Thermoelastic effects on resonance frequency of rock columns at daily scale, and modeling by acousto-elasticity

Antoine GUILLEMOT
(ISTerre, Géolithe)

With Eric LAROSE, Laurent BAILLET (ISTerre)
Pierre BOTTELIN (SAGE, ADRGT)

EGU 2022

Sharing not permitted

25th May 2022

Overview of the study

- Plenty of observations to monitor erosion and fracturing of rock masses/ slope instabilities
  - Meteorology (environmental forcing)
  - Photogrammetry
  - Extensometry
  - Environmental seismology
  - Statistics

- Deterministic processes : need for better understanding
  - Environmental forcings (rain/moisture, freezing, solar radiation) > chemical forcings (dissolution, alteration)

  D'Amato et al. (2016), Loew et al. (2022)

  - Influence of solar radiation on jointed rock blocks fracturing

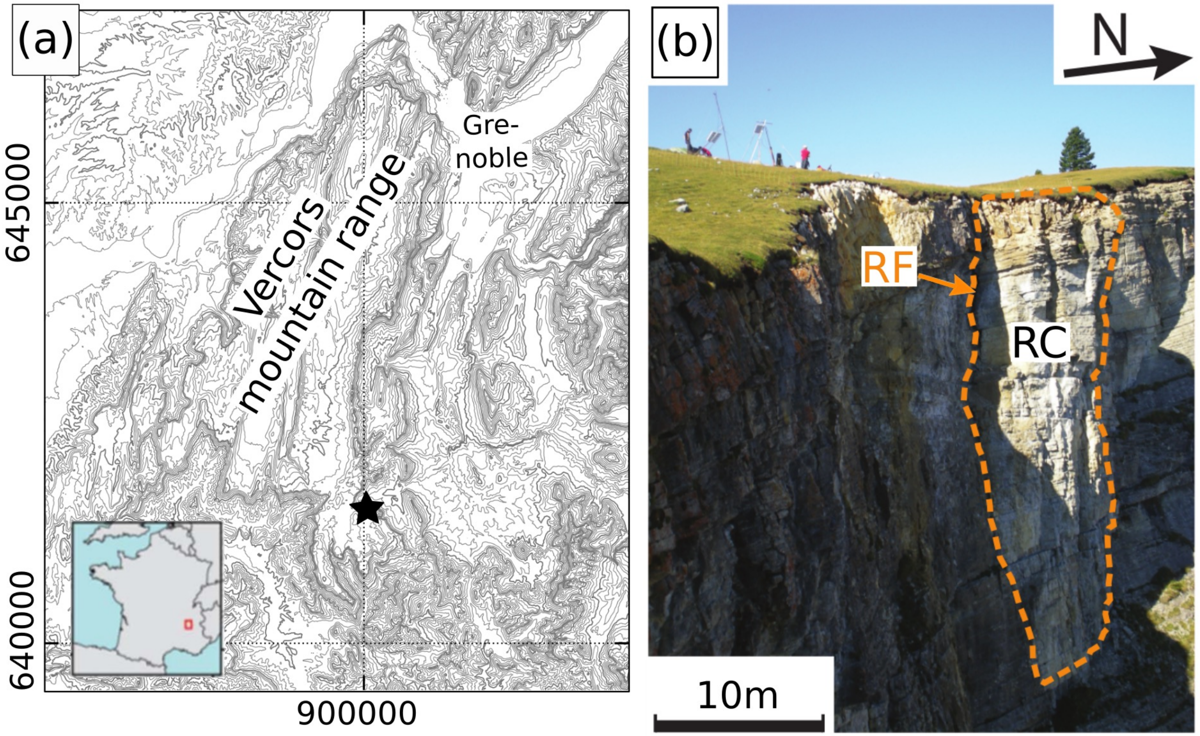
  Marmoni et al. (2020)

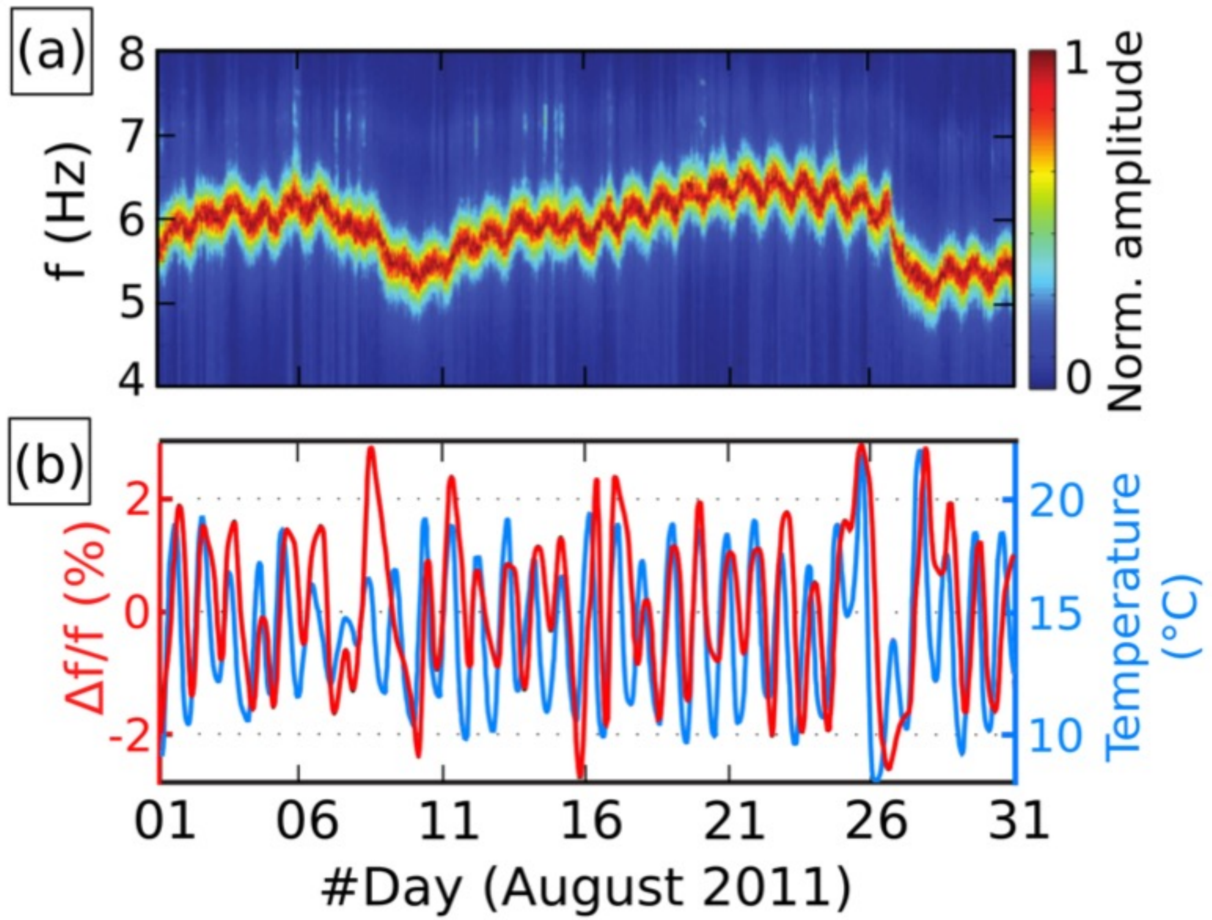
➡ The evolution of stress-stiffening near the surface of rock columns:
Key parameter to understand damaging and fracturing processes

➡ Here: we explain changes in elastic properties (thermally-induced stresses) observed on rock columns
By 3D thermo-acousto-elastic modelling

Observations (Les Arches, Vercors, France)
Daily scale

- Daily variations of air temperature ($\Delta T = \sim 10°C$)
- Daily variations of resonance frequencies ($\Delta f / f = \sim 4\ \%$)





