Mechanisms and Models for Nonclassical Nonlinearity in Heterogeneous Materials

Christoph Sens-Schönfelder

GFZ German Research Centre for Geosciences, Potsdam, Germany

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Location of dynamics

	quartz	sandstone
sound velocity (c)	5800 m/s	2000-3500 m/s
dc/dp for $p = 1 \rightarrow 200$bar	1 %	200 %

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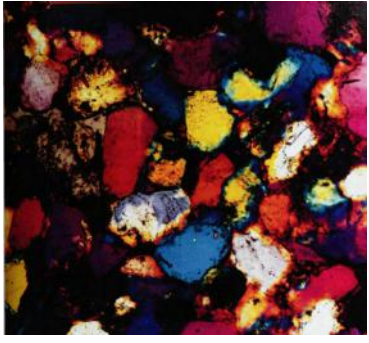
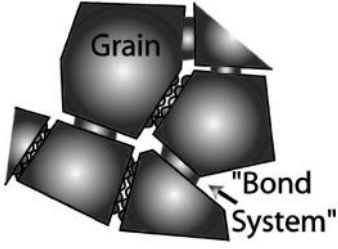


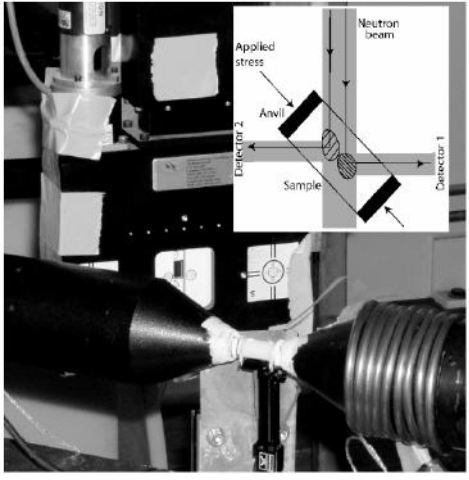


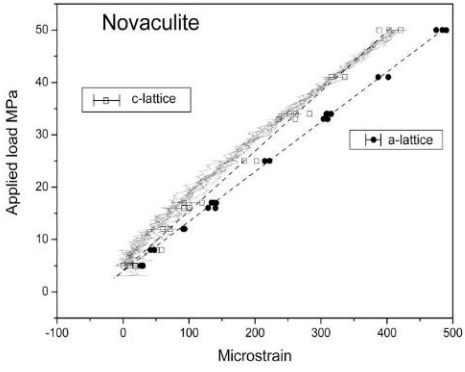
[Johnson and Sutin, 2005]

[Guyer and Johnson, 1999]

Location of dynamics

homogeneous quartzite

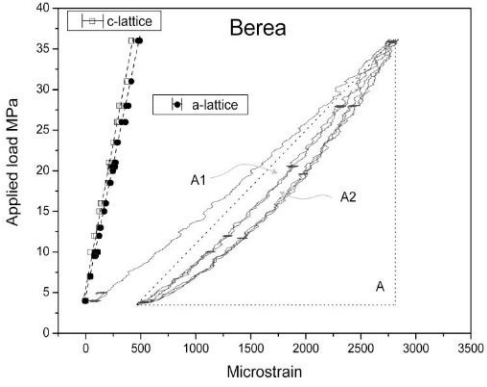




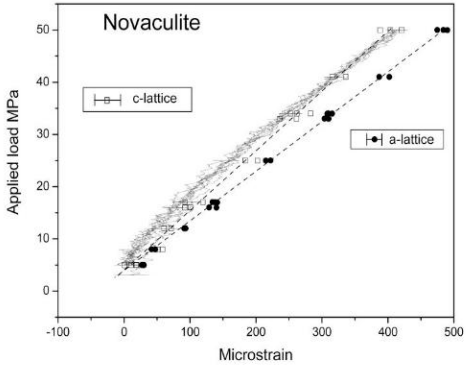
[Darling et al., 2006]

