Rock strengthening upon heating FACT or MYTH?

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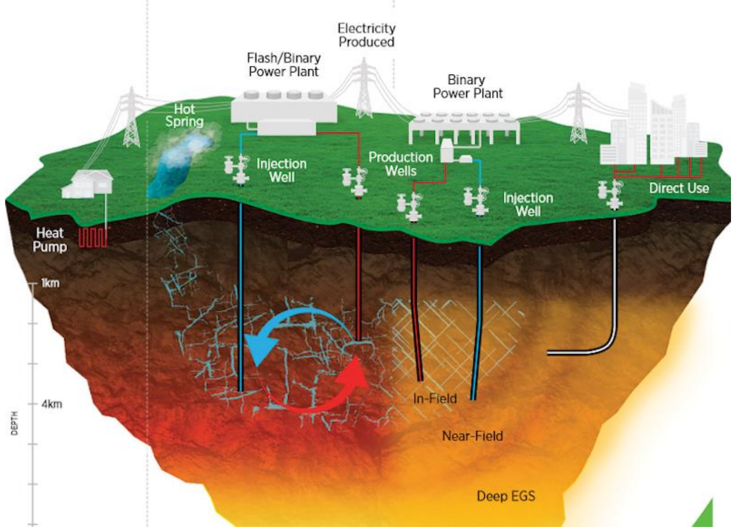
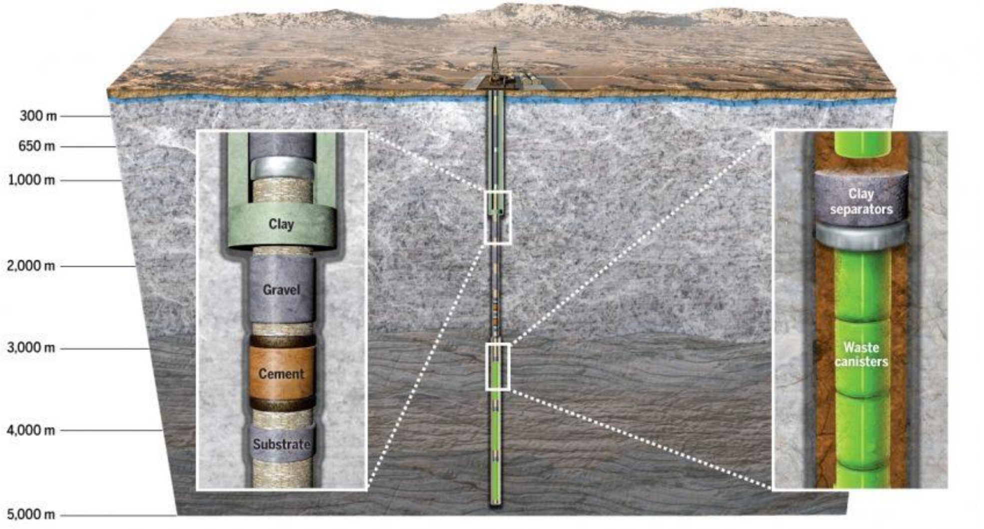
Deep underground rock engineering

Deep underground mining

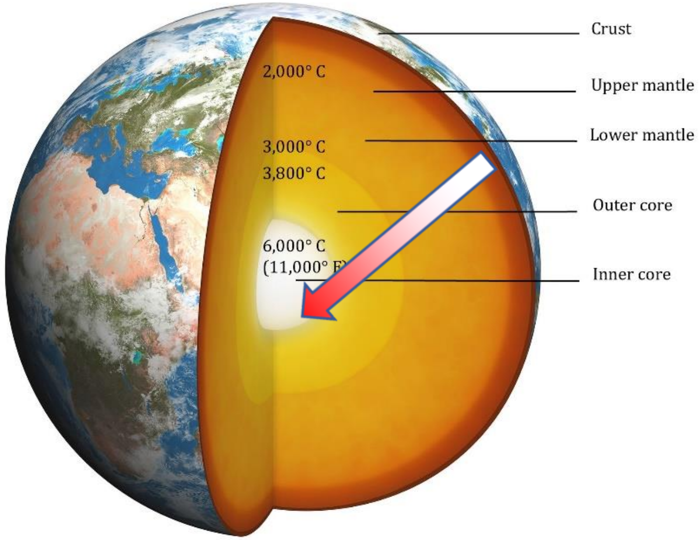


Extraction of geothermal energy



Deep burial of nuclear waste

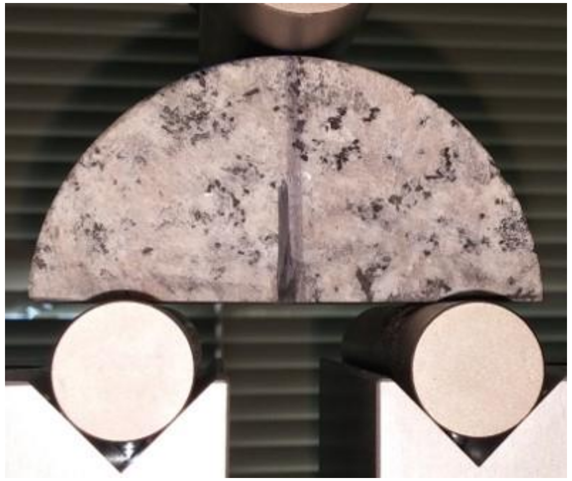
(online images)



Temperature ↑ ⇒ Rock strength

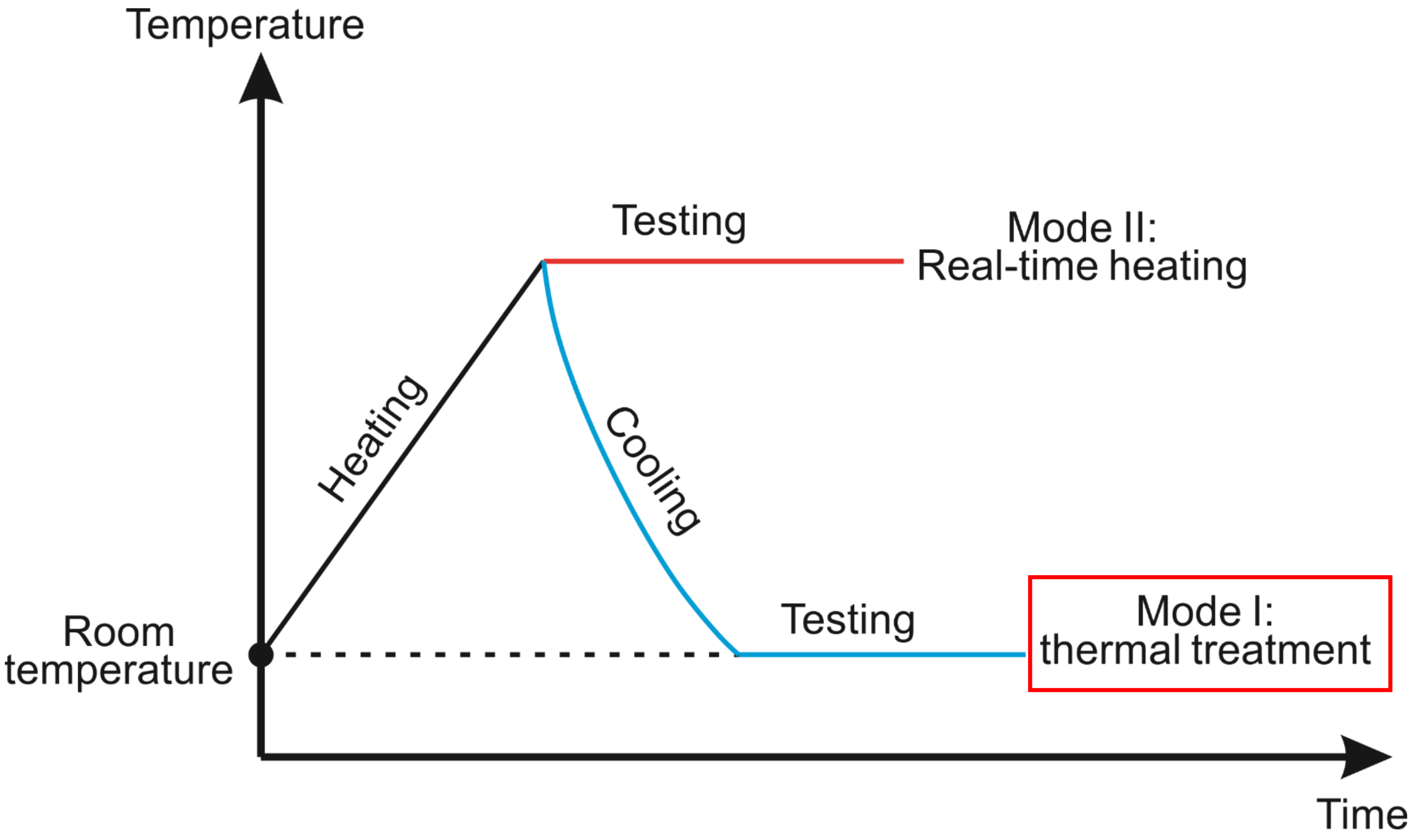
Rock strength measured in rock-mechanics laboratory