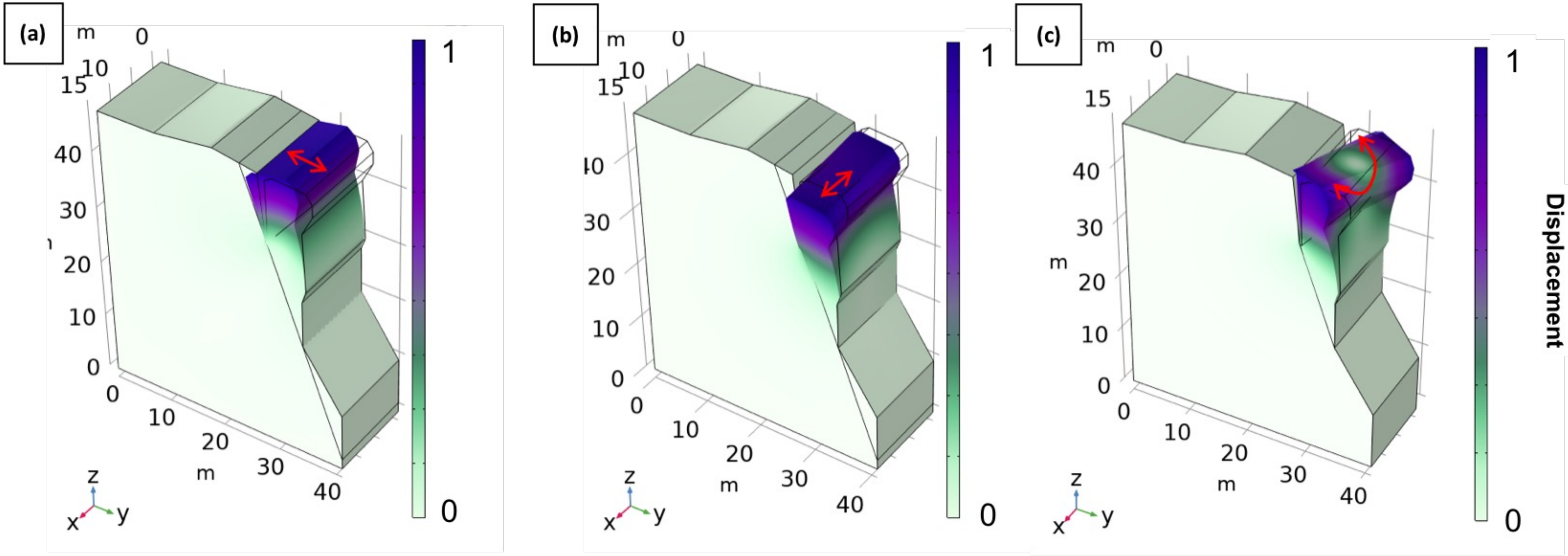
From Bottelin et al. (2013)

3D thermo-acousto-elastic modelling
Simulation over 2 days (Comsol)
Geometry – Modal analysis

Mode 1
Resonance frequency $f_1 = 6{,}18\ Hz$

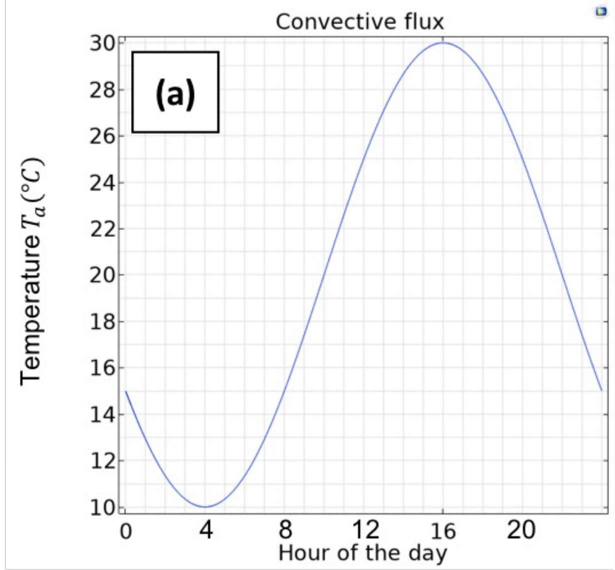
Mode 2
Resonance frequency $f_2 = 8{,}94\ Hz$

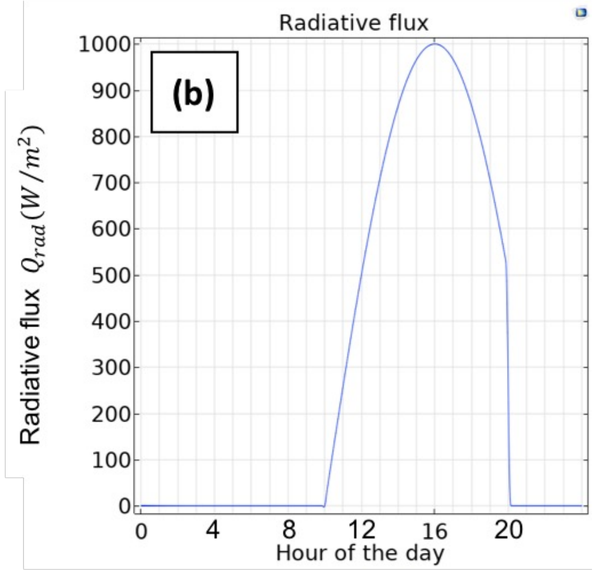
Mode 3
Resonance frequency $f_3 = 11{,}65\ Hz$

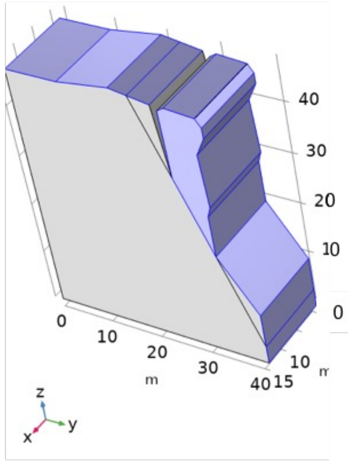


From Guillemot et al. (2022, in review)

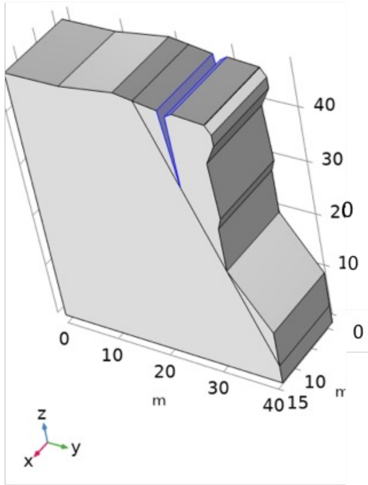
3D thermo-acousto-elastic modelling
Simulation over 2 days (Comsol)
Parametrization



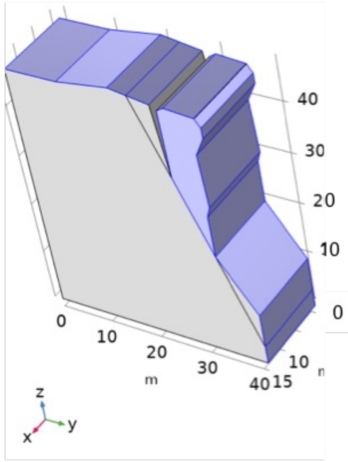




Thermal exchange coefficient
$h_1 = 50\ W/(m^2K)$



Thermal exchange coefficient
$h_2 = 10\ W/(m^2K)$



Geometry : Les Arches (Vercors, France)

Thermal parameters:

- Initial temperature: $T_0 = 20\ °C$
- Daily amplitude: $\Delta T_{day} = 20\ °C$
- Max radiation $Q_{rad,max} = 1000(W/m^2)$

Thermo-mechanical parameters:

- Thermal conductivity: $\mathrm{k} = 1\ W.mK^{-1}$
- Thermal capacity (constant pressure) : $C_p = 800\ J/(kg.K)$
- Thermal expansion coefficient: $\alpha = 2{,}8\,.\,10^{-6}\ K^{-1}$

