Please use Adobe Acrobat to view the animations. Other pdf reade

Imaging laboratory rupture nucleation at the source:

A friction experiment using ultrafast ultrasound:

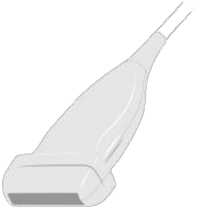
Aichele Johannes[1,2] ; Catheline, Stefan[1]; Roux, Philippe[2]; Latour, Soumaya[3]

[1]LabTAU, INSERM, University of Lyon [2]ISTerre, University of Grenoble [2]IRAP, University of Toulouse III

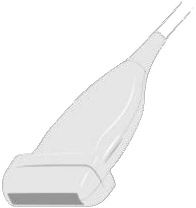
Ultrafast Ultrasound Imaging - Imaging Principles

Reflection Imaging
direct P-wave

Sonography / Echography



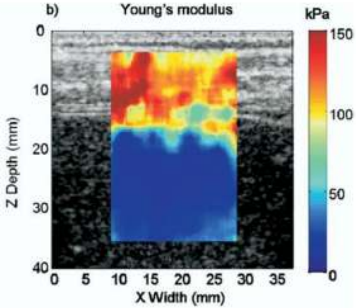
Ultrafast Ultrasound Imaging - Imaging Principles



Reflection Imaging
direct P-wave

Sonography / Echography

Shear Wave Imaging



Elastography

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Muller et al. (2009)

Ultrafast Ultrasound Imaging - Imaging Principles

Reflection Imaging
direct P-wave

- Plane waves

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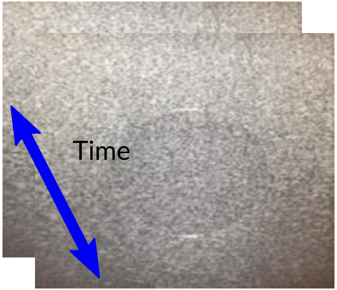
Reflection Imaging
direct P-wave



- Plane waves
- $10\,000$ FPS

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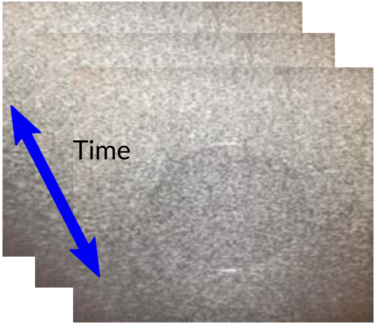
Ultrafast Ultrasound Imaging - Imaging Principles

Reflection Imaging
direct P-wave



- Plane waves
- $10\,000$ FPS
- Motion tracking

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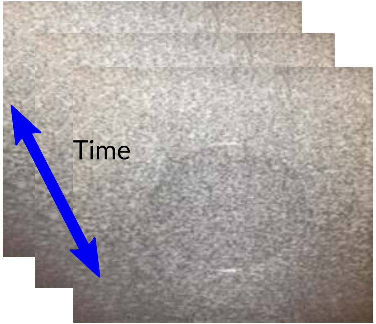
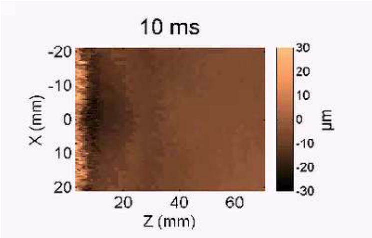
Reflection Imaging
direct P-wave



Speckle correlation

Particle velocity

Shear Wave Imaging
S-wave



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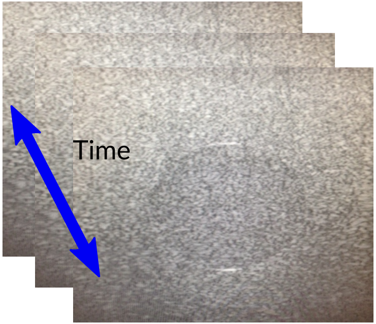
Ultrafast Ultrasound Imaging - Imaging Principles

if animation does not start,

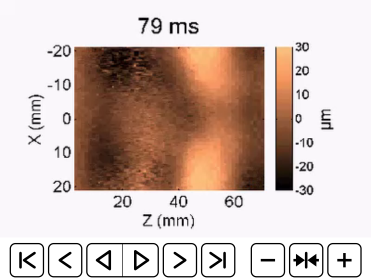
Reflection Imaging
direct P-wave



Speckle correlation

Particle velocity

Shear Wave Imaging
S-wave



Sandrin et al., (2000)

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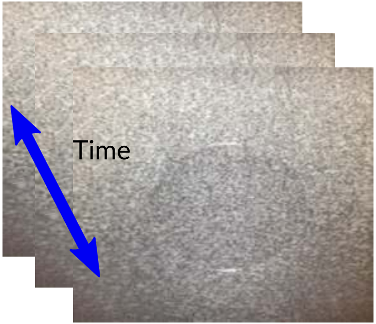
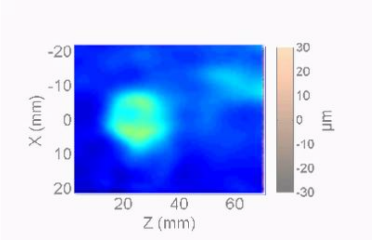
Ultrafast Ultrasound Imaging - Imaging Principles

Reflection Imaging
direct P-wave



Speckle correlation

Particle velocity



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Rupture Imaging - Introduction

Understanding rupture nucleation

- Concentrated on fault zones
- Complex dynamics
- Devastating elastic wave radiation

Rupture Imaging - Introduction

Understanding rupture nucleation

- Concentrated on fault zones
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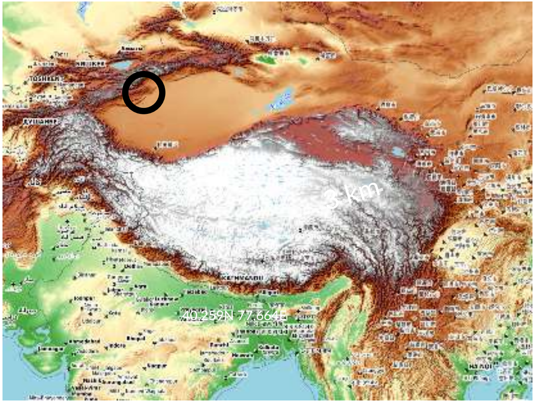

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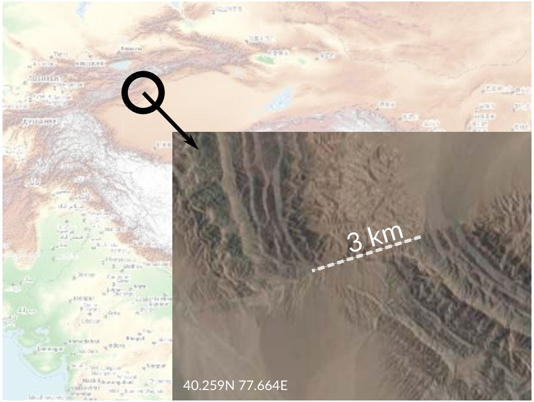
Rupture Imaging - Introduction

Understanding rupture nucleation

- Concentrated on fault zones
- Complex dynamics
- Devastating elastic wave radiation



