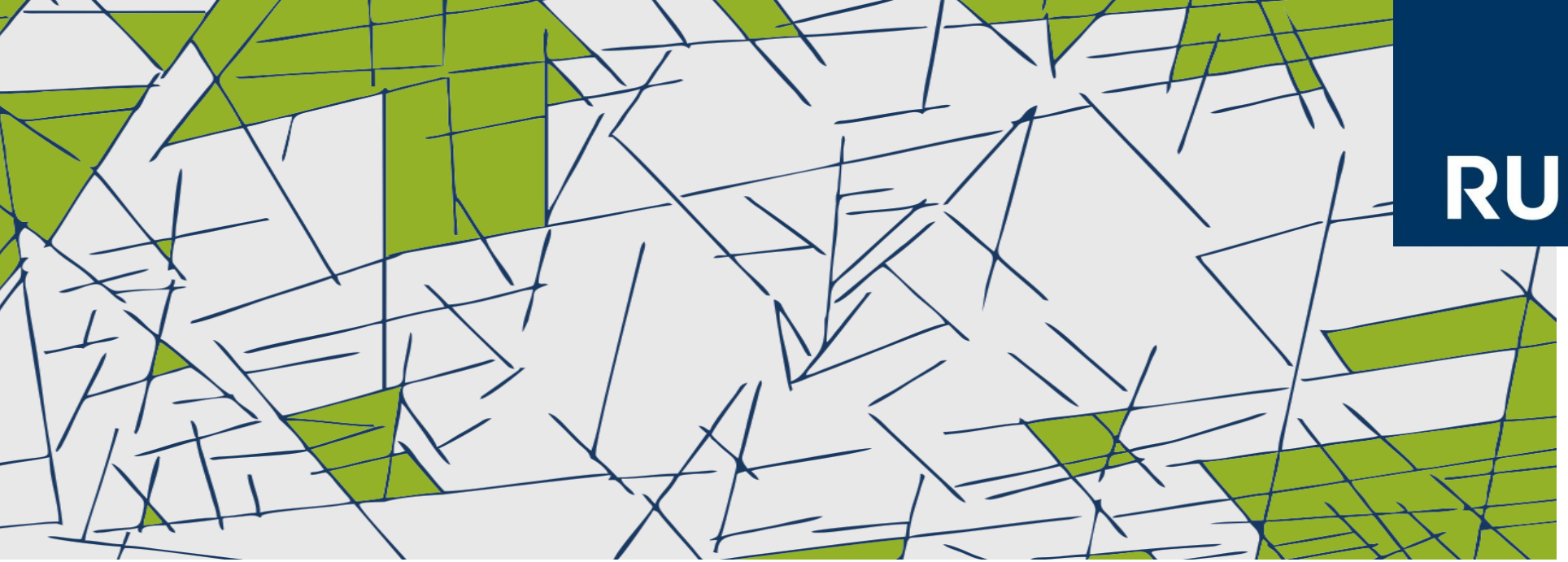


RUHR-UNIVERSITÄT BOCHUM

**Faculty of Geosciences** | Institute of Geology, Mineralogy & Geophysics

# Determining the frequency dependence of elastic properties of fractured rocks

BENEDIKT AHRENS & JOERG RENNER | 19.04.2016

# Motivation

## Scaling determines homogeneity!

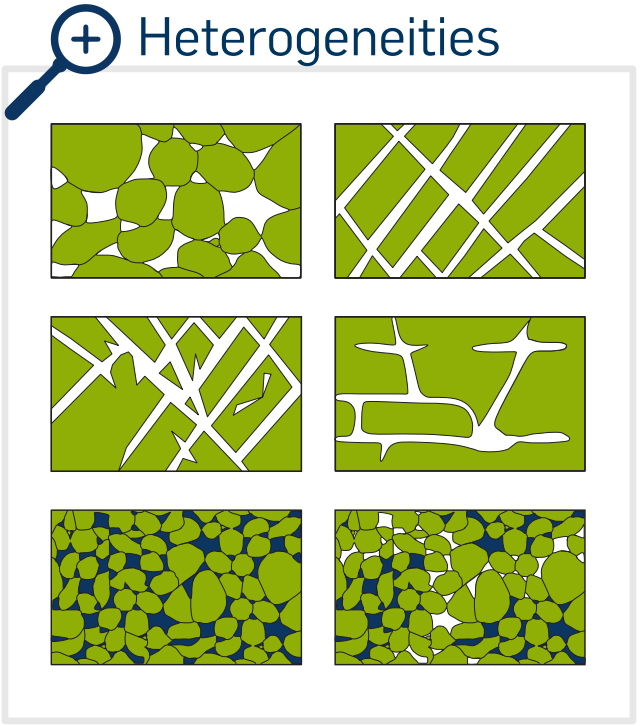
Rocks contain joints or faults on various length scales that have a profound effect on fluid flow, heat transport and elastic properties of rocks.

▼

**Understanding the effect of fractures on elastic properties is important for the characterization of deep geothermal reservoirs.**

▼

Seismic surveys are a valuable tool to investigate fractured rocks but the extraction of fracture properties remains difficult.




# Motivation

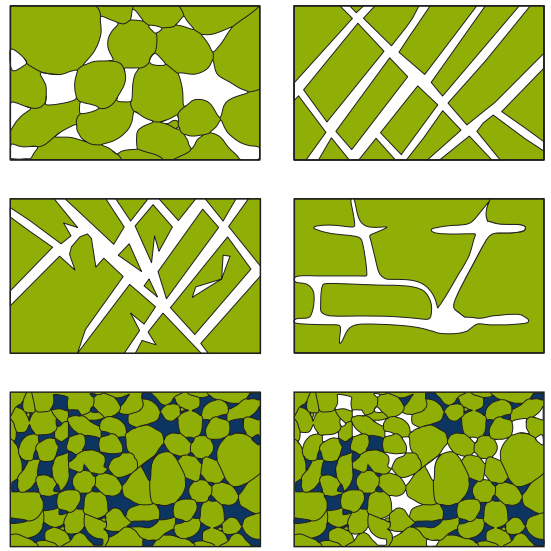
## Scaling determines homogeneity!

Frequency-dependent interaction between fractured rocks and viscous pore fluids require well-founded dispersion analyses.

▼

**Experimental investigation of the effective elastic properties of fractured reservoir rocks over relevant frequencies:**

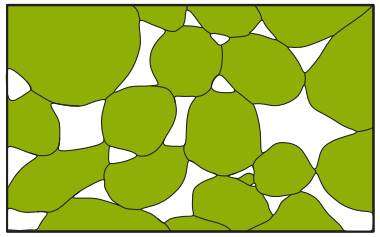

Heterogeneities



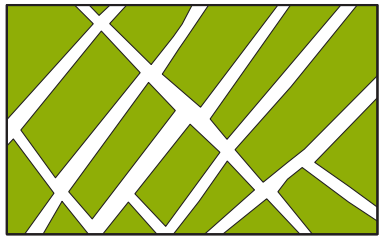
# Motivation

## Scaling determines homogeneity!

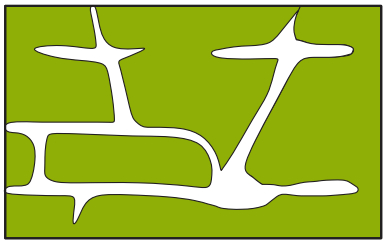
**Rock frame**



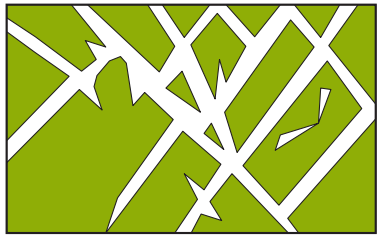
pores (µm)



joints (cm...m)

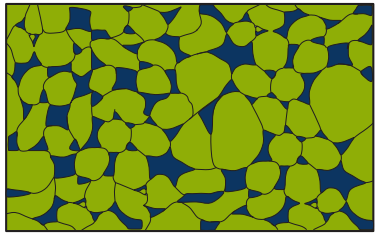


karsts (m)



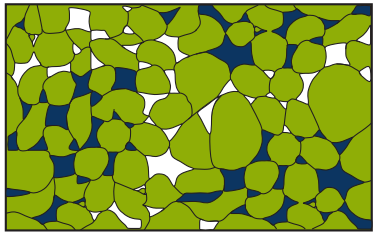
faults (µm...km)

**Fluid saturation**



fully saturated

patchy saturated (mm...km)



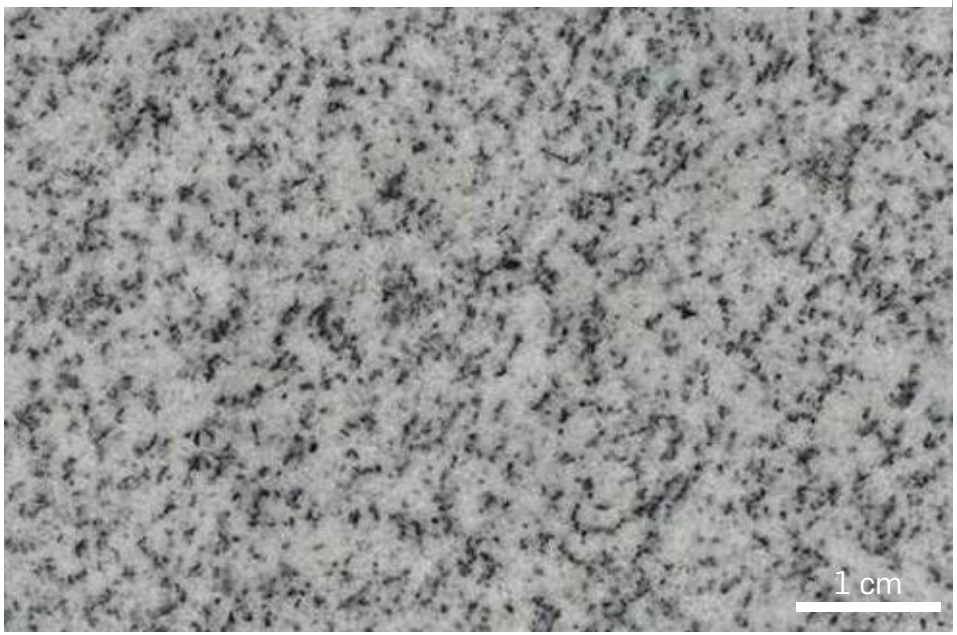
# Sample material

## Solnhofen limestone


http://geo.hlipp.de/photo/142

- Low attenuation
- Easy preparation of sample material
- Natural isotropic fracture roughness

## Padang granodiorite




http://eurasian.com/china/granite/images/g633_500.jpg

- Rather free of cracks/fractures
- Geothermal relevance („hot rocks“)
- Represents crystal basement

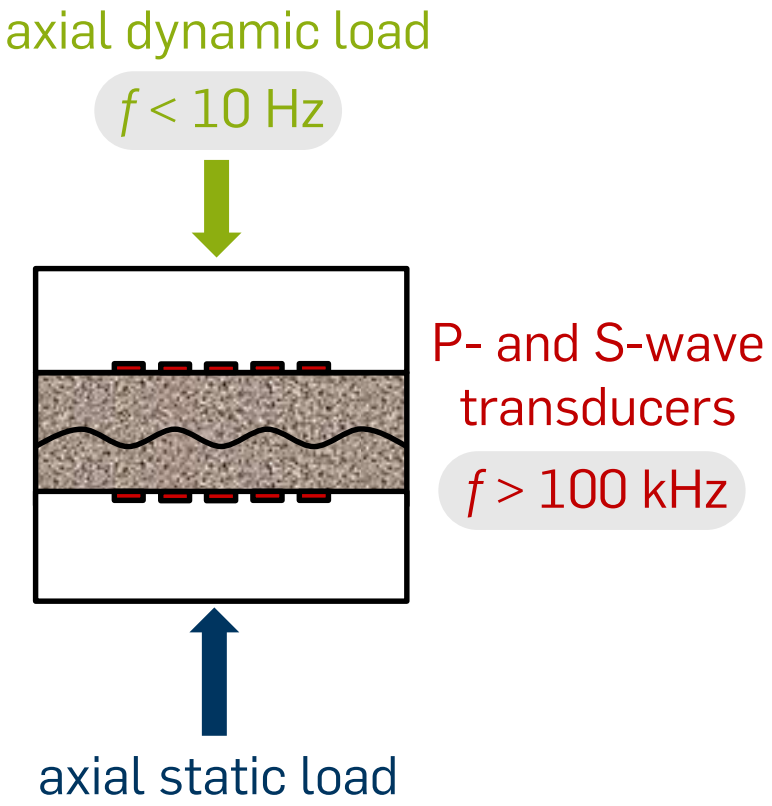
# Experimental approach

## Cyclic axial loading

Samples contain an idealized fault, created by stacking two sample discs on top of each other.

Transmission properties of fractured rocks in dependence of:

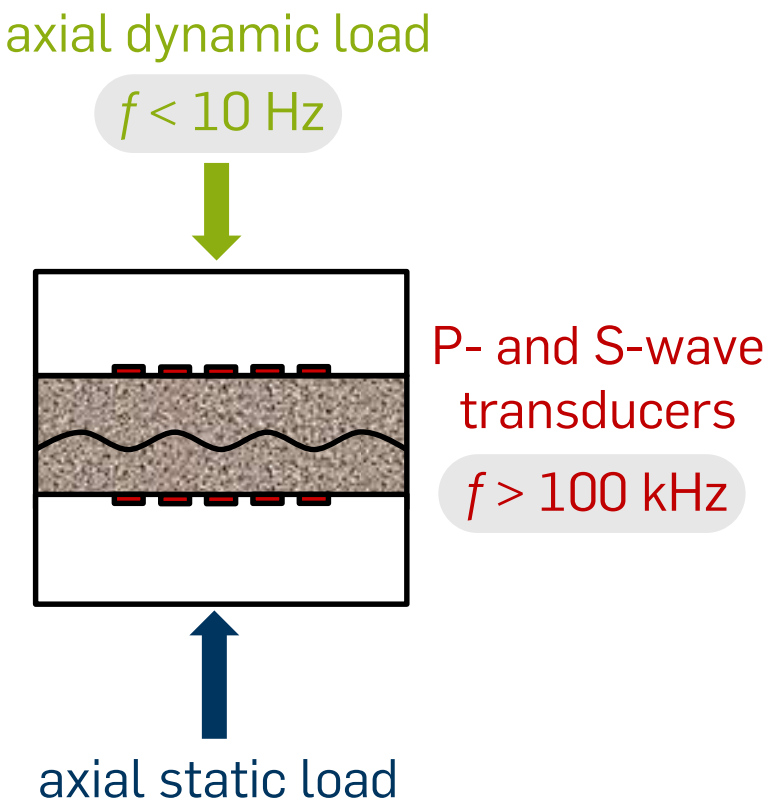
- **normal stress**
- **frequency**
- **reflection and transmission angle**

