New insights into the spatiotemporal structure of plastic flow by combination of modeling and in-situ experimental techniques

Kristián Máthis, Michal Knapek, František Chmelík

Péter Dusán Ispánovity, Dávid Ugi, Szilvia Kalácska, Gábor Péterffy, Zoltán Dankházi, Dániel Tüzes, István Groma

FACULTY
OF MATHEMATICS
AND PHYSICS
Charles University

Characterization of deformation behavior in bulk

Universal Testing Machines, (Micro)hardness

- Stress-strain (or load-time) dependence

Complementary *"quasi in-situ"* techniques

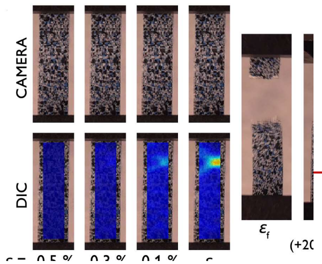
- Scanning electron microscopy (incl. EBSD)
- Diffraction methods (X-ray, neutrons, tomography)

→ **Data acquisition takes time**
(deformation test needs to be repeatedly halted)

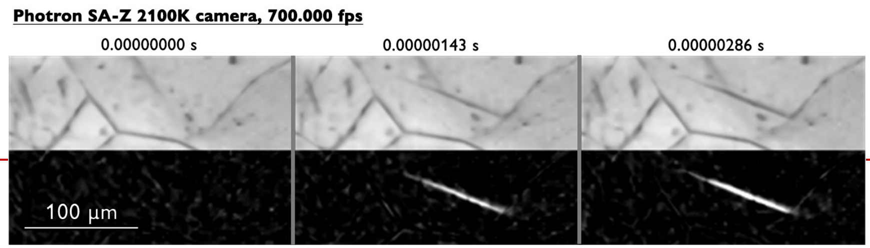
Complementary *in-situ* techniques

- High-speed camera recording (incl. DIC)

→ **High data acquisition rate**
(deformation test can run smoothly)



Knapek et al., 2022



Máthis et al., 2022, unpublished results

Characterization of deformation behavior in microsamples

Direct comparison with modeling

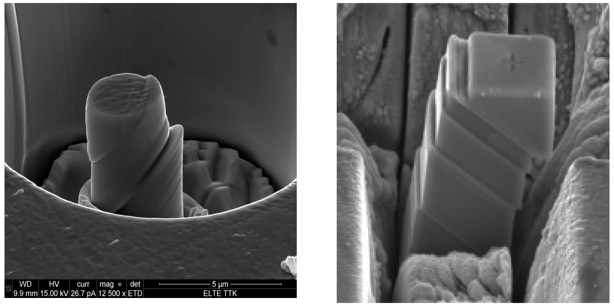
Dedicated nanodevices

- Stress-strain (or load-time) dependence

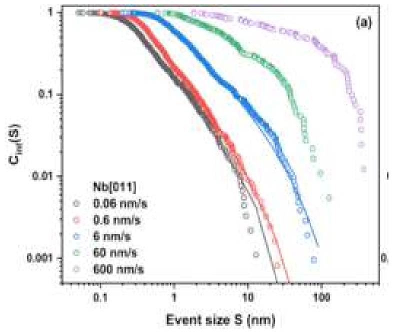
The results are very sensitive to experimental details

- Pillar shape (tapering)
- Machine stiffness
- Deformation rate
- Stage control etc.

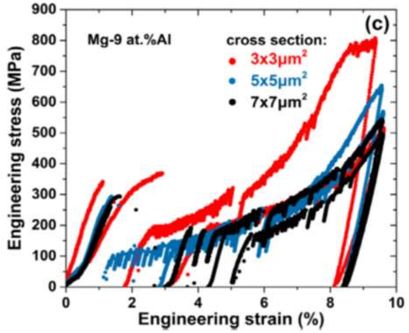
Sampling rate ~250 Hz



Á. I. Hegyi *et al.*, Micros. Microanal., 2017



Sparks and Maaß, PR Materials, 2018



J. Wang *et al.*, Acta Mater., 2020

Characterization of deformation behavior in microsamples

Direct comparison with modeling

Dedicated nanodevices - sampling rate ~250 Hz

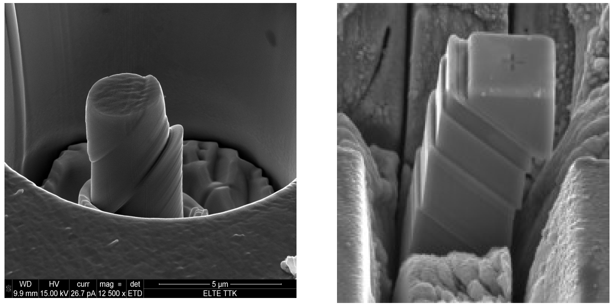
- Stress-strain (or load-time) dependence

Complementary high spatial resolution techniques

- Scanning electron microscopy (incl. EBSD)
- Transmission electron microscopy

Complementary high temporal resolution techniques

- High-speed camera recording



Á. I. Hegyi *et al.*, Micros. Microanal., 2017

→ Low sampling rate

~ 1-2 Hz

→ either low image resolution

~ 128 x 32 px @ 2.1M FPS

or short acquisition time

~100 µs @ 5M FPS

Characterization of deformation behavior in micropillars

250 Hz

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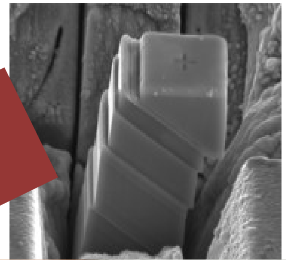
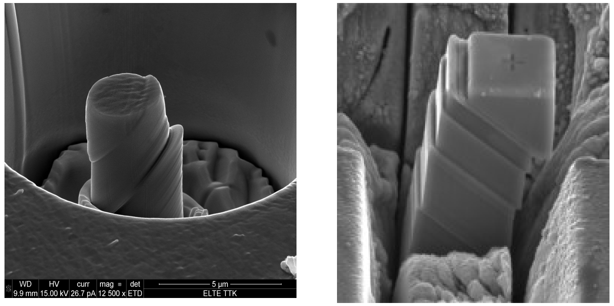


Acoustic emission (AE)

shutterstock.com · 2074183925

Characterization of deformation behavior in micropillars

Direct comparison with modeling



Á. I. Hegyi *et al.*, Micros. Microanal., 2017

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Complementary high spatial resolution techniques

