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Deep U-tube heat exchanger breakthrough: combining laser and cryogenic gas for geothermal energy exploitation

Drilling rocks with laser, Sci-Fi or new reality?
A DeepU case study

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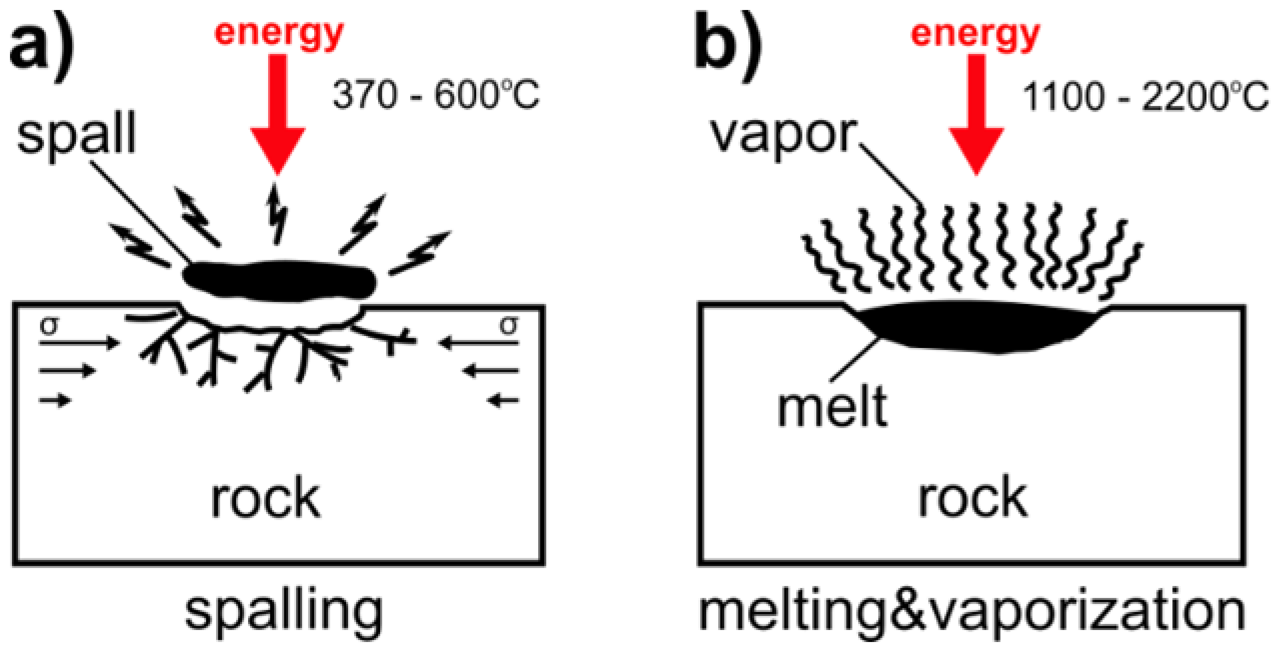
Why drill with a laser?

Penetration mechanisms in non mechanical drilling techniques (after Mauer 1980)



Advantages of laser technology

- commercial availability
- modularity
- no losses on transmission

Drawbacks of laser technology

- low absorbance on rocks (>50%, 1070nm)
- complicated optical system
- low efficiency for evaporation (**not confirmed!)**

DeepU Laser

- Ytterbium fiber laser
- Power range 0.17 – 30 kW
- Wavelength 1070 ± 10 nm
- Continuous beam

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Laser drilling experiments

Experimental setups

- Linear track tests (LTT)
- Punctual tests (PT)
- DeepU drill-head tests (DeepU)

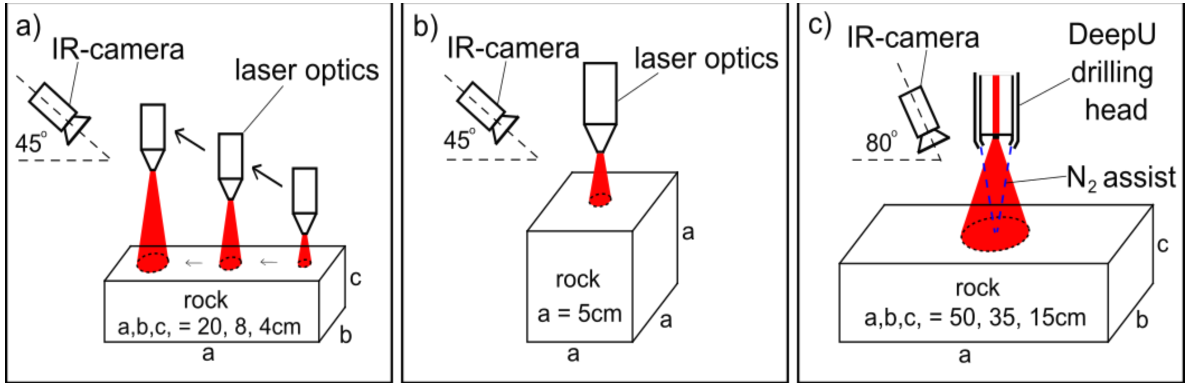
Selected lithologies

- primary lithologies; **granite, sandstone, limestone**
- secondary lithologies; gneiss, basalt, slate, migmatite

Methods

- **IR-imaging (FLIR GF77a)**
- photogrammetry
- optical and electron microscopy
- XRD, XRF

LTT **PT** **DeepU**



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Laser-rock interactions

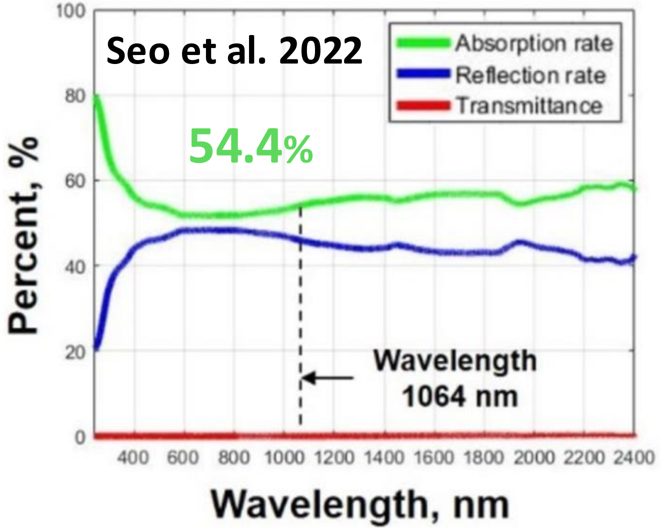
How radiation interact with rocks?
- **absorption and reflection**
- scattering, transmission

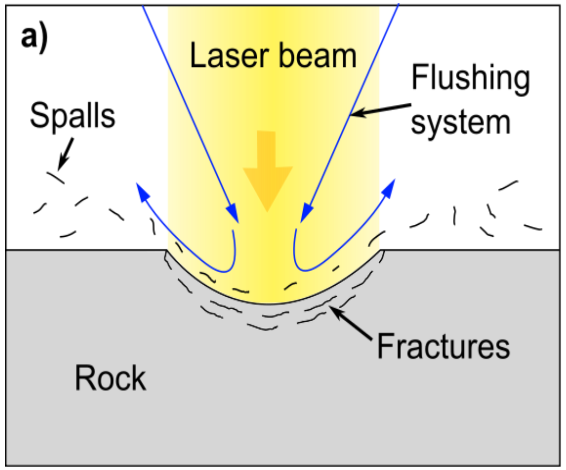
Parameters controlling absorption rate
- radiation wavelength
- angle of incident
- surface roughness
- **rock type**

