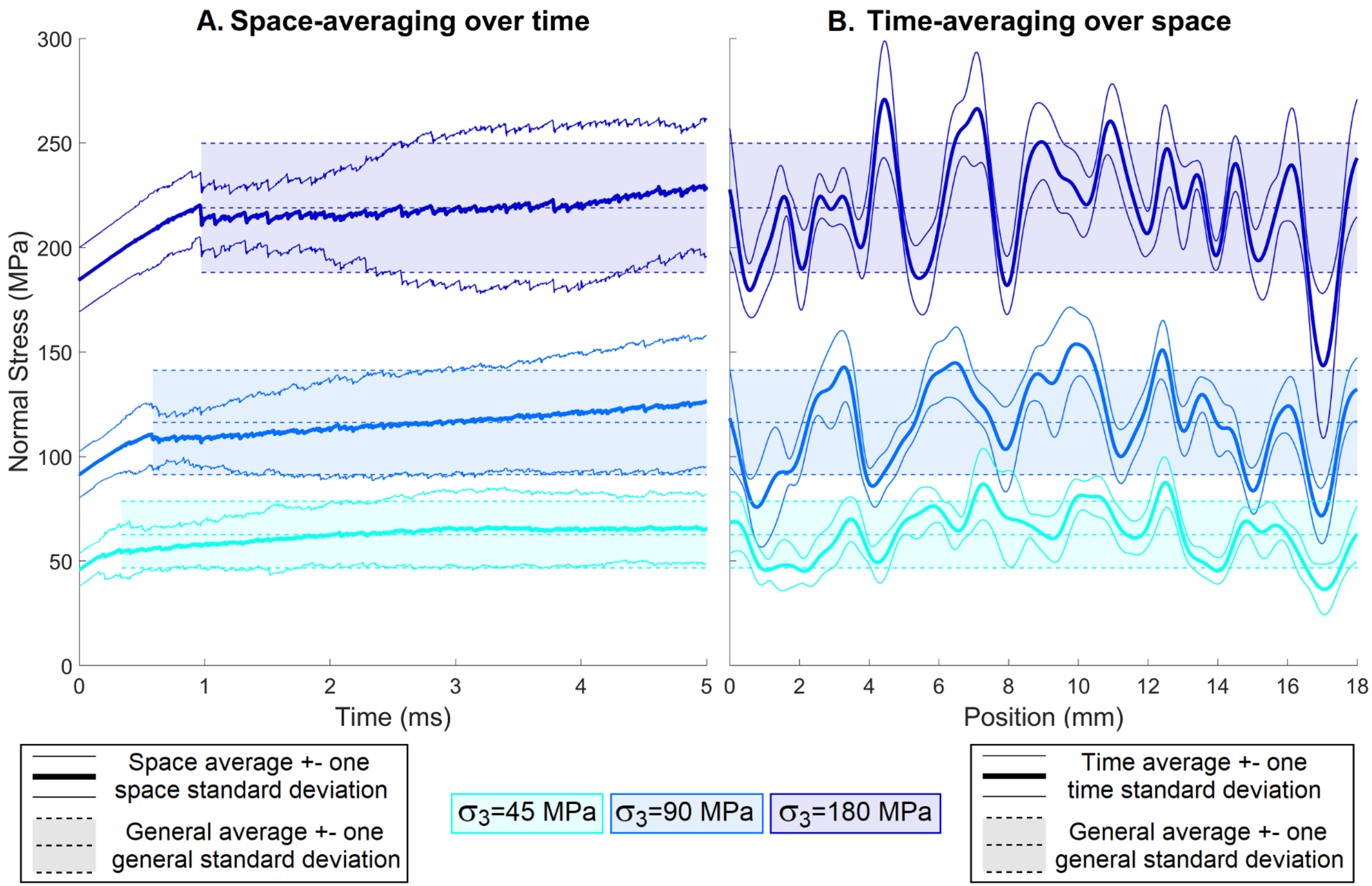

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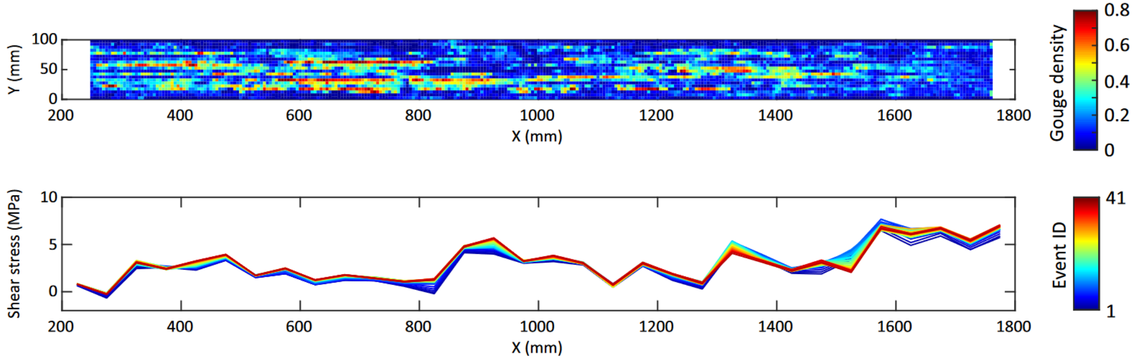
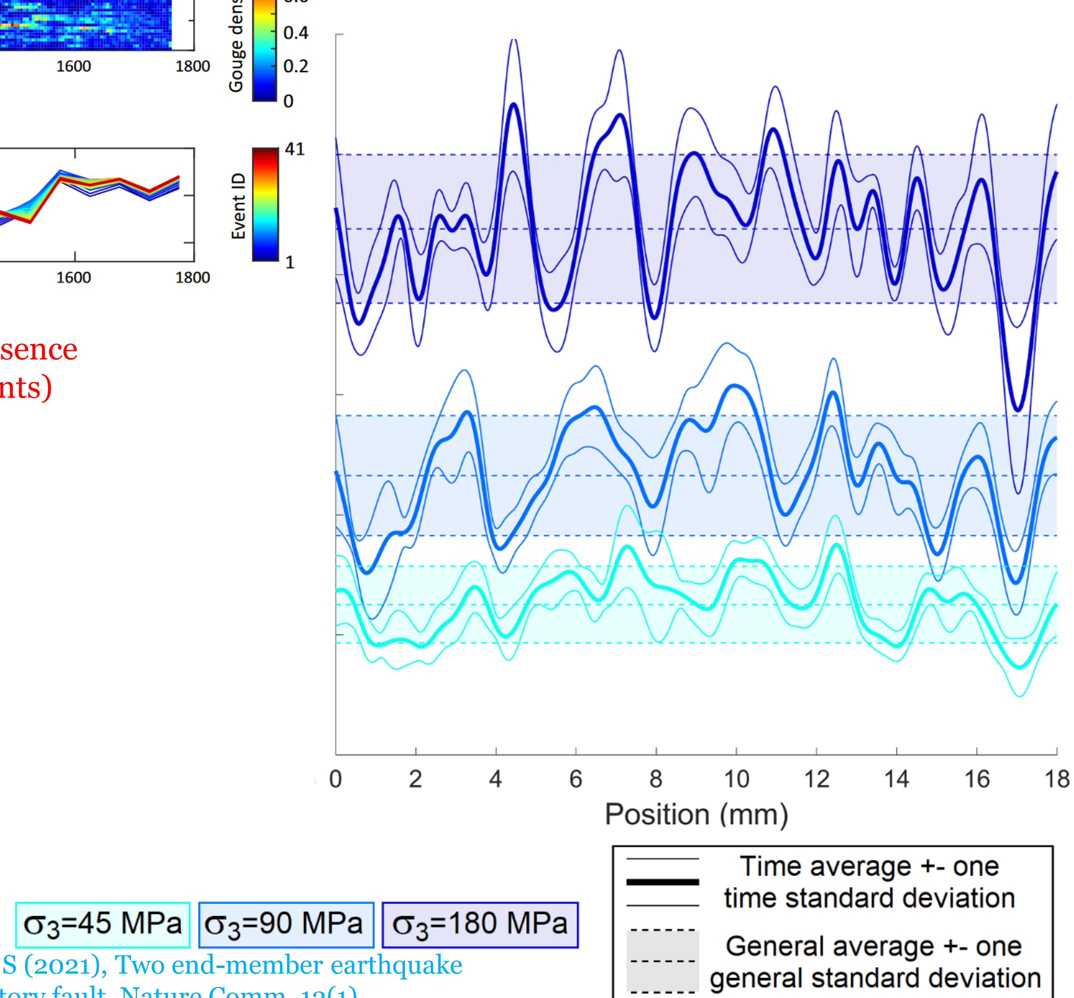


Persistence of stress heterogeneity in the presence of gouge supported by experiments (41 events)

Yamashita et al. 2021



Yamashita F, Fukuyama E, Xu S, Kawakata H, Mizoguchi K, Takizawa S (2021), Two end-member earthquake preparations illuminated by foreshock activity on a meter-scale laboratory fault, Nature Comm, 12(1)

