Imager les contraintes thermiques

Thermomechanical aspects of high-frequency cycling in salt storage caverns

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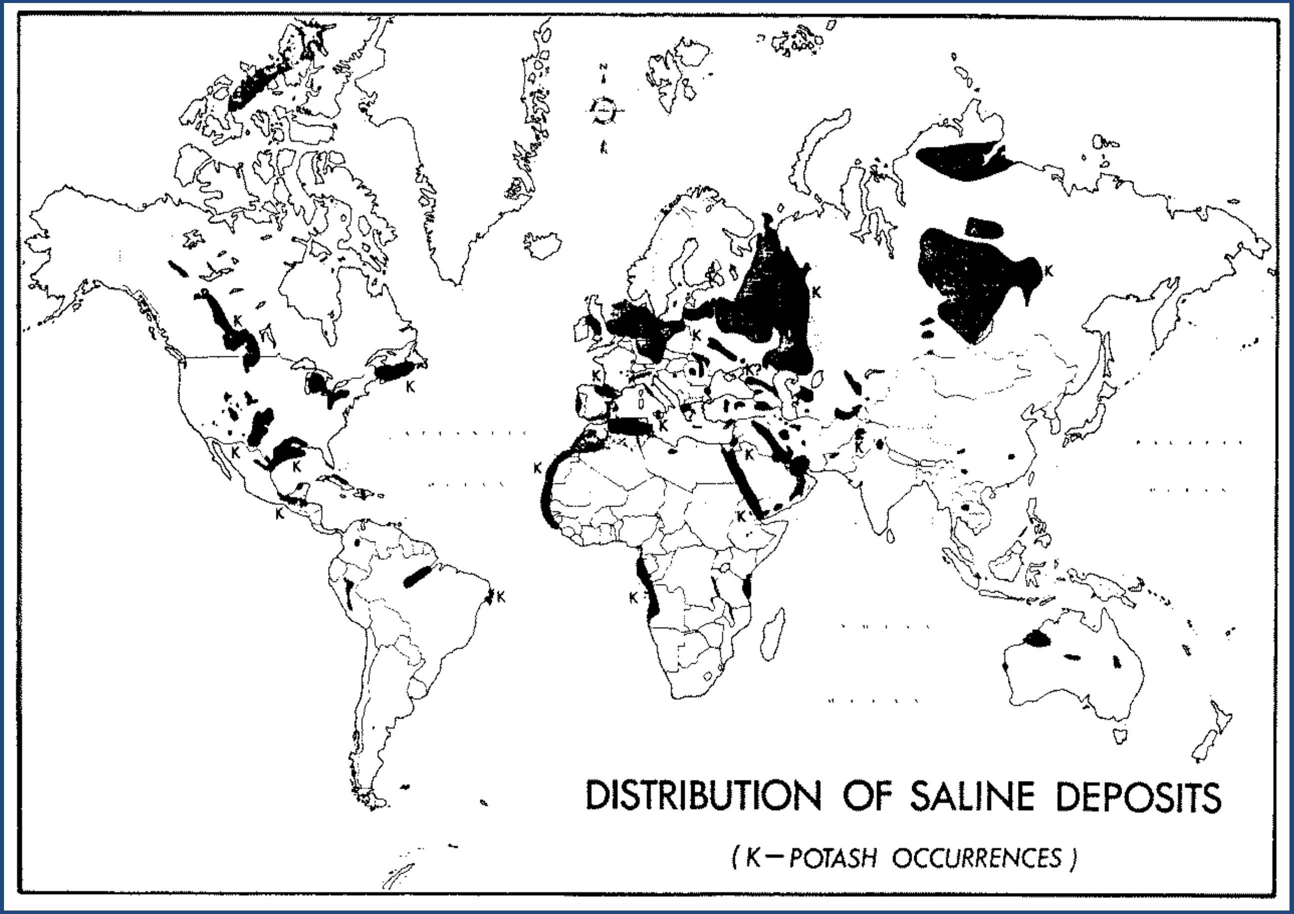
(Ecole Polytechnique, Brouard Consulting, Geostock, Storengy)

Summary

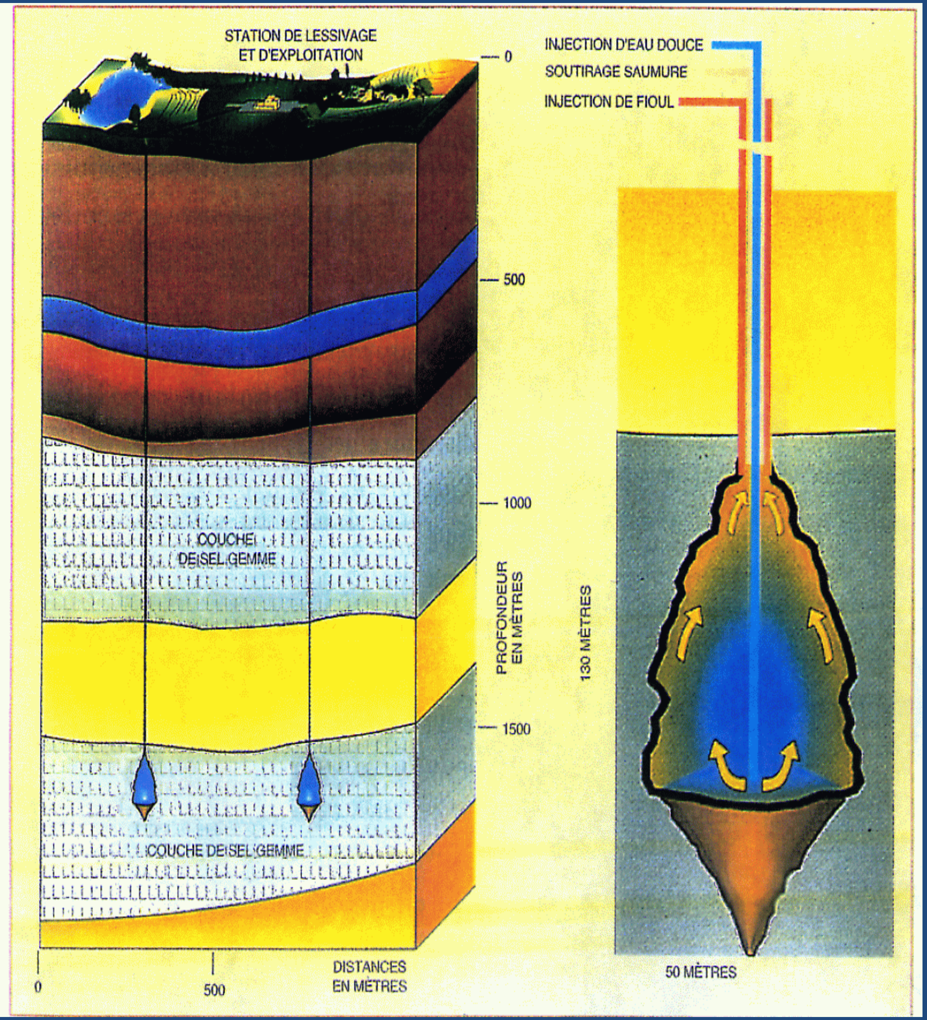
1. Gas storage caverns
2. New trends in gas cavern operation
3. Thermodynamics of gas-filled caverns
4. A (very) short course in rock mechanics
5. Mechanics of gas-filled caverns
   - Tensile stresses
   - Onset of dilation
6. Conclusions

Distribution of saline deposits



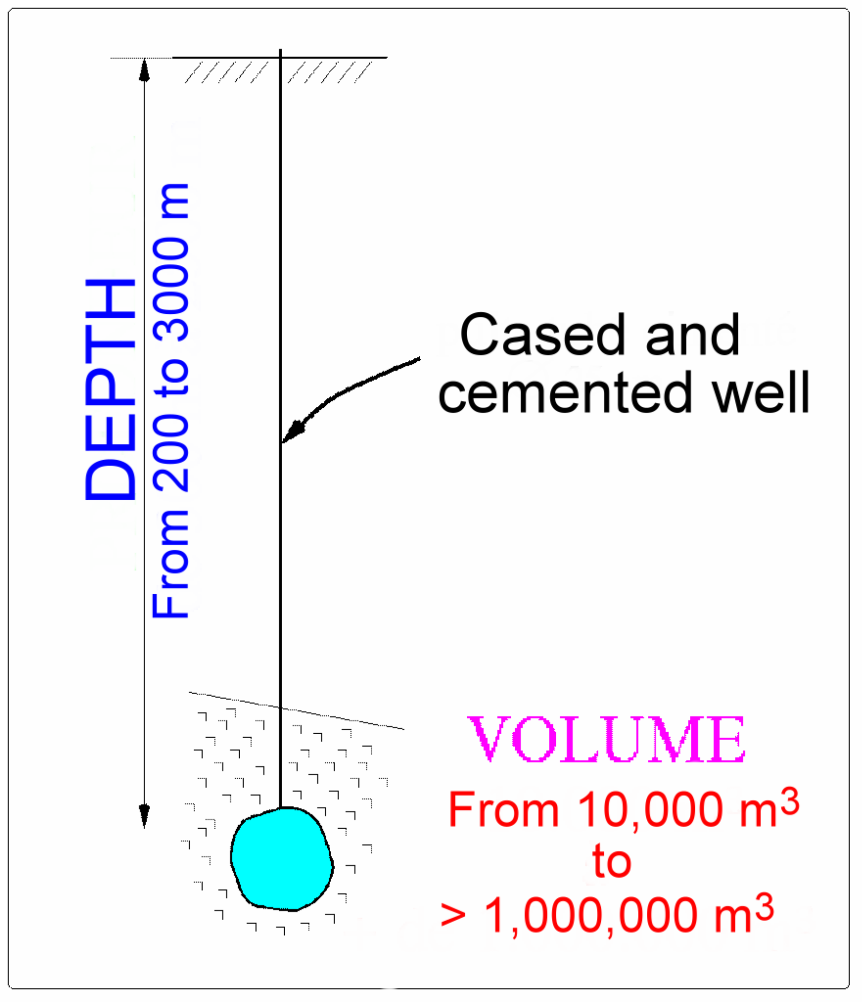
(After Pendery)