Laser-rock interaction
- rock texture (grain size)
- mineral composition
- chemical composition
- **power**
- **irradiation time**

thermo-physical properties

Radiation absorbance of granite





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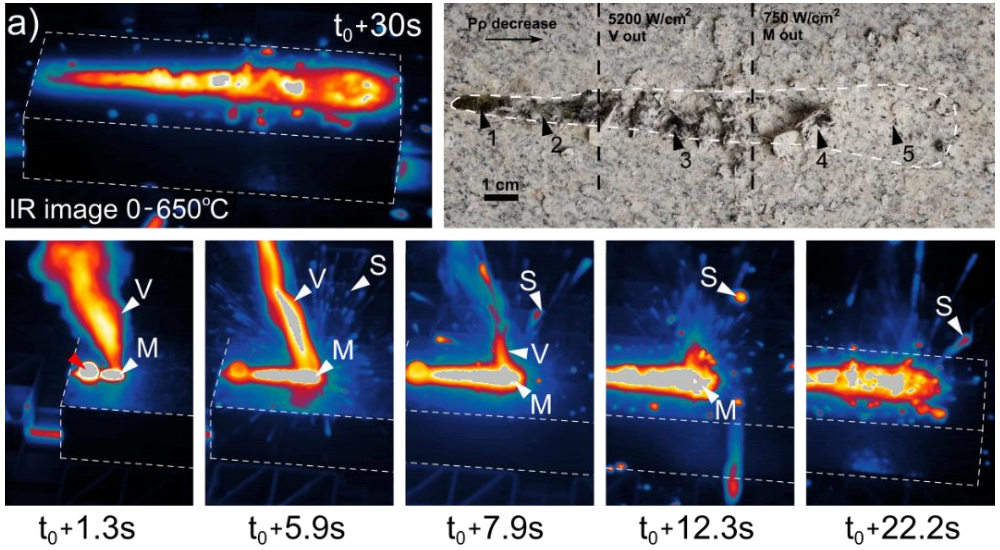
Laser-rock interactions - results

Linear Track Tests

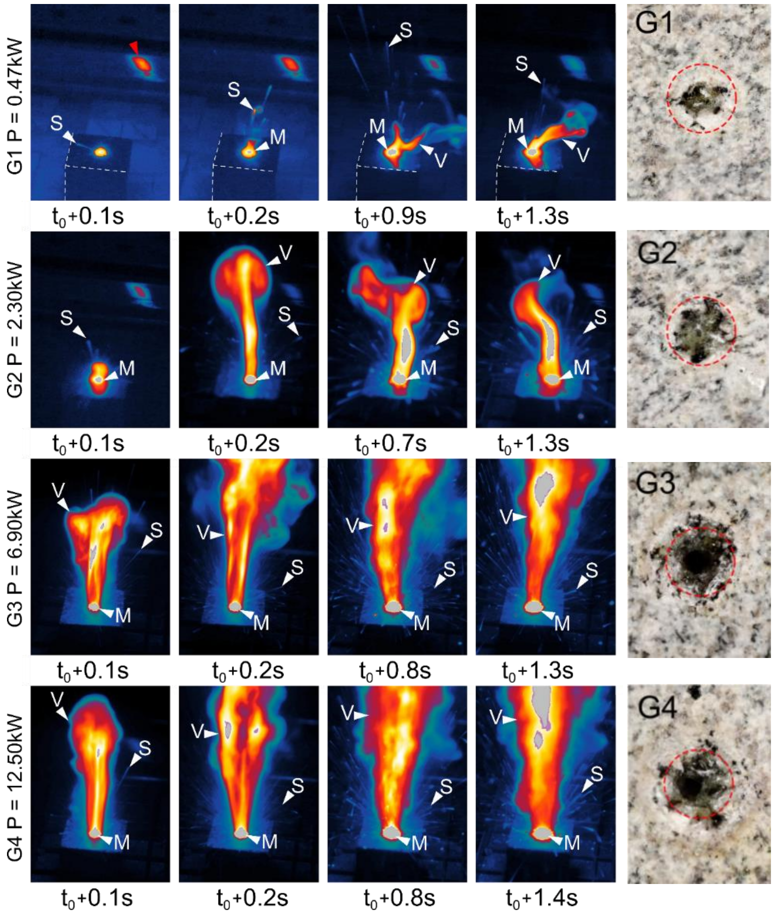


Lower power density

Combination of IR-imaging and analysis of lasing products allow to **correlate observable process to power density**

higher power

Punctual Tests



time

Expected order

spallation -> melting -> vaporization

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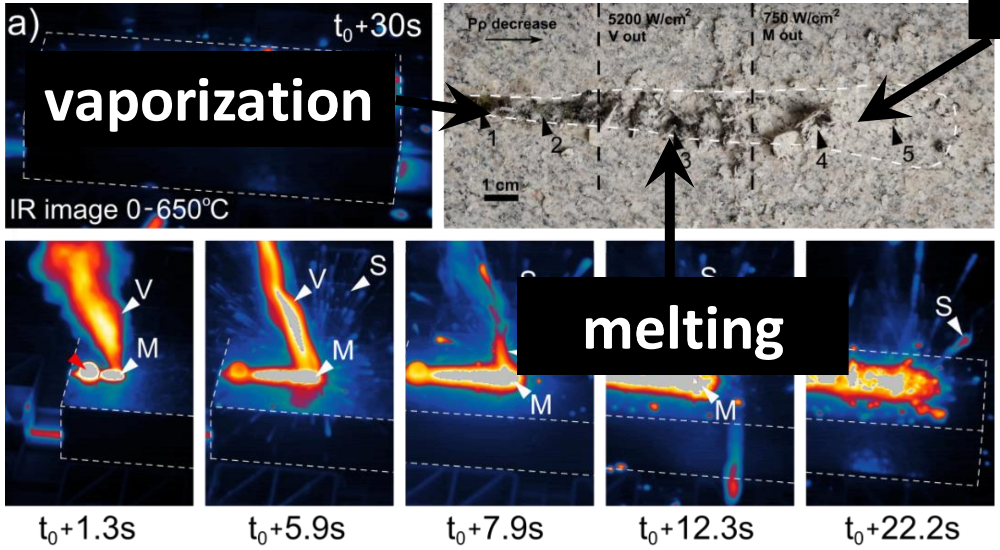
Laser-rock interactions - results

Linear Track Tests



Lower power density

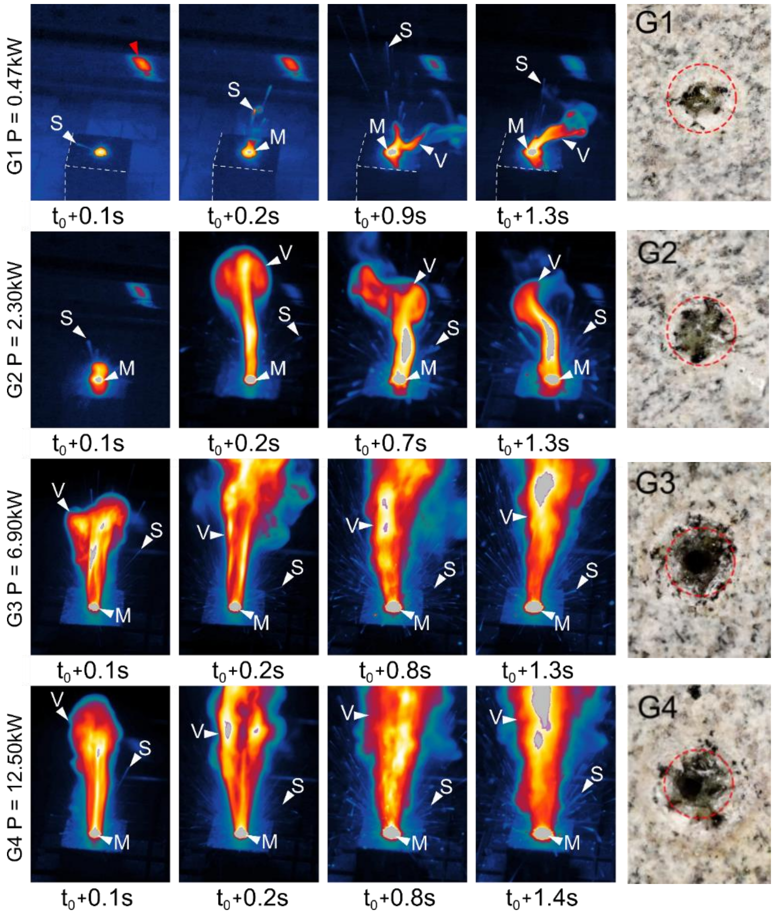
Expected order
spallation -> ~~melting~~ -> vaporization

Combination of IR-imaging and analysis of lasing products allow to **correlate observable process to power density**

higher power

All three processes often occur simultaneously!