- Scanning electron microscopy (incl. EBSD)
- Transmission electron microscopy

→ Low sampling rate

~ 1-2 Hz

Complementary high temporal resolution techniques

- High-speed camera recording
- **ACOUSTIC EMISSION -** sampling rate up to 40 MHz

→ either low image resolution

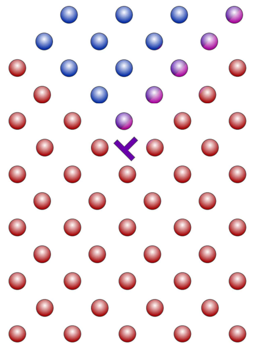
~ 128 x 32 px @ 2.1M FPS

or short acquisition time

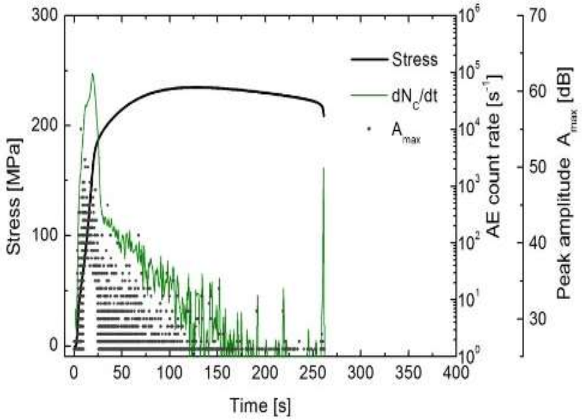
~100 μs @ 5M FPS

Introduction to the acoustic emission (AE)

- ASTM E610-82: Acoustic emissions are **transient elastic waves generated by the rapid release of energy from localized sources within the material.**
- AE is **sound of danger** in the nature (earthquakes, rockbursts, avalanches)
- **AE in materials -** information on the dynamic processes involved in plastic deformation and failure **(collective dislocation motion, twinning, crack propagation etc.)**