Uniaxial (left) and triaxial (right) compressive strength



Indirect tensile strength

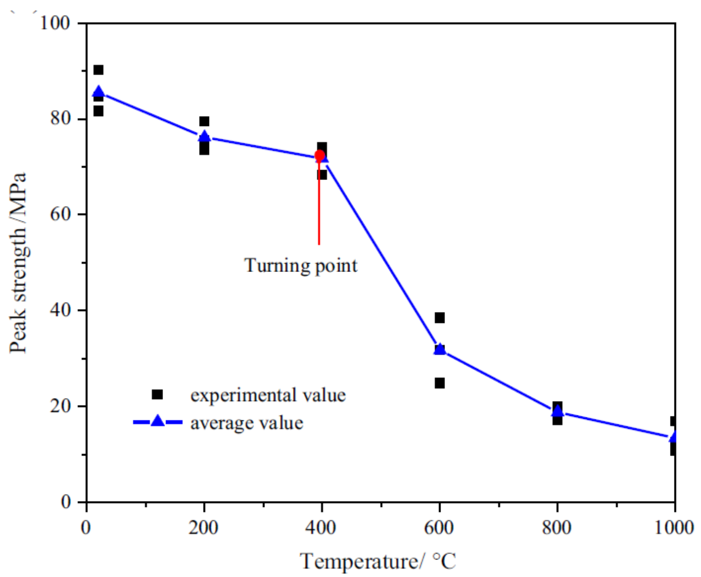
Two modes of heating and strength testing



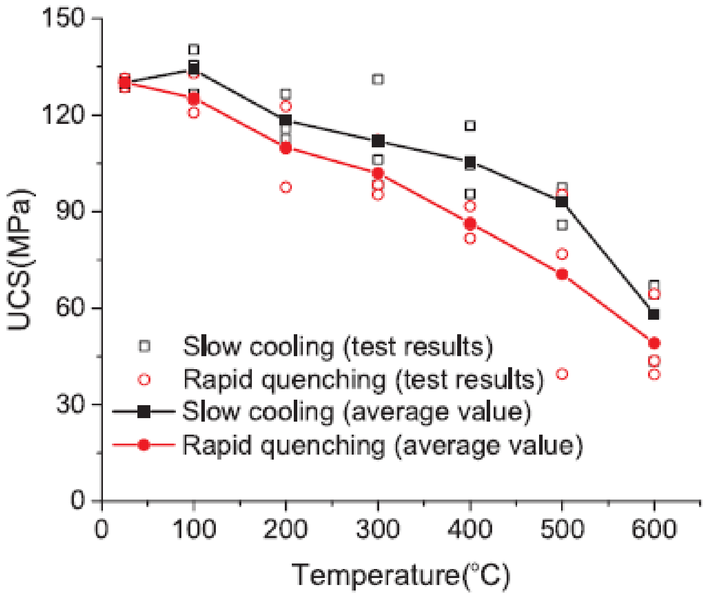
Outline

- Background (👌)
- Laboratory test results – thermal weakening
- Laboratory test results – thermal strengthening
- In quest of thermal strengthening
- Lessons learnt

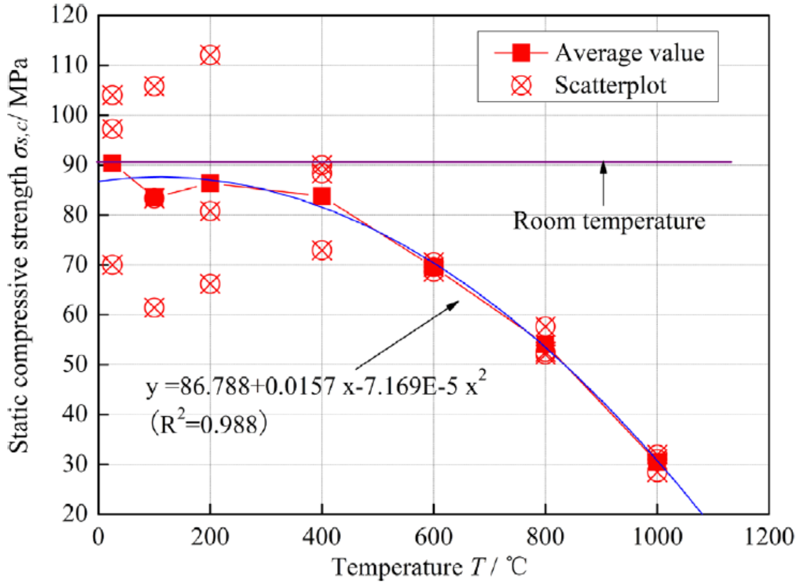
Uniaxial compressive strength VS temperature suggesting thermal weakening



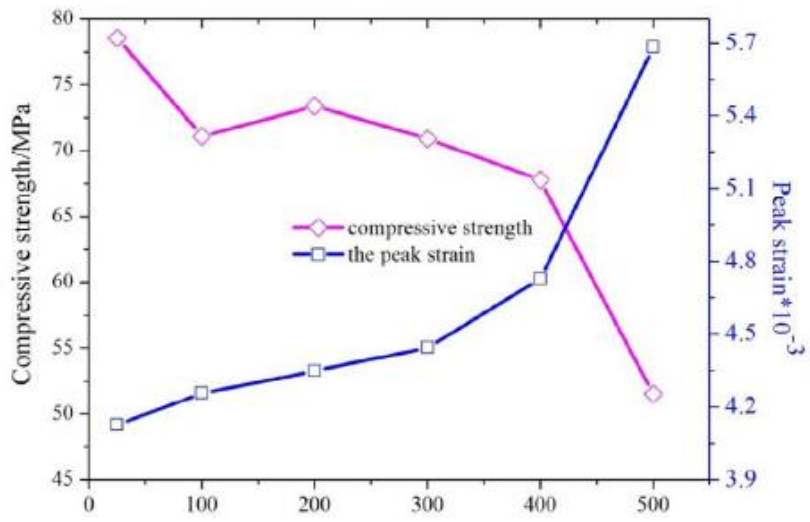
Granite (Sun et al., 2015)



