DeepU
This research is funded by the European Union
(EIC, Pathfinder Programme, G.A. 101046937)

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

Laser drilling, laser-rock interactions

Work Package 3

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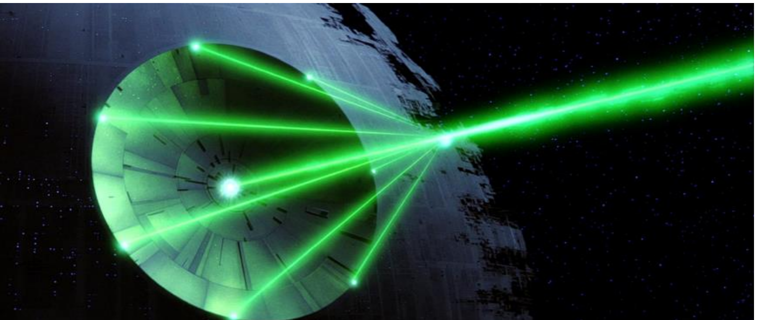

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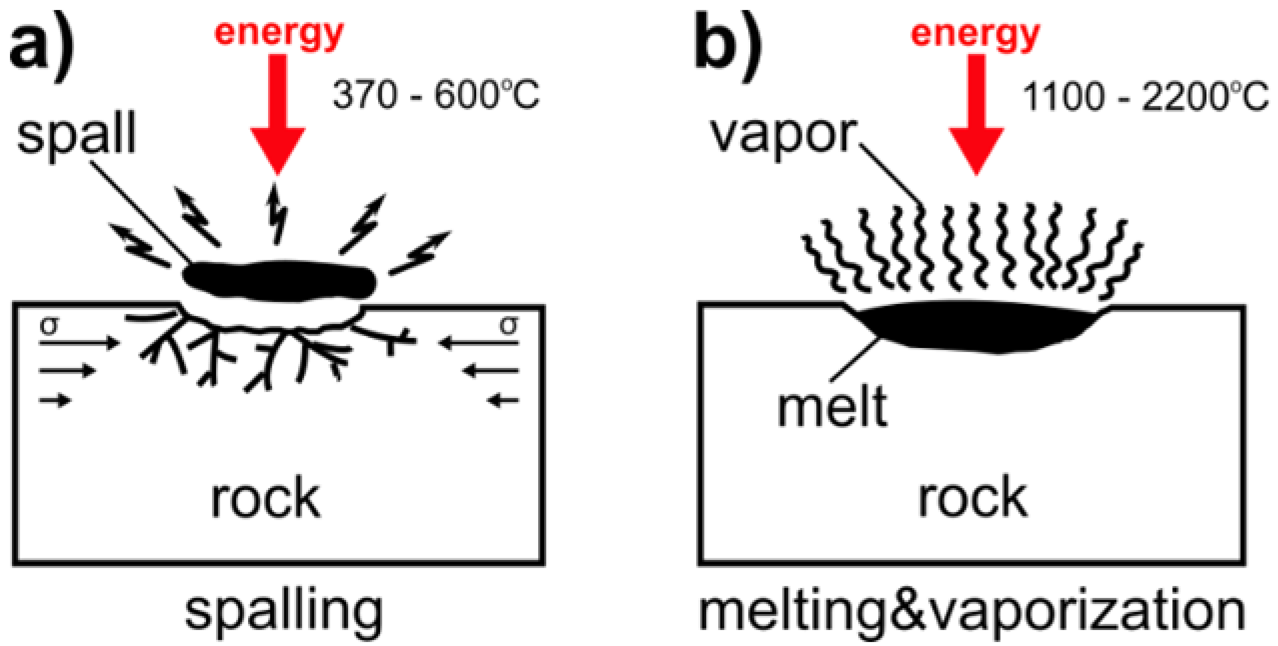
Why drill with a laser?

Penetration mechanisms (after Mauer 1980)



Advantages of laser technology

- commercial availability
- modularity
- high power
- no losses on transmission

DeepU Laser

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

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

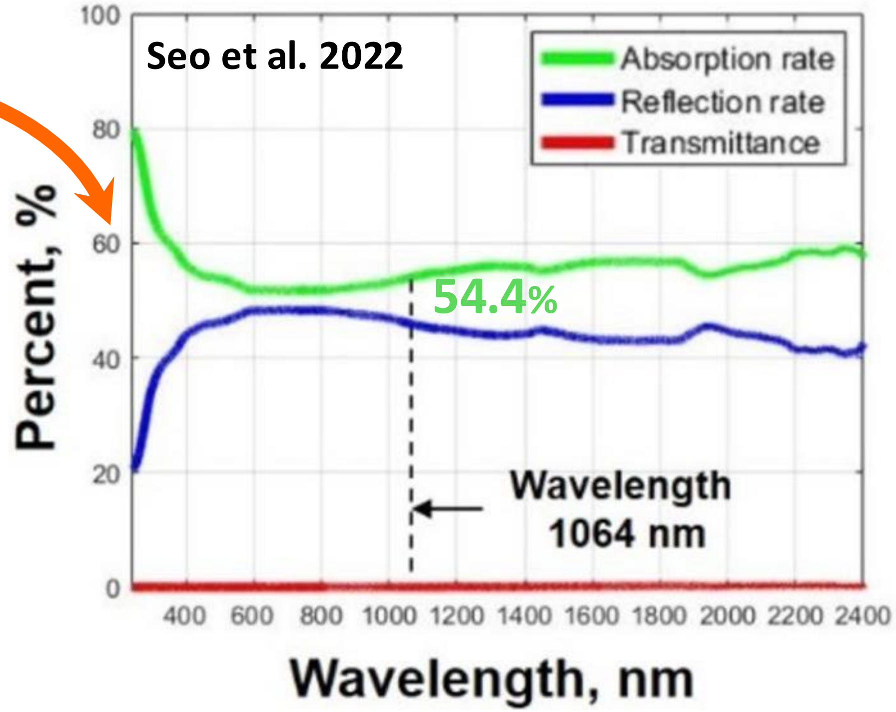
Laser-rock interaction

- rock texture (grain size)
- mineral composition
- chemical composition

thermo-physical properties

- **power**
- **irradiation time**

Radiation absorbance of granite



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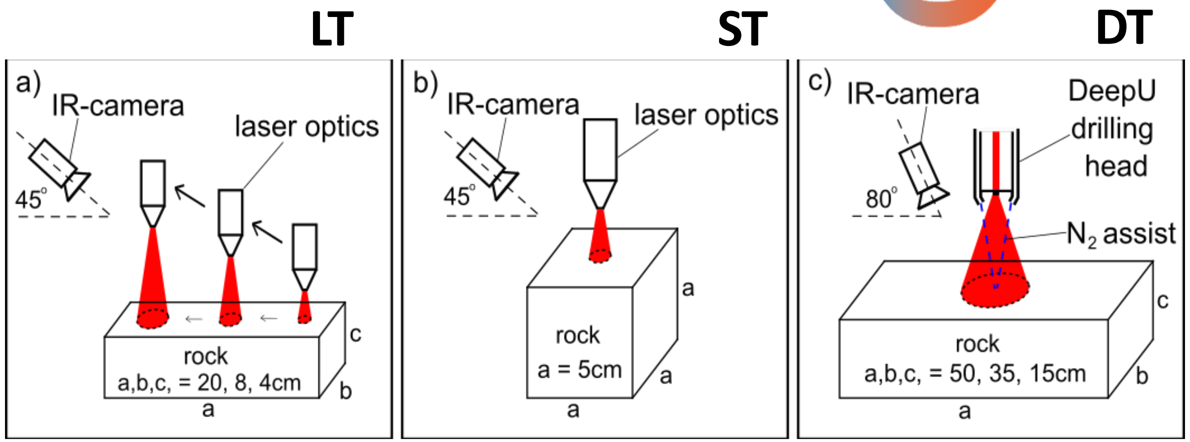
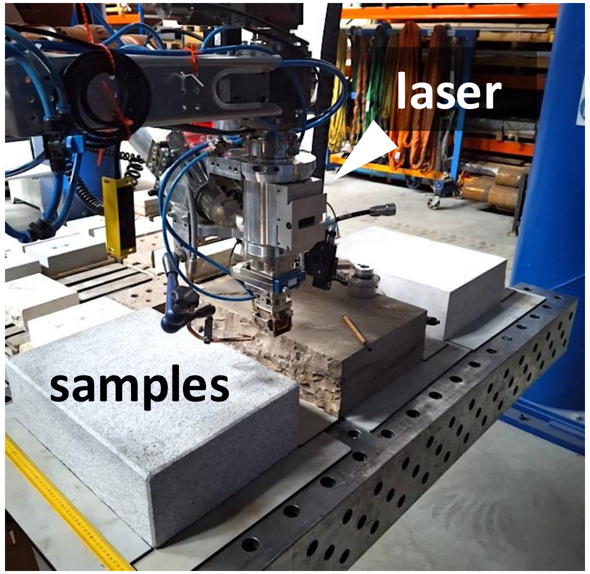
Laser drilling experiments