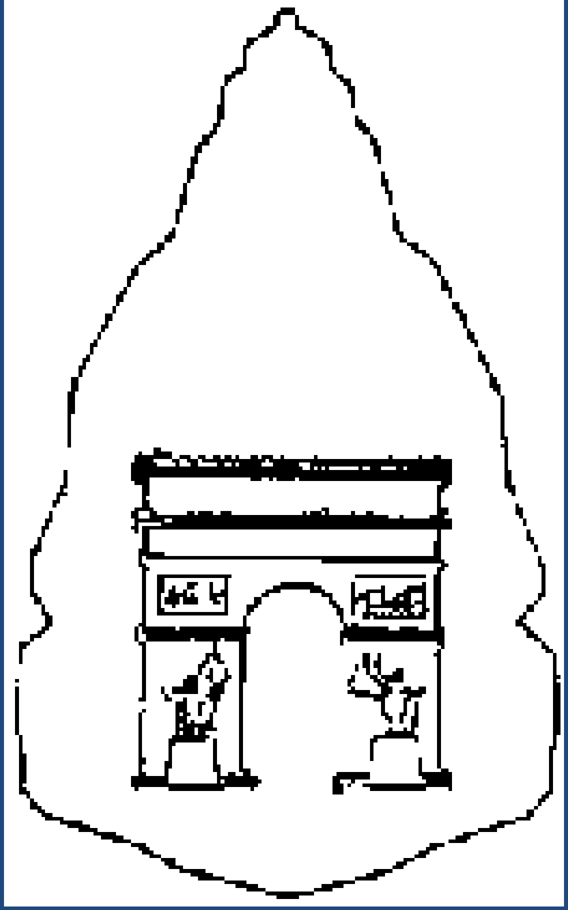
Cavern creation



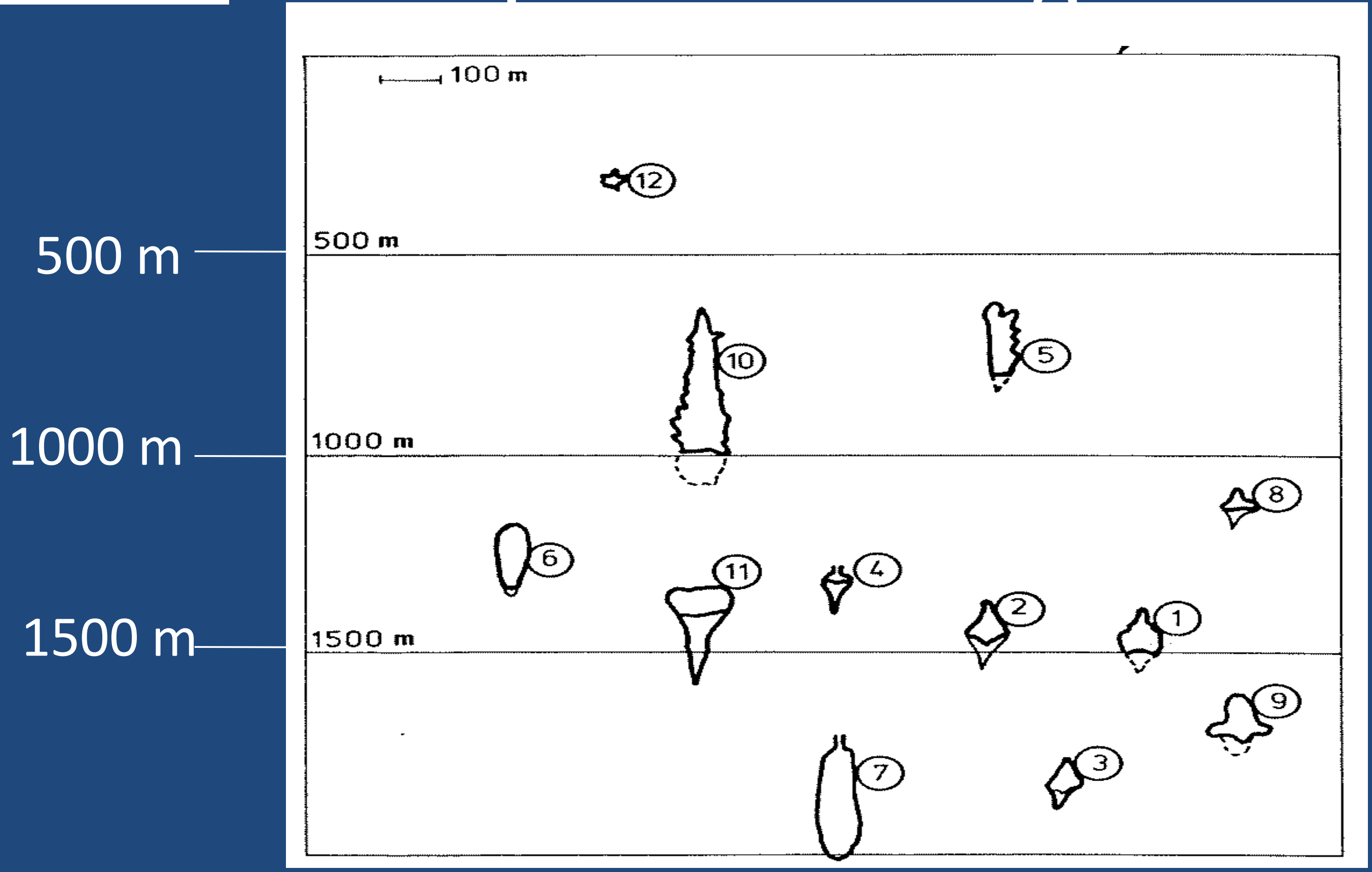
(STORENGY)

Caverns size and depth





Examples of storage caverns



1. Tersanne (France) 2. Etrez (France) 3. Atwick (UK)
4. Kiel (Germany) 5. Huntorf (Germany) 6. Epe (Germany)
7. Eminence (USA) 8. Melville (Canada) 9. Regina (Canada)
10. Manosque (France) 11. Hauterives (France) 12. Salies de Béarn (France)

Salt Rheological Behavior

Rock salt behaves as a non-Newtonian viscous fluid

Water : $\mu = 10^{-3}\,\text{Pa.s}$

Honey : $\mu = 10^{1}\,\text{Pa.s}$

Ice : $\mu = 1.5 \times 10^{13}\,\text{Pa.s}$

Salt : $\mu = 10^{17}\,\text{Pa.s}$

Salt Rheological Behavior

In the long term, any cavern shrinks and ultimately closes. In a brine-filled cavern:

- At a 250 m depth: $\dot{V}/V = 10^{-5}$ / yr
- At a 1000-m depth: $\dot{V}/V = 3 \times 10^{-4}$ / yr
- At a 2000-m depth: $\dot{V}/V = 10^{-2}$ / yr

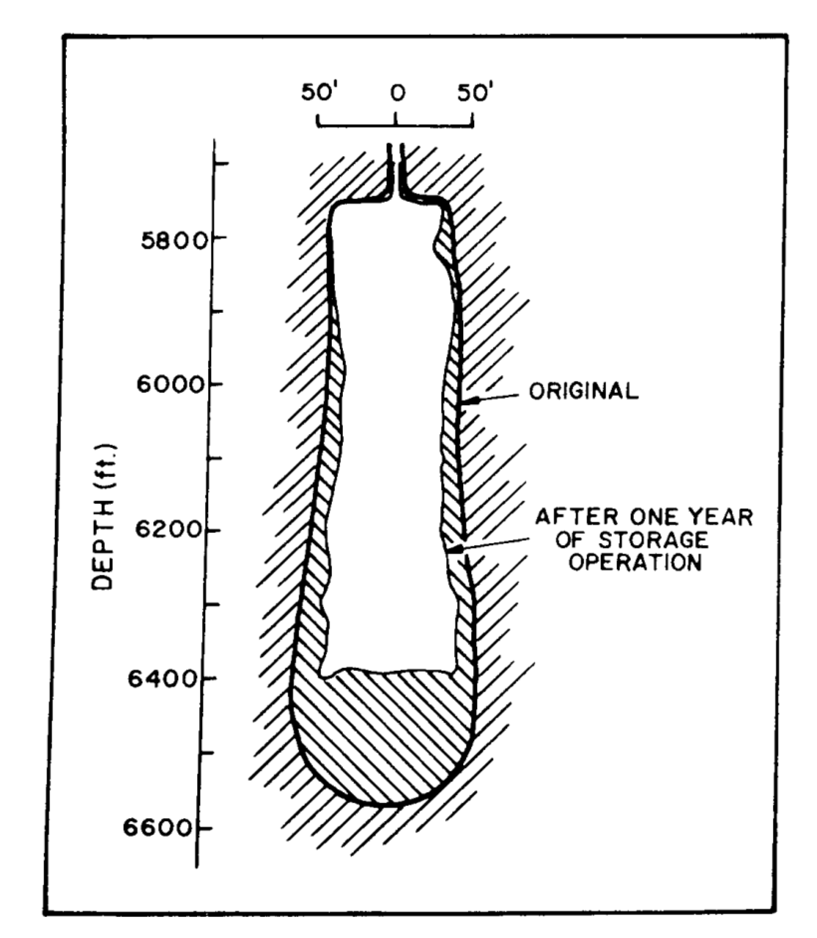
- In a gas-filled cavern, closure rates are still faster

Cavern creep closure

Several deep gas storage caverns experienced large losses of volume

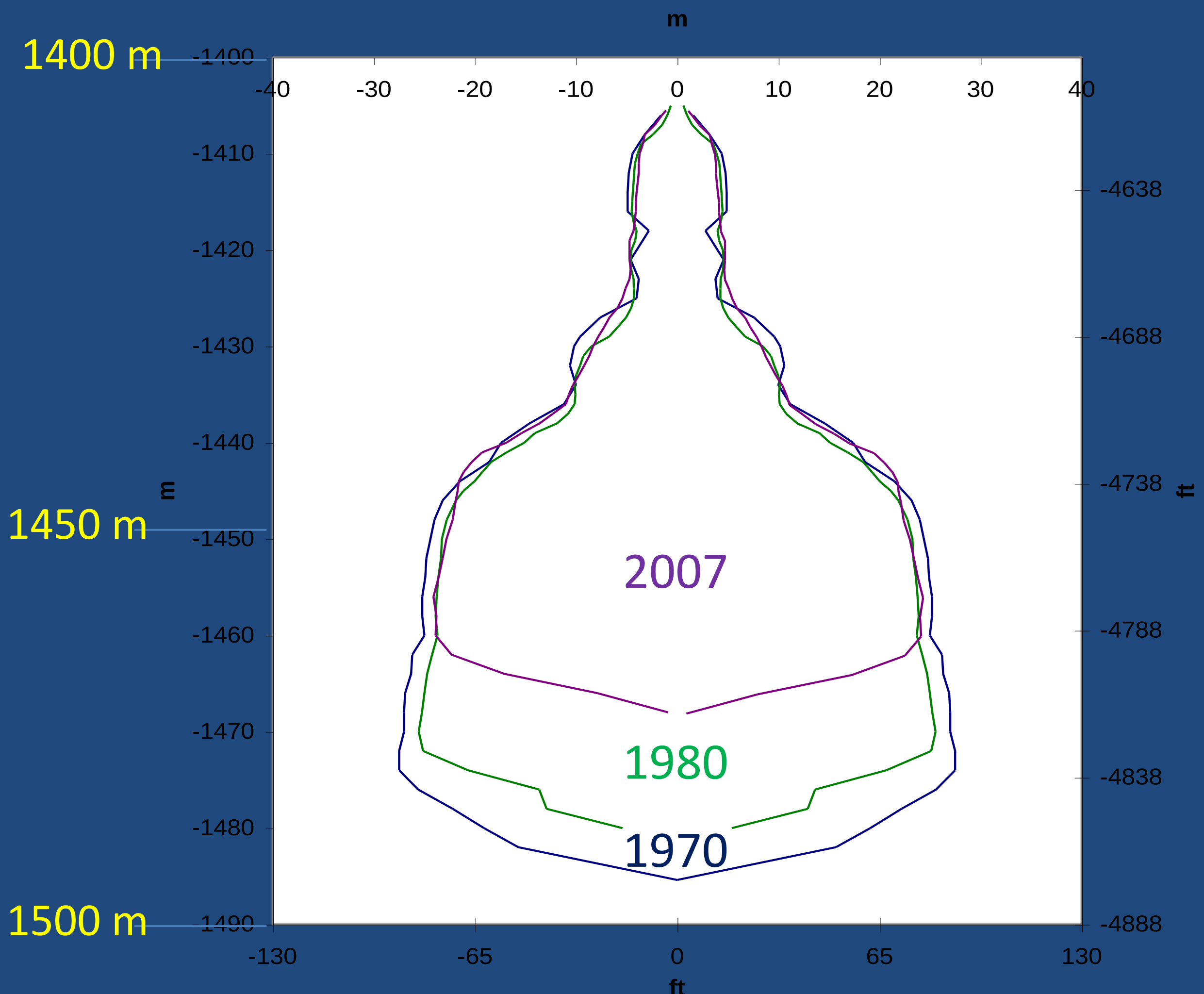
Which originate in salt creep, which is especially fast when gas pressure is low

Eminence #1, Mississipi



Serata and Cundey, 1984

Tersanne #2 (France)



STORENGY

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New trends is cavern operation

In the 70's-80's, gas storage caverns were developed mainly for seasonal storage. Gas was injected in summer and withdrawn in winter

Needs of energy traders are changing toward more aggressive operating modes, with large swings to take advantage of daily market prices

New trends is cavern operation

What is an “aggressive mode”?

Depends on the specific point of view:

$$Nm^3 / hr$$

$$m / s$$

$$bar / day$$

$$°C / day$$

What is an "aggressive mode"?