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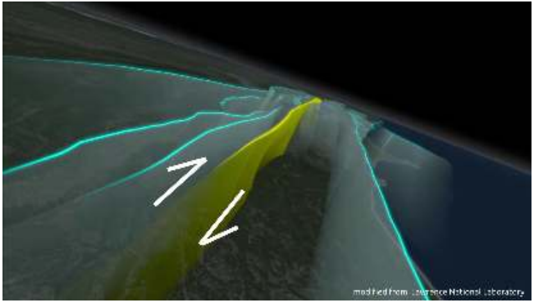
Rupture Imaging - Introduction



km-scale

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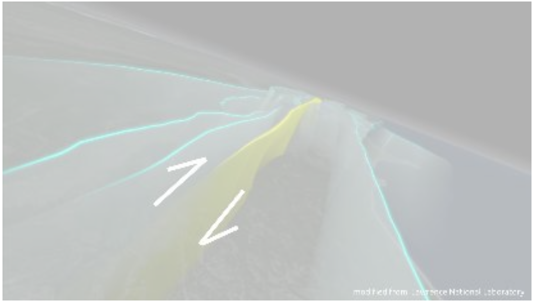
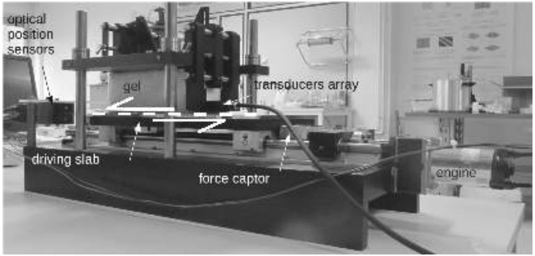
Rupture Imaging - Introduction



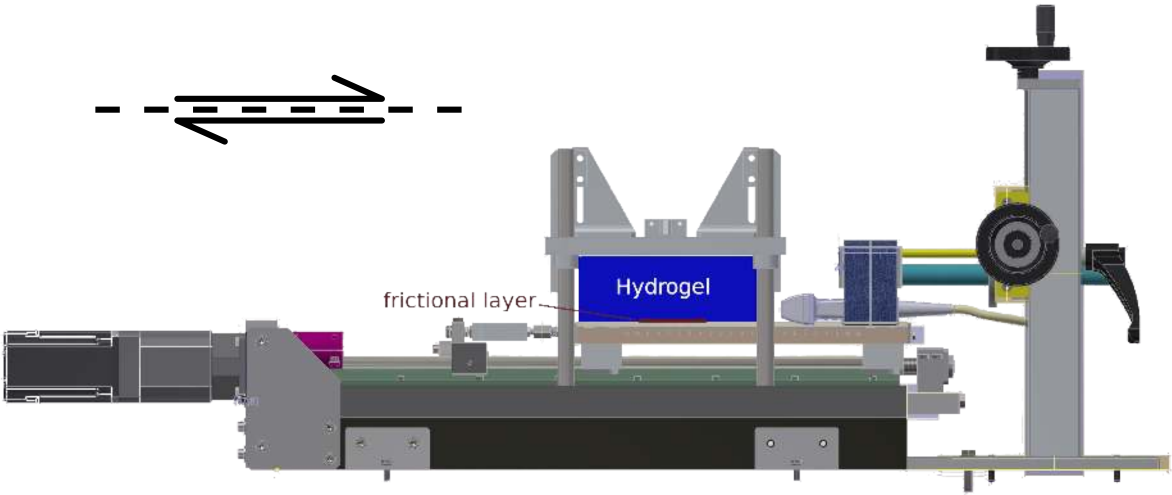


km-scale

cm-scale

Latour (2011)

Rupture Imaging - Experimental Setup



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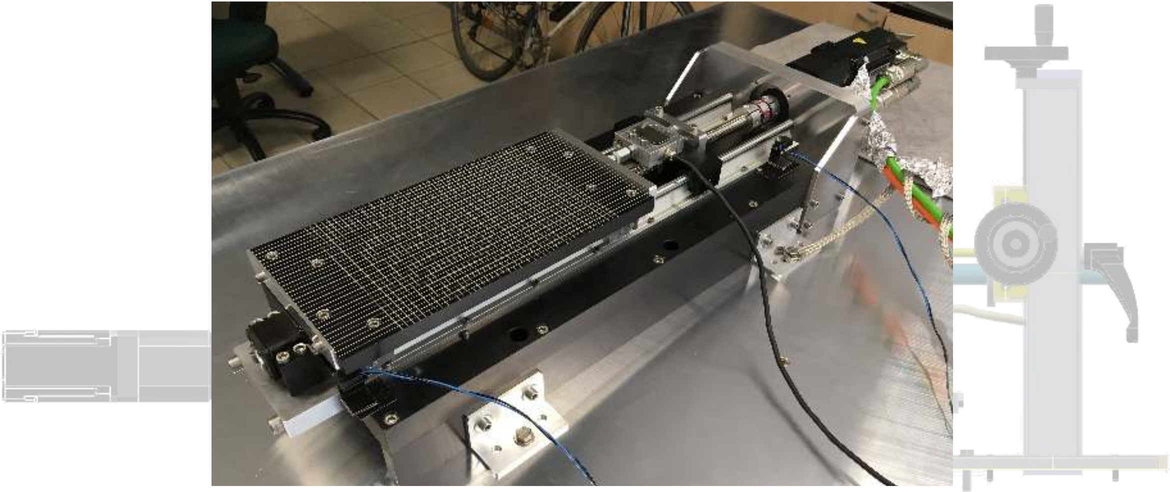
Rupture Imaging - Experimental Setup



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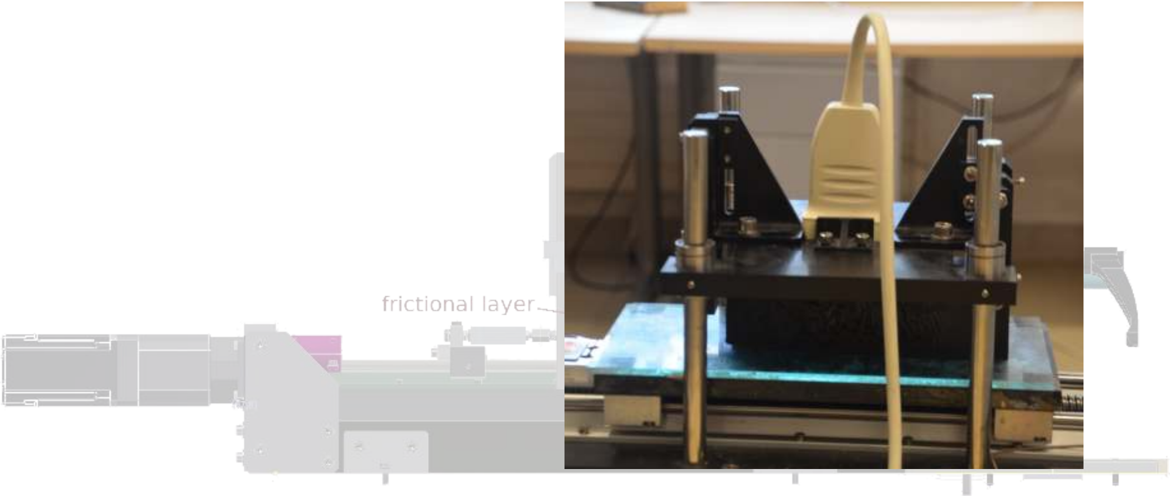
Rupture Imaging - Experimental Setup