Experimental setups
- Linear track tests (LT)
- Single spot tests (ST)
- DeepU system tests (DT)

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





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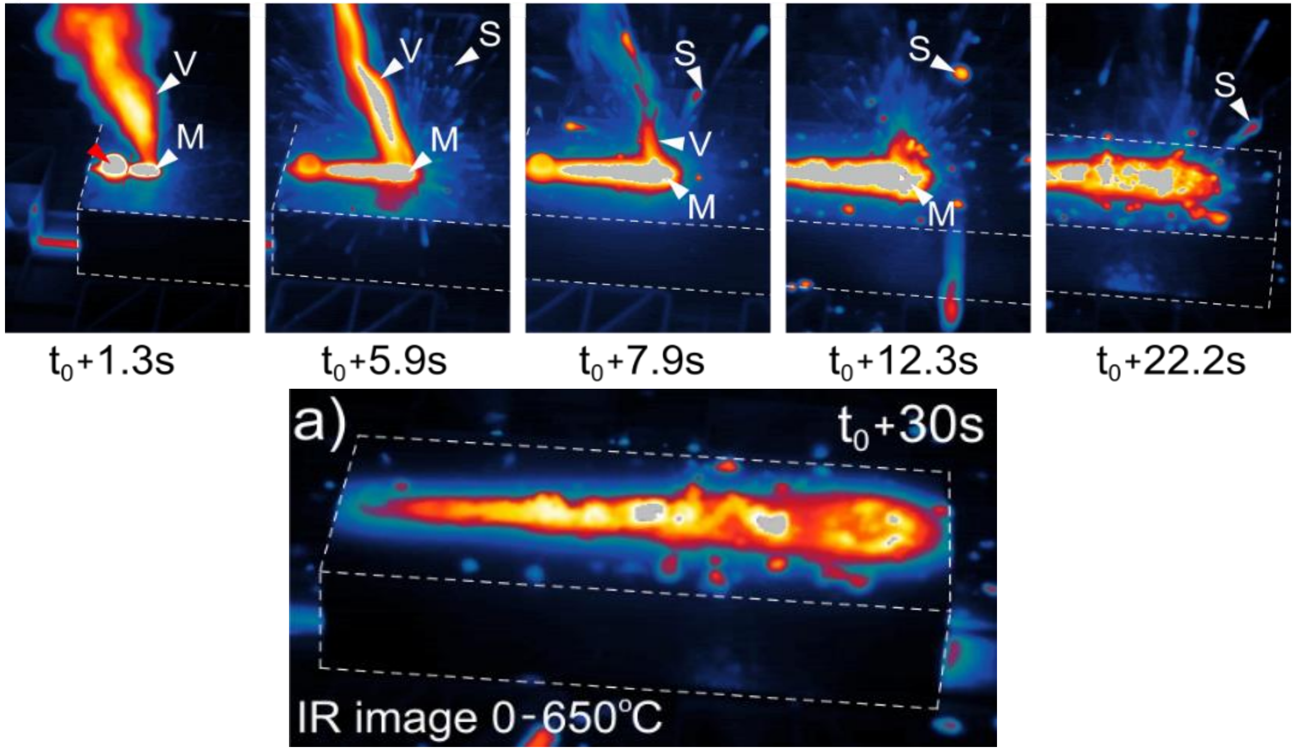
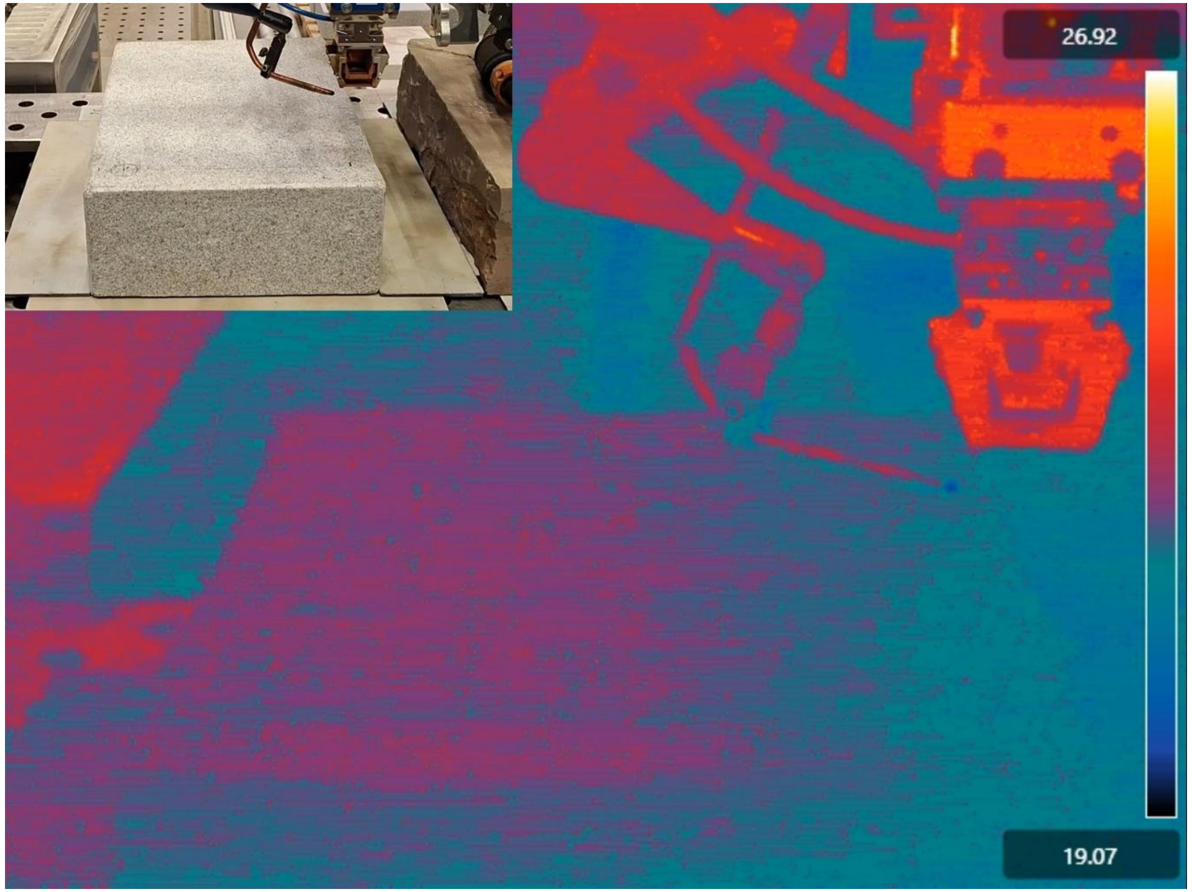
Results: laser-rock interactions

Rock response depends on:

- **Power density (W/cm²)**
- Irradiation time (s)
- Rock type: chemical, mineral composition, grain size etc.



