EGU General Assembly 2022

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# Stress triggering and the spectrum of fault slip behavior

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SAPIENZA UNIVERSITÀ DI ROMA

PennState

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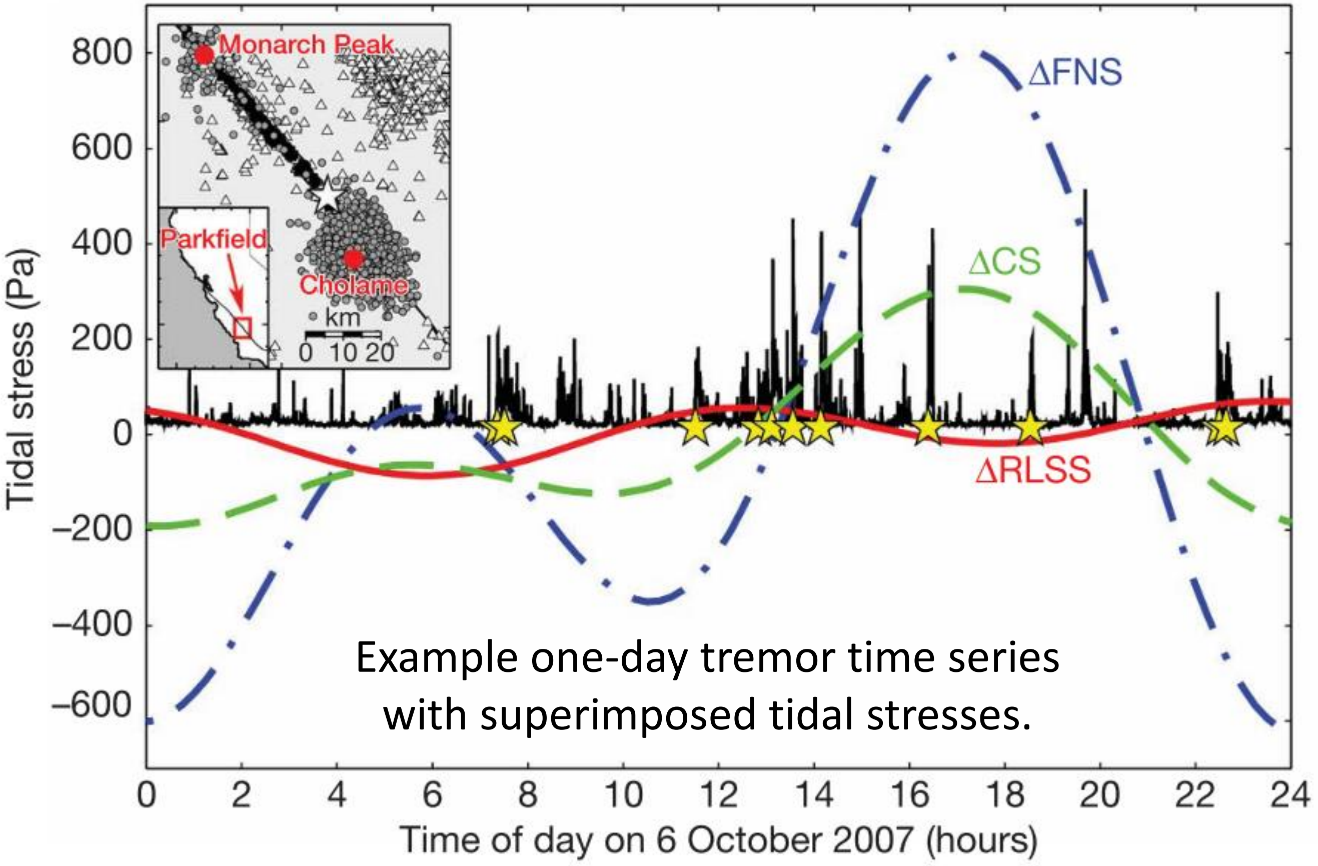
# Introduction

Stress perturbation can **trigger earthquakes**

Slow-slip and tremors are also **sensitive to small stress variations**




Gomberg et al, (1997) Thomas *et al. Nature* (2009)

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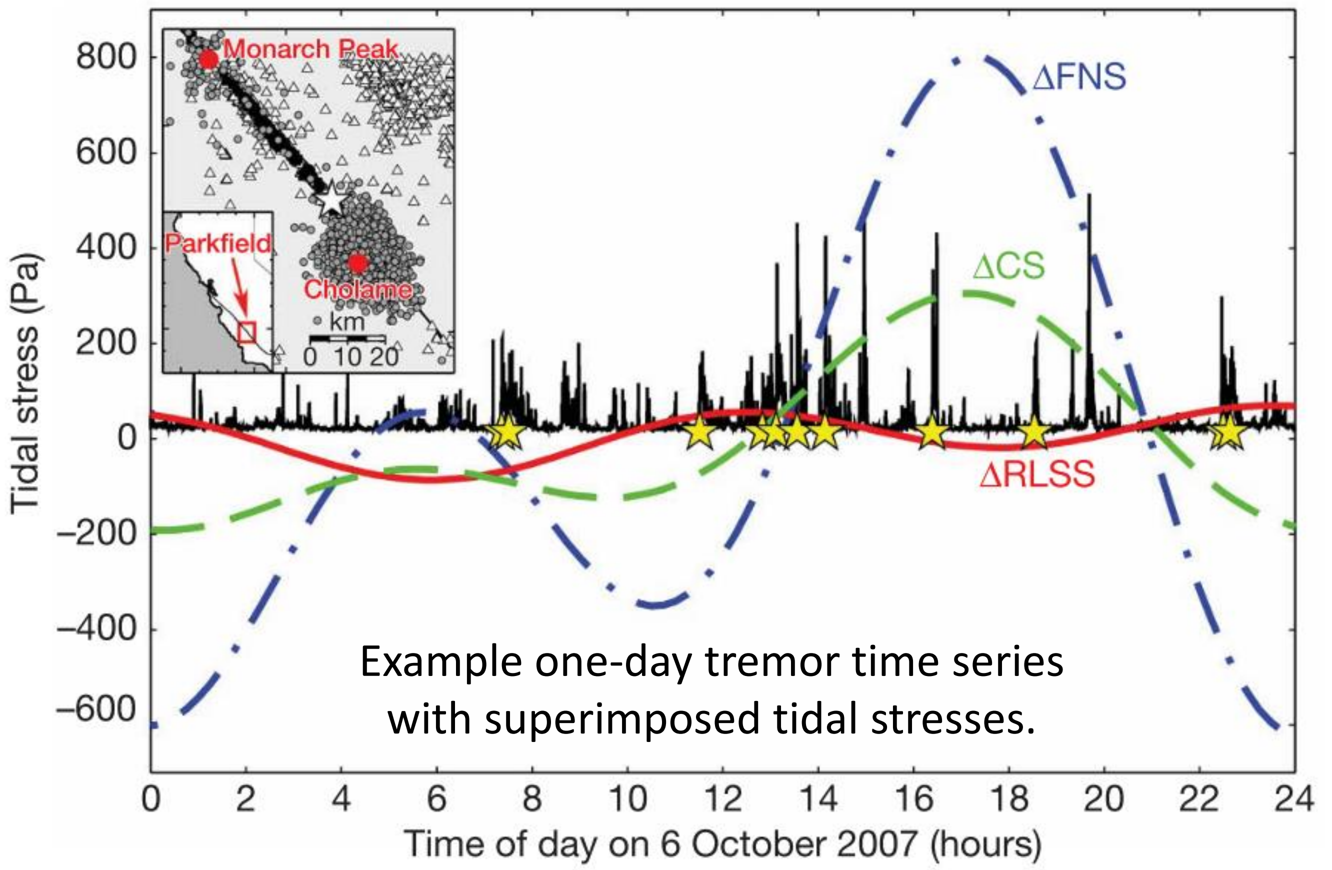


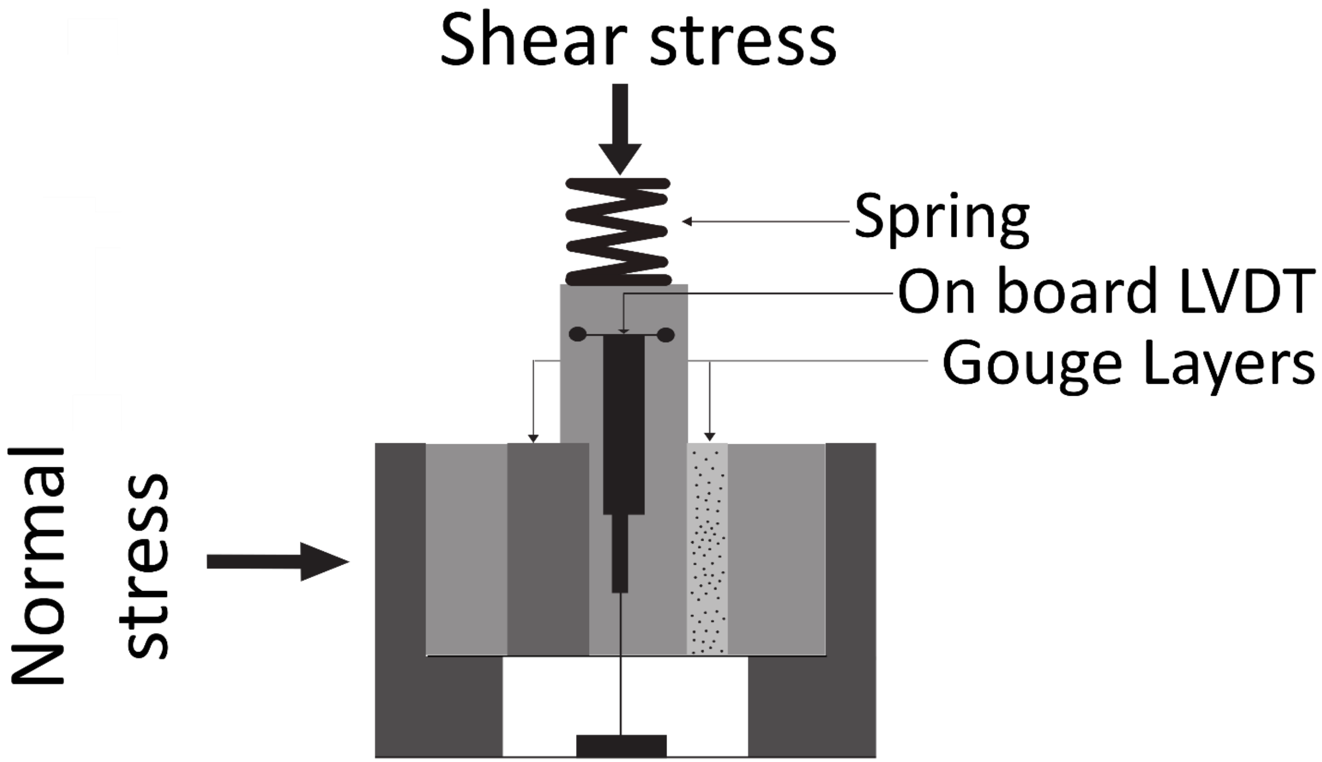

Example one-day tremor time series with superimposed tidal stresses.

## Outstanding questions

1. Relation between normal stress oscillation and **slip behavior** ?
2. Normal stress oscillation **reduce fault strength**?
3. **Rate-and-state framework** describe the laboratory results ?