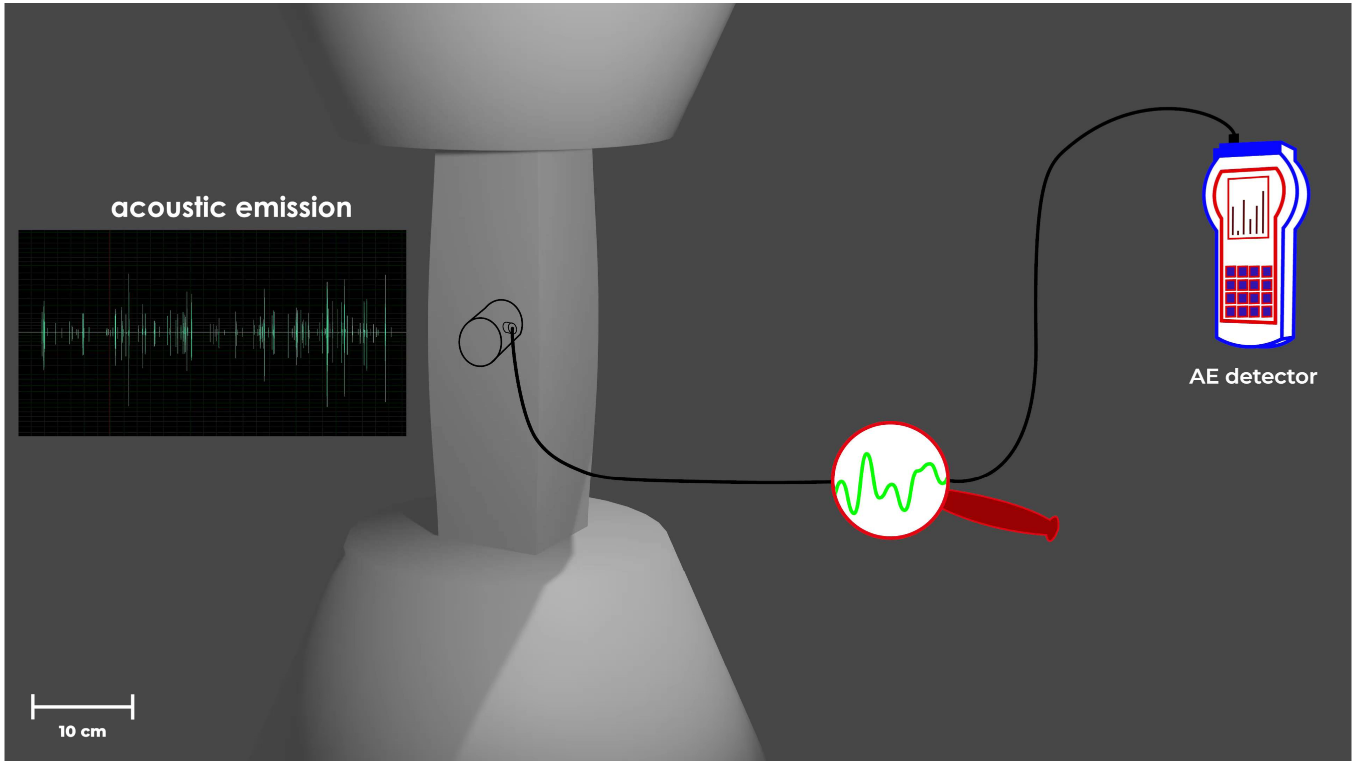


https://www.youtube.com/watch?v=HoRvTnsiaE8&t=85s



D. Drozdenko et al., Acta Phys. Pol., A, 2015

Basic principles of the AE measurements

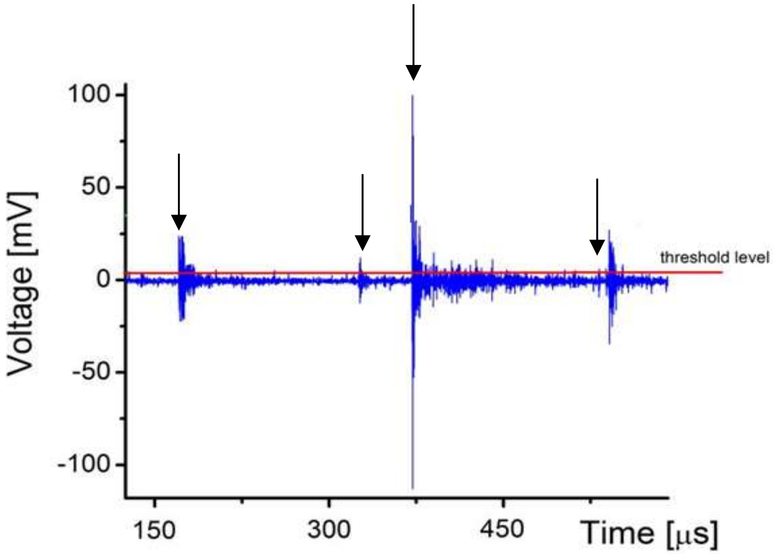


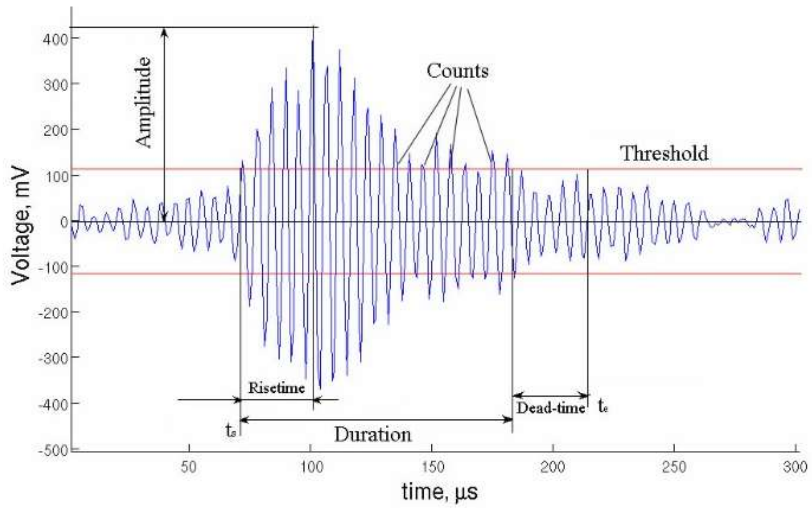
https://www.youtube.com/watch?v=HoRvTnsiaE8&t=85s

Basic principles of the AE measurements

Hit-based method

- Threshold level - exclusion of the background noise
- Recording of an AE hit starts, when signal cross first the threshold level and terminates, if signal is below threshold for hit-definition-time (dead time)
- The results are sensitive on proper (pre-experiment) choice of threshold and HDT

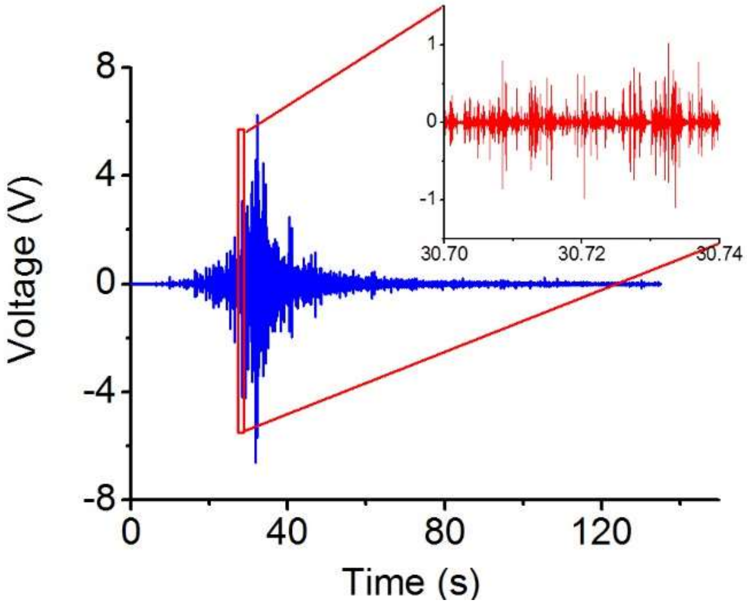


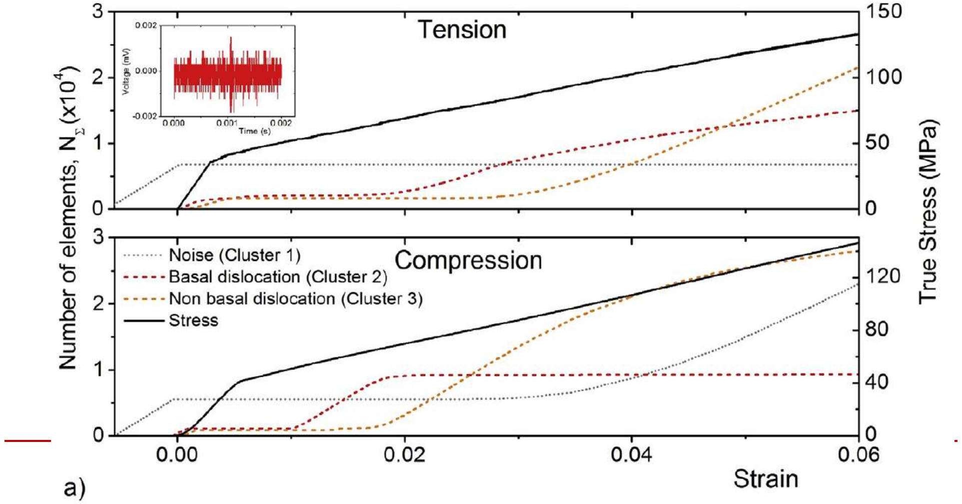


Basic principles of the AE measurements

Data streaming

- Continuous sampling and storing of the signal – **acquisition rate up to 40 MHz**
- AE parameters from post-processing – no data loss, better fit of set-up parameters
- Getting **dynamic information** about the plastic deformation

