Exploration of deep geothermal resources: Towards a new drilling technology

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About me

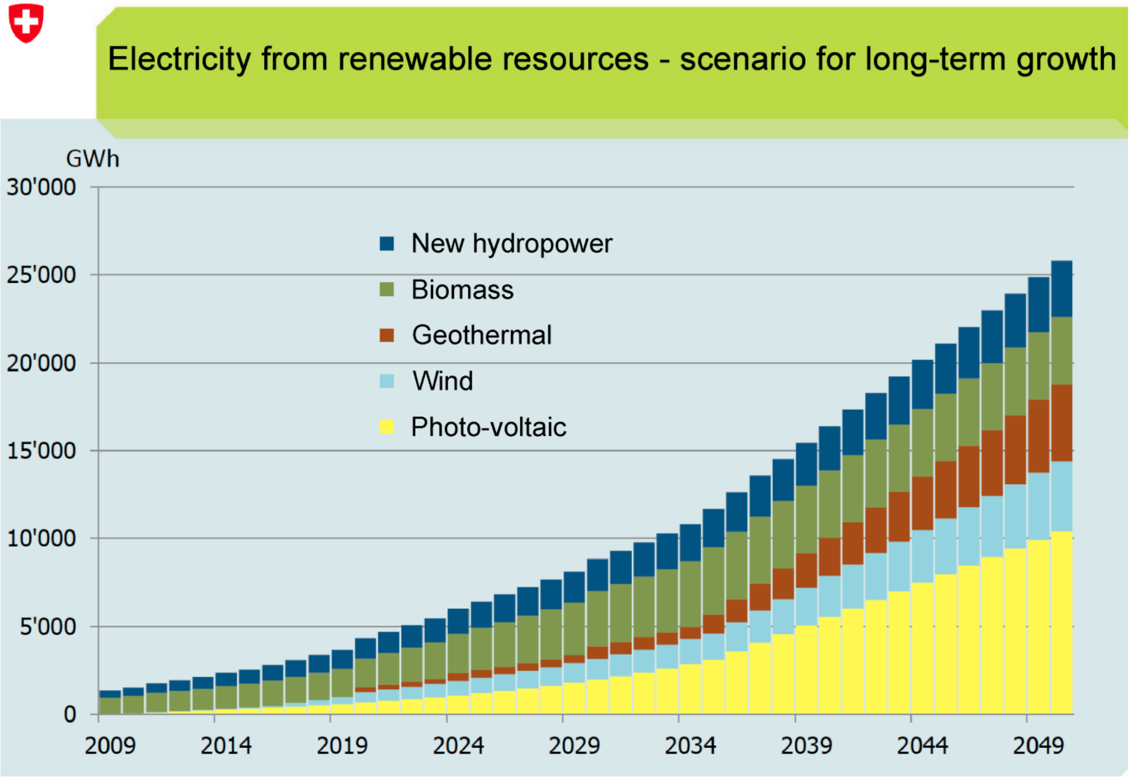
- (2011-14): BSc in Mechanical Engineering at Università Politecnica delle Marche, Italy
- (2014-16): MSc in Mechanical Engineering at ETH Zürich
- (from 2016): PhD student at ETH Zürich

Outline

- Introduction
- Conventional drilling techniques
- Flame-jet spallation drilling
- Combined thermo-mechanical drilling
- Conclusions & Outlooks

Switzerland's Energy Strategy 2050

- Structural reform of Switzerland's energy supply system
- Reduce pro-capita energy consumption
- Lower proportion of fossil-based energy
- Compensate for a potential abandonment of nuclear energy



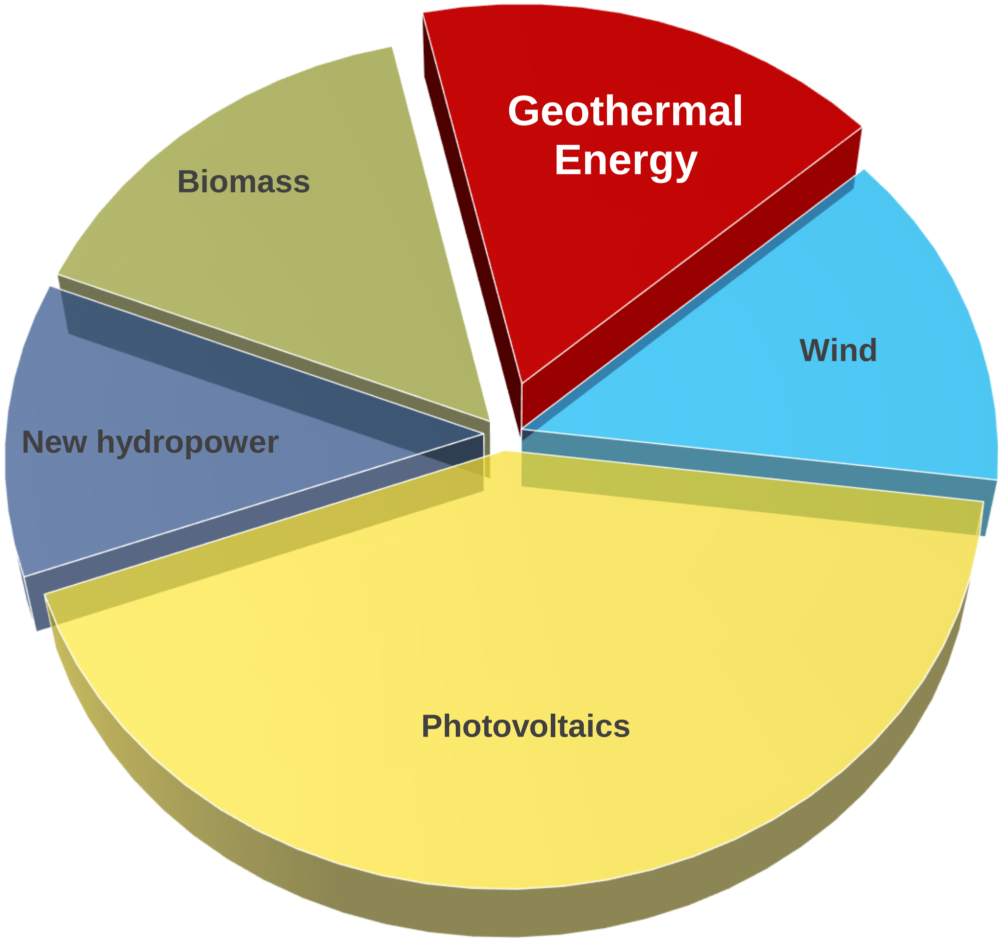
Source: Swiss Federal Office of Energy

Switzerland’s Energy Strategy 2050

2050 - Energy targets

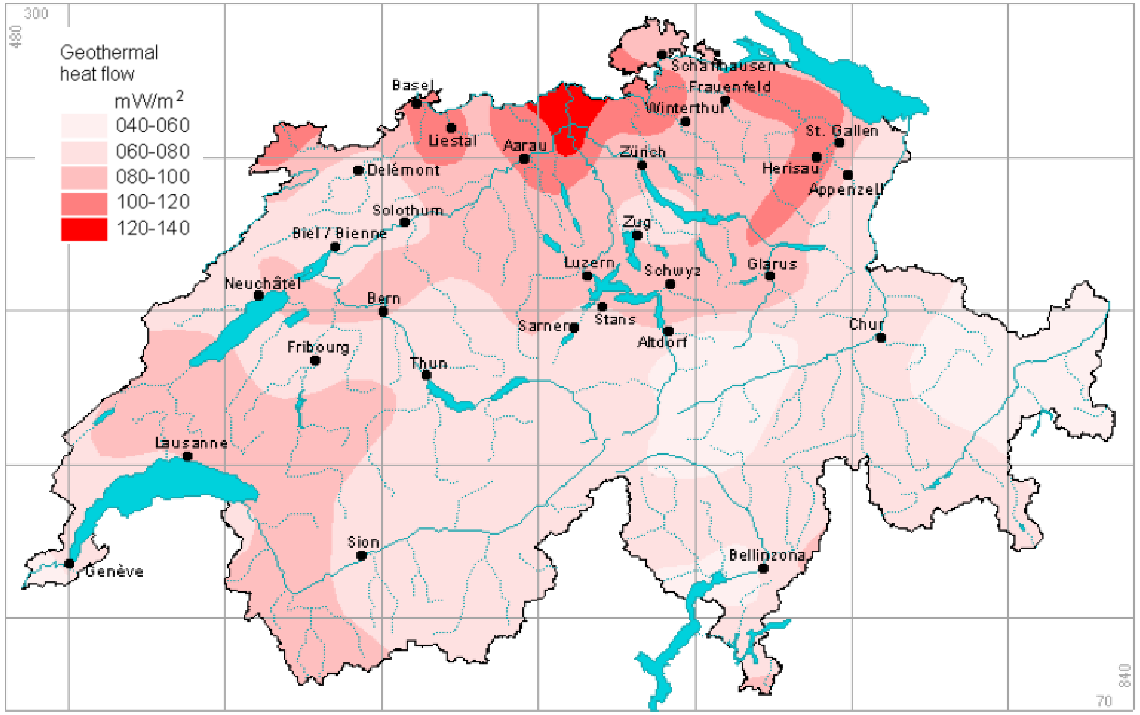
- 7-8% of overall electricity supply from geothermal energy by 2050
- 4.4 TWh per year from geothermal
- 10% annual growth after 2020 is required