# Experimental approach

## Experimental settings

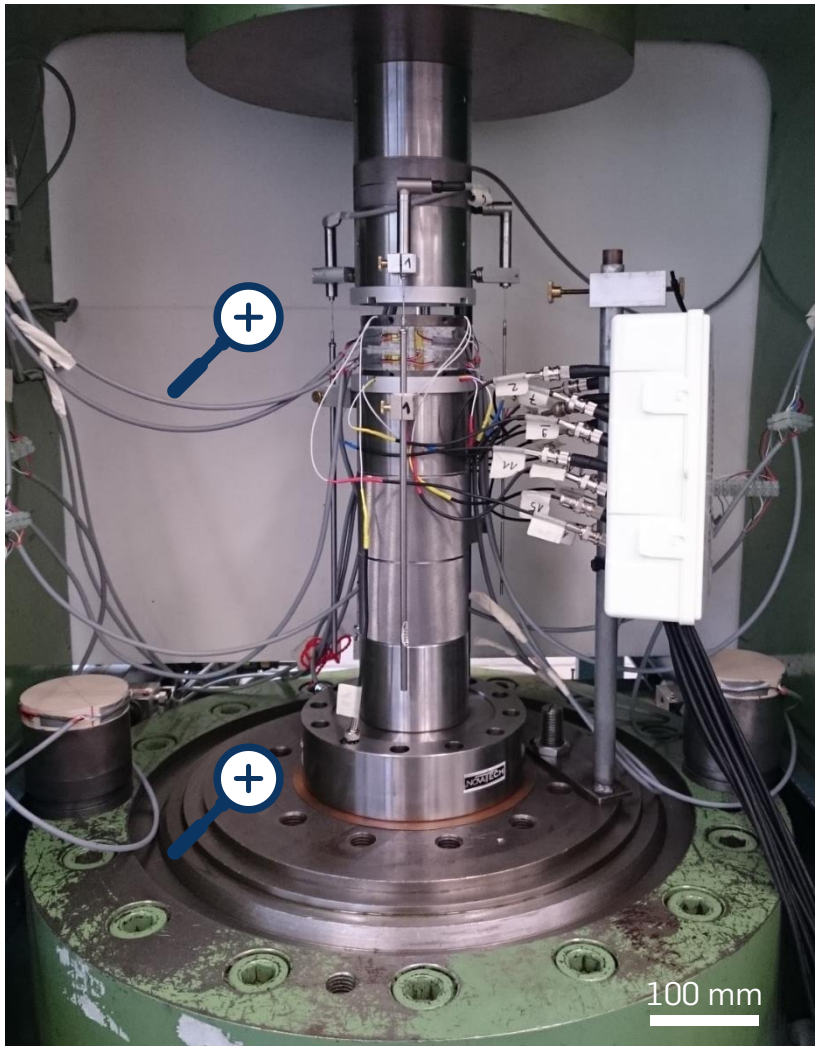
- Characterization of single intact and stacked fractured rock
- Various frequencies and axial stresses
- Defined fracture roughness
  - creation of isotropic roughness
  - 3D image analysis
- Fracture-filling fluids with different viscosities
  - water: $\eta_{water} \sim 10^{-3}$ Pa·s
  - silicone oil: $\eta_{silicone} \sim 10^{2} \ldots 10^{6} \cdot \eta_{water}$



# Experimental approach

## Mechanical characterization

- Two stacked sample discs
  - diameter: 100 mm
  - height: 20 mm
- Axial loading piston and load cell
- Three displacement transducers (LVDT)
  - arranged at an angle of 120°
- Four strain gauges (DMS) on each sample
  - measure longitudinal and lateral strain
  - temperature compensation



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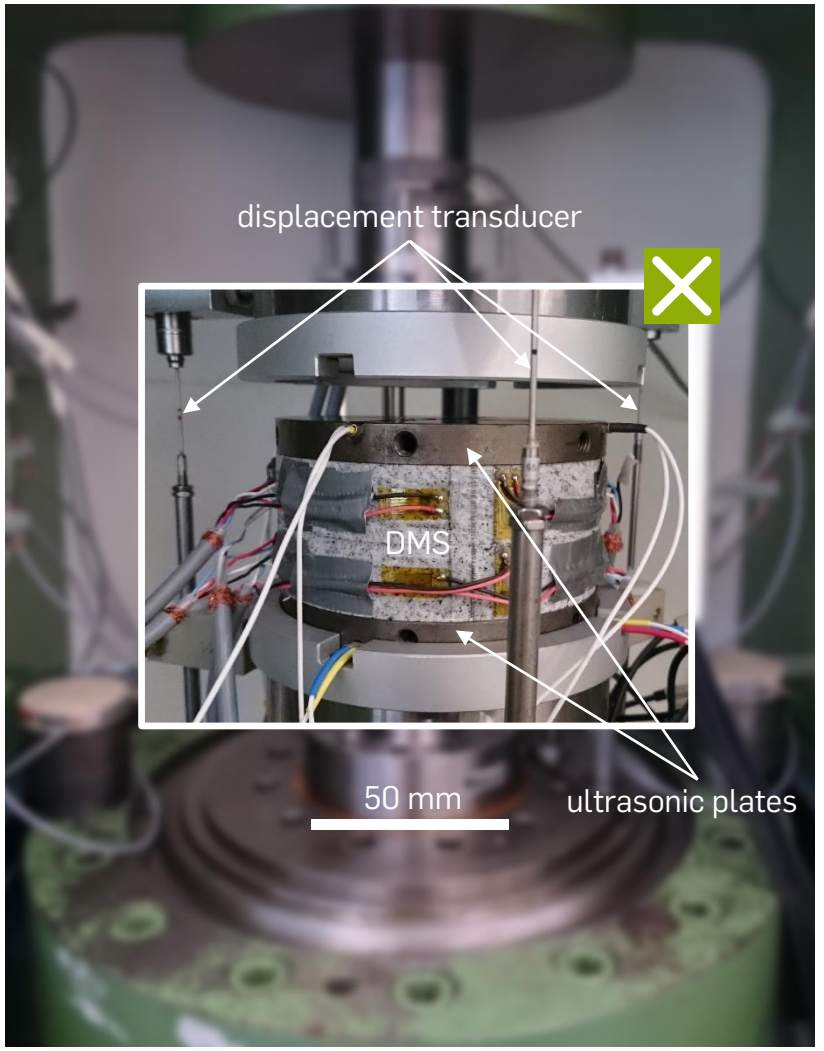

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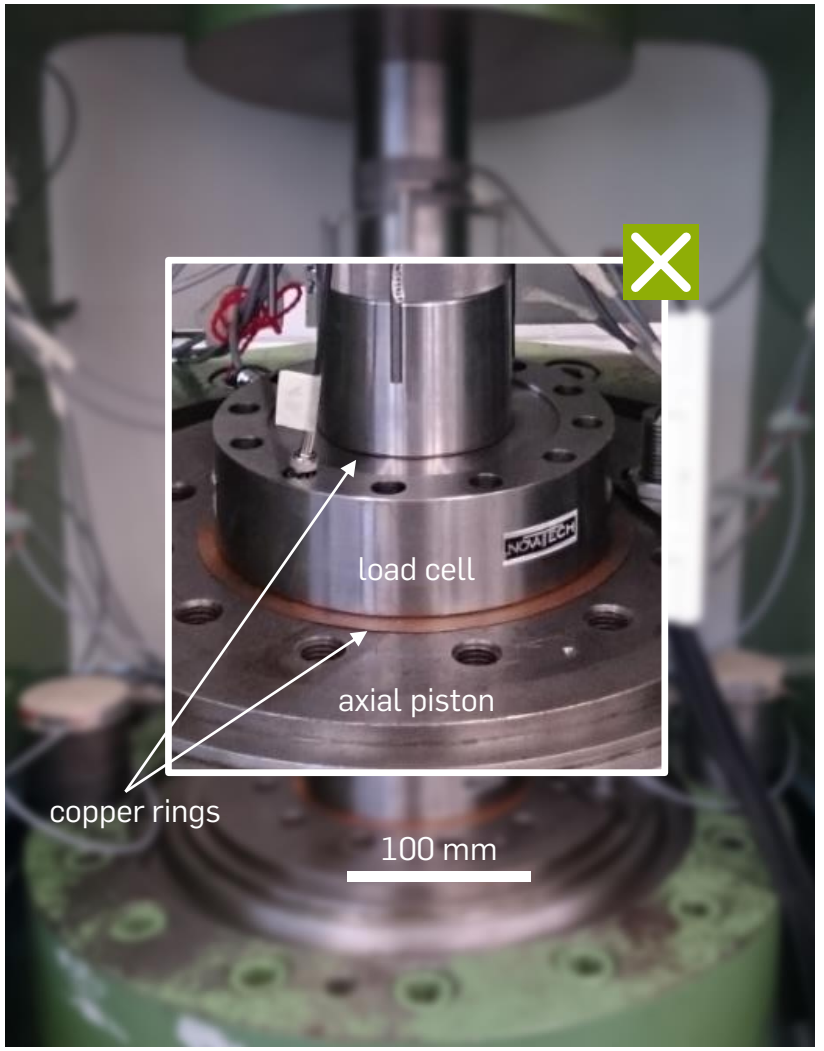
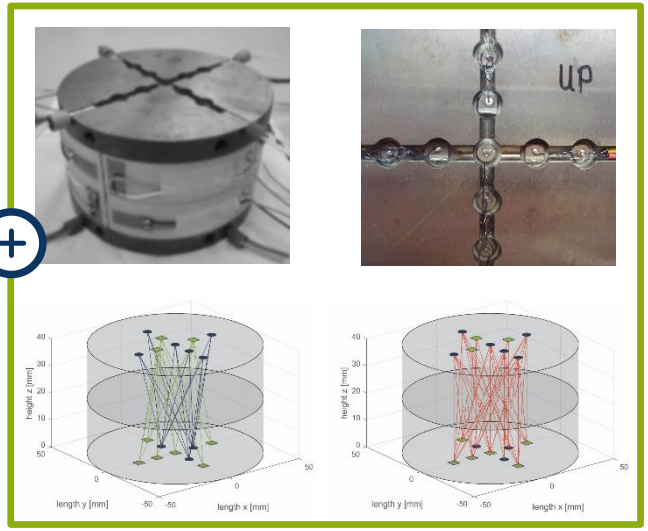
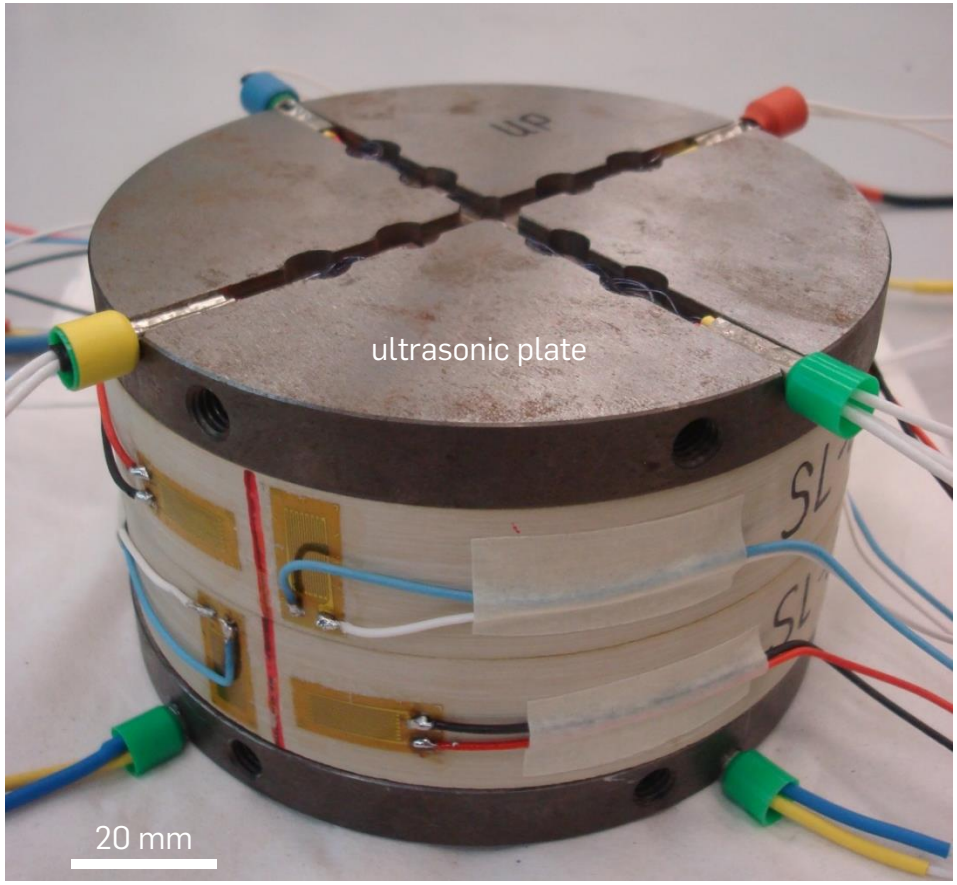


# Experimental approach

## Acoustical characterization




Upper ultrasonic plate:

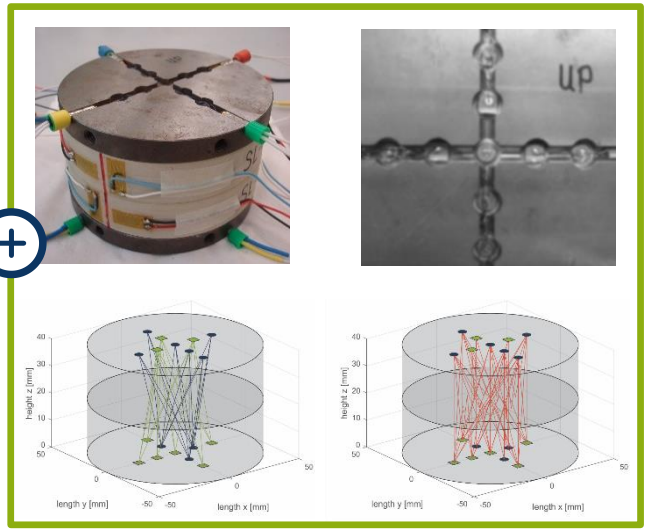
- 6 **P**-wave & 3 **S**-wave sensors

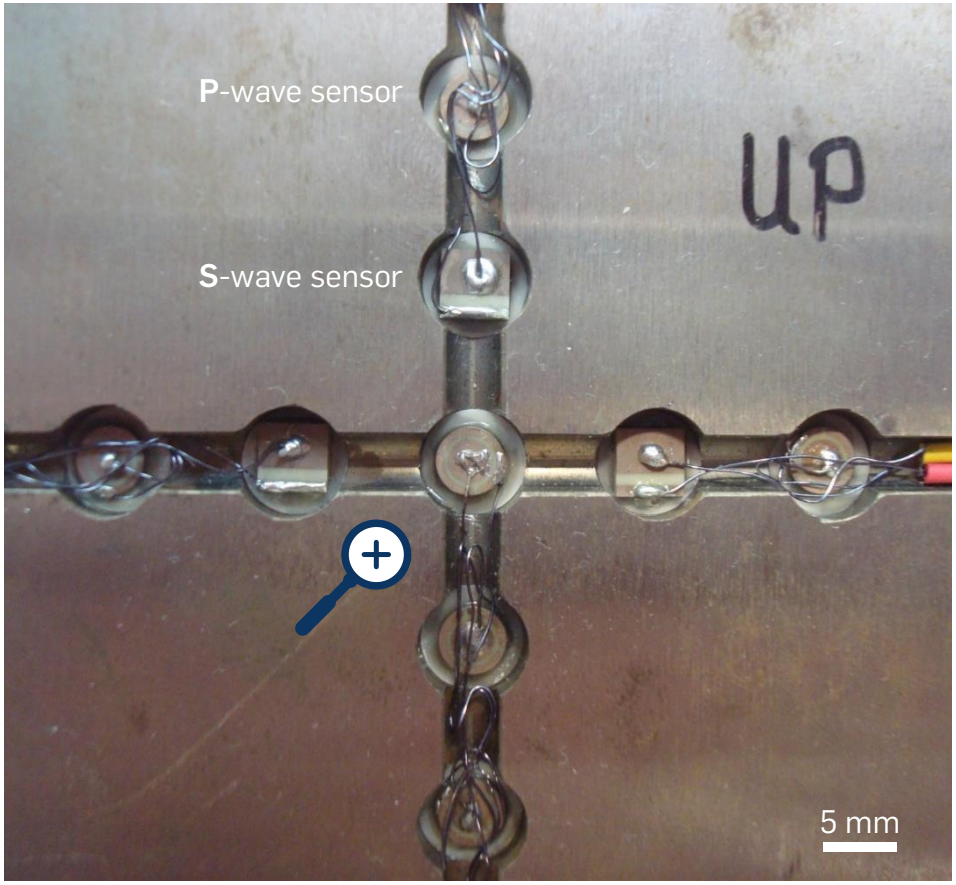
Lower ultrasonic plate:

- 3 **P**-wave & 6 **S**-wave sensors

# Experimental approach

## Acoustical characterization

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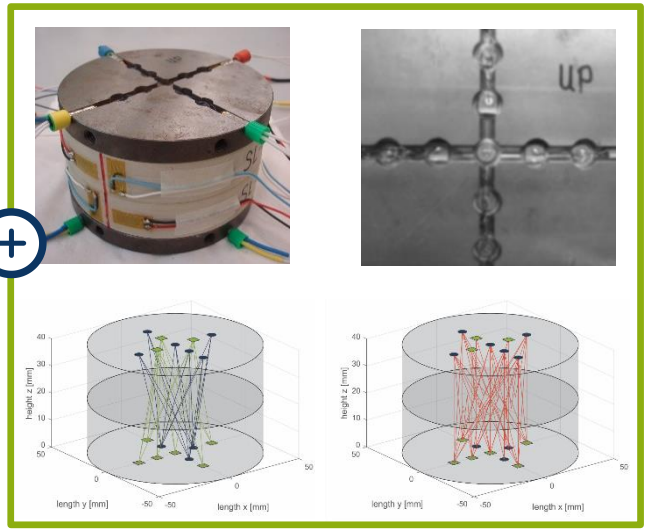
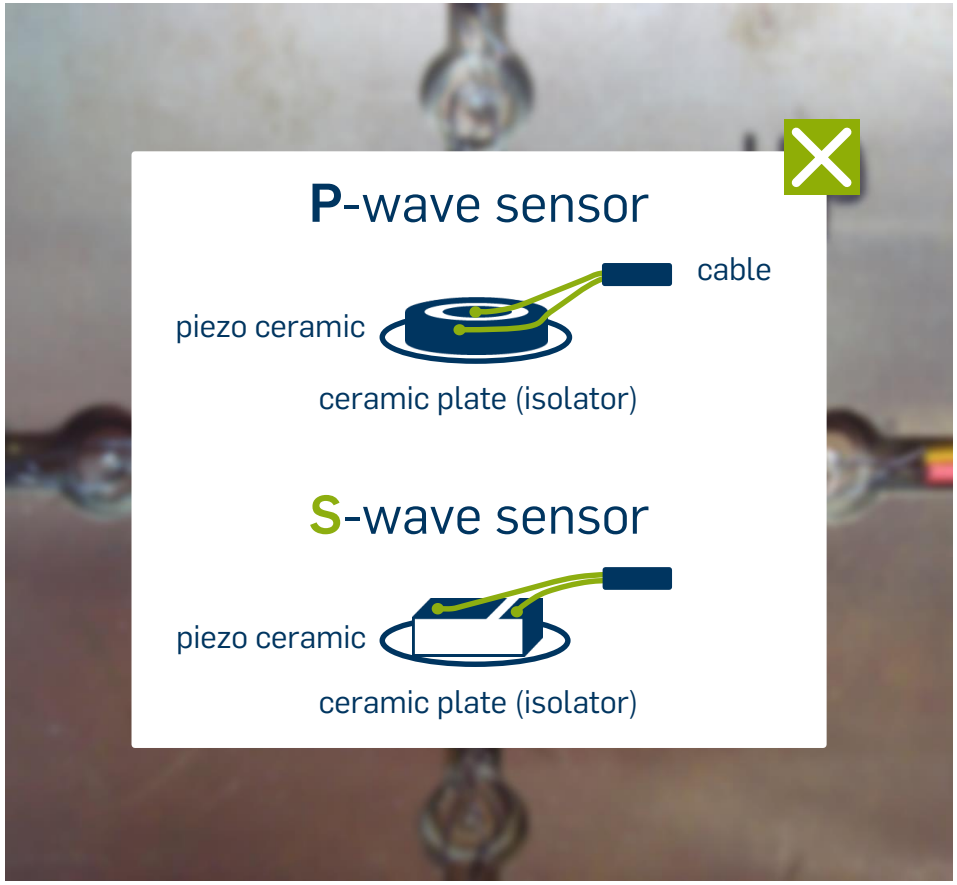
Lower ultrasonic plate:

- 3 **P**-wave & 6 **S**-wave sensors

# Experimental approach

## Acoustical characterization

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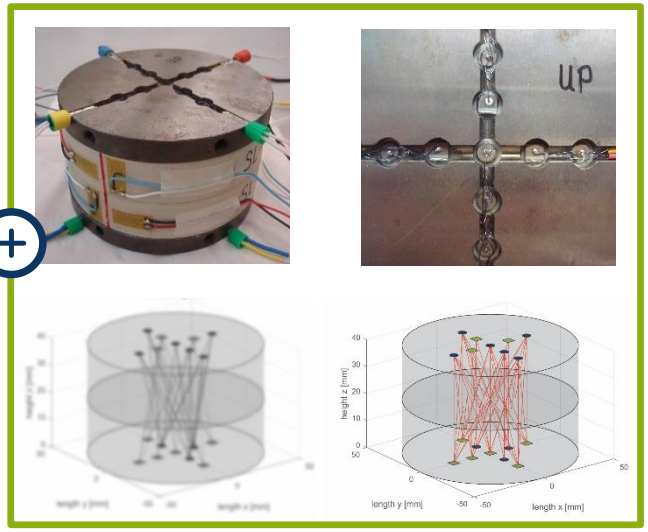
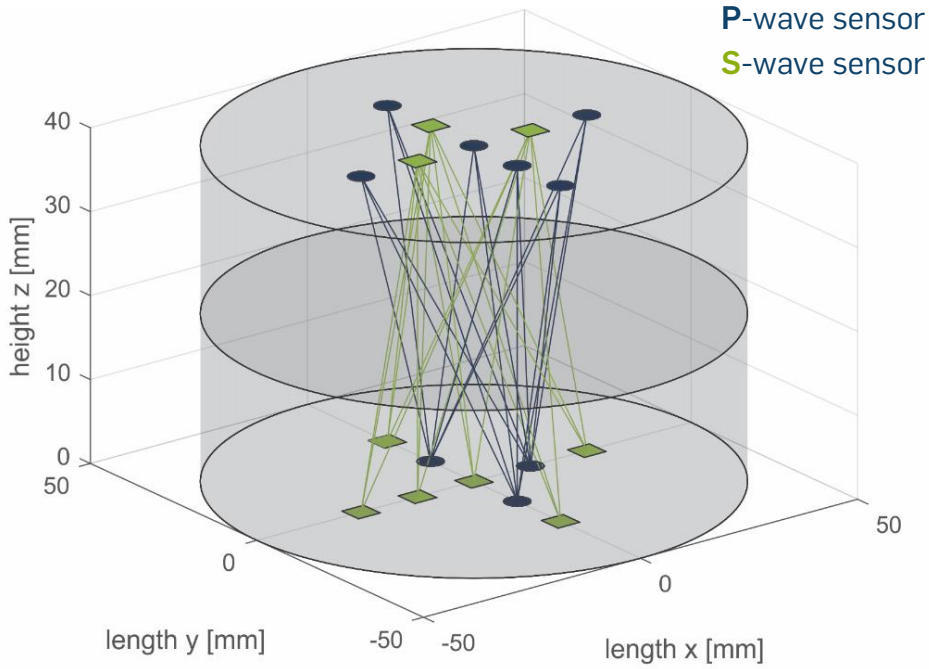
# Experimental approach

## Acoustical characterization




**Transmisson** ray paths




**Transmission** angles:

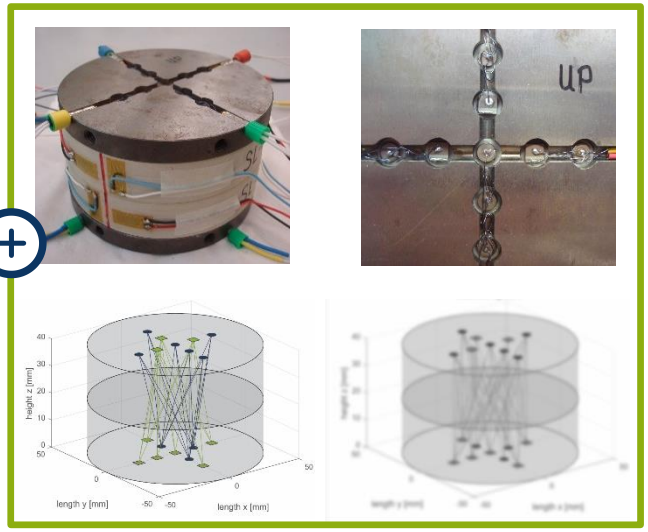
- 0, 17.6 , 24.2, 32.4, 35.3 & 43.6°

Reflection angles:

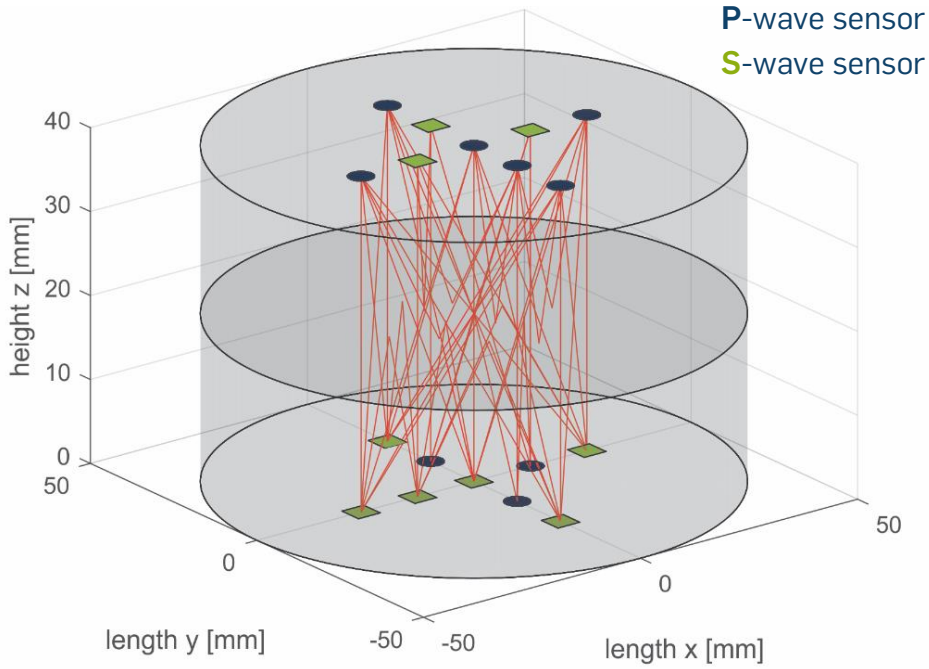
- 0, 17.6, 24.2, 32.4, 35.3, 41.9, 43.6 & 51.7°

# Experimental approach

## Acoustical characterization




**Reflection** ray paths




Transmission angles:

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**Reflection** angles:

- 0, 17.6, 24.2, 32.4, 35.3, 41.9, 43.6 & 51.7°

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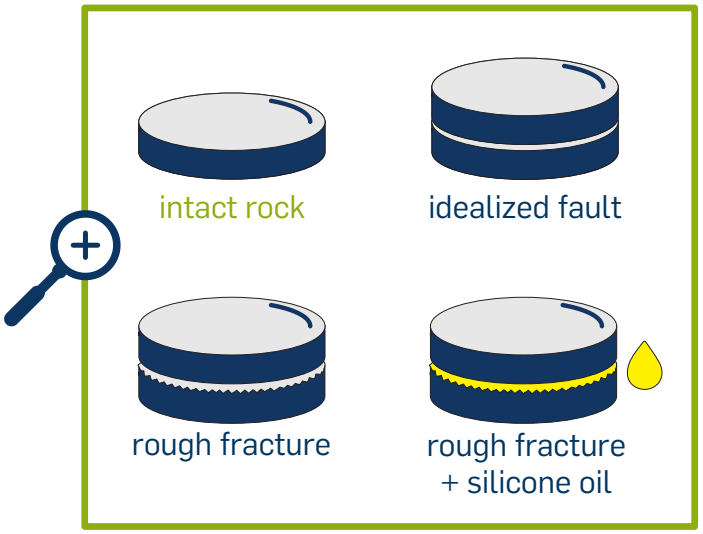
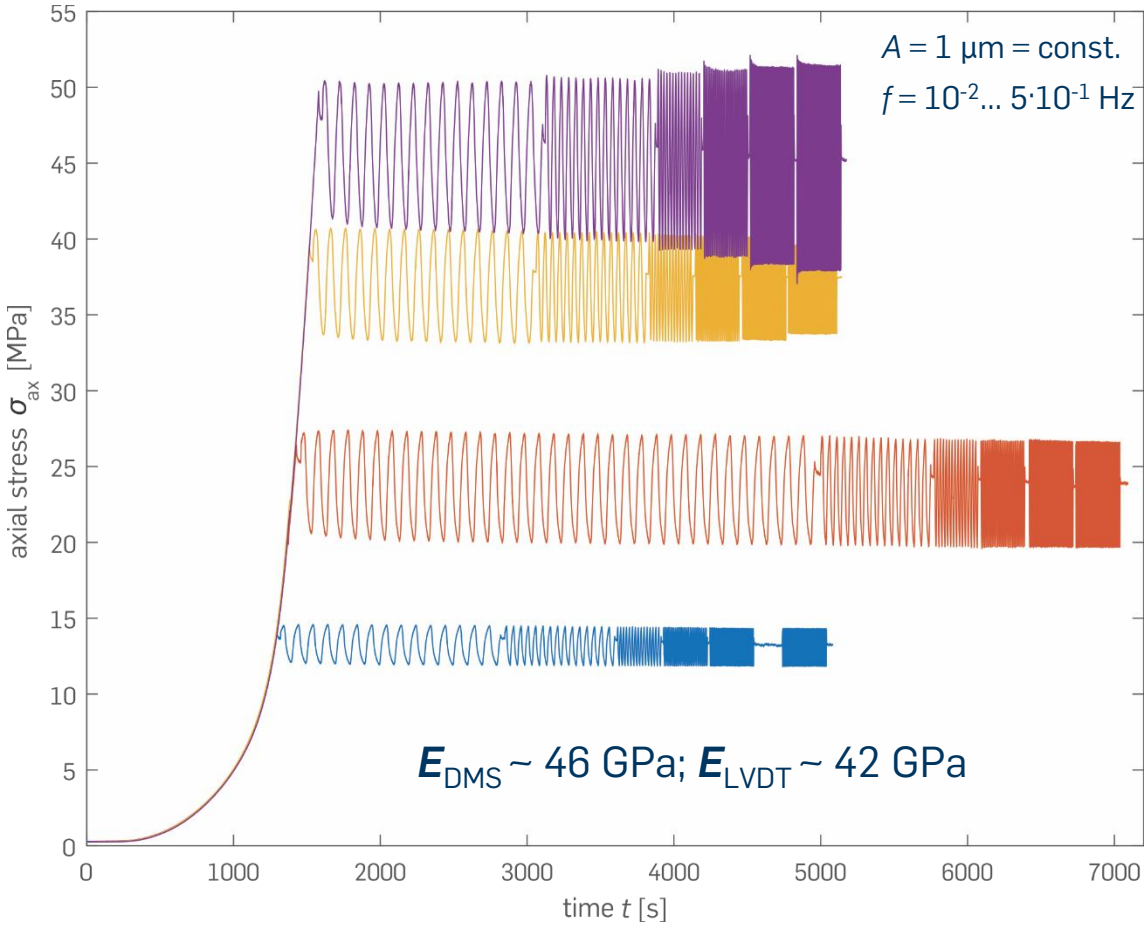
# **Preliminary results** – Stress relaxation