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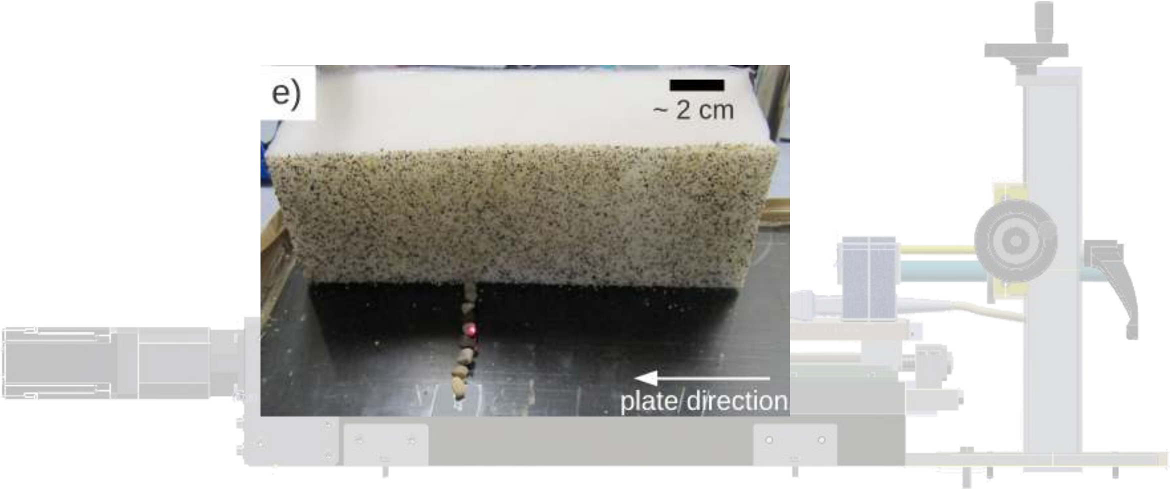
Rupture Imaging - Experimental Setup



Latour (2011)

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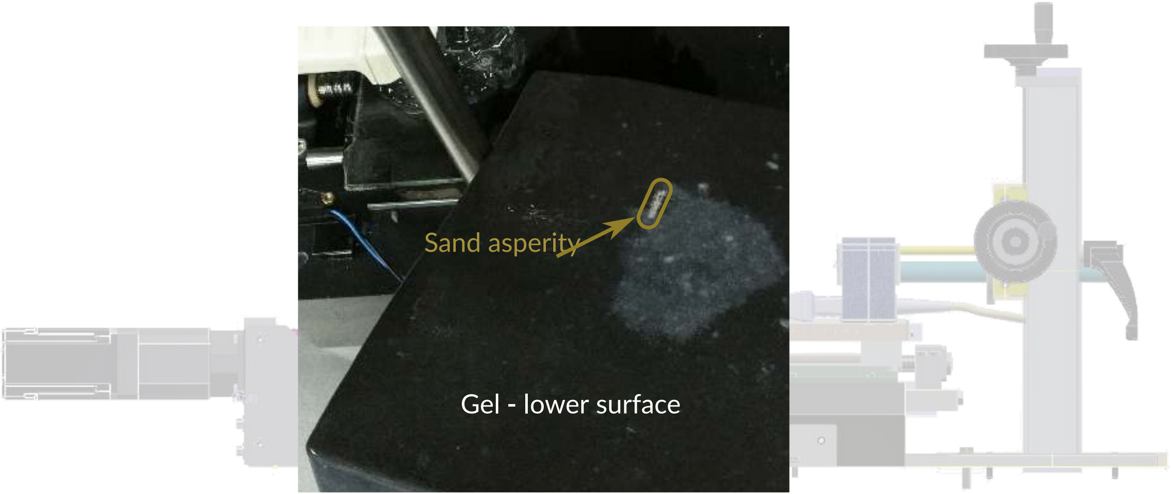
Rupture Imaging - Experimental Setup



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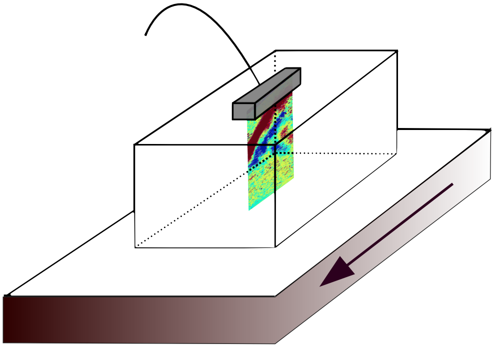
Rupture Imaging - Fault Normal



Probe above gel

- Vertical particle velocity retrieved
- Bulk wavefield

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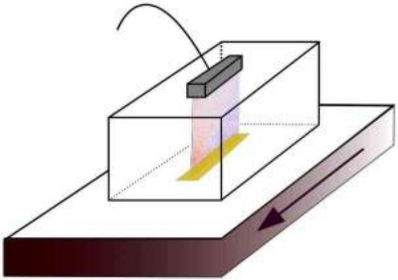
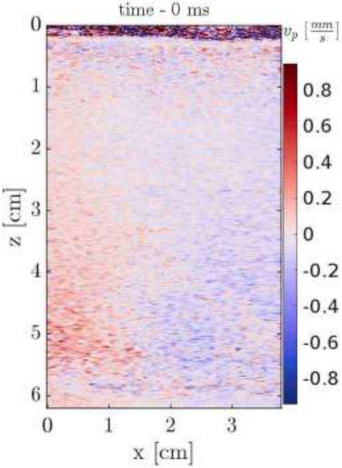
Rupture Imaging - Fault Normal





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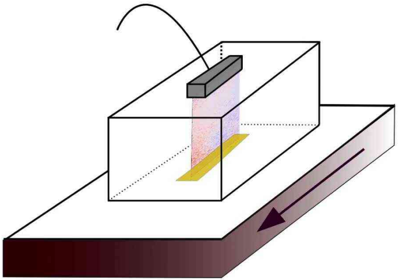
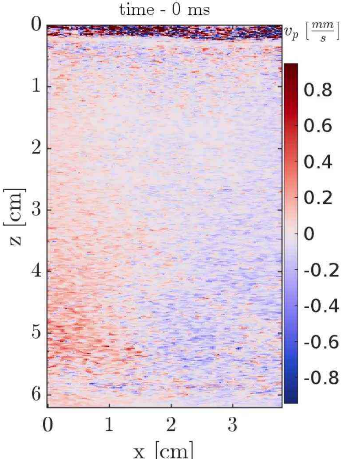
Rupture Imaging - Fault Normal

if animation does not start,





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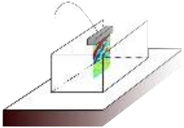
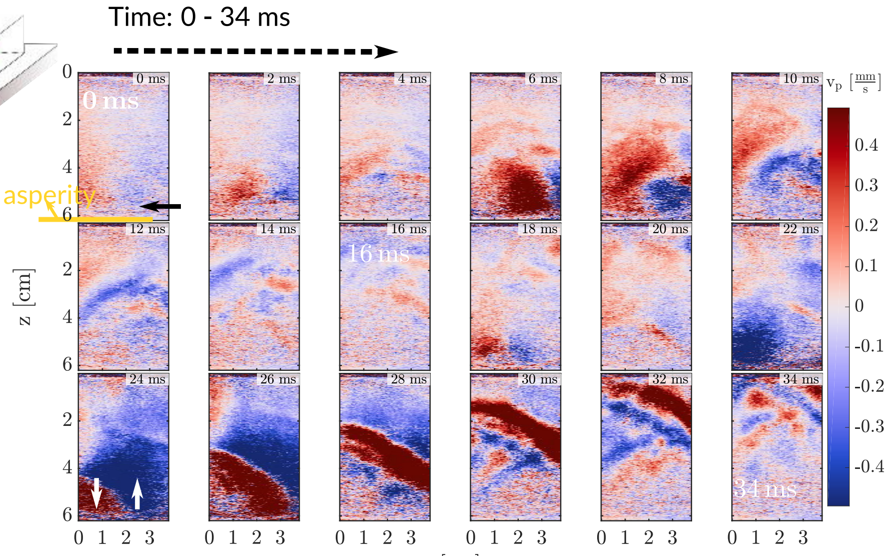
Rupture Imaging - Fault Normal