Location of dynamics

Berea sandstone



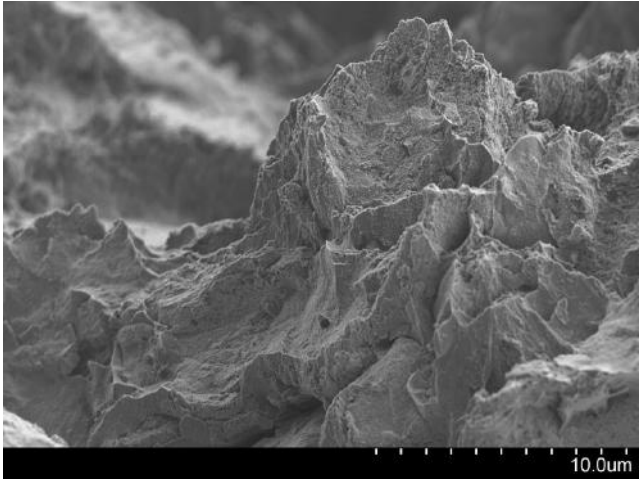
homogeneous quartzite



[Darling et al., 2006]

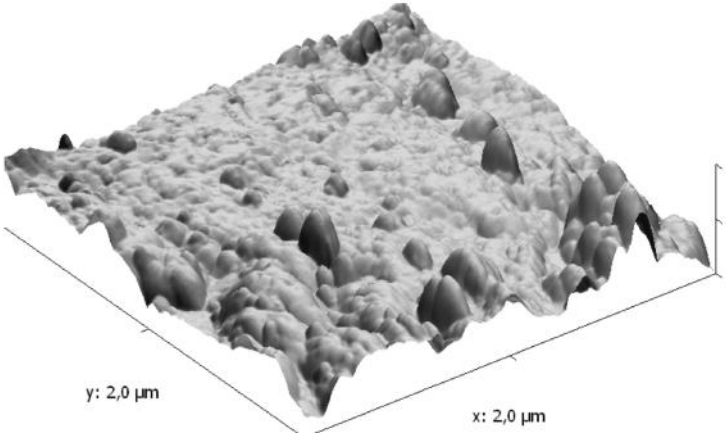
Contents

Size of contacts



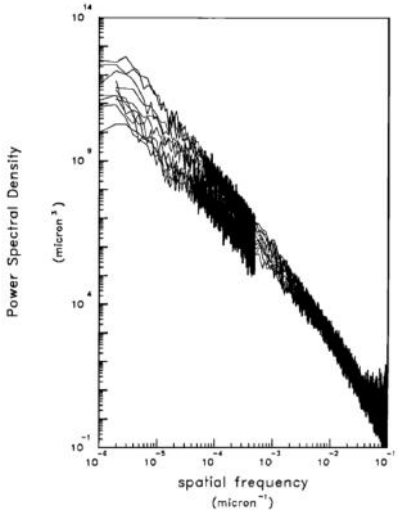
Size of contacts

AFM image of the surface of a glass bead



[Zaitsev et al., 2014]

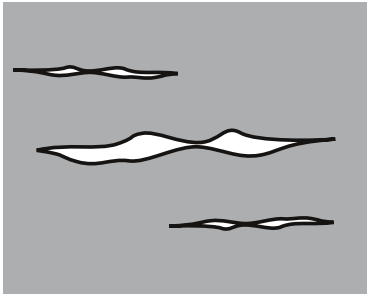
Size of contacts



There are structures that can produce asperities of any size.

[Brown and Scholz, 2008]

Bistable asperities



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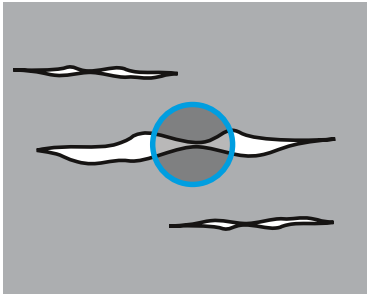

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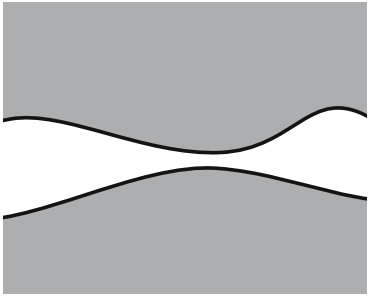

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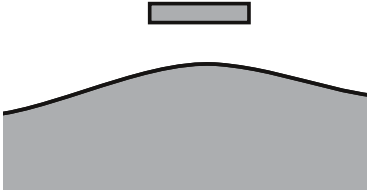