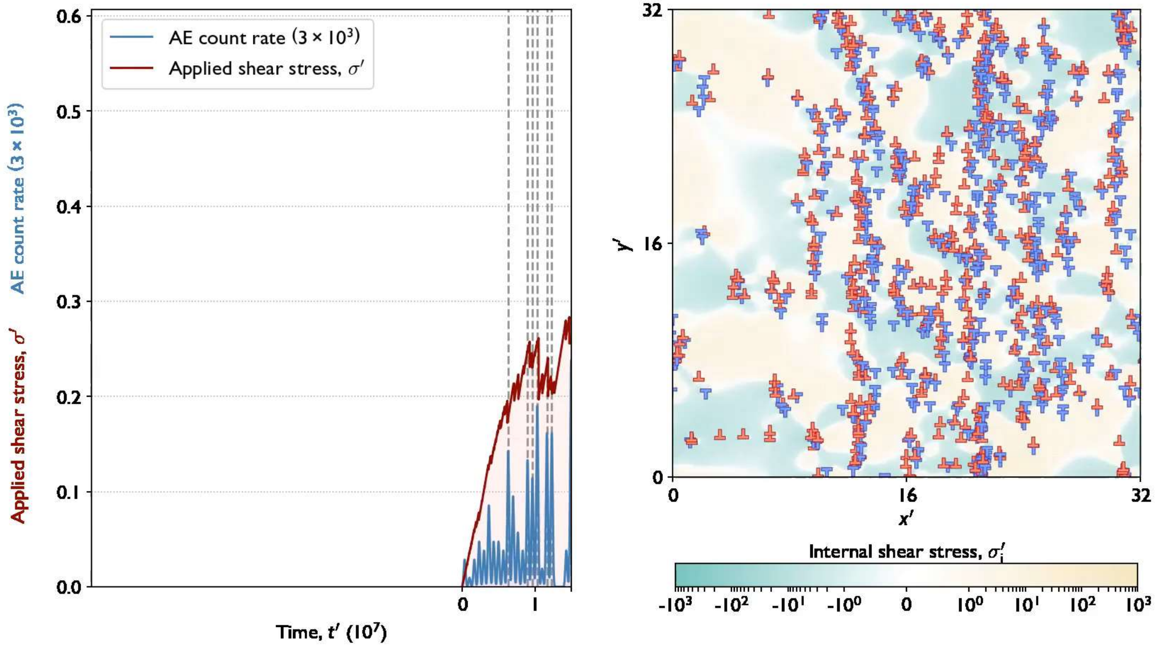




K. Máthis et al. ,Int. J. Plast. 2015

AE and dislocation movement

- Scruby et al. (1981) – single dislocation: surface displacement of **10^{-15} m**, **detectable by AE: >10^{-13} m.** ⇒ AE sensitive to **collective correlated movement of large dislocation ensembles** (dislocation avalanches);



P.D. Ispánovity et al., Nature Comm. 2022

AE and dislocation movement

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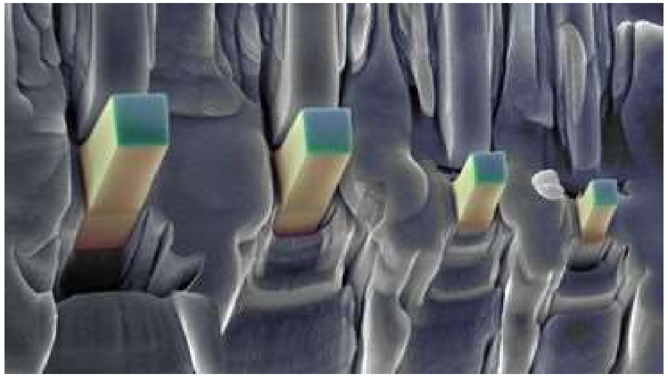
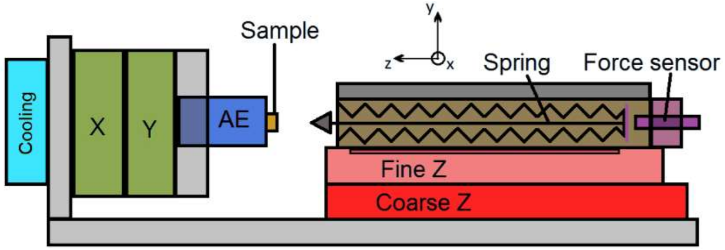
- Experimental evidence of intermittent character of PD – **AE signals during mechanical loading of materials.** [M.-C. Miguel et al., *Nature*, 410(6829), 667-671, 2001; J. Weiss et al., *Science*, 299(5603), 89-92, 2003]
- Up to now, **deformation and AE experiments only on macroscopic samples** (mono-, poly-crystals).
- **QUESTION: Can AE be employed to investigate plasticity in microsamples?**

Plastic deformation in microsamples

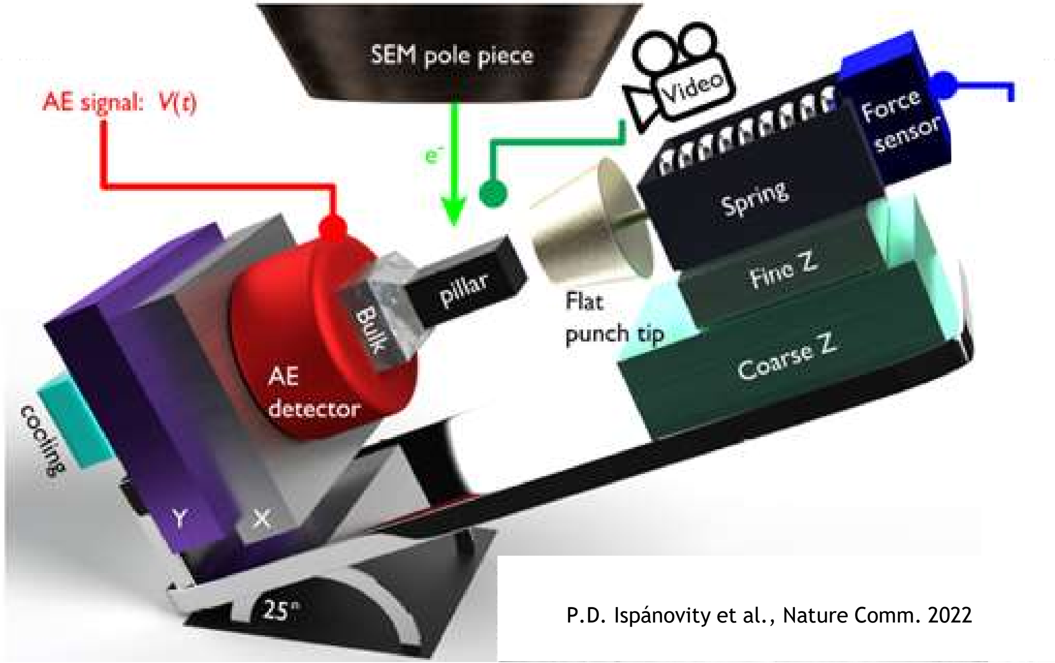
- **FIB - focused ion beam** – new production method was developed: rectangular micropillars (non-tapered, faster production, …).
- In-situ micromechanical device "Nanotest" and AE transducer **placed directly in SEM (FEI Quanta 3D)**.
- **Sample attached to the sensor** (metallic strip + vacuum grease).
- **Deformation test** – flat diamond tip.
- **AE:** Vallen Systeme GmbH AE system and preampifier + Physical Acoustic Corp. sensor.