Renewable Energy budget 2050



Adapted from Swiss Federal Office of Energy

Geothermal Energy potential in Switzerland



Geothermal heat flow map in Switzerland, from Medici & Rybach (1995)

- High heat flows in northern areas
- Potential thermal gradient 25-40°C/km
- Necessary to go deeper than 3 km to find exploitable resources for electricity production

  → Even higher costs
- But: alpine areas not precisely characterized

Engineered Geothermal Systems (EGS)

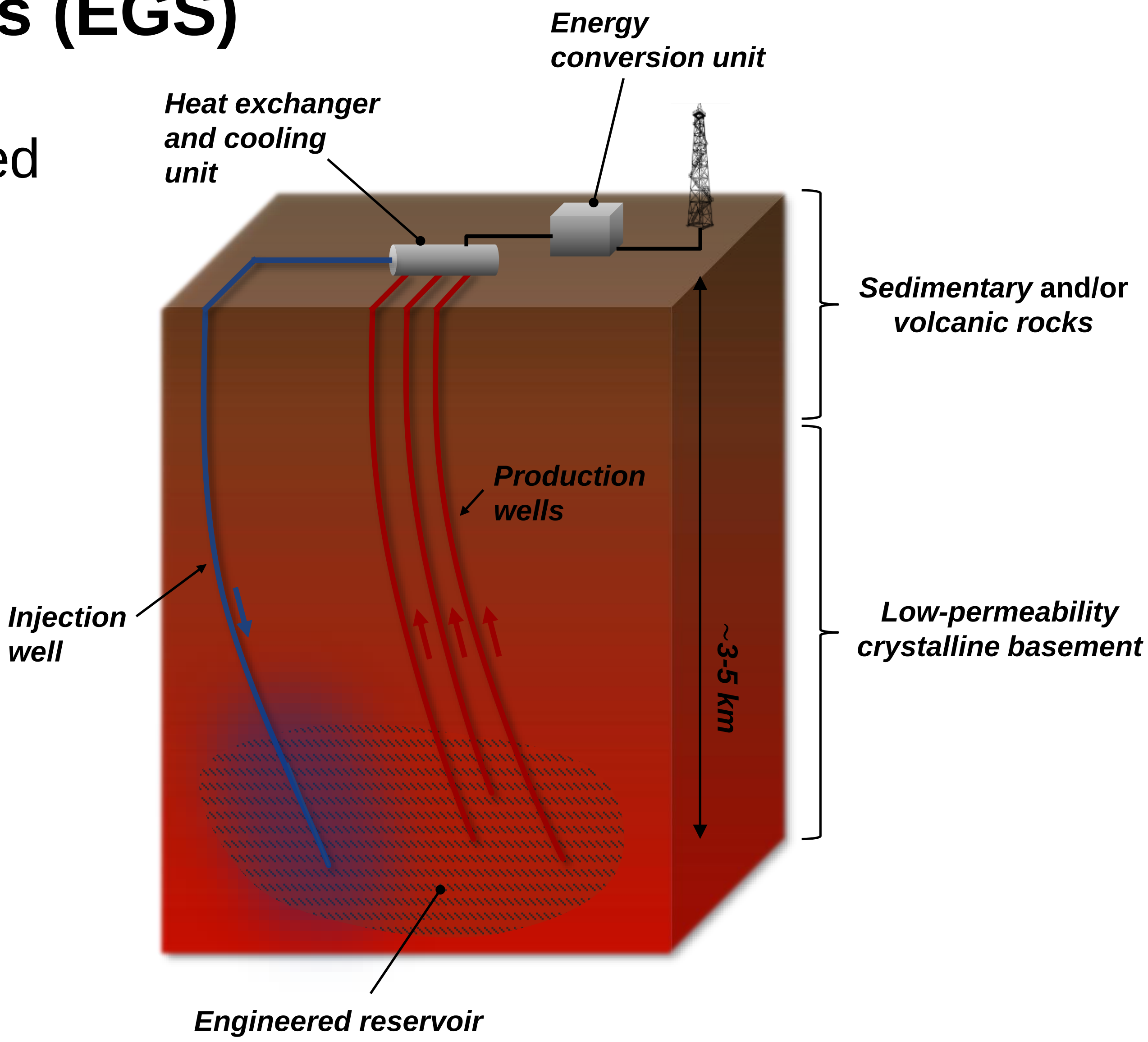
- The reservoir is engineered or enhanced in terms of permeability

  → Allow for fluid circulation

- Reach low-porosity basement with temperatures of 150-220°C

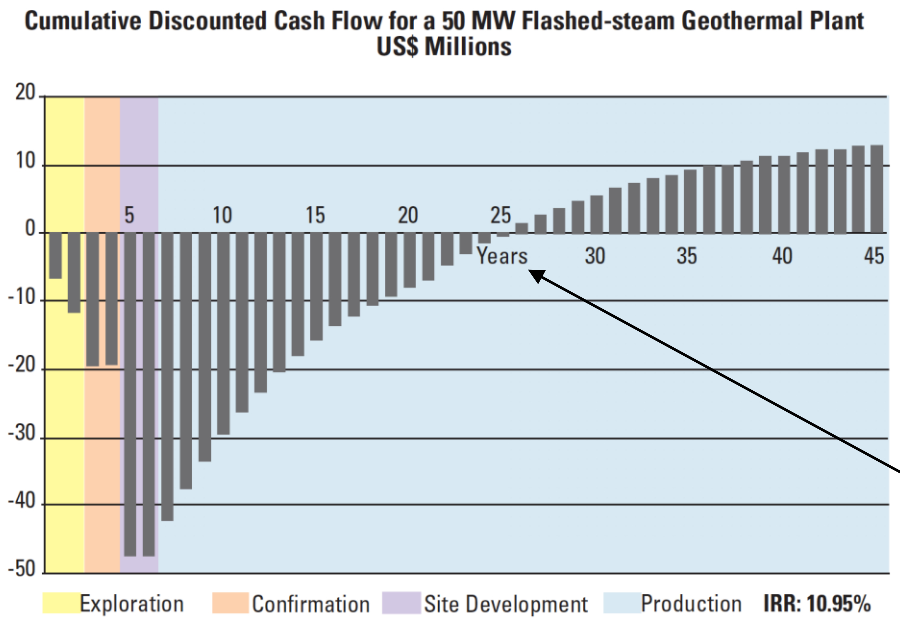
- Need to drill until depths of **3-5 km**

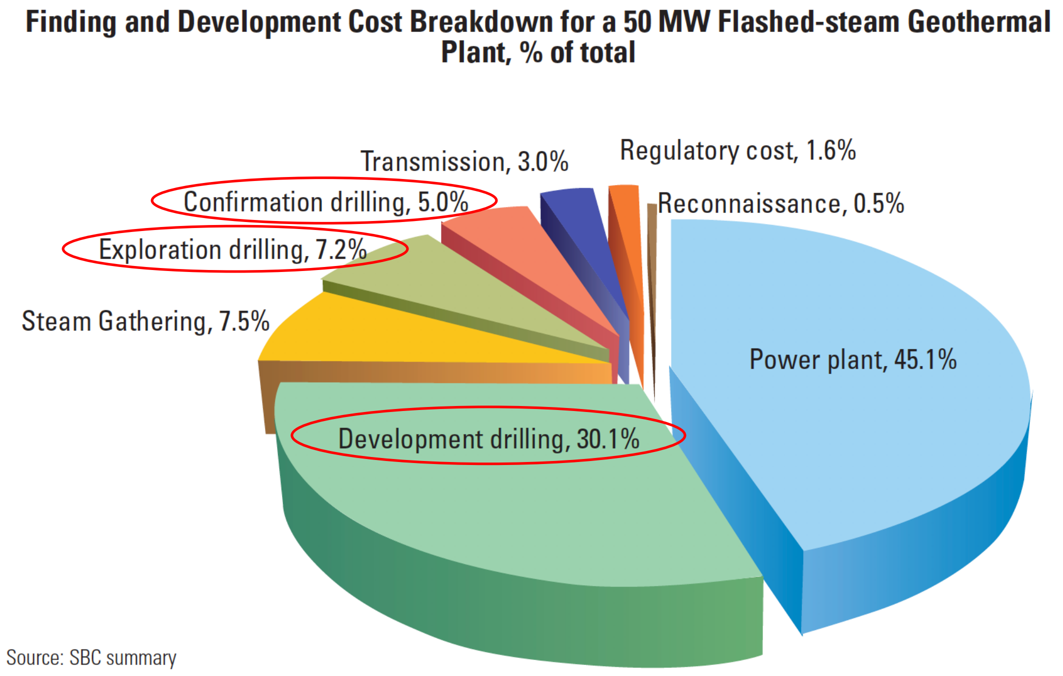
- Further challenge is to create the subsurface heat exchanger



Drilling costs and the Economics of a Geothermal Project

- Drilling operations responsible for ≈ 40% of overall costs of a geothermal project
- Two 3km-deep boreholes for geothermal energy cost up to *€15m* [1]





Source: Schlumberger Business Consulting (SBC) summary

20 or more years to break-even!