Heterogeneity emergence and evolution

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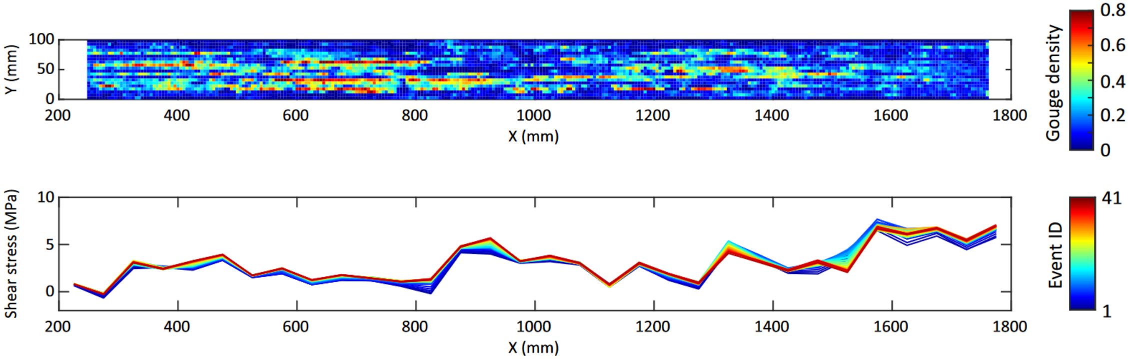
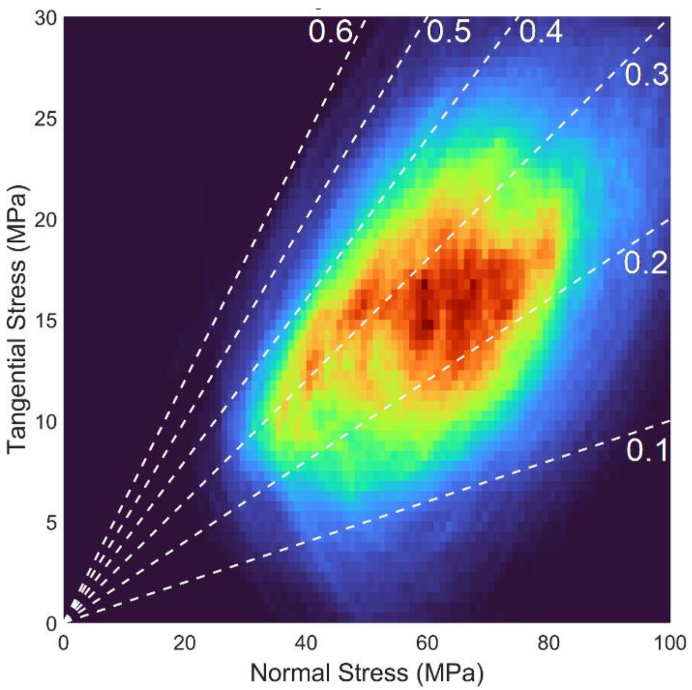
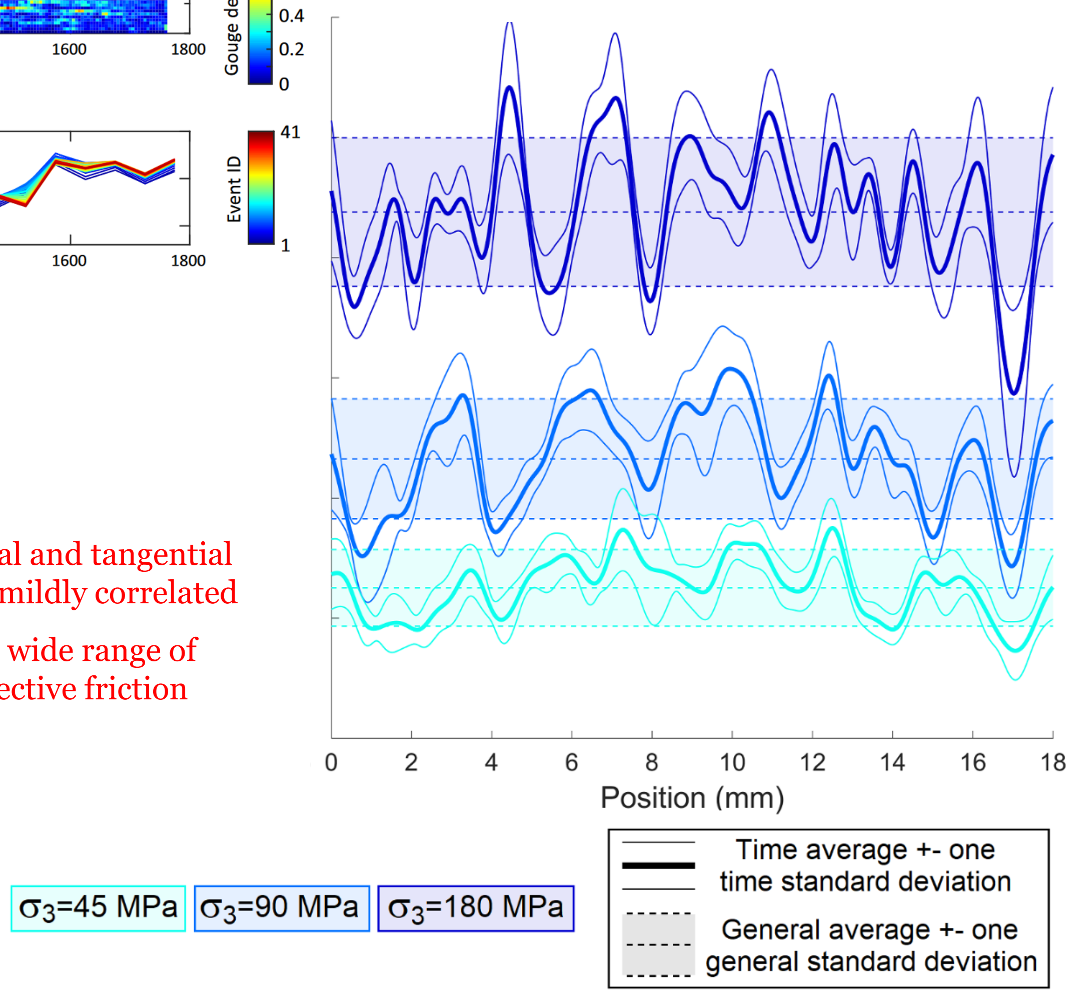