Linear track tests (LT) 0.9 - 30 mm



Results: laser-rock interactions

Lasing products analysis

Strongly bonded glass

Loose glass

Partially molten spalls, deep grove

Spalls, shallow grove

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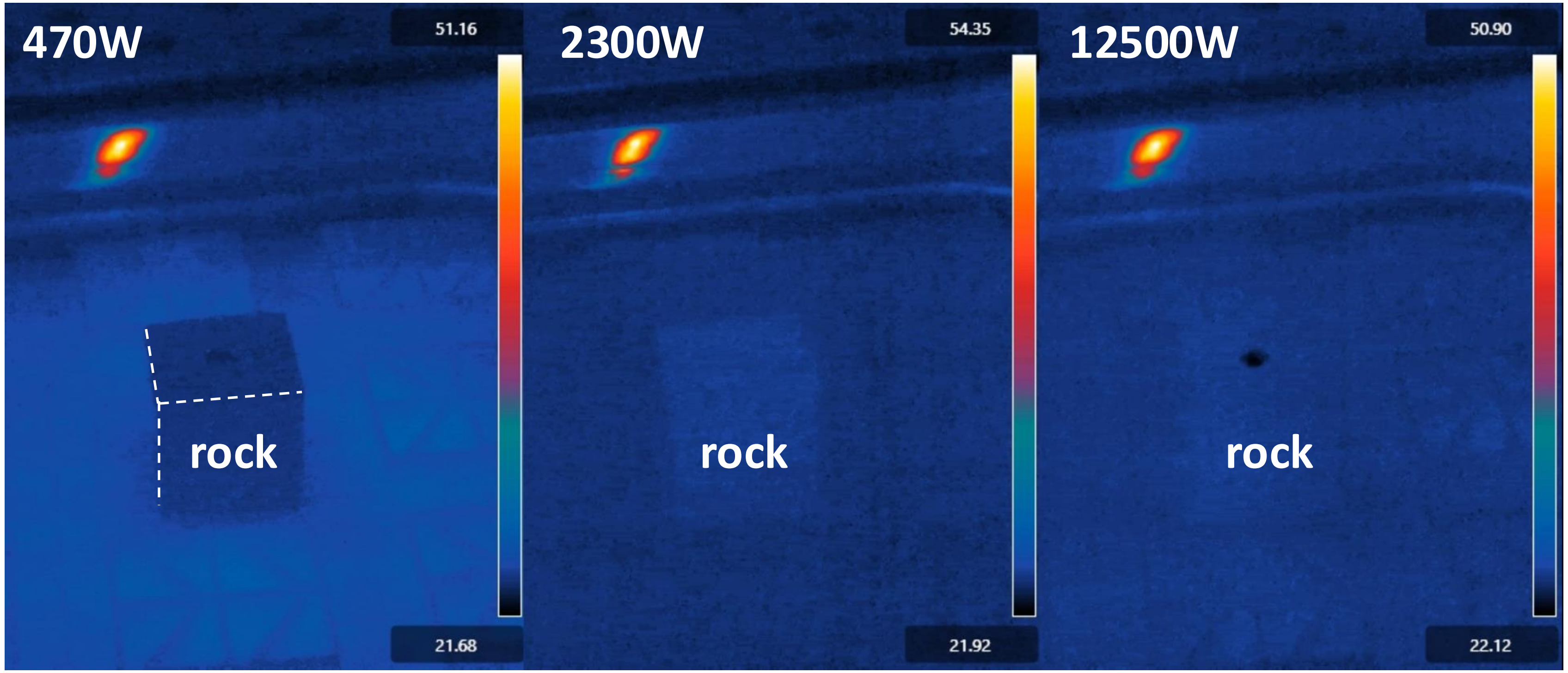
Results: laser-rock interactions

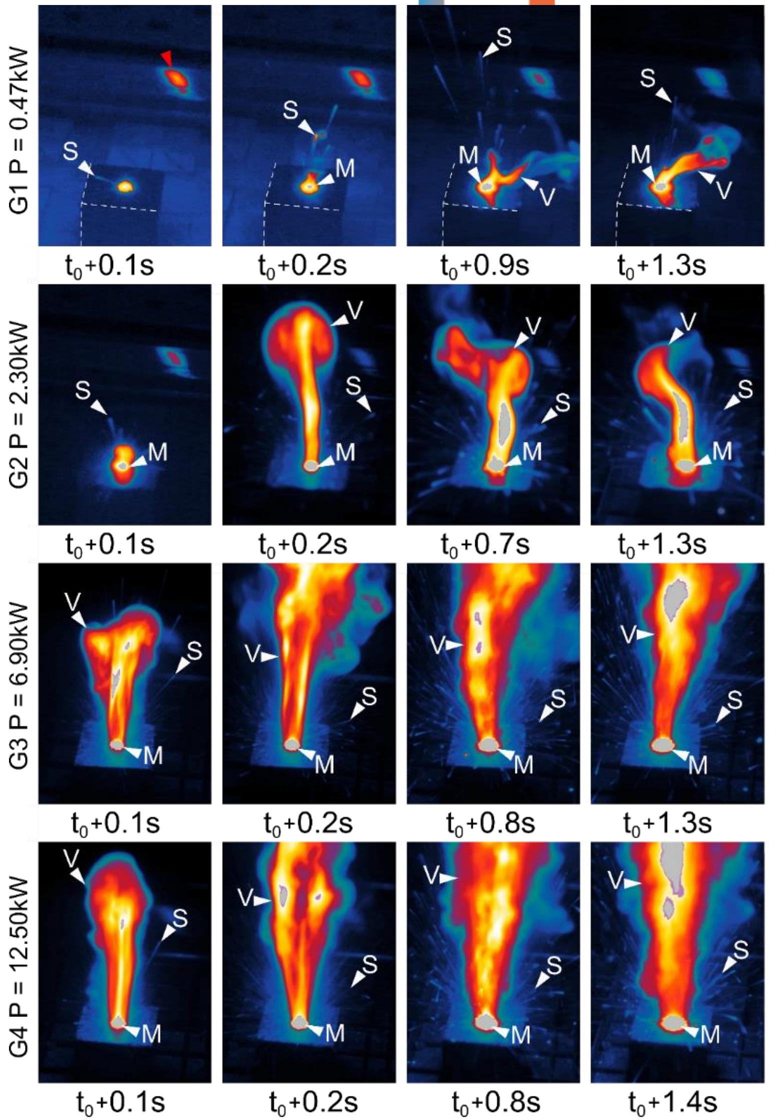
Rock response depends on:

- Power density (W/cm^2)
- Irradiation time (s).