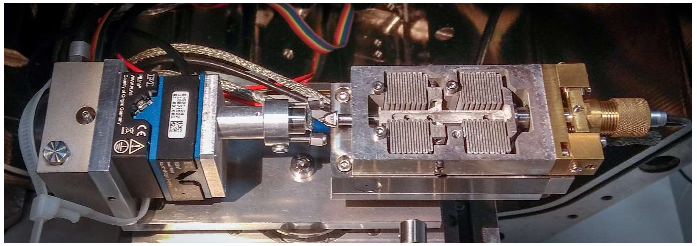


[Á. Hegyi, et al., *Microsc. Microanal.* 23(6), 1076–1081, 2017]

Plastic deformation in microsamples



P.D. Ispánovity et al., Nature Comm. 2022



Part name	Total range	Resolution	Accuracy
X and Y stages	±8 mm	0.5 μm	0.01 μm
Coarse Z stage	9 mm	2 μm	0.5 μm
Fine Z stage	35 μm	1 nm	0.1 nm
Force sensor (with two possible presets)	20/50 mN	1/2.5 μN	1/2.5 μN

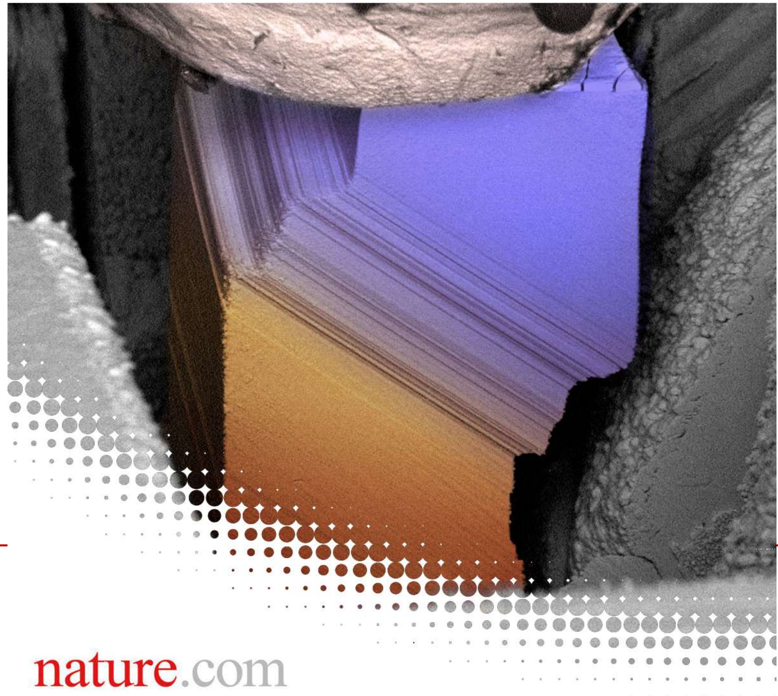
P. D. Ispánovity, D. Ugi*, G. Péterffy, M. Knapek, S. Kalácska, D. Tüzes, Z. Dankházi, K. Máthis, F. Chmelík, I. Groma*

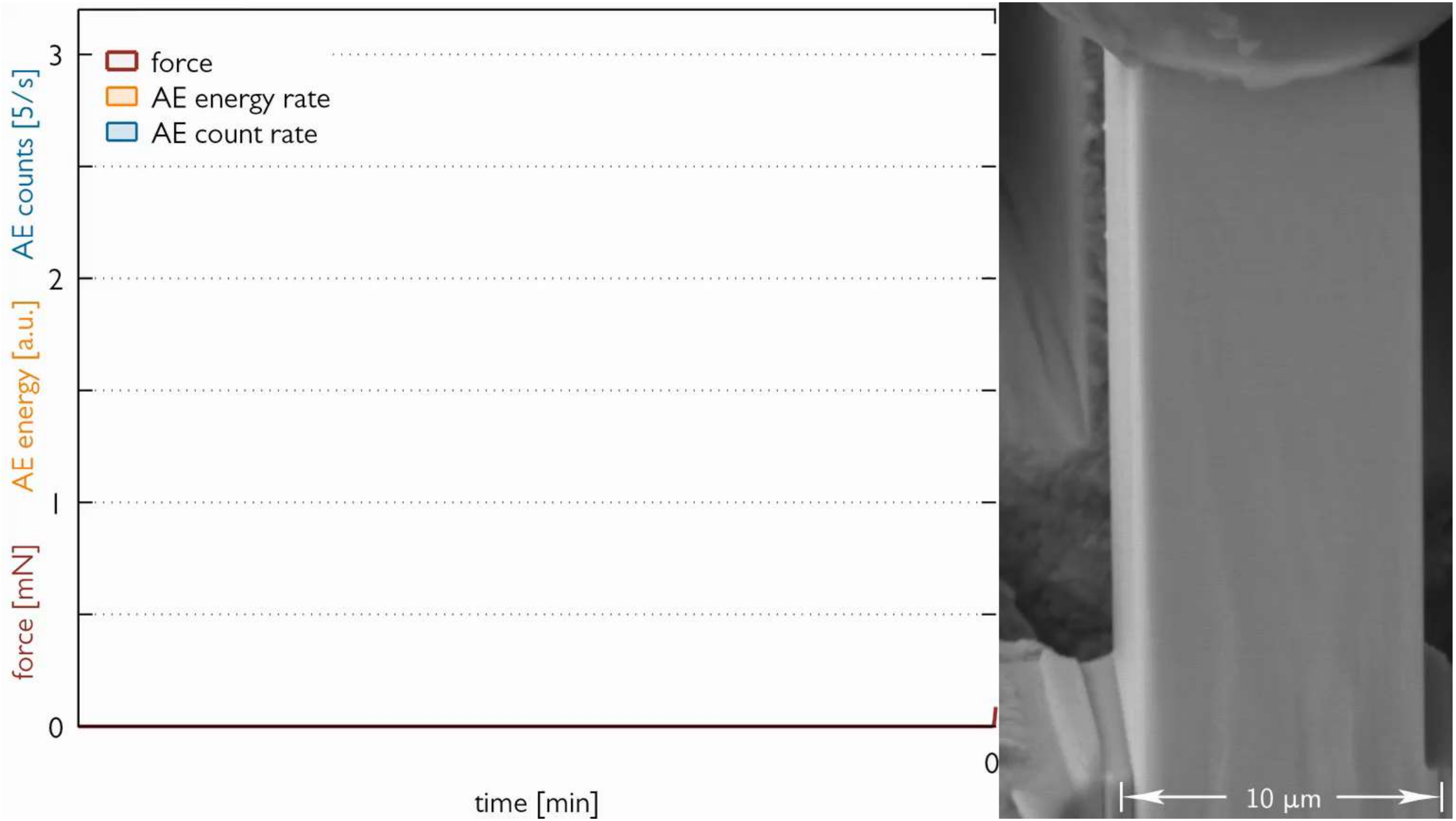
Dislocation avalanches are like earthquakes on the micron scale