## Padang granodiorite



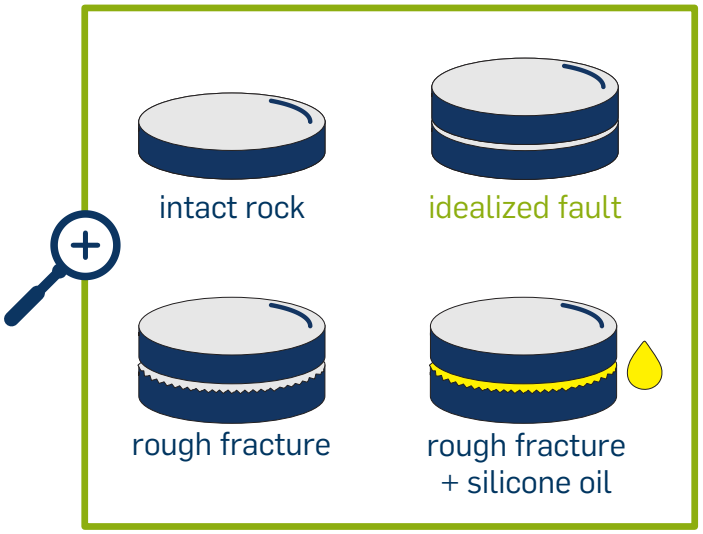

- Axial stiffness increases with increasing load
- Stress relaxation is slightly affected by stress state

### Intact rock



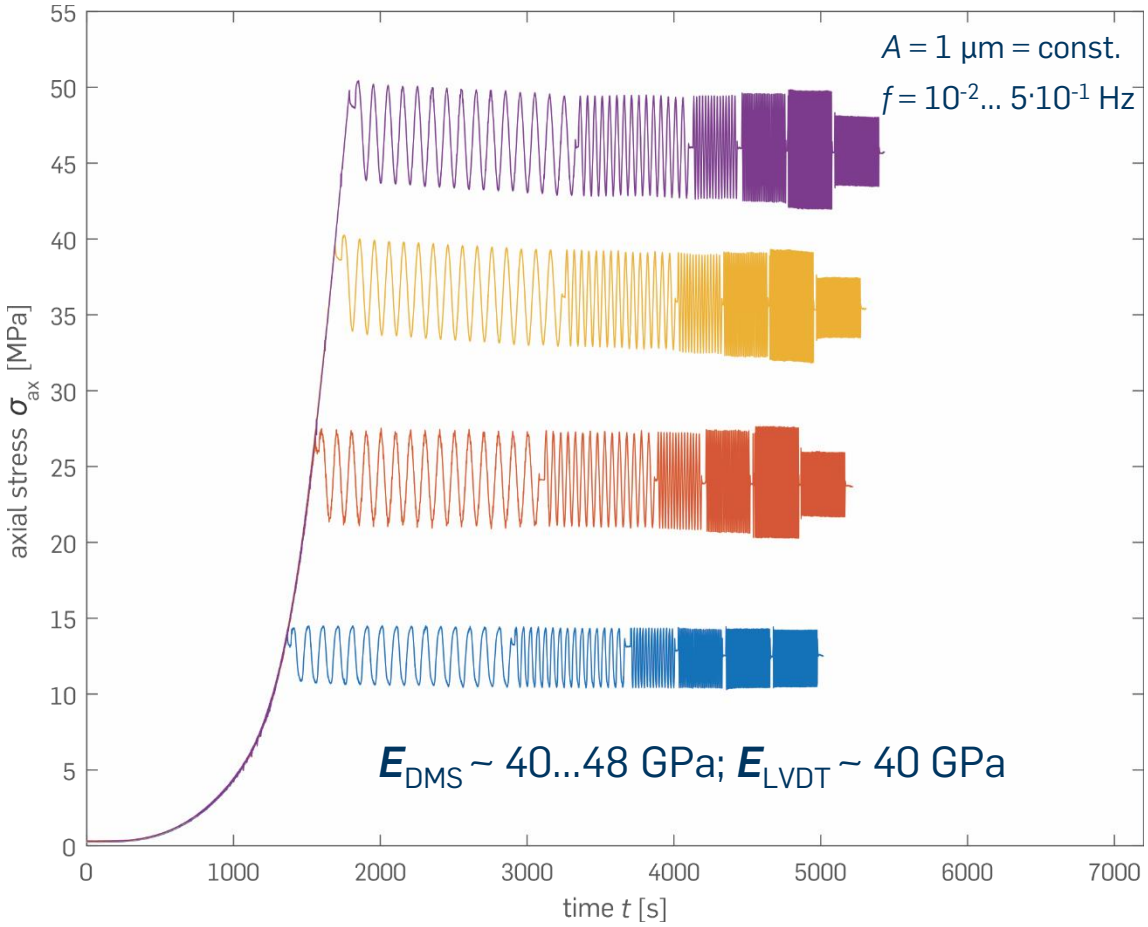
# **Preliminary results** – Stress relaxation

## Padang granodiorite



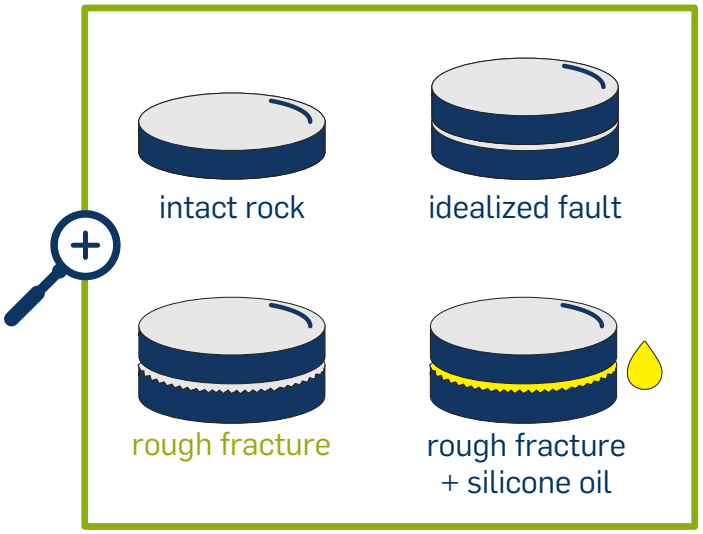

- Total stiffness decreases due to idealized fault
- Idealized fault has a minor effect on Young's modulus

### Idealized fault



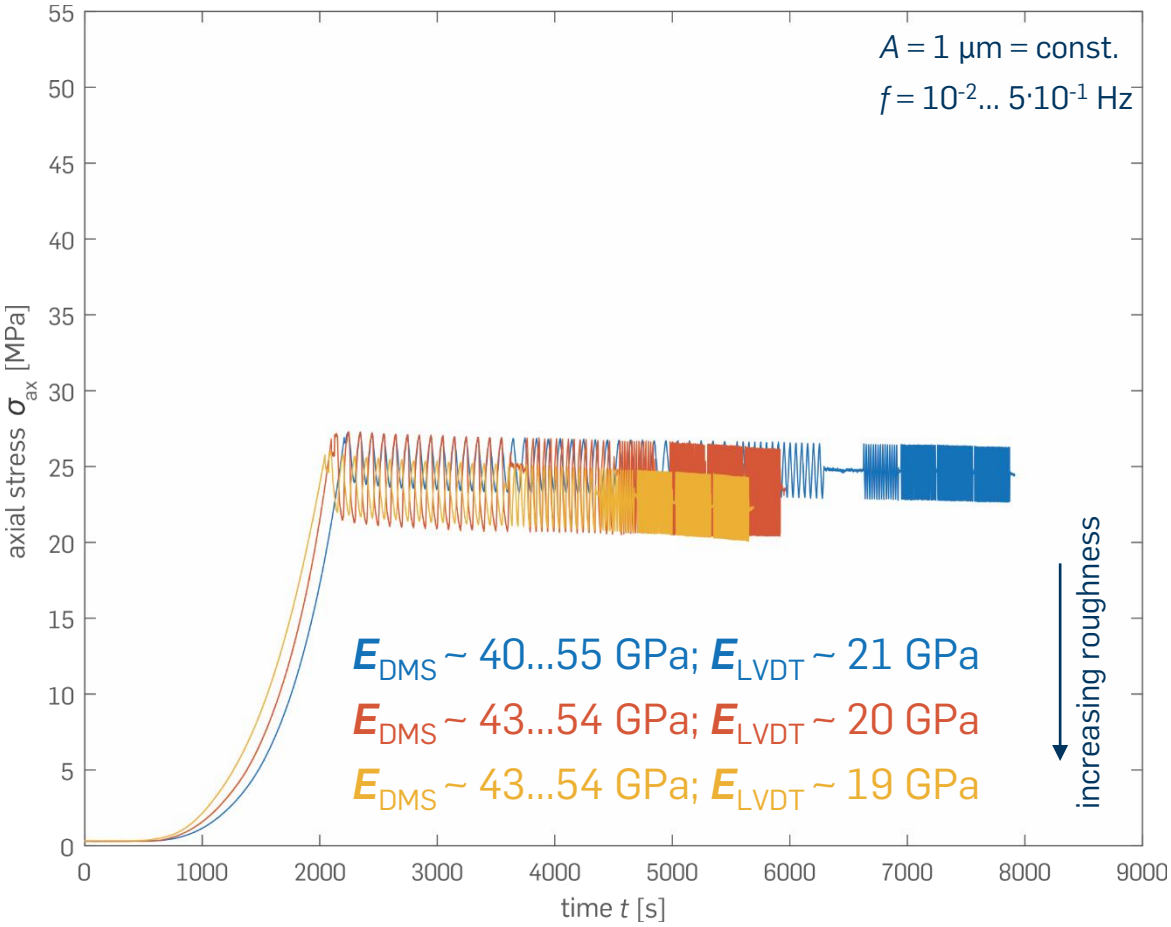
# **Preliminary results** – Stress relaxation

## Padang granodiorite



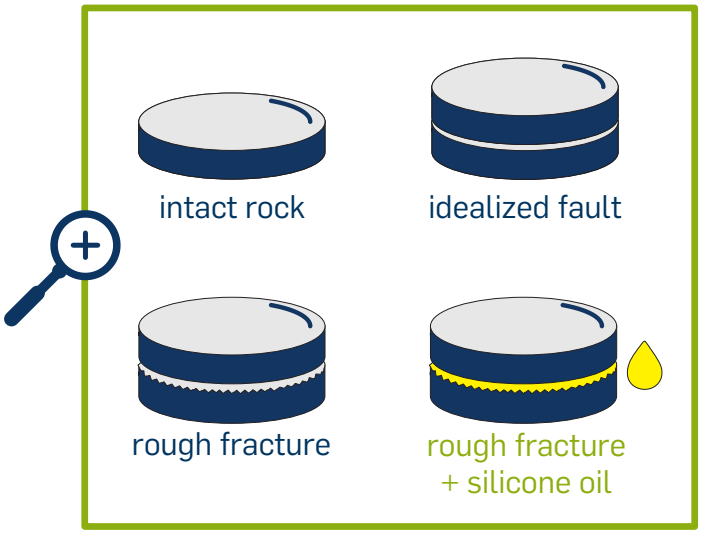

- At the same axial stress, roughness variation has a minor influence on the stiffness

## Idealized fault with rough fracture



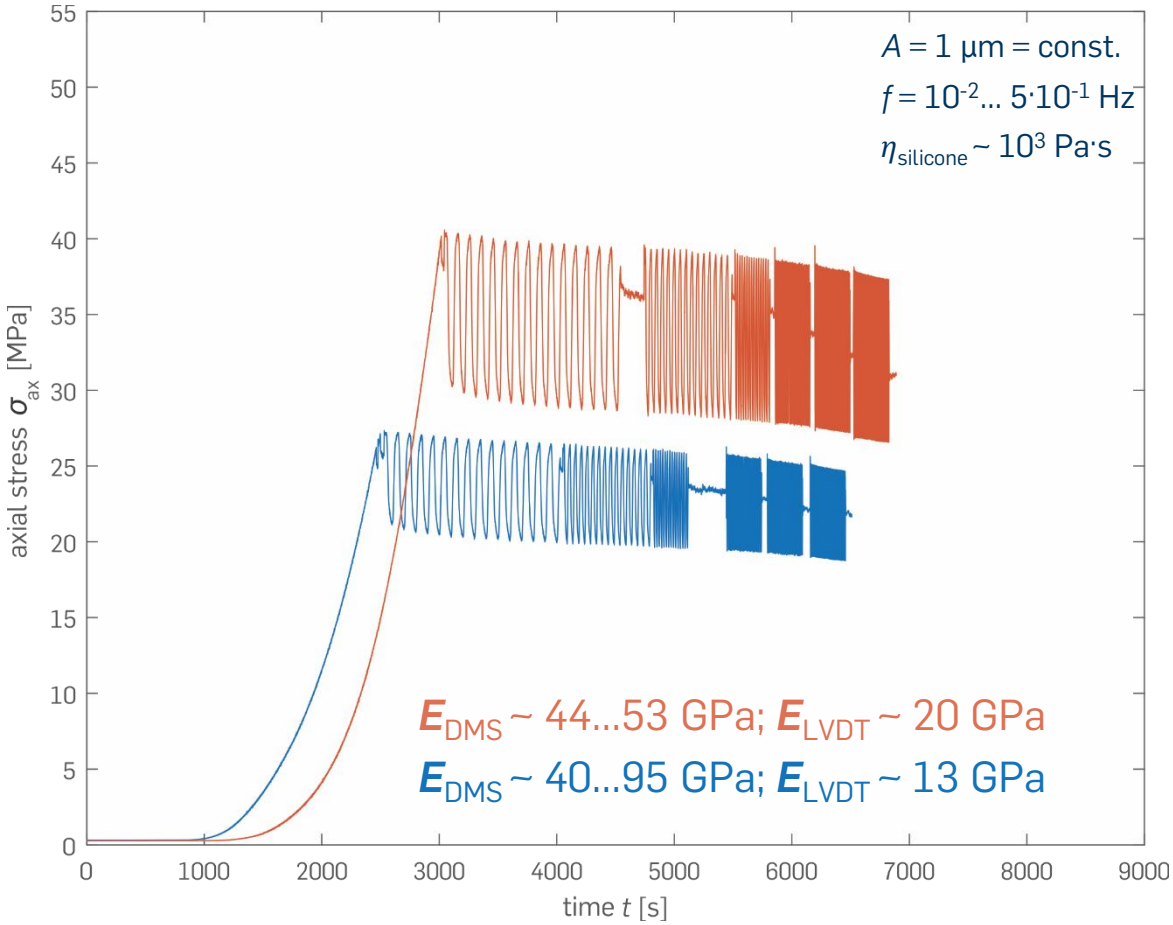
# **Preliminary results** – Stress relaxation

## Padang granodiorite




- Viscous fluid delays loading, decreases total stiffness and enlarges relaxation
- Strain gauges yield increased apparent stiffnesses