[1] *Overcoming Research Challenges for Geothermal Energy – European Commission, 2014*

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- **Conventional drilling techniques**
- Flame-jet spallation drilling
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Drilling methods

Conventional drilling methods

- Rotary drilling
  - Roller cone bits
  - PDC bits

Source: Baker Hughes – Kymera drill bit

Alternative techniques

- Hammering
- Laser drilling
- Electro-pulse drilling
- Thermal spallation drilling
- Combined methods

Conventional rotary drilling

Roller cone drilling bits

- 3 cones on bearing pins (1930s design)
- Steel teeth or tungsten carbide inserts
- Grinding and chipping action

Source: Hughes, B., 2004, "Hughes Christensen Drill Bit Catalog, "www.bakerhughes.com/news-andmedia/resources/brochures/hugheschristensen-drill-bit-catalog

Conventional rotary drilling

Source: Baker Hughes

PDC drilling bits

- Polycrystalline Diamond Bits (1980s)
- Scraping action to export material
- No rotating parts → long bit runs
  - Cost-effective in offshore drilling
- Very expensive
- Fluid circulation to prevent overheating of the matrix and diamonds
- TSP (thermally stable polycrystalline) diamond bits

Conventional rotary drilling – Costs & Risks

Drilling costs:

$$C_{d,i} = \frac{C_{b,i} + C_r\left(T_{d,i} + T_{t,i} + T_{c,i}\right)}{\Delta D_i} \qquad \left[\frac{CHF}{m}\right]$$

$C_{b,i}$: cost of the bit run i $[CHF]$
C_r: rig cost $\left[\frac{CHF}{h}\right]$
$T_{d,i}$: drilling time $[h]$
$T_{t,i}$: trip time $[h]$
$T_{c,i}$: connection time $[h]$
ΔD_i: drilled distance $[m]$

- Trip time strictly linked to drill bit wearing
- Drilling time related to rate of penetration ROP
- Problems encountered during drilling (fractures, unconsolidated zones, collapsed casing, wellbore geometry...)

Conventional drilling for Geothermal exploitation

Problems of conventional drilling

- Mechanical energy input not efficient (friction losses and vibrations)

- Geothermal systems require very deep wells
    - Hard rocks induce high drill bit wearing
    - Low rates of penetration (ROP): 1-6 m/h [1]
- Drilling costs increase <u>exponentially</u> with depth [2]

[1] Armstead H.C., Tester J.W., Heat Mining: A new source of energy, Chapman & Hall (1987)
[2] Tester J.W. et al., The future of geothermal energy: Impact of enhanced geothermal systems (EGS) on the United States in the 21st century, Massachusetts Institute of Technology 209 (2006)

Drilling methods

Conventional drilling methods

- Rotary drilling
  - Roller cone bits
  - PDC bits

Alternative techniques

- Hammering
- Laser drilling
- Electro-pulse drilling
- Thermal spallation drilling
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- …

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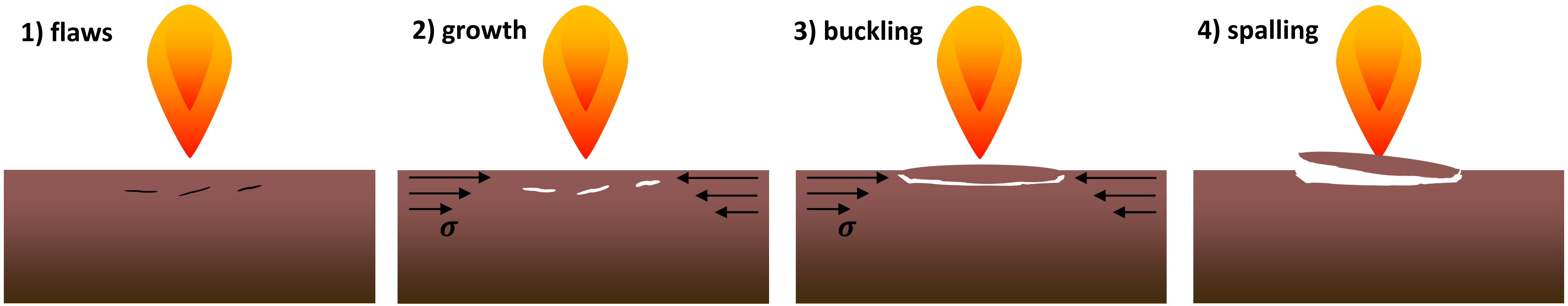
Thermal spallation drilling to reduce drilling costs

Working process:

- High heat flux from flame-jet
- Thermal stresses lead to crack initiation
- Pre-existing and induced cracks combine
- Rock-flakes ejected from surface

Features

- **Non-contact** exportation approach
- **No mechanical energy** input
- Take advantage of **hard rock properties**



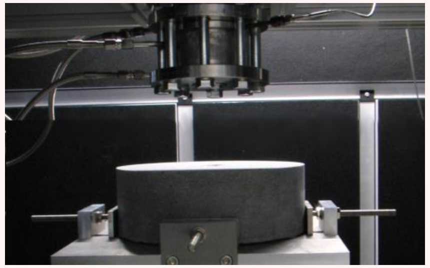

Spallation Process
Edoardo R

Experimental Facilities at ETH

Experimental setups

Ambient environment

L-ASDP



1 bar, 1400 °C, 100 kW

- Combustion process
- Heat transfer
- Penetration rate
- Parametric studies and optimization

S-ASDP-DRY

1 bar, 2500 °C, 30 kW

- Operating conditions
- Rock fracturing mechanism
- Spallability of rocks

Simulated downhole conditions

WCHB-4

500 bar, 2000 °C, 120 kW

- Heat flux measurements
- Burner design
- Process optimization
- Feasibility & application

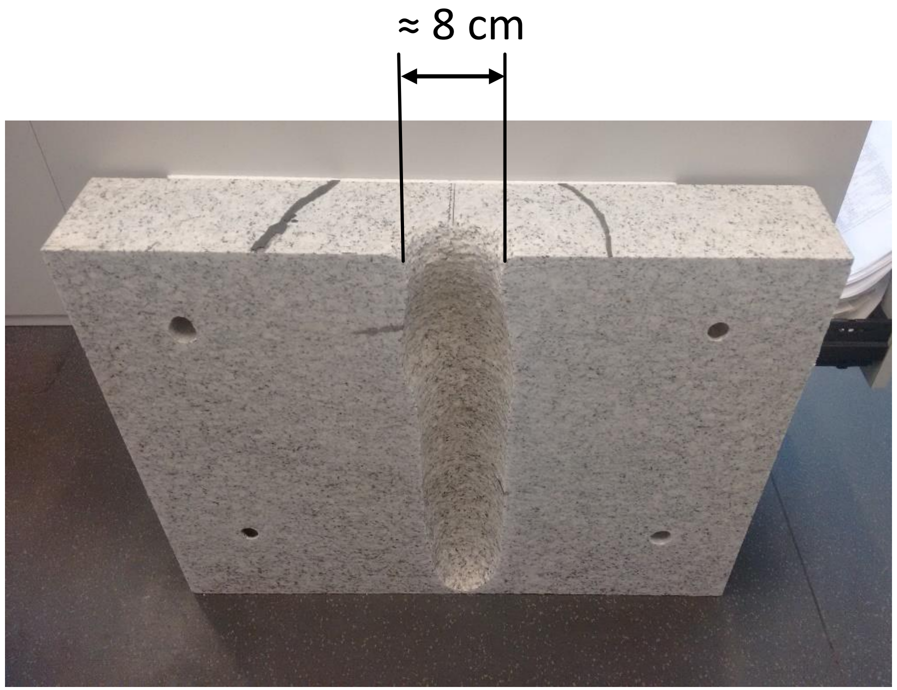
S-ASDP-WET

1 bar,
2500 °C
30 kW

- Efficient nozzle design
- Drilling under realistic conditions
- Testing of hybrid systems

Thermal spallation drilling to enhance the exploitation of deep geothermal resources

- Improved (5-10 times higher [1]) rates of penetration in hard crystalline rocks
- Non-contact method implies *no bit wearing*



[2]

[1] Tester, J.W., Herzog H.J., Chen Z., Potter R.M., 1994. Frank M.G., Prospects for Universal Geothermal Energy from Heat Mining, Science and Global Security 5, 99-121
[2] Meier, T., 2017. PhD Thesis, ETH Zürich

Thermal spallation drilling to enhance the exploitation of deep geothermal resources

- Improved (5-10 times higher [1]) rates of penetration in hard crystalline rocks
- Non-contact method implies *no bit wearing*
- *Efficient energy transport* to the rock