Punctual Tests



time

Deep U
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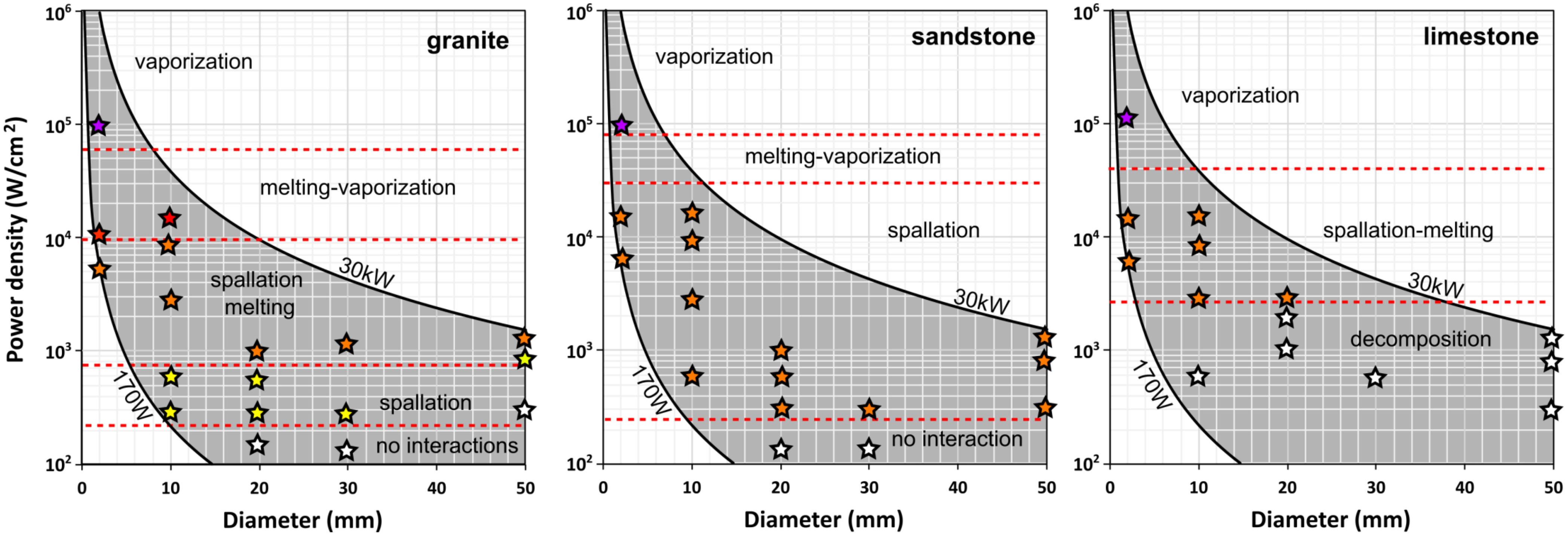
Laser-rock interactions - results

- spallation, melting and vaporization often occur together but **to various intensity**
- occurrence of each process depends on **power density,** irradiation time and rock type
- Power density based **process diagrams** were constructed for granite, sandstone and limestone

Laser-rock interaction dependance on power density



DeepU
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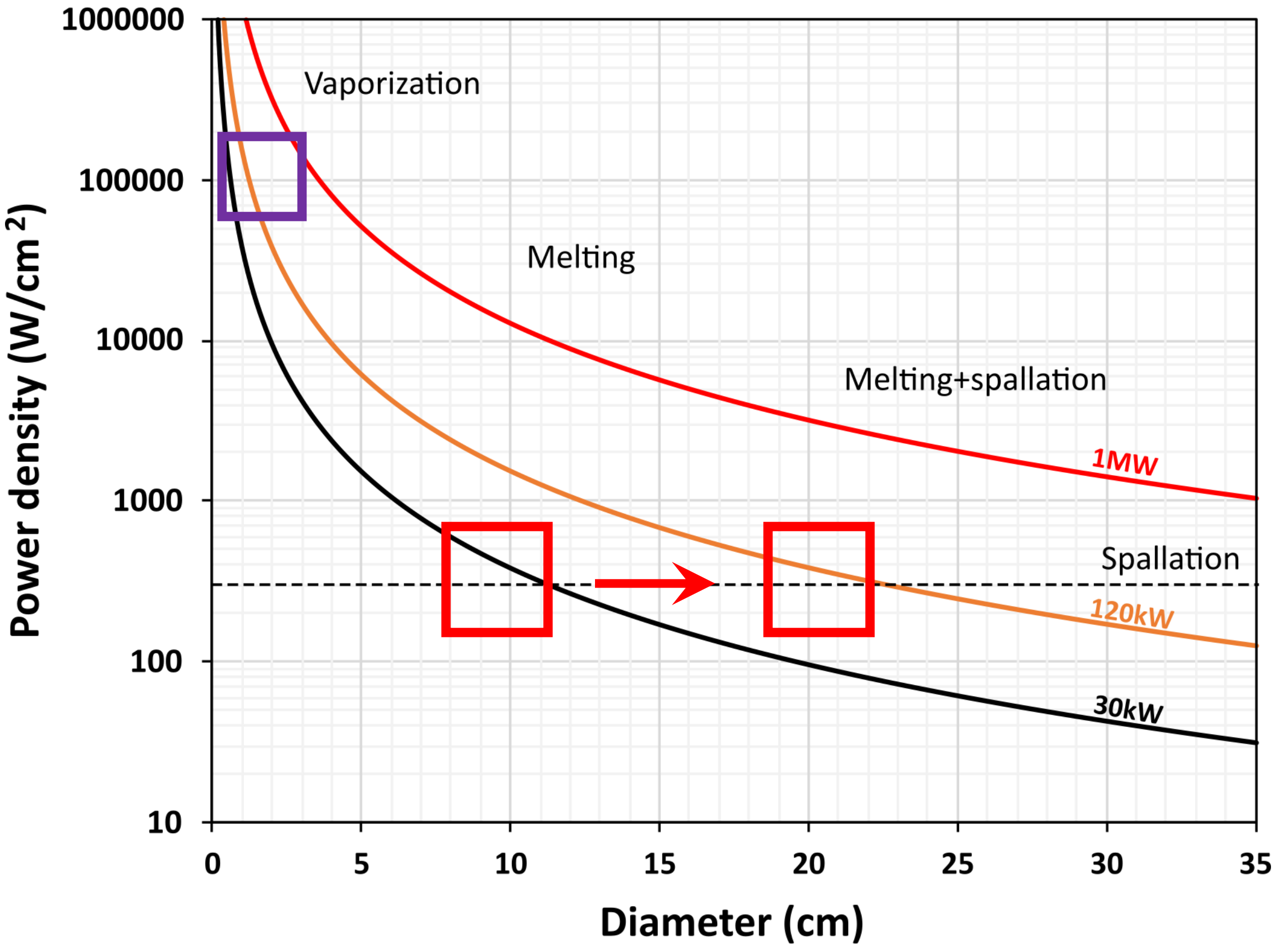
Laser-rock interactions - results

Implications for laser drilling techniques

- penetration by **laser induced thermal spallation is possible** for useful borehole diameters
- drilling boreholes with useful diameters by melting-vaporization require more power that is <u>currently</u> available