Normal and tangential stress mildly correlated

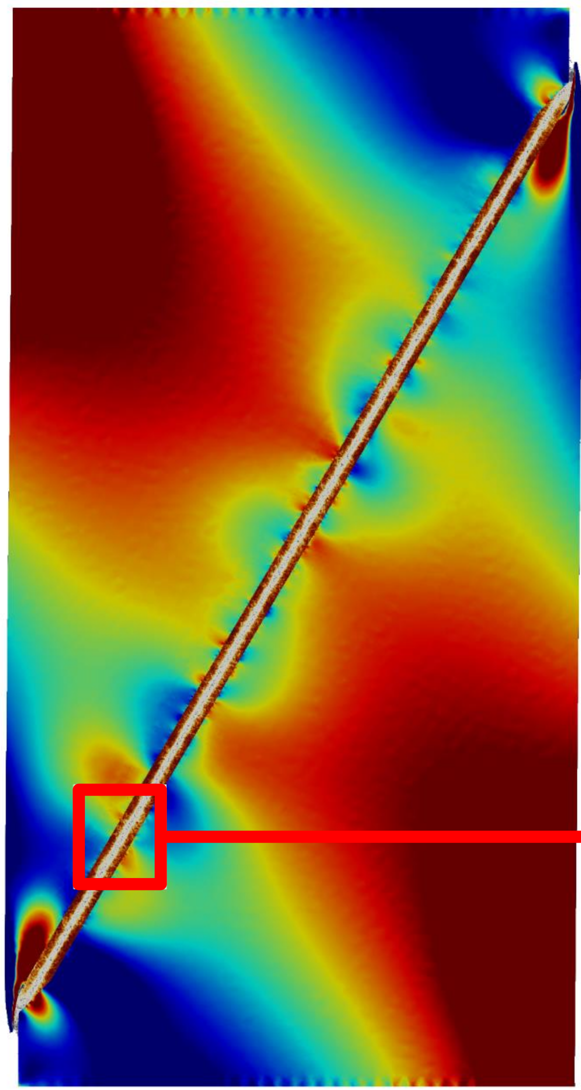
–> wide range of effective friction

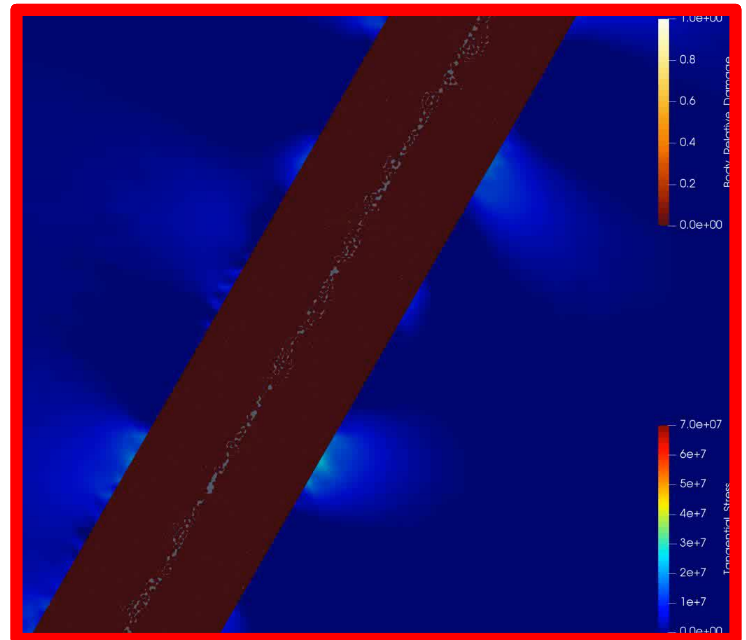
Yamashita et al. 2021



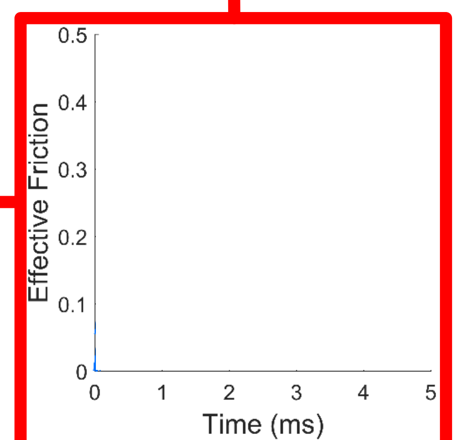
Interface phenomena

- Damaging and gouge production



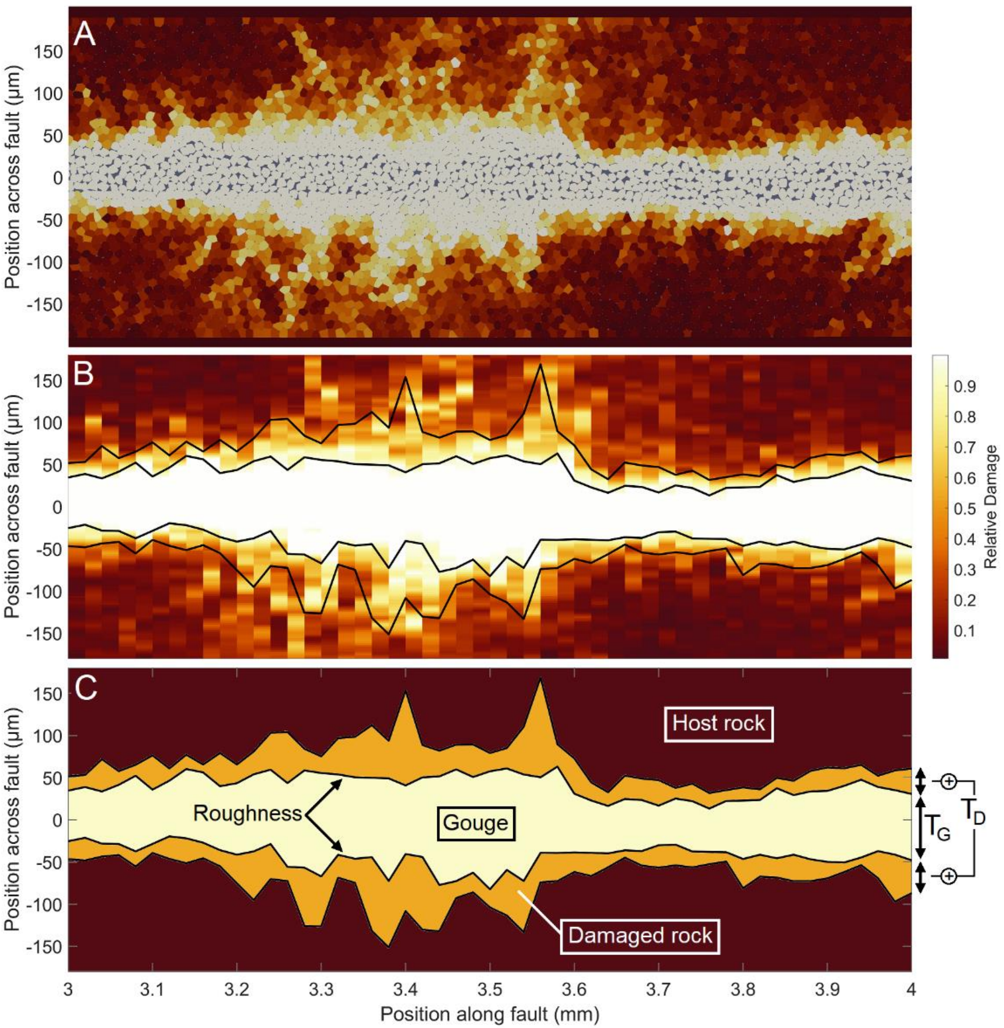


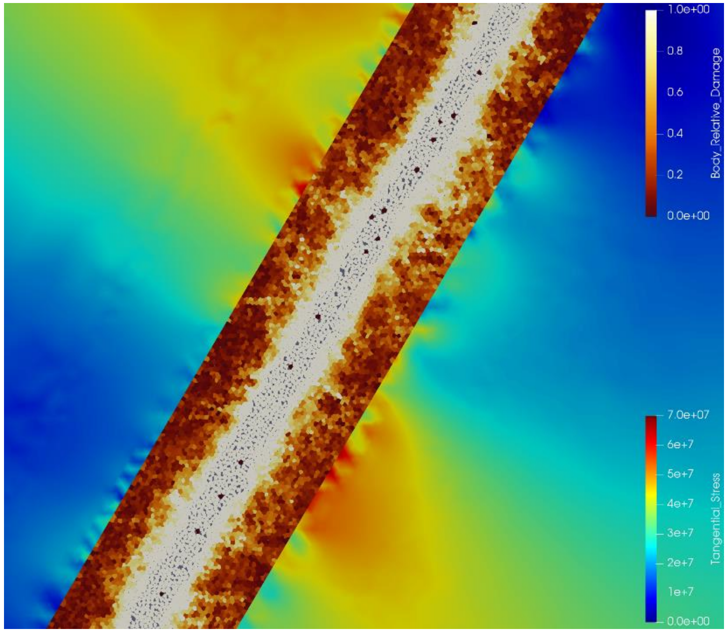
Selected region of the fault
(Damage and Shear stress)