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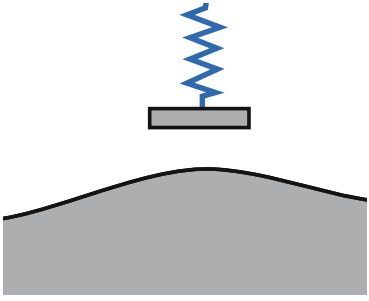

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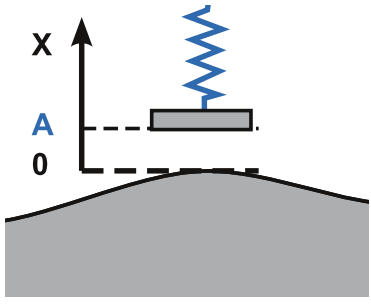

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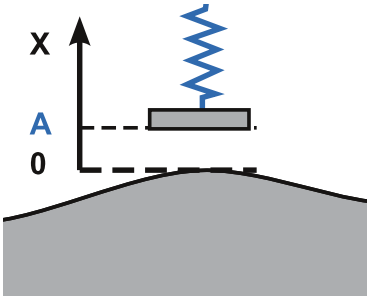

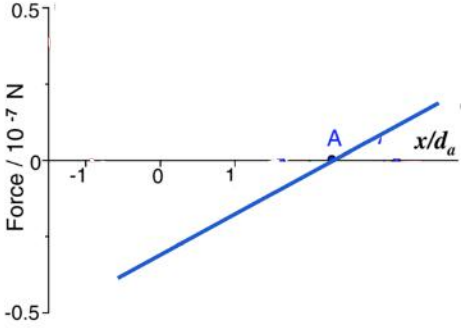

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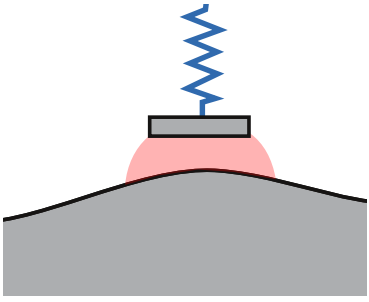

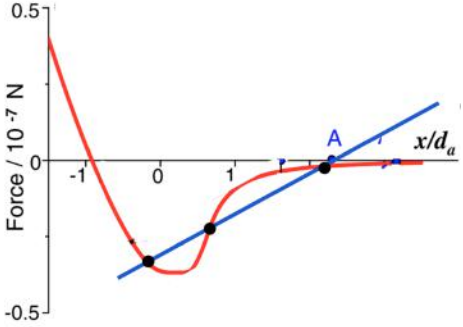

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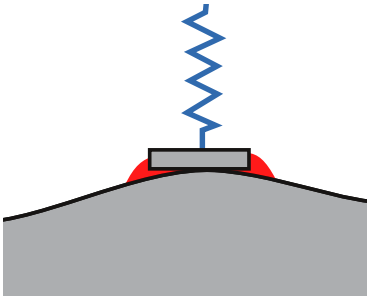
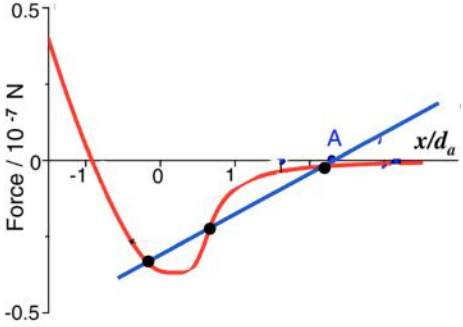
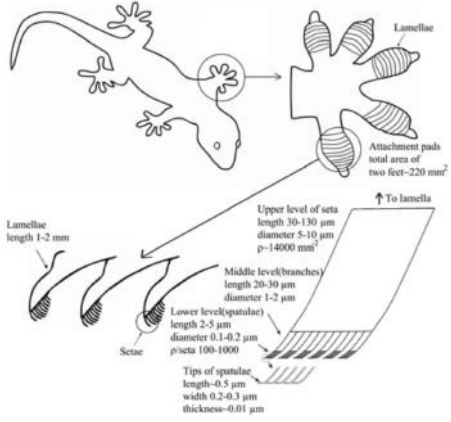