Nm^3 / hr (trading): 1 to several 10^5 Nm^3 / hr

m / s (tube erosion, noising): 18-25 m/s

bar / day (head losses, creep closure): 10-20 bars/day (5 bars/hr in a CAES)

°C / day (hydrates formation; tensile stresses at cavern wall)

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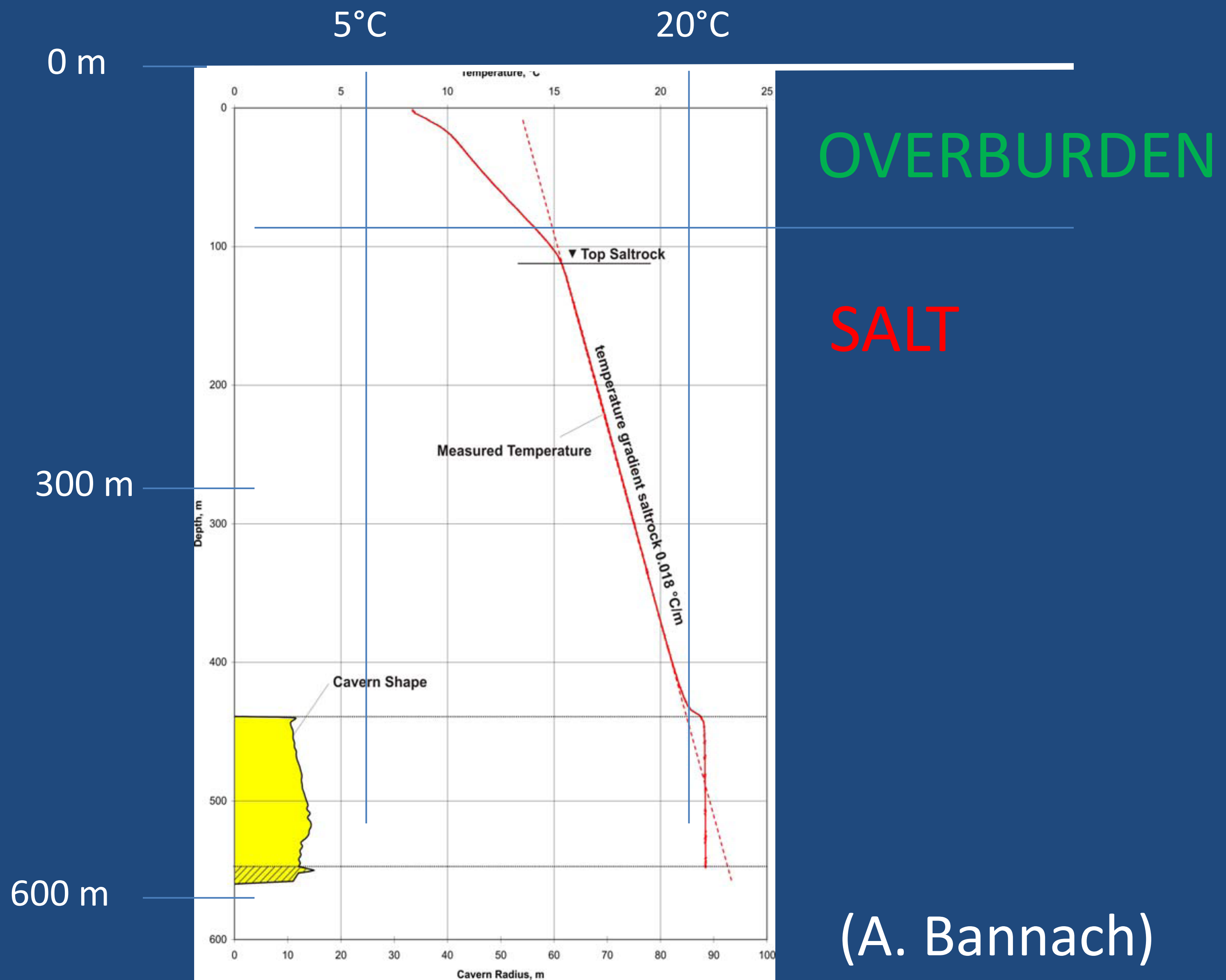
Cavern Thermodynamics

Virgin rock temperature increases with depth

In the cavern itself, gas is stirred by (turbulent) natural convection and gas temperature is almost uniform through the cavern

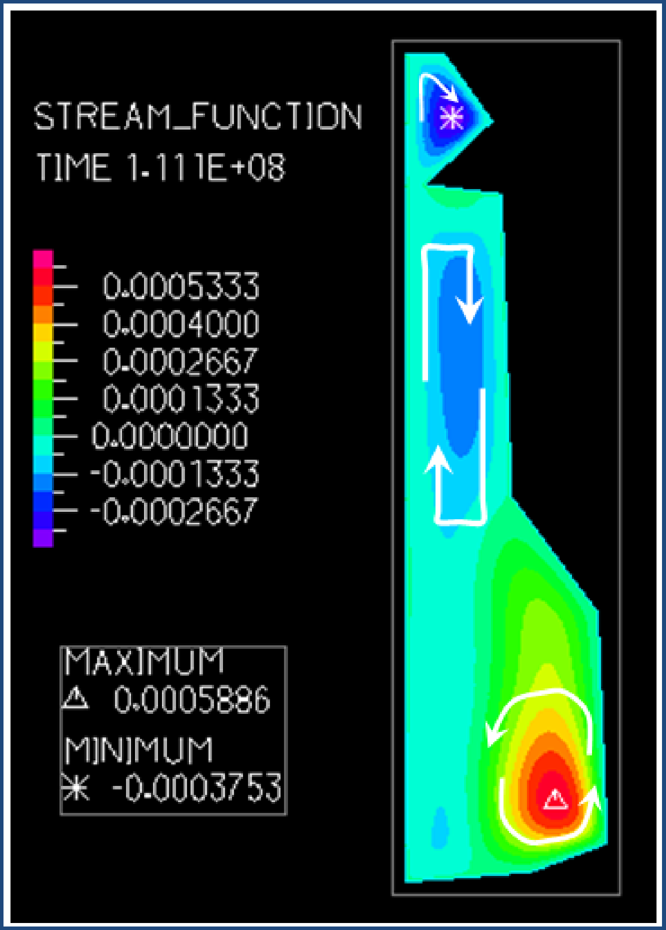
Gas cooling generated by gas withdrawal is dramatic

Stassfurt (Germany)



(A. Bannach)

Natural convection in a brine-filled cavern



Karimi-Jafari
Et al., 2007

Cavern Thermodynamics

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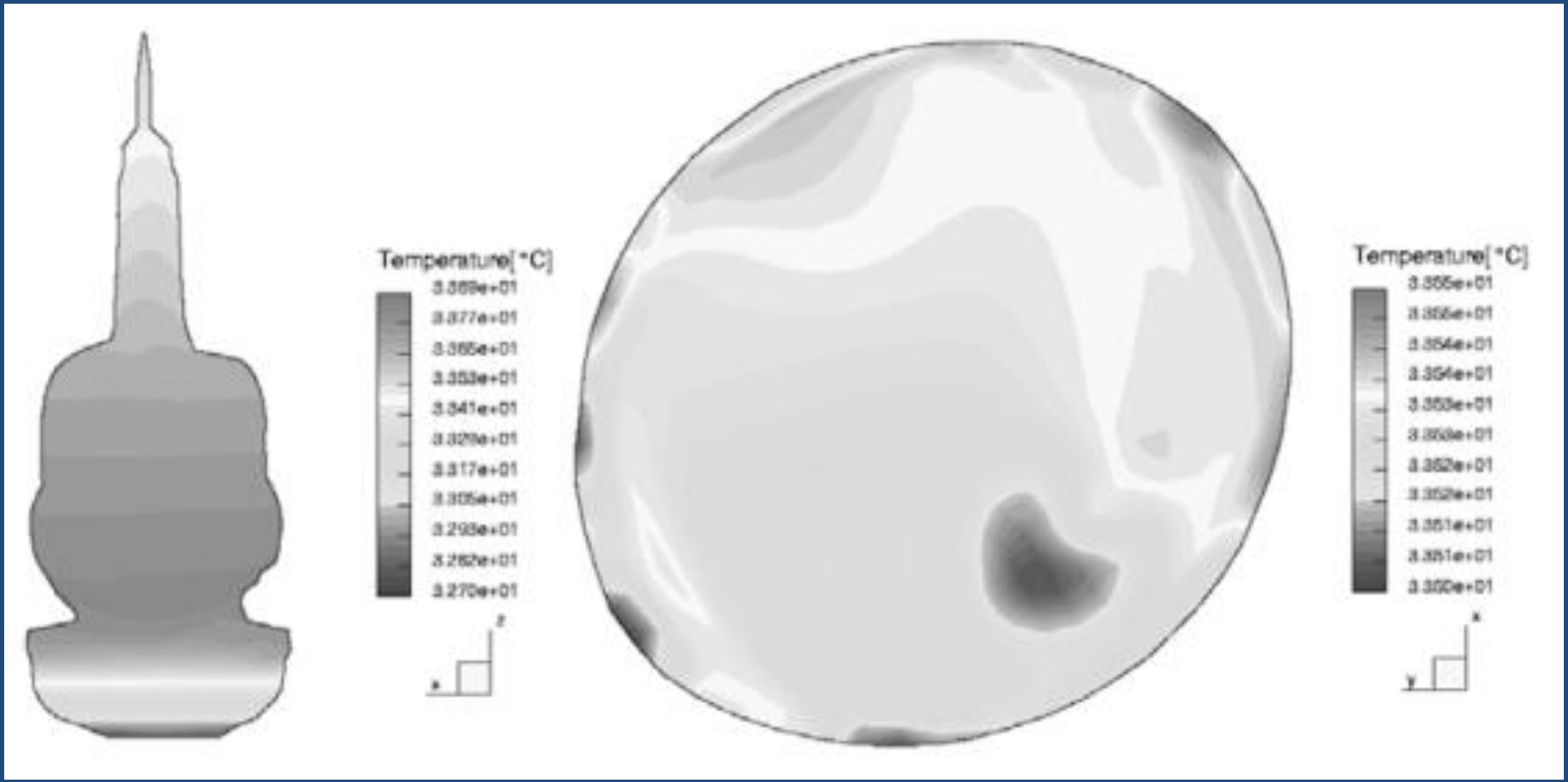
Temperature distribution in a 300-m high gas cavern



Vertical and horizontal temperature differences are less than 0.5°C an 0.05 °C, respectively (Klafki & al, 2003)

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TEMPERATURE EVOLUTION

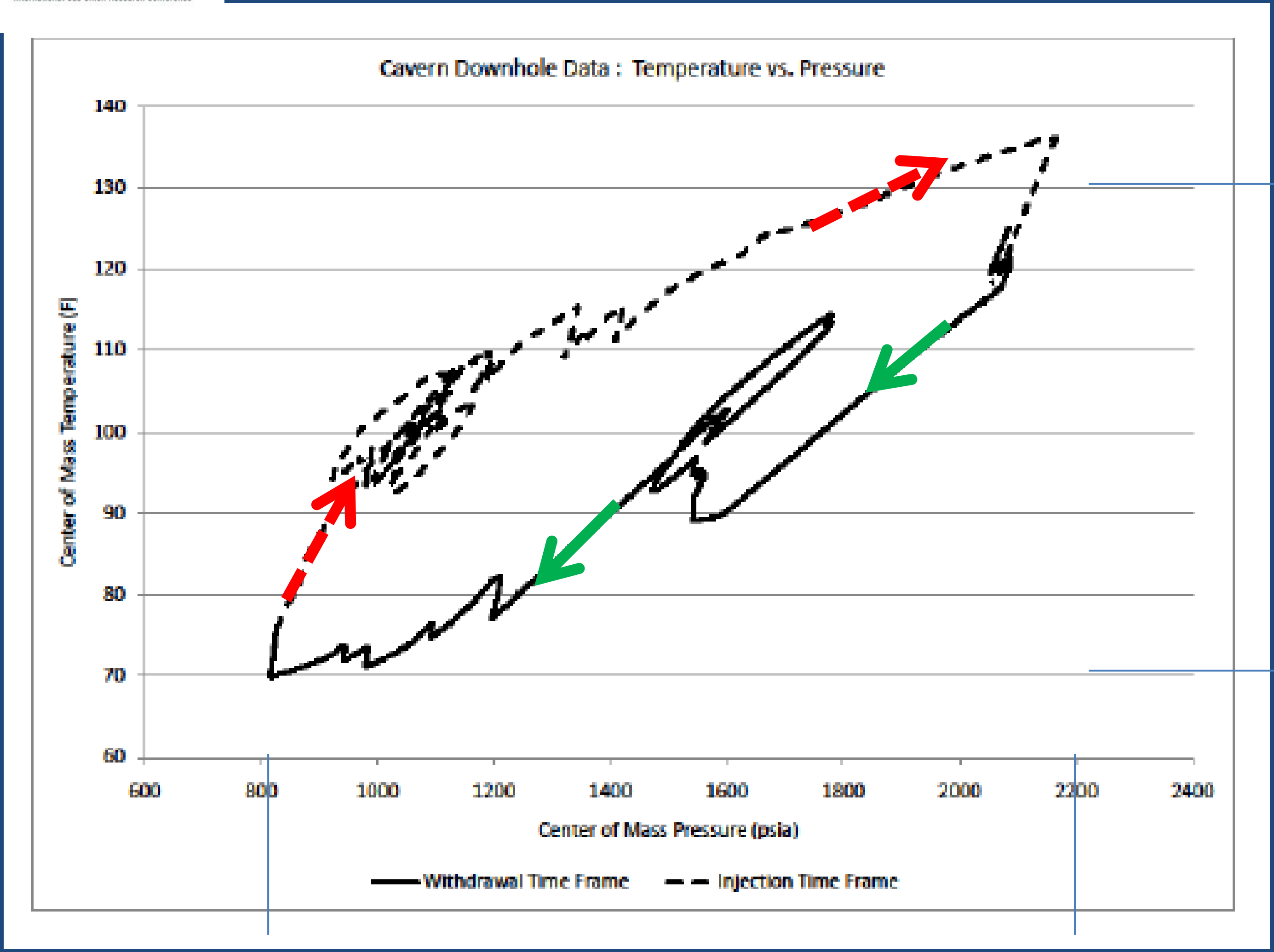
$$m\left(C_P\dot{T}-\frac{\dot{P}}{\rho}\right)=\iint -K\frac{\partial T}{\partial n}da+\dot{m}C_P(T_{inj}-T)$$