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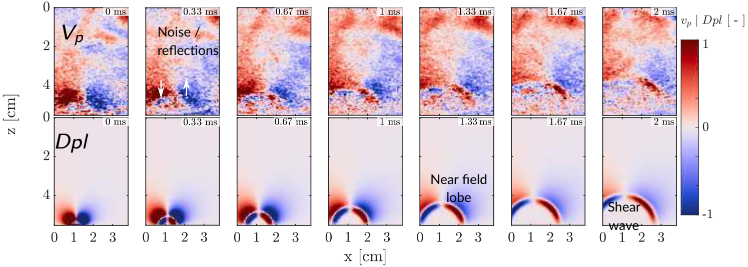
Rupture Imaging - Fault Normal - Precusory event



Kinematic simulation

Green's function

Single shear force

Dynamic experiment

Event at 18ms

Near field and shear wave field well reproduced

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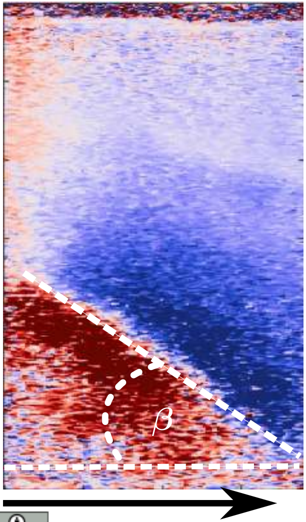
Rupture Imaging - Fault Normal - Rupture speed



Rupture propagation

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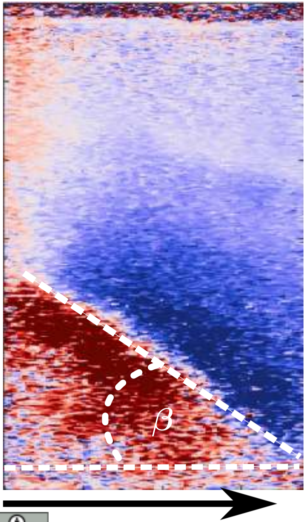
Supershear rupture

- Straight wavefront (Mach cone)

Rupture Imaging - Fault Normal - Rupture speed



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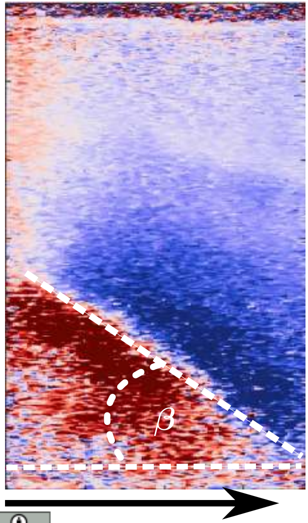
Rupture propagation

Supershear rupture

- Straight wavefront (Mach cone)
- $\sin\beta = \frac{c_s}{v_r}$

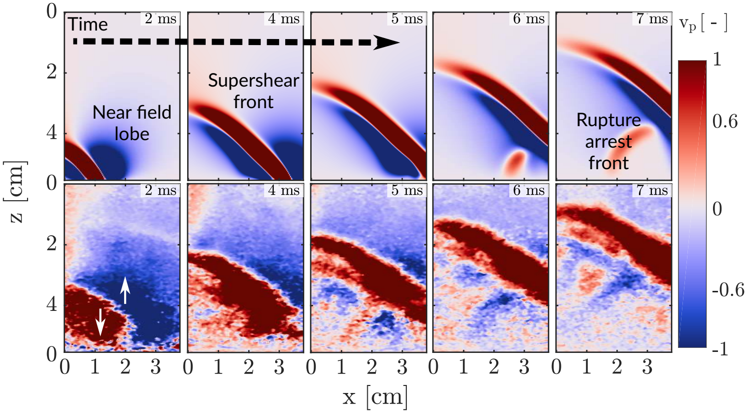


Rupture propagation

Supershear rupture

- Straight wavefront (Mach cone)
- $\sin\beta = \frac{c_s}{v_r}$
- Constant average angle for all ruptures
  $\Longrightarrow \text{v}_\text{R} \approx [17\text{-}20]\,\mathrm{m\,s^{-1}} \quad \text{v}_\text{S} \approx 7\,\mathrm{m\,s^{-1}}$

Rupture Imaging - Fault Normal - Experiment versus Simulation



Kinematic simulation

Green's function

Dynamic experiment

Complex rupture

Elastic effects highlighted $\rightarrow$ slip not reproduced

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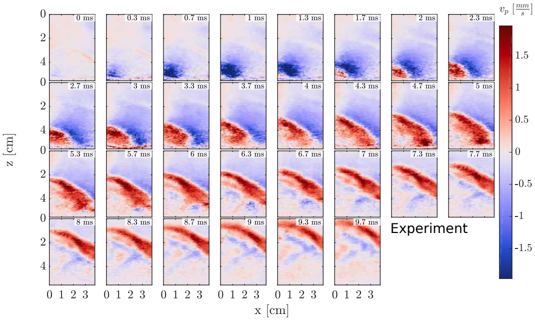
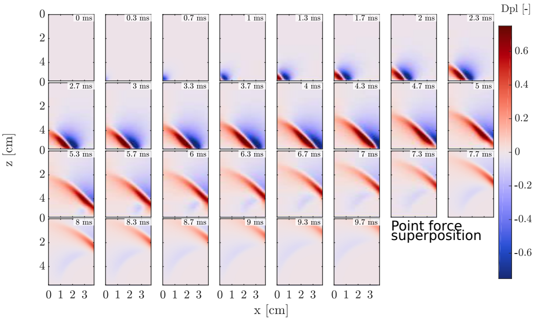
Rupture Imaging - Fault Normal - Experiment versus Simulation





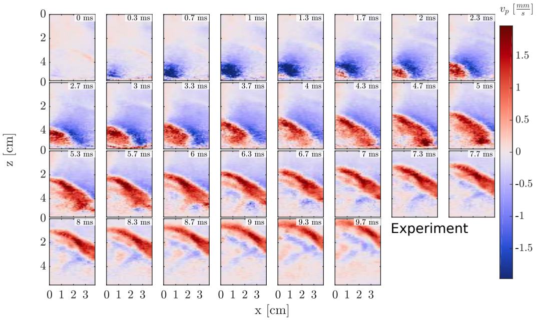
Kinematic simulation Shear force

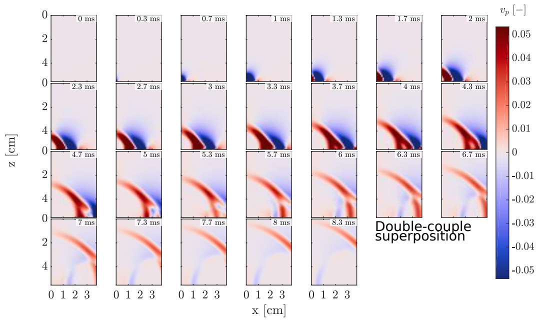
Source: Gaussian shaped force; Snapshots: Displacement field ($\int_0^t (v_p) dt$)

$u(t) = \int_0^t (F * G) dt$ fits better than $v_p(t) = F * G$

Gaussian shear force misses continuous displacement of source

Rupture Imaging - Fault Normal - Experiment versus Simulation





Kinematic simulation DC

Source: Displacement ramp; Snapshots: Particle velocity field

Qualitative fit better, but wavefield in DC-solution appears more complex

Rupture Imaging - Fault Normal - Experiment versus Simulation

Bimaterial contrast - Precursory event

- well reproduced by single shear force
- does not exhibit radiation pattern of double-couple
  $\Rightarrow$ We interpret the events either as microslips or grain rearrangements in the sand layer.