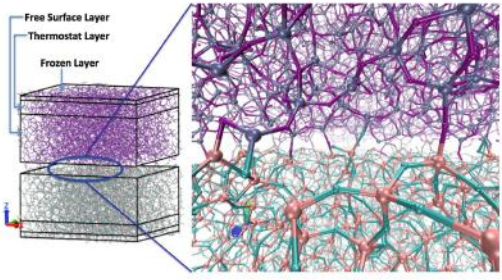


Bistable asperities

Van der Waals bonds



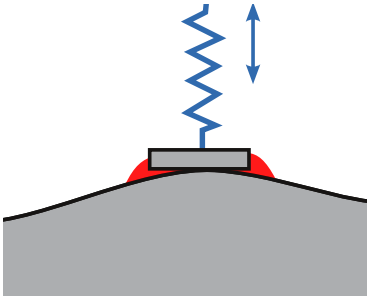
Chemical bonds

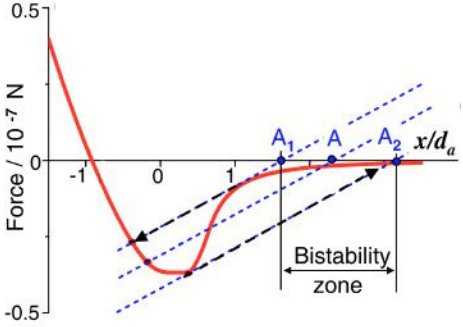


[Li et al., 2014]

[?]

Bistable asperities





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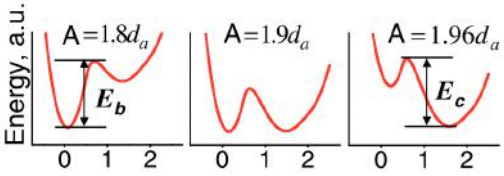
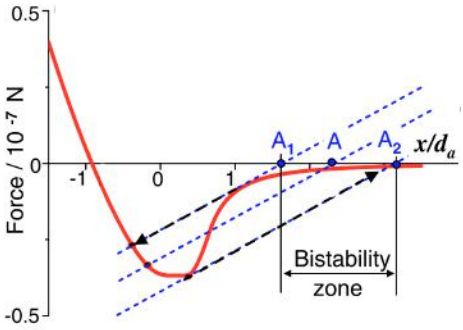


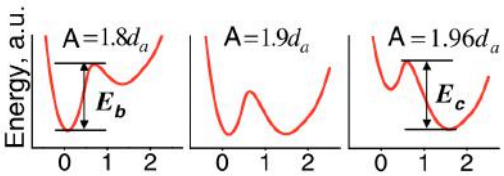
$$\tau = \tau_0 \exp\left(\frac{E_{b,c}}{k_B T}\right)$$

[Zaitsev et al., 2014]



Bistable asperities

Pulling the contact apart



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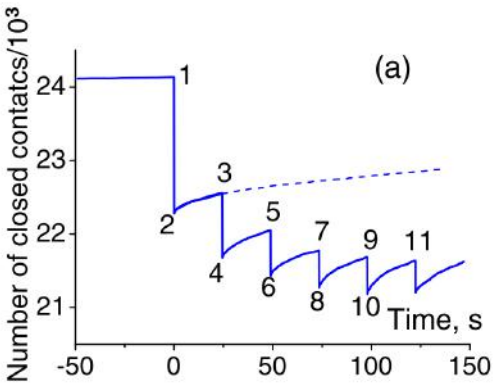
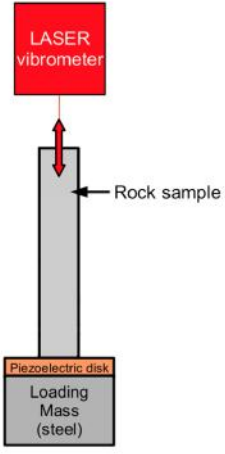
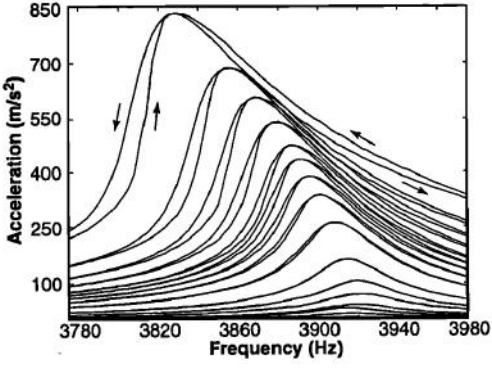