## Idealized fault with rough fracture and viscous oil

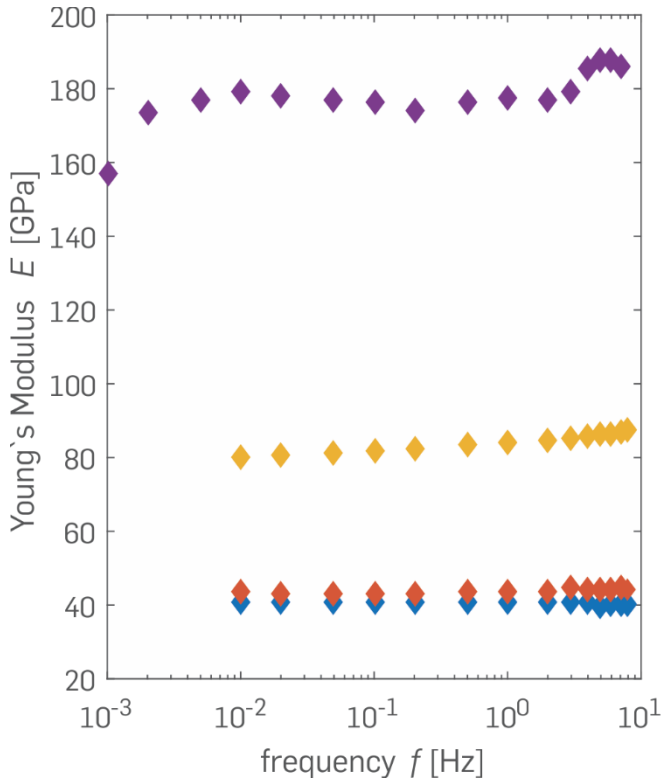


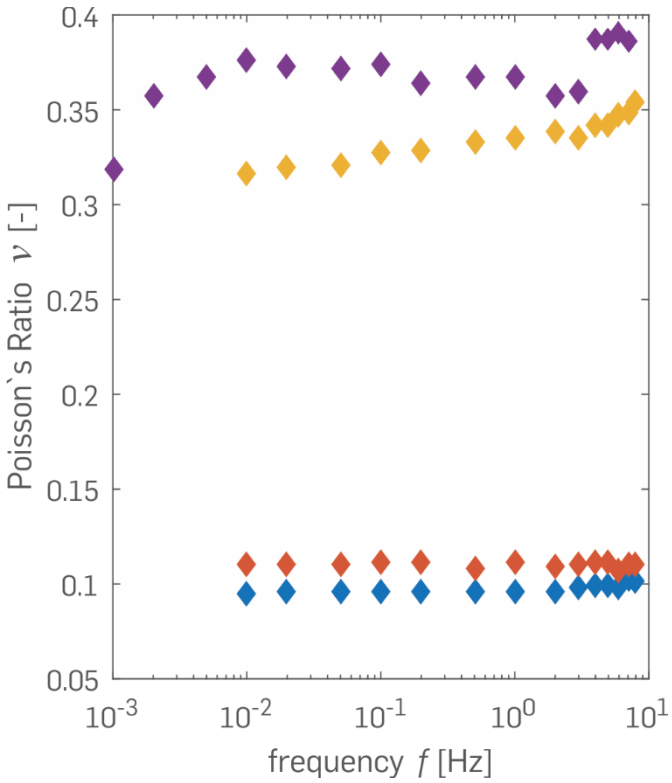
# Padang granodiorite

- Small dispersion of Young's modulus and Poisson's ratio
- Rough fractures and the effect of viscous fluids yield increased apparent elastic properties

Elastic properties of sample discs ($\sigma_{ax}$ = 25 MPa)

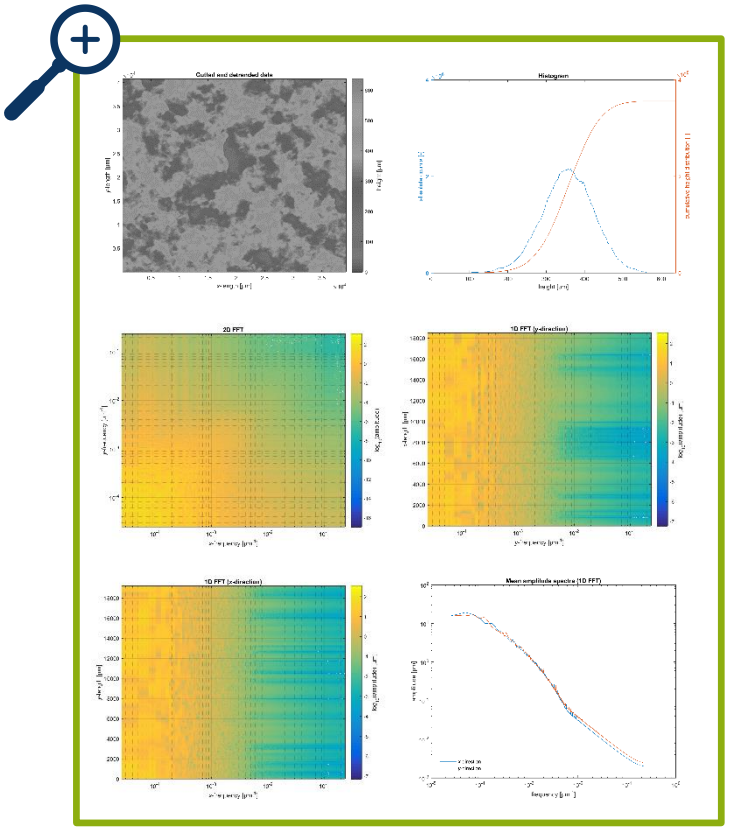
intact rock | idealized fault | rough fracture | rough fracture + silicone oil



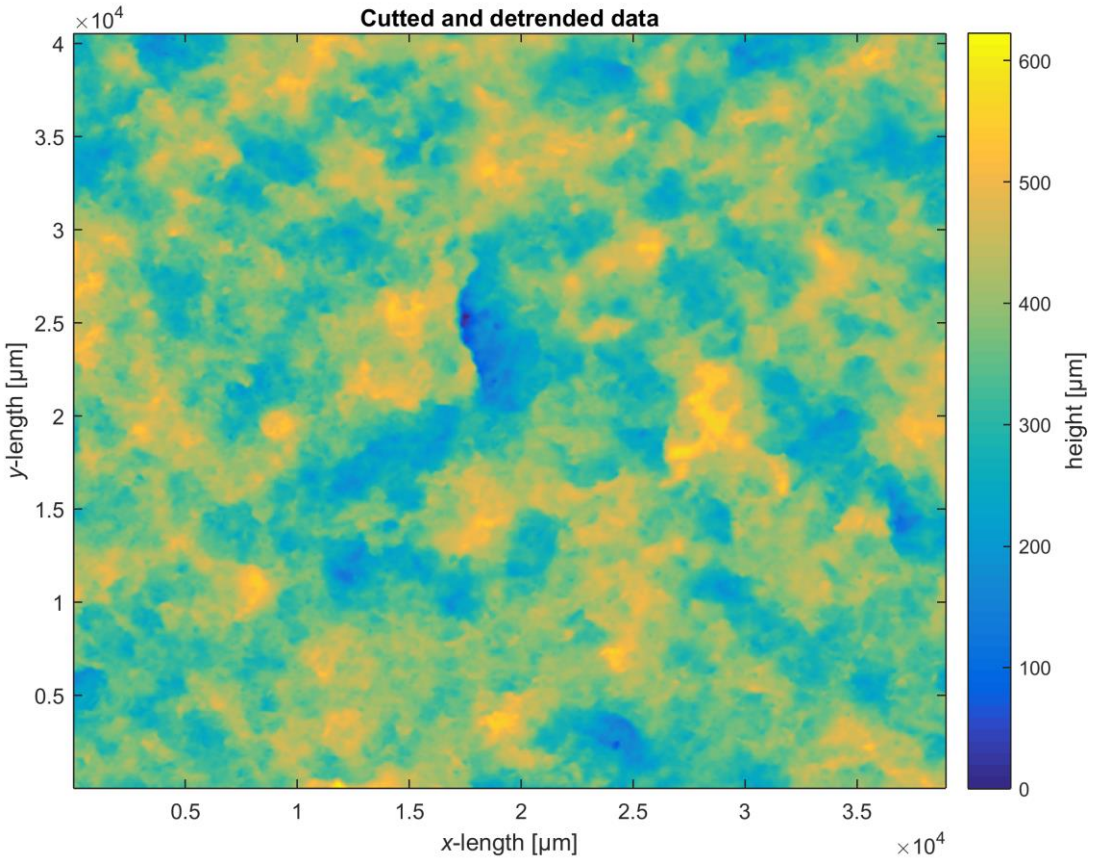



# **Preliminary results** – Roughness analysis

## Padang granodiorite



before → after



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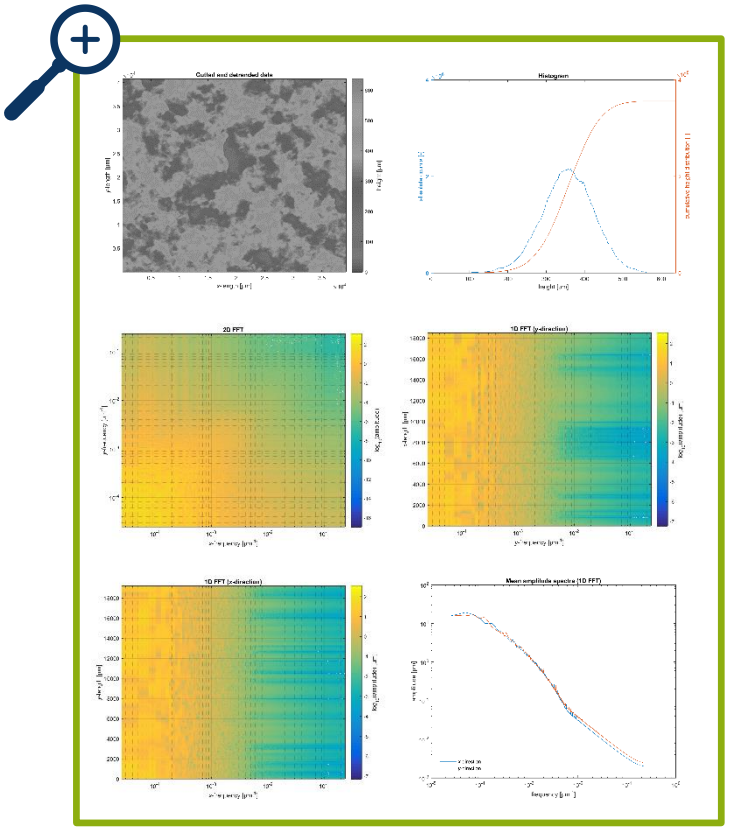

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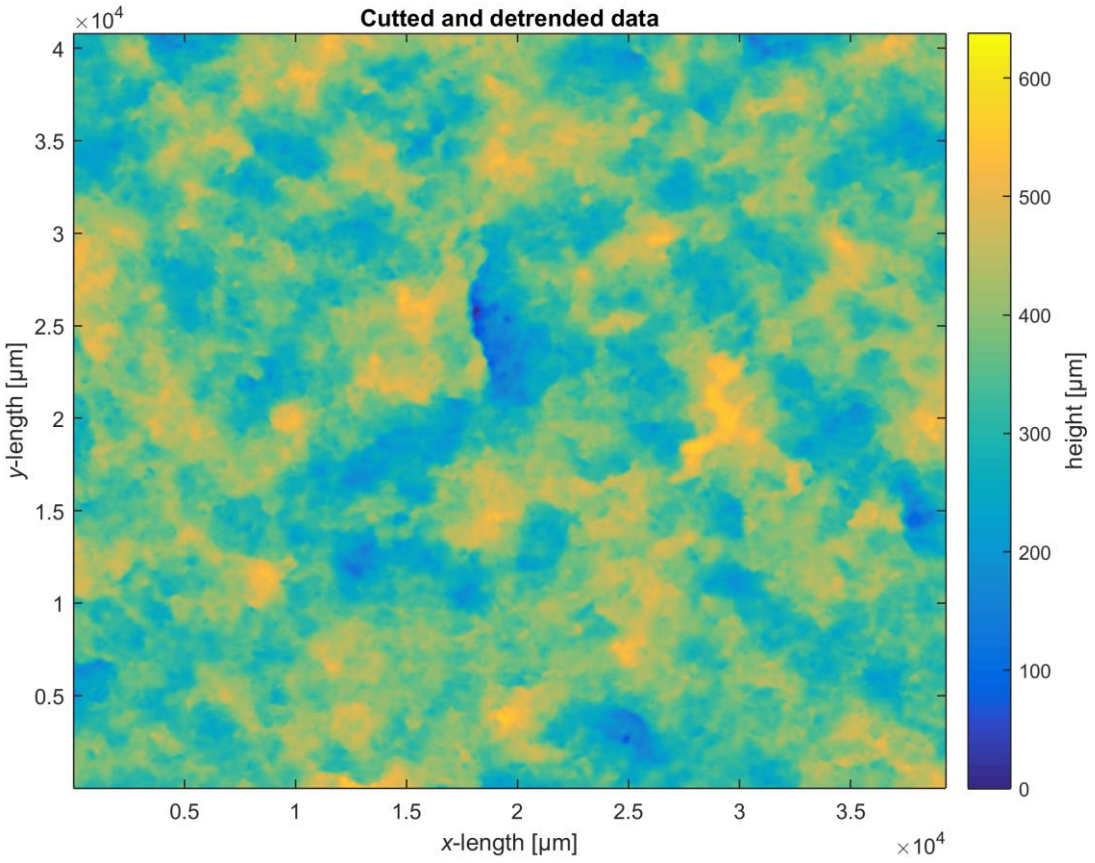

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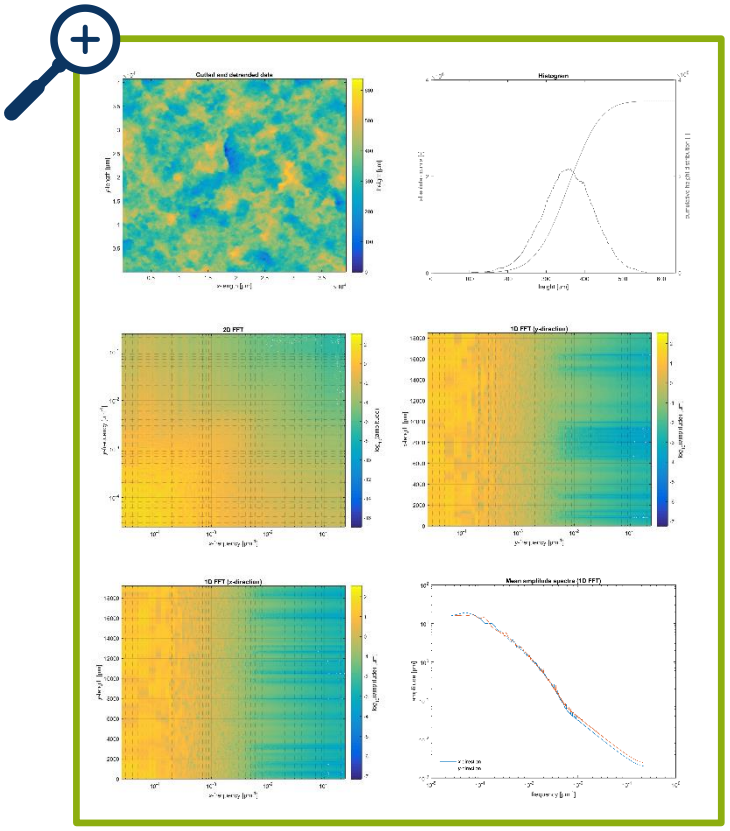