Interface phenomena

- Damaging and gouge production
- Identification of thickness profiles

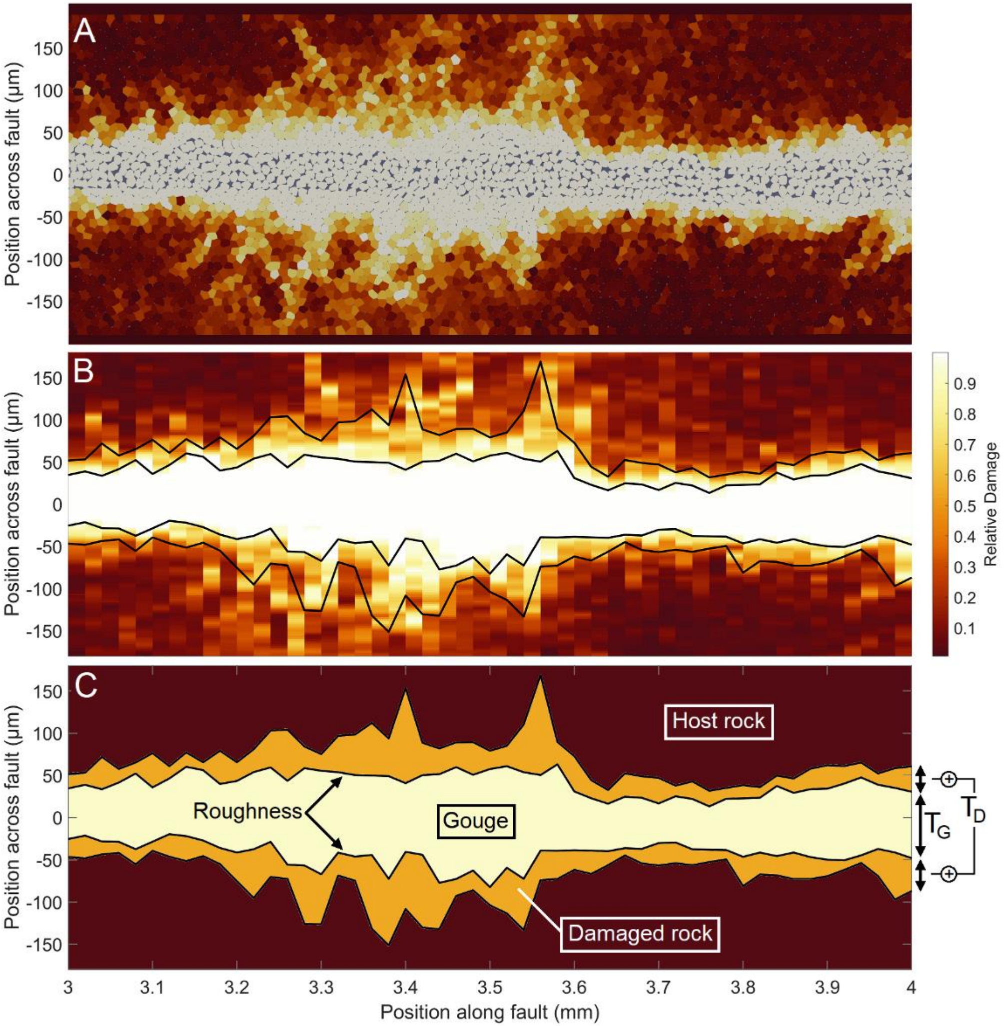


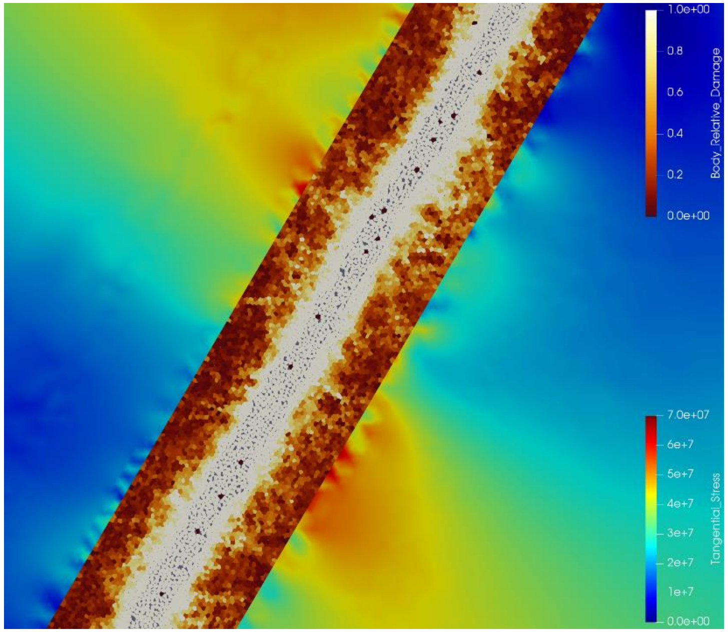


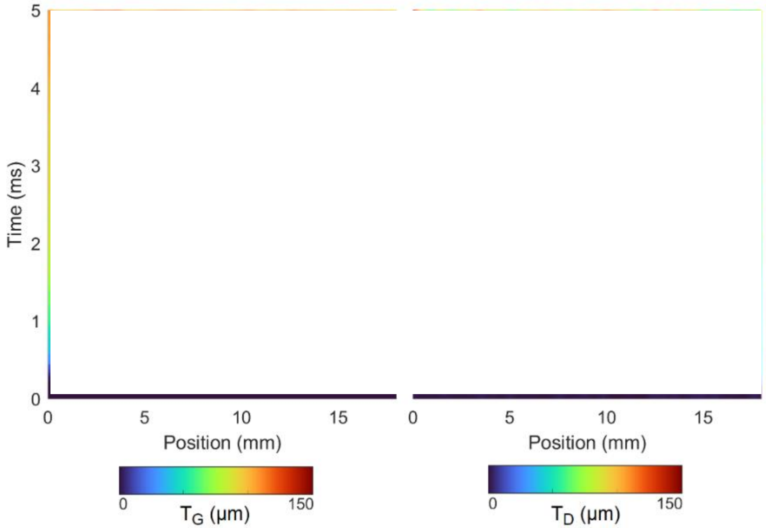
Extraction of gouge thickness, damage thickness, and fault roughness

Interface phenomena

- Damaging and gouge production
- Identification of thickness profiles

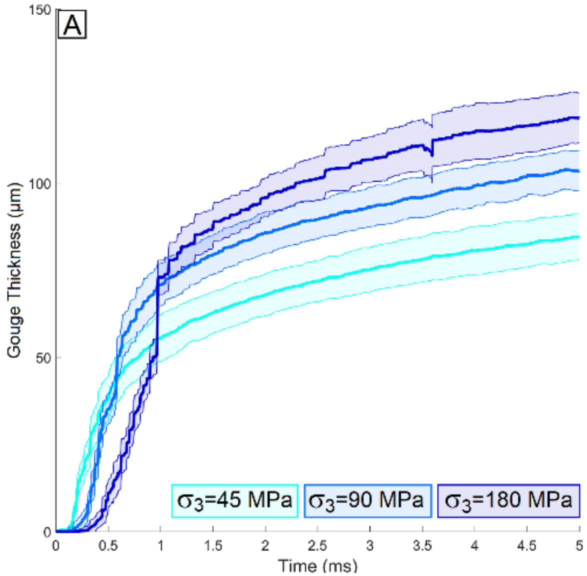




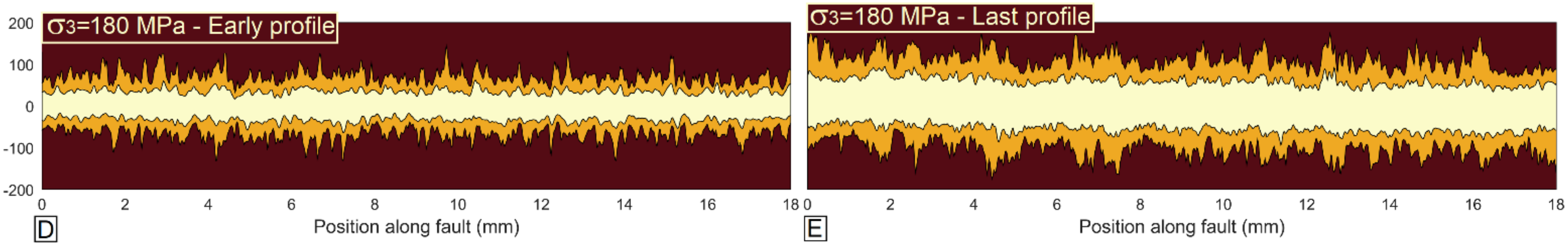


Gouge, damage, roughness

- Variation in gouge thickness stabilizes, and is independent on confining stress

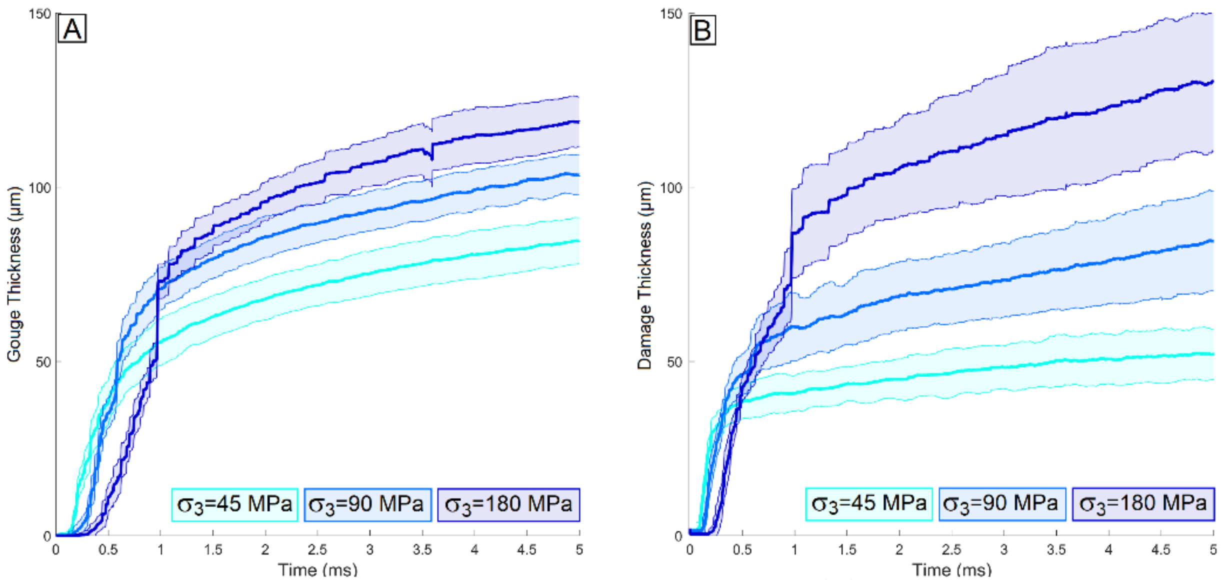


Fault profile (factor 10 on the vertical scale)



Gouge, damage, roughness

- Variation in gouge thickness stabilizes, and is independent on confining stress
- Variation in damage thickness keeps increasing, especially at high confining stress