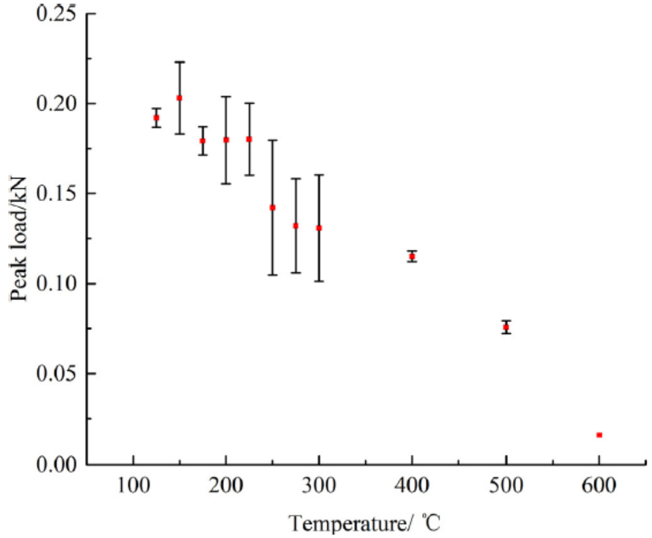
Granite (Jin et al., 2019)



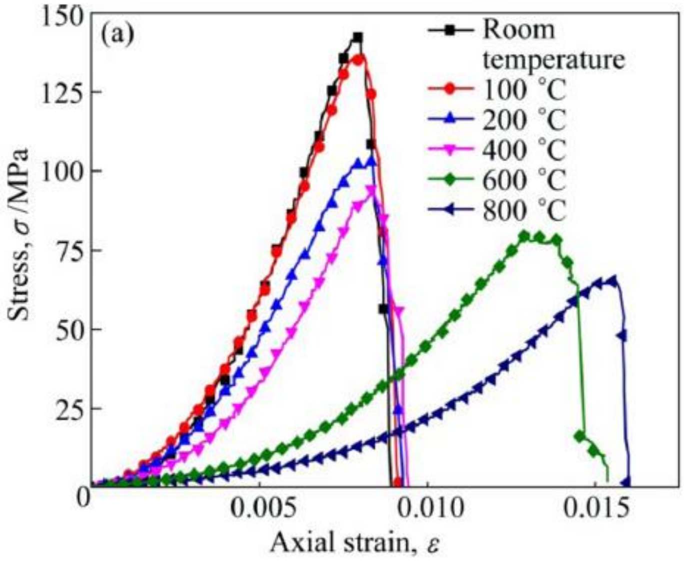
Biotite granite (Liu et al., 2014)



Sandstone (Zhang et al., 2016)

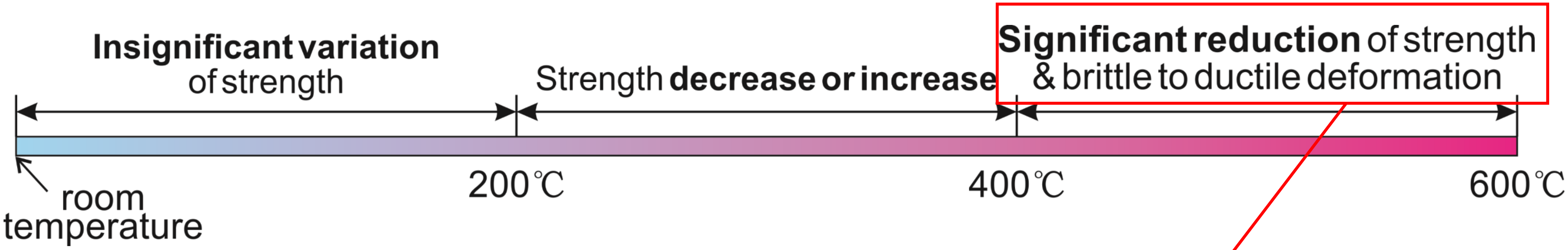


Beishan granite (Zuo et al., 2017)



Granite (Yin et al., 2016)

General results from laboratory studies:



A consensus : **Rock would be WEAKENED upon heating** by

(1) the extension of existing cracks or formation of new **microcracks**

(2) **structural collapse** of minerals due to the enhanced thermal reactions

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- Laboratory test results – thermal strengthening
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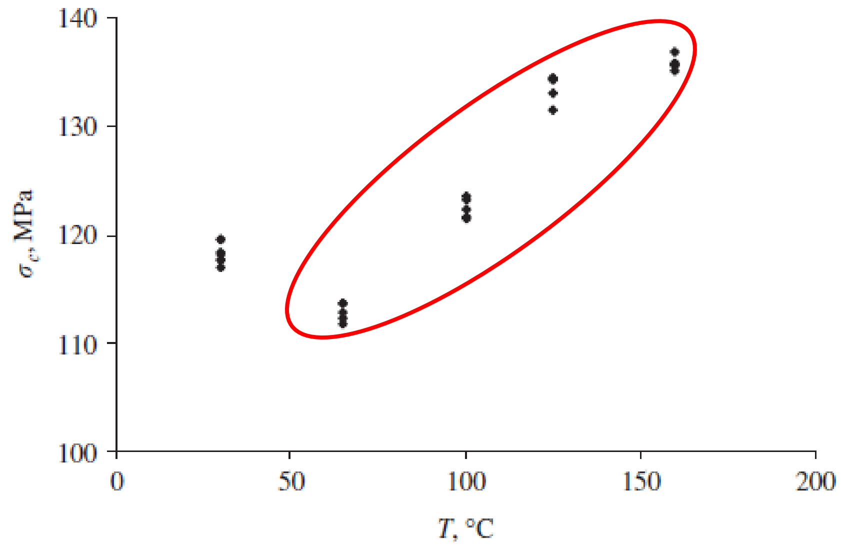
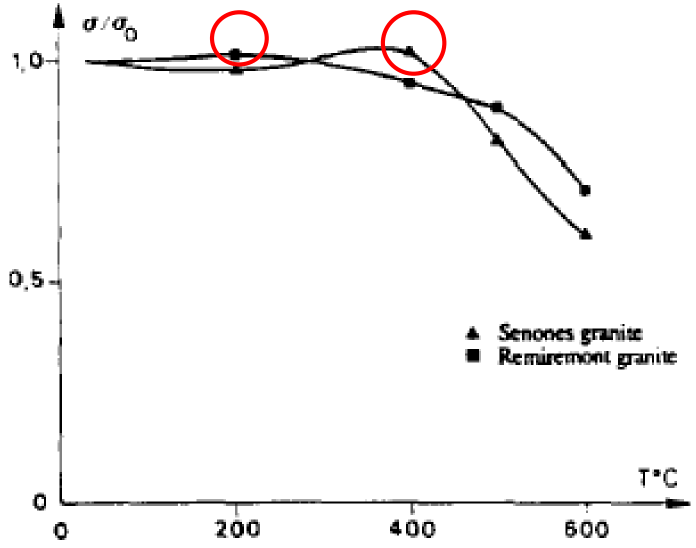
Decrease of rock porosity and/or permeability with increased temperature suggesting **rock strengthening** **(Wong et al., 2020)**