Gomberg et al, (1997) Thomas *et al. Nature* (2009)

# Experimental method

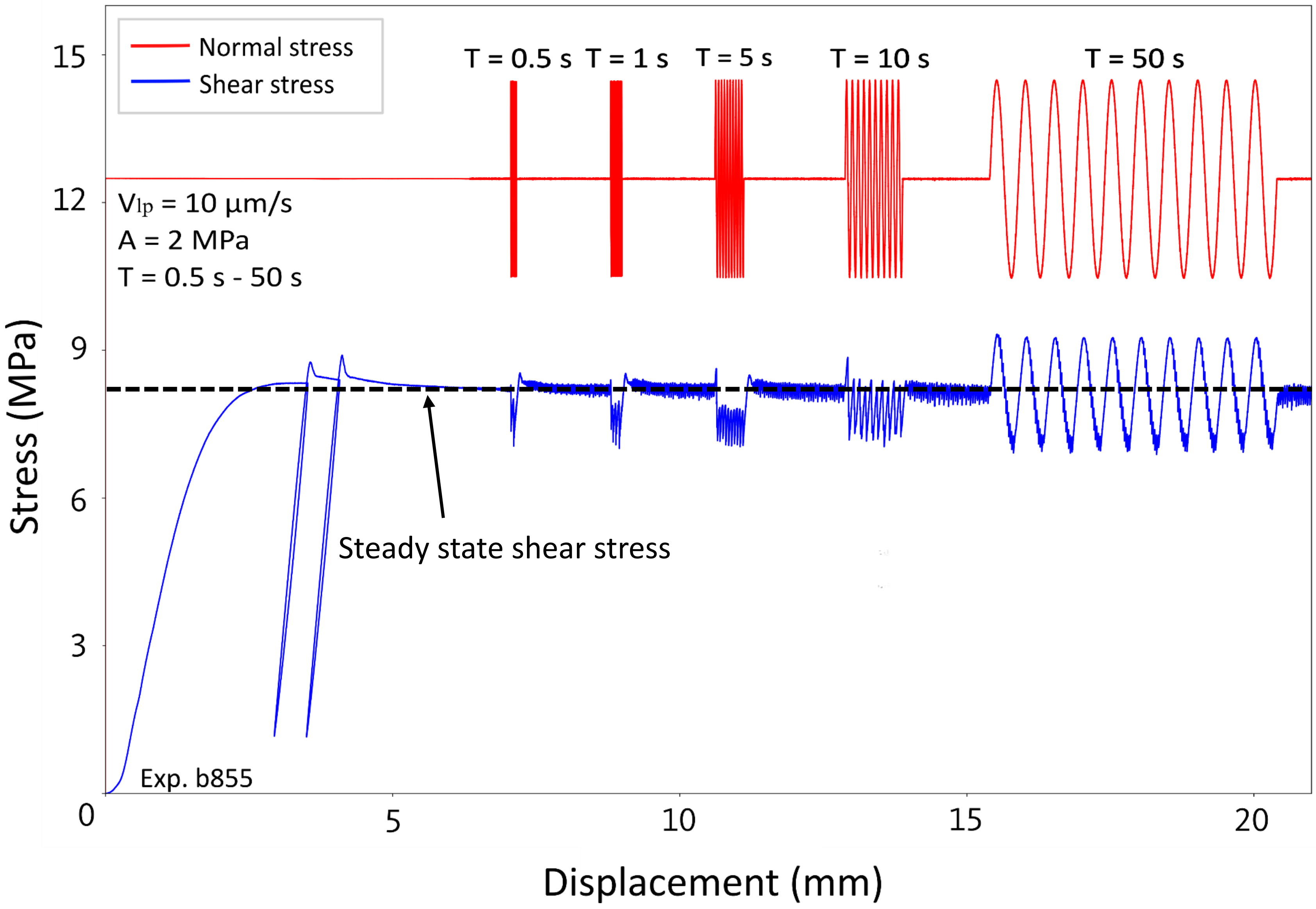



## Experimental conditions

- **Biaxial apparatus**
- **Double Direct-Shear** (DDS) configuration
- Using **quartz gouge**
- Under controlled **100% humidity** conditions
- Critically stiffness condition ***K'/Kc'* ~ 1.3**

BRAVA, Collettini et al., (2014)

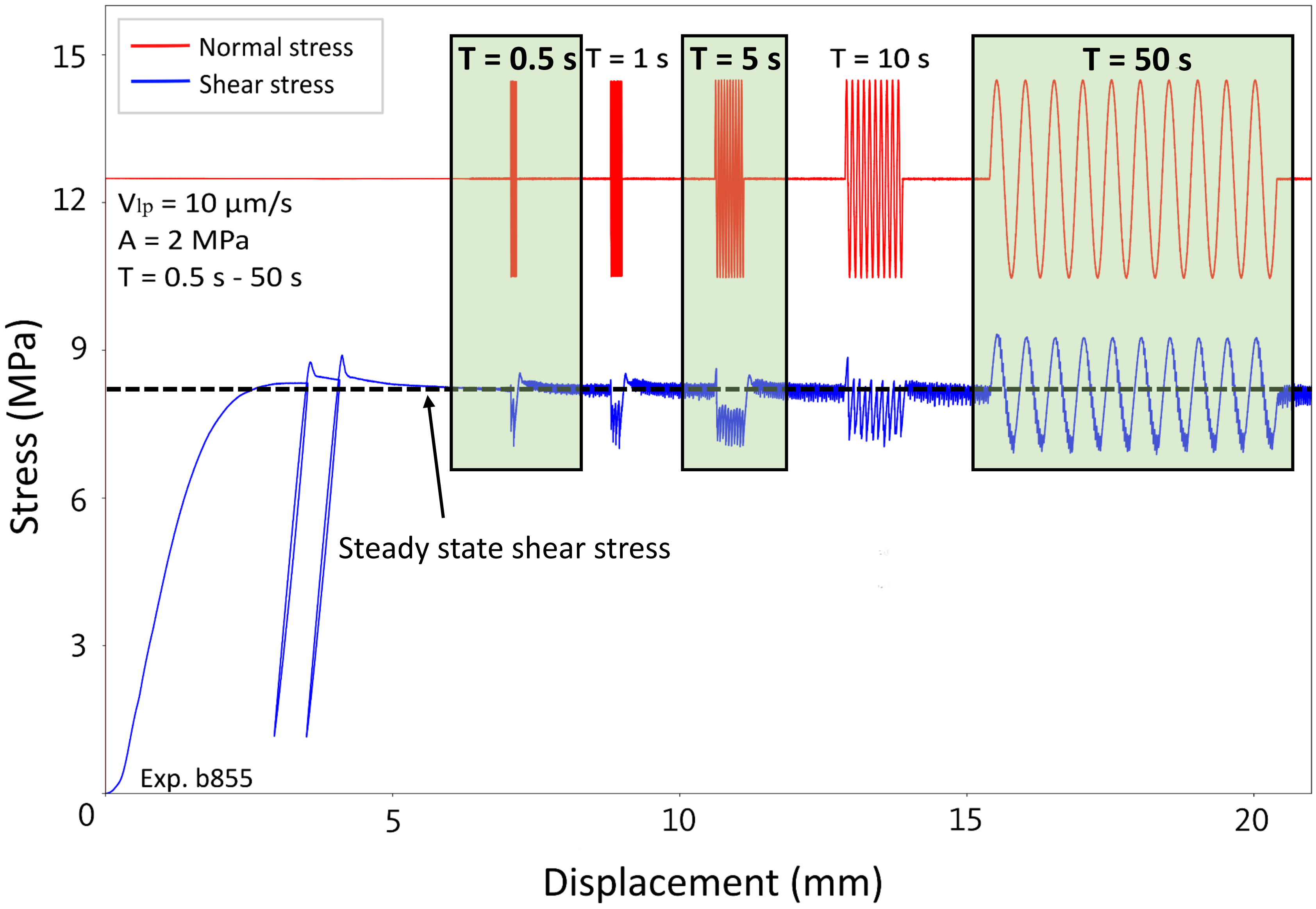
# Experimental method




## Experimental conditions

- Mean normal stress
  **$\sigma_n^{mean}$ = 12.5 MPa**
- Loading rate
  **$V_{lp}$ = 10 μm/s**
- Oscillation periods
  **T = 0.5 s** to **50 s**
- Oscillation amplitudes
  **A = 0.5 MPa, 1 MPa** and **2 MPa**

# Experimental method

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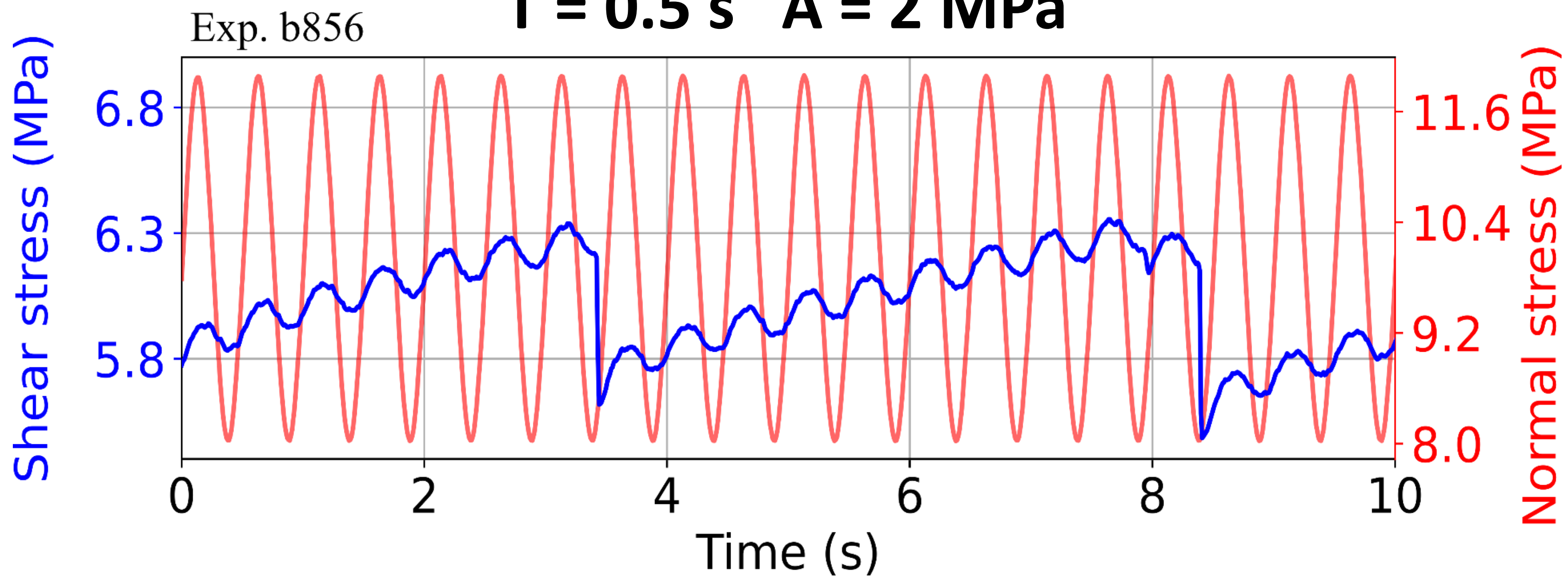
# Mechanical data