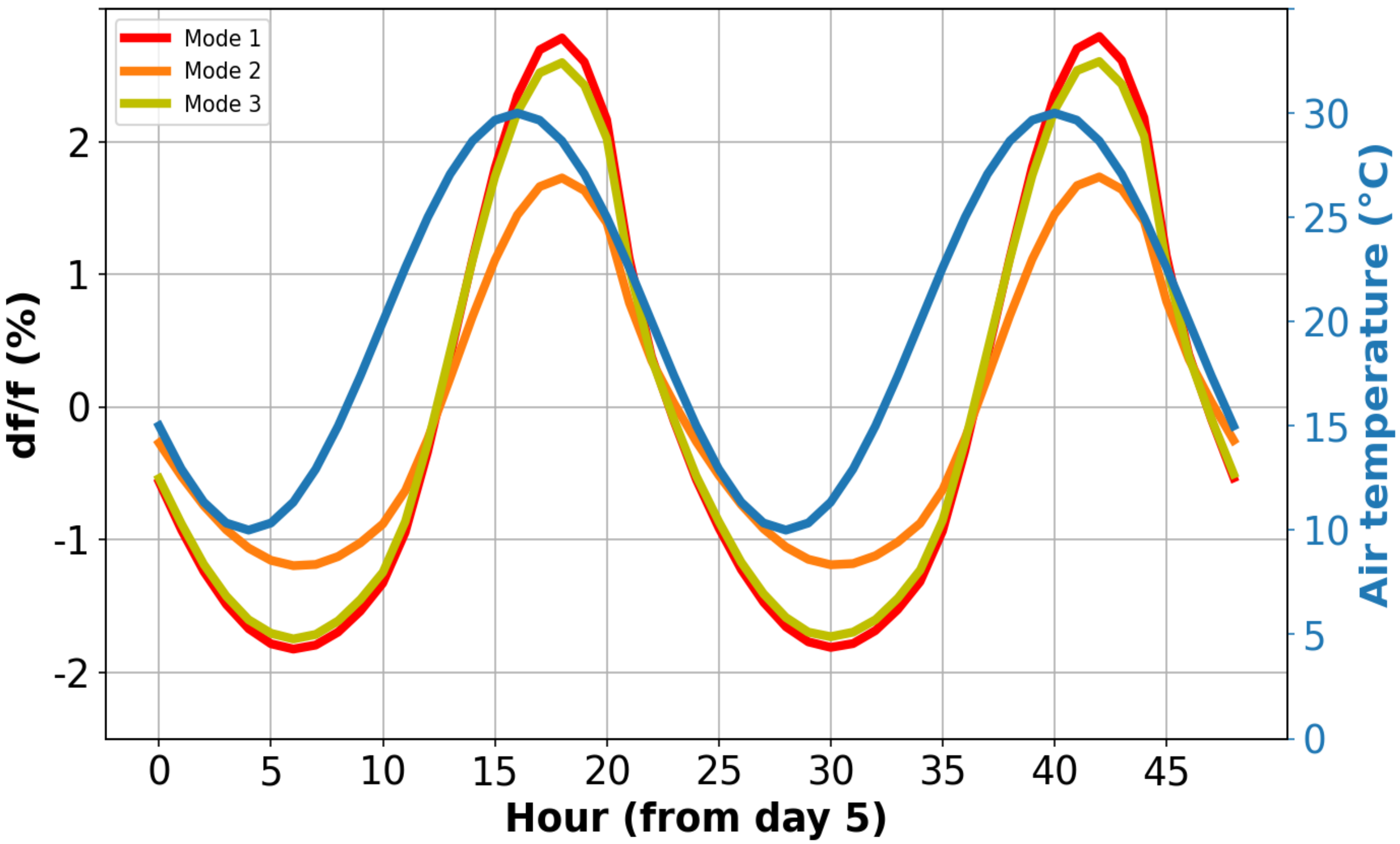
Acousto-elastic parameters

- P-wave velocity : $V_P = V_P^0(1 + A_P\Delta\sigma)$
- S-wave velocity: $V_S = V_S^0(1 + A_S\Delta\sigma)$
- $V_P^0 = 2722\ m/s$
- $V_S^0 = 954\ m/s$
- $A_P = 6.10^{-8}\ Pa^{-1}$
- $A_S = 5.10^{-7}\ Pa^{-1}$
- Density $\rho = 2650\ kg.m^{-3}$

From Guillemot et al. (2022, in review)

3D thermo-acousto-elastic modelling
Simulation over 2 days (Comsol)
Results

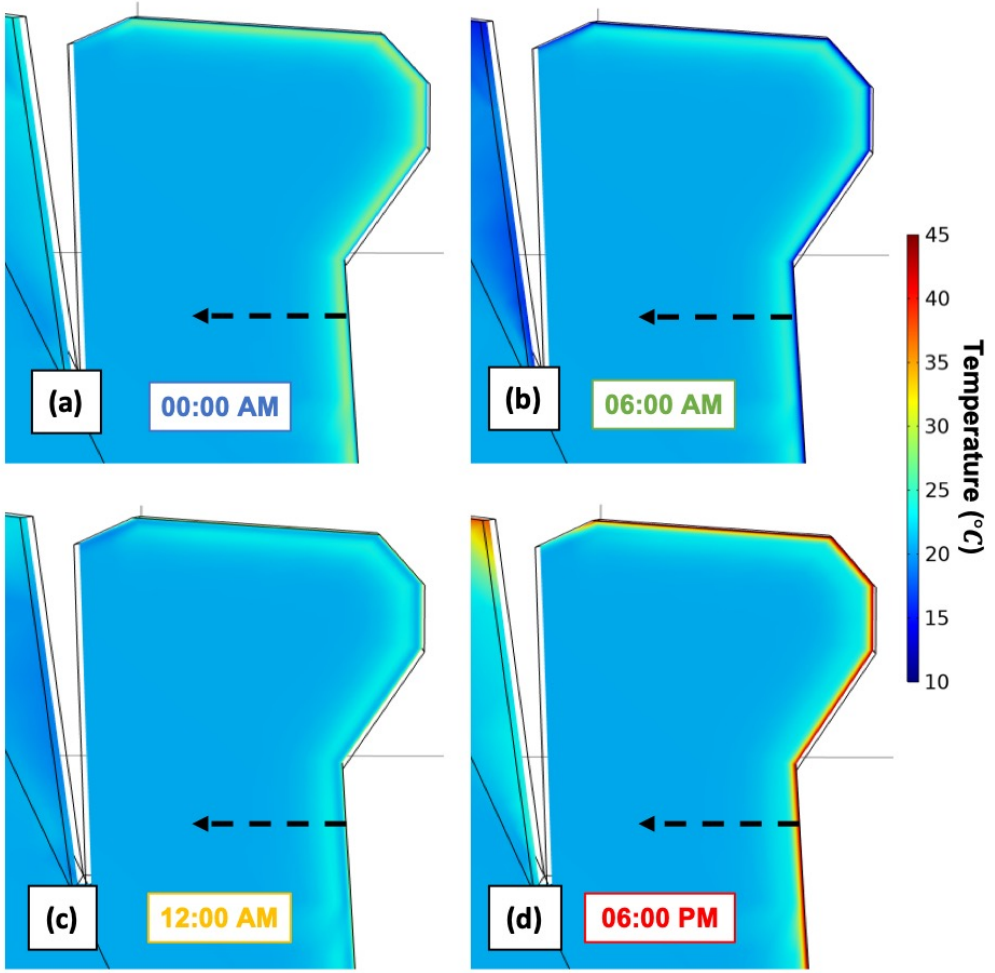
Relative variation of resonance frequency
$df/f \sim 4\%$
Delay time with air temperature
$d\varphi \sim 2{,}5\ h$