Rock type/name	Temperature increase	Porosity/permeability change	Reference
Granite	25 to 300°C	0.828% to 0.685%*	Yang et al., 2017a
Sandstone	25 to 400°C	Little variation between 7.78% and 7.89%	Zhang et al., 2017a
Sandstone	25, 200, 400°C	2 MPa: 2.07, 1.84, 1.71 ($\times 10^{-15}$ m^2) 5MPa: 5.79, 5.30, 5.15 ($\times 10^{-15}$ m^2) 8MPa: 4.48, 4.28, 4.06 ($\times 10^{-15}$ m^2)	Ding et al., 2016b
Sandstone	25, 100, 200°C	5.33, 4.46, 4.64 ($\times 10^{-11}$ m^2)	Yang et al., 2017b
Dholpur Red Sandstone	50, 100, 150, 200°C	10.84%, 11.08%, 10.61%, 6.68%	Sirdesai et al., 2017
Postaer Sandstone	RT, 150, 300°C	22.9%, 22.7%, 22.4%	Hajpál, 2002
Denizli Travertine	RT, 100, 200°C	3.42%, 2.22%, 2.18%	Yavuz et al., 2010
Granite	25, 50, 100°C	0.88%, 0.75%, 0.74%	Sun et al., 2015
Granite	20, 80, 200°C	1, 0.51, 0.39	Ge´raud et al., 1992
Luhui Granite	RT, 50, 100, 150, 200°C	0.90, 0.92, 1.20, 1.60, 1.16 ($\times 10^{-6}$ m^2)	Zhao et al., 2017
Claystone	RT, 80, 150, 200°C	6.54 %, 8.17%, 7.71%. 7.24%	Tian et al., 2014

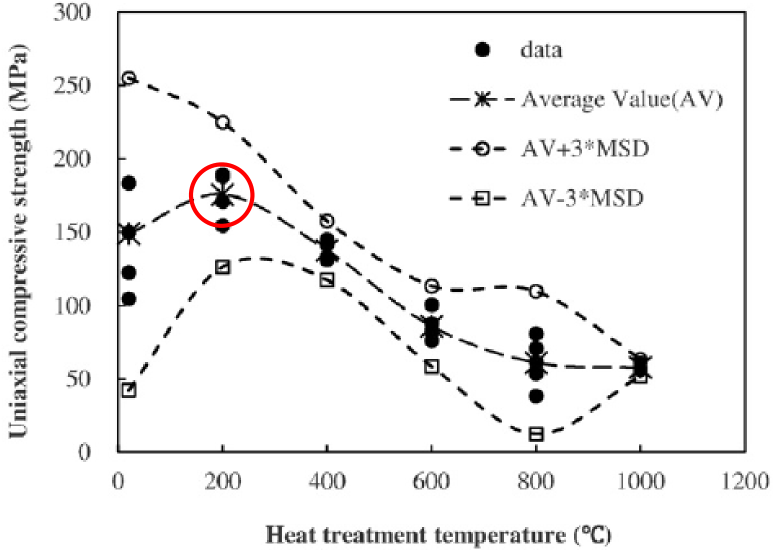
Uniaxial compressive strength VS temperature suggesting thermal strengthening



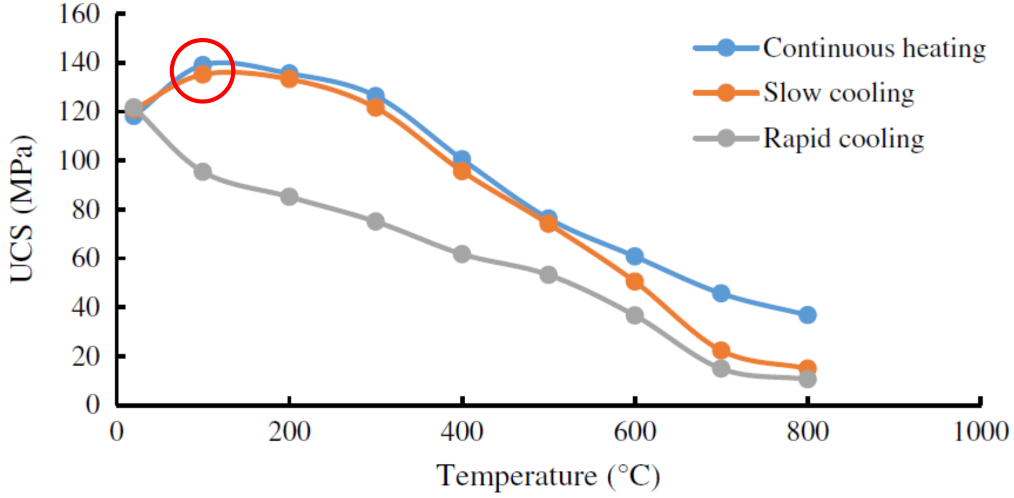
Indian granite (Dwivedi et al., 2008)



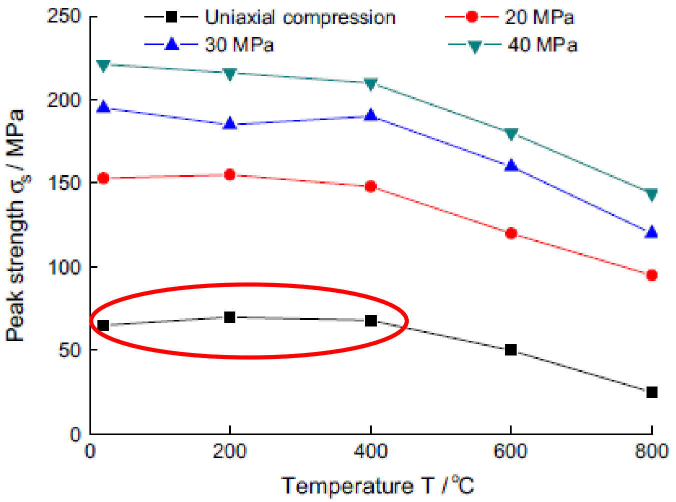
(Homand-Etienne and Houpert et al., 1989)



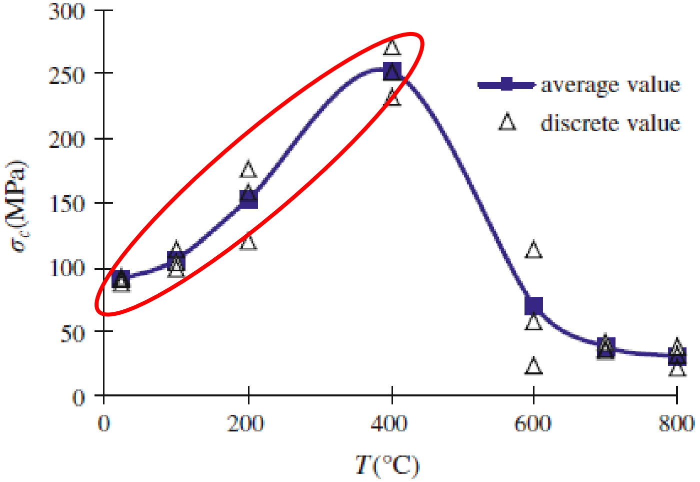
Granite (Chen et al., 2017)
MSD = mean-square deviation



Australian Strathbogie granite (Kumari et al., 2017)



Sandstone (Ding et al., 2016)



Mudstone (Zhang et al., 2014)

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How deep can we reach?