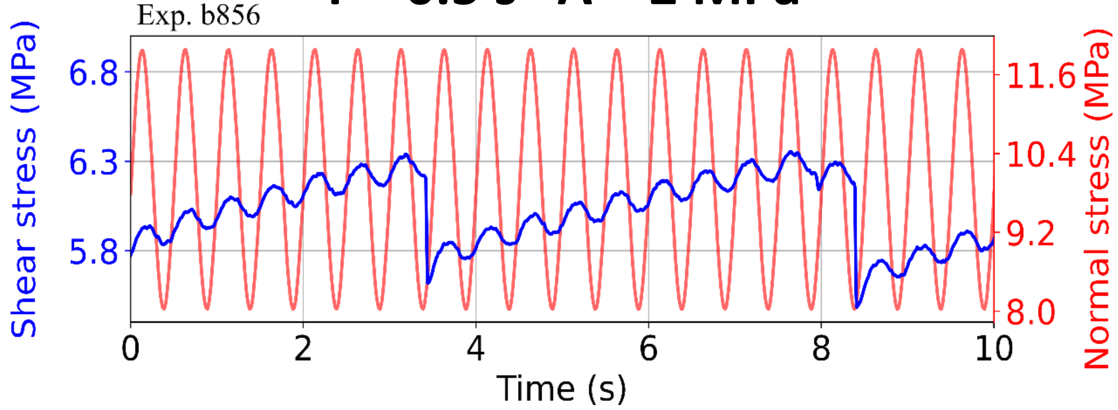
## T = 0.5 s   A = 2 MPa




**T = 0.5 s**: **In phase response** superimposed to a **shear stress accumulation**

# Mechanical data

**T = 0.5 s   A = 2 MPa**

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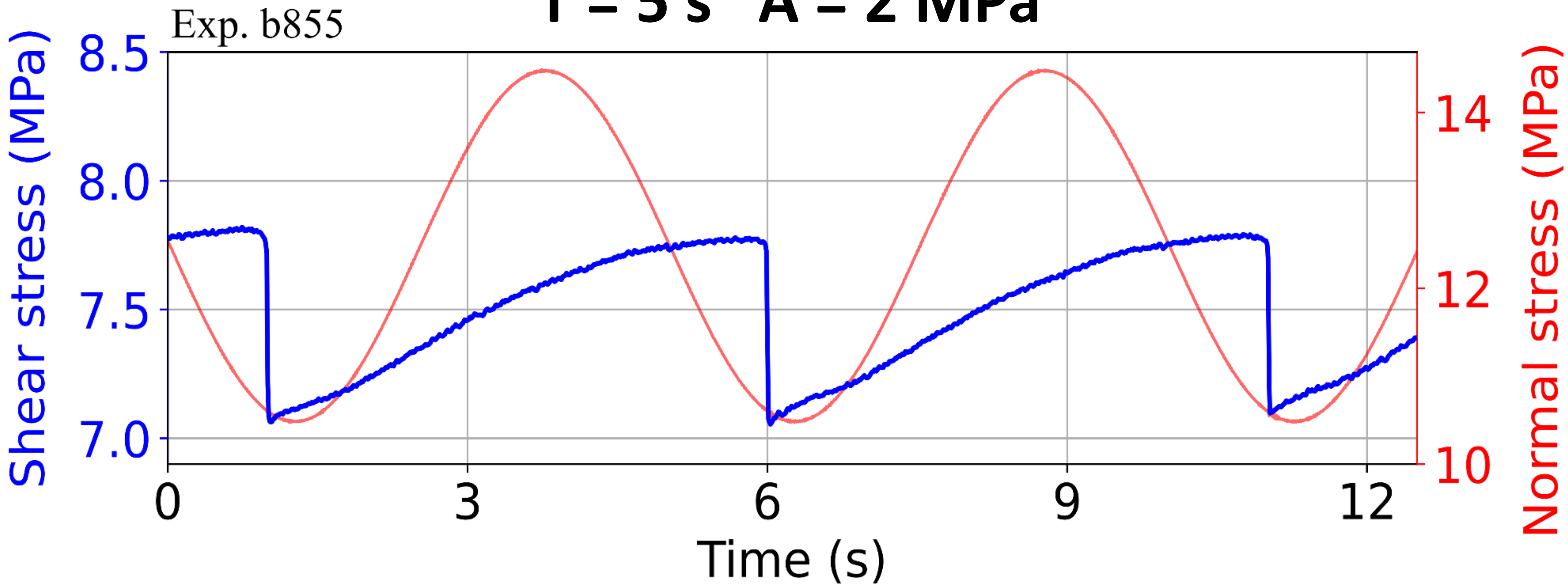
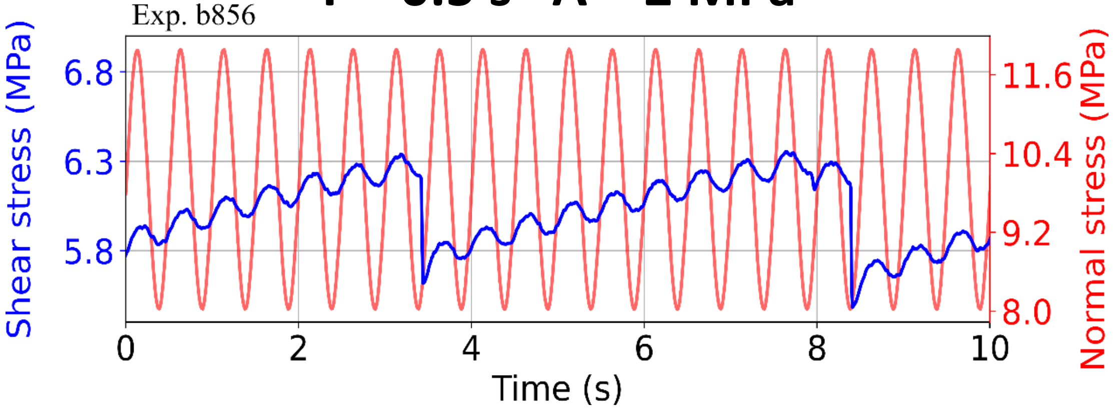



**T = 5 s**: Regular **stick slip behavior out of phase** with the oscillation

# Mechanical data

## T = 0.5 s   A = 2 MPa

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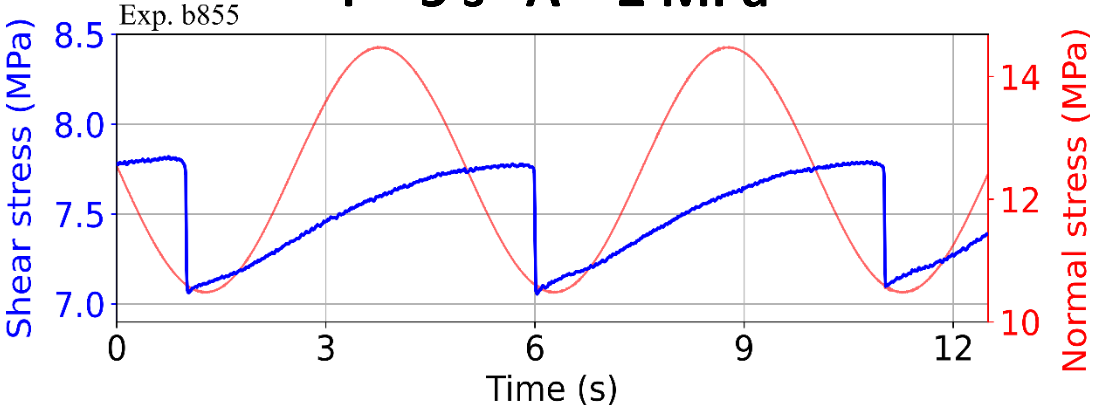
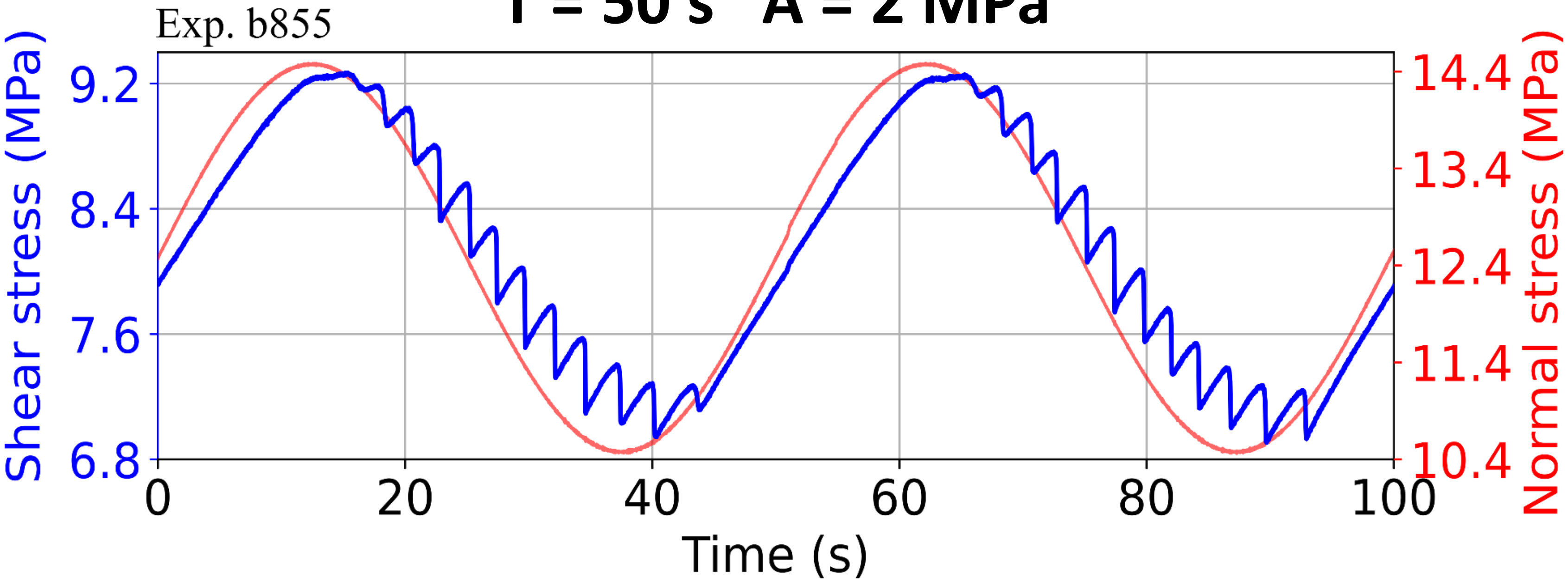
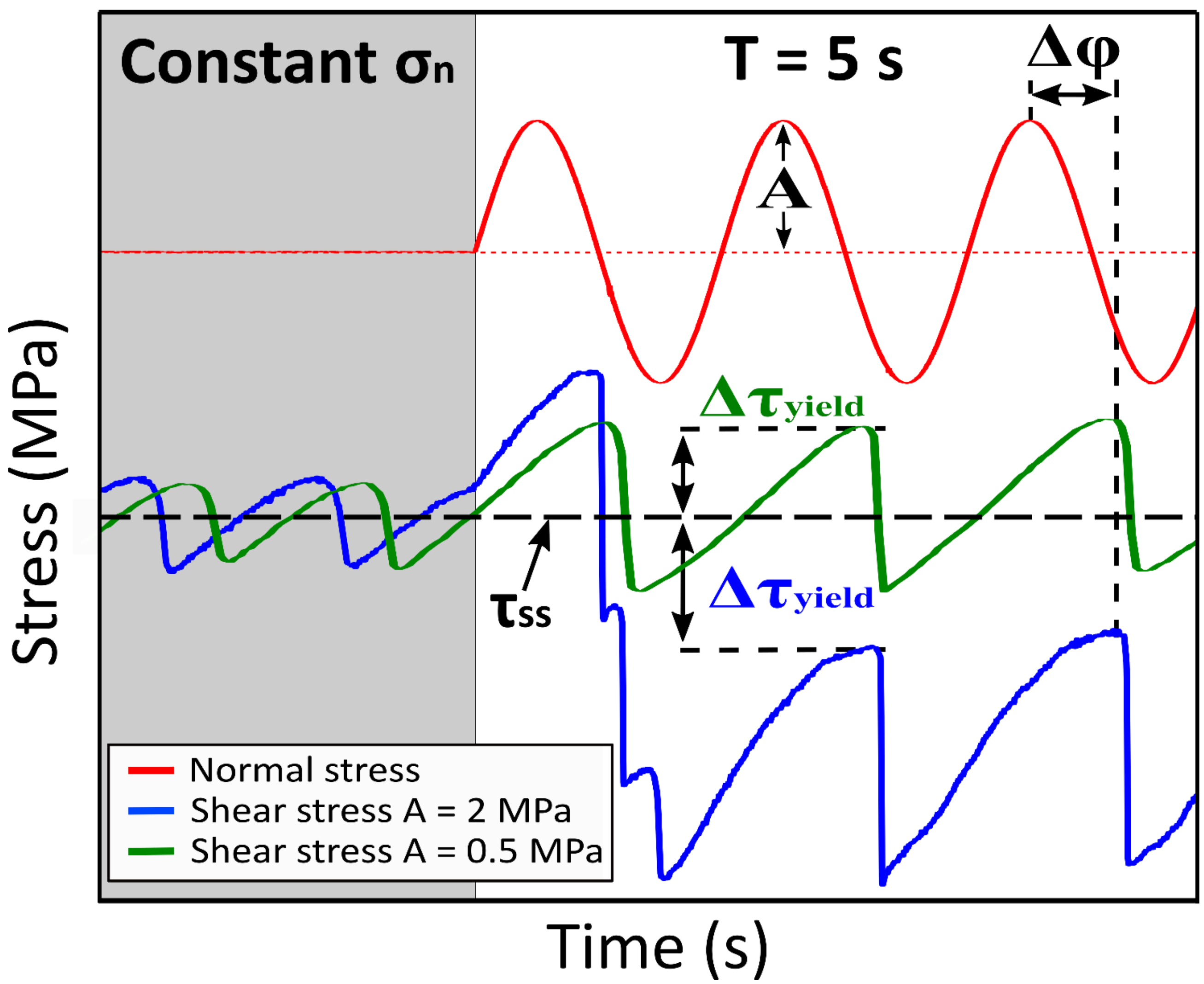