Bimaterial contrast - Breaking of asperity

- Double-couple source of a displacement ramp is more appropriate
- The full analytical DC solution shows a wavefield that exposes terms not identifiable in the experiment
- Either those terms are hidden due to limitations of the method or the true source mechanism is not an ideal double-couple.
  $\Rightarrow$ For the natural bimaterial system of glacial sliding, DC moment tensor inversion has been shown to be inaccurate[1]. $\Rightarrow$ The softness of the gel in combination with the poly-layer of grains could also lead to off-fault contributions.

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Rupture Imaging - Fault Normal

Snapshot

- 2D x-z data
- $> 100\,000$ data points

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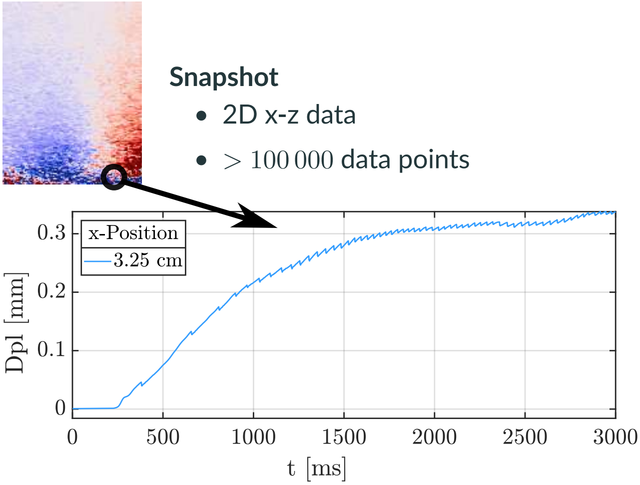
Rupture Imaging - Fault Normal



Snapshot

- 2D x-z data
- $> 100\,000$ data points

1D data

- Temporal evolution
- Asperity stick-slip

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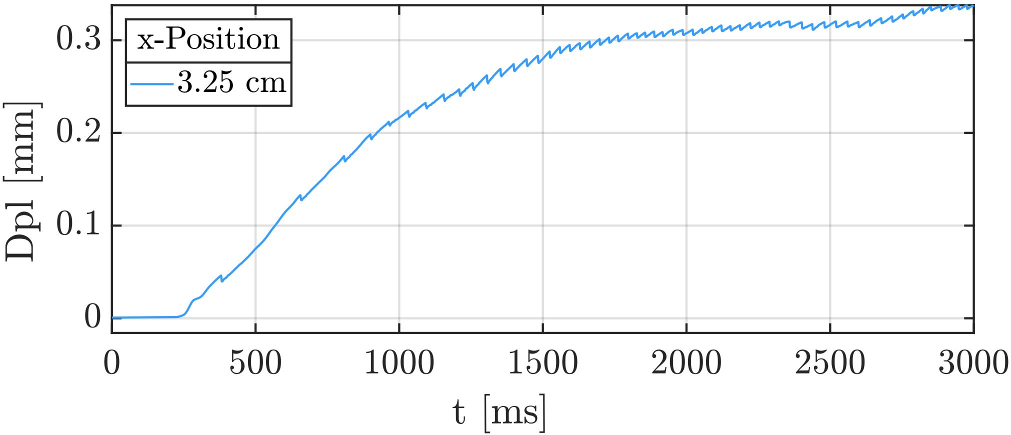
Rupture Imaging - Fault Normal



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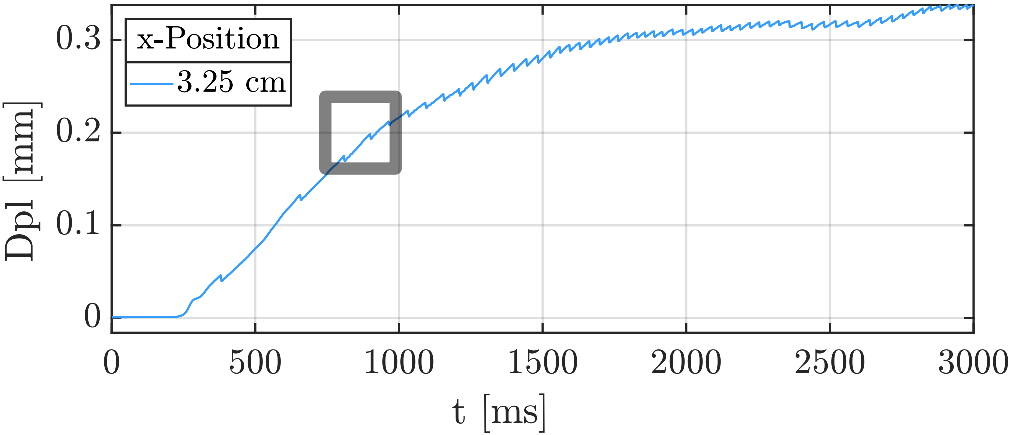
Rupture Imaging - Fault Normal



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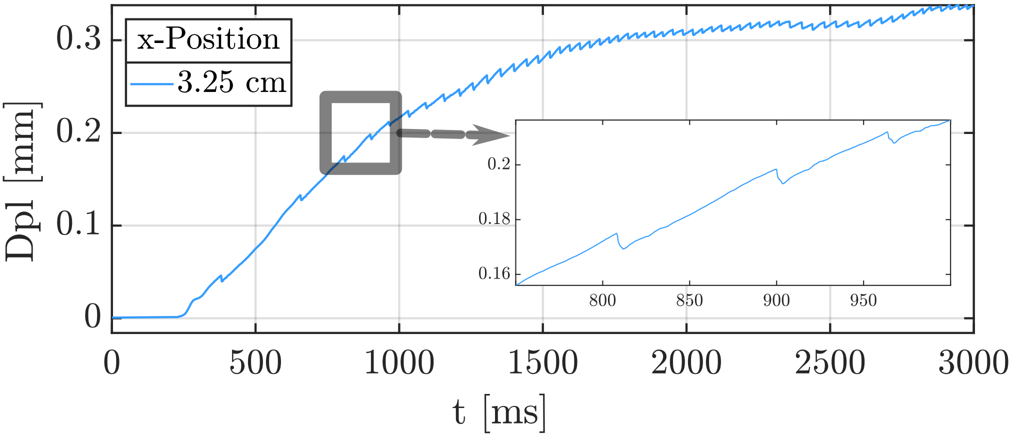
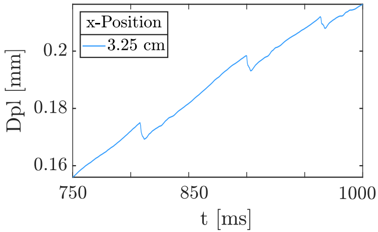
Rupture Imaging - Fault Normal