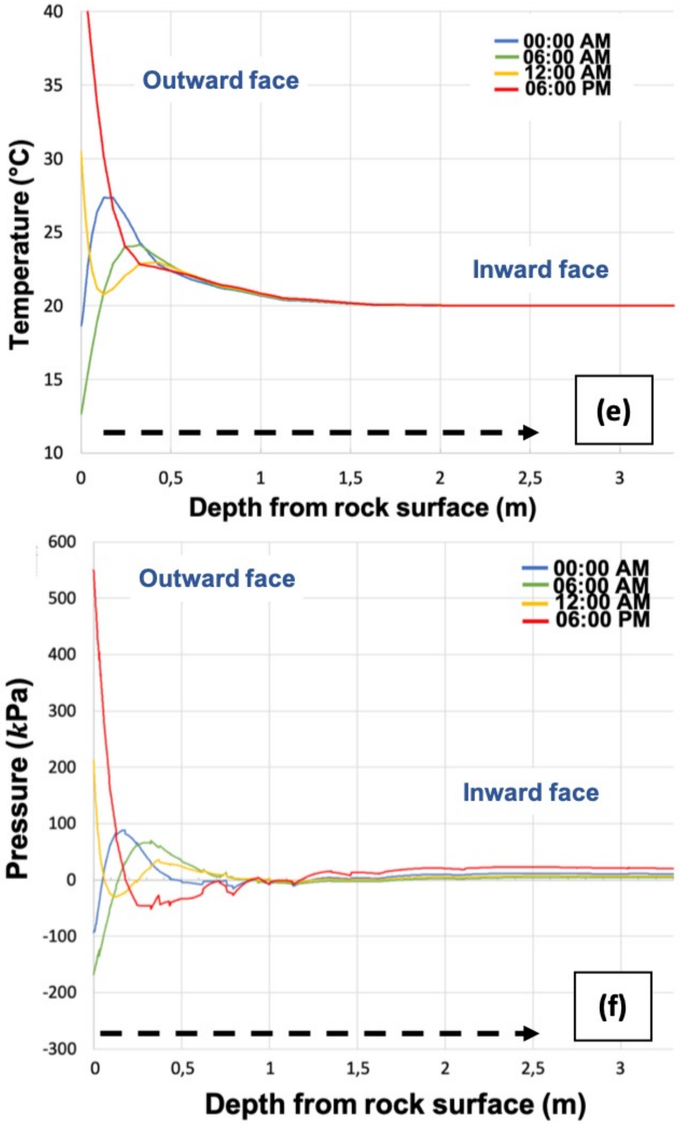
From Guillemot et al. (2022, in review)

3D thermo-acousto-elastic modelling
Simulation over 2 days (Comsol)
Results

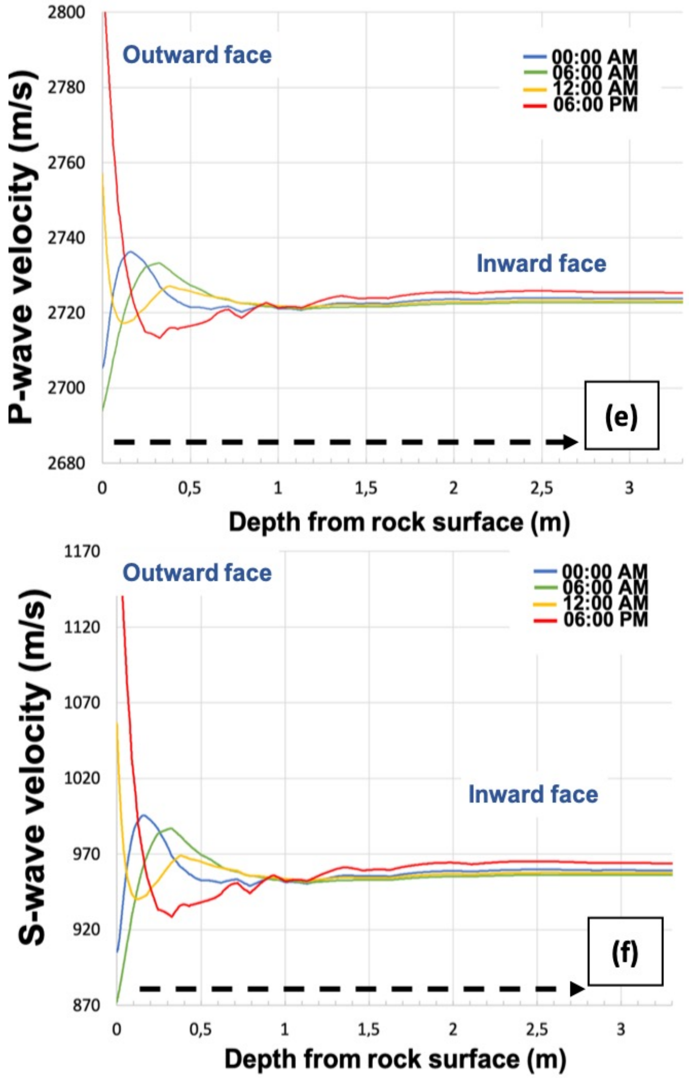
Evolution of elastic properties over around 60 cm depth