## T = 50 s   A = 2 MPa




**T = 50 s**: complete **modulation** with **instabilities** only during the normal stress decreasing

# Frictional response

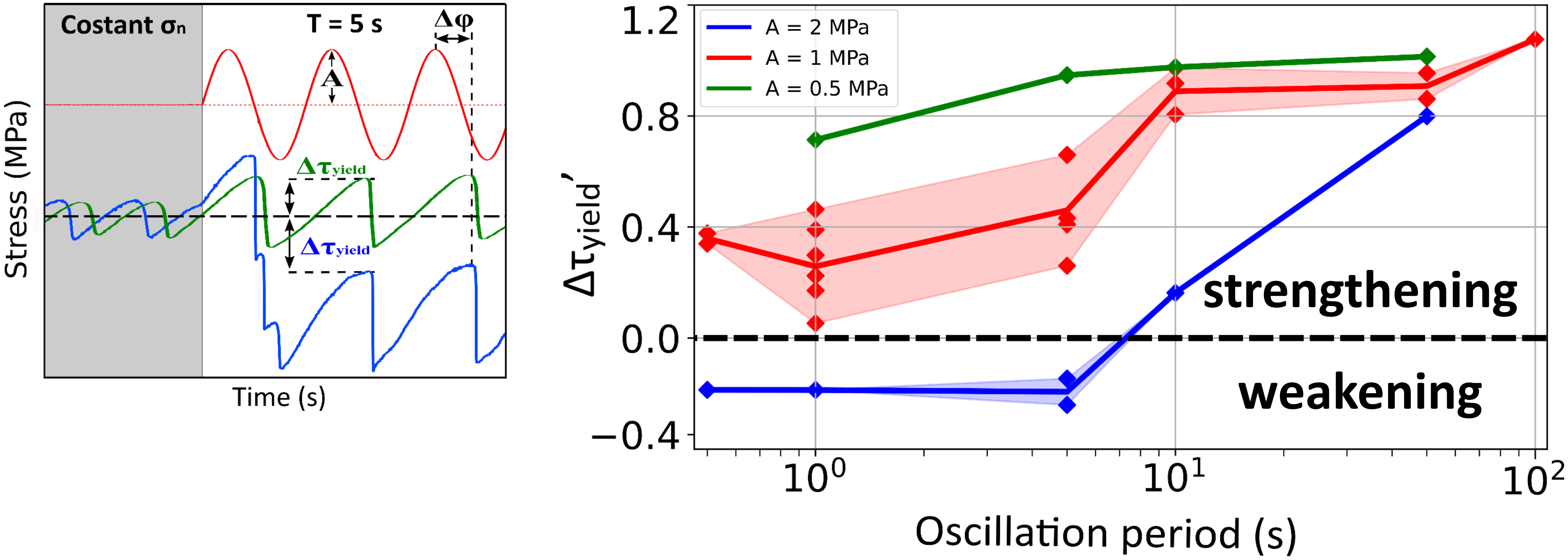



Two parameters to quantify the frictional response:

1. **$\Delta\tau_{yield}$**, the variation in peak yield strength.
2. **$\Delta\varphi$**, the phase lag.

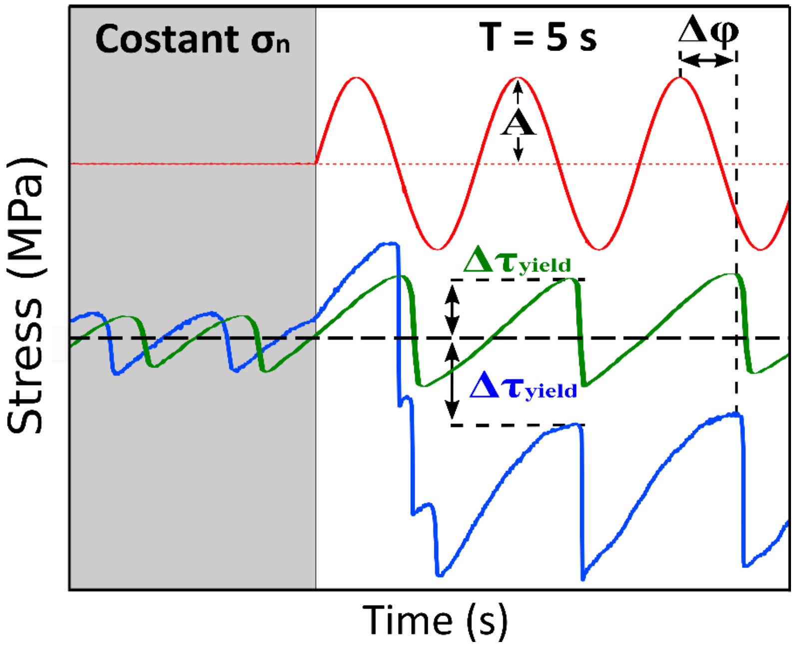
# Frictional response

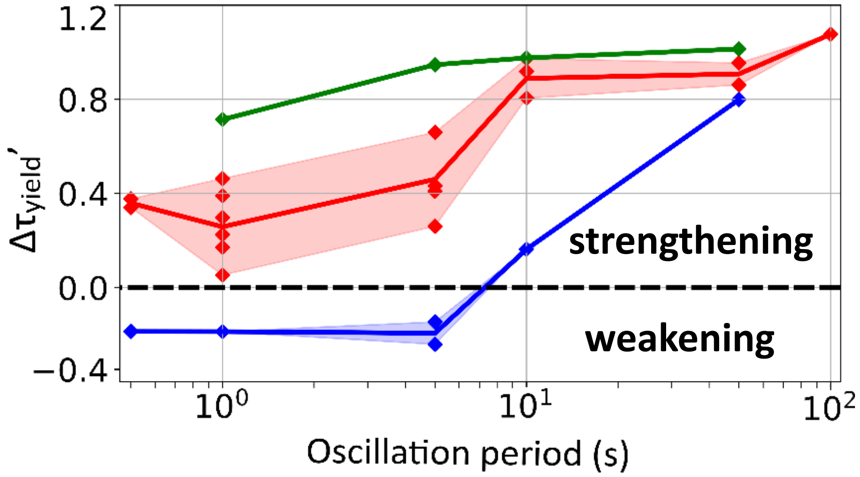
**$\Delta\tau_{yield}'$ < 0 dynamic weakening**, while **$\Delta\tau_{yield}'$ > 0 dynamic strengthening**