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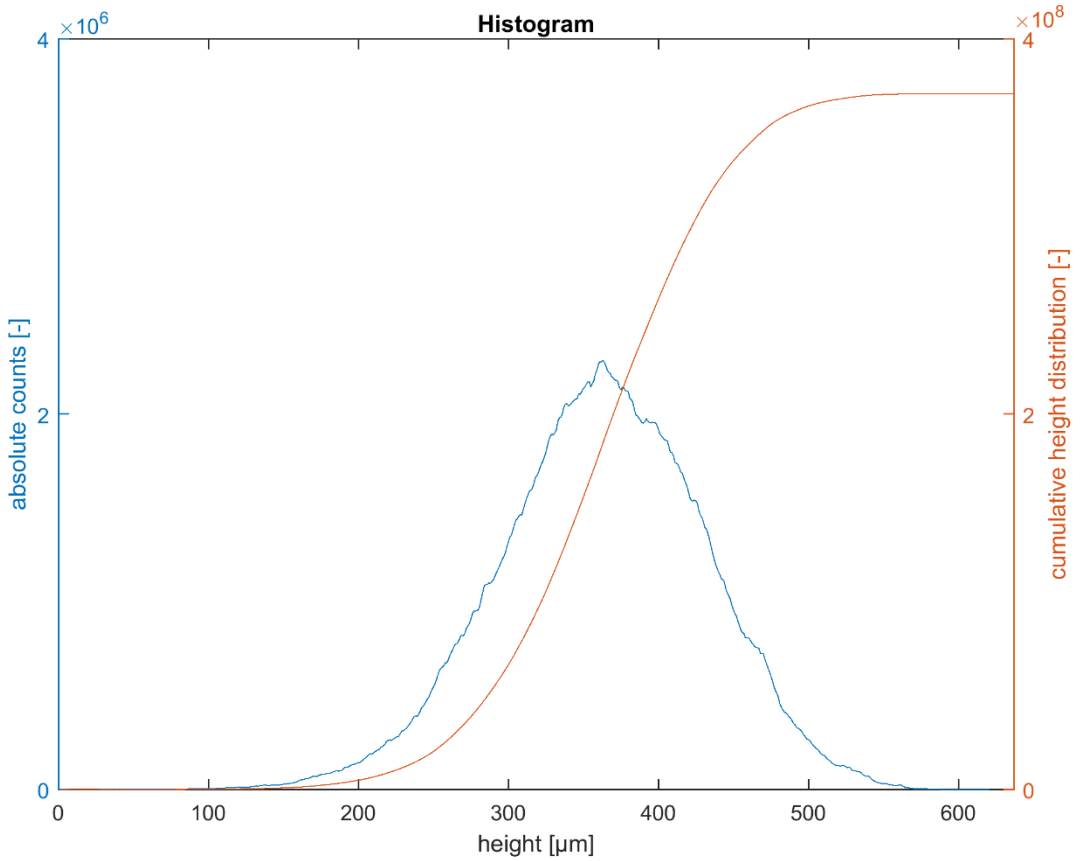

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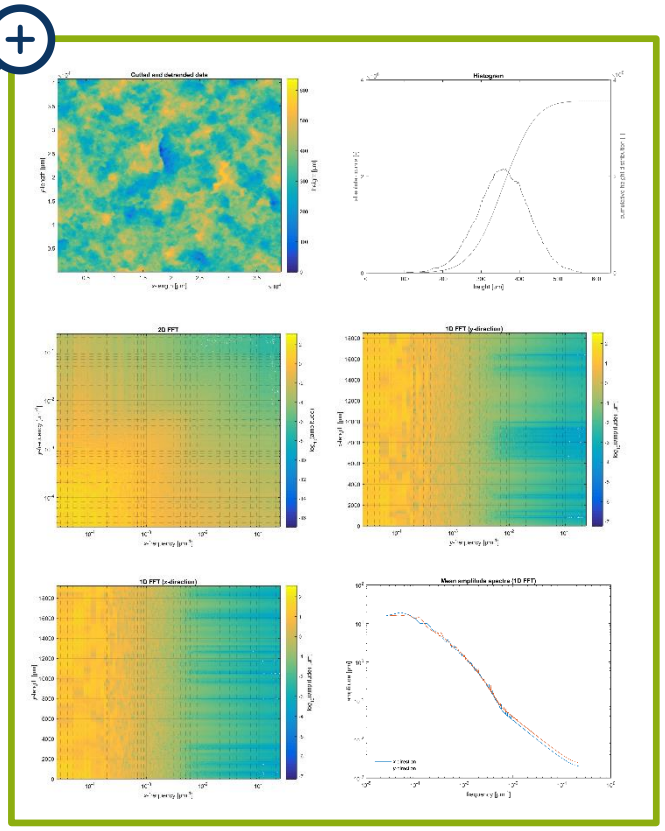

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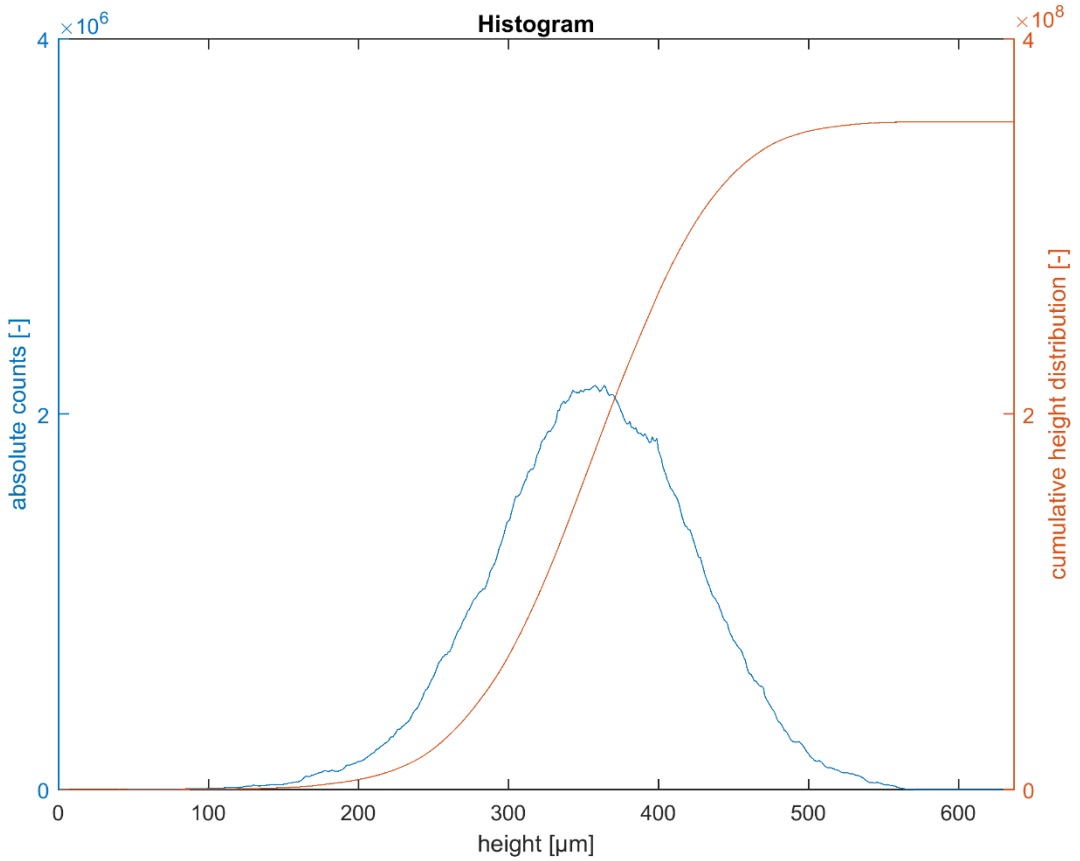

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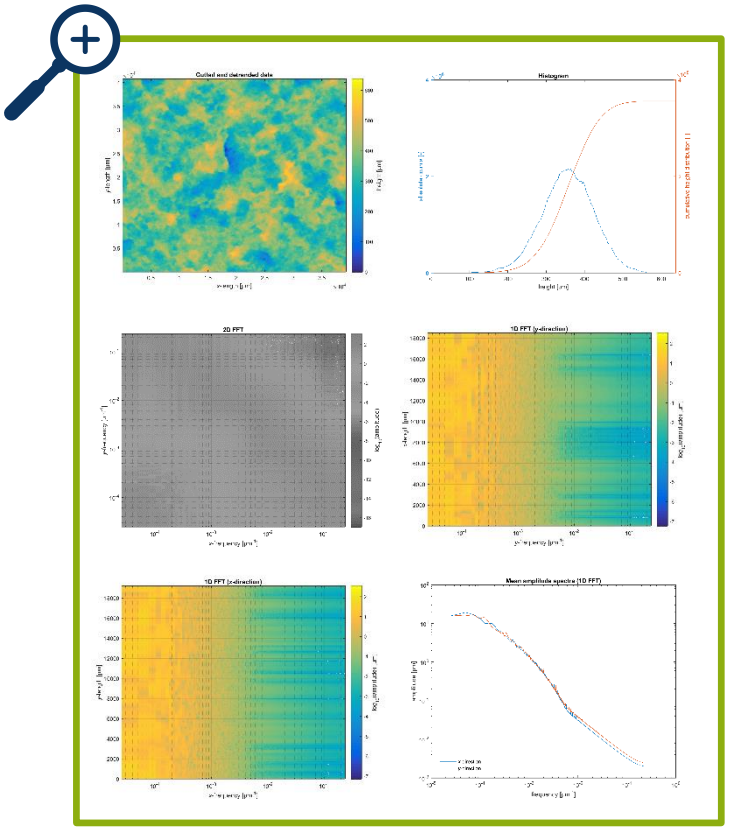
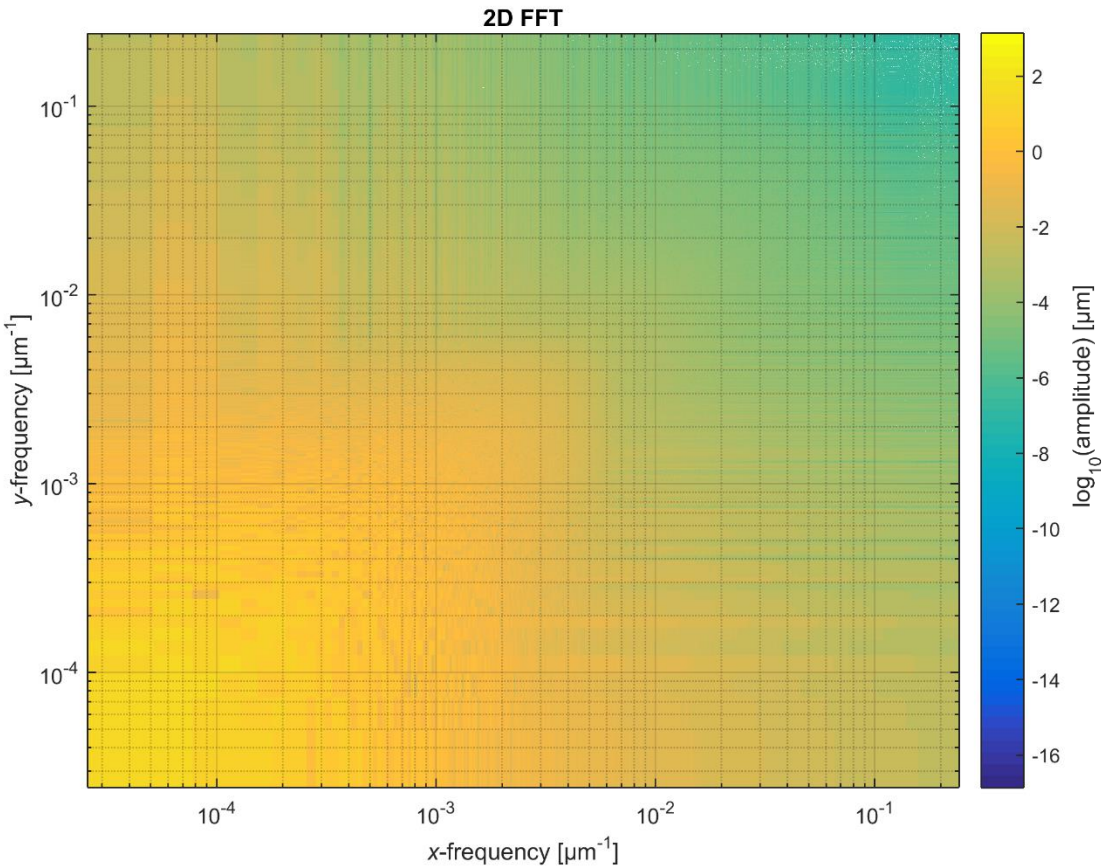


before ▶ after



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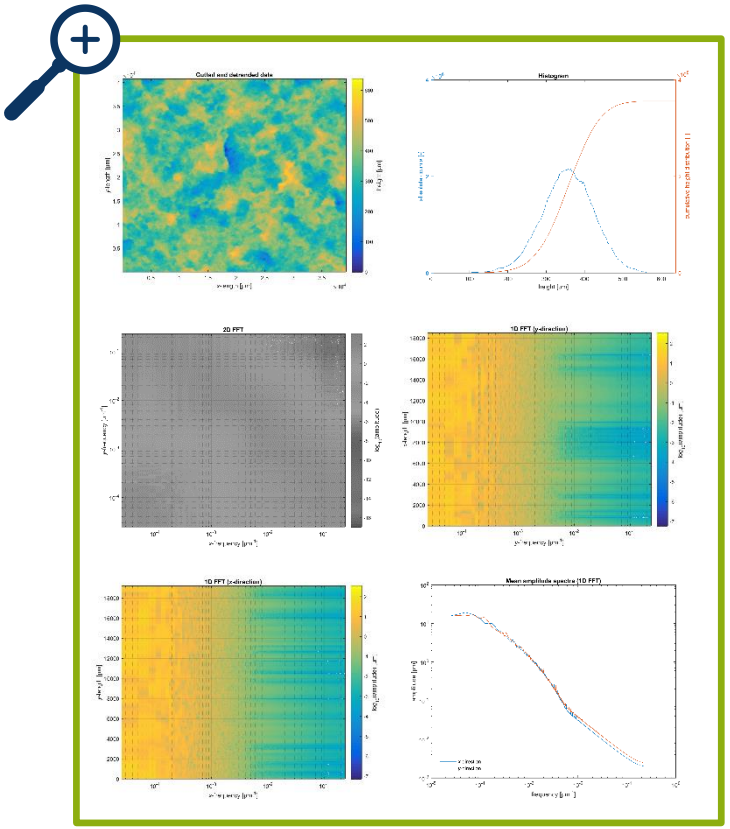