Temperature and Stress

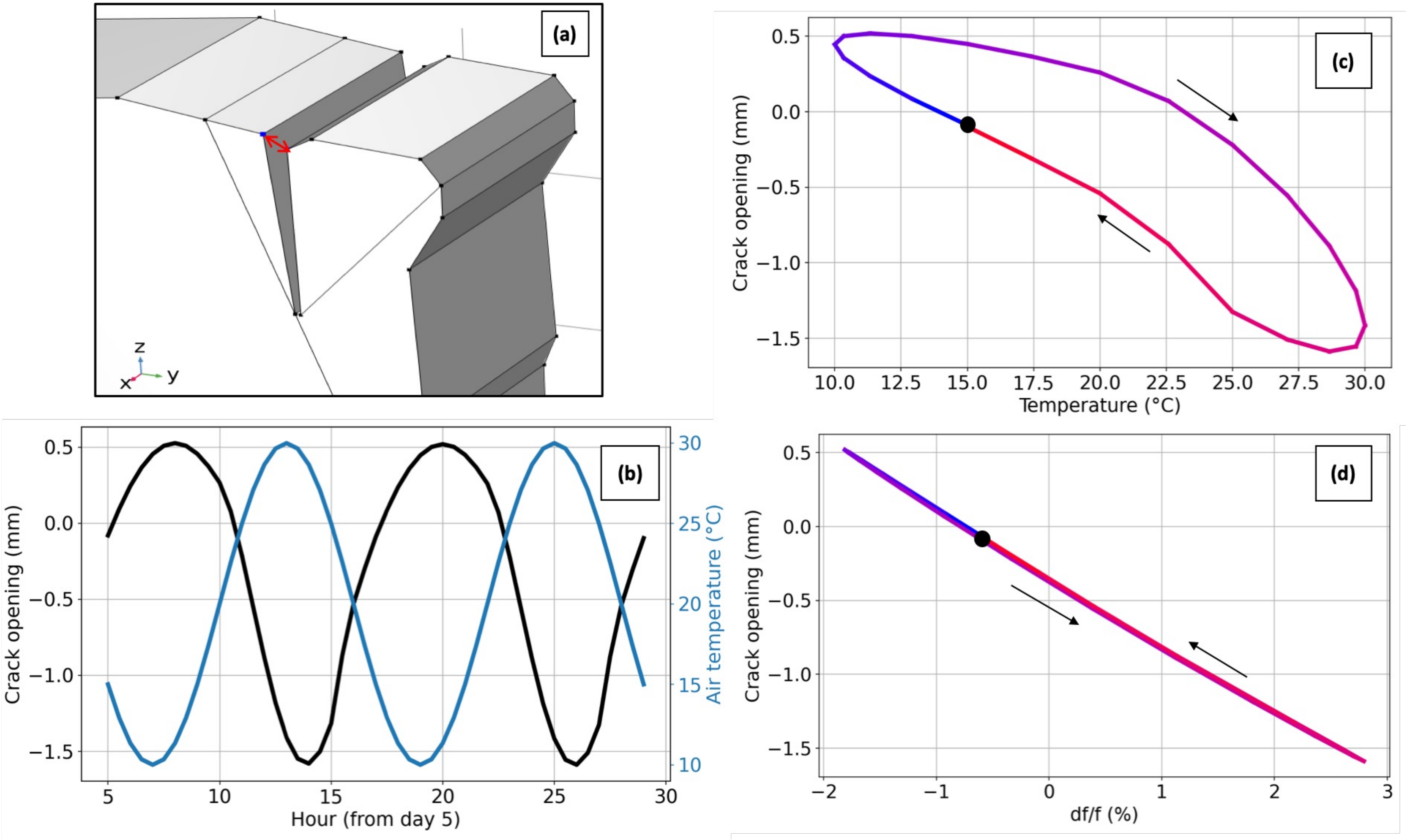


Seismic velocities



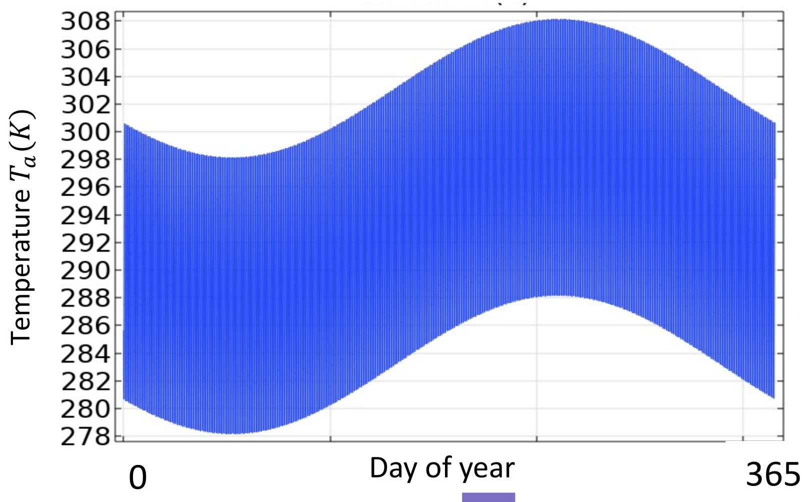
3D thermo-acousto-elastic modelling
Simulation over 2 days (Comsol)

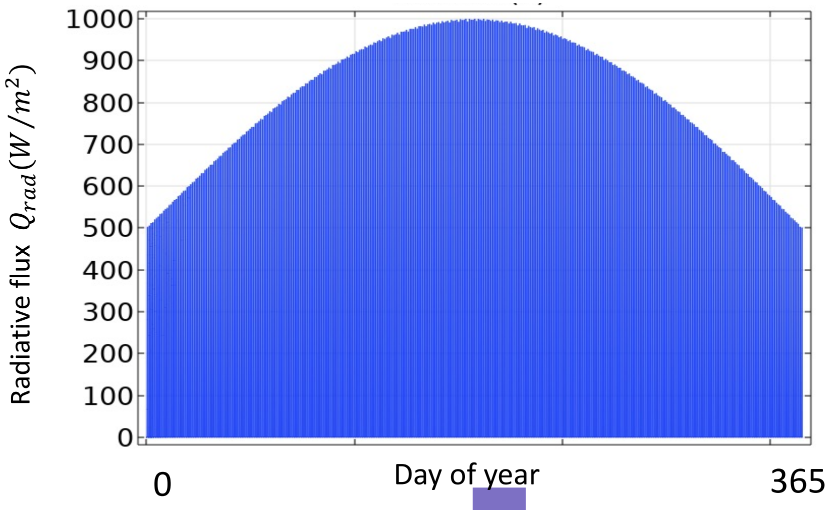
Response of the fracture on thermal forcing : fracture opening

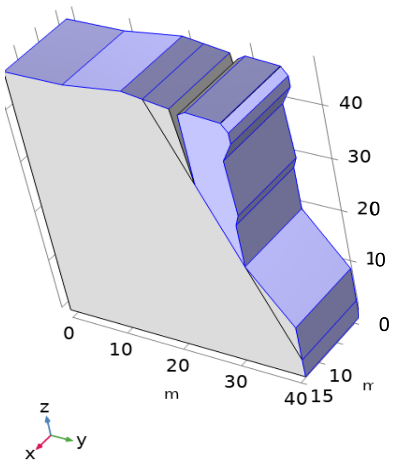


From Guillemot et al. (2022, in review)

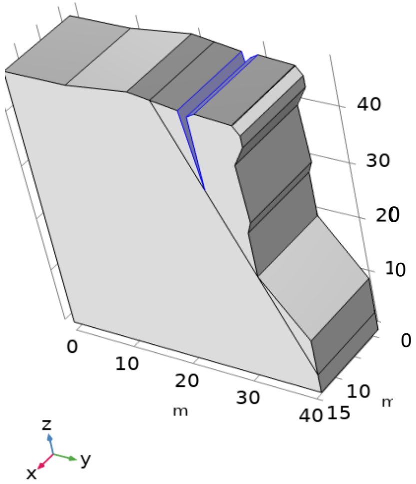
3D thermo-acousto-elastic modelling
Simulation over one year (Comsol)
Parametrization



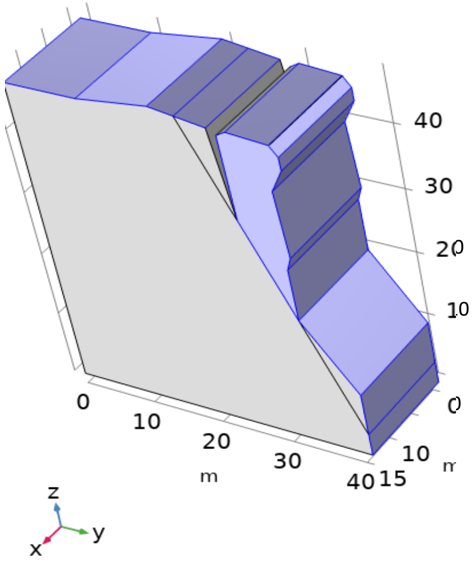




Thermal exchange coefficient
$h_1 = 50\, W/(m^2K)$



Thermal exchange coefficient
$h_2 = 10\, W/(m^2K)$



Geometry : Les Arches (Vercors, France)

Thermal parameters:

- Initial temperature : $T_0 = 15\,°C$
- Yearly mean temperature : $T_m = 20\,°C$
- Daily amplitude: $\Delta T_{day} = 10\,°C$
- Yearly amplitude: $\Delta T_{year} = 10\,°C$
- Minimum radiation $Q_{rad,min} = 500(W/m^2)$
- Maximum radiation $Q_{rad,max} = 1000(W/m^2)$

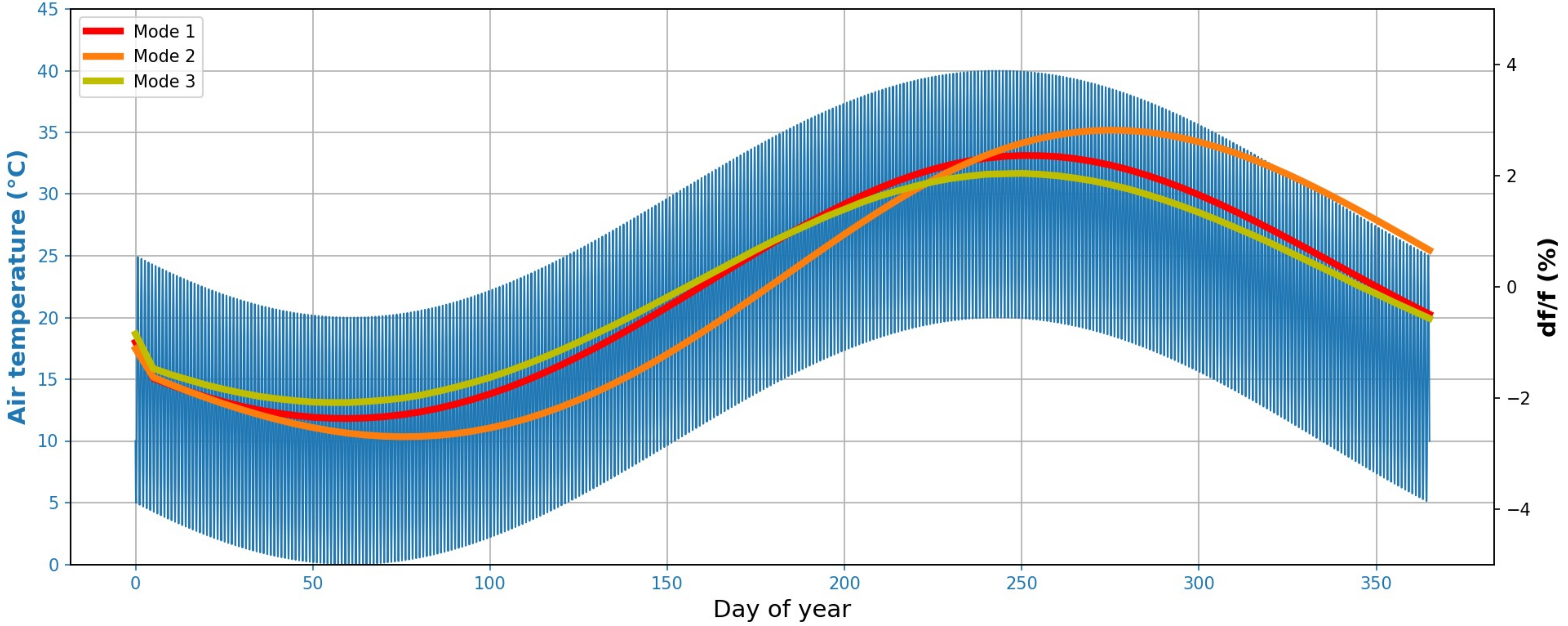
Thermo-mechanical parameters:

- Thermal conductivity: $\mathrm{k} = 1\, W.mK^{-1}$
- Thermal capacity (constant pressure) :
  $C_p = 800\ J/(kg.K)$
- Thermal expansion coefficient:
  $\alpha = 2{,}8\,.\,10^{-6}\ K^{-1}$

Acousto-elastic parameters

- P-wave velocity : $V_P = V_P^0(1 + A_P\Delta\sigma)$
- S-wave velocity: $V_S = V_S^0(1 + A_S\Delta\sigma)$
- $V_P^0 = 2722\ m/s$
- $V_S^0 = 954\ m/s$
- $A_P = 6.10^{-8}\ Pa^{-1}$
- $A_S = 5.10^{-7}\ Pa^{-1}$
- Density $\rho = 2650\ kg.m^{-3}$

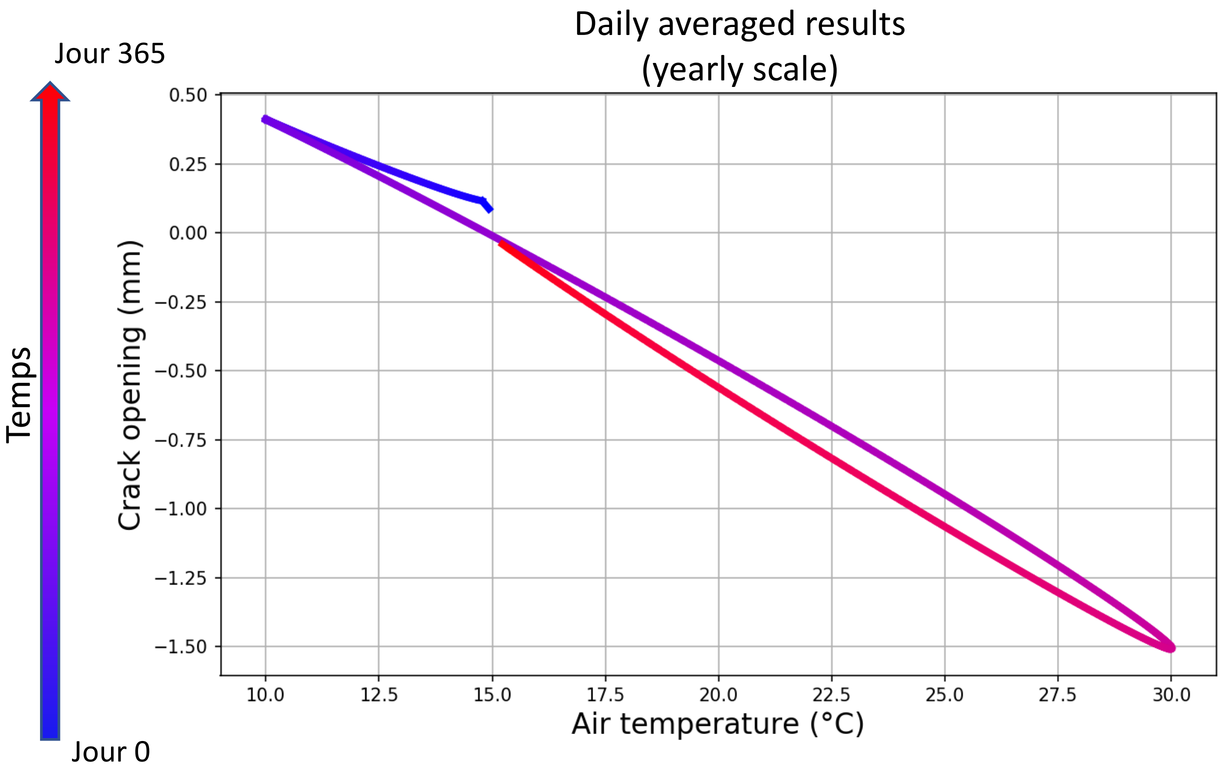
3D thermo-acousto-elastic modelling
Simulation over one year (Comsol)
Results
Link temperature – resonance frequency

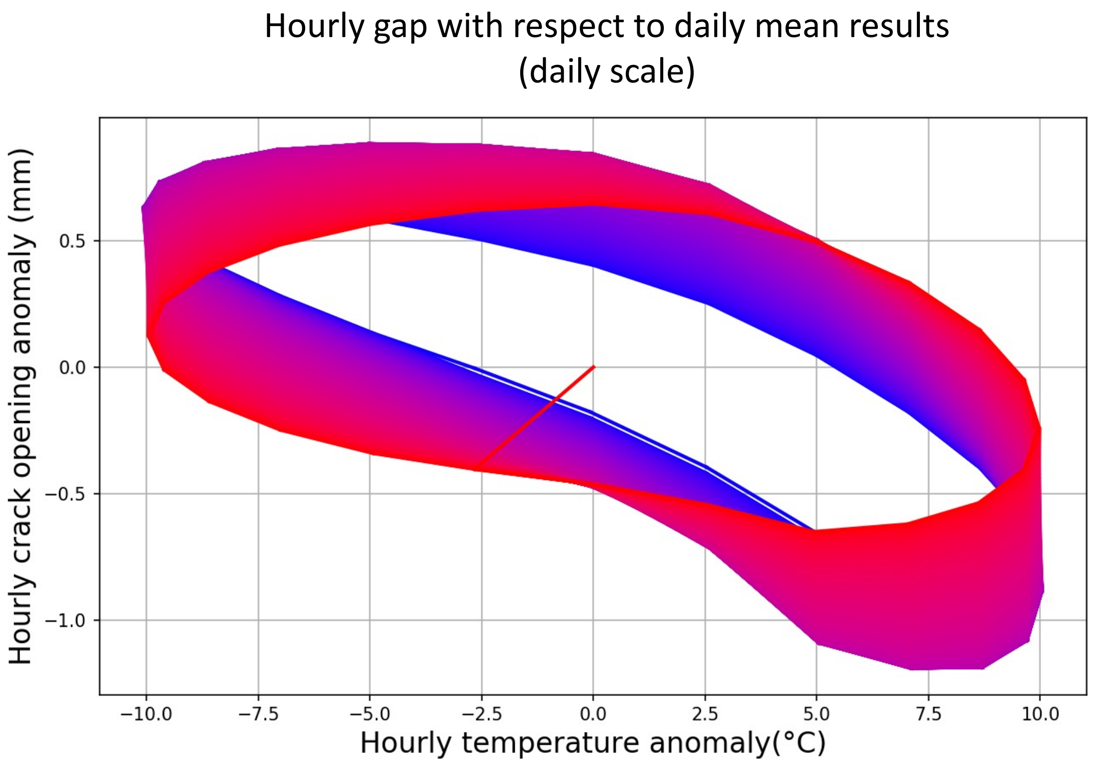


- Resonance frequencies of the rock column every 5 days (same hour)
- Positive correlation with temperature (for the three modes)
- Variability of amplitude (+/- 2-3%) and time delay (30-55 days) with modes
- In the future : Possibility to invert an « apparent » acousto-elastic coefficient ? Machine Learning ?

3D thermo-acousto-elastic modelling
Simulation over one year (Comsol)
Results

Link temperature – fracture opening





Good accordance between modelled results and observations (negative correlation)
Strong dependency on geometry and thermal forcing
In the future : Possibility to invert an « apparent » thermal expansion coefficient ? Machine Learning ?