2022

https://doi.org/10.1038/s41467-022-29044-7

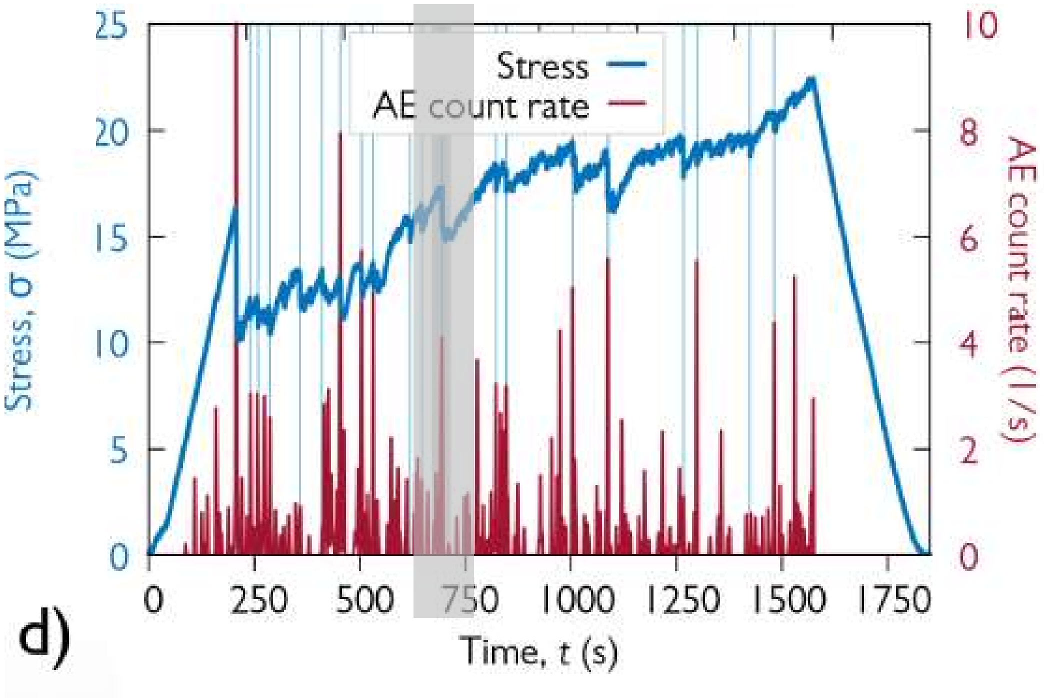
nature COMMUNICATIONS





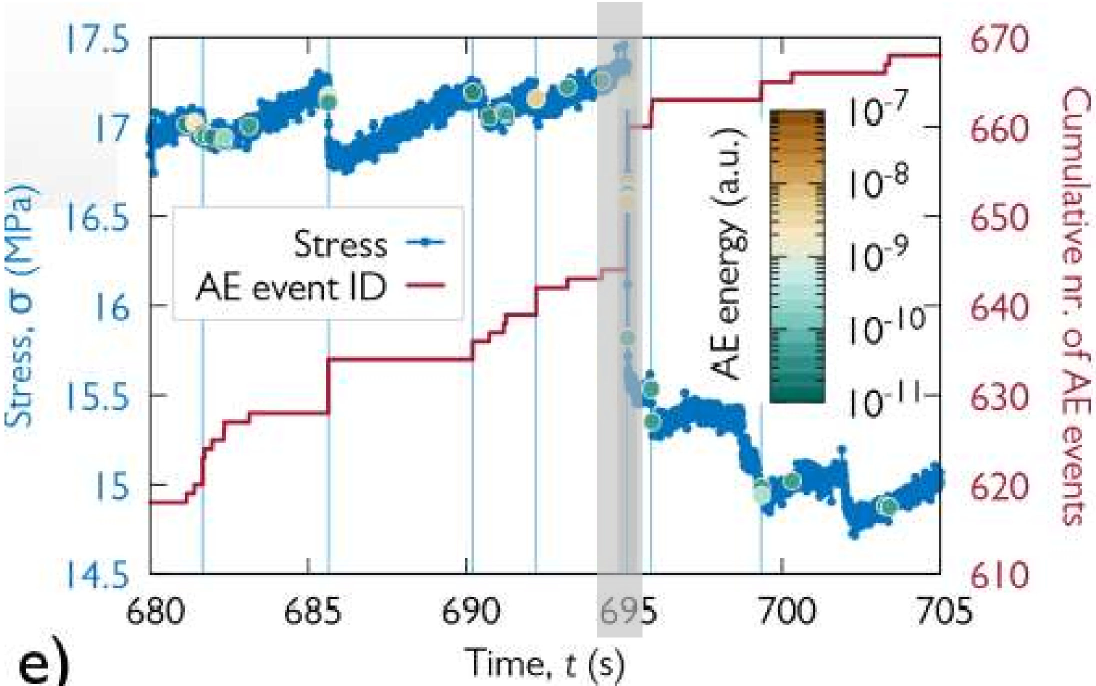
force
AE energy rate
AE count rate
AE counts [5/s]
AE energy [a.u.]
force [mN]
0
1
2
3
0
time [min]
10 μm