- the **deepest tunnel** in the world - *Gotthard Base Tunnel*: **~ 2400 m**
- the **deepest oil well** in Asian land - *Tarim Oilfield*: **8882 m**

thermal gradient: 25 to 30 °C/km

400°C → **17 km**

Deeply-buried rock temperature ：

- *Enhanced Geothermal System in Fenton Hill* in the United States (**3500 m** deep): **234 ^{o}C**
- after many years of strong radioactivity of nuclear wastes under **1000 m: <165 °C**

Rarely exceeds 300°C; the much more relevant temperatures: **below 200 °C**

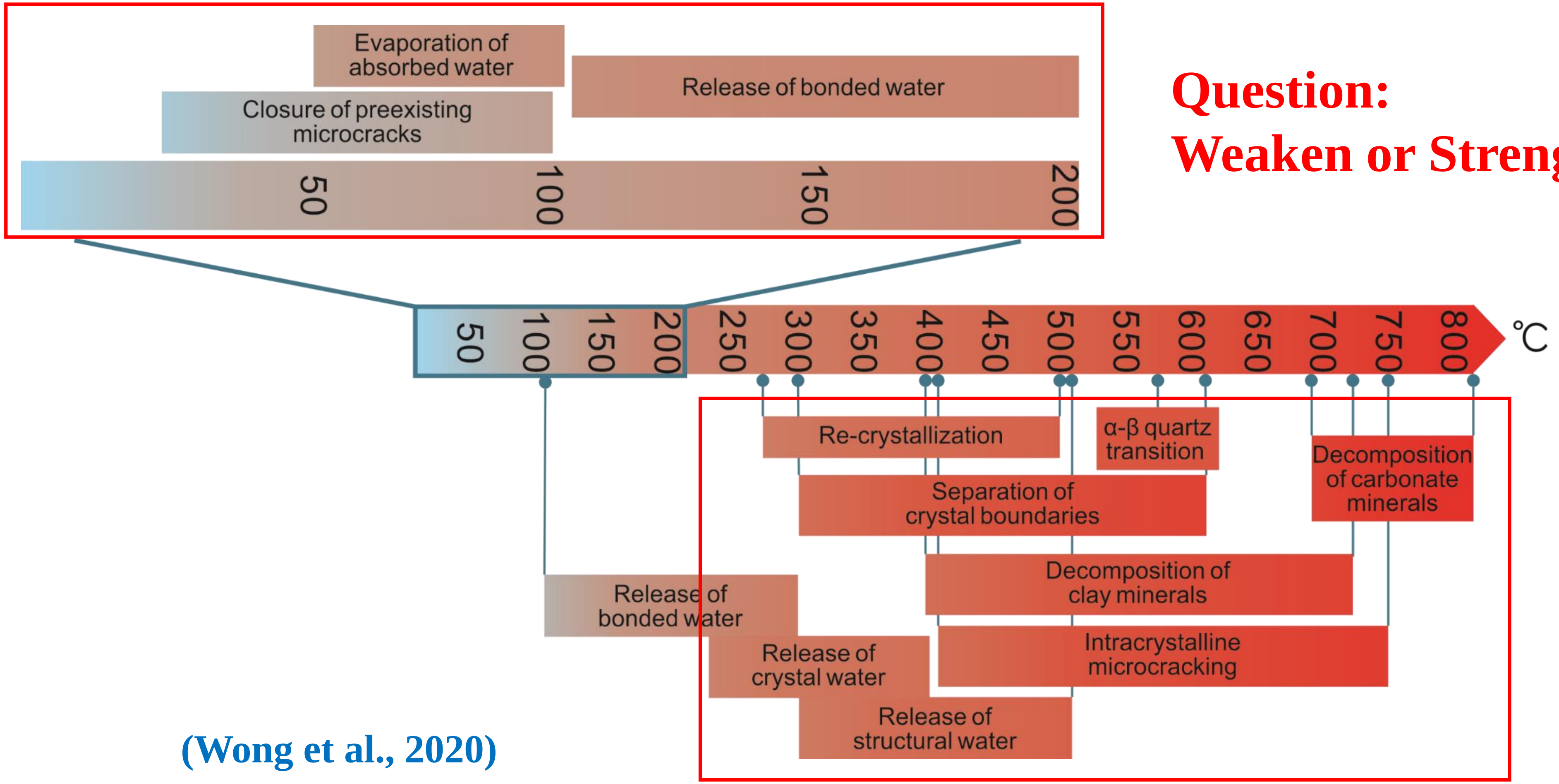
the mild temperature range

Major changes in rock at elevated temperatures

In the mild temperature range (25-200 °C)

Limited chemical reactions

Question:
Weaken or Strengthen??



(Wong et al., 2020)

Weakening mechanisms at high temperatures

Relevant findings suggesting rock strengthening in a mild temperature regime

Temperature **increase** → Pore structure change → Porosity/permeability **increase** → Rock **weakening**

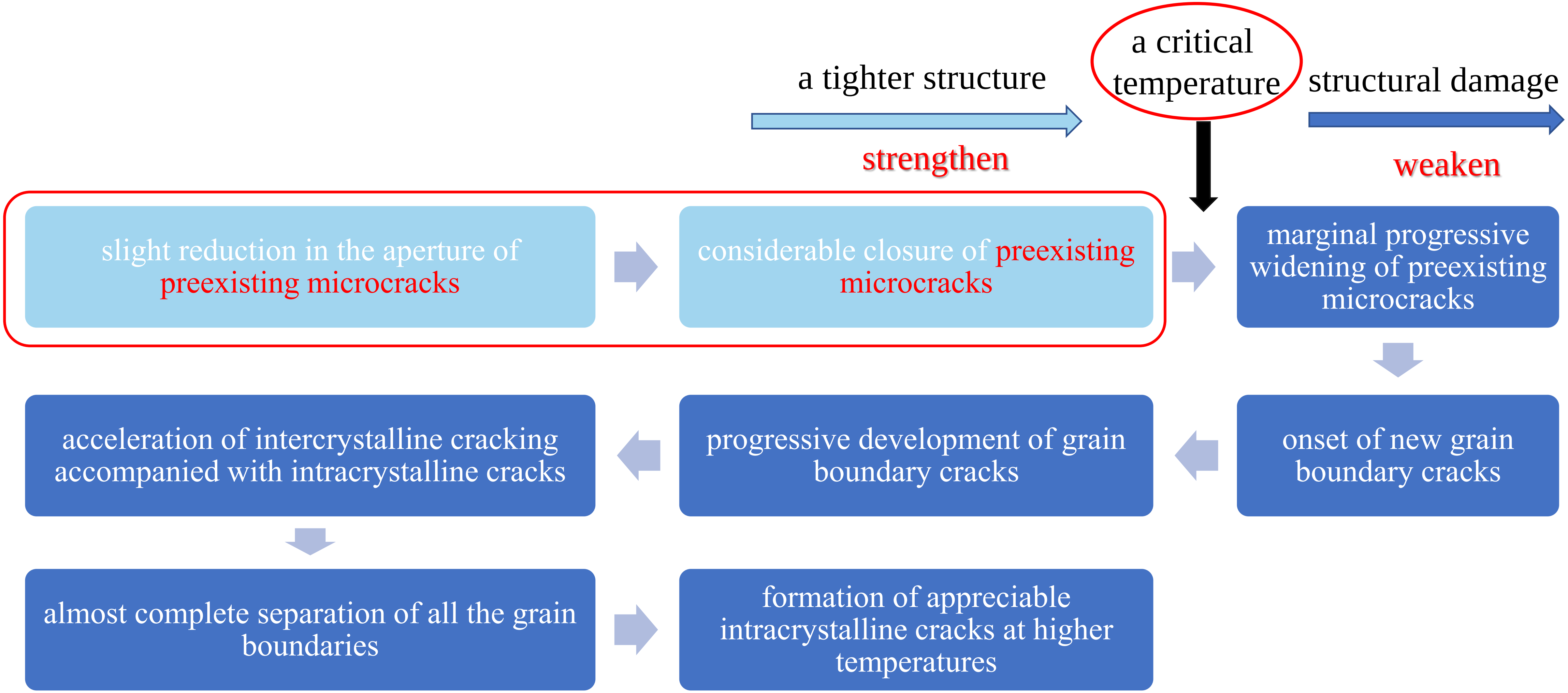
What if ...