Input: Combustion gases

Output: Heat power

→ **No friction and mechanical inefficiencies**
→ **Lower input power needed**

[1] Tester, J.W., Herzog H.J., Chen Z., Potter R.M., 1994. Frank M.G., Prospects for Universal Geothermal Energy from Heat Mining, Science and Global Security 5, 99-121
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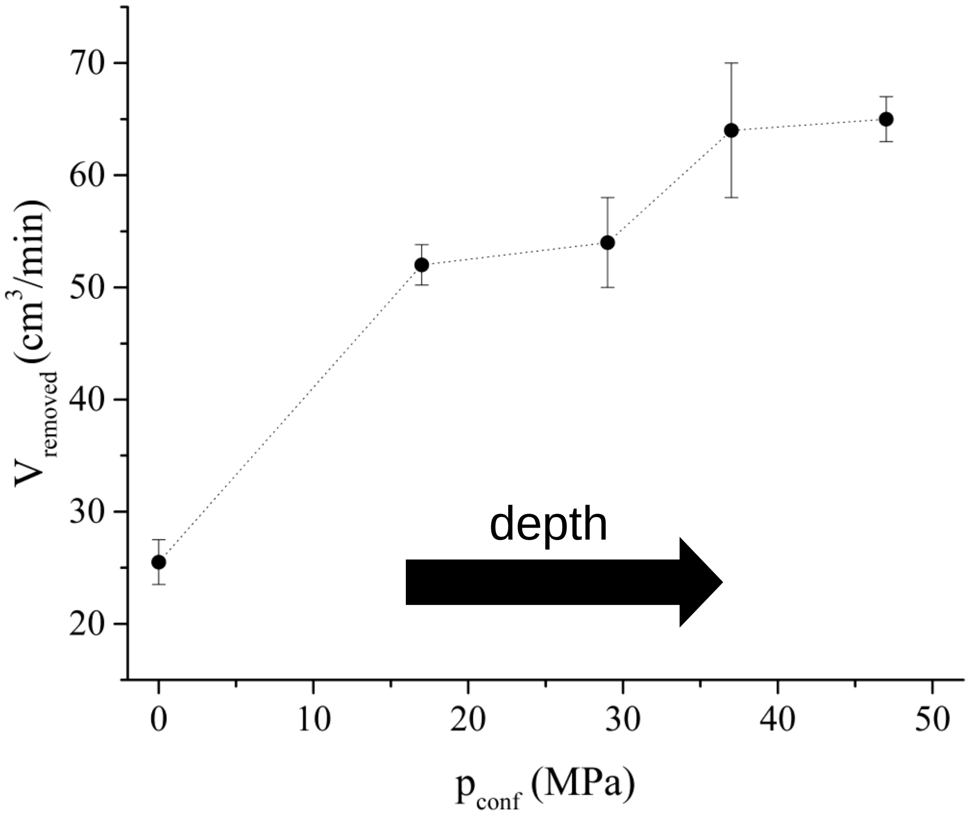
Thermal spallation drilling to enhance the exploitation of deep geothermal resources

- Improved (5-10 times higher [1]) rates of penetration in hard crystalline rocks
- Non-contact method implies *no bit wearing*
- *Efficient energy transport* to the rock
- Proven to work better for greater depths [3]

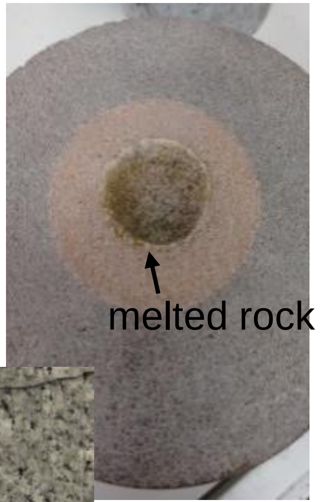


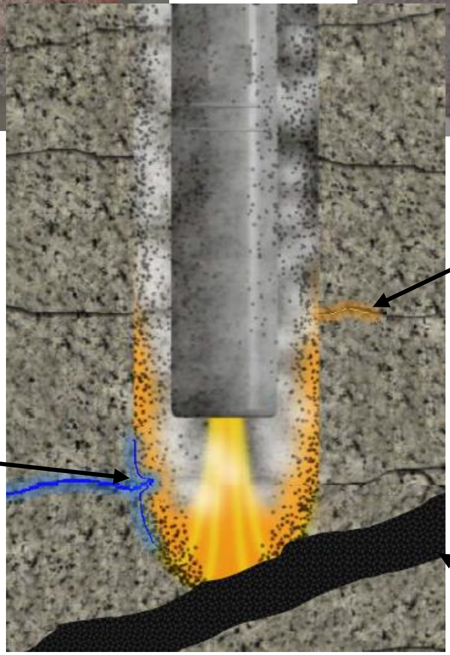
[1] Tester, J.W., Herzog H.J., Chen Z., Potter R.M., 1994. Frank M.G., Prospects for Universal Geothermal Energy from Heat Mining, Science and Global Security 5, 99-121
[2] Meier, T., 2017. PhD Thesis, ETH Zürich
[3] Höser, D., 2016. Flame-jet assisted drilling technology. PhD Thesis No. 23896, ETH Zürich

Thermal spallation drilling to enhance the exploitation of deep geothermal resources

Problems of flame-jet spallation drilling

- Poor control of borehole shape
- Not all rock types are spallable (soft, non-quartzitic rocks)
- Discontinuities and fractures relieve the thermal stress field





→ ***Not applicable in the real world as a standalone technology***

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- **Combined thermo-mechanical drilling**
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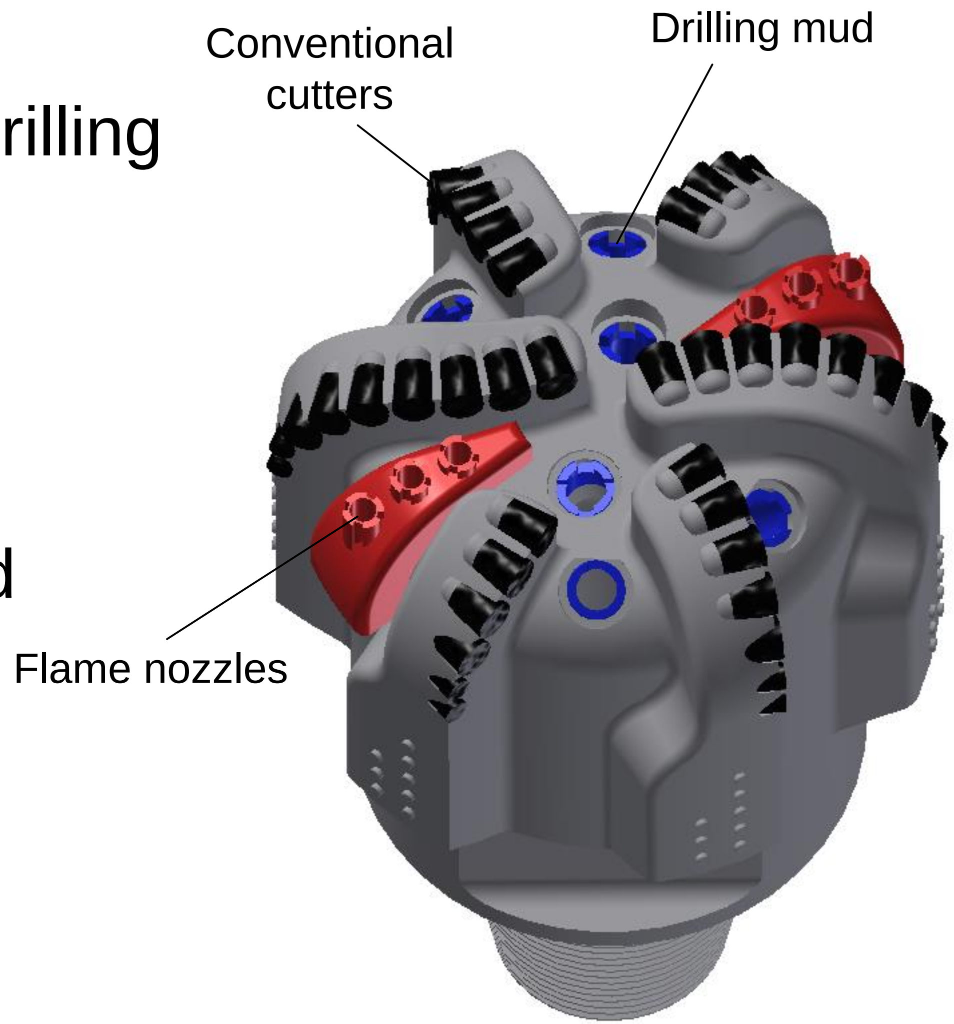
Combined Thermo-Mechanical drilling method - Concept