RATE OF INTERNAL ENERGY MINUS WORK OF EXTERNAL FORCES

RATE OF HEAT FLUX FROM THE ROCK MASS

RATE OF ENTHALPY INJECTED IN THE CAVERN

Pressure-Temperature evolutions during a cycle (Benefield, 2010)



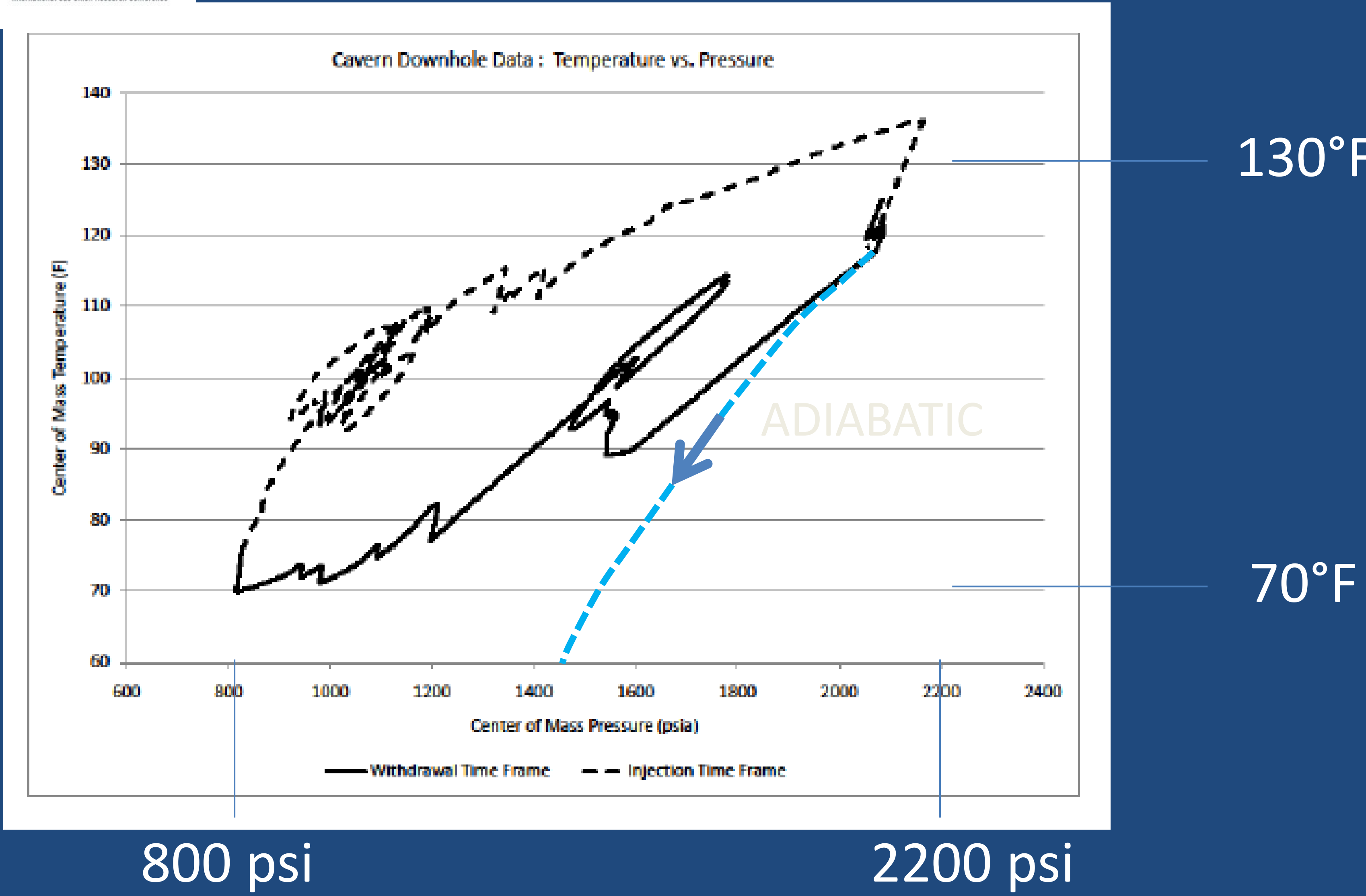
130°F

70°F

800 psi

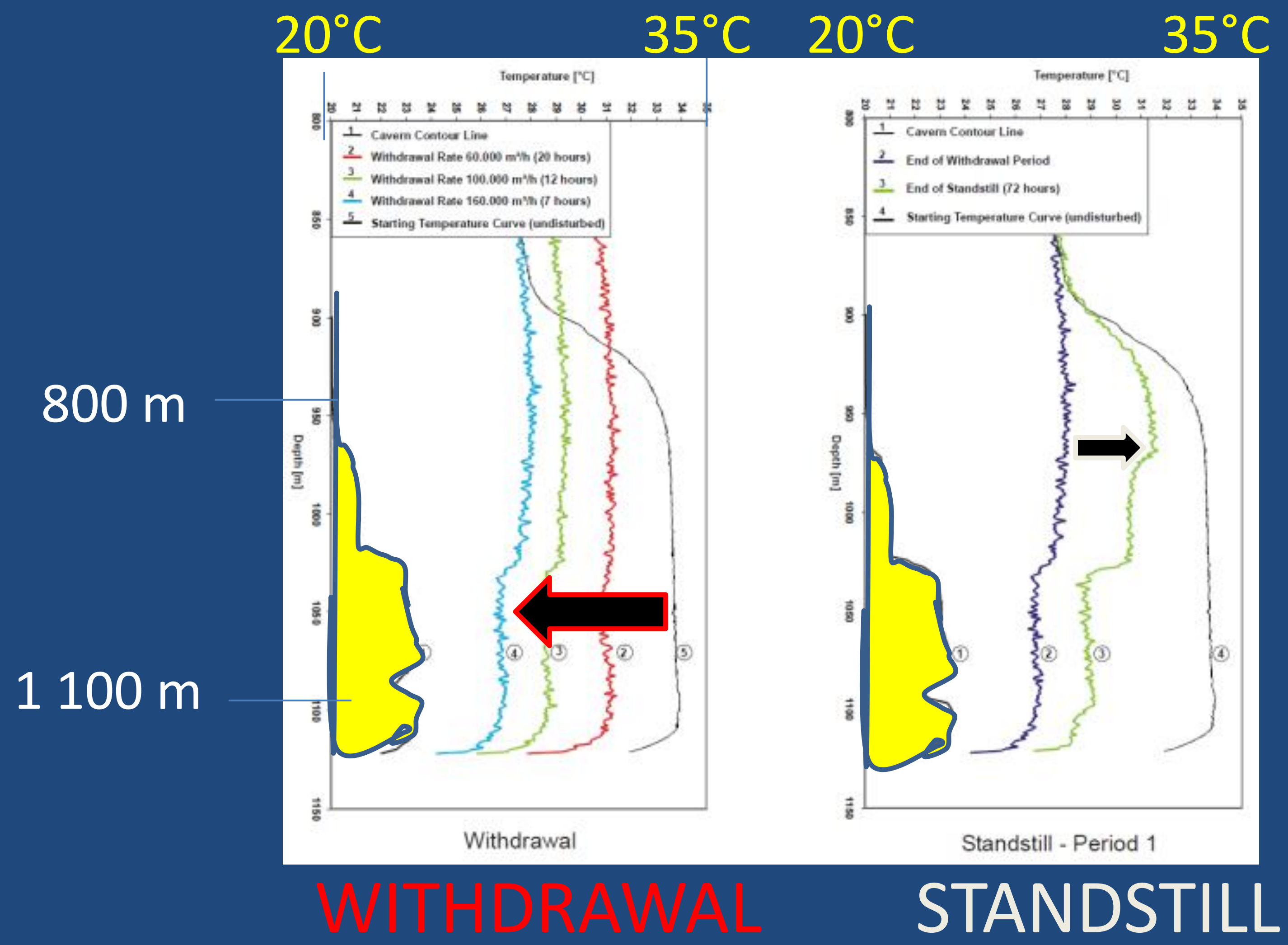
2200 psi

Pressure-Temperature evolutions during a cycle (Benefield, 2010)



Gas temperature changes

(Klafki & al, 2003)



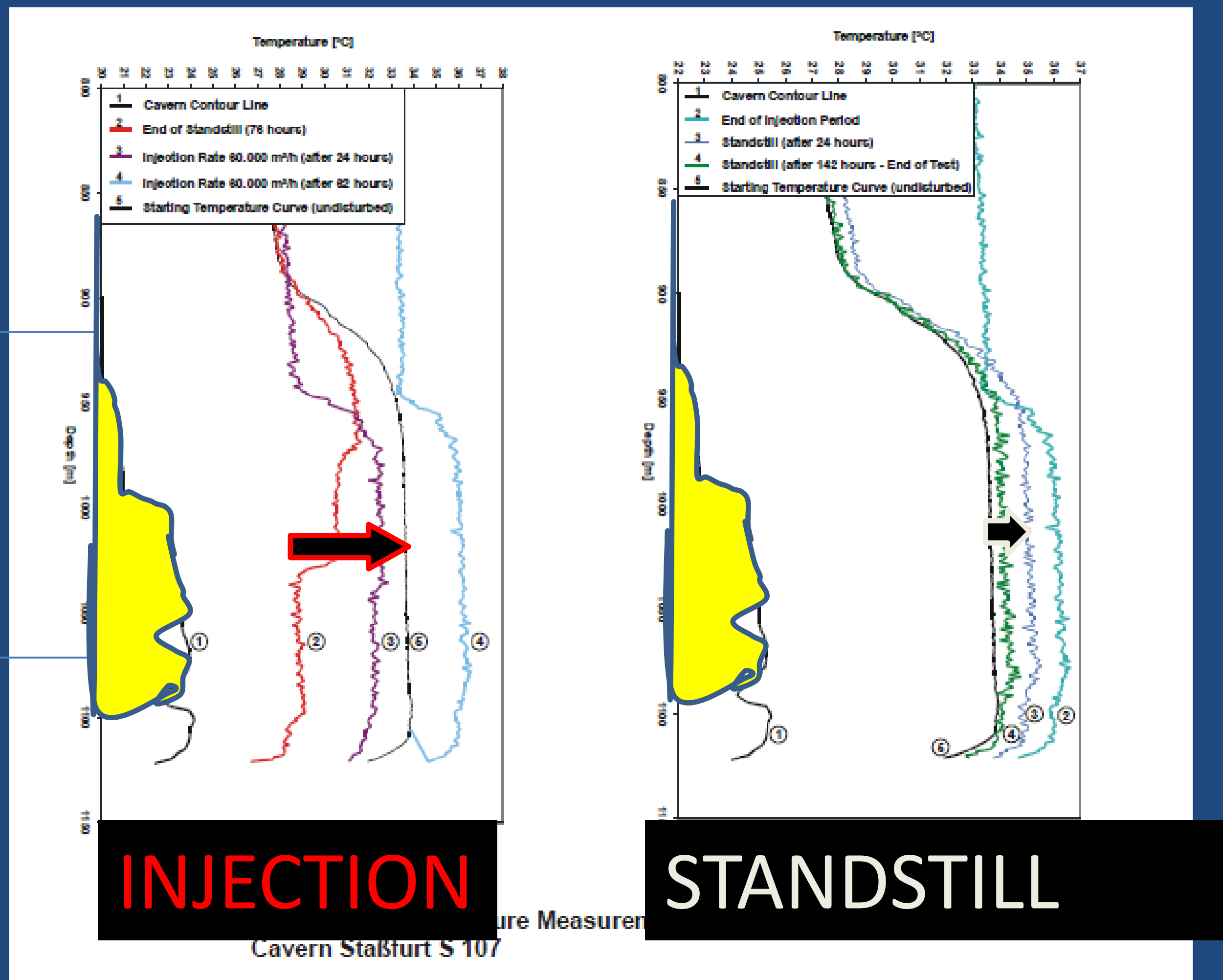
Gas temperature changes

(Klafki & al, 2003)

20°C 35°C 20°C 35°C

800 m

1 100 m



Depth of penetration of temperature changes

Depth of penetration of temperature changes

In the rock mass is small.