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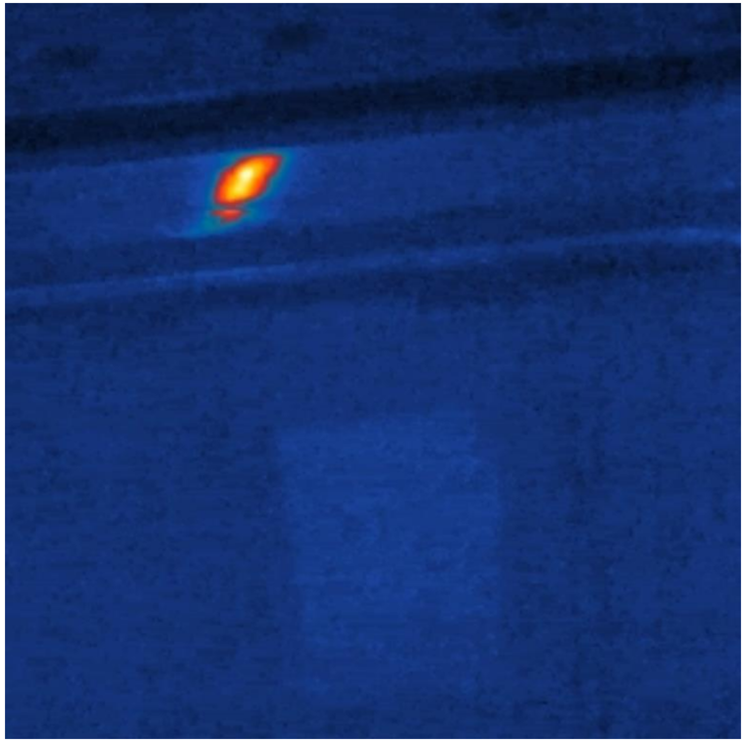
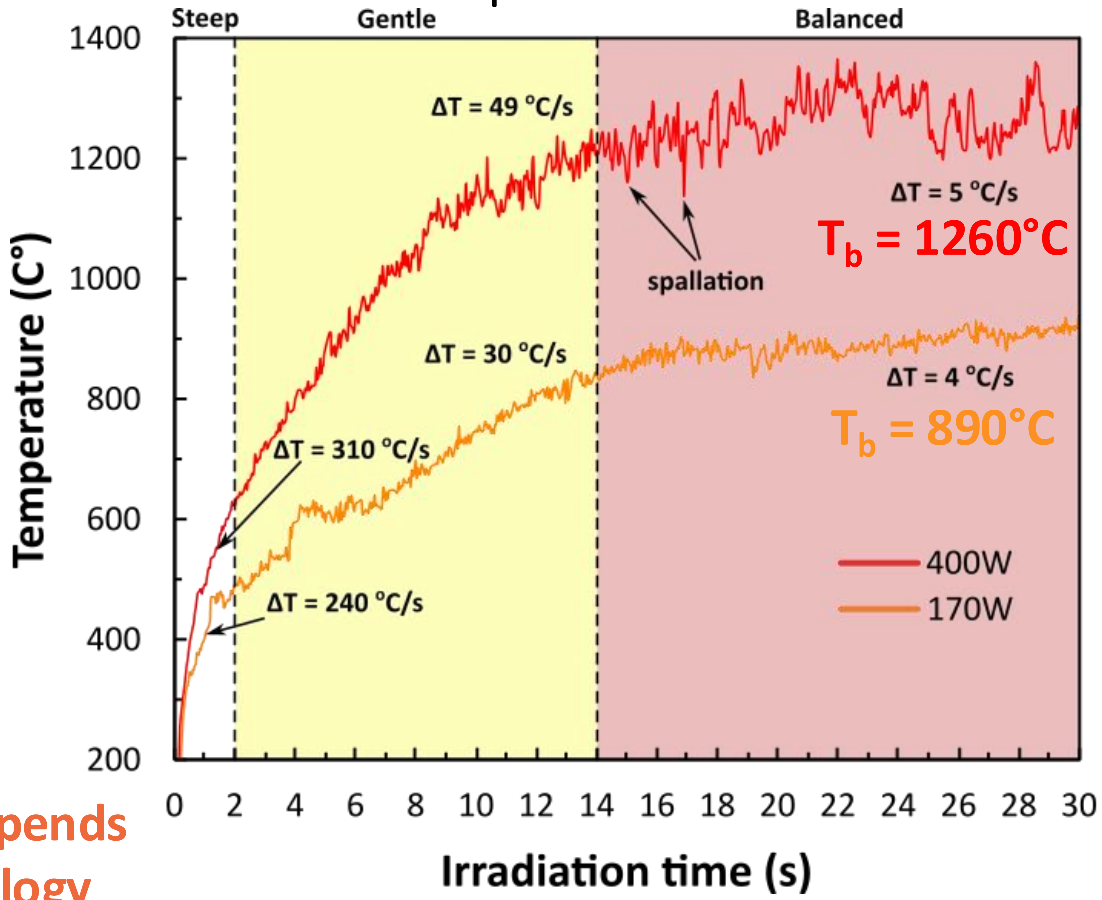
Melting-vaporization laser drilling

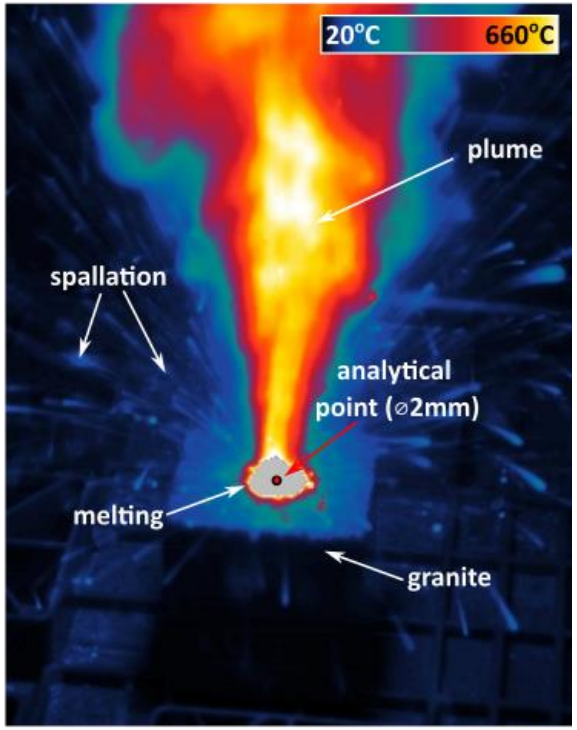
IR-record of laser drilling in melting-spallation field