Temperature **increase** → Porosity/permeability **decrease** → Rock **strengthening??**

Strengthening mechanisms in the mild temperature range

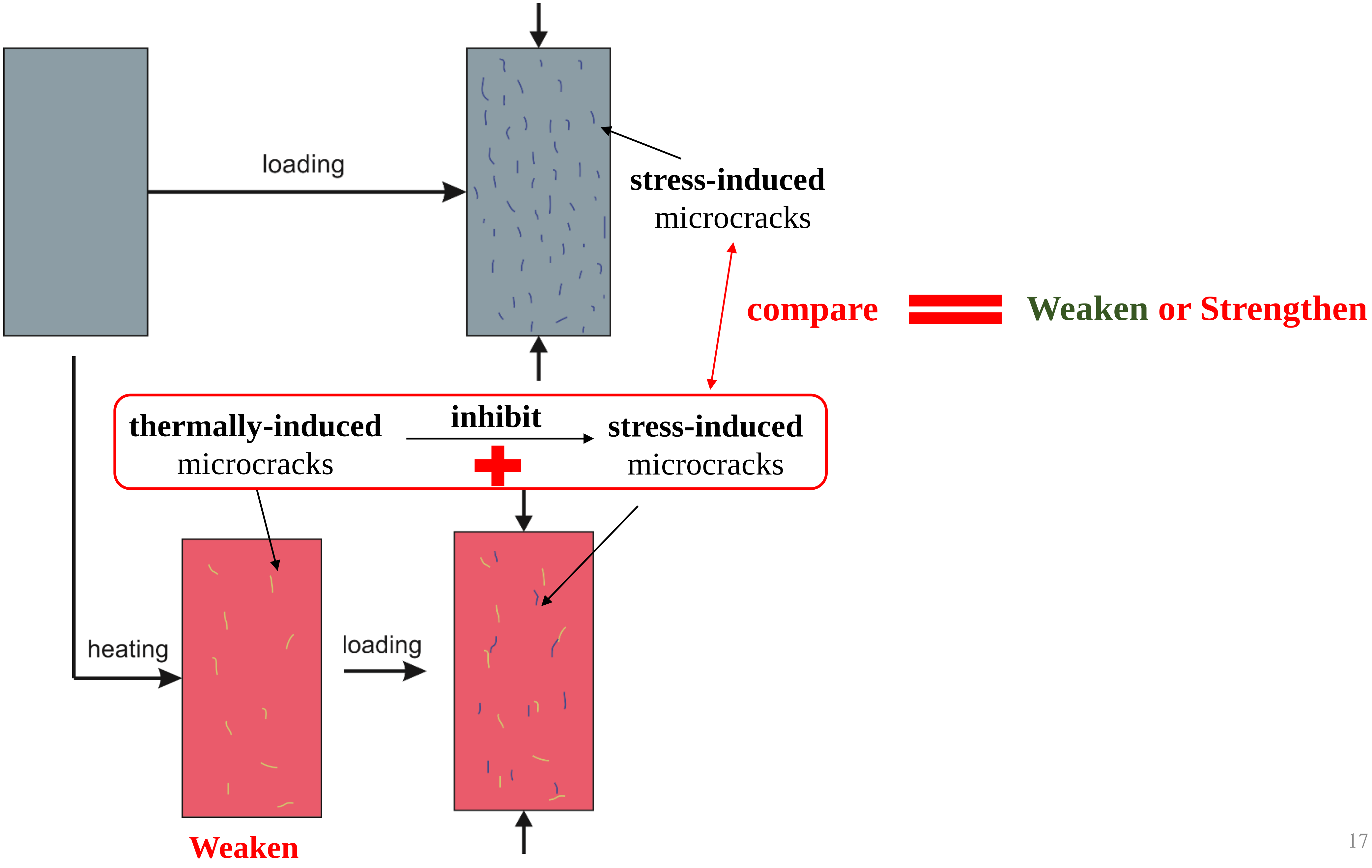
- Strengthening effect of microcrack closure
- Dual effect of thermally induced microcracks
- Dual effect of water-related changes

Strengthening effect of microcrack closure



The general sequences of thermal microcracking behavior against treated temperature

Dual effect of thermally induced microcracks



Dual effect of water-related changes

Absorbed water (water content) → completely released 100-110°C →
- effective stress ↑
- friction between mineral particles ↑
- pores for mineral expansion ↑