Resonance Experiments





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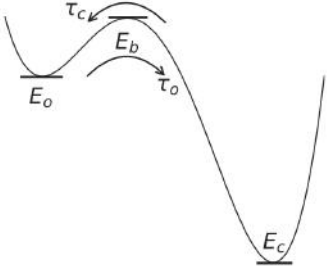

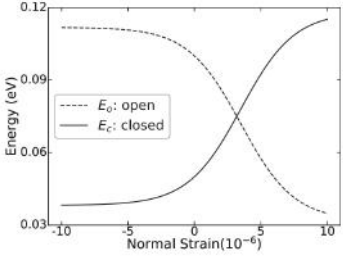

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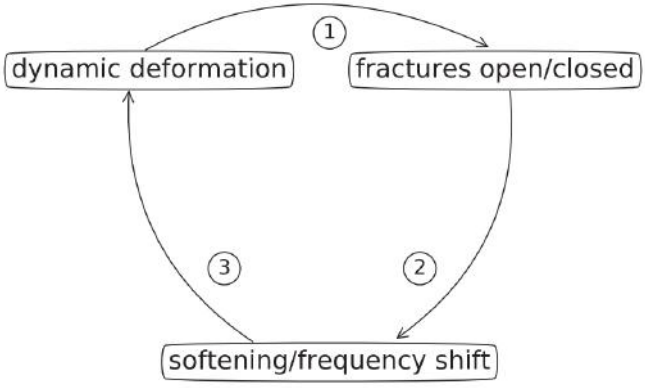
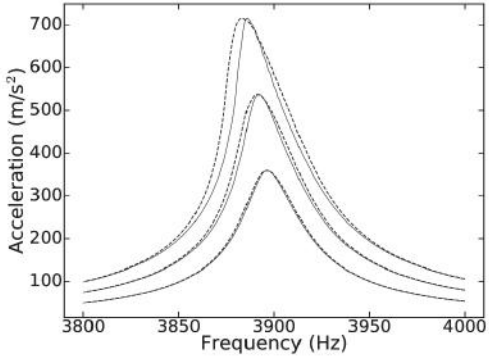


[Li et al., 2018]

Resonance Experiments

Can explain

- decrease in resonance frequency
- difference between up and down sweep
- asymmetry / increasing steepness
- time dependency (relaxation)
- speed dependency



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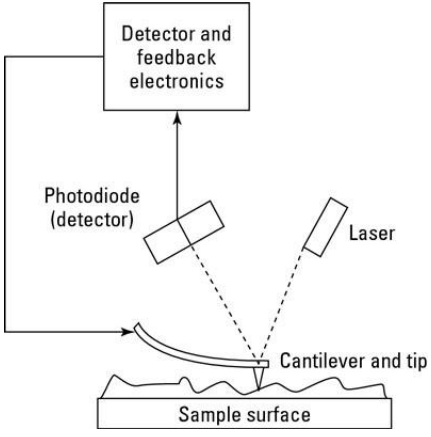
Formation of bonds in AFM

Atomic force microscope



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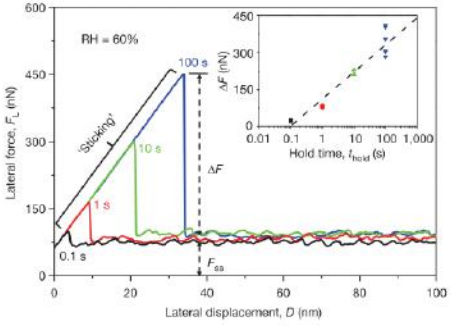


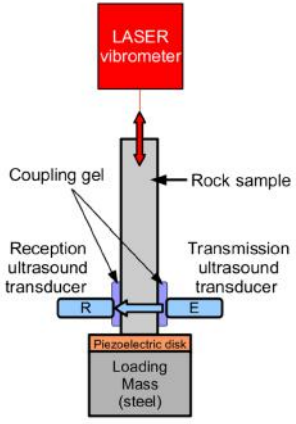
[Li et al., 2011]