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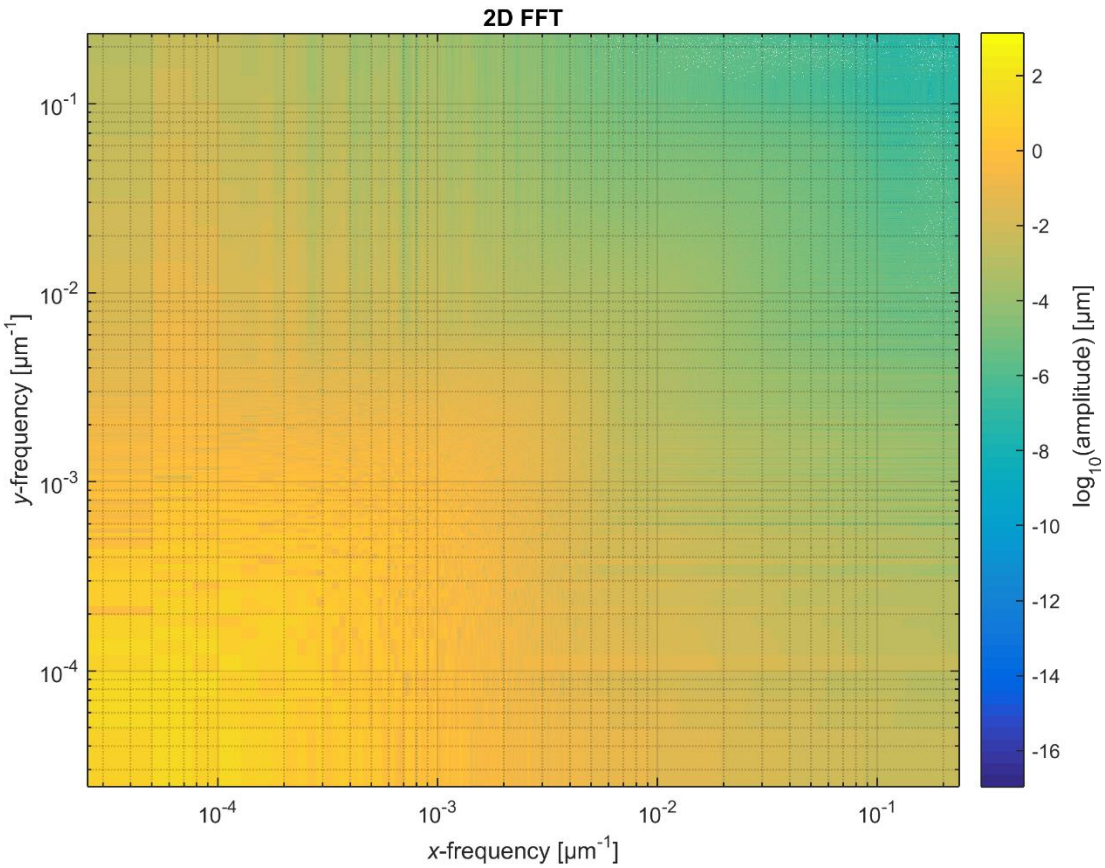
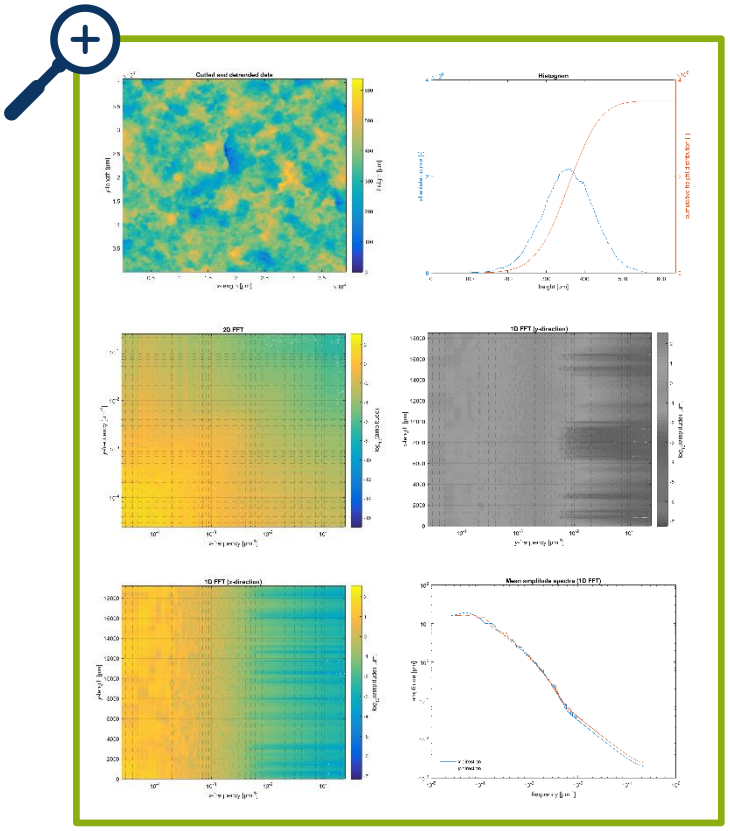



3 / 3

## Padang granodiorite



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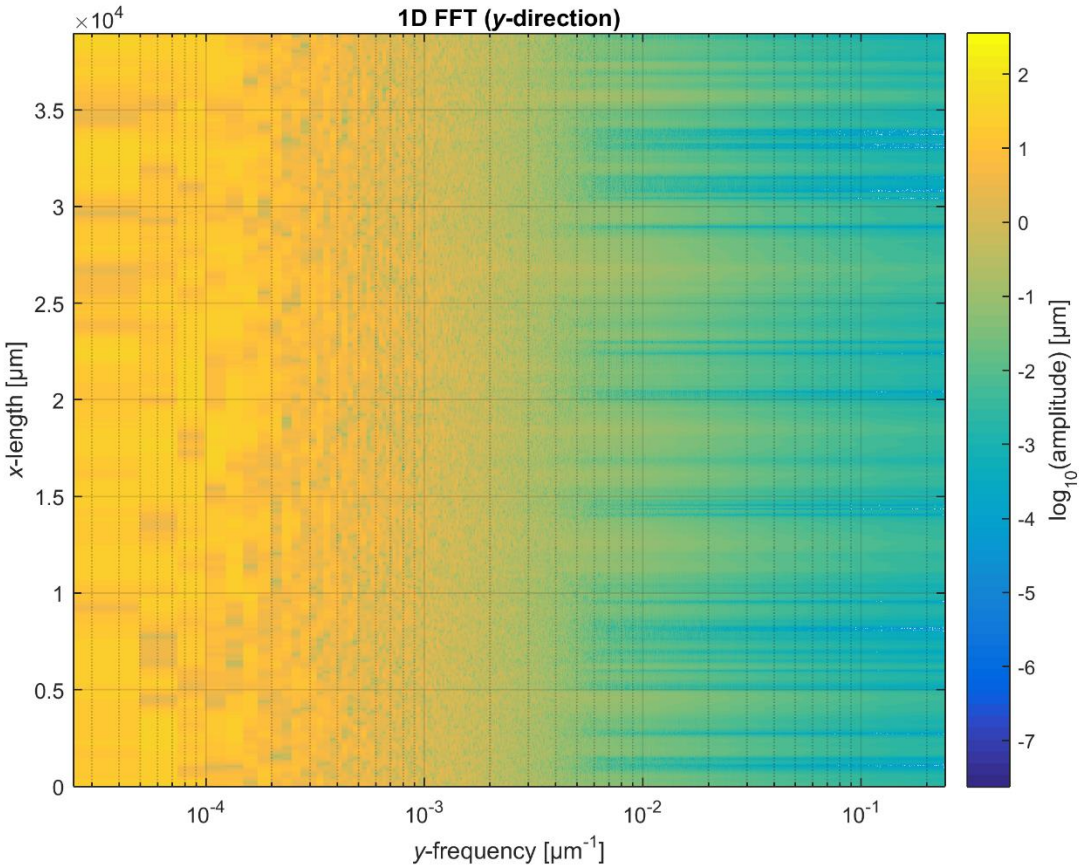

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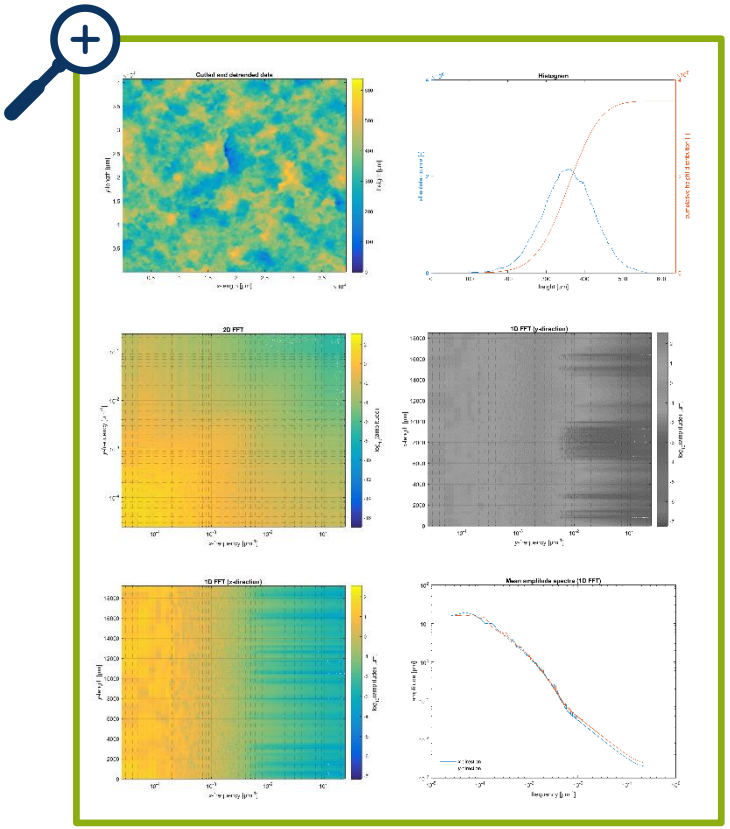
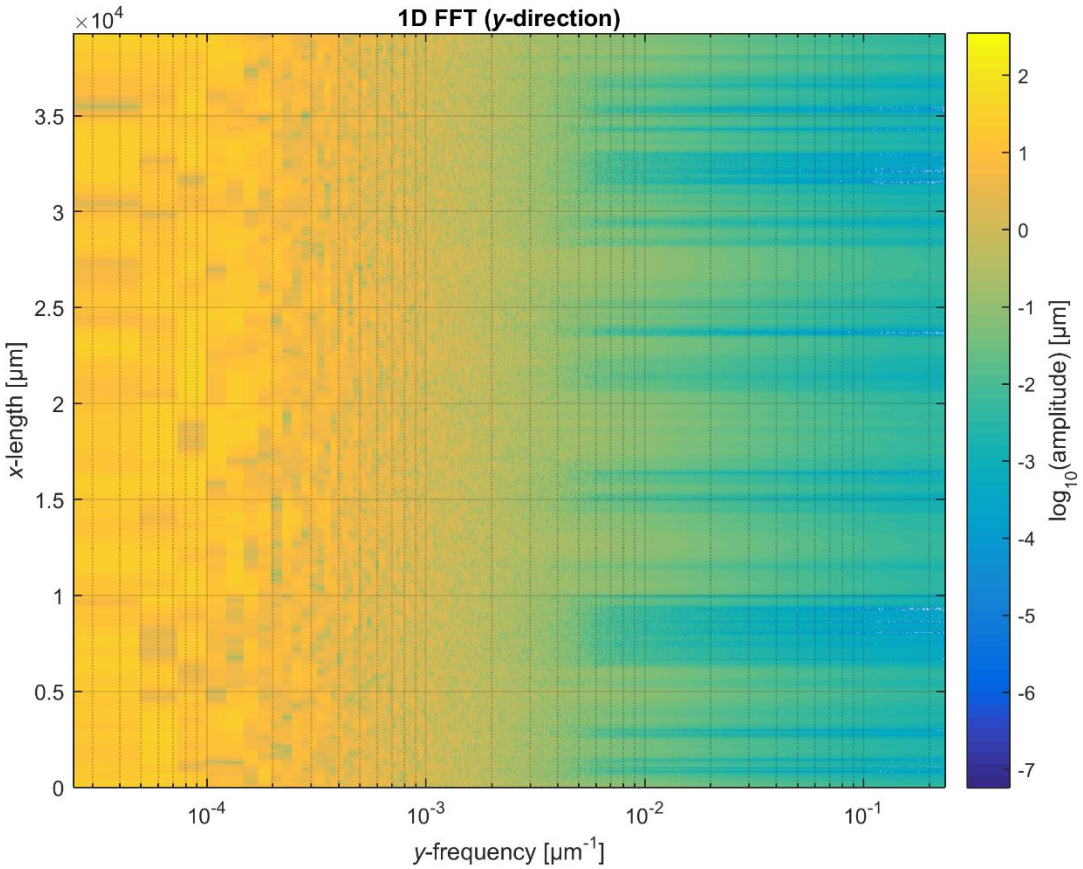
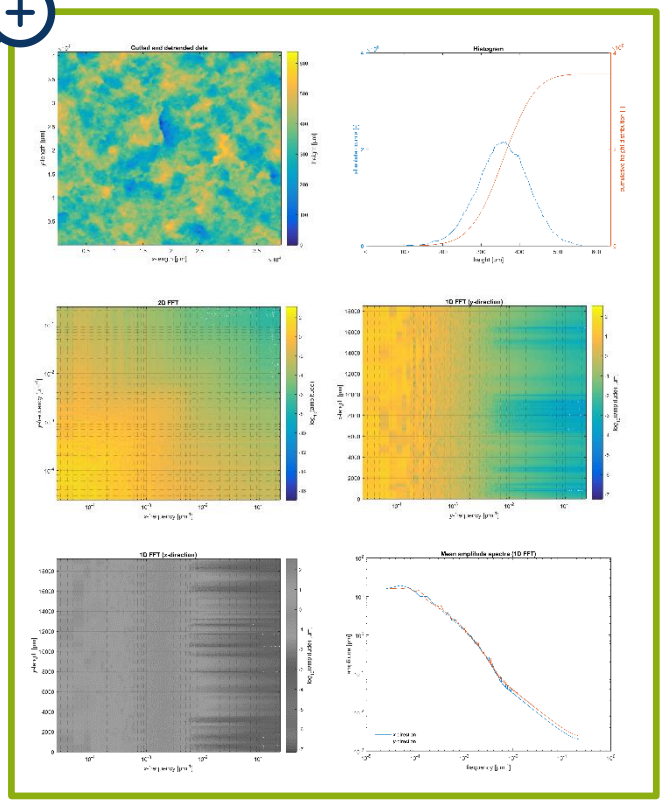