A gas temperature change during a *t*-long period has no effect at a depth larger than:

$$h \approx \sqrt{kt} \quad \text{or} \quad h(\text{metres}) \approx 0.5\sqrt{t(\text{days})}$$

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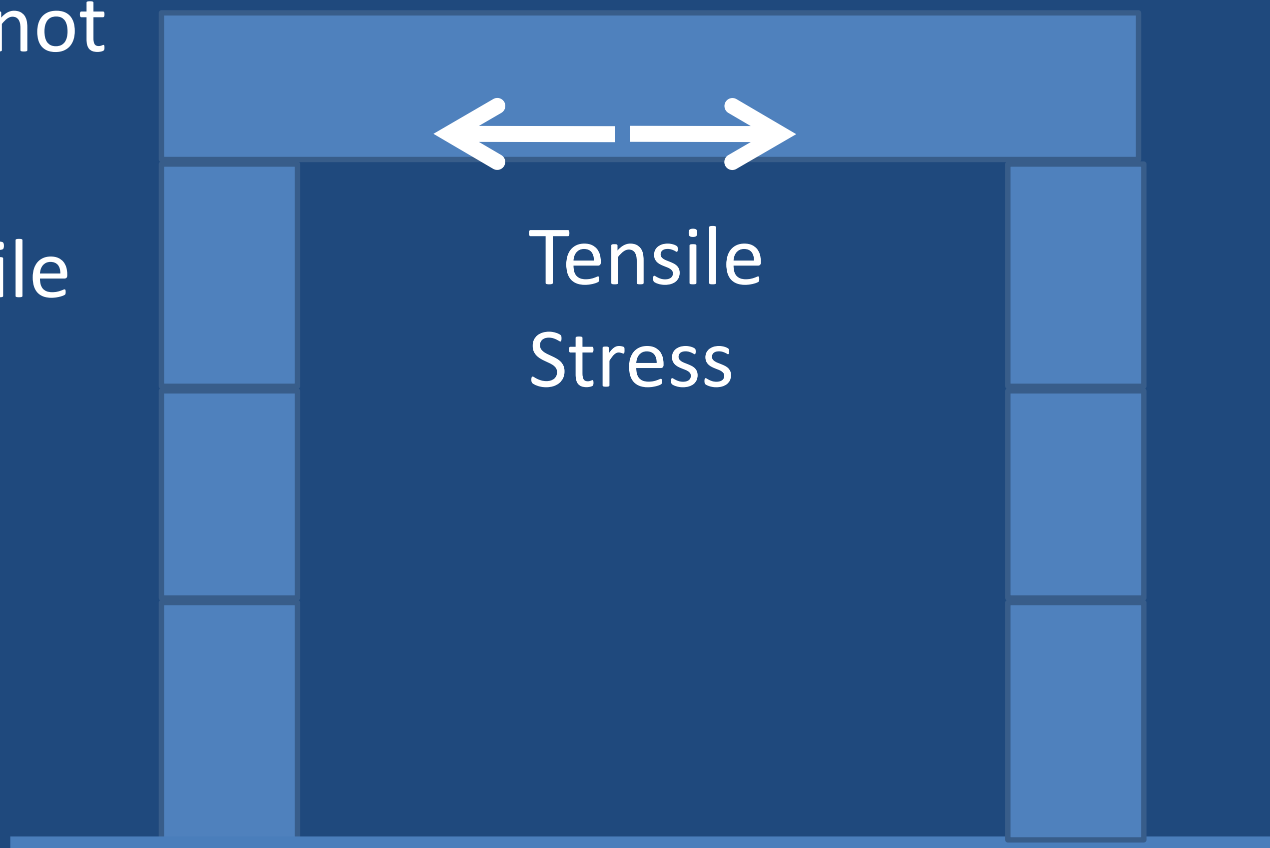
A (very) short course in Rock Mechanics

Rocks can withstand large compressive stresses

A (very) short course in Rock Mechanics

Rocks cannot withstand large tensile stresses



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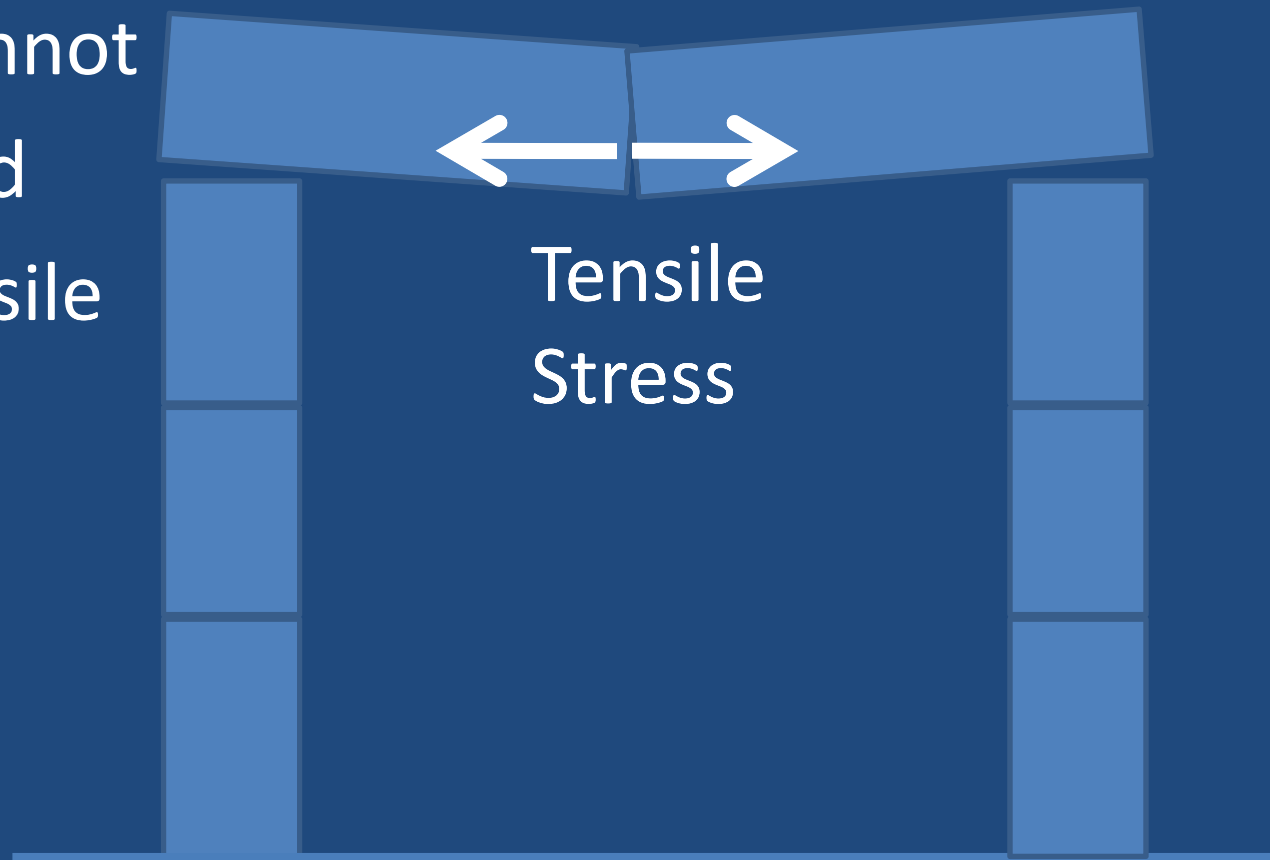
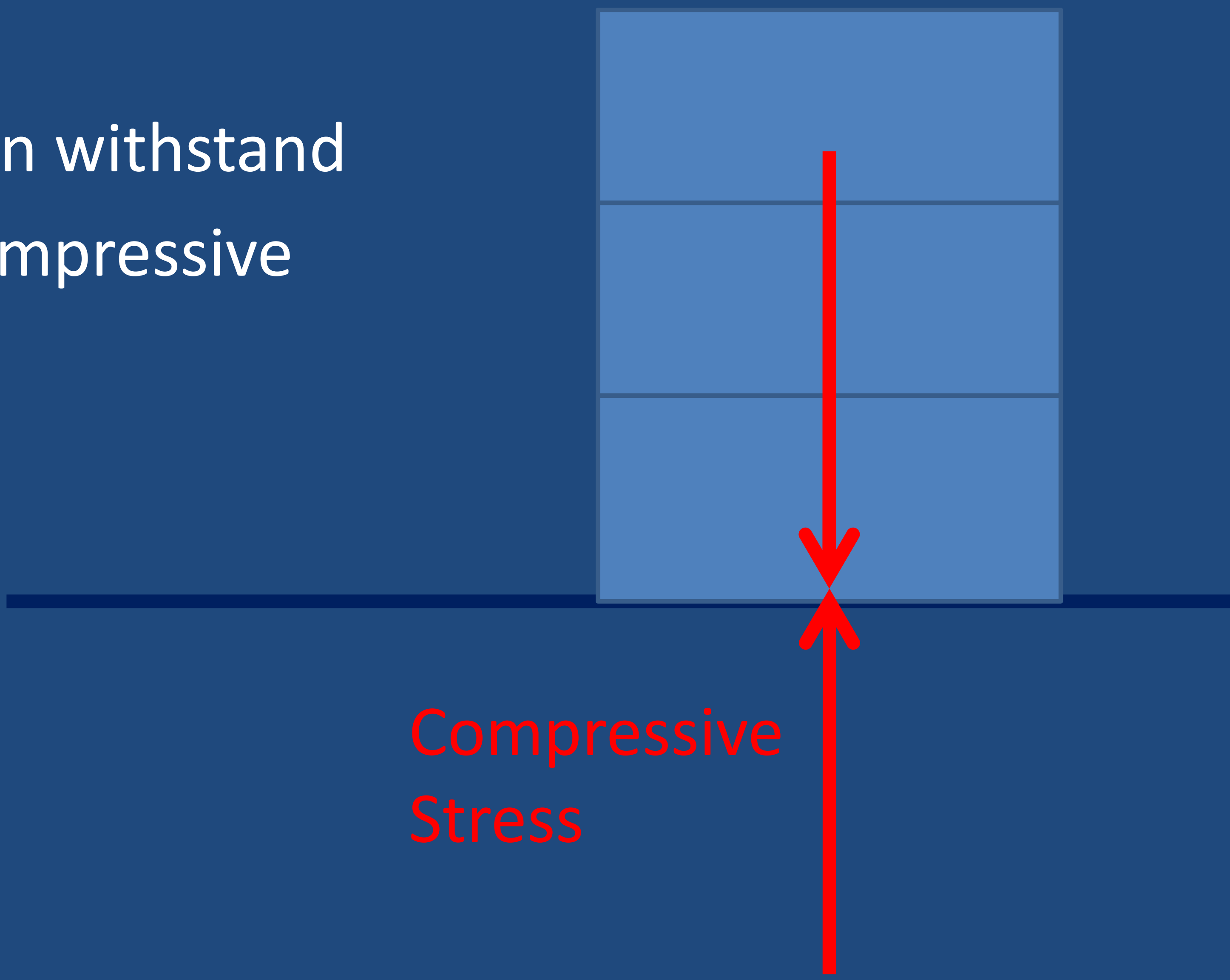
A (very) short course in Rock Mechanics

Rocks cannot withstand large tensile stresse



A (very) short course in Rock Mechanics

Rocks can withstand Large compressive stresses



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A (very) short course in Rock Mechanics