Temperature vs time in vaporization field



Power density corresponds to vaporization field



- **Balance temperature depends on laser power and lithology**

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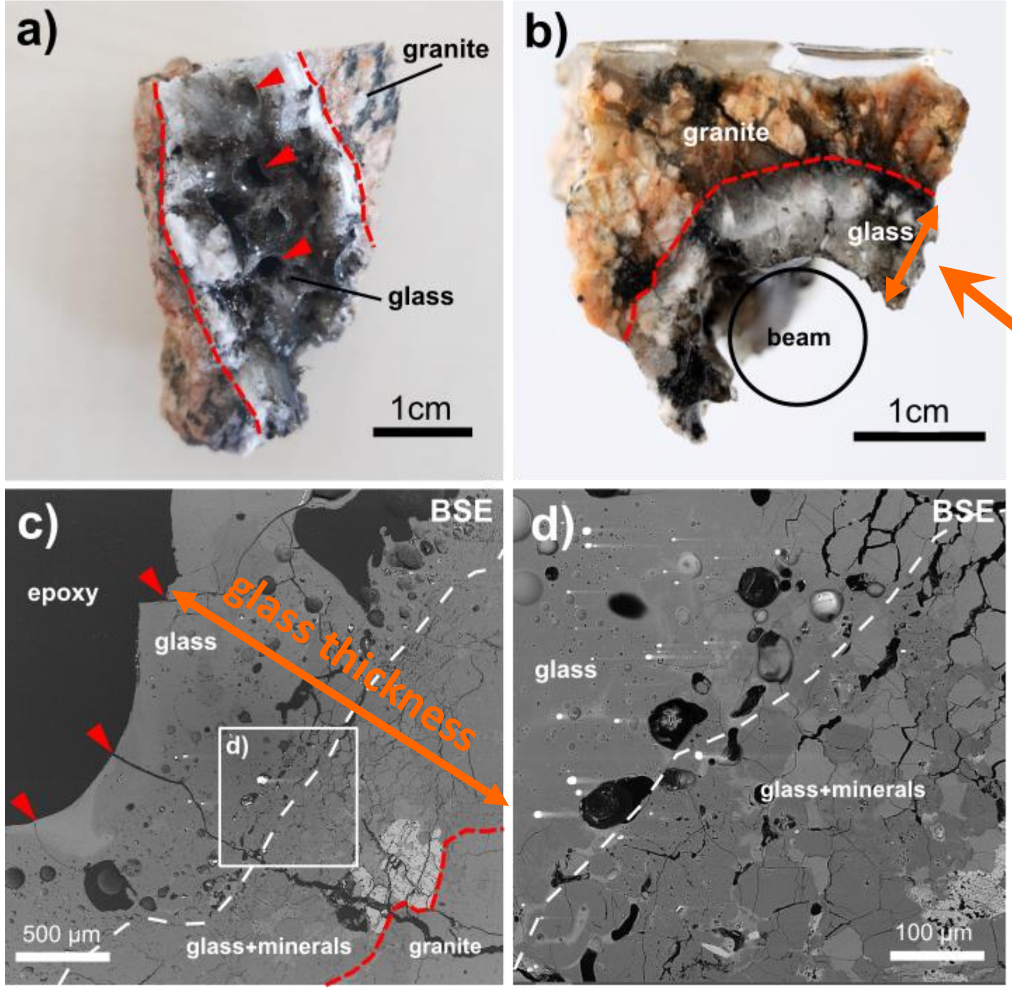
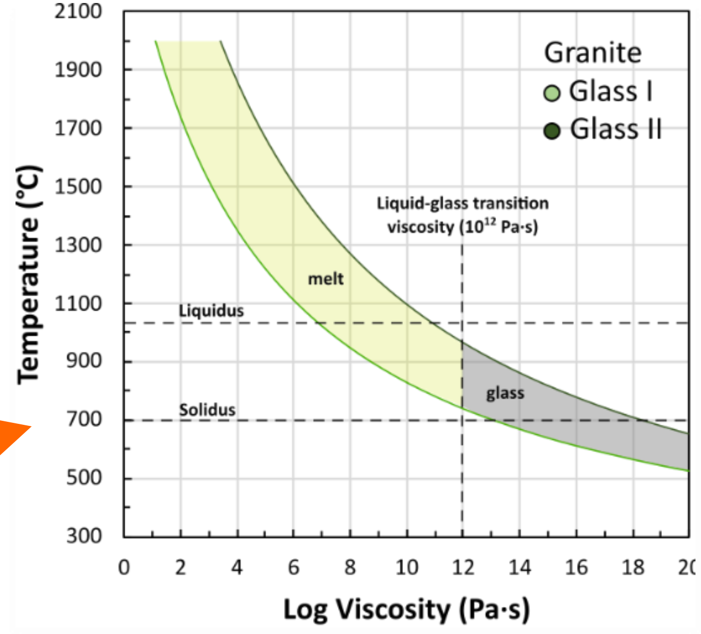
Vitrification



- Vitrification of borehole walls is **possible with melting-vaporization** drilling
- Layer of glass is 5 - 10 mm thick in granite sample
- Glass transition temperature is **750-950°C** depending on chemical composition of melt
- Glass is heterogenous, it fills fractures and microlites might be present

Viscosity of granitic melt



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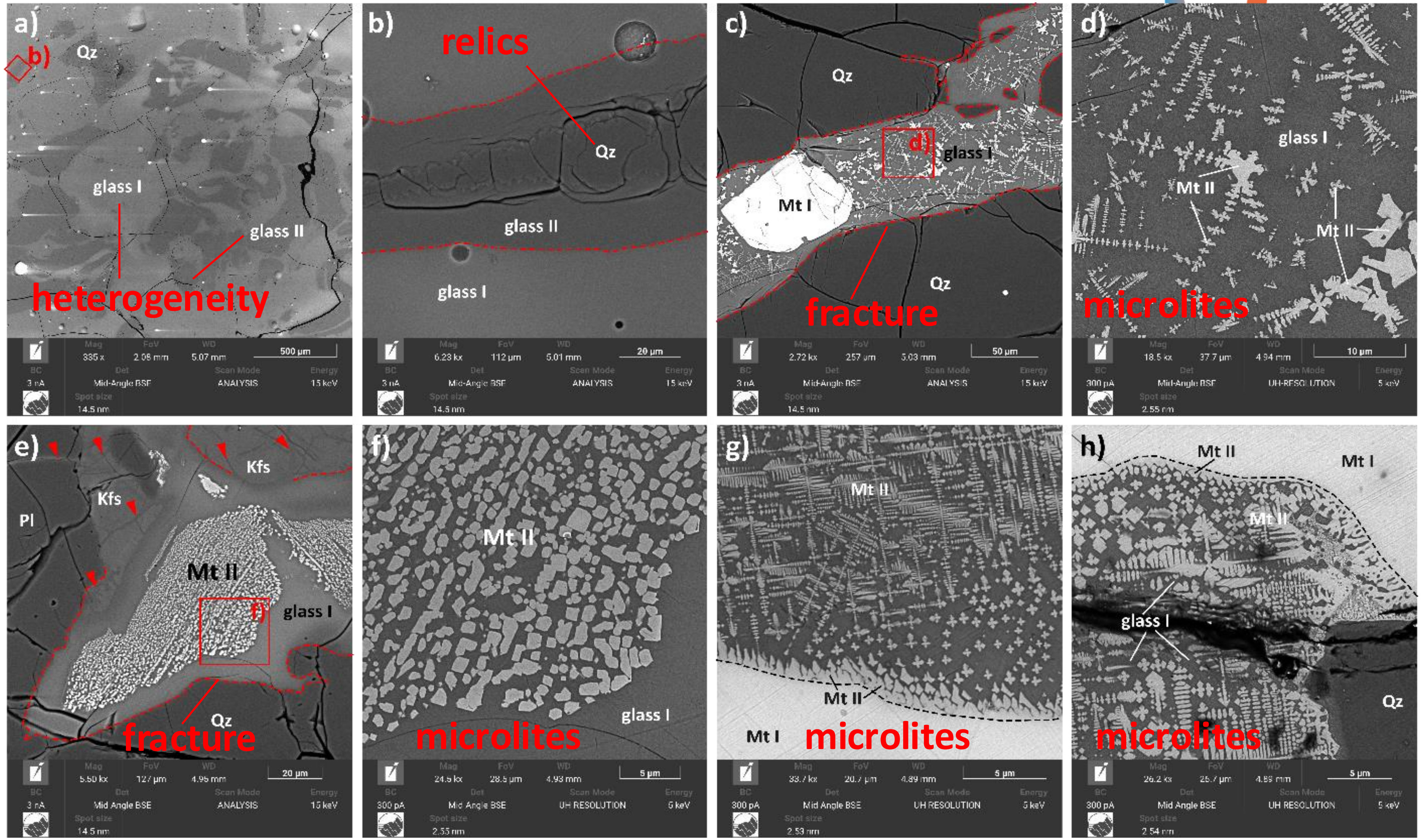
Vitrification

- glass is heterogenous
- contain relic minerals
- filling fractures
- contain microlites

What are mechanical properties of laser-generated glass?

Can laser-generated glass substitute borehole casing?