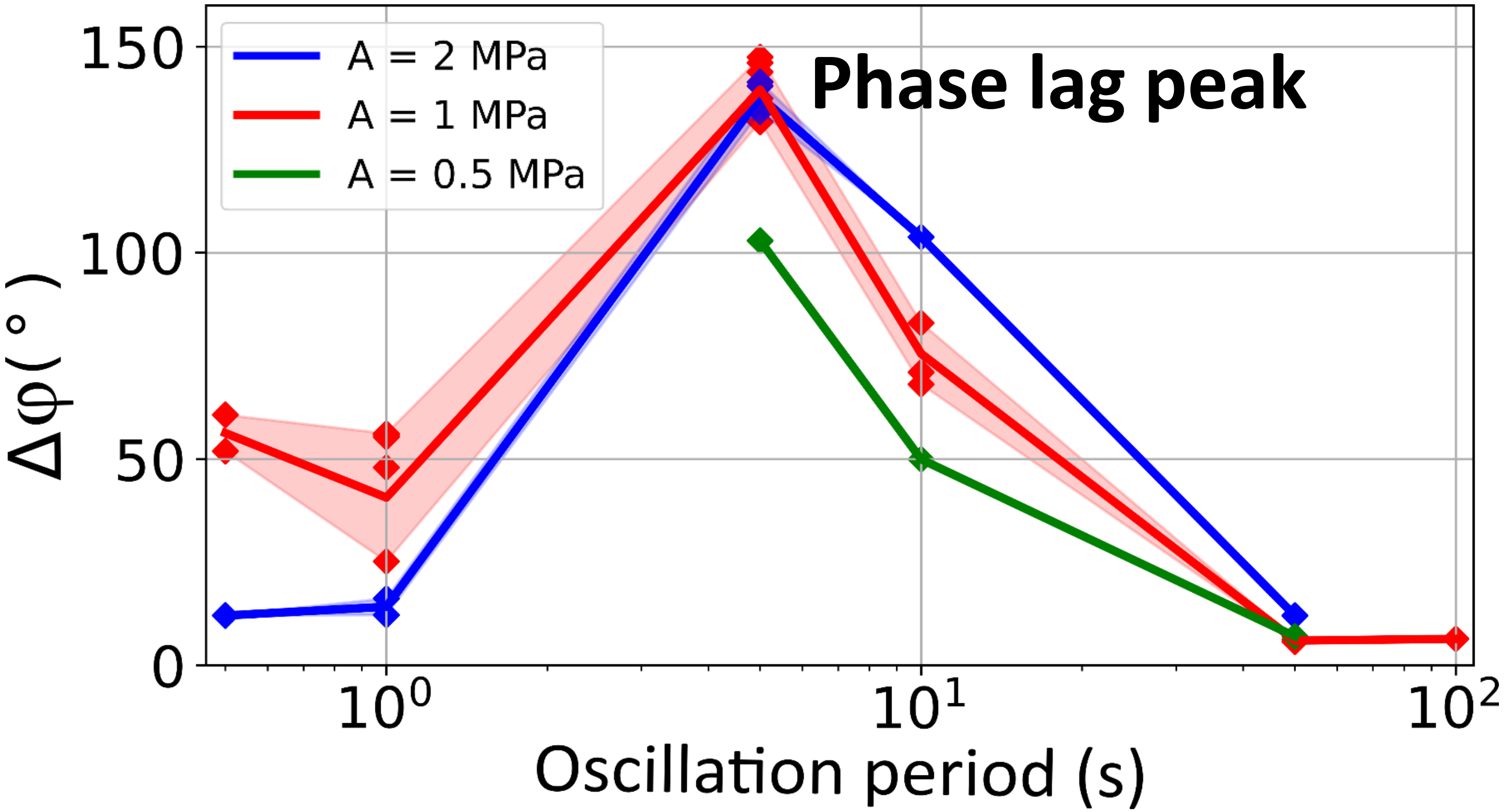


# Frictional response

**Δφ** is close to zero at short and long oscillation period, and is **maximum at *T* = 5 *s***



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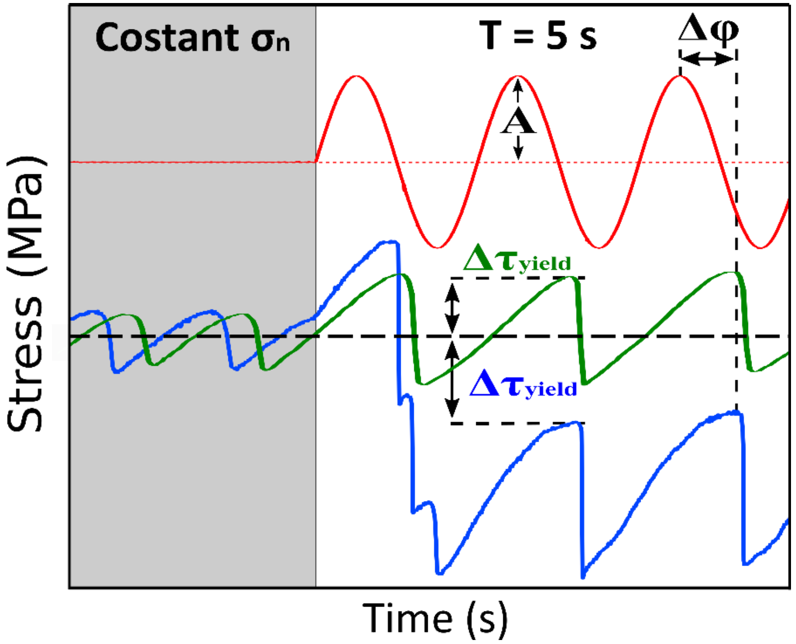
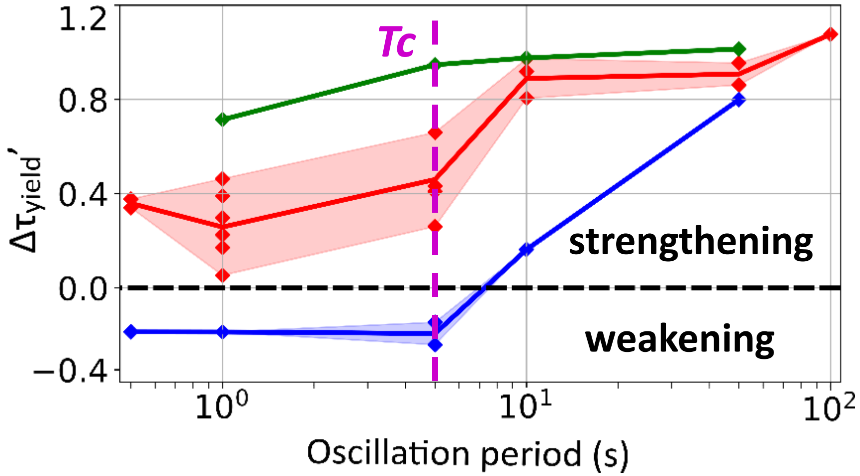
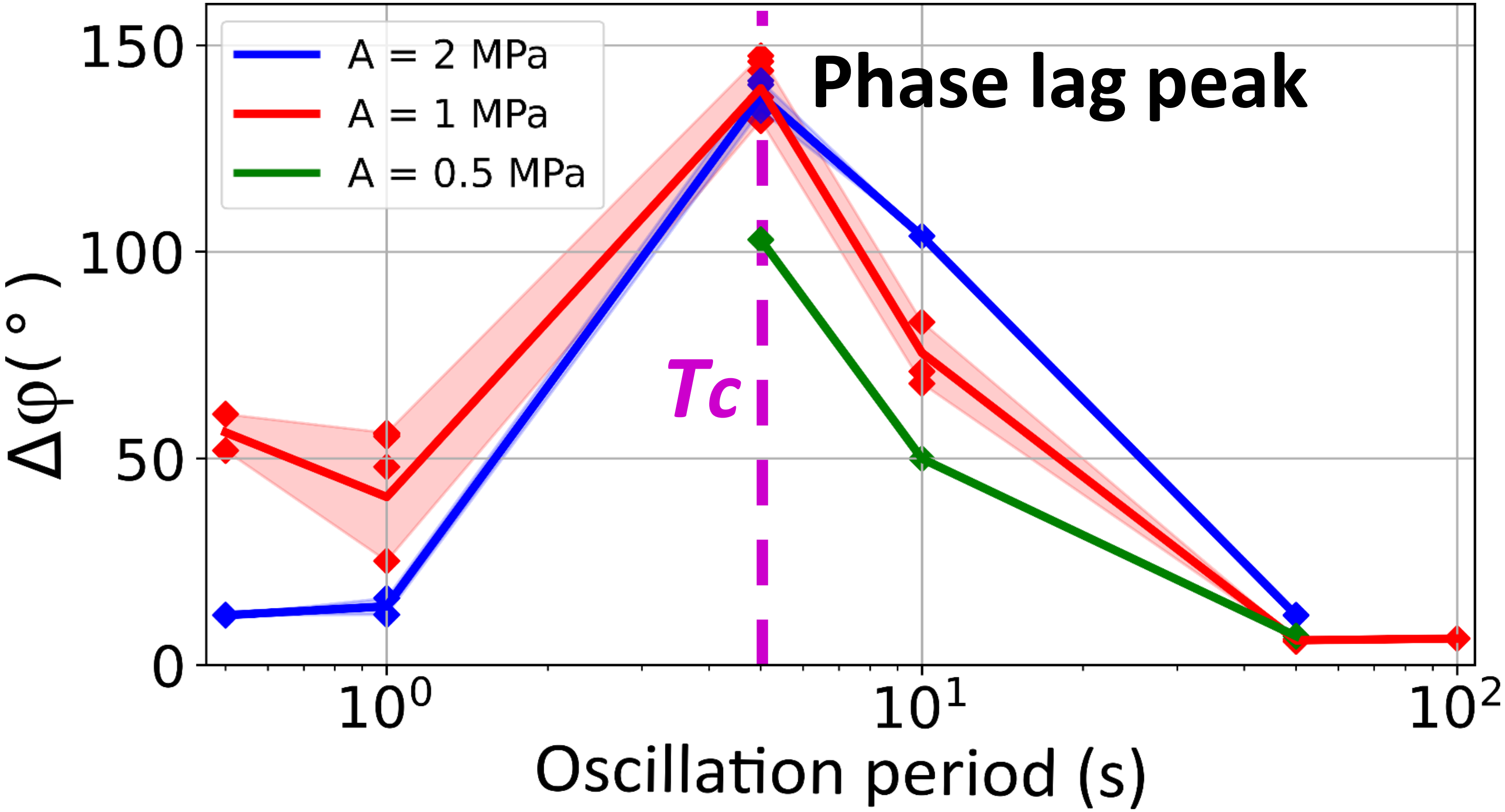