Conclusions

Thermal forcings (radiative + convective) → Pyranometers, thermometers

Surficial dilation of the rock mass → Extensometers

Additional thermally-induced stress → Seismometers

Daily scale

Reversibility ?
Inversion of thermo-acousto-elastic parameters ?

Yearly scale

State of damaging ?
Fracturation monitoring ?

…new monitoring tools (instrumentation + modelling)

Questions ?

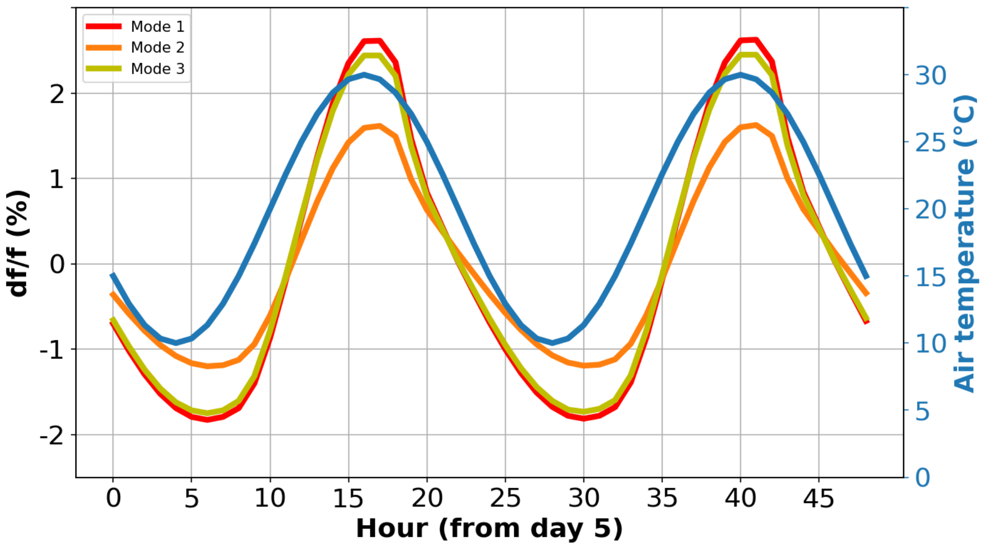
References

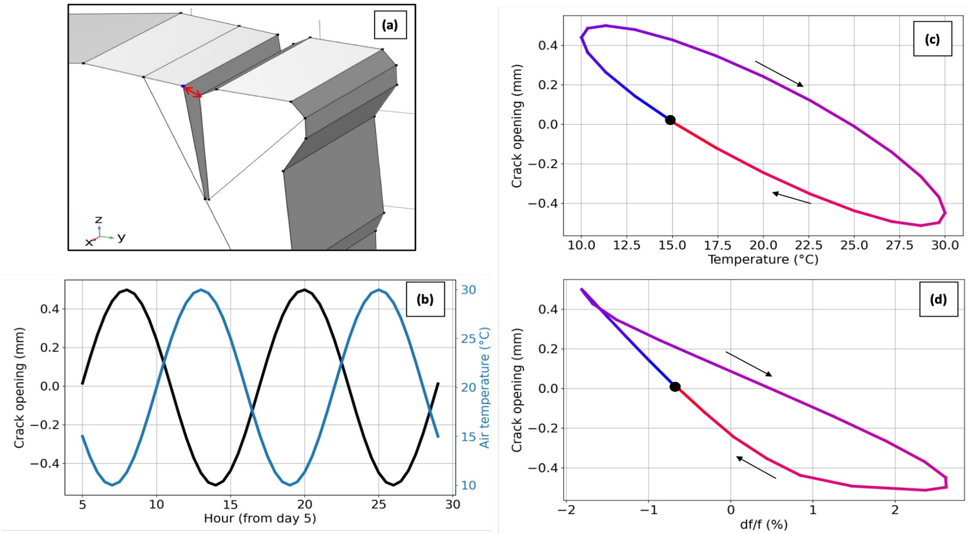
- D'Amato J., Hantz D., Guerin A., Jaboyedoff M., Baillet L., Mariscal A. (2016) Influence of meteorological factors on rockfall occurrence in a middle mountain limestone cliff. *Natural Hazards and Earth System Sciences*, 16: 719-735.
- Bottelin, P., Lévy, C., Baillet, L., Jongmans, D. & Guéguen, P. (2013) Modal and thermal analysis of Les Arches unstable rock column (Vercors massif, French Alps). *Geophys J Int*, **194**, 849–858. doi:10.1093/gji/ggt046
- Marmoni, G. M., Fiorucci, M., Grechi, G., & Martino, S. (2020). Modelling of thermo-mechanical effects in a rock quarry wall induced by near-surface temperature fluctuations. *International Journal of Rock Mechanics and Mining Sciences*, *134*, 104440
- Guillemot A., Bottelin P., Baillet L., Larose E., (2022) Changes in resonance frequency of rock columns due to thermoelastic effects on a daily scale: observations, modelling and insights to improve monitoring systems, *Geophysical Journal International*, under review
- Loew, S., Hantz, D., Gerber, W., 2022. Rockfall Causes and Transport Mechanisms – A Review. In: Shroder, J.J.F. (Ed.), Treatise on Geomorphology, vol. 5. Elsevier, Academic Press, pp. 137–168.

Appendix A

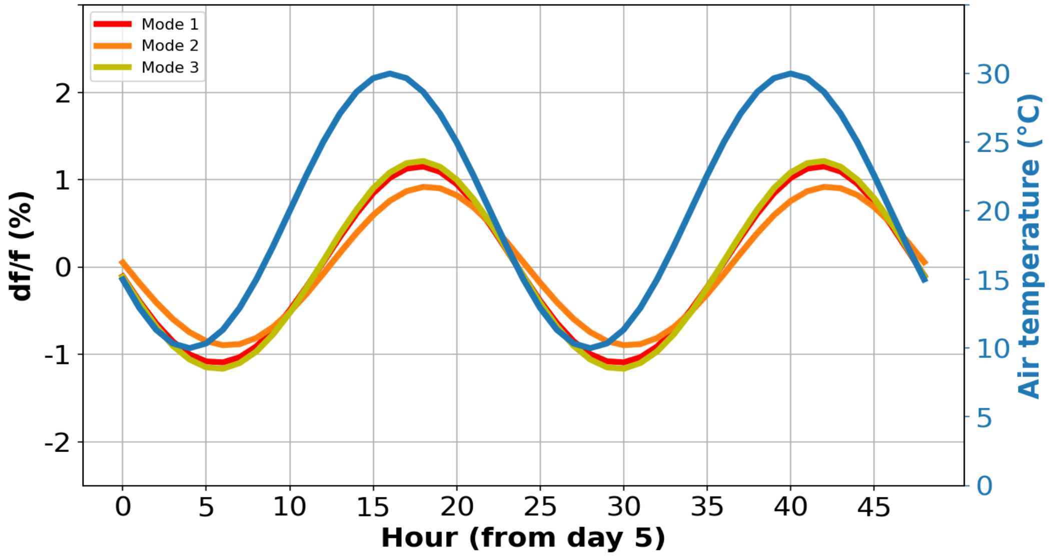
3D thermo-acousto-elastic modelling
Simulation over 2 days (Comsol)
Sensitivity to thermal forcing