→ **Strengthen**

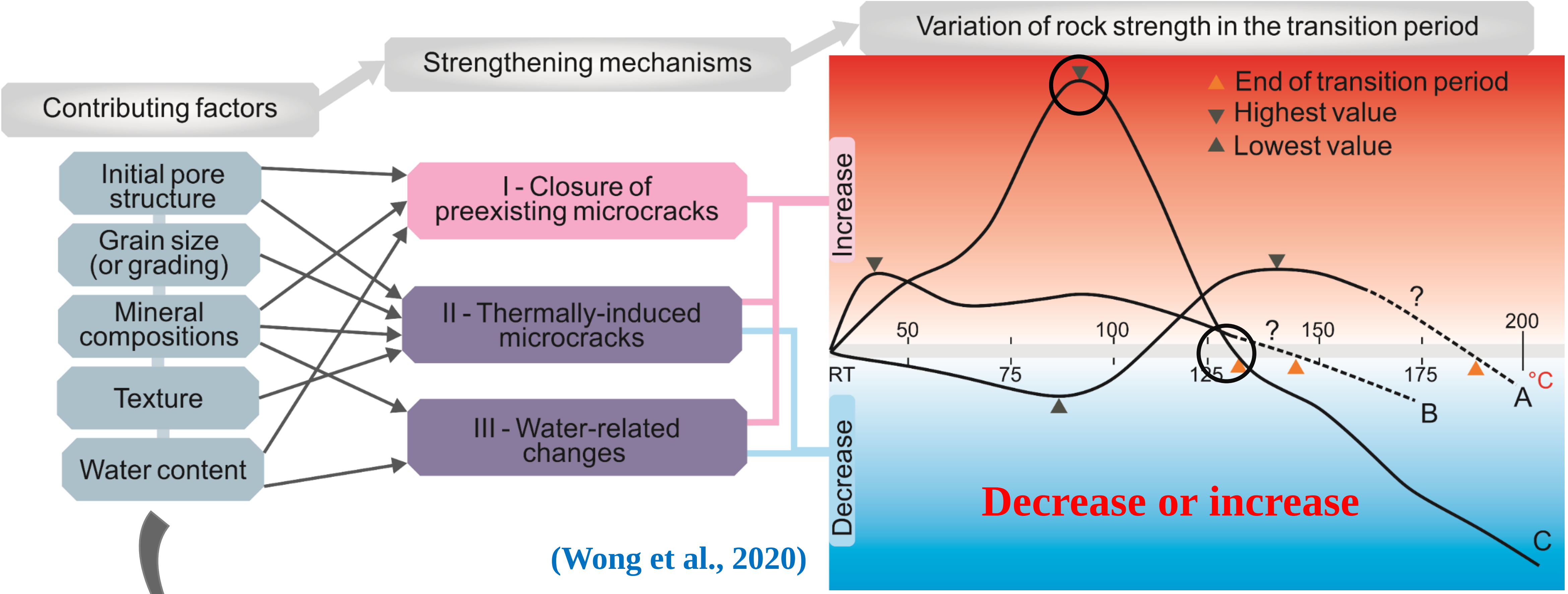
Bond water
- Weakly bonded water (~150°C)
- Strongly bonded water (200-300°C)

Mineral water
- Crystal water (~ 400°C)
- Structural water (> 300°C)

→ damage of crystal structure → **Weaken**

Dual effects in **clay minerals (100-450°C)**
- rapid contraction of clay minerals → collapse of clay structure → **Weaken**
- hardening of clay minerals → friction between mineral grains ↑ → **Strengthen**

Transitional behavior and contributing factors

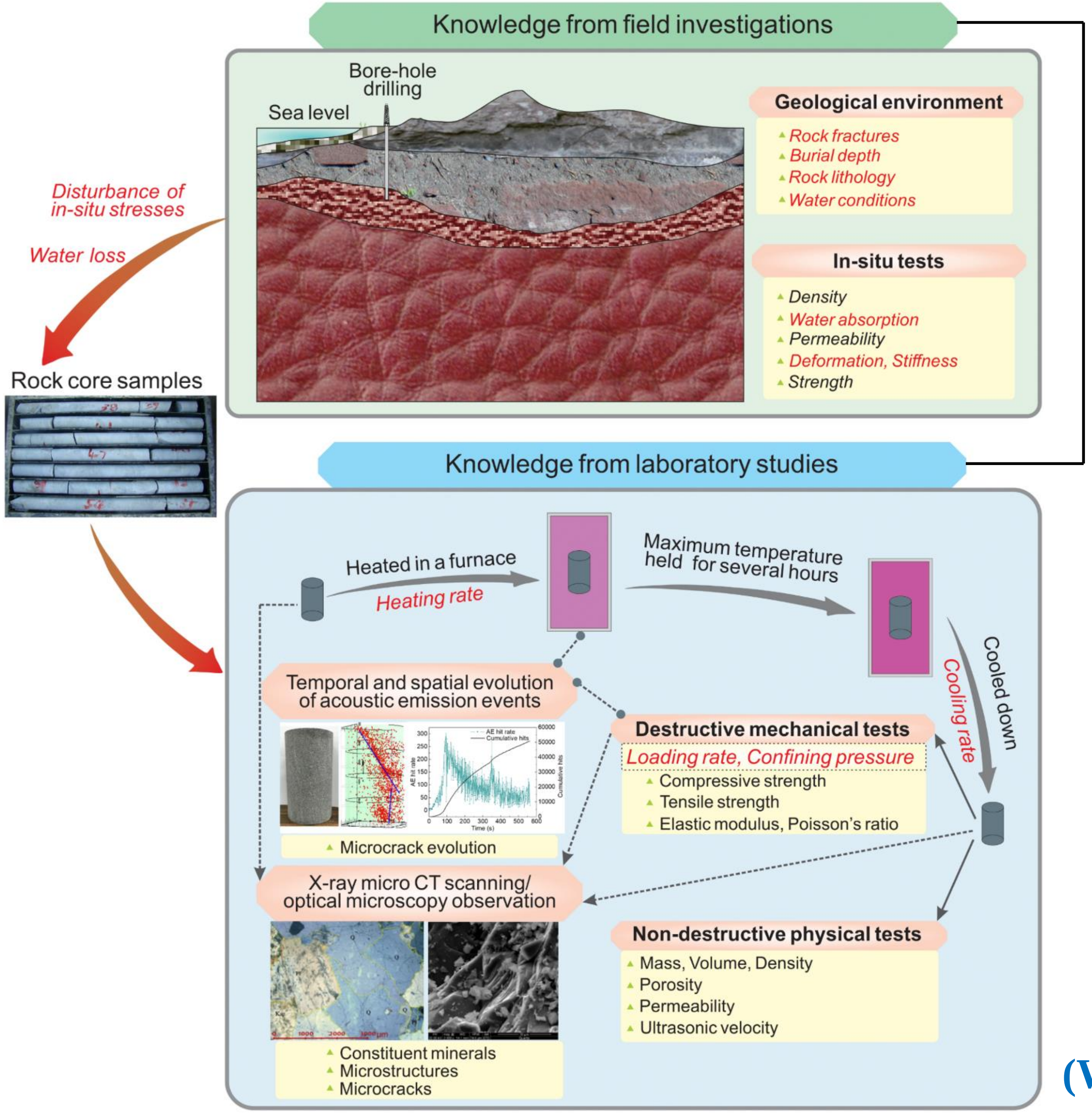


A-Indian granite (Dwivedi, et al., 2008), **B**-Biotitic granite (Chen et al., 2014), and **C**-Khondalitic Rock (Vishal et al., 2011).

To understand:

- the end of the strengthening trend
- rock strength lower than that at the room temperature

Future studies on rock strengthening behavior



Rock strength influenced by various environmental and testing factors

- **Finer increment of temperature** to investigate the transitional behavior. **~~50-100°C~~** **10-30°C**

- **Detailed information** on rock textural attributes and testing conditions.