Electron microscope images of laser-generated glass in granite



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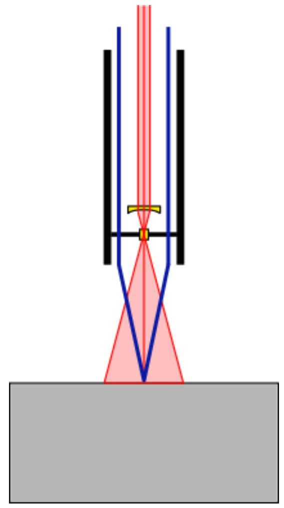
Deep U-tube heat exchanger breakthrough: combining laser and cryogenic gas for geothermal energy exploitation

Thermal spallation laser drilling

DeepU laser system

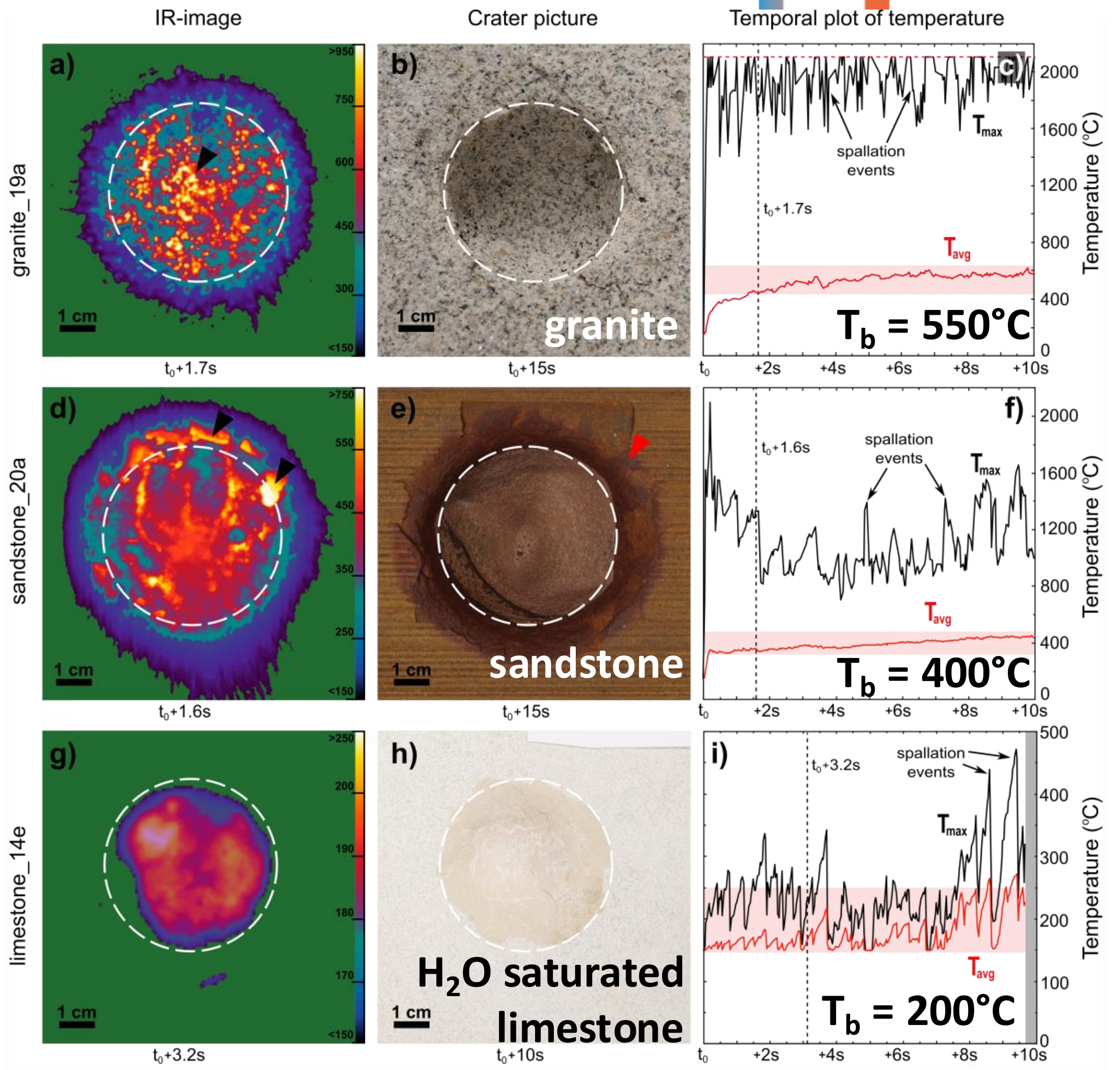
- divergent beam
- N_2 flushing system



IR-record of DeepU laser thermal spallation

Summary

- successful penetration in granite, sandstone and H_2O saturated limestone
- balanced temperature (T_b) of spallation was determined



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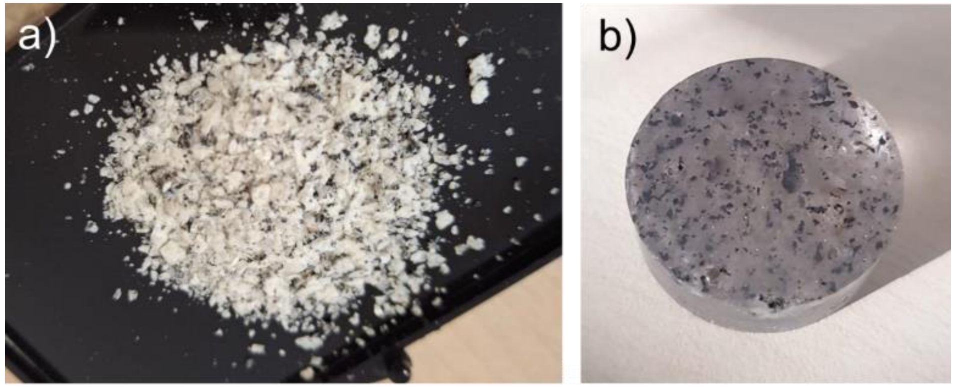
Spalls characterization

Spalls collection and preparation



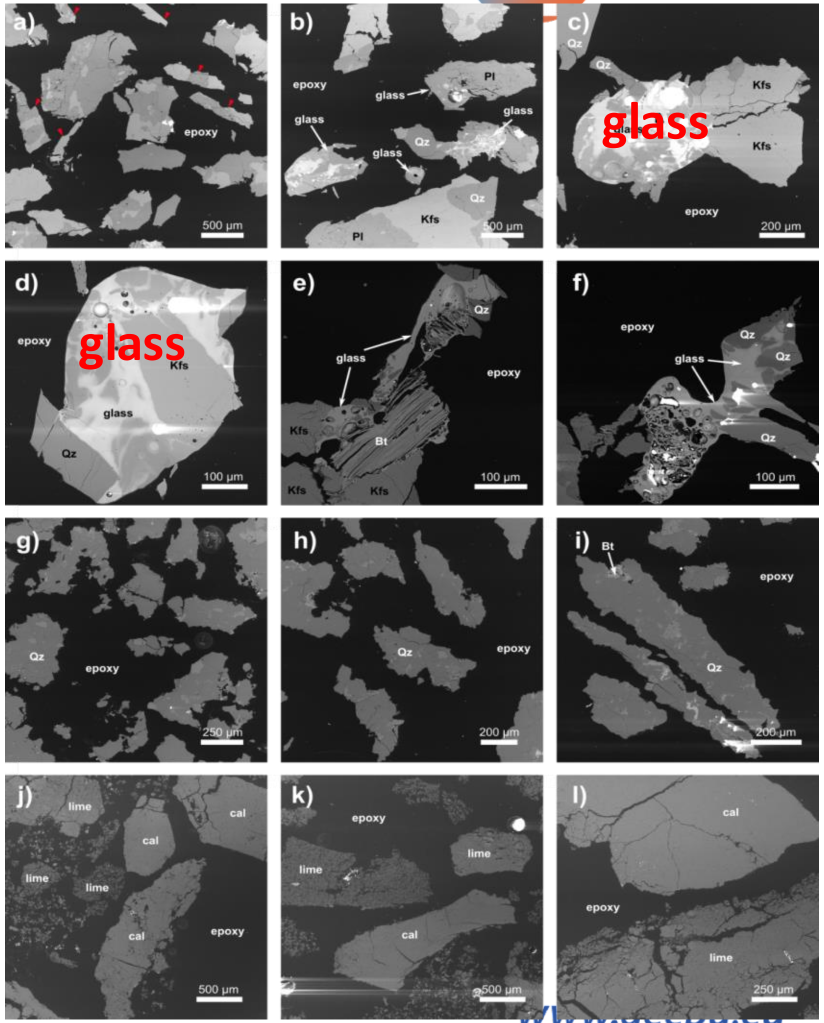
- size of the particles can be controlled with laser power
- thermally spalled particles were characterized **(size distribution, sphericity, roundness)**
- spalls can be removed from borehole and transported to the surface by pneumatic force of flushing system **(See in next presentation!)**