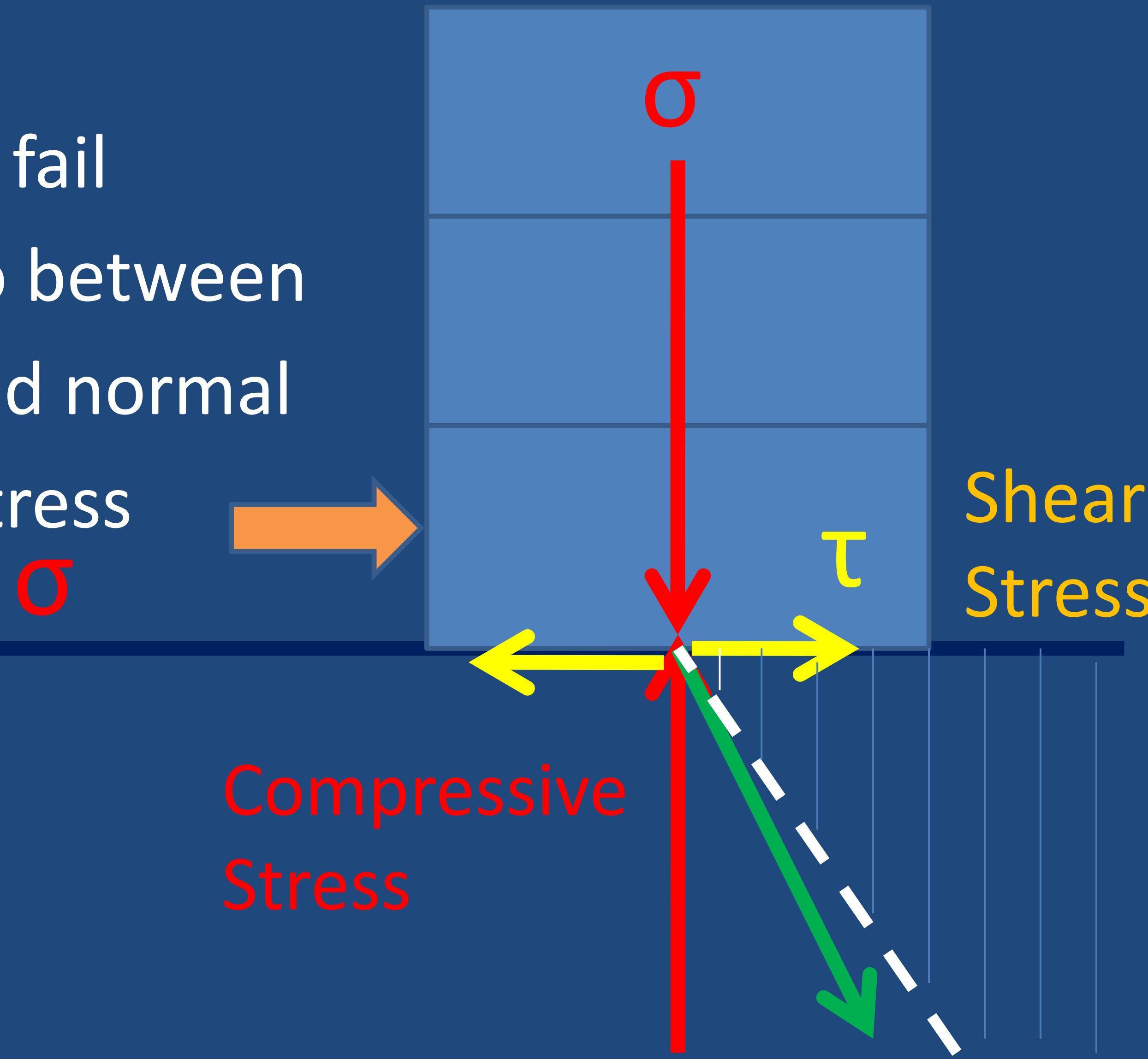
However rocks fail

When the ratio between

Shear stress and normal

Compressive stress

Is high



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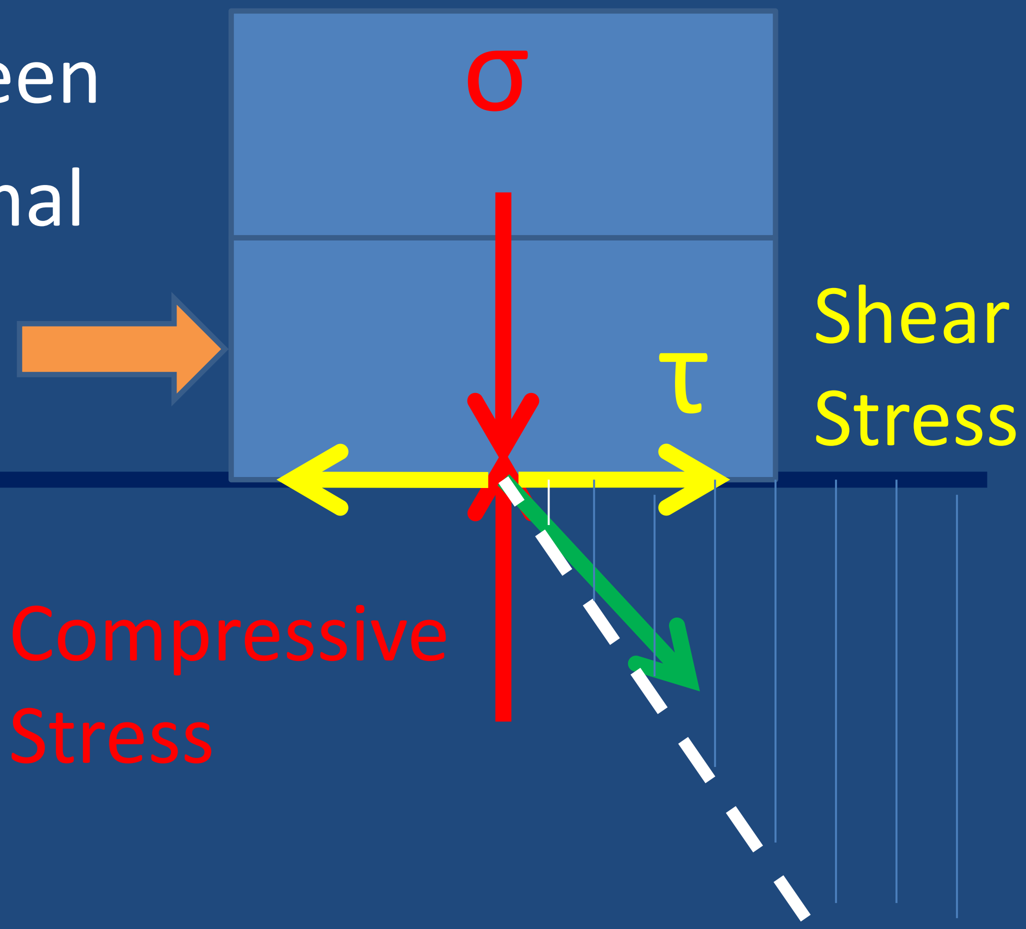

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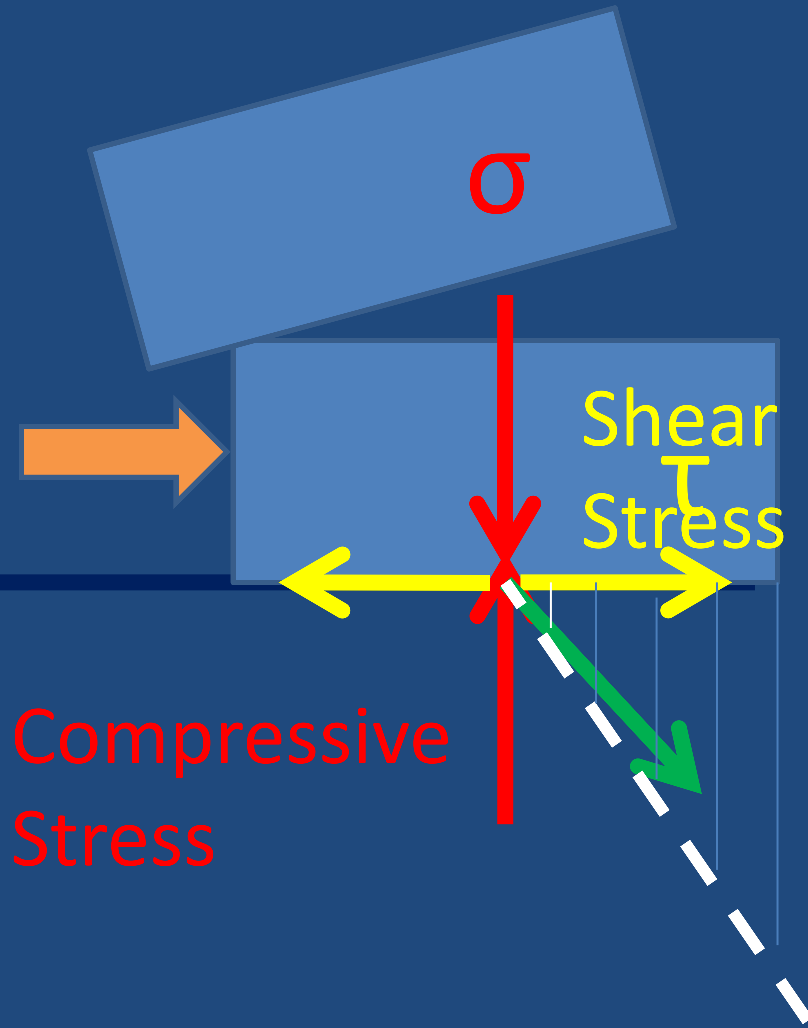

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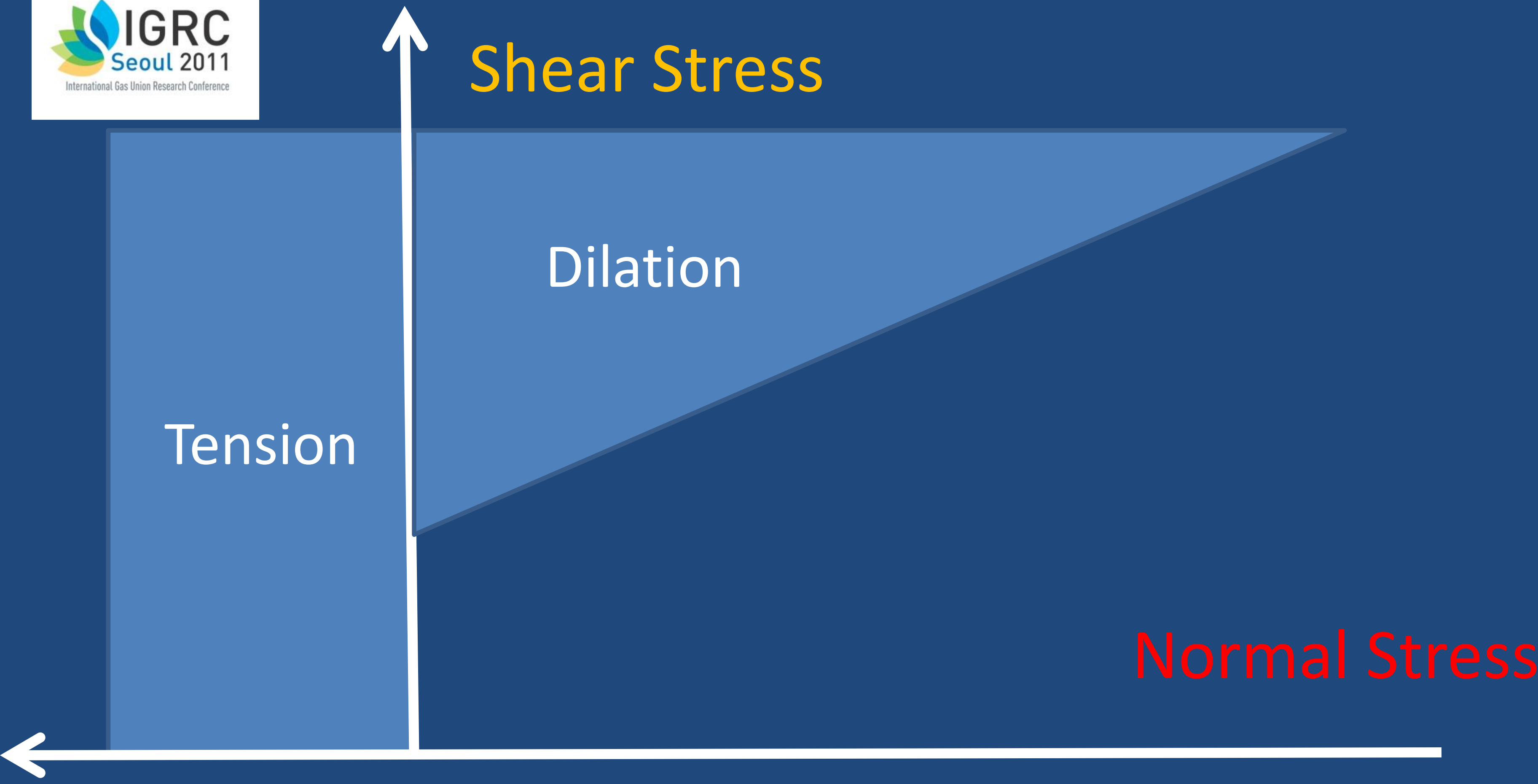