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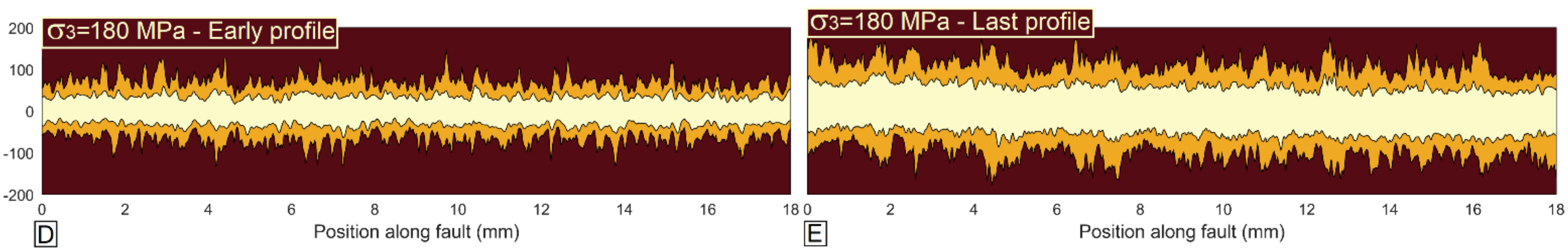

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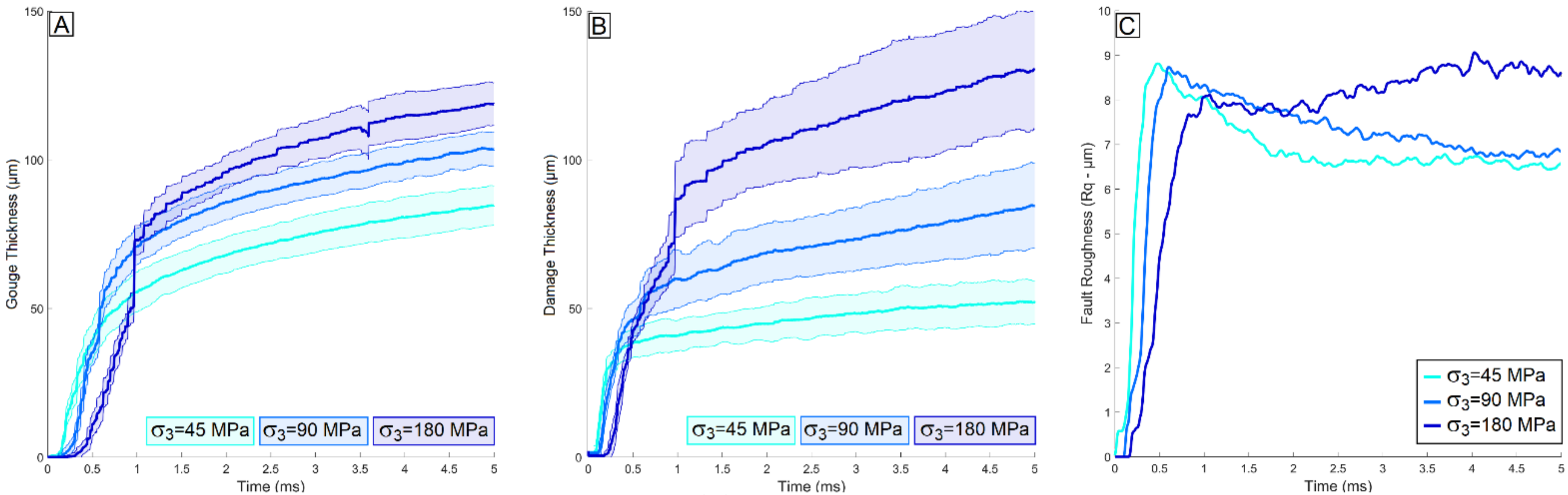
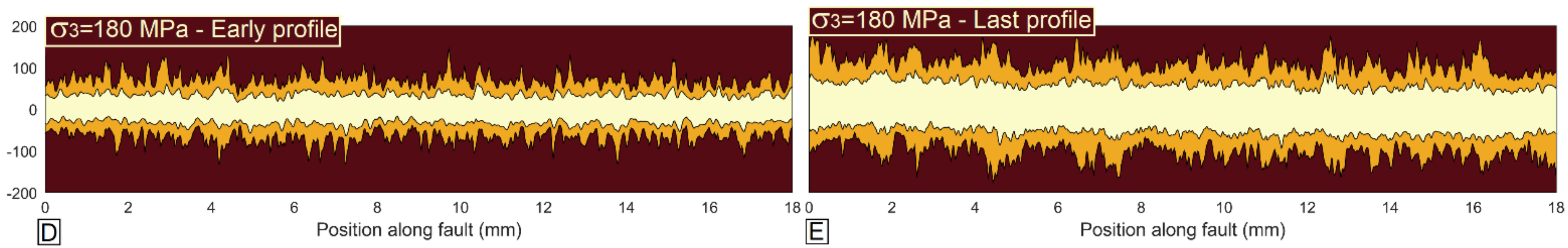
Gouge, damage, roughness

- Variation in gouge thickness stabilizes, and is independent on confining stress
- Variation in damage thickness keeps increasing, especially at high confining stress
- Fault roughness essentially stable after first major stress drop



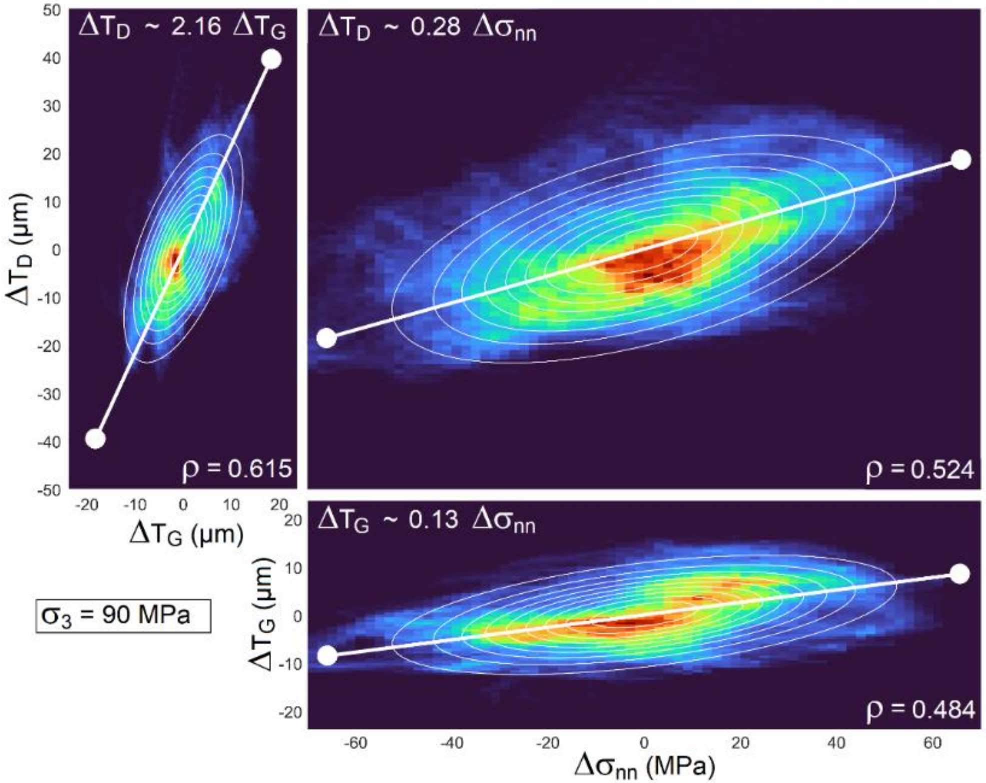
Fault profiles (factor 10 on the vertical scale)



A few illustrative statistical results

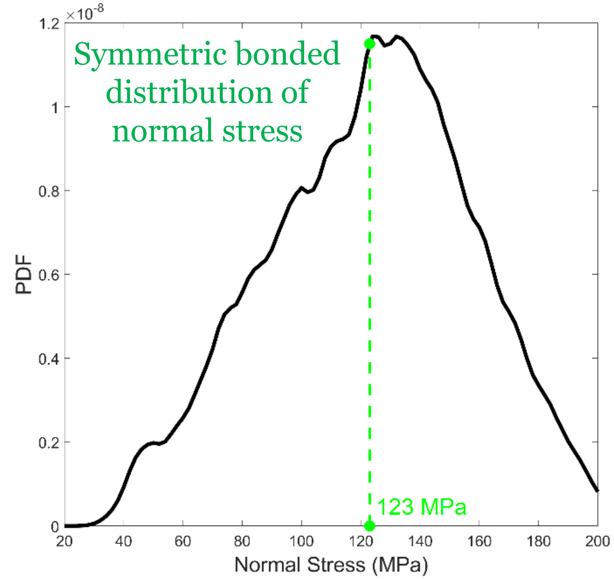
- Correlation between quantities

Strong positive correlations between normal stress, gouge thickness, and damage thickness