Single spot tests (ST) – 10 mm

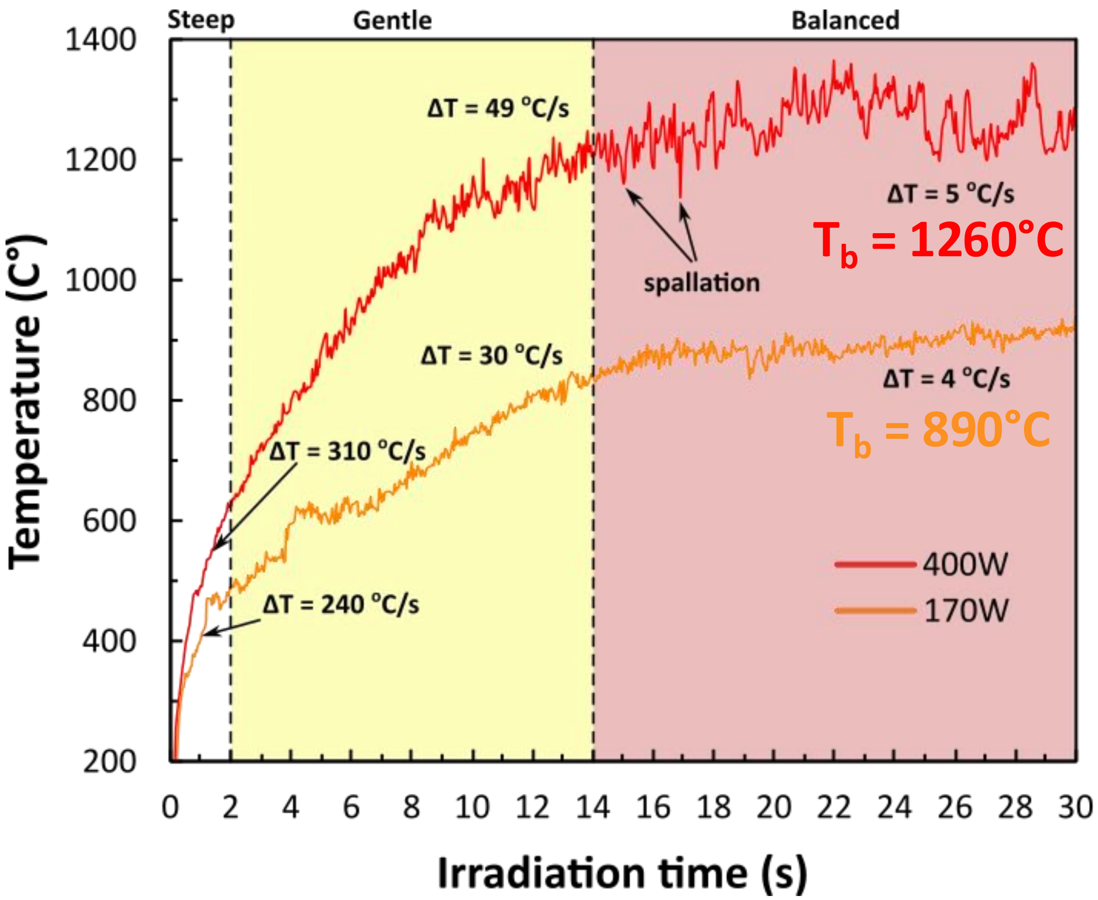


Spallation | **Spallation-melting** | **Melting-vaporization**

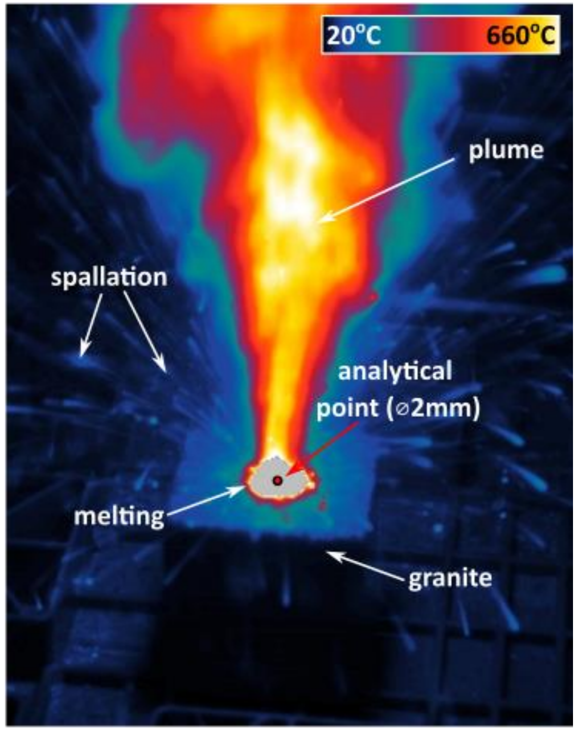


Results: laser-rock interactions

Temporal record of temperature



IR image of vaporization



Balance temperature depends on laser power and lithology

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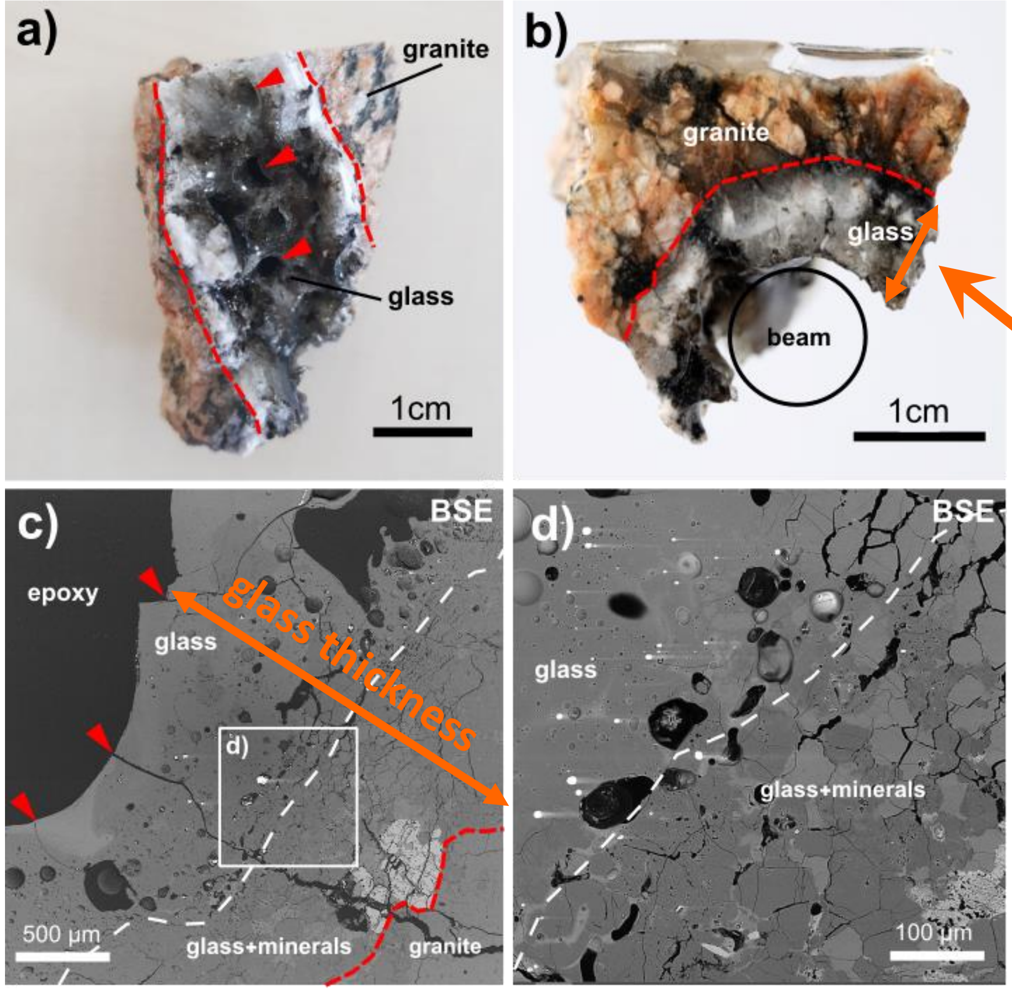
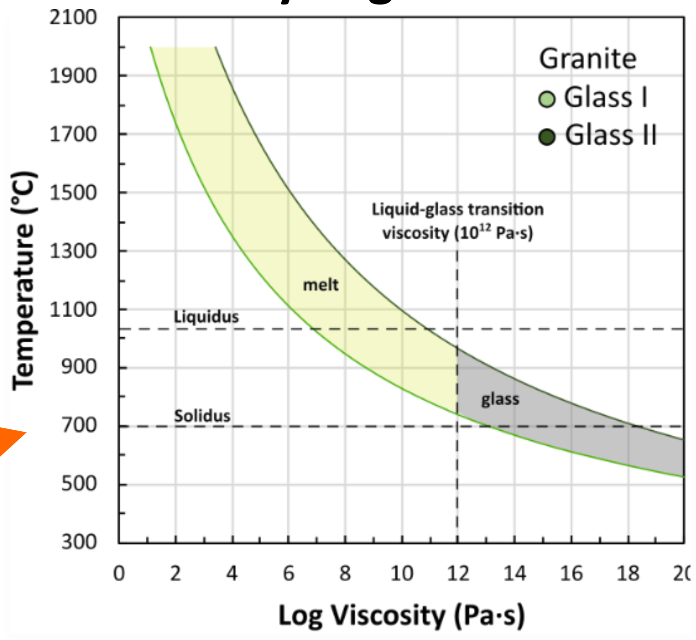
Vitrification



- 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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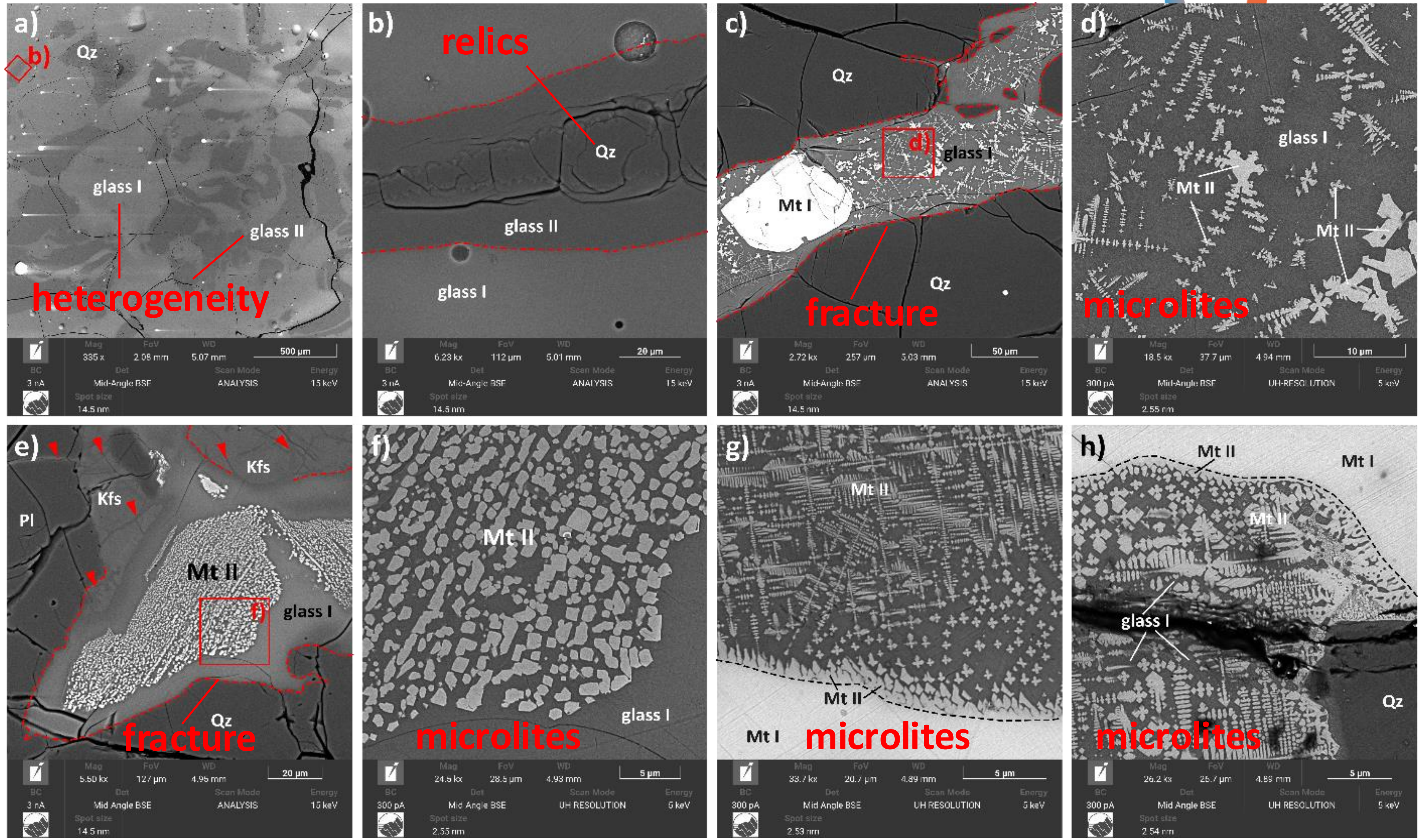
Vitrification