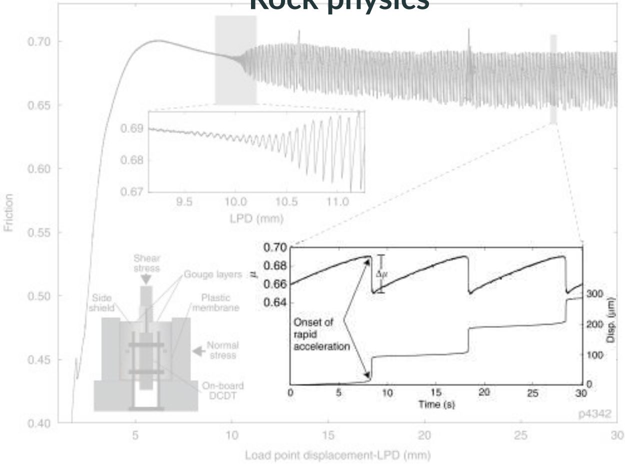


Rupture Imaging - Fault Normal

Hydrogel physics

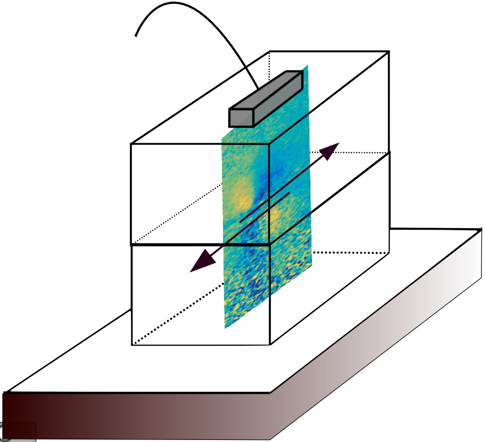


Rock physics



Leeman, Marone et al. (2016)

Rupture Imaging - Gel on Gel



Probe above gel

- Two elastic halfspaces
- Vertical particle velocity

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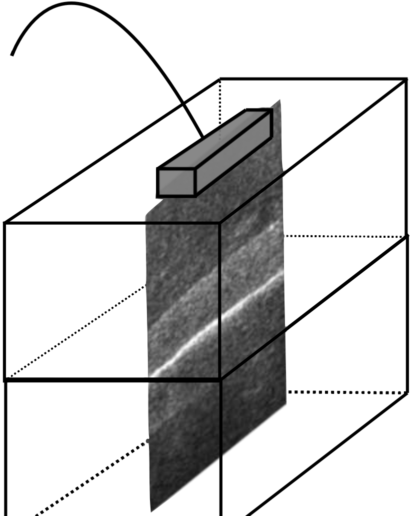
Rupture Imaging - Gel on Gel



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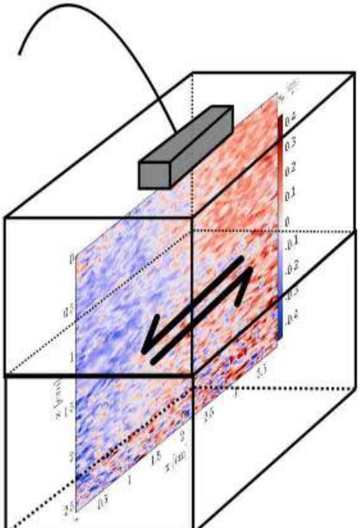
Rupture Imaging - Gel on Gel



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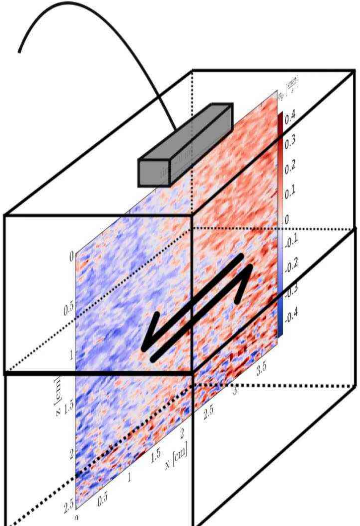
Rupture Imaging - Gel on Gel

if animation does not start, click on ima



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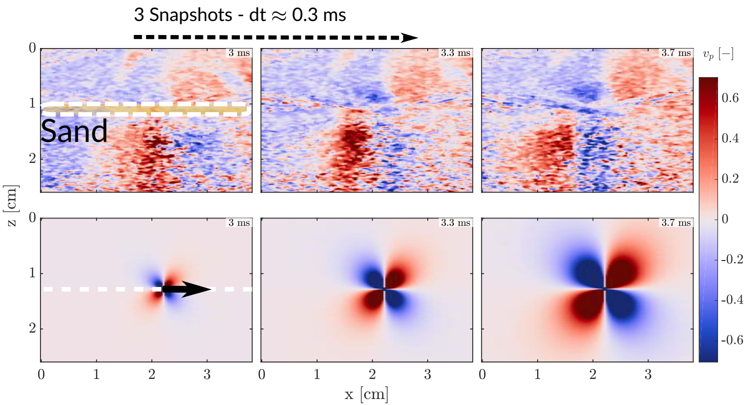
Rupture Imaging - Gel on Gel - Precursory event

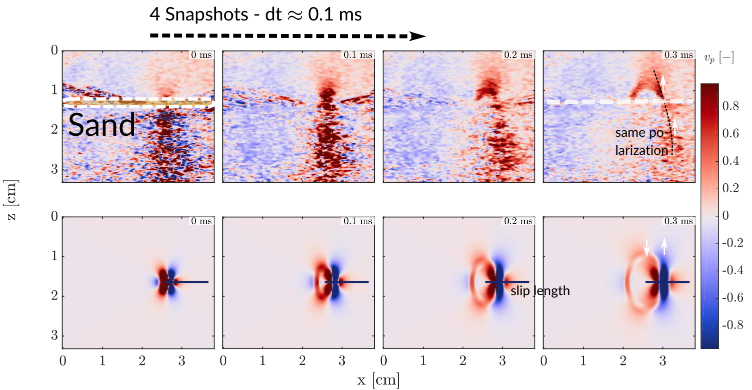


Experiment

Point source simulation

Quadripole of a single force reproduced

Rupture Imaging - Gel on Gel - Precursory event



Experiment

DC superposition simulation

Coherent polarization in upper and lower halfspace reproduced

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Rupture Imaging - Gel on Gel - Experiment versus Simulation

Precursory events

- Single shear force qualitatively reproduces radiation pattern
- Long rise time of 3ms

Rupture events

- Single shear force insufficient for radiation pattern
- DC reproduces coherent polarization in upper and lower halfspace
- Experiment does not show the complete radiation pattern of the analytic DC solution $\Rightarrow$ might be hidden in noise and global movement of the gel blocks $\Rightarrow$ neither the pure double-couple nor the simple shear force might reproduce the gel-on-gel sliding. We hypothesize that off-fault terms are likely due to the setup of two soft, not perfectly homogeneous gels with a hard grain layer in-between.