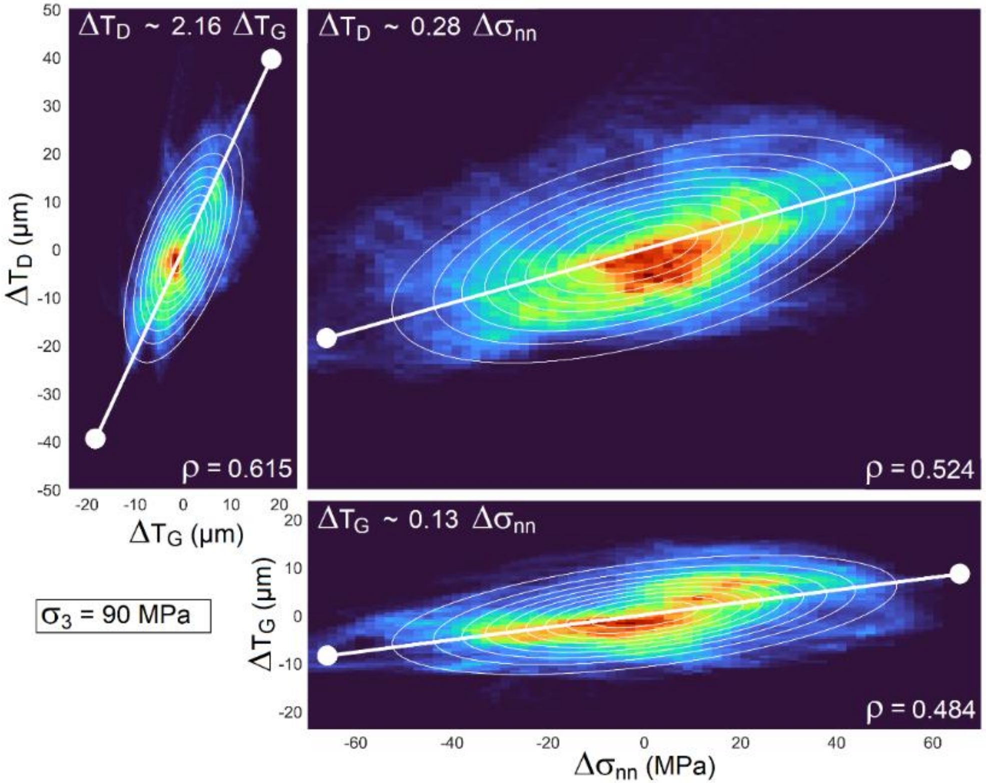


A few illustrative statistical results

- Correlation between quantities
- Probability distributions of quantities



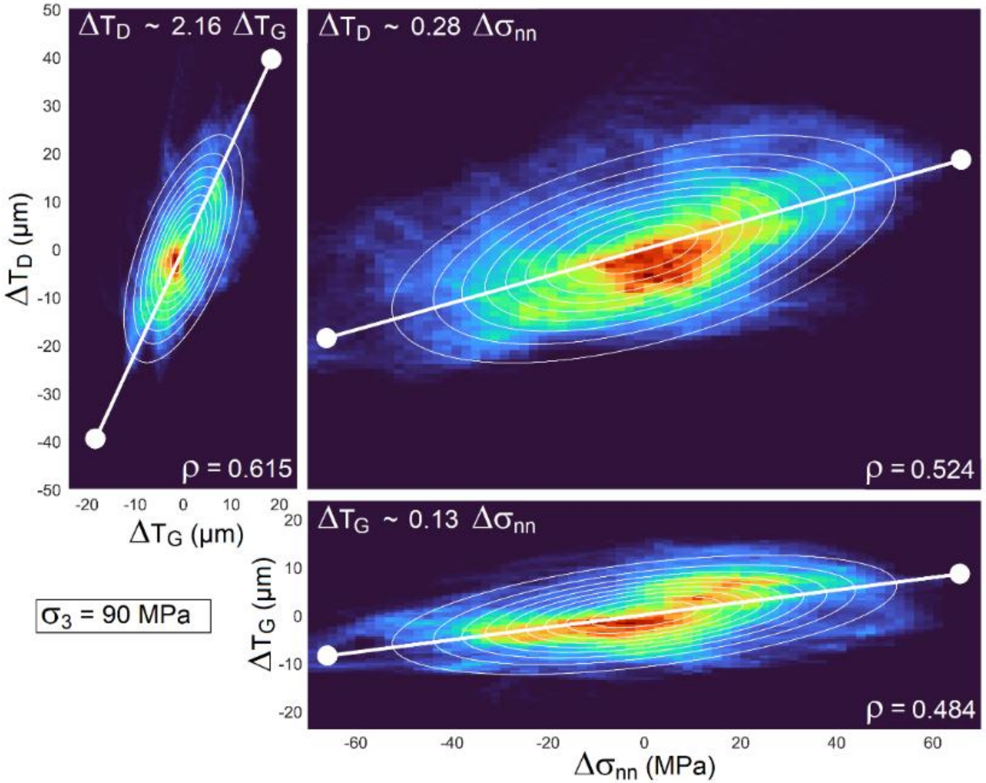
Strong positive correlations between normal stress, gouge thickness, and damage thickness

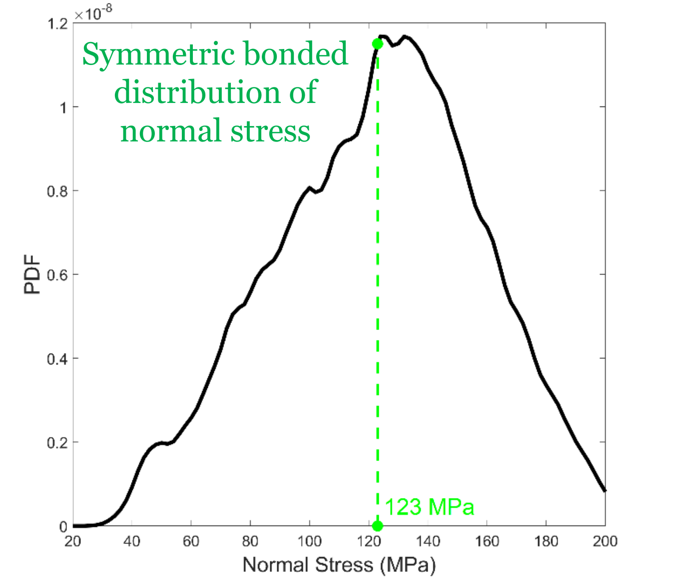


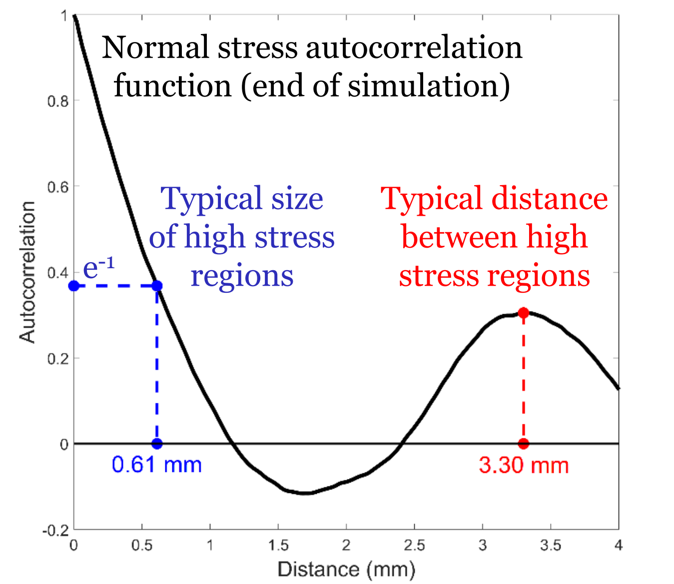
A few illustrative statistical results

- Correlation between quantities
- Probability distributions of quantities
- Spatial correlations of quantities

Strong positive correlations between normal stress, gouge thickness, and damage thickness







Perspectives

Guilhem Mollon[1]