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

What are thermophysical properties of laser-generated glass?

Electron microscope images of laser-generated glass in granite



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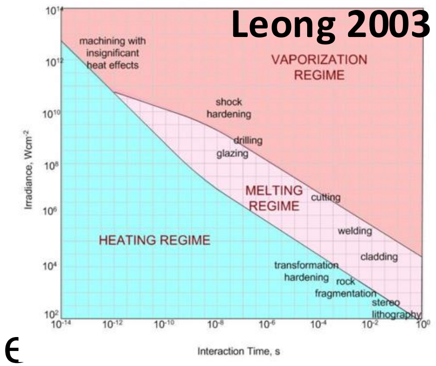
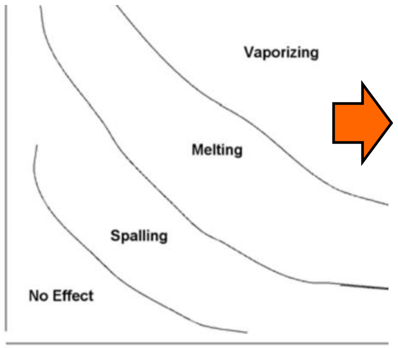
Results: laser-rock interactions

- **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

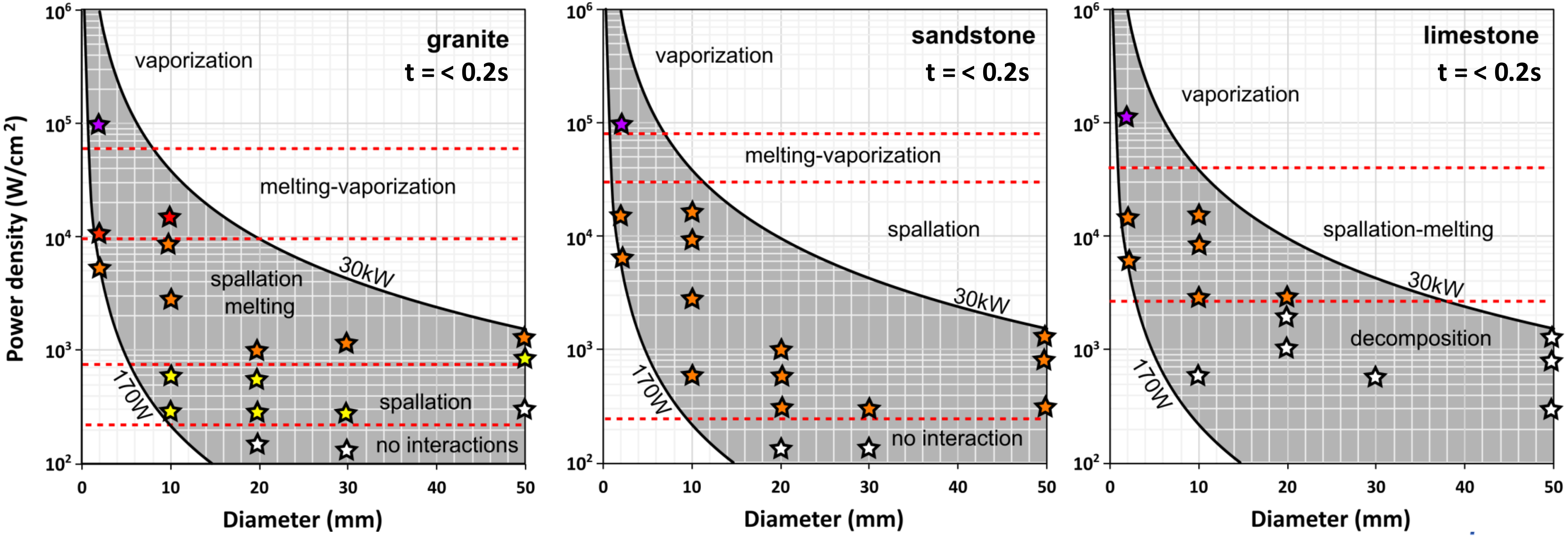


Leong 2003



Gahan B. C. et al., 2002

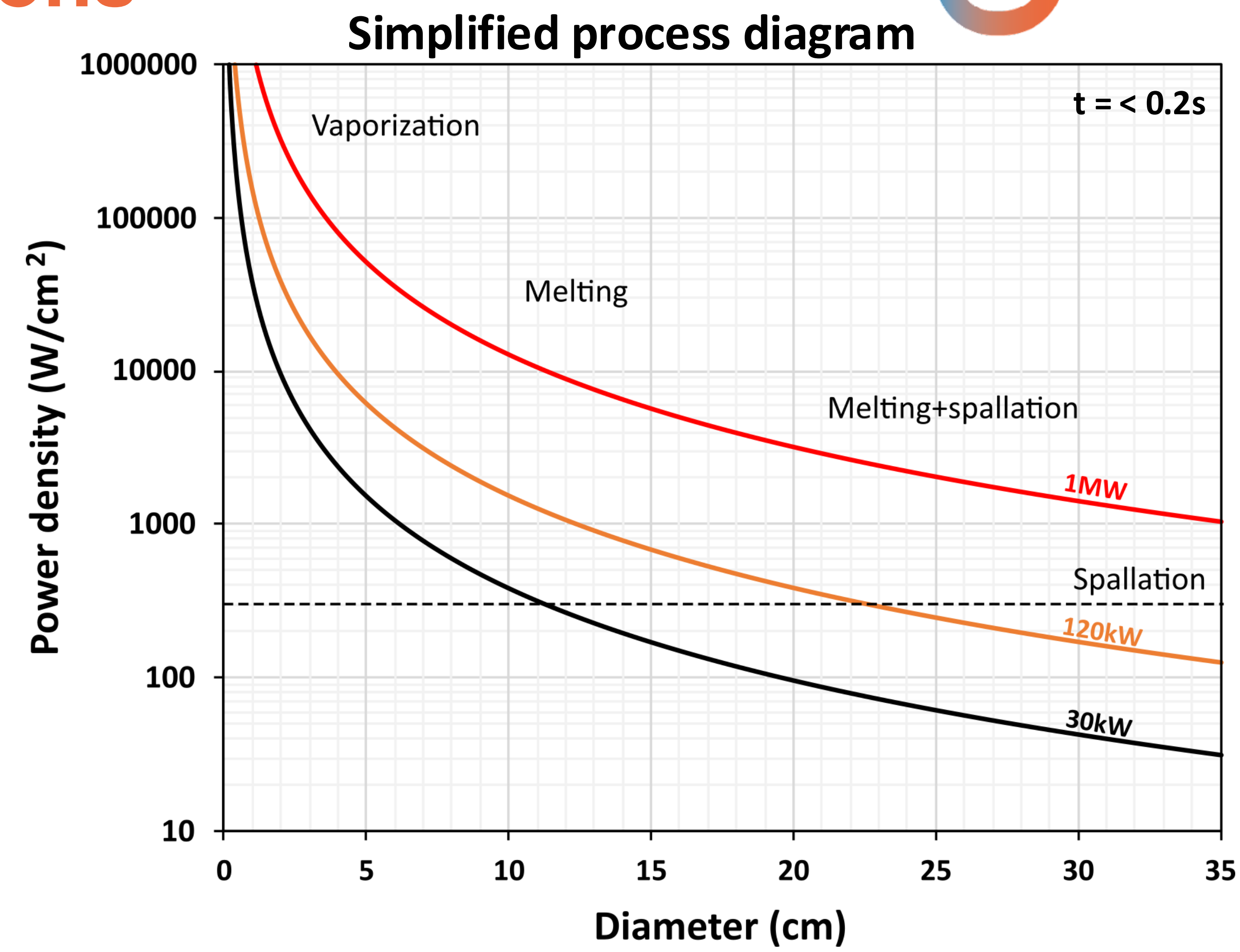
Process diagrams



Results: laser-rock interactions

Implications for laser drilling technique

- Drilling economically useful diameters with **laser-induced thermal spallation is possible**
- Laser-induced melting-vaporization require much more power than spallation