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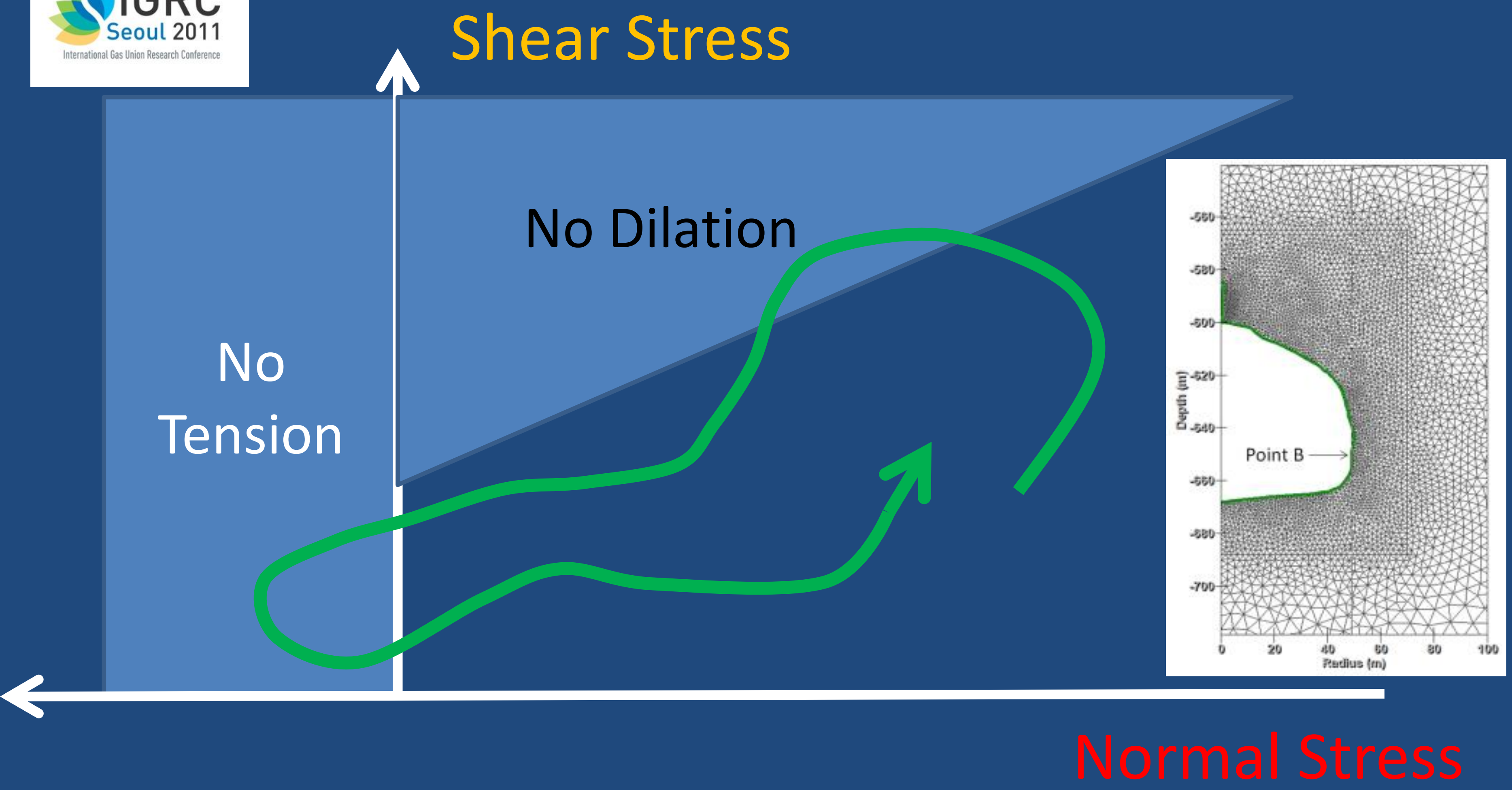

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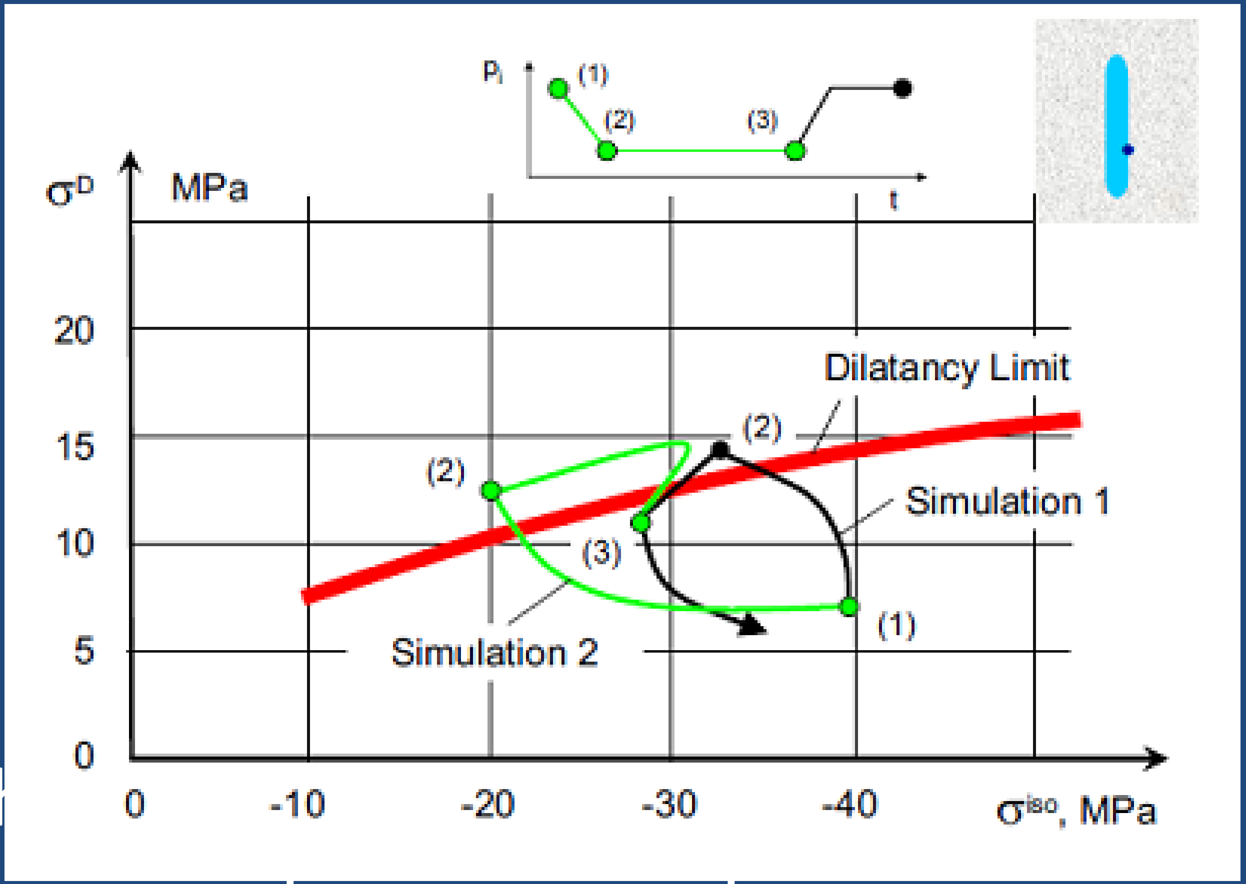
"Bumble-bee flight"



During cavern operations, State of stress at each point of the rock-mass, experiences a complicated path in the mean pressure – shear stress plane (K. Staudmeister, 2008)

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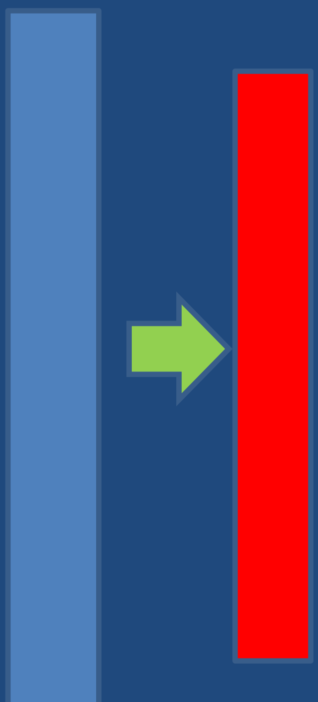
TENSILE STRESSES

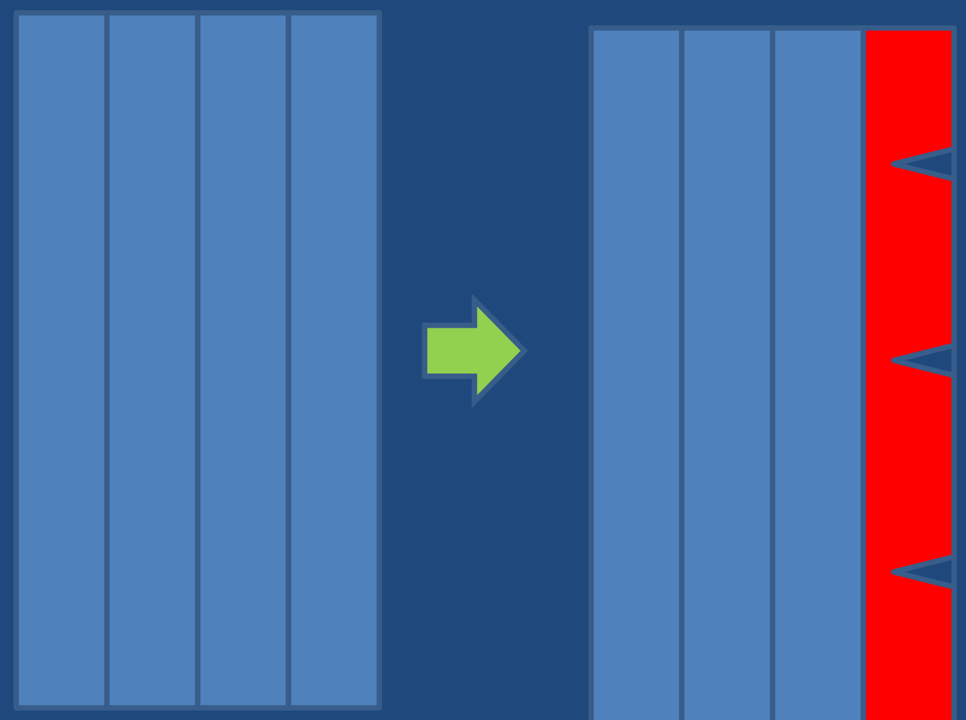
Gas cooling by ΔT (°C) generates an
$\alpha E \Delta T$ (MPa) Tensile stress at cavern wall

$\alpha \Delta T$ is as large as 1 MPa/°C !

However temperature (and tensile stresses) penetration depth is small: shallow fractures are created. They are perpendicular to cavern wall and generate no or small spalling

TENSILE STRESSES





COOLING
(CONTRACTION)

COOLING AT CAVERN WALL

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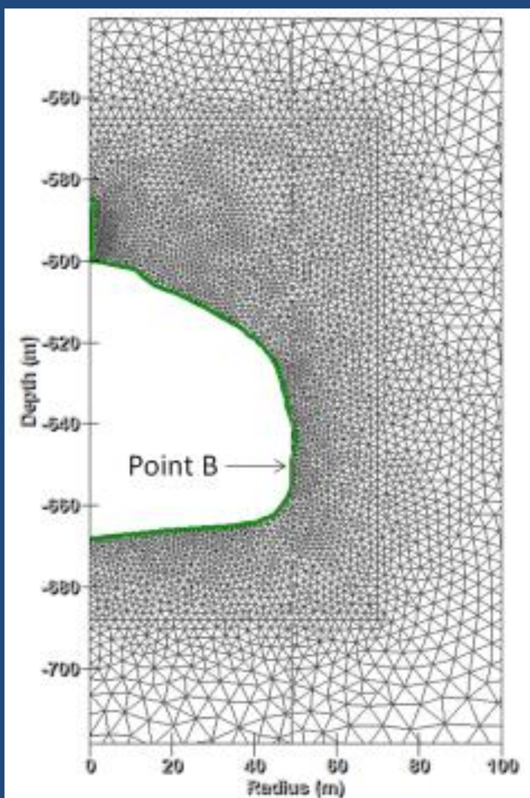
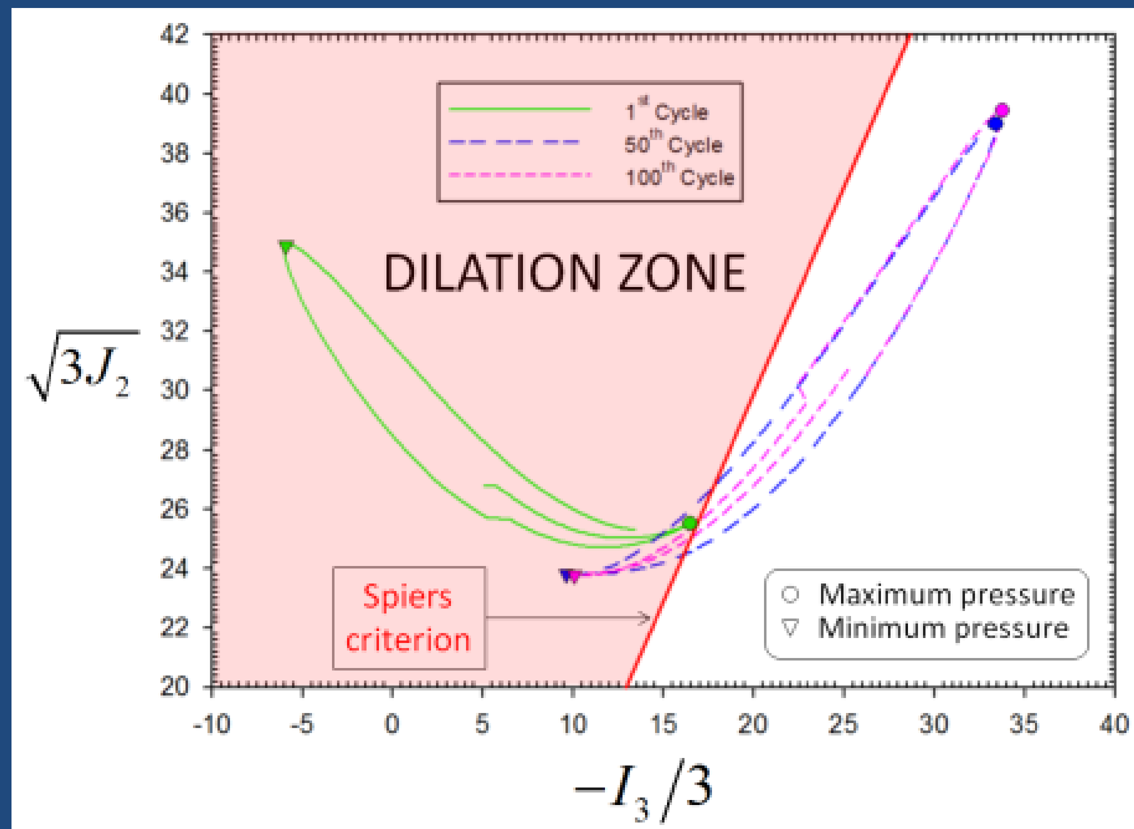
Bumble-bee flight, 100 cycles