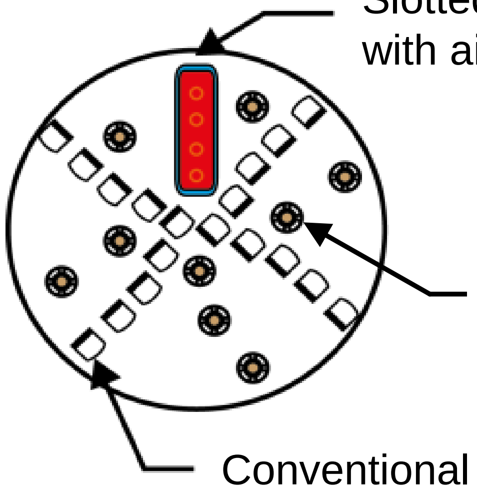
- Combine flame-jet spallation & mechanical drilling
- Take advantage of both technologies
- Tackle limitations of spallation drilling method
- Allow an easier practical applicability



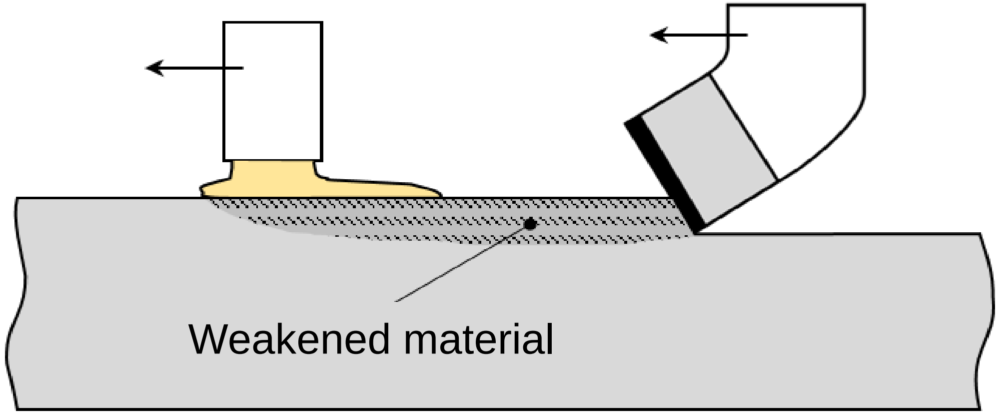
Why a combined Thermo-Mechanical method is convenient?

Drilling modes:

- ***Pure spallation* drilling**
  - When favourable rock properties are encountered



- **Flame-jets as *thermal assistance***
  - Weakening of rock material
  - All rock types can be drilled
  - Perfect control of borehole shape



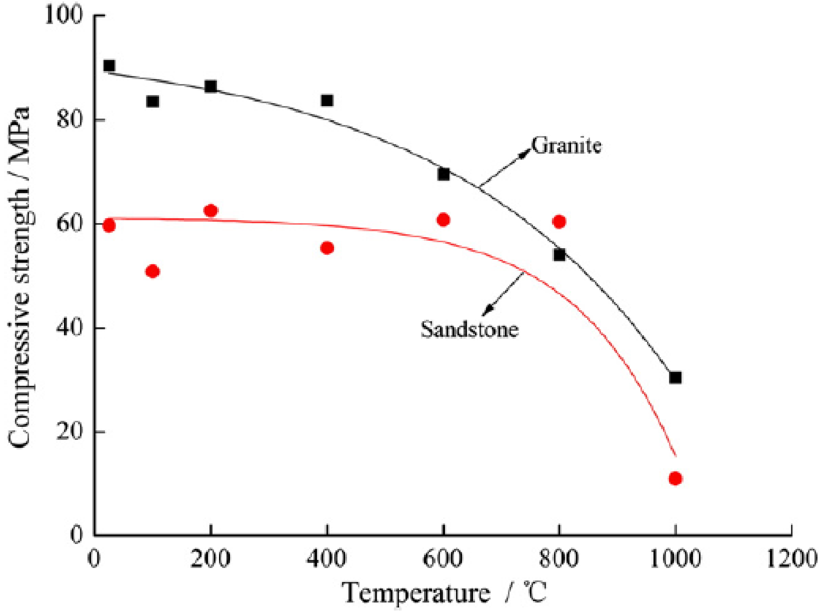
Motivation – High Temperature Effects on Rocks

Effects of high temperature:

- Differential expansion of rock's minerals [1]
- Water evaporation [2]
- Damage of grain's boundaries [3]

Involved mechanical and physical properties:

- Peak stress and strain
- Young's modulus
- P-wave propagation velocity
- Porosity
- Permeability
- …



From: Liu S, Xu J, 2012. Engineering Geology 185, 63-70

But: Will a flame induce the same effects?

[1] Chen Y-L., Ni J., Shao W., Azzam R., 2012. International Journal of Rock Mechanics & Mining Sciences 56, 62-66.
[2] Zhang W., Sun Q., Hao S., Geng J., Lv C., 2016. Applied Thermal Engineering 98, 1297-1304.
[3] Yavuz H., Demirdag S., Caran S., 2010. International Journal of Rock Mechanics & Mining Sciences 47, 94-103

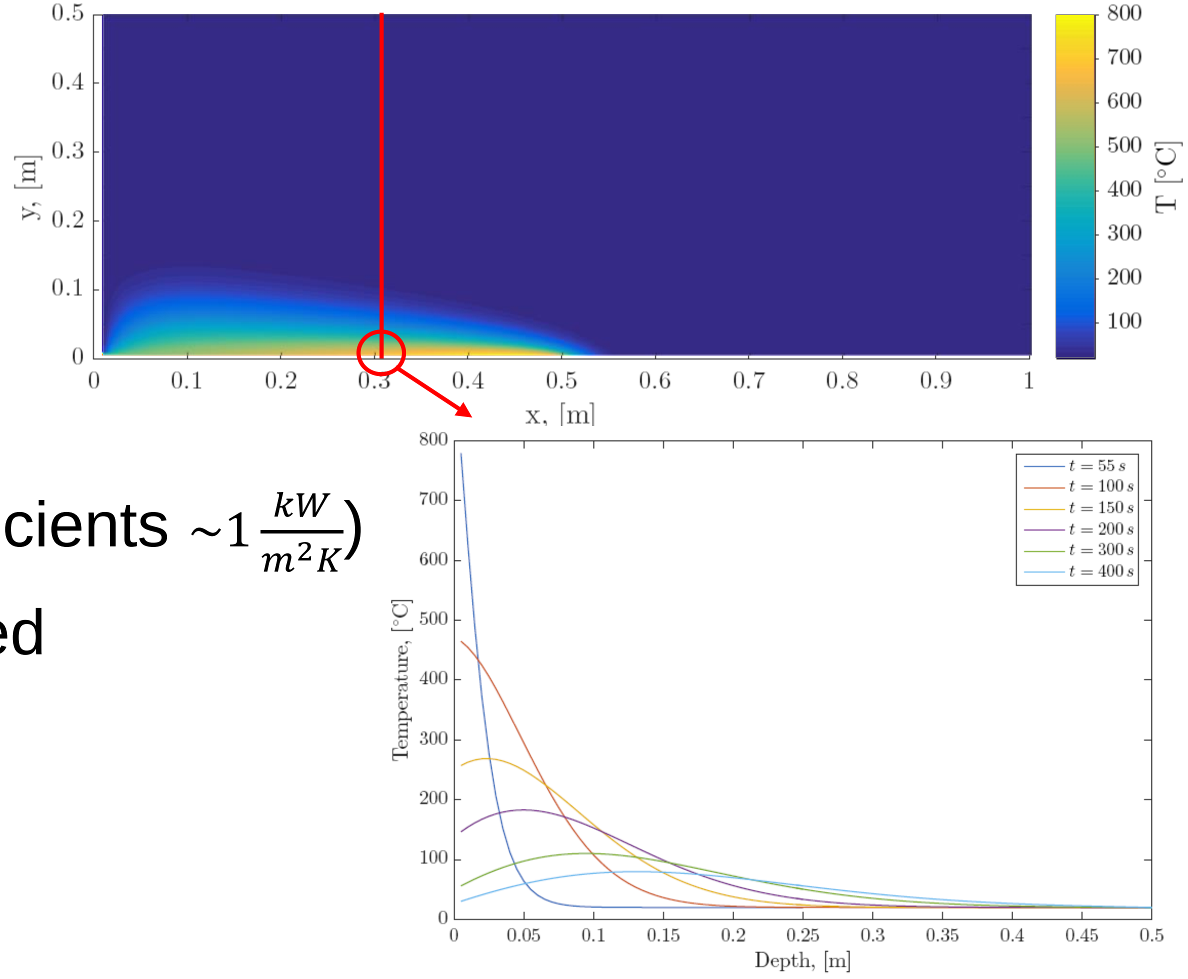
Why flame thermal treatments are important?