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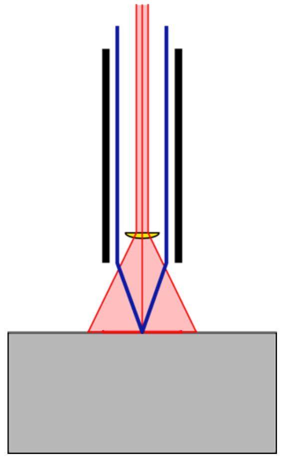
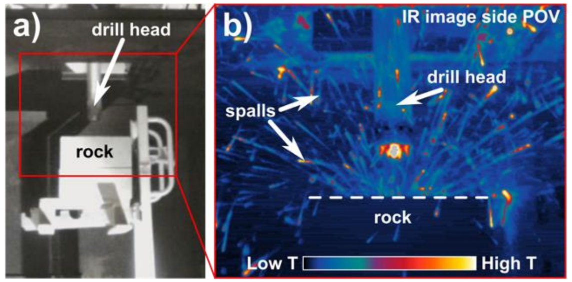
Thermal spallation laser drilling

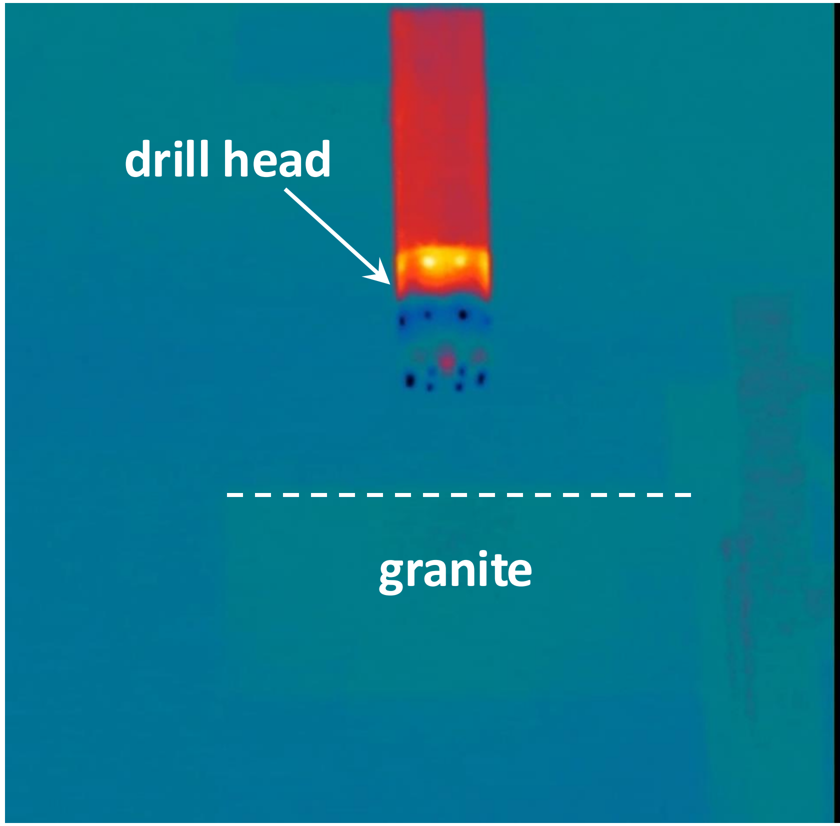
DeepU laser system

- divergent beam
- N_2 flushing system





Side View

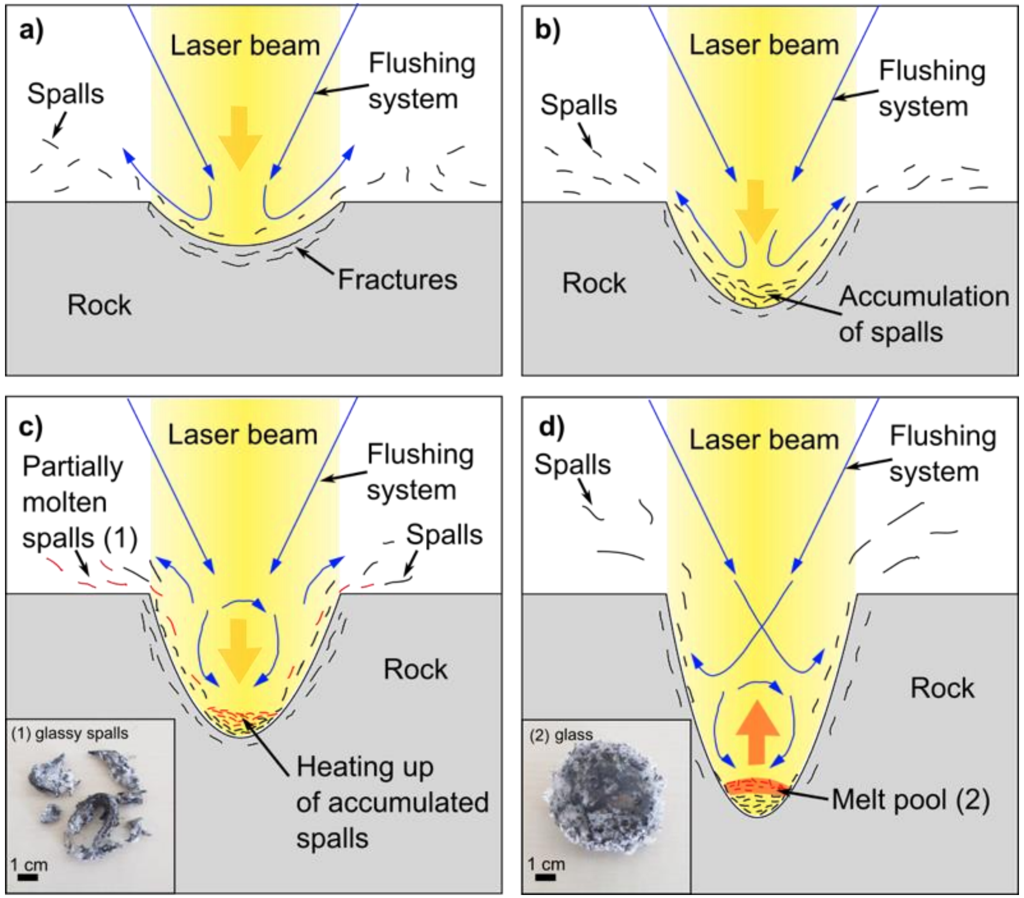


Top View

IR-record of DeepU laser thermal spallation

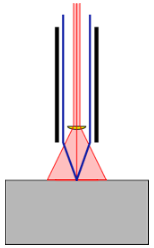
Thermal spallation laser drilling

Penetration by thermal spallation



Important optimalization features:

- Flushing system and power
- Drill-head decent rate and working distance



divergent beam

Rate of drill-head decent

correct

incorrect

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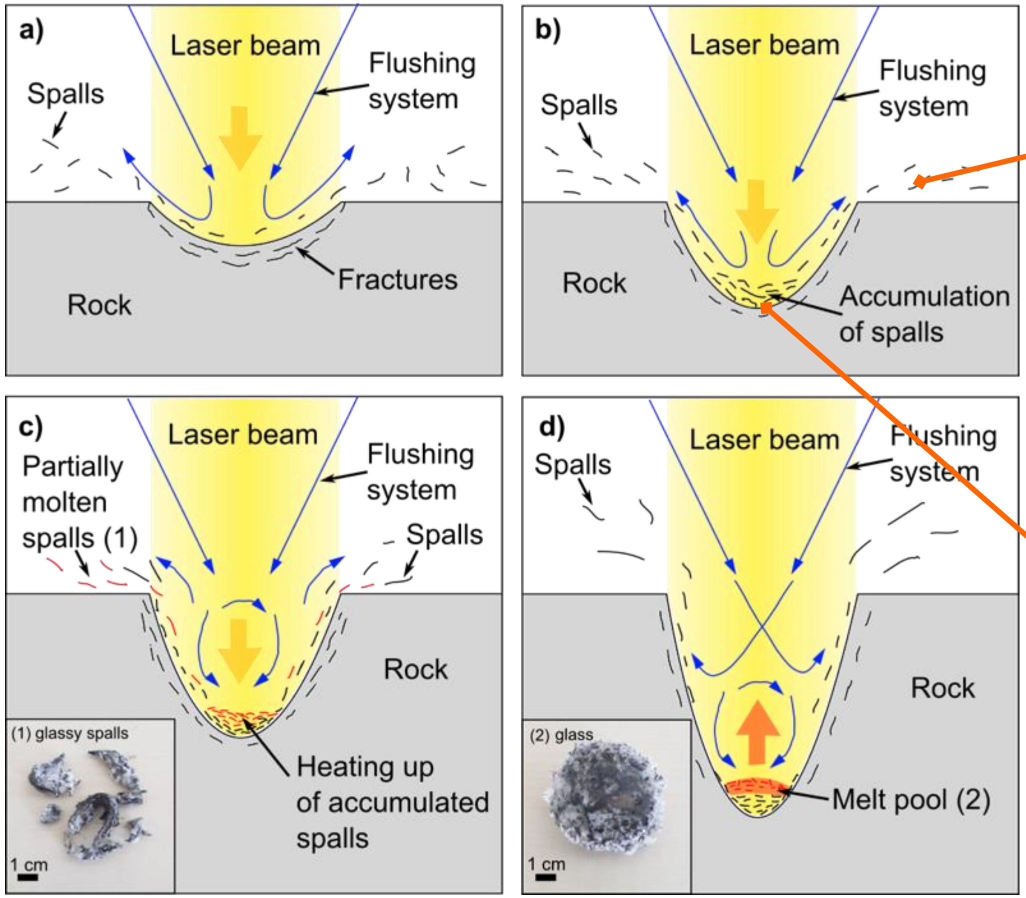
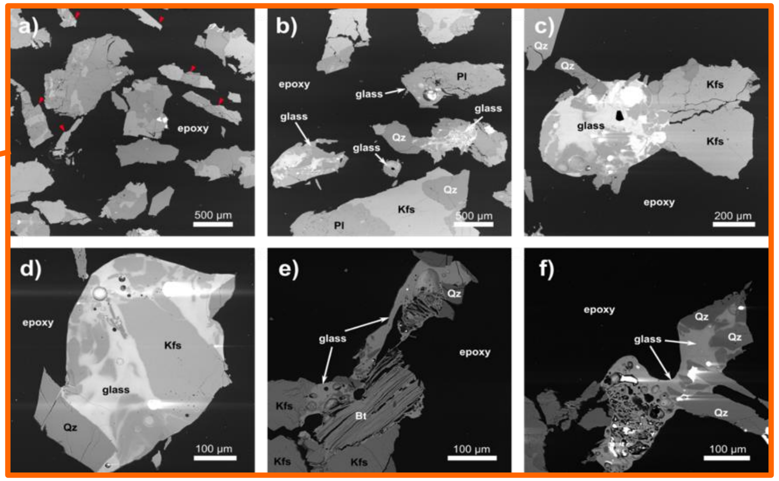
Deep U-tube heat exchanger breakthrough: combining laser and cryogenic gas for geothermal energy exploitation

Thermal spallation laser drilling

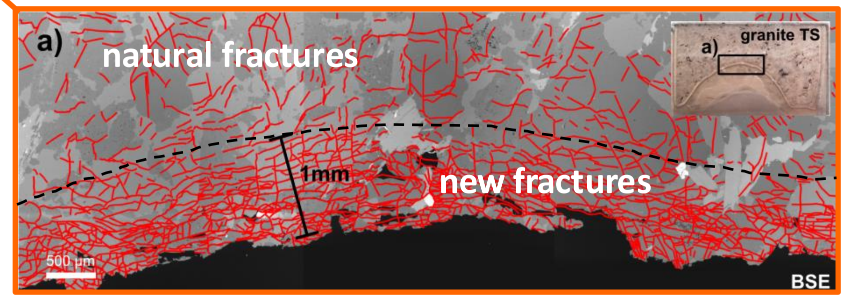
Penetration by thermal spallation



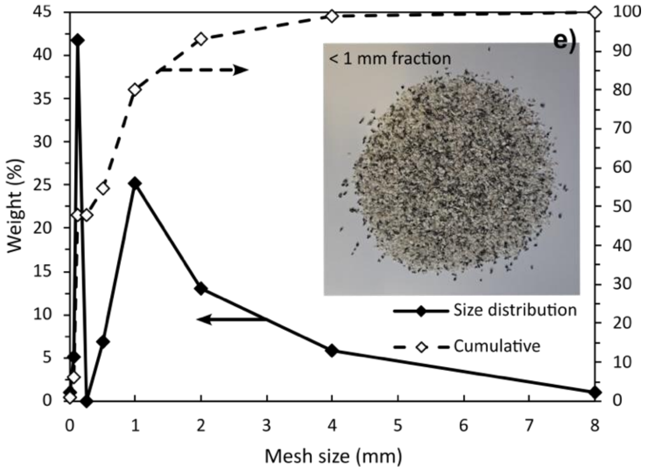
Spalls morphology

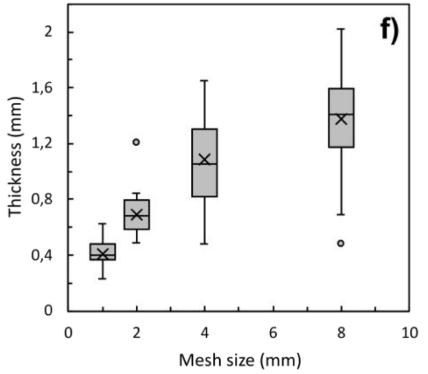


Crater wall BSE image



Spalls size distribution





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DeepU

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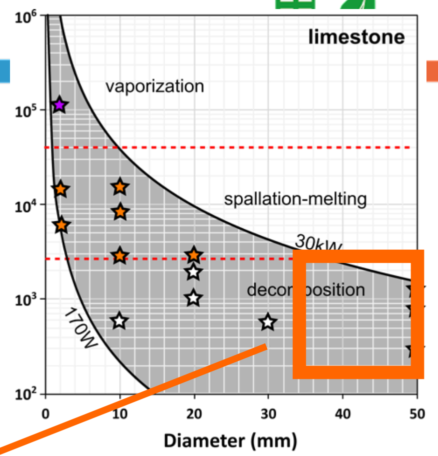
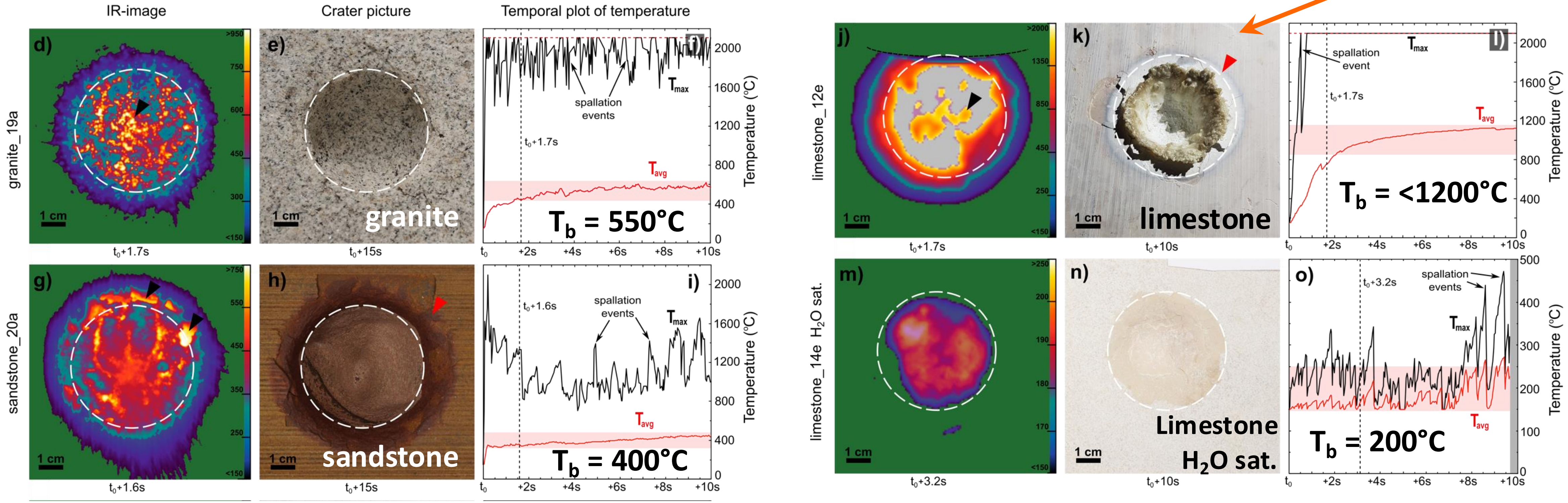
Thermal spallation laser drilling