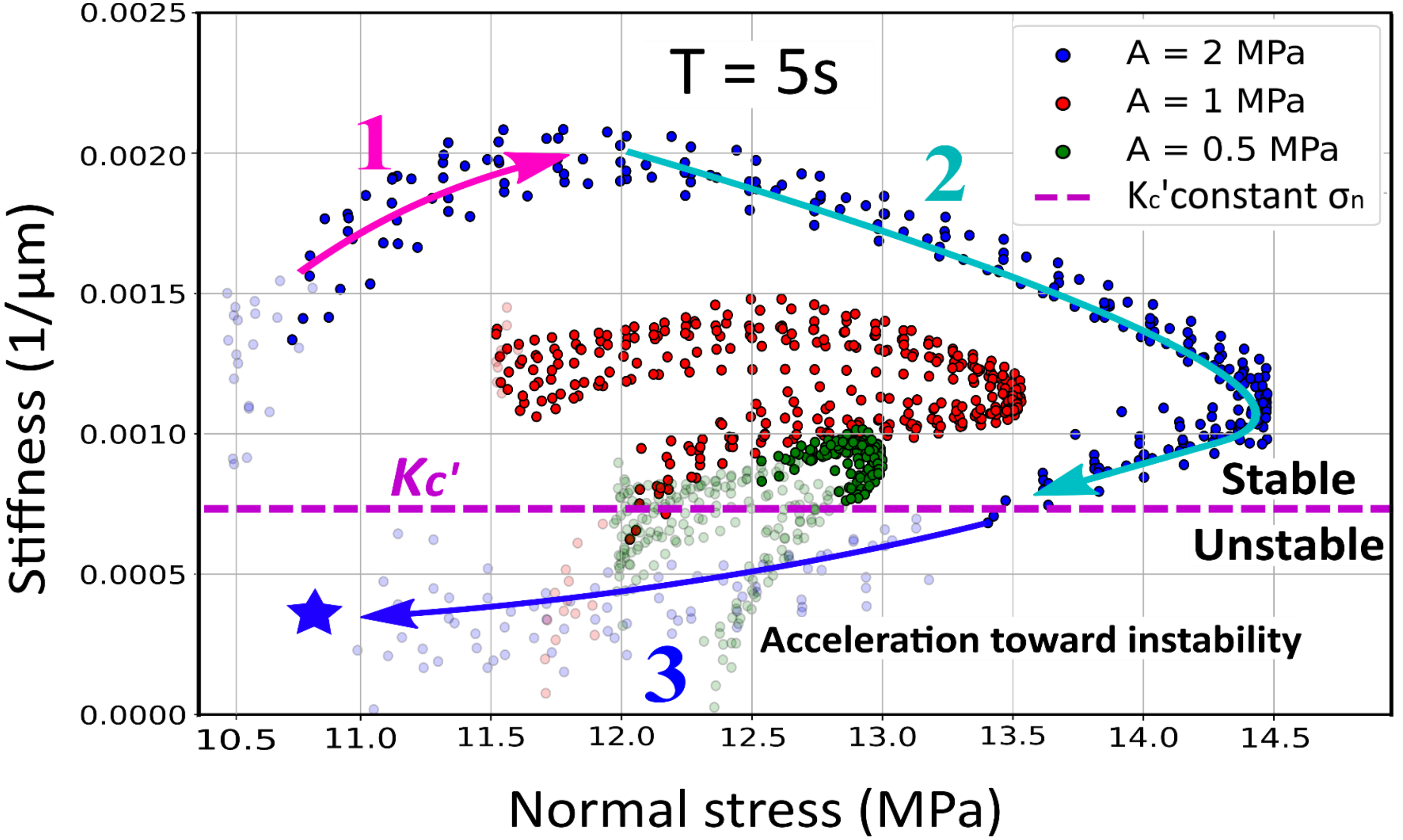



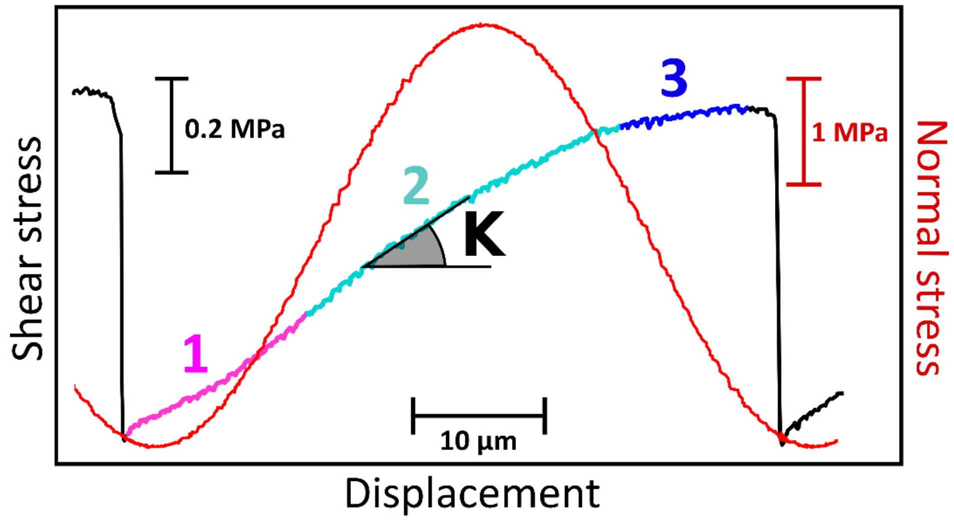




***T = 5 s*** correspond to the **critical period, *Tc***

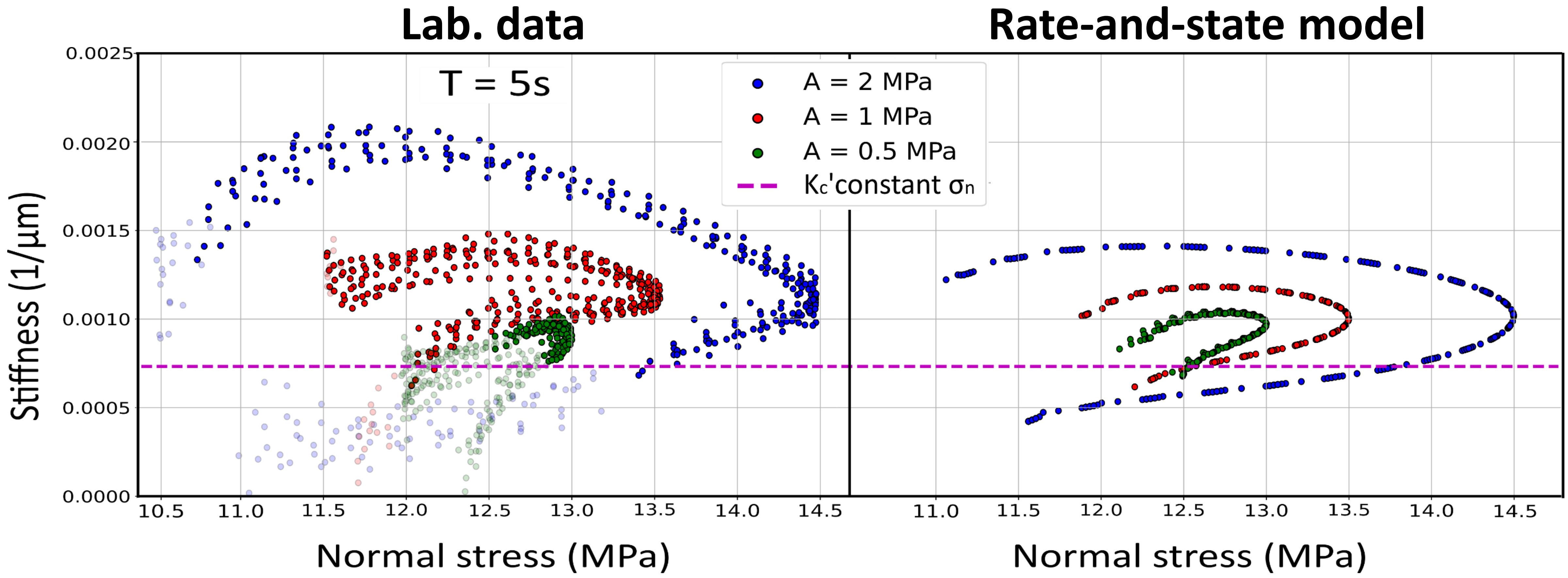
# Stiffness evolution

**Acceleration** when *K'* cross the **critical rheological stiffness (*Kc'*)**

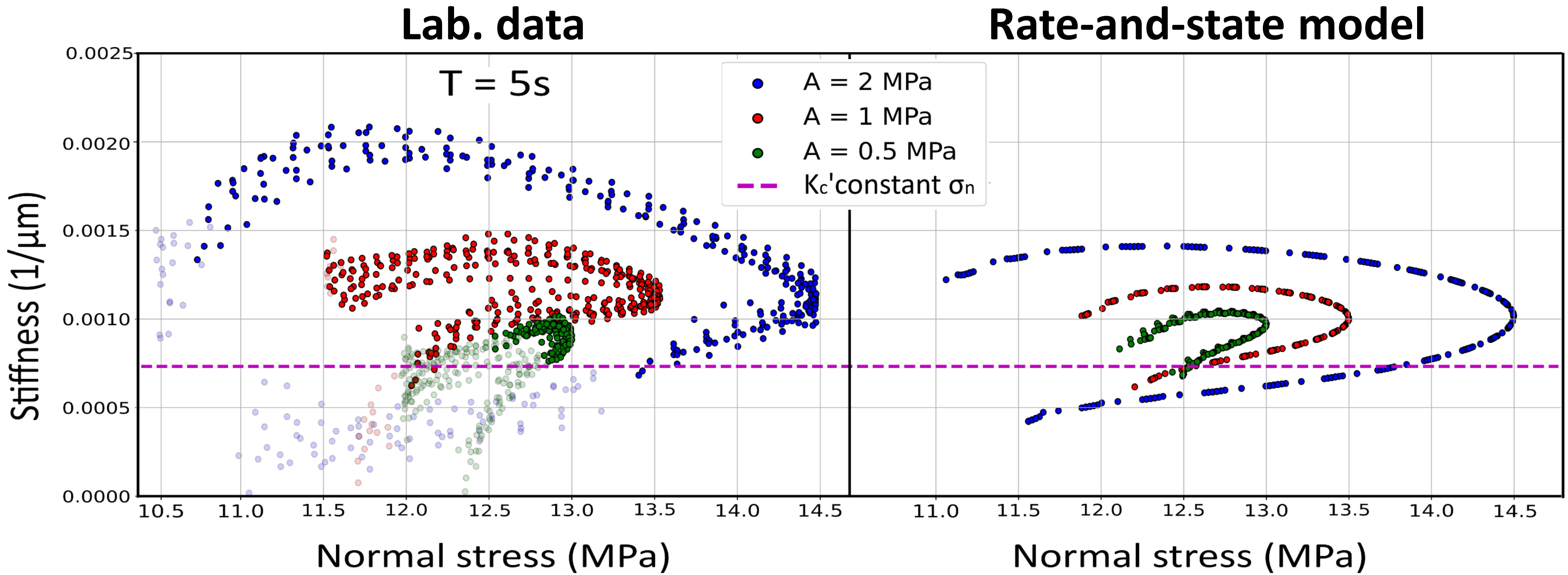


# Stiffness evolution



# Take home message




## Conclusions

- The fault slip behavior is **controlled by oscillation amplitude and period**.
- Low oscillation amplitude **strengthen the fault**. High oscillation amplitudes at short periods (*T ≤ 5 s*) **destabilize the fault**.
- **Rate-and-state modeling** is consistent with the laboratory data.

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# Thank you for your attention

If you have any questions I'm happy to discuss it
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*ERC adv. grant TECTONIC Nr. 835012*

# Rate-and-state model

**Friction costitutive law**

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

**Extended Dieterich evolution law**

$$\frac{\partial\theta}{\partial t} = 1 - \ln\left(\frac{V\theta}{D_c}\right) - \alpha\frac{\theta}{b\ \sigma_n}\frac{\partial\theta}{\partial t}$$

**Extended Ruina evolution law**

$$\frac{\partial\theta}{\partial t} = \frac{V\theta}{D_c}\ln\left(\frac{V\theta}{D_c}\right) - \alpha\frac{\theta}{b\ \sigma_n}\frac{\partial\theta}{\partial t}$$

With $\alpha = \dfrac{\Delta\tau_\alpha/\sigma_n^{step}}{\ln(\sigma_n^{step}/\sigma_n^0)}$

**Elastic interaction**

$$\frac{\partial\mu}{\partial t} = K'(V_{lp} - V_{\mathrm{f}})$$

# Critical oscillation period

$$T_c = 2\pi\sqrt{\frac{a}{(b-a)}\frac{D_c}{V}}$$

Time necessary for shear strength to evolve to a new steady level following a single step in normal stress

# Critical rheological stiffness

$$K_c = \frac{(b-a)\sigma_n}{D_c}$$

# Normalized parameters

$$\Delta\tau' = \frac{\Delta\tau}{2A\mu_{ss}}$$

$$\Delta\tau_{yield}' = \frac{\Delta\tau_{yield}}{A\mu_{ss}}$$

$$\Delta\varphi = \frac{t_{\sigma_{\mathrm{n}}}^{\max} - t_{\tau}^{\max}}{T}\times 360$$