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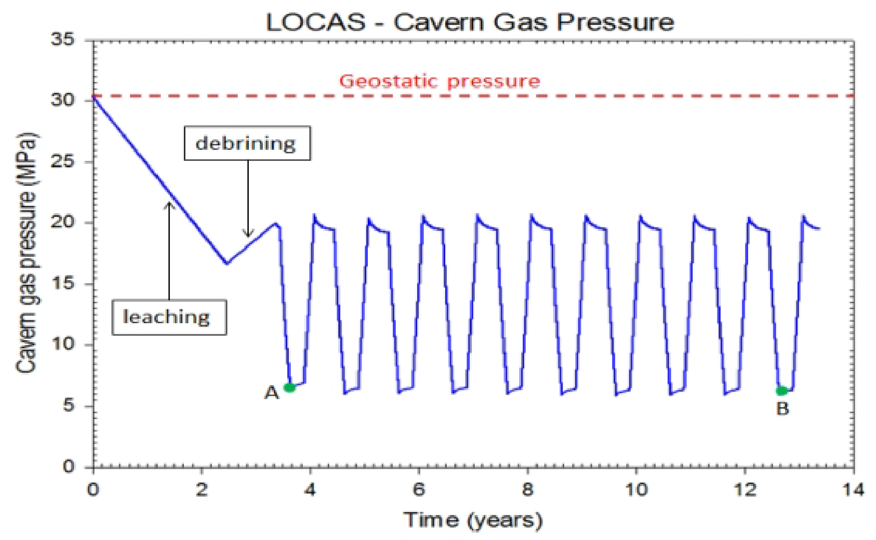

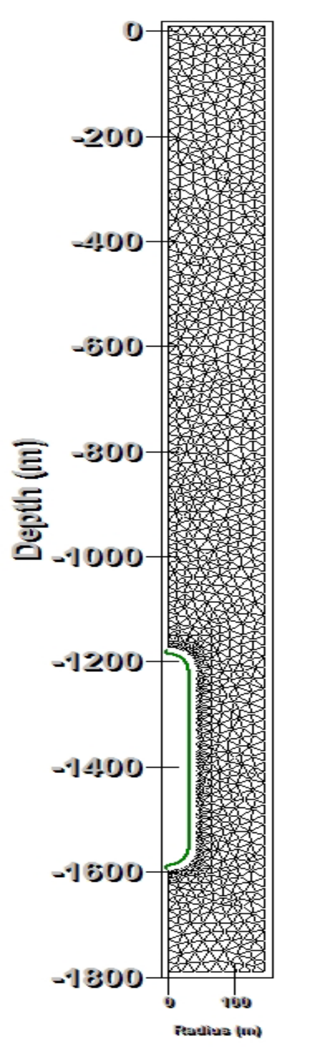

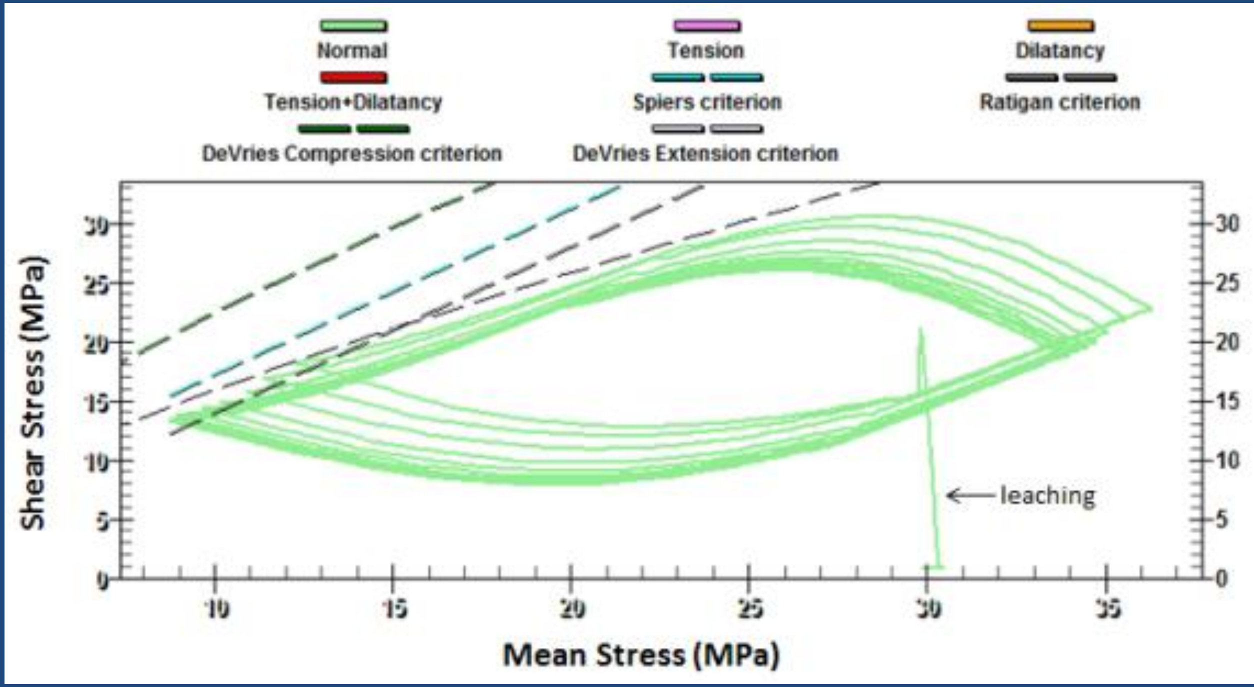

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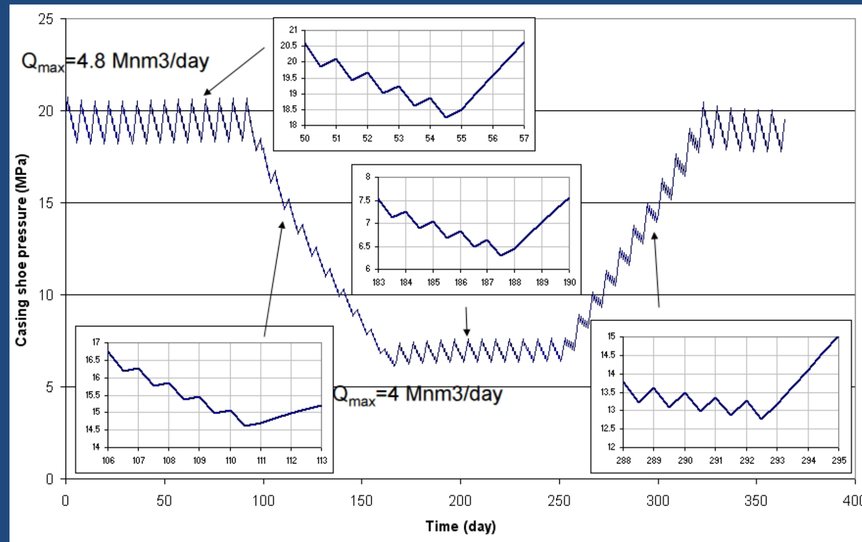

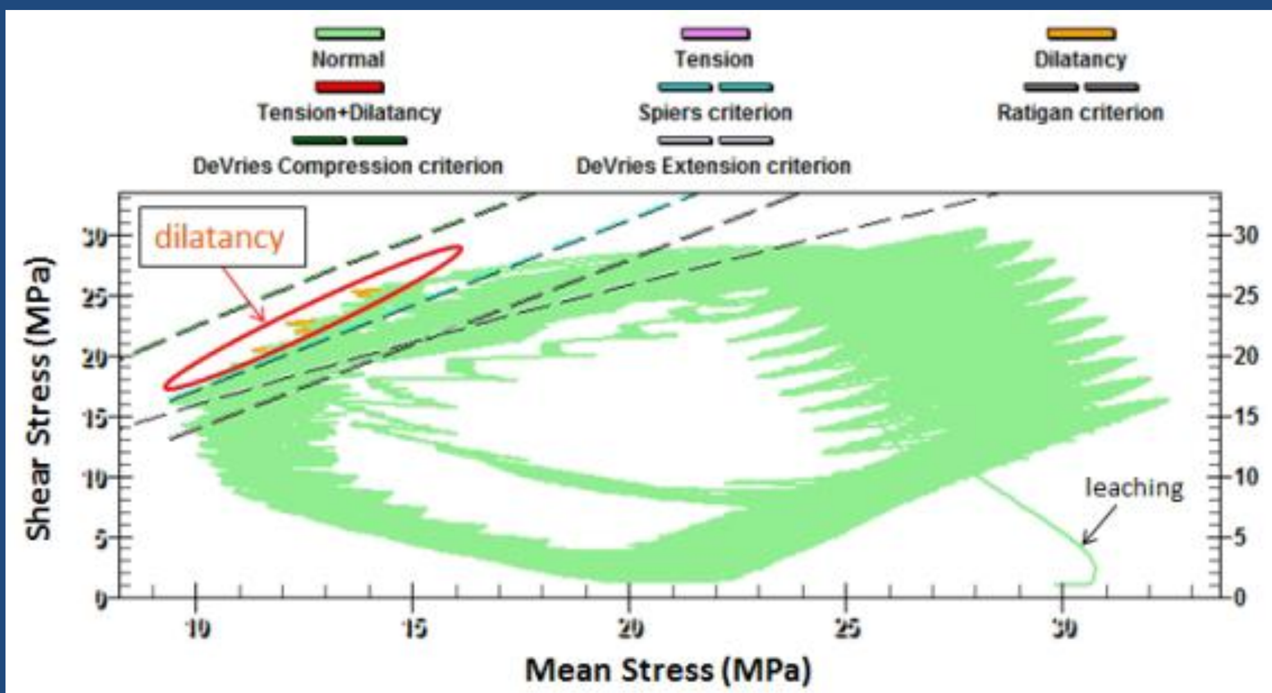

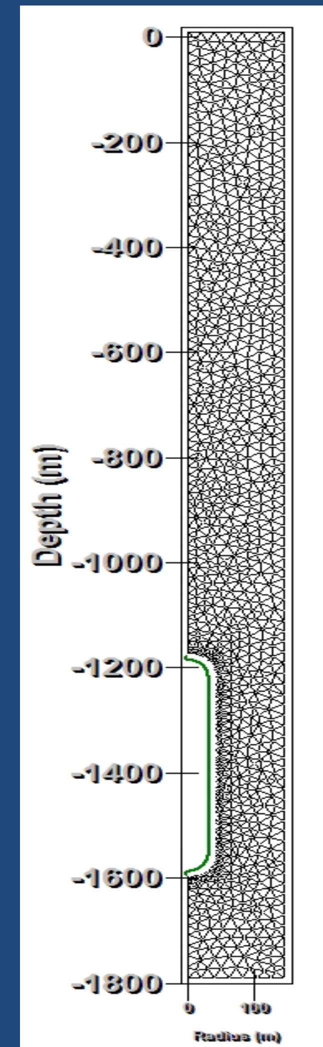

Conclusions

In a seasonal gas storage cavern, gas pressure changes are slow and temperature changes are small.

When faster pressure changes are considered – the present trend – severe gas cooling and additional tensile stresses (1 Mpa/°C) are generated at the cavern wall and roof. However depth of penetration is small and no or minute “spalling” is generated.

Conclusions

Onset of dilation (excessive shear stress, when compared to normal stress) is more likely in a highly-cycled cavern.

- Whether the dilation criterion is sensitive to stress rate is an open question
- Whether constitutive equations are to be modified to take into account cycling (fatigue) also is an opened question, requiring a large effort in laboratory tests.
- Numerical tools are able to compute the effects of complex cavern pressure history.
- Two CAES (COMPRESSED AIR ENERGY STORAGE) facilities experiencing rapid daily pressure changes have been operated successfully over several decades

QUESTIONS?

heading

- text