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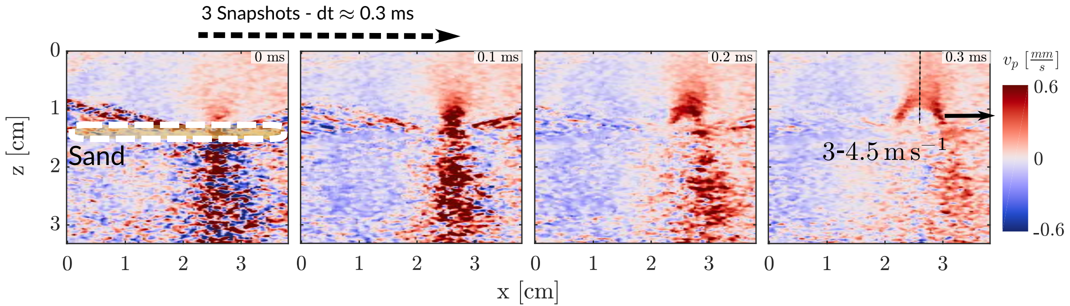
Rupture Imaging - Gel on Gel - Sub-shear



Sub-shear rupture

- Right-traveling
- Complex source mechanism

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Rupture Imaging - Summary

Observed

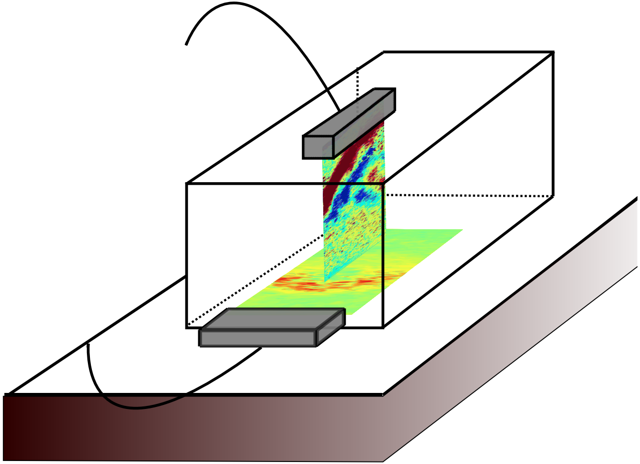
- Super- and sub-shear rupture
- Precursors
- Reproducible ruptures $\rightarrow$ statistics

Observed

- Super- and sub-shear rupture
- Precursors
- Reproducible ruptures → statistics

Work in progress

- Cross-plane acquisition
- Improve detection → statistics



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Glacial sliding

©Ugo Nanni

https://resolve.osug.fr/?lang=fr

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Glacial sliding

- Strong bimaterial contrast
  $\rightarrow$ Analog to glass-gel

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Rupture Imaging - Outlook

Glacial sliding

- Strong bimaterial contrast
  $\rightarrow$ Analog to glass-gel
- Smaller scale than fault

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Rupture Imaging - Outlook

Glacial sliding

- Strong bimaterial contrast
  $\rightarrow$ Analog to glass-gel
- Smaller scale than fault
- Recently equipped study site - Dense seismic array

©Ugo Nanni

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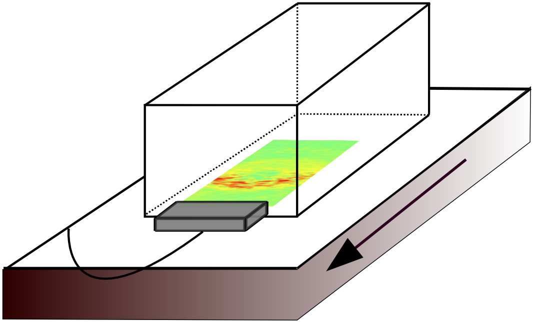
Bonus: Rupture Imaging - Fault Parallel



Probe parallel - side view

- Horizontal particle velocity
- Near-field of rupture

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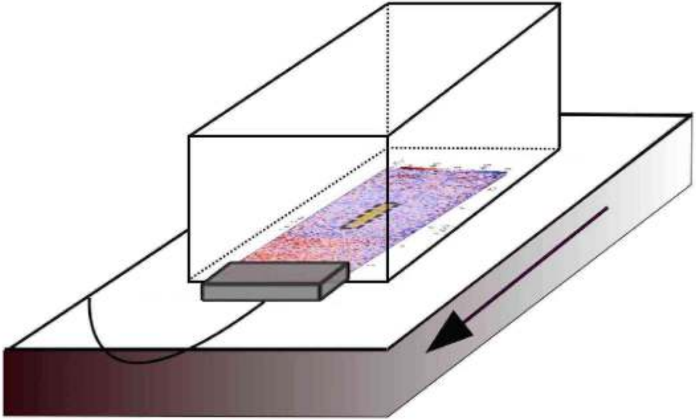
Bonus: Rupture Imaging - Fault Parallel



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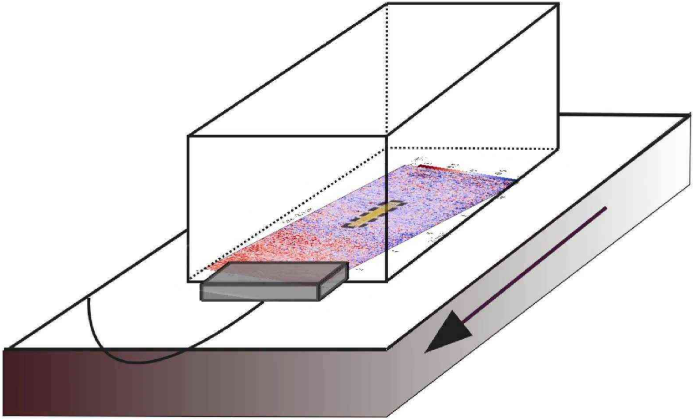
Rupture Imaging - Fault Parallel

if animation does not start,



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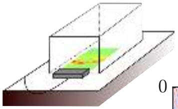
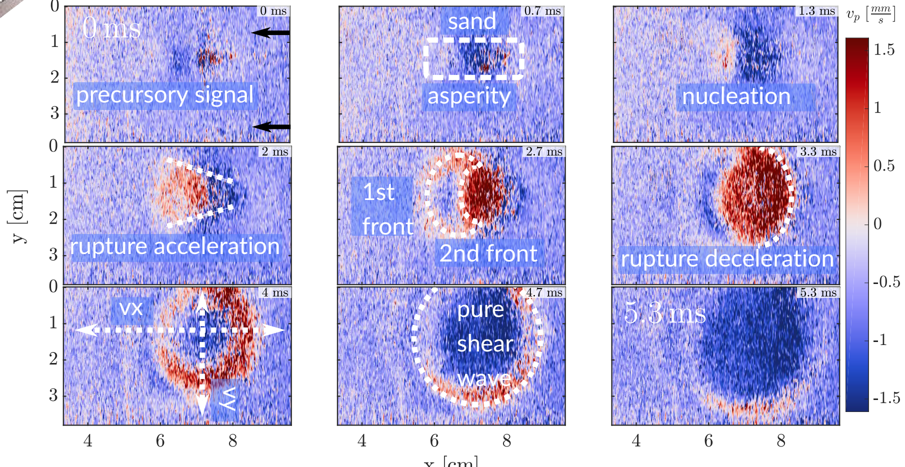
Bonus: Rupture Imaging - Fault Parallel