[1]LaMCoS
INSA LYON
Villeurbanne, France

EPFL Summer School, Viège, August 2021

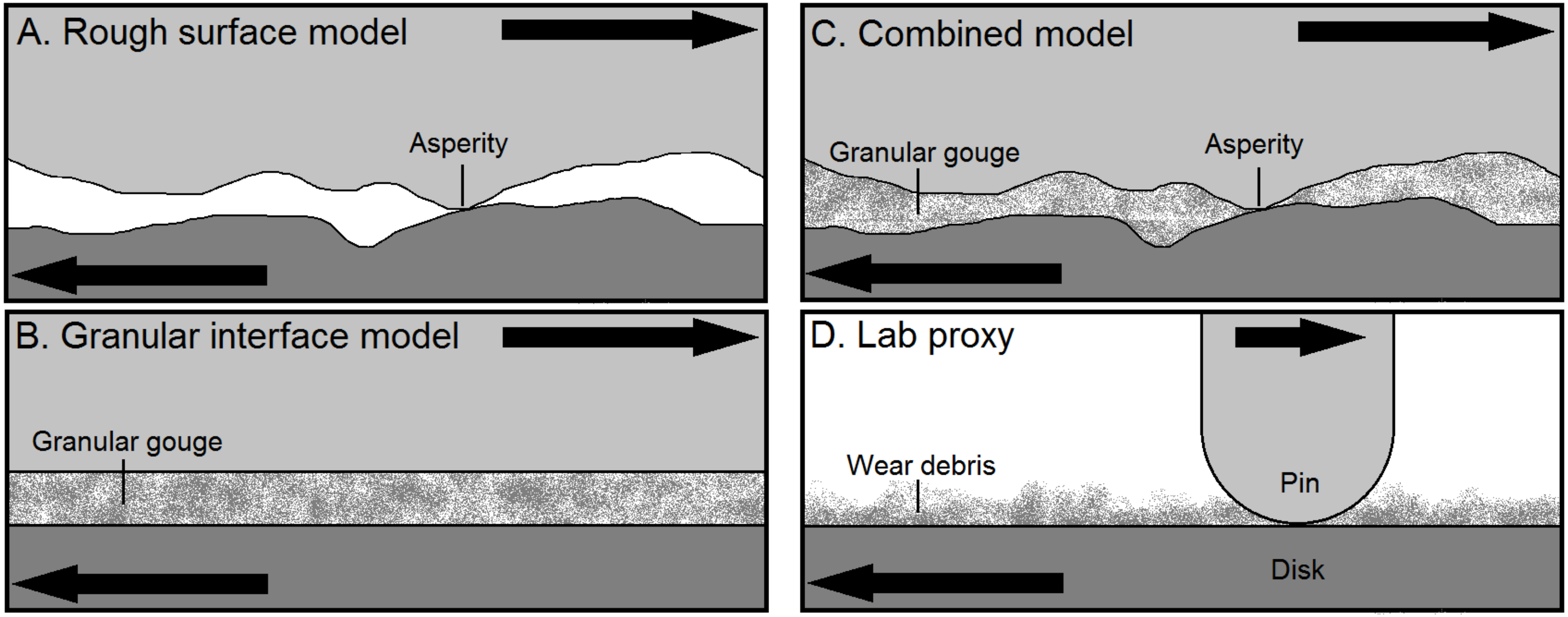
An exciting, newly founded project, about to start!

Do Rock Fault Asperities Melt or Abrade during earthquakes? – DRAMA

Purpose: unifying two common models of faults

-> Rough bare rock (promotes asperity melting)

-> Smooth gouge-filled (requires asperity abrasion)



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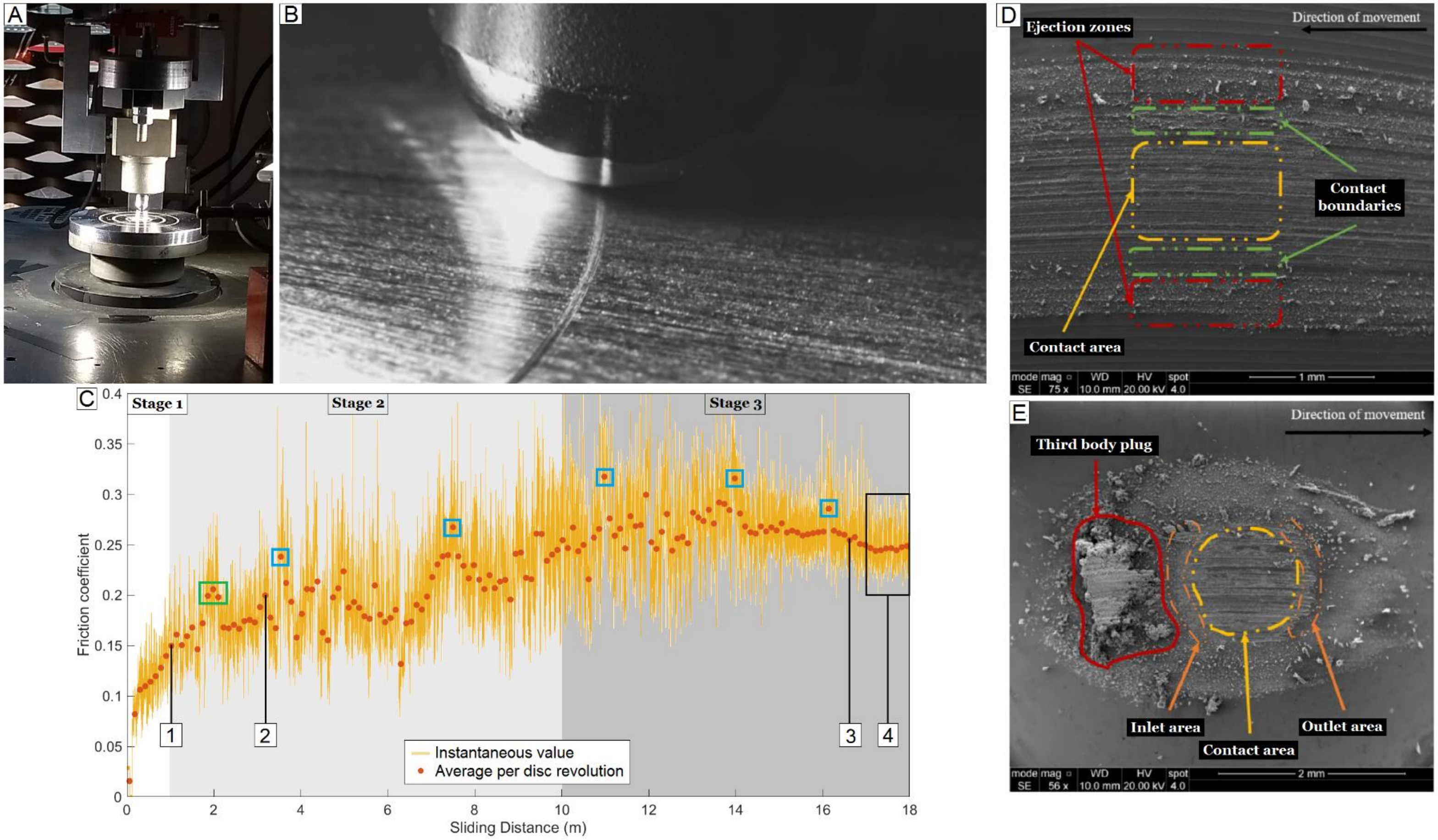
Do Rock Fault Asperities Melt or Abrade during earthquakes? – DRAMA

Main idea: using modern tribometry techniques to monitor closely a contact.



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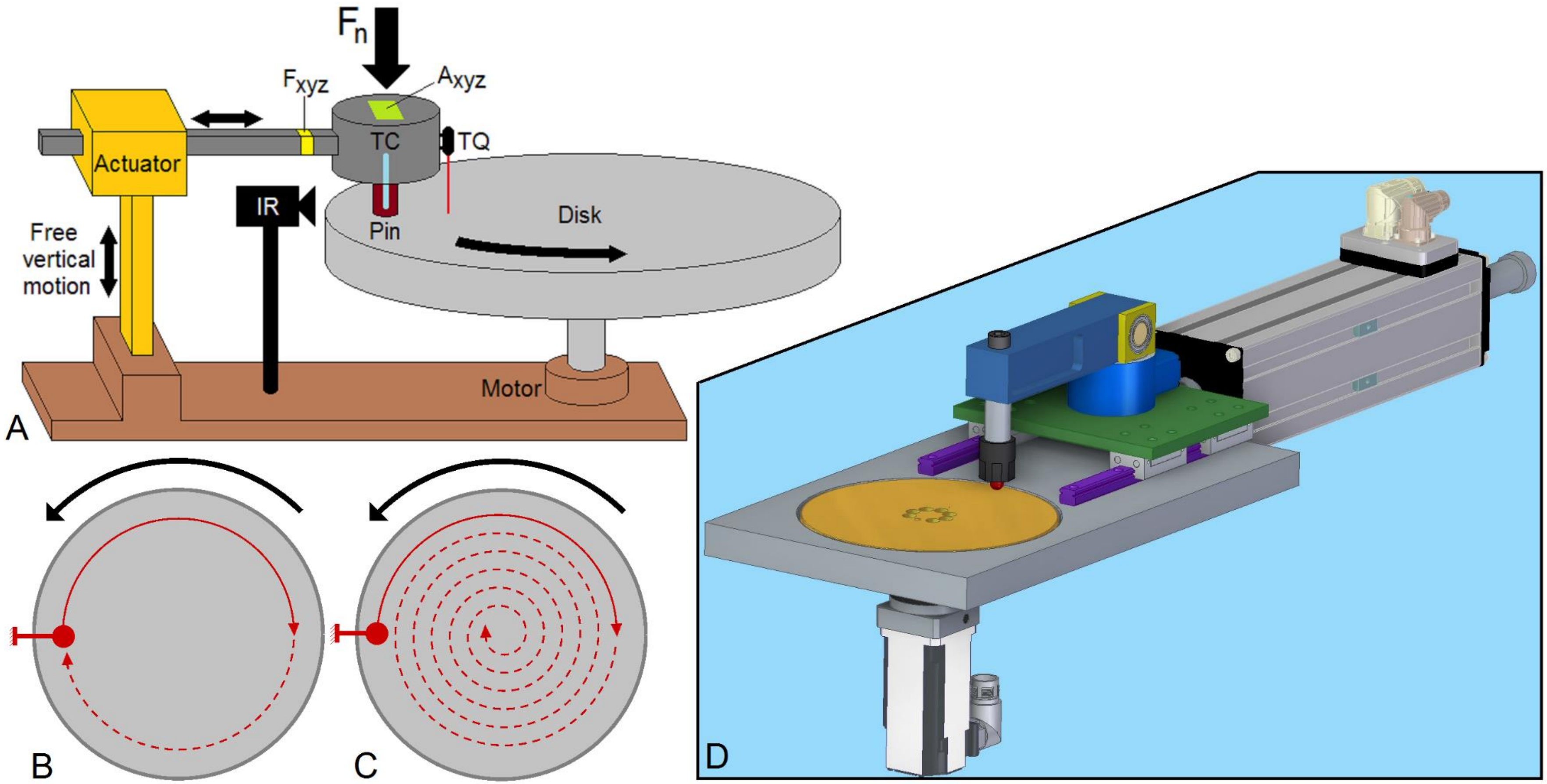
Do Rock Fault Asperities Melt or Abrade during earthquakes? – DRAMA

A brand new rock tribology apparatus will be designed, built, and used.