before → after

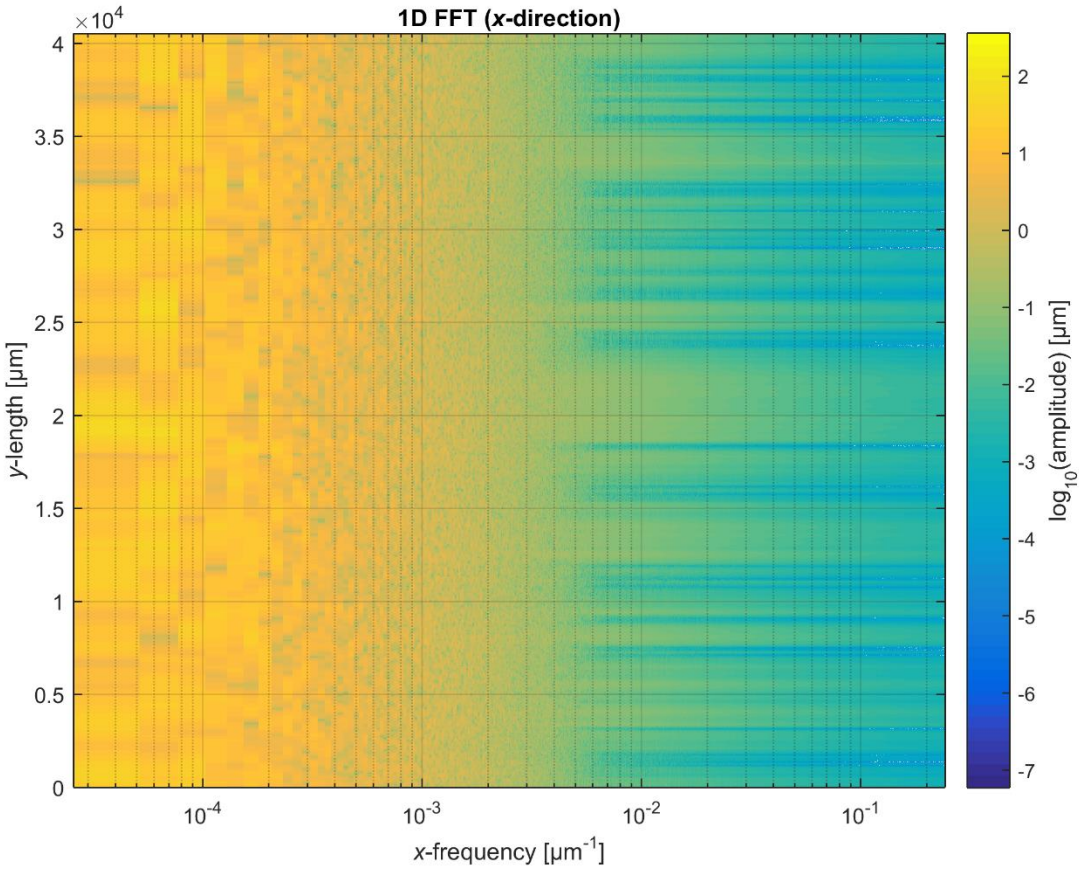


# **Preliminary results** – Roughness analysis

## Padang granodiorite

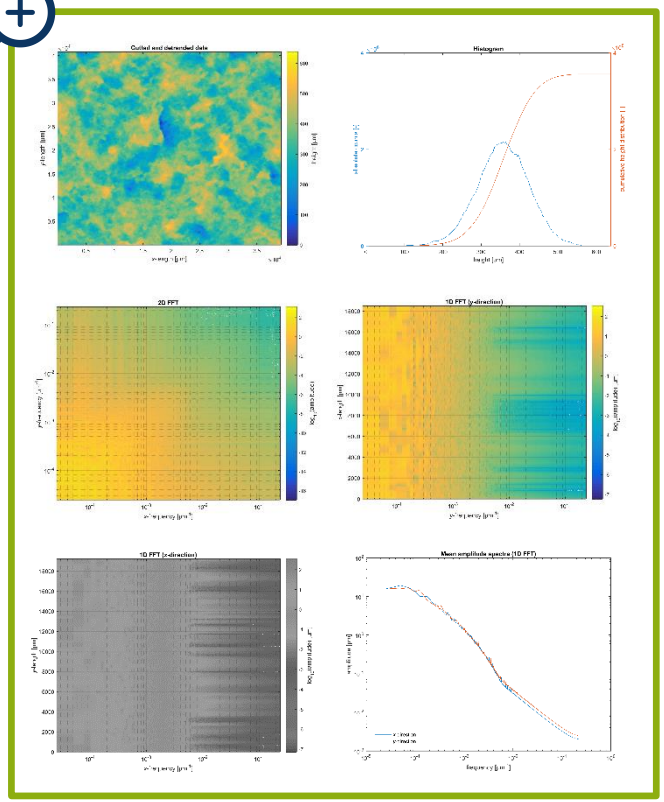


before → after

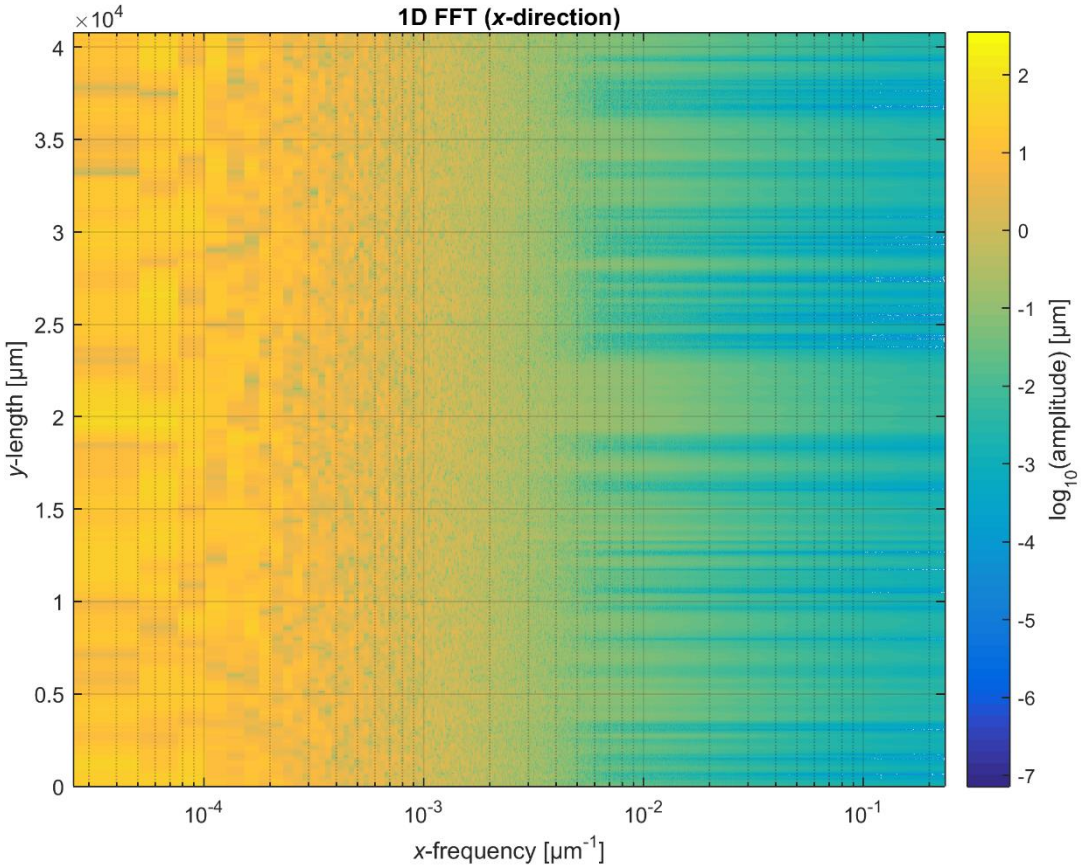


# **Preliminary results** – Roughness analysis

## Padang granodiorite



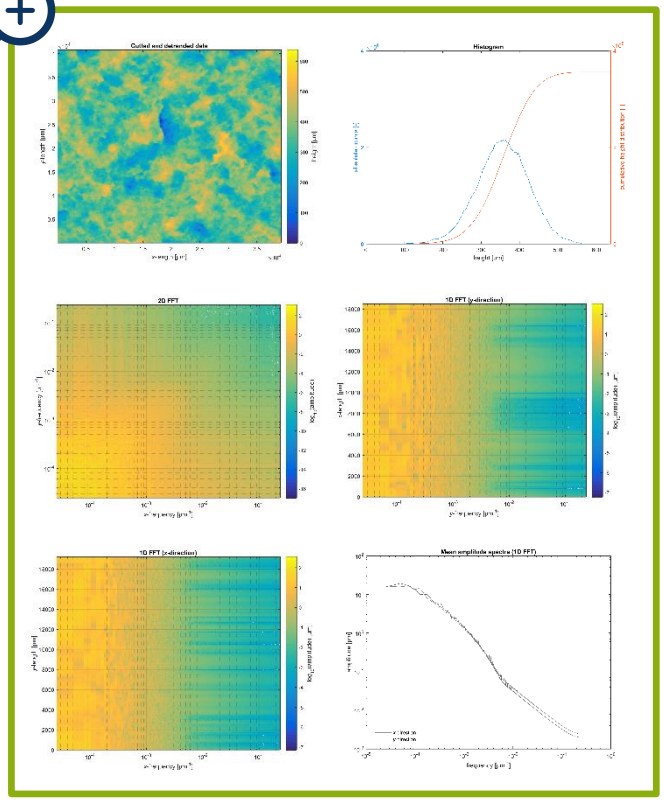
before → after

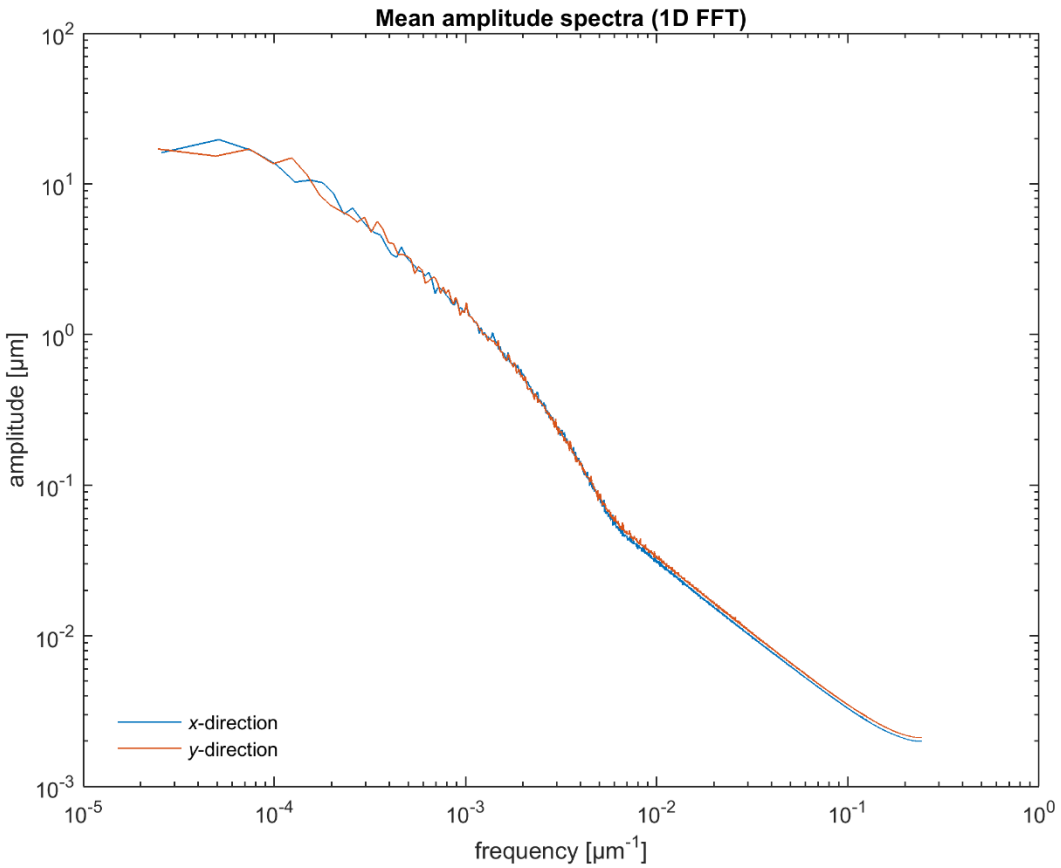


# **Preliminary results** – Roughness analysis

## Padang granodiorite

before → after

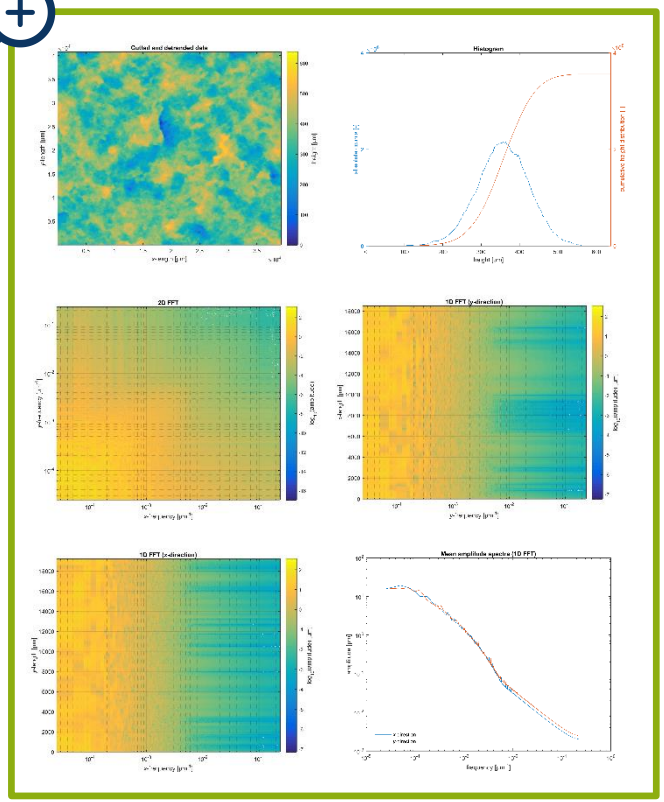


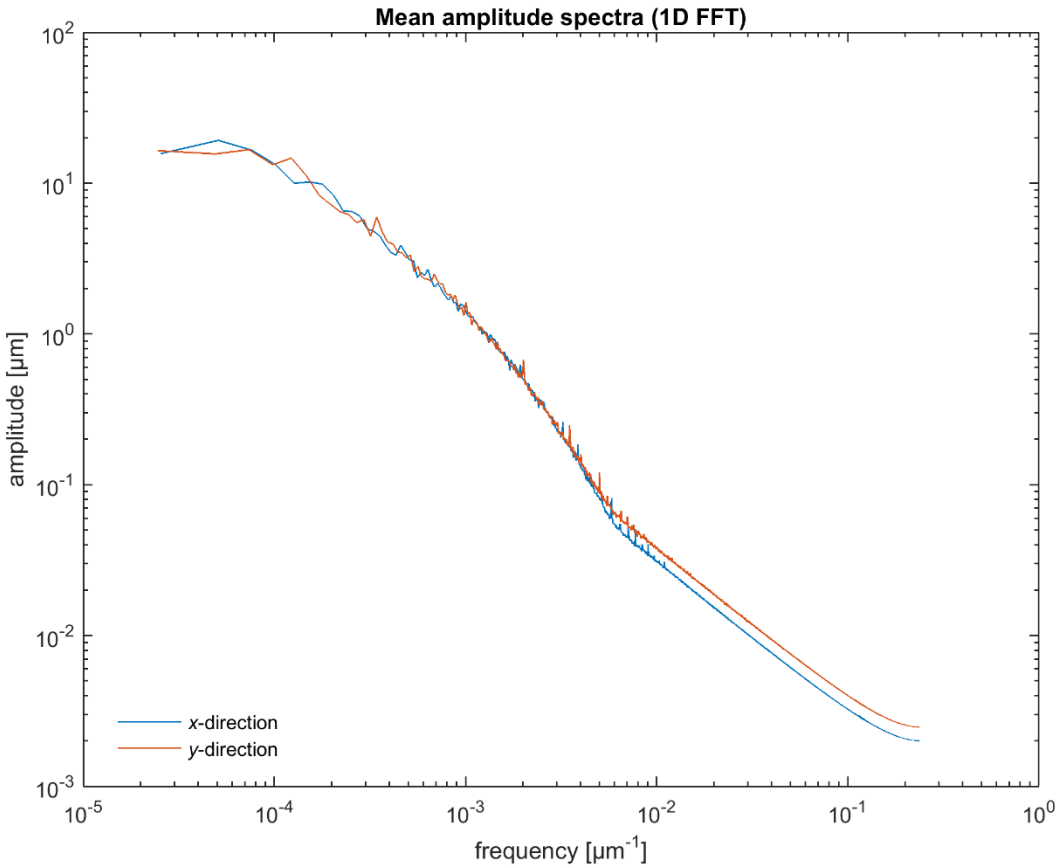


# **Preliminary results** – Roughness analysis

## Padang granodiorite

before → after





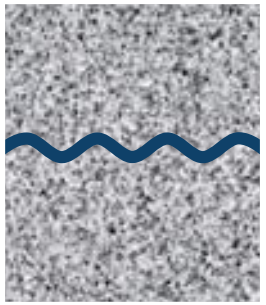
# Discussion

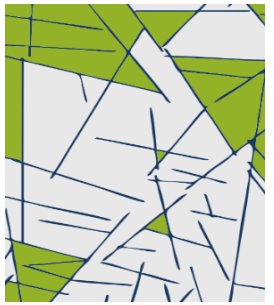
- Stress **relaxation**:
  - elastic properties depend on stress state and degree of relaxation
- Frequency **dispersion** in elastic properties:
  - small dispersion in the frequency range between $10^{-3}$ and $10^{1}$ Hz
- Effect of **idealized fault**:
  - fault decreases Young's modulus of stacked system
- Effect of **rough** fracture and fracture-filling **viscous fluid**:
  - fracture roughness decreases stiffness of the the fractured system
  - apparent elastic moduli are highly increased possibly due to hetero-geneous deformation of the plates
  - compaction/shearing of viscous fluid contributes to system stiffness

# Outlook

- Data processing of ultrasonic measurements
  - characterize fault state by calculating transmission and reflection coefficients and their dependence on incident angle
- Displacement transducer
  - calibration during cyclic displacement to correct for hysteresis
- Numerical modeling
  - quasi-static finite-element simulations of fluid-filled fractures
  - comparison between model and experimental results

Fractured rock





Numerical model