Summary of DeepU laser system tests



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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 cm⌀)		Melting-vaporization (1 cm⌀)	
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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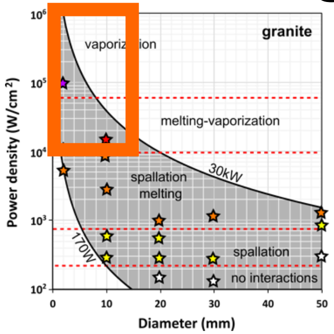
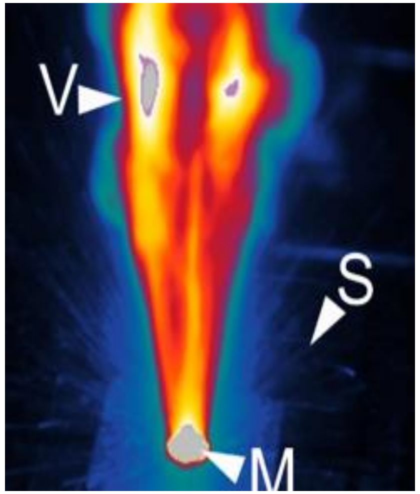
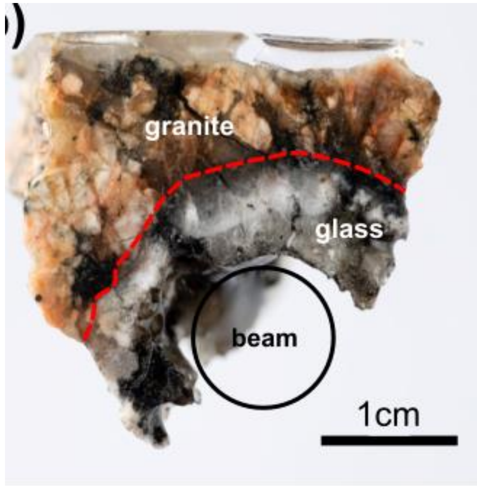
Summary

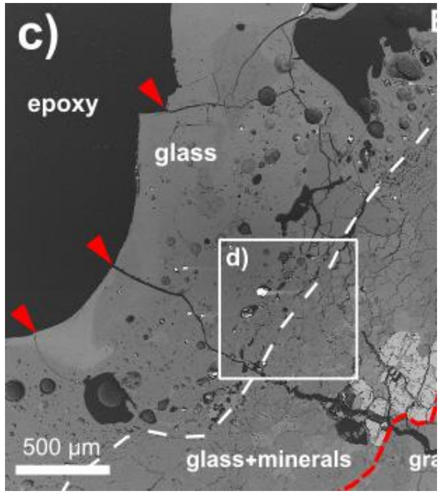
	IR image of the process	Crater morphology	Crater walls BSE images	Drilling method

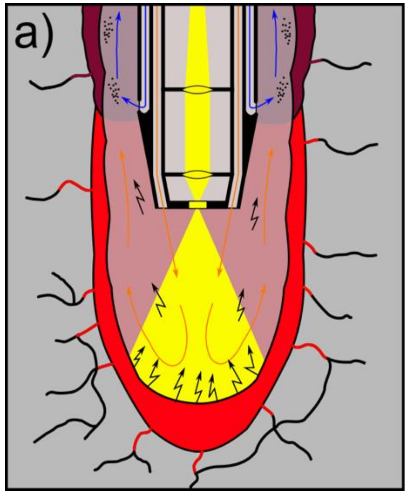
Melting-vaporization laser drilling



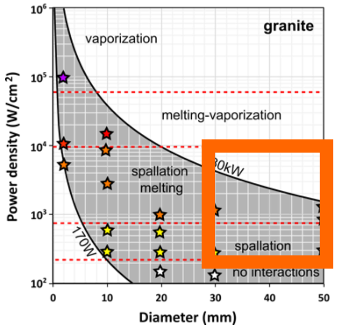


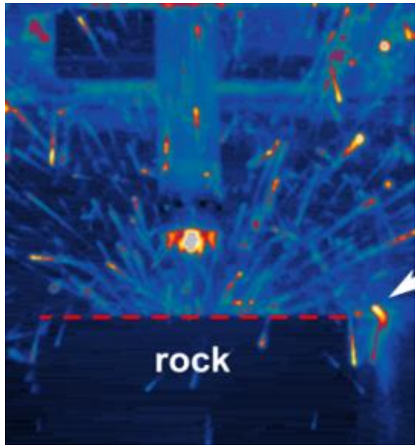


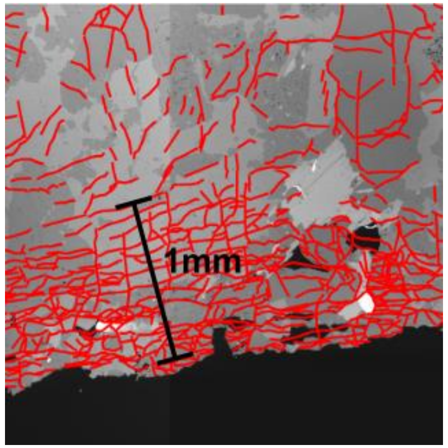


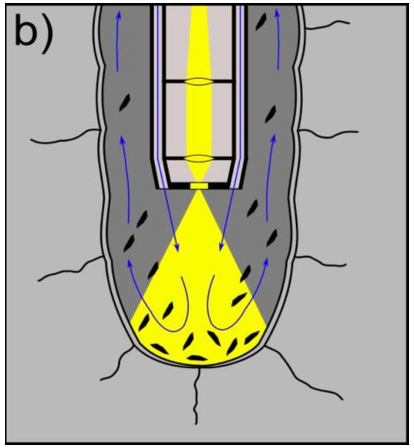


Thermal spallation laser drilling



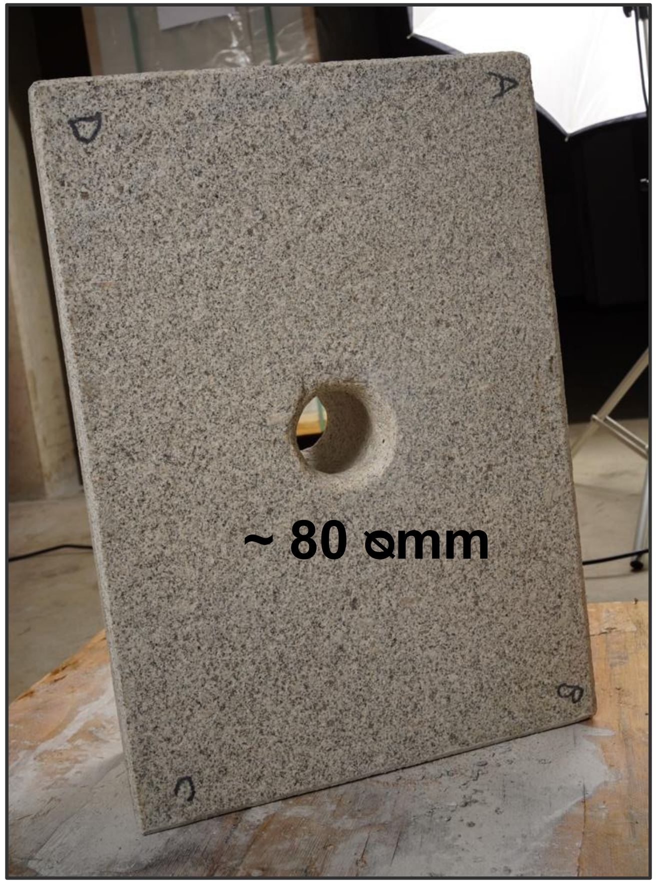






Take home messages

- Drilling rocks with a laser is possible
- Laser-induced **thermal spallation is the most efficient** rock penetration process
- Laser-induced melting-vaporization require much more energy but **create a vitrified layer** on the rock surface
- **The first** thermal spallation laser drilling system (DeepU) was successfully tested at laboratory scale (granite ~15 m/h)



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Specific energy (kJ/cm^3)