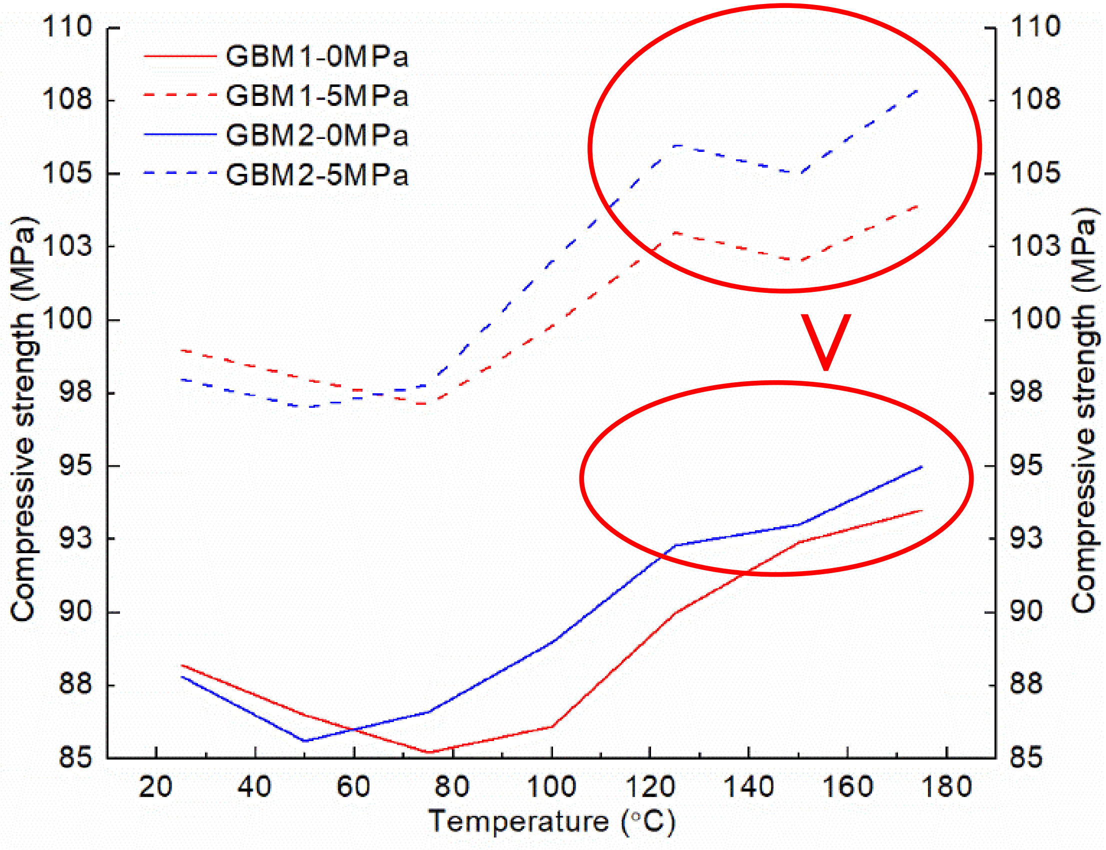
  Not well described in the current literature, hard to compare the results

- Combining effects of **temperature and confining pressure**.

  Confining pressure may amplify the thermal strengthening effect

(Wong et al., 2020)

Discussion: the role of confinement in thermal strengthening – numerical study



- ❑ Confirmation of thermal strengthening
- ❑ Difference of strength enhancement between GBM2 and GBM1: 5 MPa > 0MPa

⬇

- **Rock texture** responsible for the degree of thermal strengthening
- **Confining pressure** amplifies the impact of microstructural heterogeneity.

- ➢ Numerical simulation of the variation of rock strength with temperature (**GBM = grain-based model).**
- ➢ GBM2 is more heterogeneous in texture than GBM1.

(Wong and Zhang, 2019)

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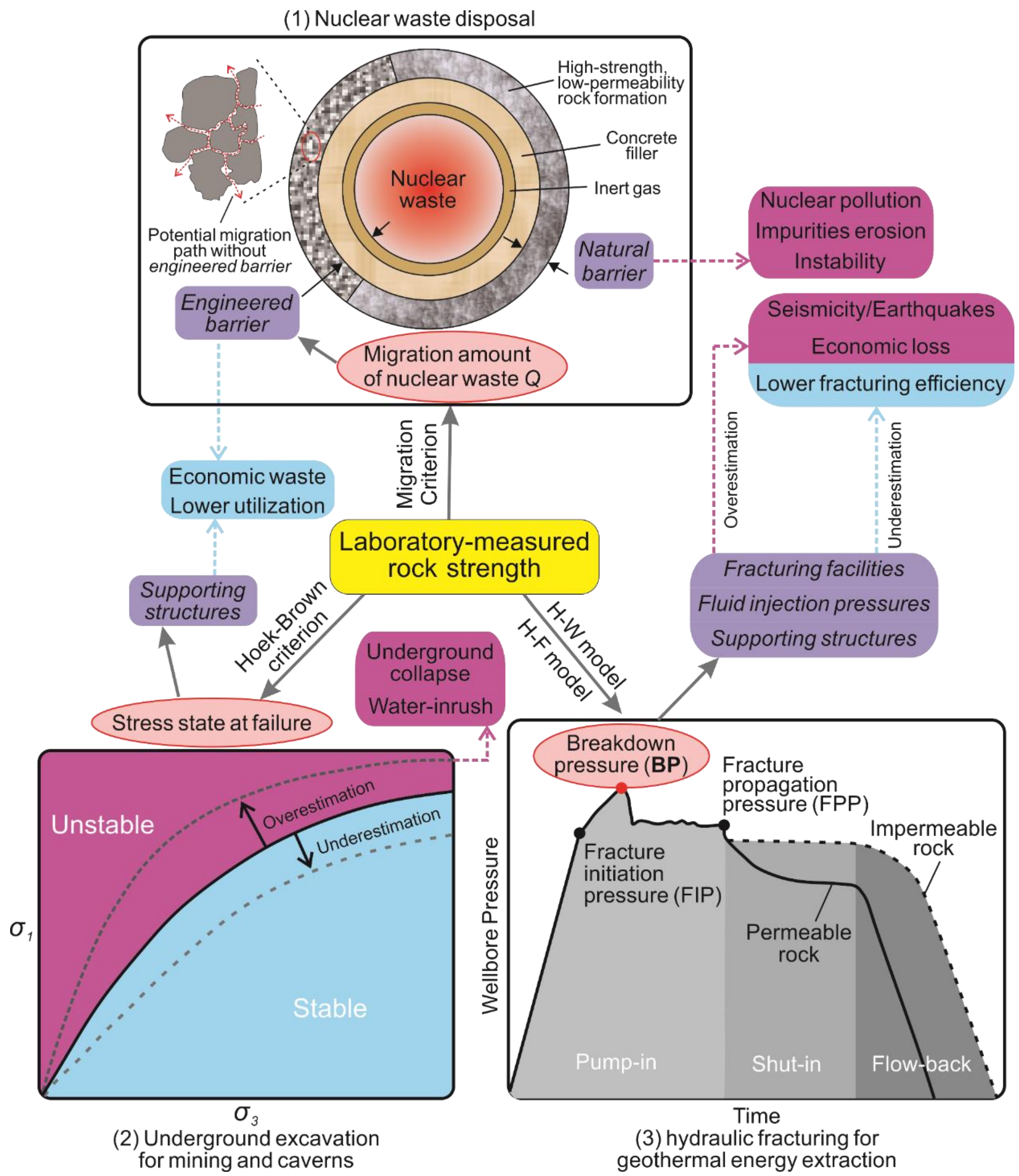
Importance of laboratory-measured rock strength



- Bearing capacity of intact rock
- **A safe and economic design of rock structures**

temperature effect??

(1) **Underestimated** rock strength

- insufficient fluid injection pressure, low fracturing efficiency (*example* 3)
- overdesign of supporting structures, higher economic and labor costs (*example* 2)

(2) **Overestimated** rock strength

- larger fluid injection pressure, earthquakes & economic loss (*example* 3)

(Wong et al., 2020)

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