Oven thermal treatments

- Slow process (low heating rates)
- Spatially more homogeneous

Flame heating

- Fast process (high heat transfer coefficients $\sim 1 \frac{kW}{m^2 K}$)
- Shallower ($\kappa_{rock} \sim 1 \cdot 10^{-6} \frac{m^2}{s}$) and localized



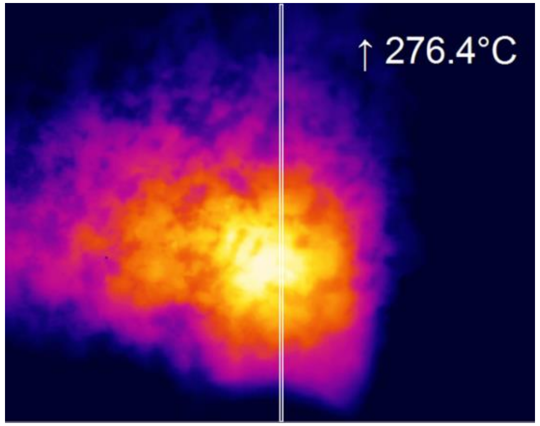
κ: thermal diffusivity

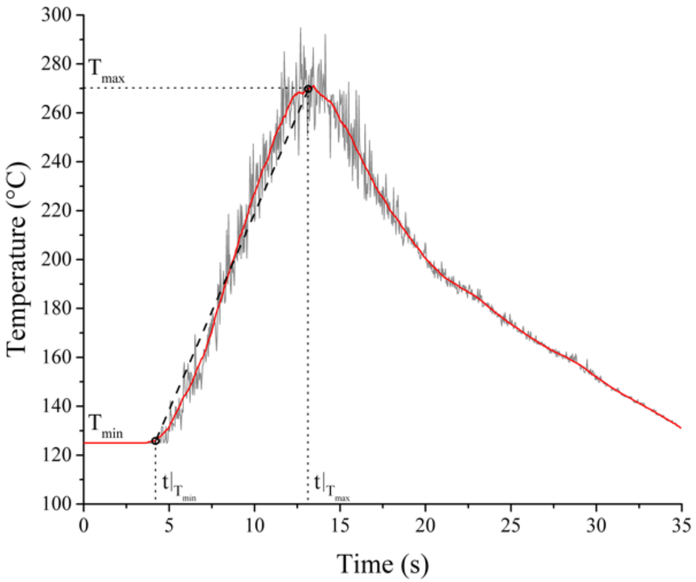
Flame thermal treatments – Experiments

- **Operating conditions**
  - Maximum temperature
  - Heating rate
  - Confinement pressure

Weakening of the material

- Compressive strength (scratch test)





$$\begin{cases} T_{max} = \max(T(t)) \\ \dot{T} = \dfrac{T_{max} - T_{min}}{\Delta t} \end{cases}$$

Flame thermal treatments – Experiments

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  - Maximum temperature
  - Heating rate
  - Confinement pressure

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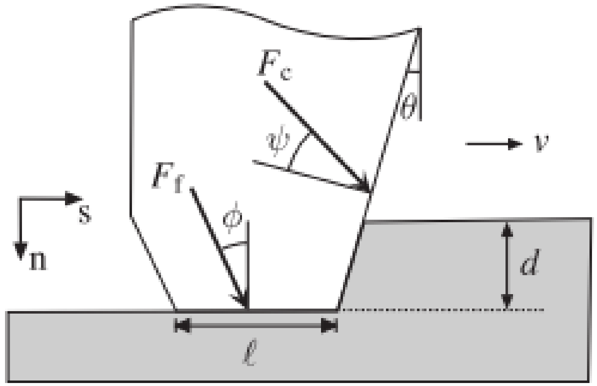
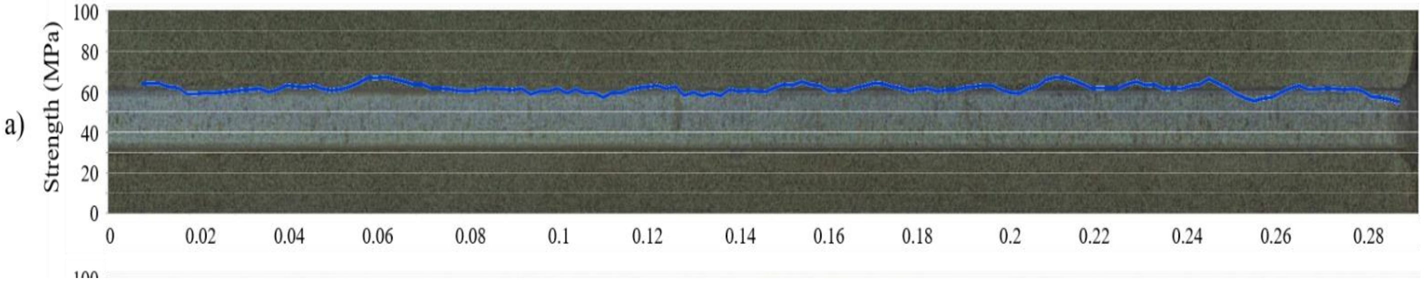
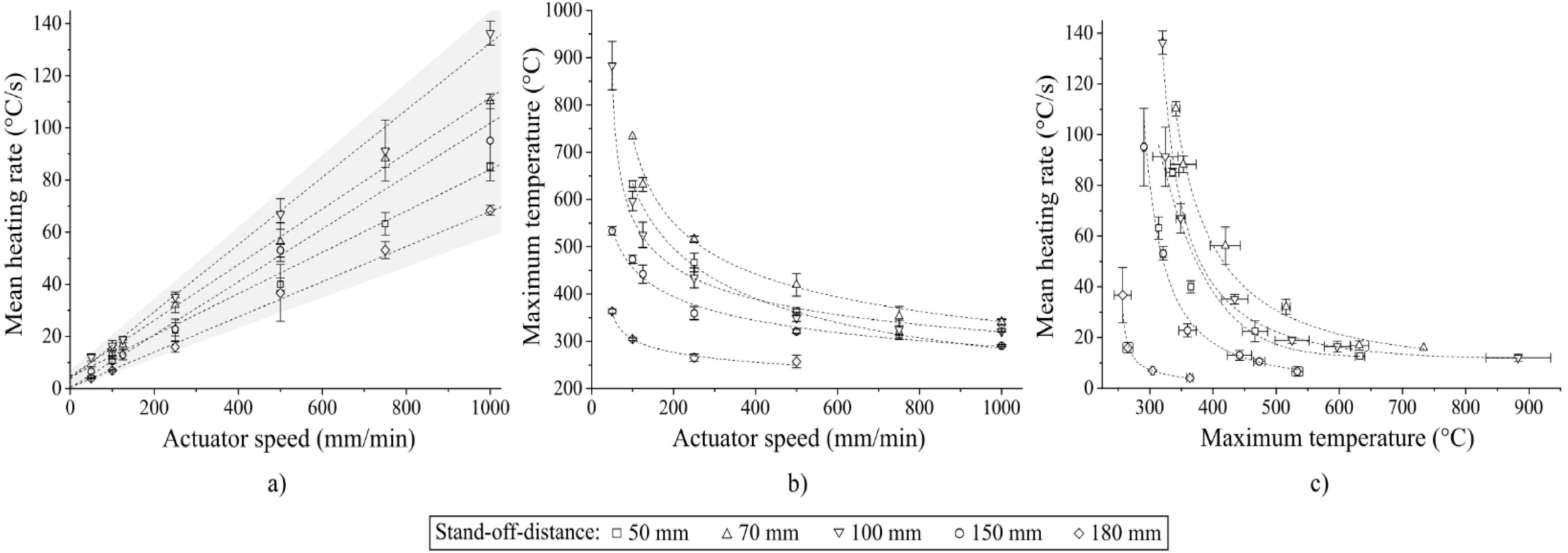