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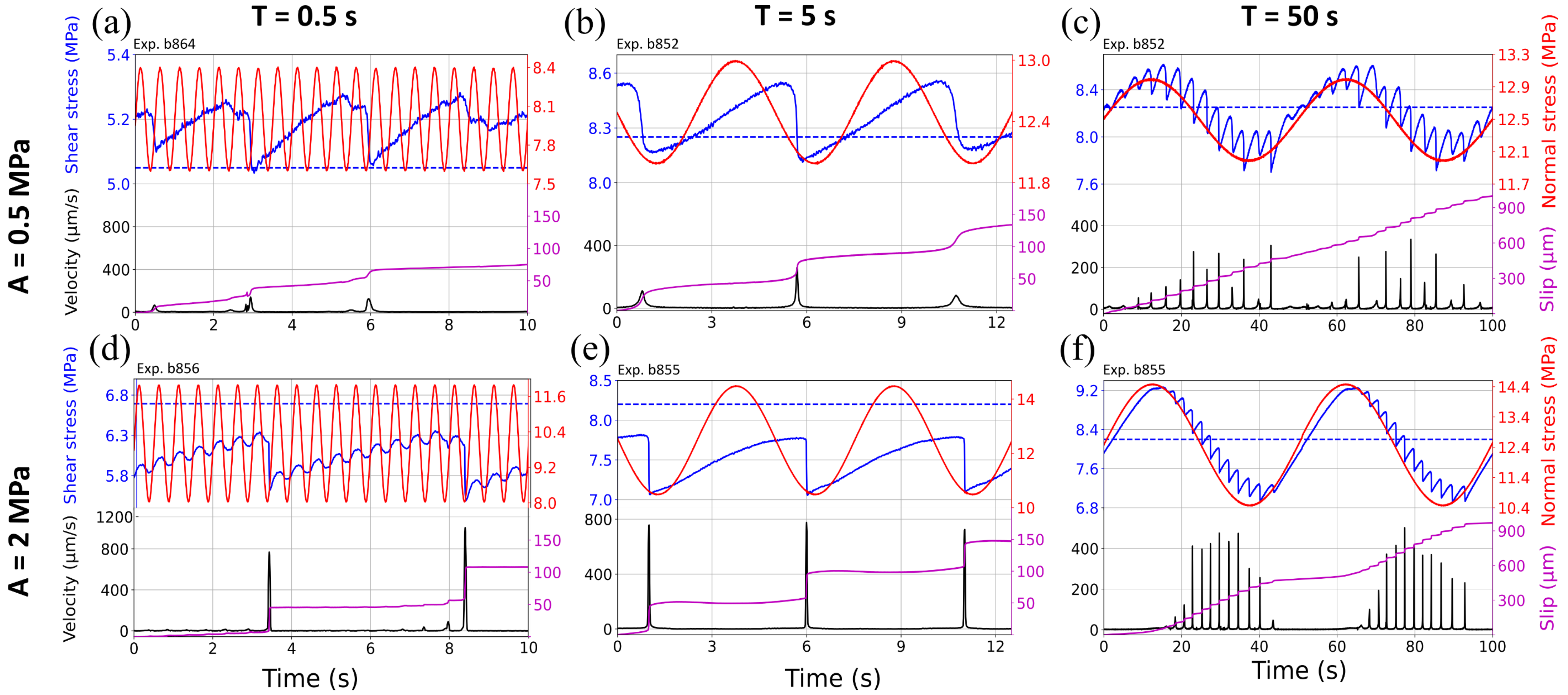
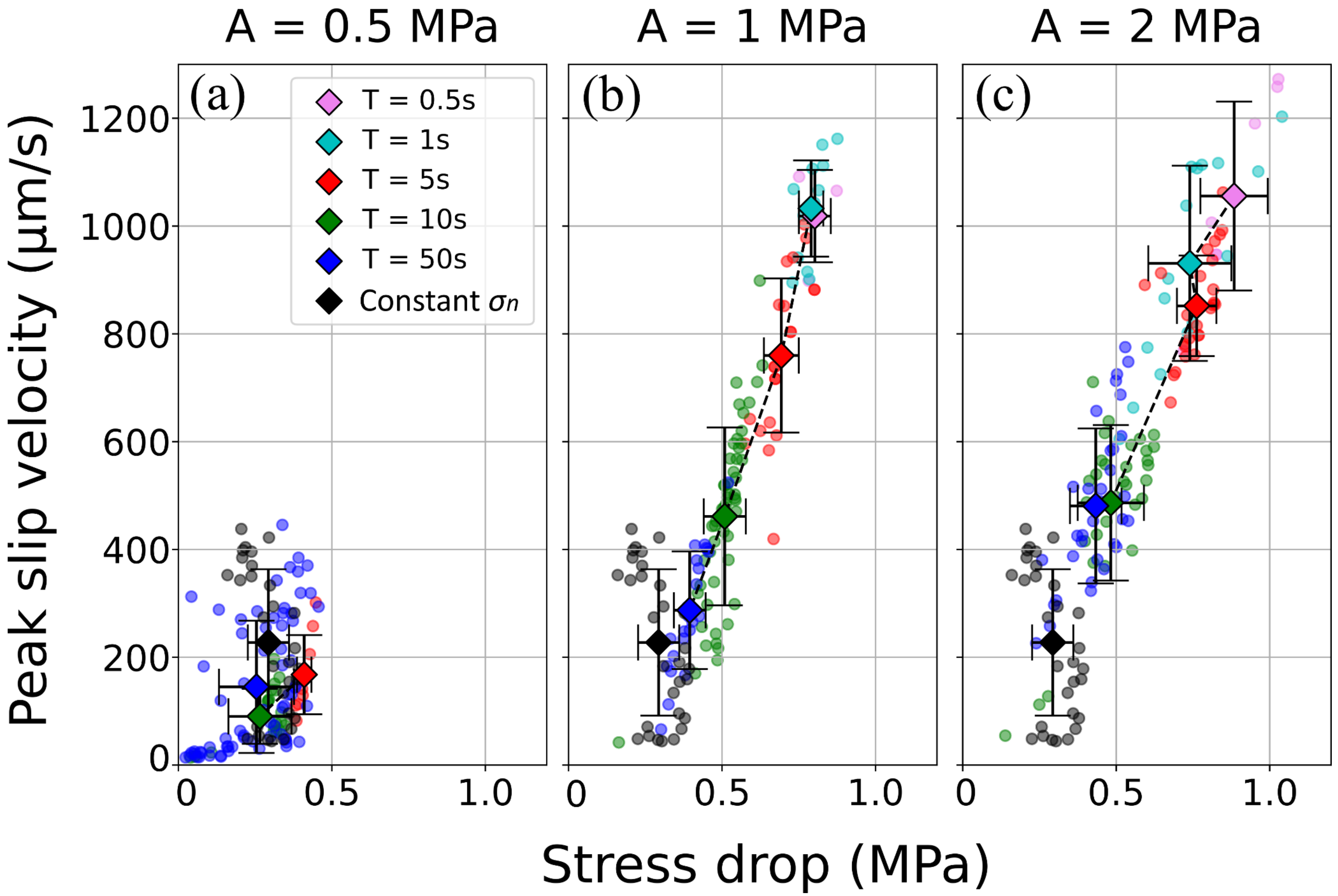
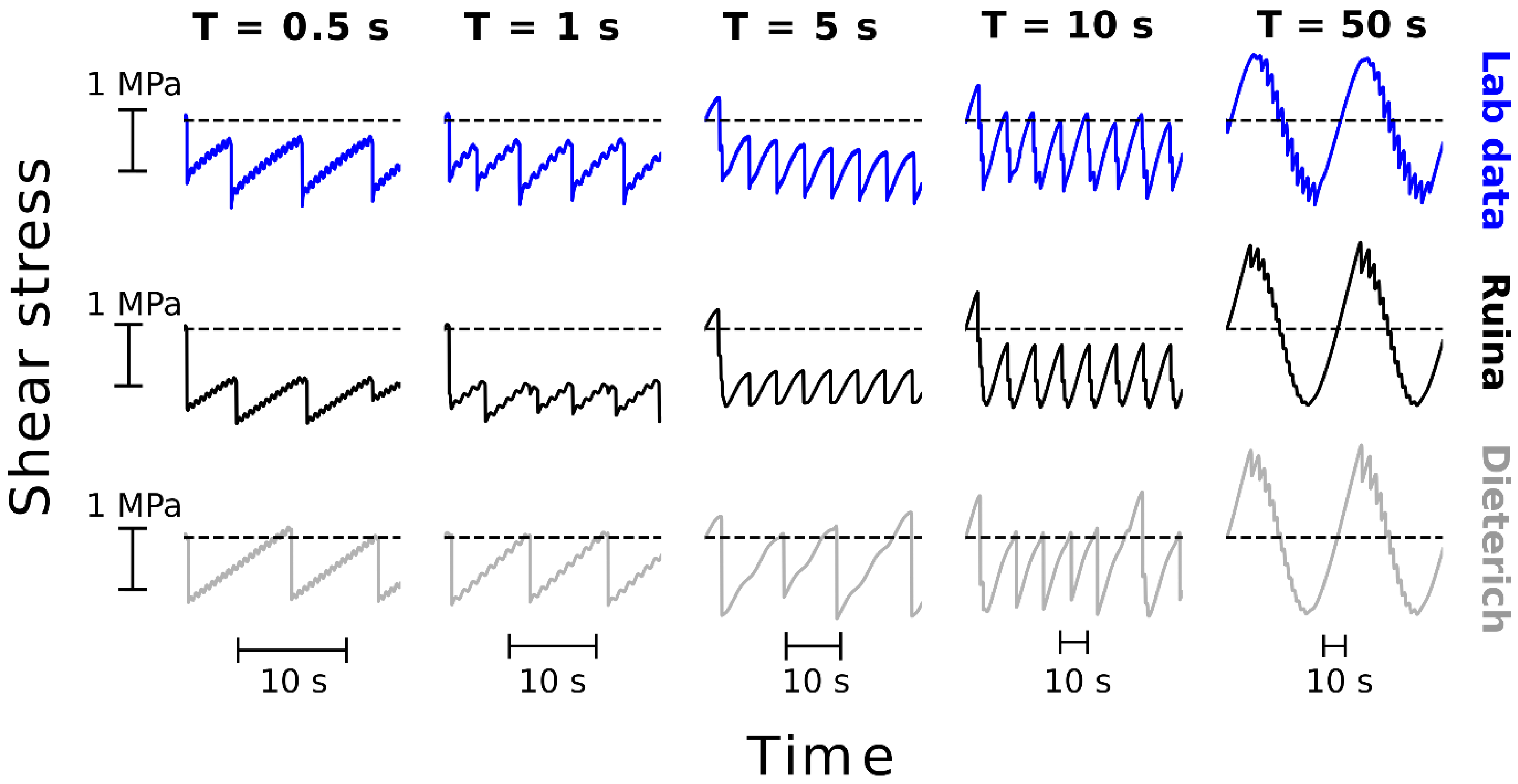



A = 0.5 MPa
A = 1 MPa
A = 2 MPa
(a)
(b)
(c)
T = 0.5s
T = 1s
T = 5s
T = 10s
T = 50s
Constant σn
Peak slip velocity (μm/s)
Stress drop (MPa)
0
200
400
600
800
1000
1200
0
0.5
1.0


T = 0.5 s
T = 1 s
T = 5 s
T = 10 s
T = 50 s
1 MPa
1 MPa
1 MPa
Shear stress
Lab data
Ruina
Dieterich
10 s
10 s
10 s
10 s
10 s
Time

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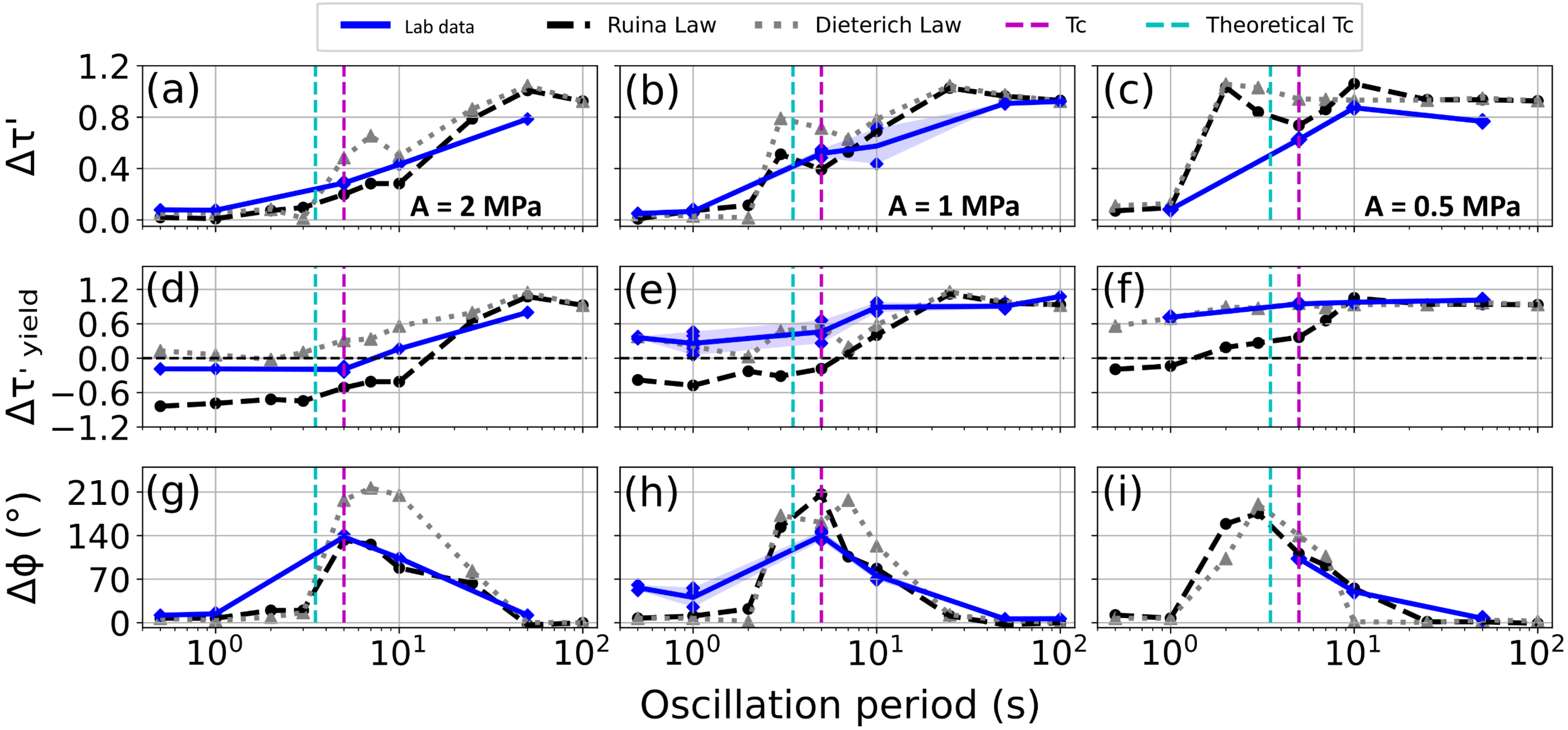