Electron microscope images of spalls

Granite

Sandstone

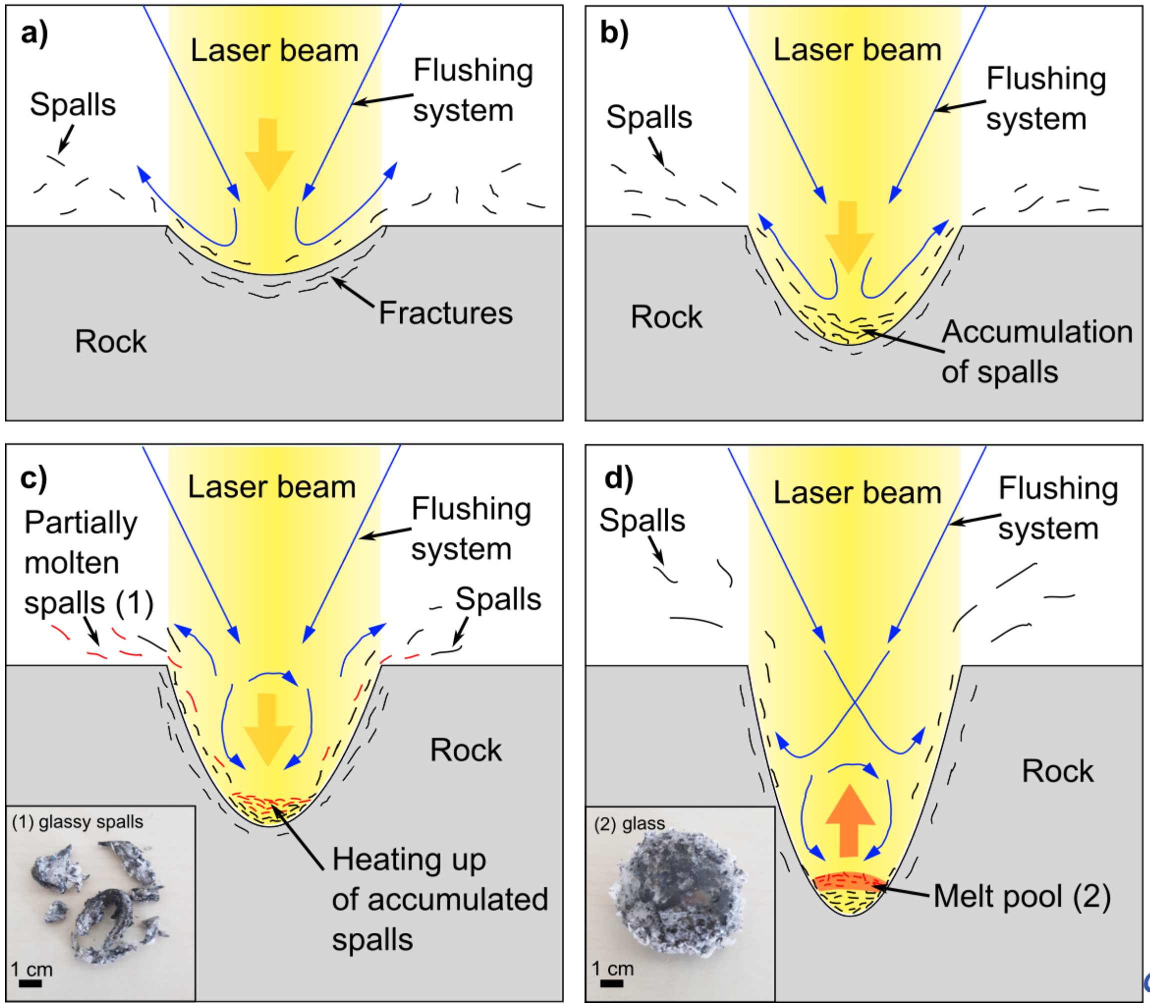
Limestone



Thermal spallation laser drilling

Sustainable thermal spallation laser drilling

- rate of lowering down drilling string has to correspond to penetration rate
- flushing system must efficiently remove all the spalls from the borehole bottom
- pneumatic force of flushing system must be able to transport spalls to the surface



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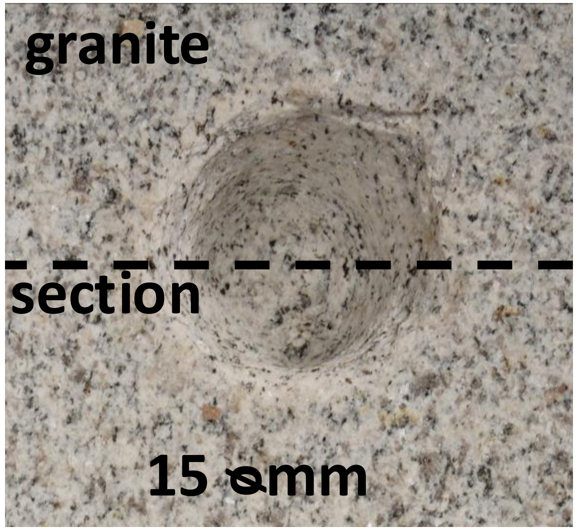
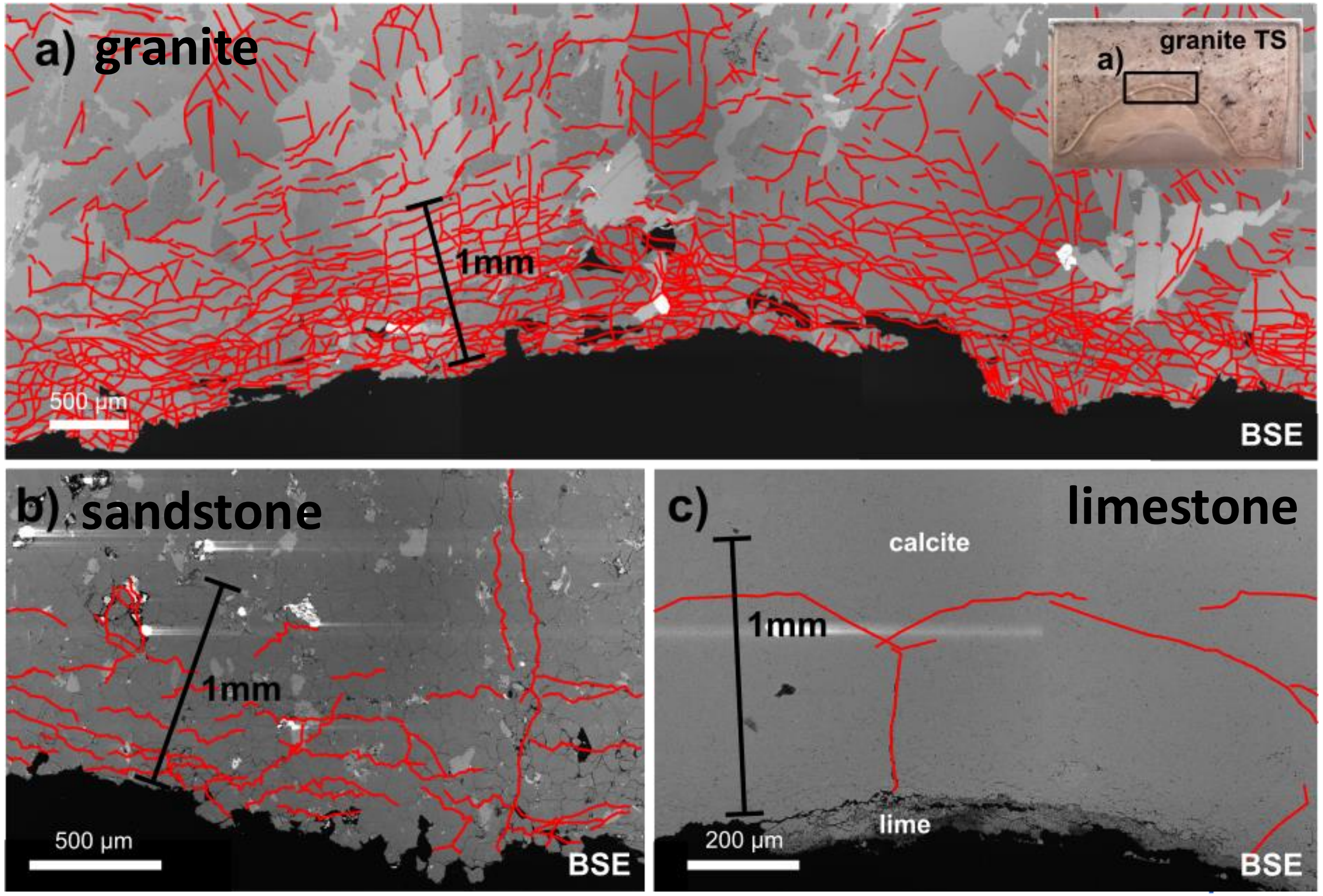
Laser-induced damage