Flame thermal treatments – Results

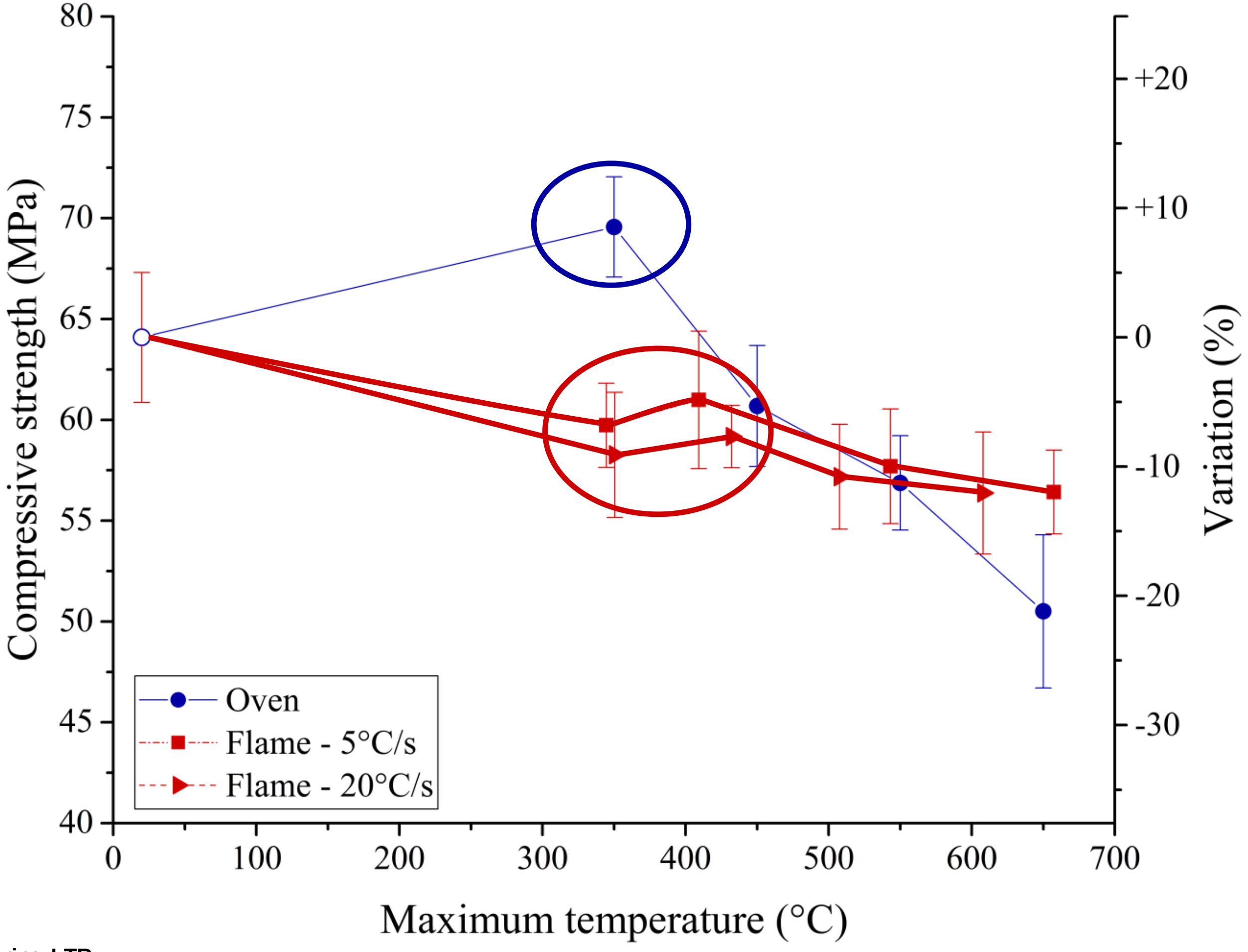
Heating rate and surface temperature at different operating conditions



Flame thermal treatments – Results

Material weakening – strength

- No hardening effects after flame treatments



- Monotonous decrease of strength

Flame thermal treatments – Results

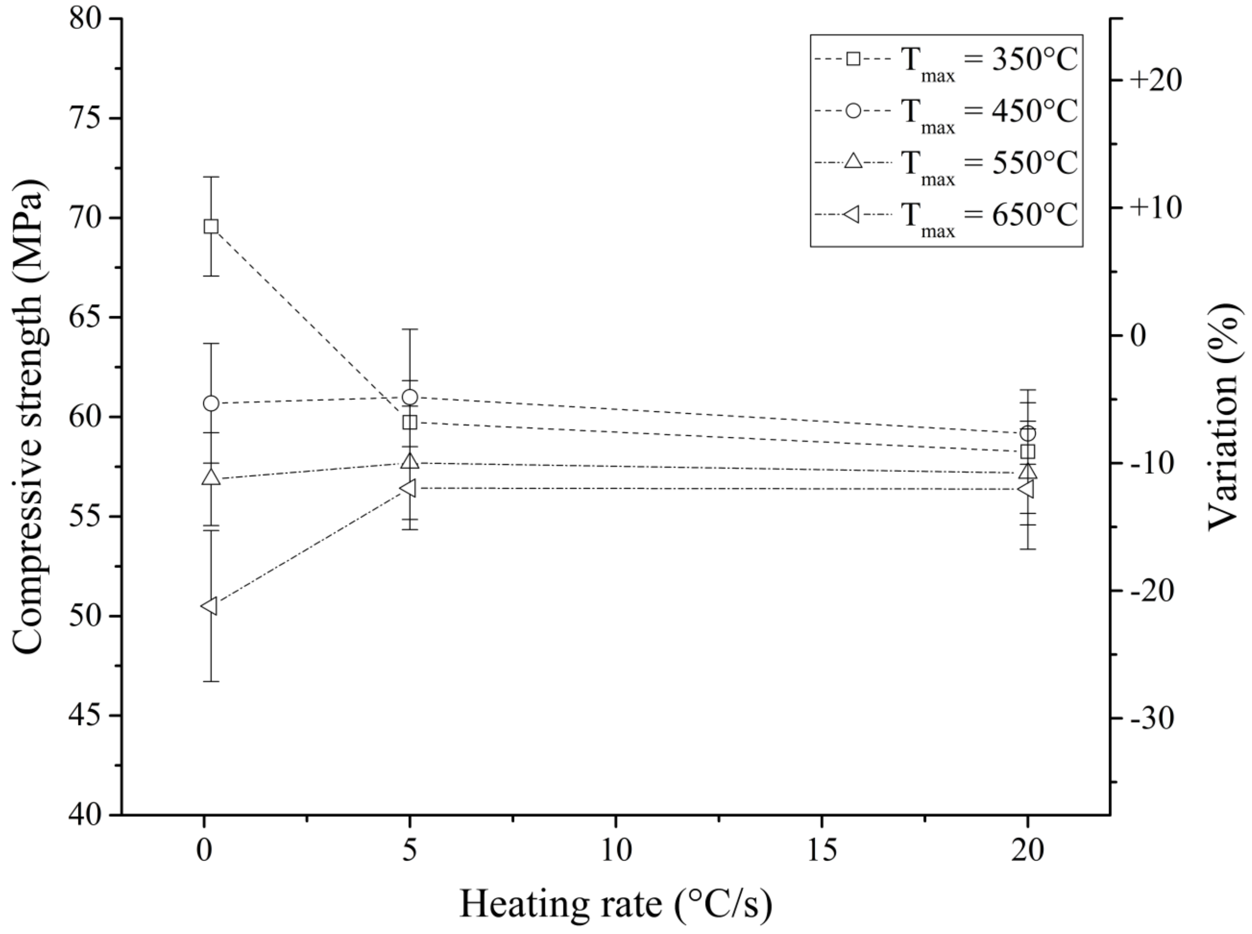
Strength minimization:

- T_{max} < 500 °C → Flame → high heating rates

  → **High rotational drill head speeds**

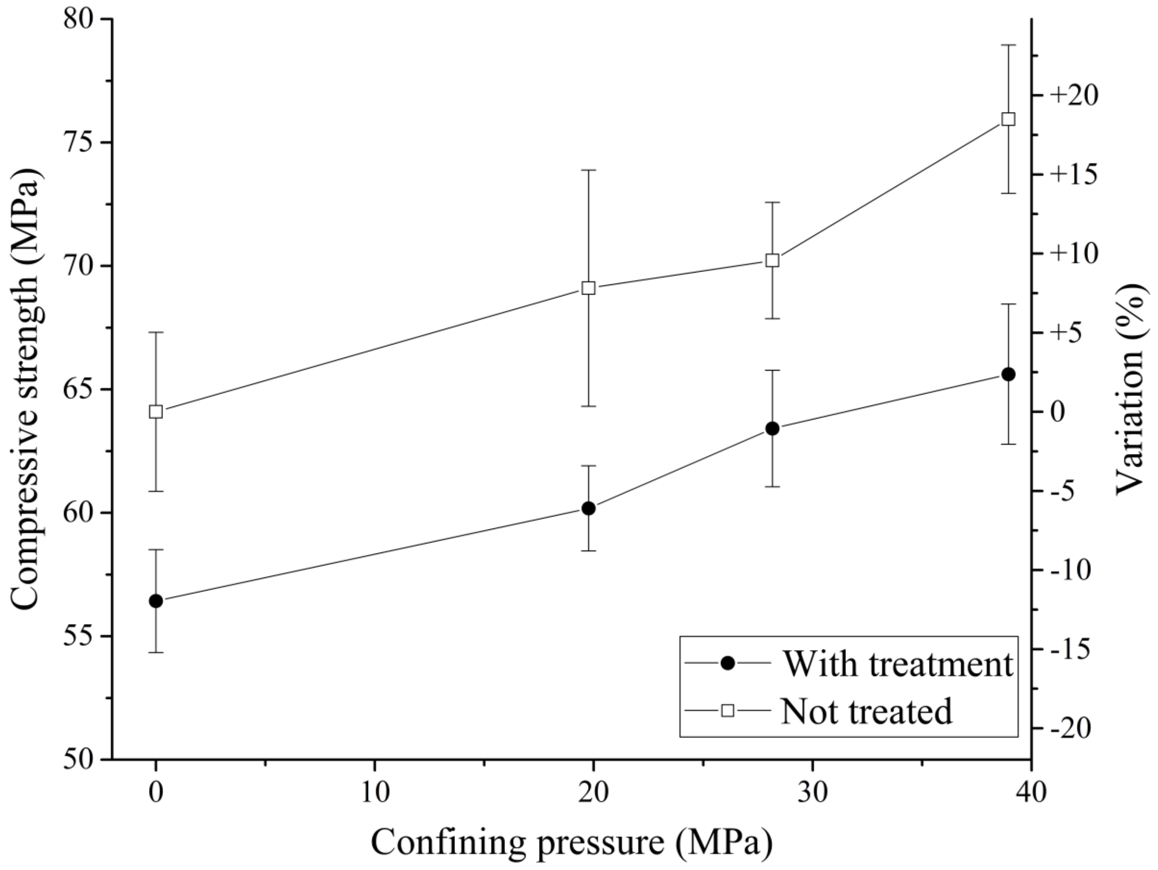
- T_{max} > 500 °C → Oven → low heating rates