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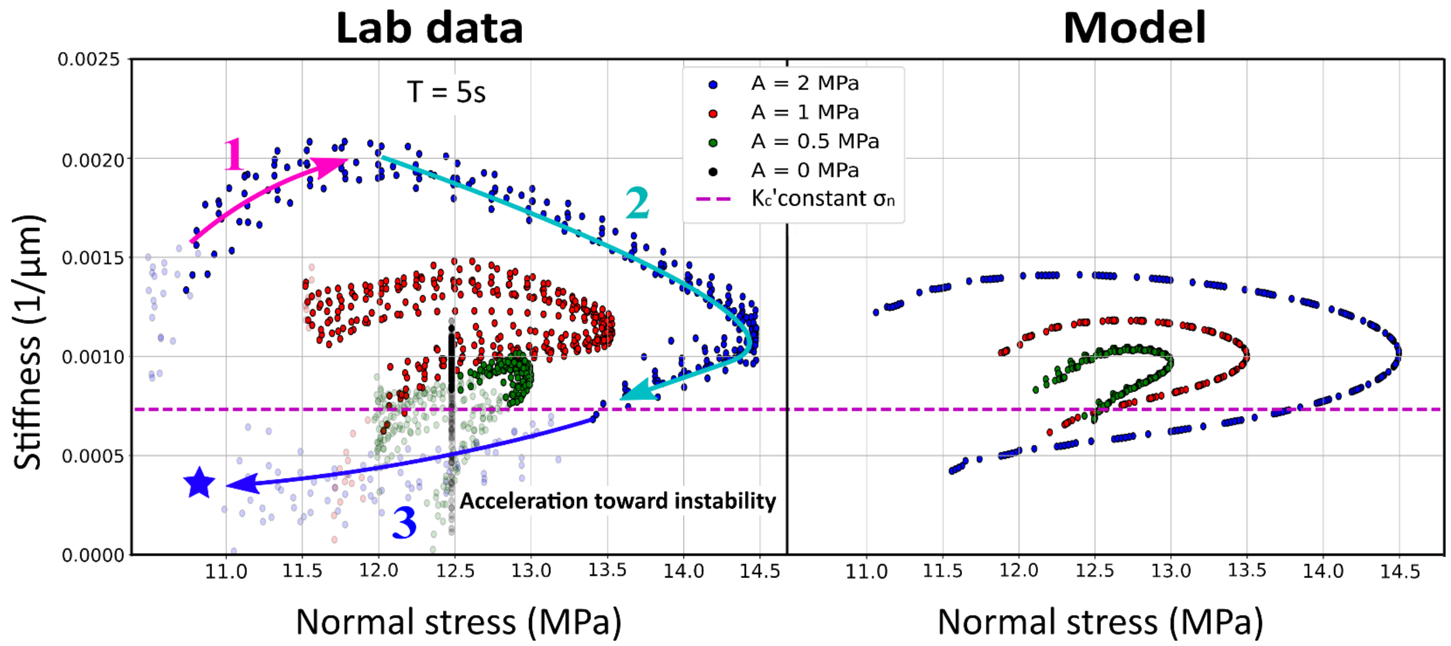
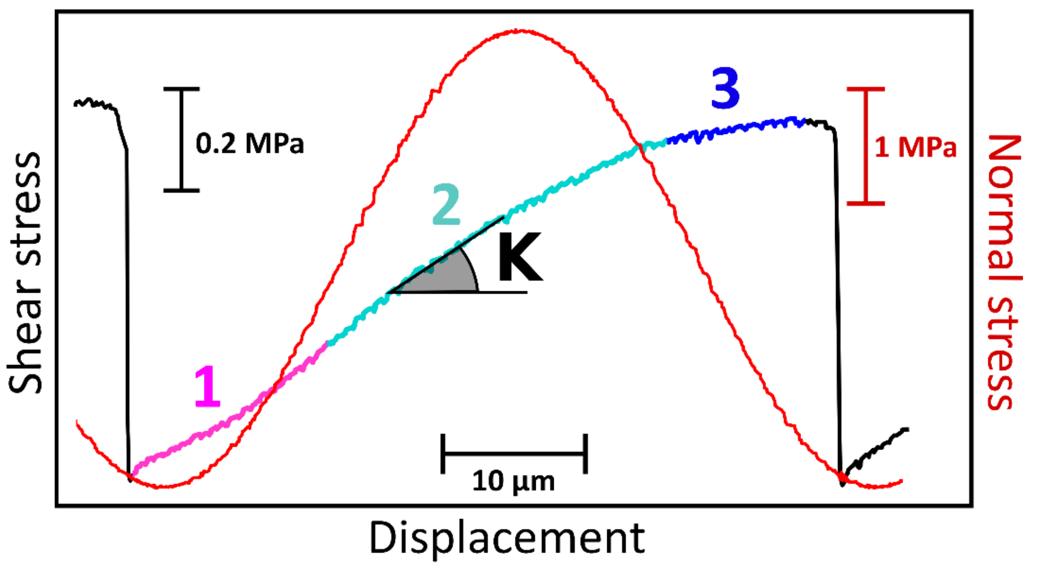
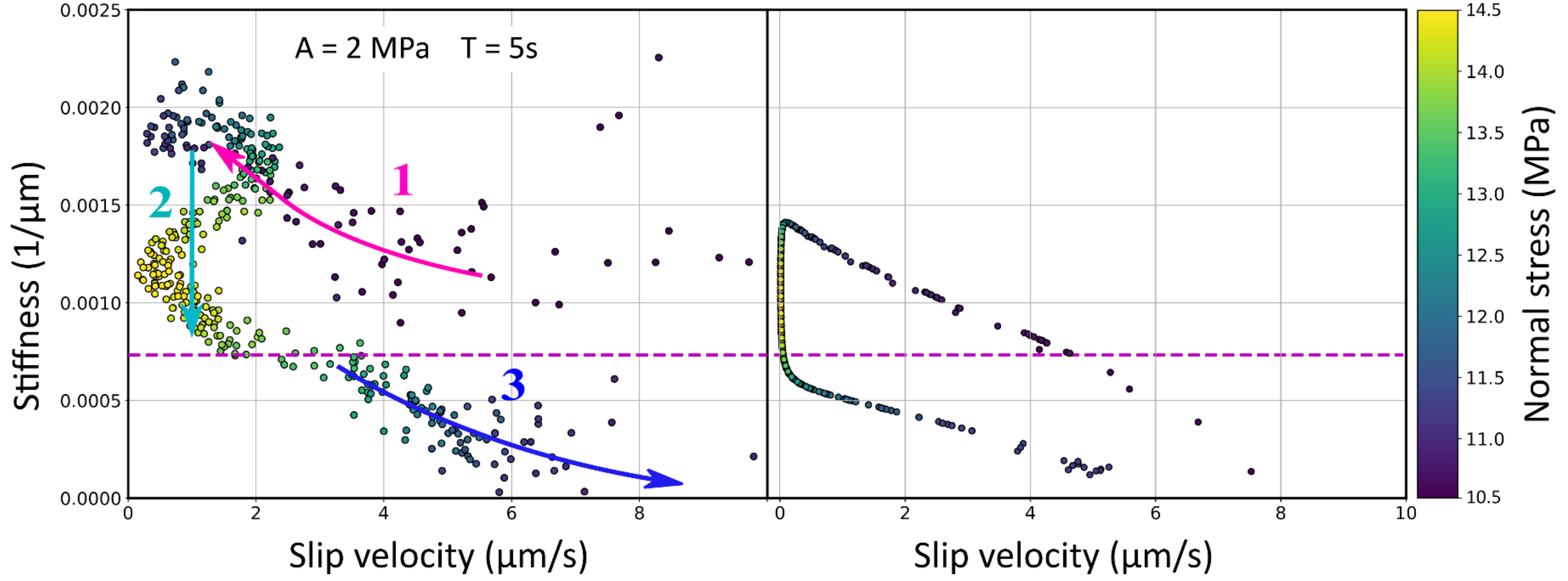
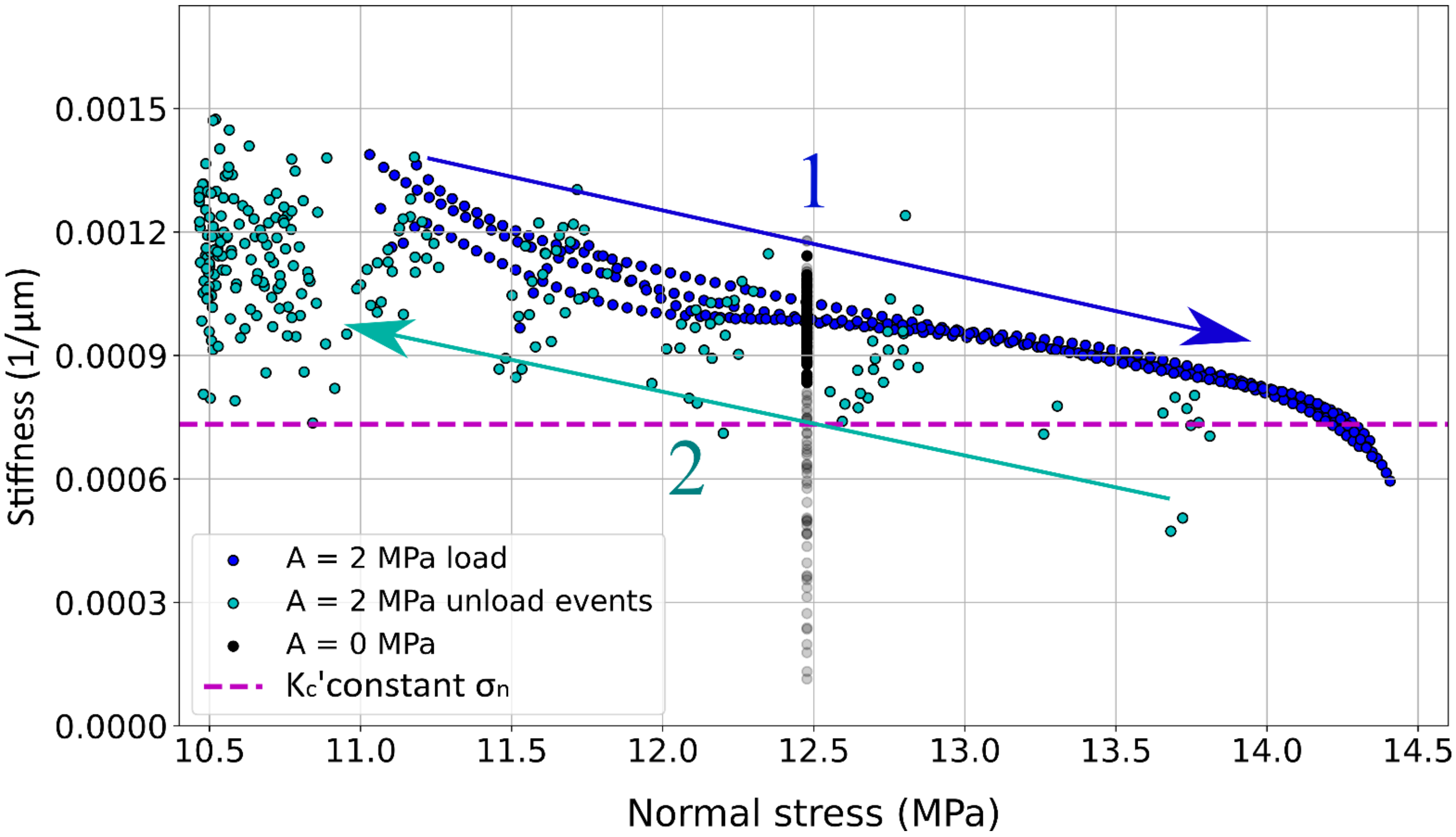
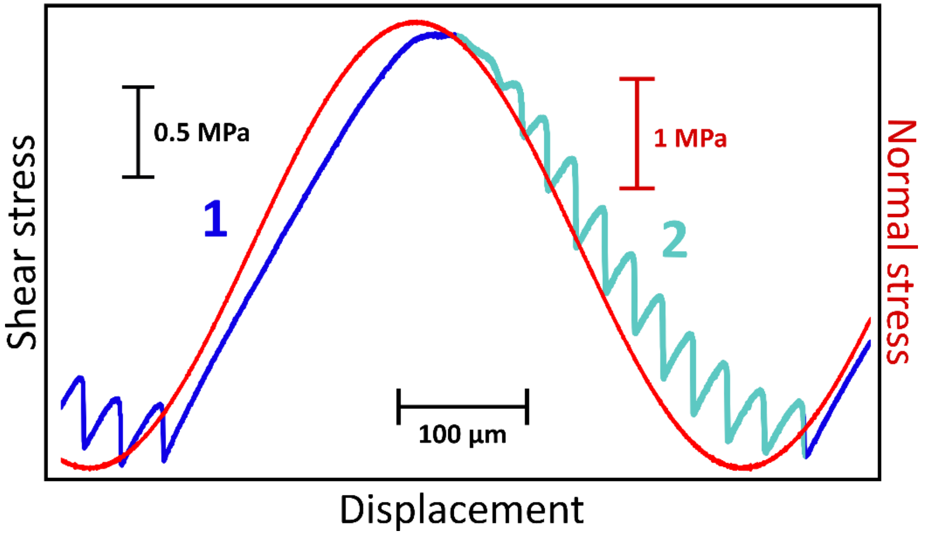



Stiffness (1/µm)
Normal stress (MPa)
0.0015
0.0012
0.0009
0.0006
0.0003
0.0000
10.5
11.0
11.5
12.0
12.5
13.0
13.5
14.0
14.5
1
2
A = 2 MPa load
A = 2 MPa unload events
A = 0 MPa
Kc'constant σn


Shear stress
Normal stress
Displacement
0.5 MPa
1 MPa
100 µm
1
2