Thermally spalled crater



Electron microscope images of fractures (red lines)



- shearing fractures related to spallation reach maximum **1mm in depth** into the rock
- spallation does not affect thermo-physical properties of rocks (not detectable)

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Efficiency of laser drilling

Rate of penetration

$$ROP = \frac{h}{t_i}\left(\frac{mm}{s}\right)$$

Specific energy for fiber laser drilling

$$S_e = \frac{Pt_i}{V}\left(\frac{kJ}{cm^3}\right)$$

	Thermal spallation (5 cmø)		Melting-vaporization (1 cmø)	
Lithology	**ROP (m/h)**	**S_e (kJ/cm³)**	**ROP (m/h)**	**S_e (kJ/cm³)**
granite	10.0	5.6	0.52	40.1
sandstone	14.8	4.1	2.26 spal.	9.2
limestone	2.5 melt.	86.7	0.44	47.3
limestone_H_2O sat.	4.5	16.3		
sandstone_H_2O sat.	25.1	2.3		

Thermally spalled borehole

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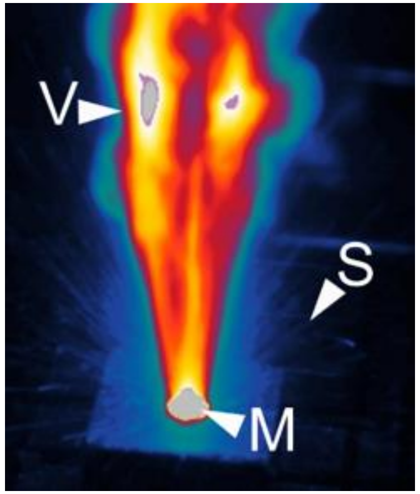
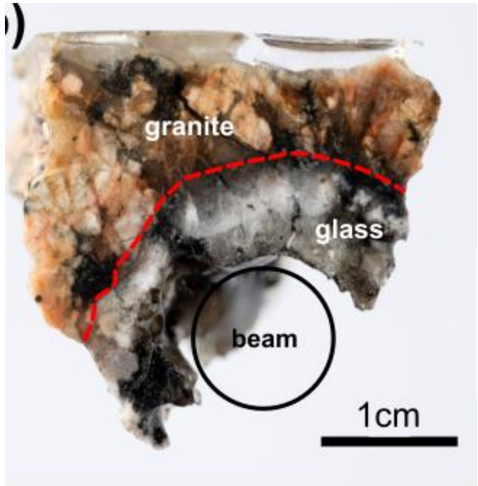
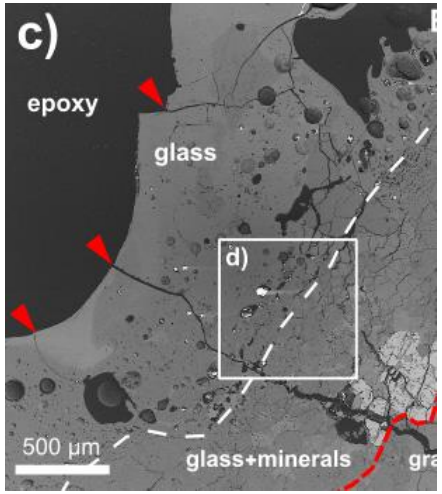
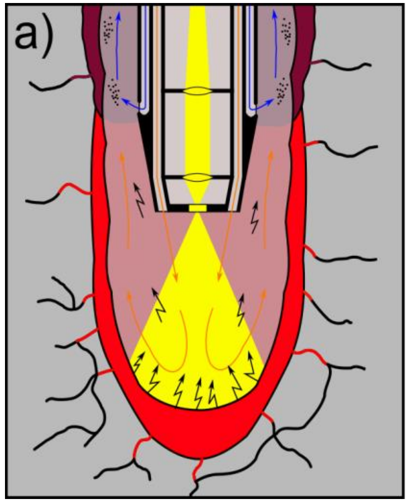
Summary – drilling regimes

melting-vaporization laser drilling

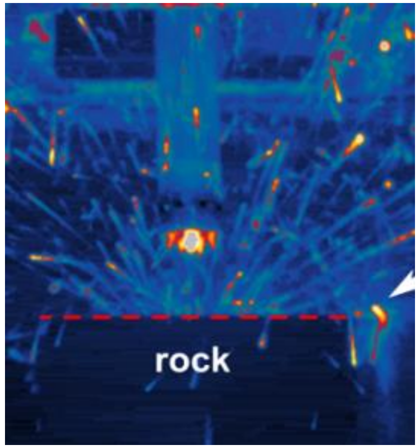


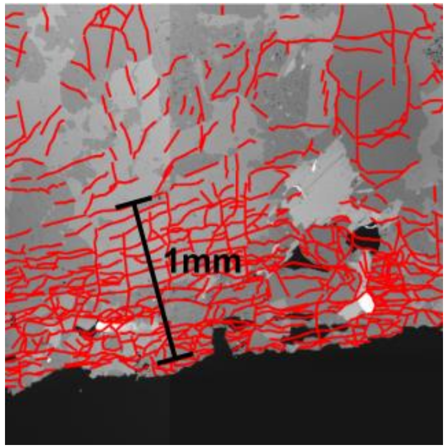


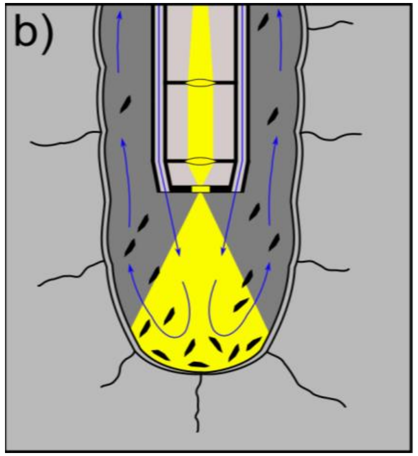




thermal spallation laser drilling







Conclusions

- drilling rocks with laser is possible!
- laser-induced thermal spallation is the most efficient rock penetration process
- laser-induced melting-vaprorization is more demanding energetically but form a vitrified layer on the rock surface
- first thermal spallation laser drilling system (DeepU) was successfully tested at laboratory scale

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