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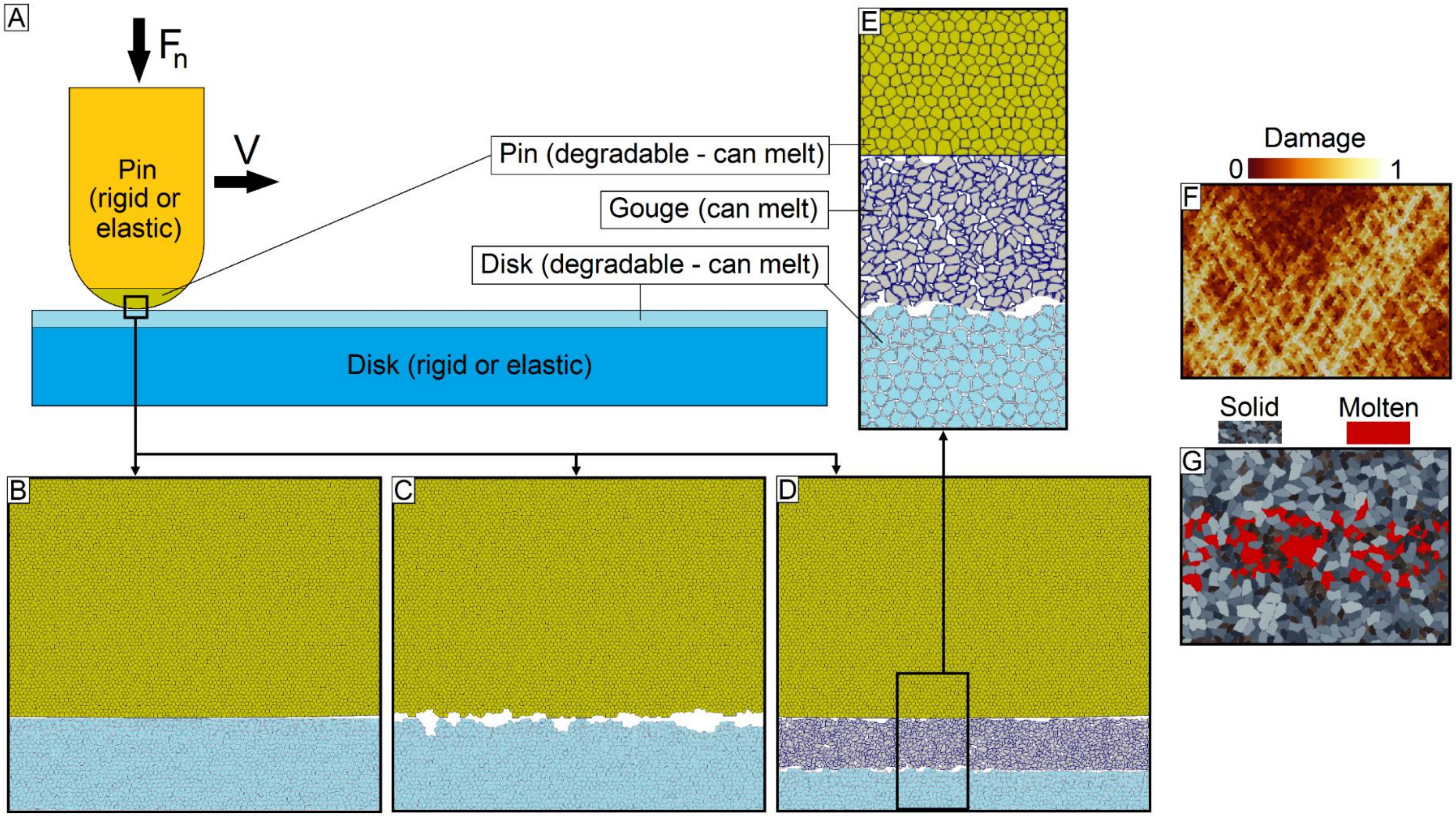
Do Rock Fault Asperities Melt or Abrade during earthquakes? – DRAMA

A comprehensive numerical clone will be implemented, with rock damaging and fracturing, gouge granular flow, heat creation and diffusion, melting, etc.



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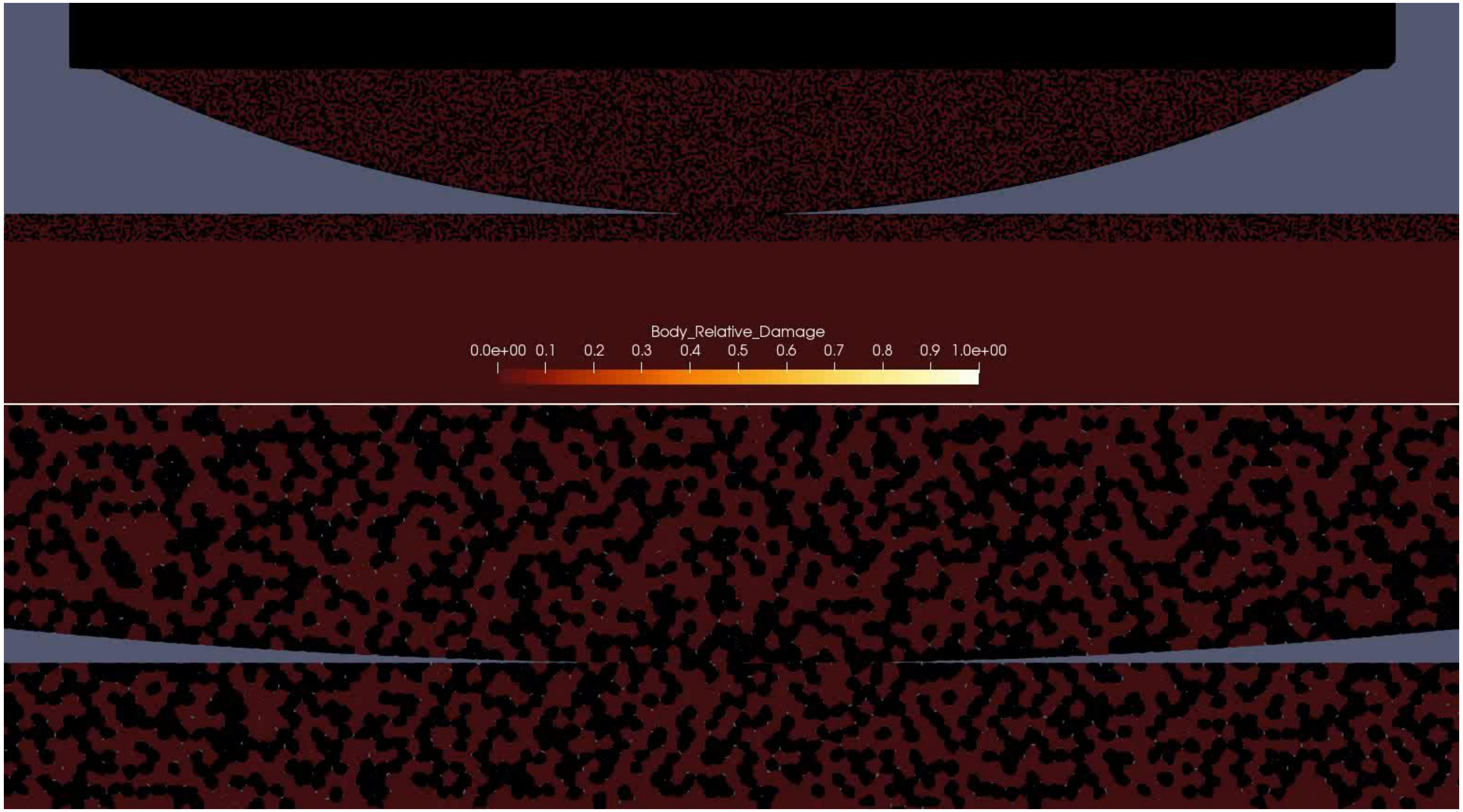

Thank you!

Guilhem Mollon[1]

[1]LaMCoS
INSA LYON
Villeurbanne, France

TRAMME, July 2023