Slide-hold-slide experiment with AFM

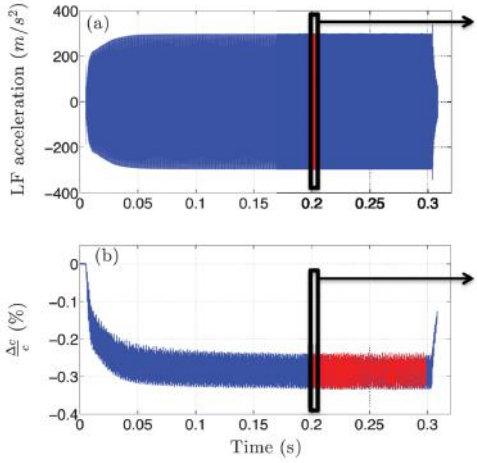
- microscopic aging effect much larger compared to macroscopic contact aging
- contact aging involves changes in contact quality
- formation of chemical bonds across the contact are likely involved in the aging process

Dynamic Acousto-Elastic Testing (DAET)

time series



[Renaud et al., 2013]



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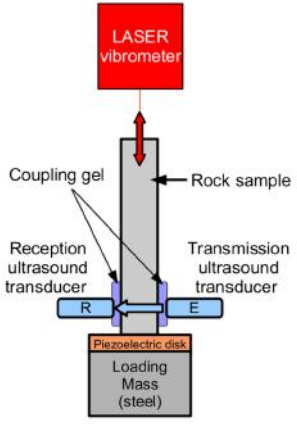
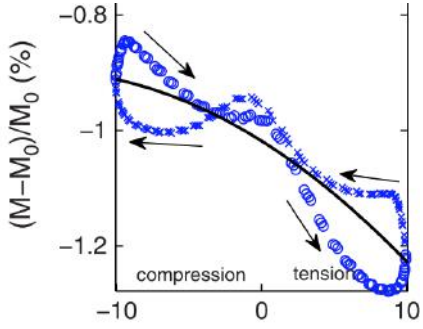


nonlinear signature



[Renaud et al., 2013]

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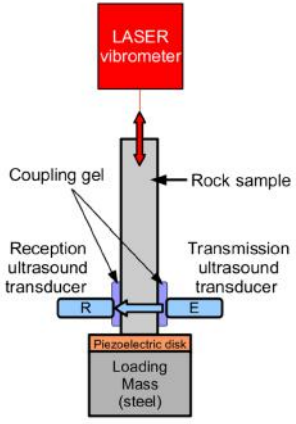
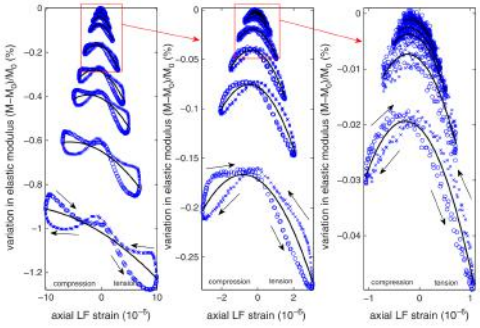


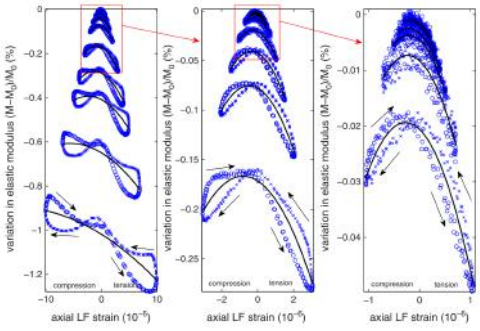


[Renaud et al., 2013]

Dynamic Acousto-Elastic Testing (DAET)

Velocity *during* a strain cycle

- fast co-seismic softening
- slow post-seismic stiffening
- hysteresis
- bow tie loops indicate frequency doubling
- stiffening at maximum **and** minimum strain



Model for sheared material contact

contacts are made up of connections (micro asperities, chemical bonds, capillary bridges ...)

$$M(t) = M_0 - AN(t)$$

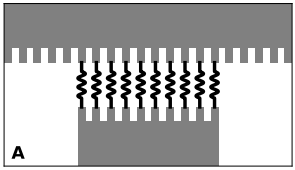
M: modulus

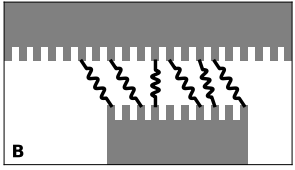
N: fraction of broken connections:

- connections break when strained
- connections are created at current strain and constant rate

$$\frac{dN_i}{dt} = \frac{\nu\dot{\varepsilon}}{\tau_i}(1 - N) - \frac{1}{\tau_i}N_i$$

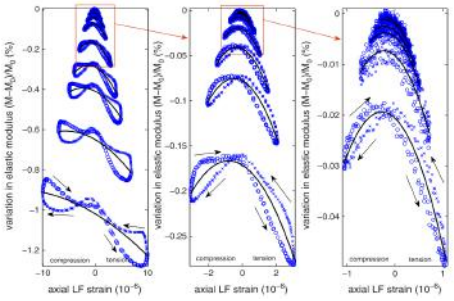
$N = \frac{\sum N_i/\tau_i}{\sum 1/\tau_i}$ for a unif. distr. of $\tau_{min} < \tau_i < \tau_{max}$.





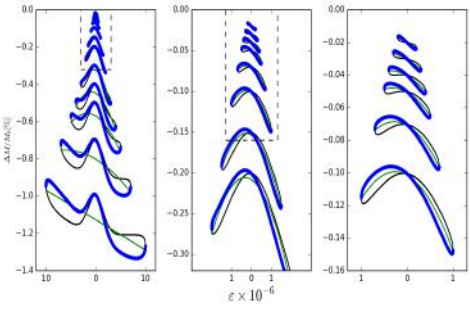
Nonlinear signatures

Observation



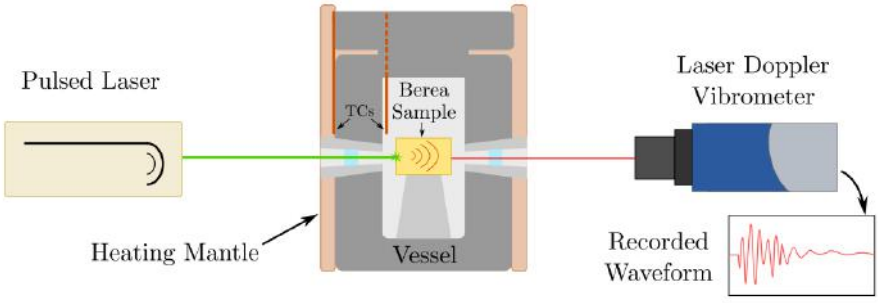
[Renaud et al., 2013]

Model



[Sens-Schönfelder et al., 2019]

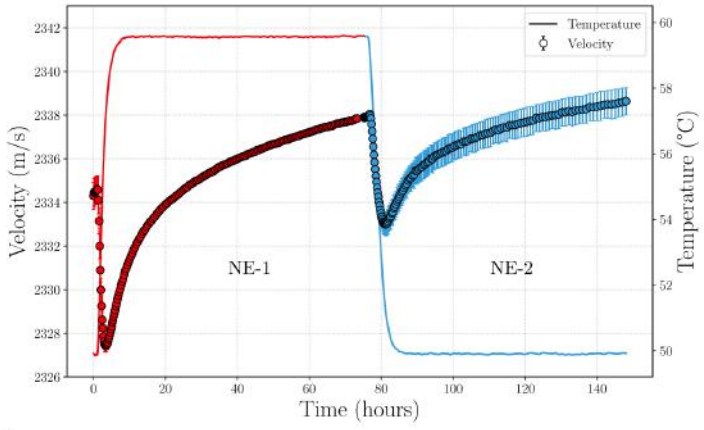
Temperature dependence



[Simpson et al., 2023]

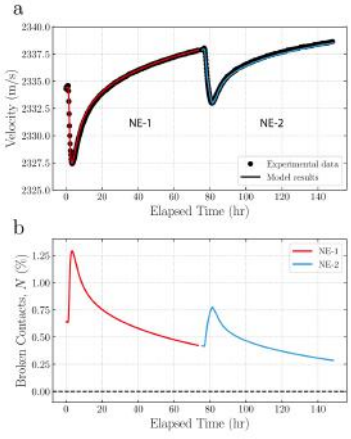
Temperature dependence

a



b

Temperature dependence



Rate dependent damage from thermal strain explains velocity changes induced by temperature variations.

- slip is required to obtain strict decrease of velocity

Summary

- nonclassical nonlinearity originates at grain contacts
- processes at the molecular level govern the behavior
- slip plays an important role in transient proceesses

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