Zn micropillars oriented for single slip



- Correlation between stress drops and AE

Zn micropillars oriented for single slip



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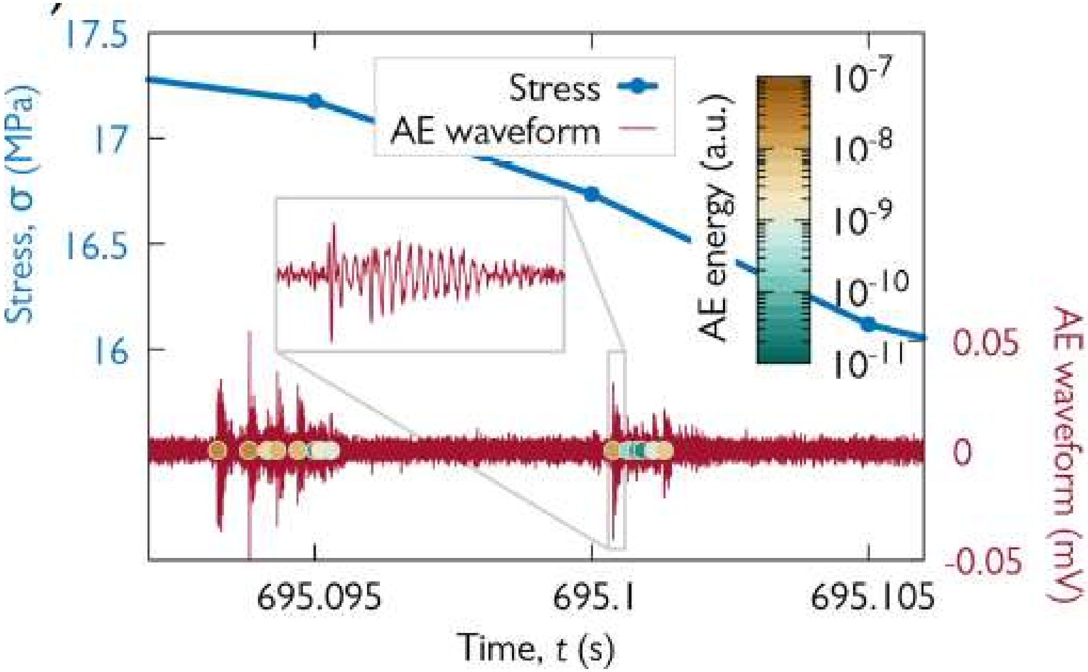
- Correlation between stress drops and AE
- Several AE events during a drop

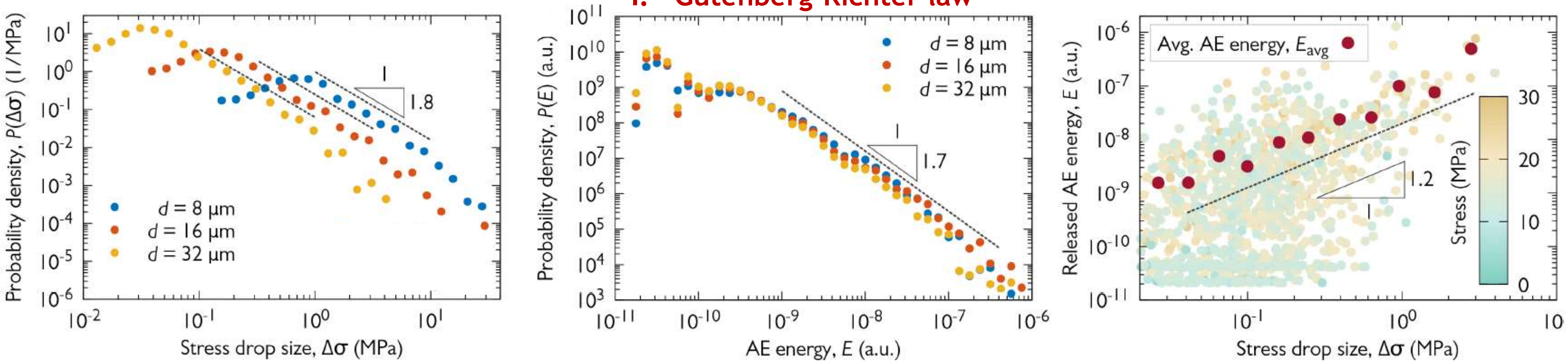
Zn micropillars oriented for single slip



- Correlation between stress drops and AE
- Several AE events during a drop
- Single stress drop is a result of complex internal dynamics on timescales not accessible by stress measurements

Dislocation slip statistics vs. earthquakes dynamics

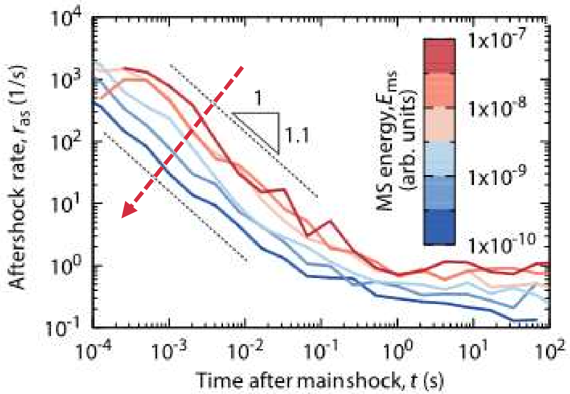
I. "Gutenberg-Richter law"



- Power-law behavior of the released energy
- **A physical relation between the particular stress drops and the corresponding AE energies**

Dislocation slip statistics vs. earthquakes dynamics

II. "Omori law" & III. "Productivity law"



- **Omori-law:**

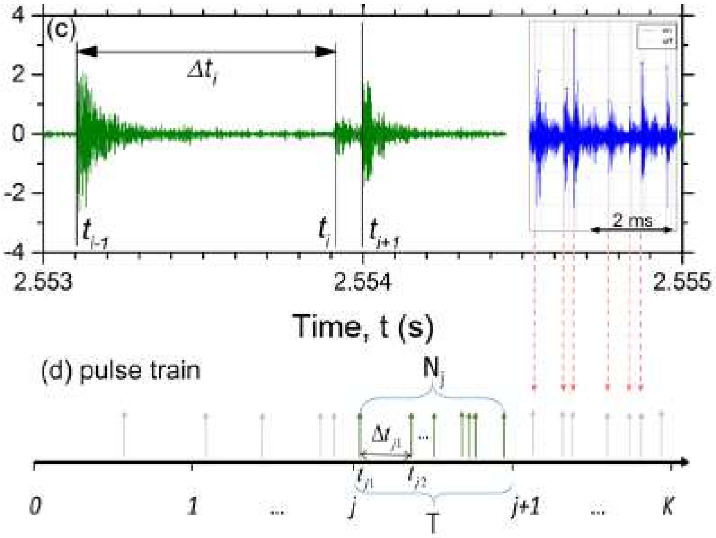
  $n(t) \sim 1/t$ (n - # of aftershocks/time unit; t – time elapsed after main shock)