  → **Low rotational drill head speeds**

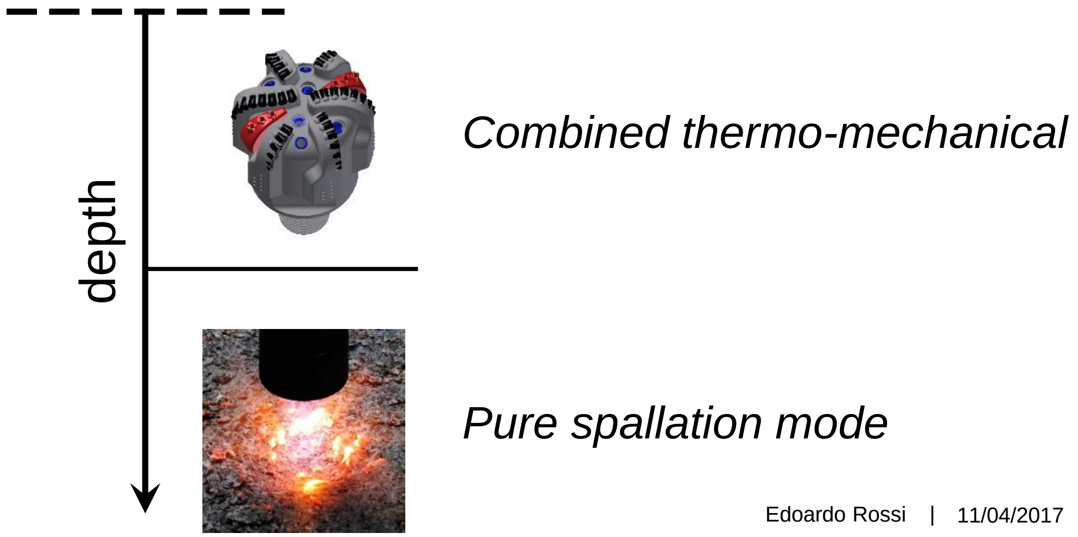


Flame thermal treatments – Results

Confinement & treatment effects – strength



- Recovery of non-treated material strength with increasing confinement
- Confinement enhances pure spallation



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Combined thermo-mechanical drilling

Advantages:

- Possibility to drill through all rock types with better ROP
- Reduction of weight on bit and thus drill bit wearing
- Boost deep drilling by a cost-effective drilling solution

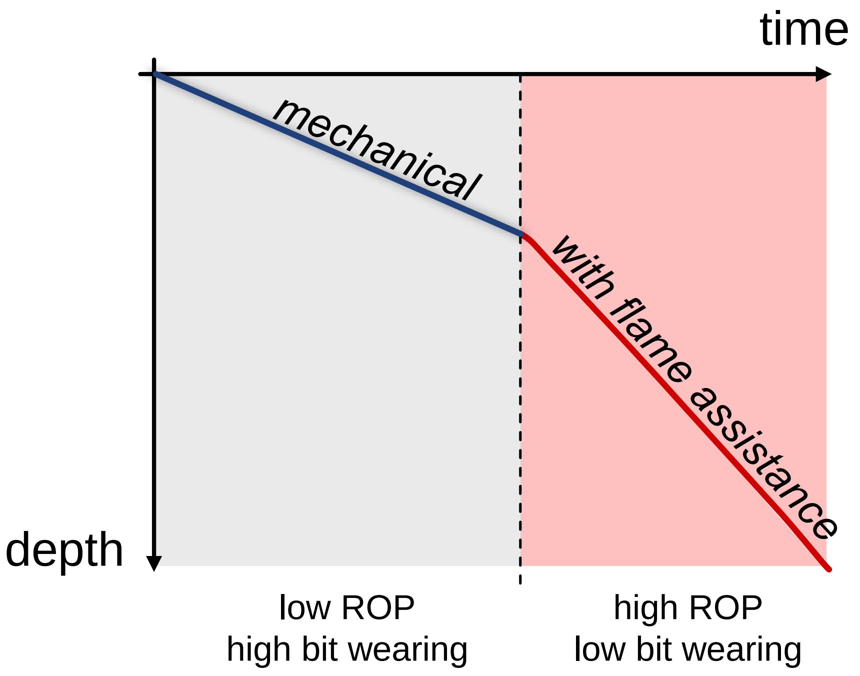
Challenges:

- Protect cutters from high flame temperatures (>1000°C)
- Enhance flame heat transfer in aqueous environment
- Downhole fuel storage

Combined drilling technology in the field

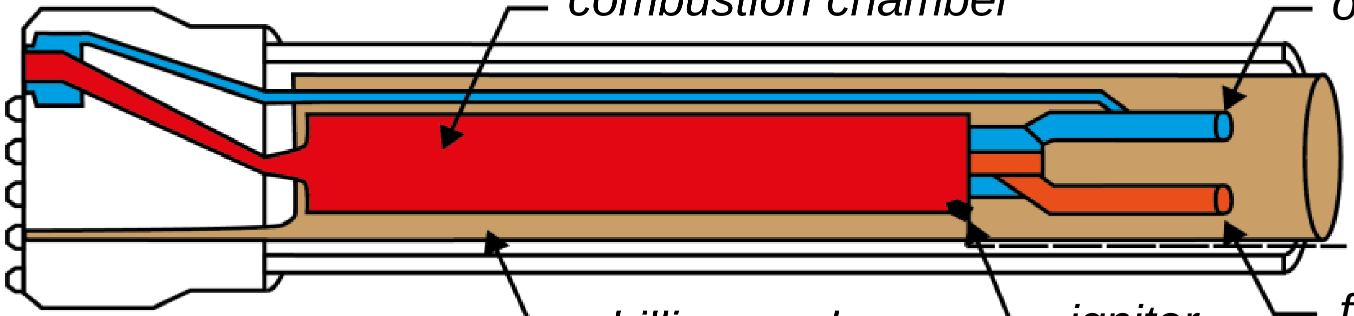
Field test planned for this year - Motivation

- Demonstrate practical applicability of the technology
- Proof of concept
- Highlight improvement in rate of penetration
  - Decreased weight on bit
- Deal with real application challenges



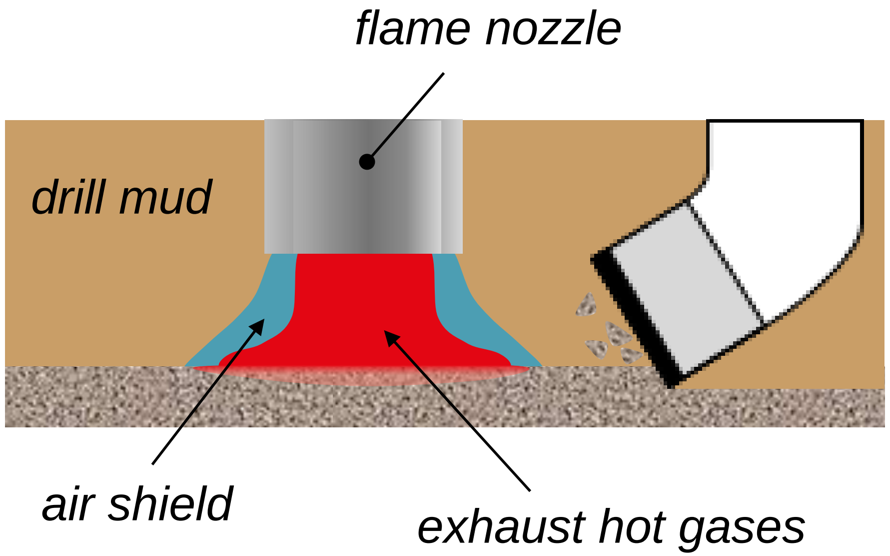
Thermo-mechanical drill head

- Air and methane as combustion fluids
- Drilling mud also used to cool down the combustion chamber
- Air shielding implemented to prevent entrainment phenomena



Kant, M., T. Meier, E. Rossi, M. Schuler, D. Becker, D. Höser, and P. Rudolf von Rohr, 2017. Thermal spallation drilling - an alternative drilling technology for hard rock drilling, European Oil and Gas Magazine

Combined drilling: air shielded–flame in aqueous environment



- Drill mud necessary for circulation of cuttings
- Maximize heat transfer to rock surface
- Avoid high temperatures on cutter material
- Modeling needed

→ Rotating speed

→ Number of cutters and flame nozzles

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Bundesamt für Energie BFE
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Thank you for your attention!