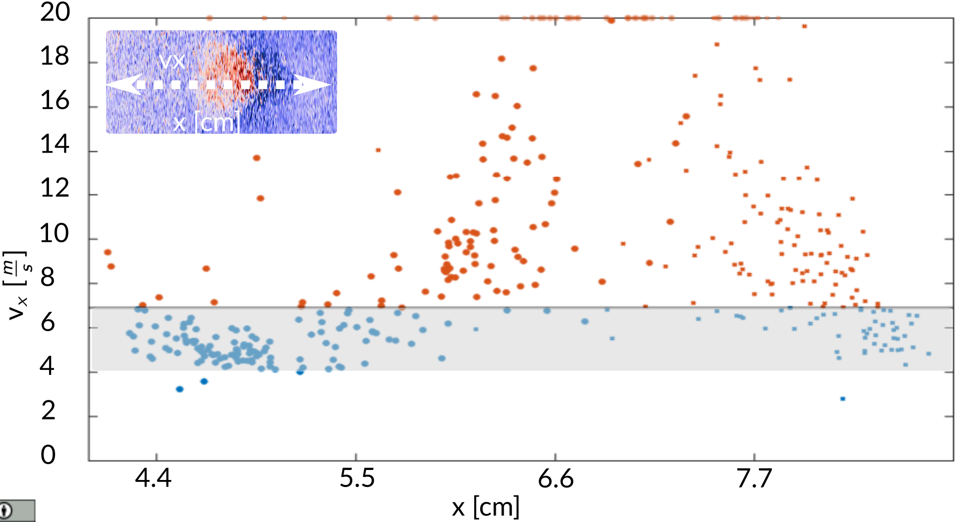


Time: 0 - 5.3 ms



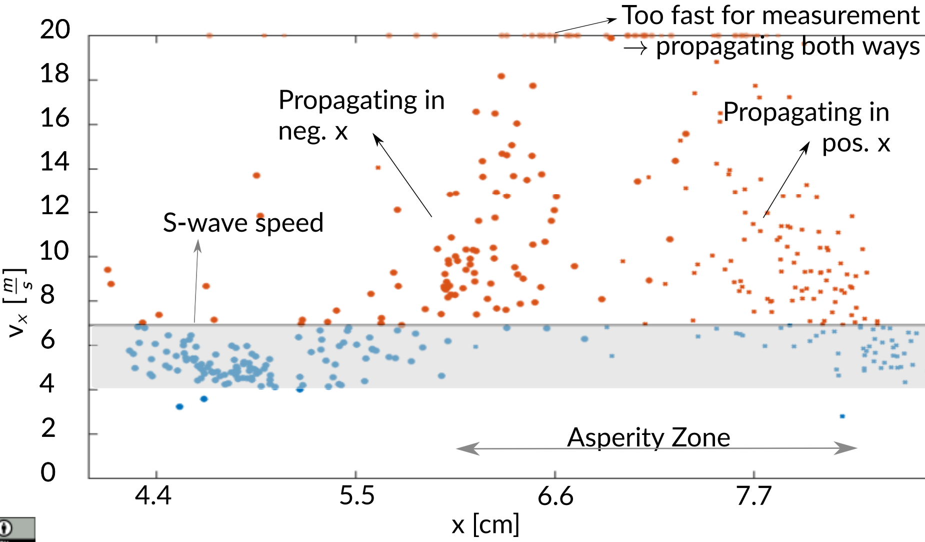
cc BY

Bonus: Rupture Imaging - Fault Parallel



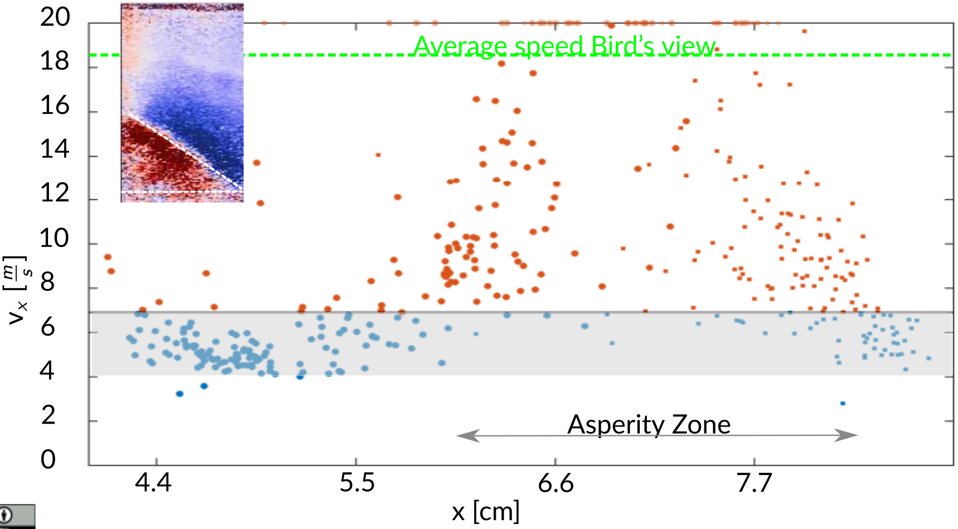
CC BY

Bonus: Rupture Imaging - Fault Parallel



CC BY

Bonus: Rupture Imaging - Fault Parallel



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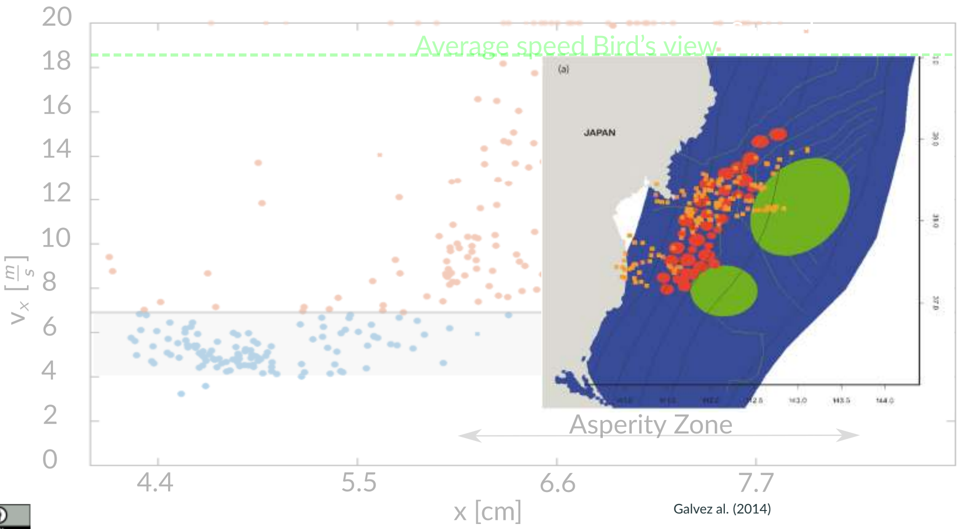
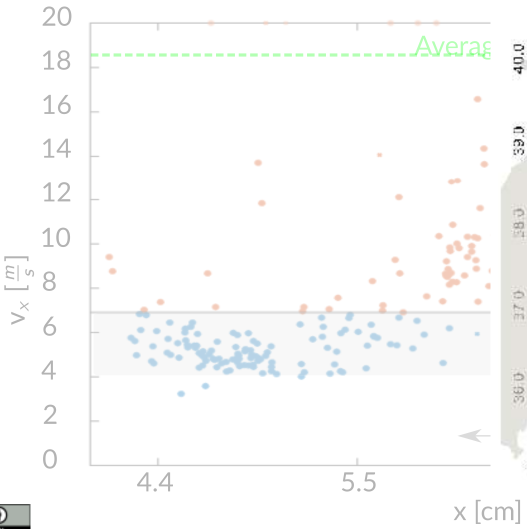
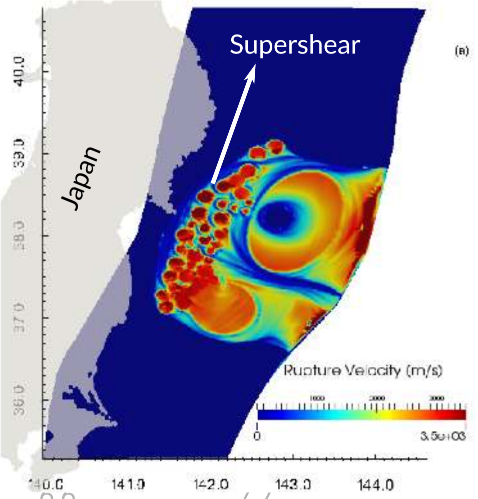


Galvez al. (2014)

CC BY

Bonus: Rupture Imaging - Fault Parallel





Galvez al. (2014)