- **Productivity-law:**

  main shocks with larger energy produce on average more aftershocks

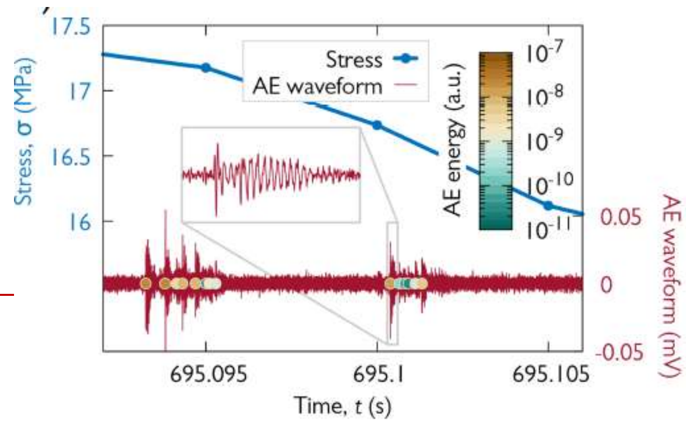
Statistical features of Zn micropillars resemble dynamics of earthquakes

Clustering in temporal processes



A. Vinogradov et al., Sci. Reports. 2019

- Analysis of the waiting times t_w between the subsequent events



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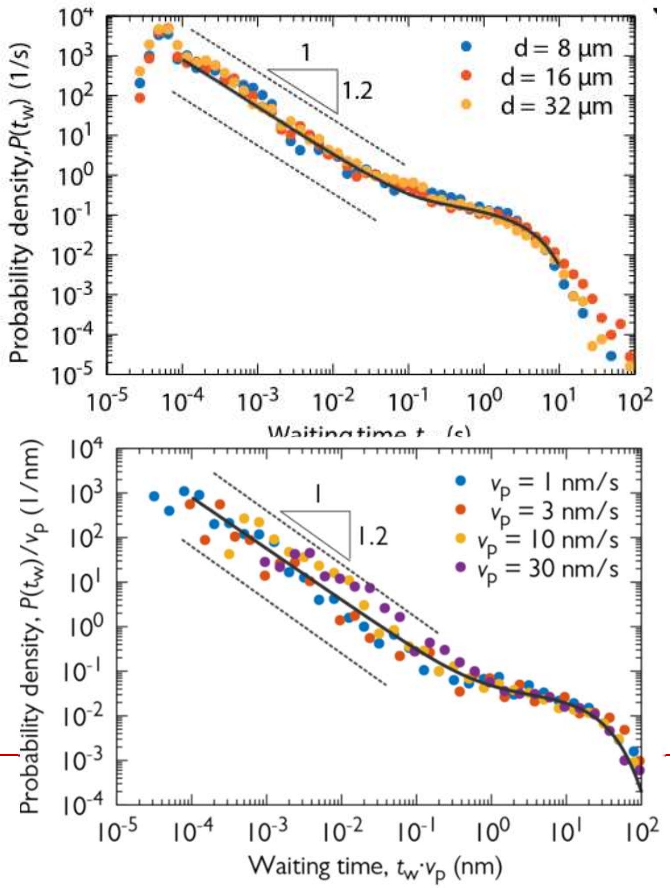
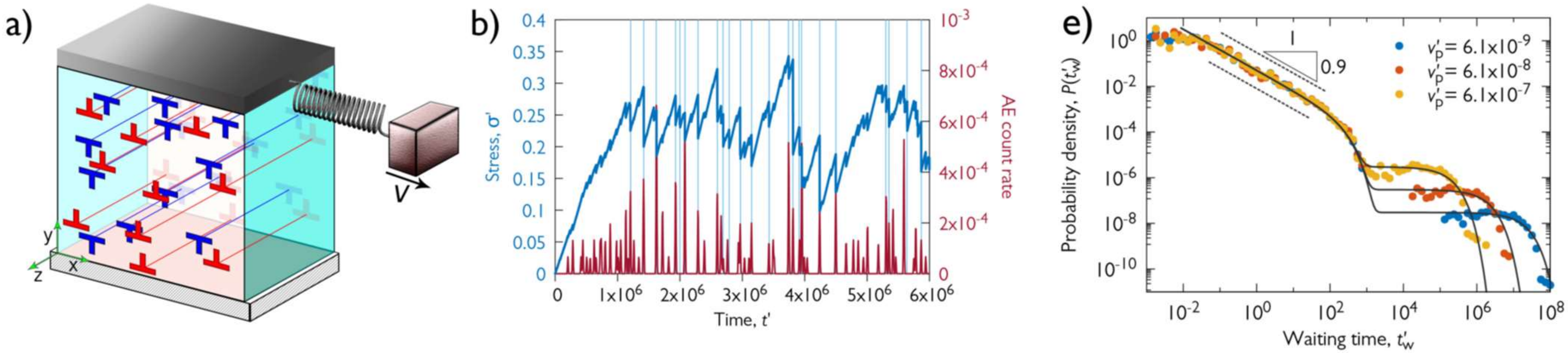


- Analysis of the waiting times t_w between the subsequent events
- Universal gamma distribution
  $$P(t_w) = \left(At_w^{-(1-\gamma)} + B\right)\exp(-\frac{t_w}{t_0})$$
- **Power-law distribution for small (≤ 0.1s) t_w** : correlation between the events of the same stress drop
- Plateau with exponential cut-off for larger times:

  Poisson-like distribution, uncorrelated main shocks
- Negligible effect of the pillar size
- Platen velocity does not influence the single event dynamics
- In the cut-off region $B \propto v_p \;\; t_0 \propto v_p^{-1}$

Discrete dislocation dynamics modeling



- Excellent agreement with the experiments
- The complex dynamic behavior observed in experiments is the result of the spatio-temporal correlations of the dislocations due to their long-range elastic interactions

Conclusions

Experimental

- **Profound correlations are observed between the energies of plastic and AE events,** induced by the collective dissipative motion of dislocations
- **AE is a convenient high-resolution "proxy" for elementary plastic events.**

Scientific

- The intermittency and scale-invariance characterizing plastic deformation of HCP single crystals are related to the self-organized critical (SOC) behavior of dislocations
- The **plastic events exhibit both spatial and temporal clustering** with long-range correlations
- Statistical analyses further show that **despite fundamental differences in deformation mechanism and involved length- and time-scales, dislocation avalanches and earthquakes are essentially alike.**

Thank you

Nat. Commun. paper:

Youtube video:

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