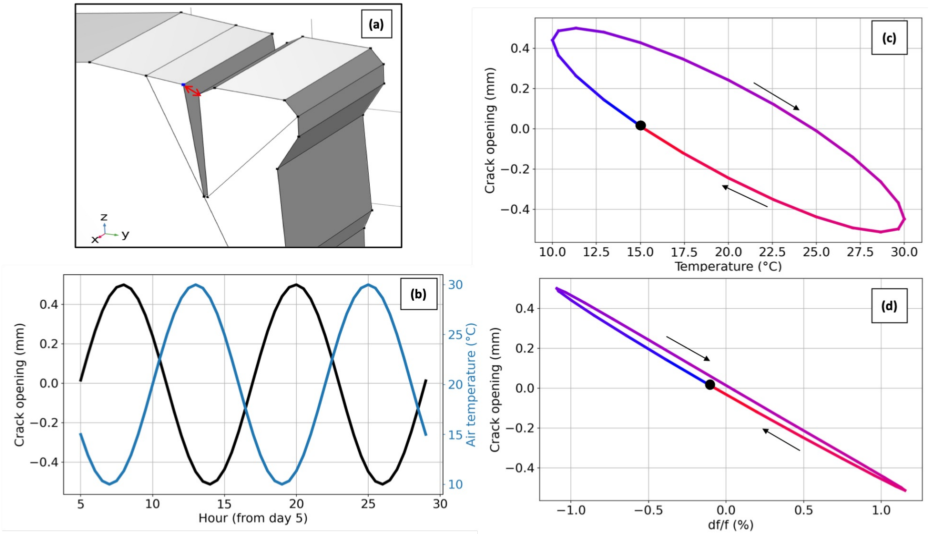
Radiative/Convective relative phases





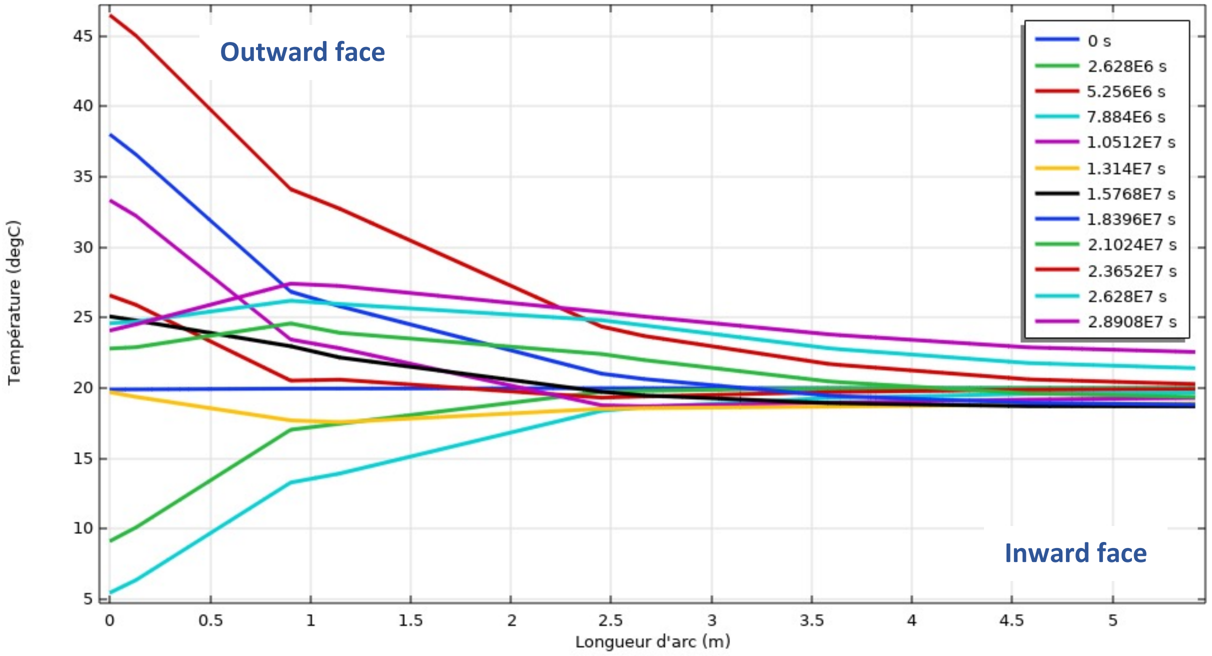
Radiative/Convective relative intensity

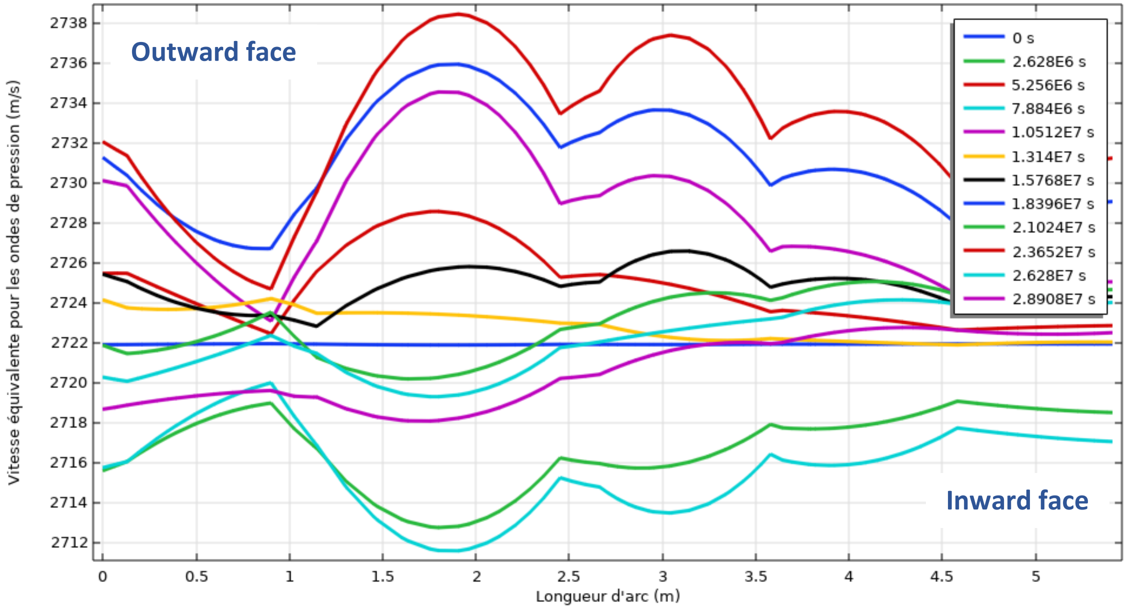


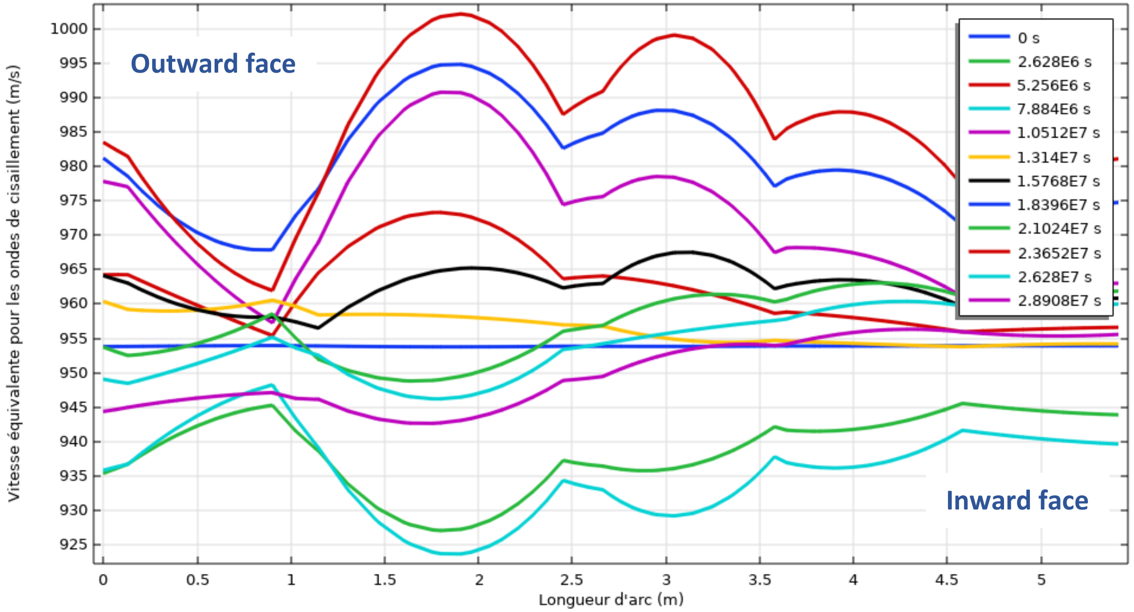


Appendix B

3D thermo-acousto-elastic modelling
Simulation over one year (Comsol)
Results







Temperature, Vp and Vs along a cross-section perpendicular to the rock column surface (at 12 times of the year) :

- Over one year, the thermal wave penetrates significantly (at > 2m depth)
- Elastic parameters evolve within the whole bulk mass