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Effect of thermal cycles on rock outcrops

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Abstract

Natural temperature variations are thought to play a role in rock slope instabilities. Rather than high temperatures, the recurrence of temperature variations (daily, or annual cycles) could contribute to a destabilization of the rock-mass. Many recent observations have shown the role of positive temperature variations in the propagation of surface fractures. Two French sites, overhanging roads and for one of them a village, subjected to periodic rockfalls during periods without triggering factors such as rainfall event, seismic activity or freeze-thaw, were monitored, and the role of temperature variation is analyzed through fracture mechanics.

The sites located in different geological and geomorphological context (a gneissic rocky slope and a limestone cliff) are first described. Their rocks were both subjected to different laboratory tests, but the limestone underwent a larger panel of experiments (about 1000 thermal cycles, DIC analyses on fracture propagation, damage evaluation with V_P/V_S *measurements). Both sites were monitored for several years with different apparatus, including the temperature variation in the rock-mass and the potential induced effects.*

Several mechanisms may coexist to explain initiation and progressive failure due to temperature variation: thermal shock, creation and pervasion of fractures between minerals at the surface linked to differences in their light-transmissivity, thermal fatigue. It is shown, that in both cases the possibility of fracture propagation could contribute to a destabilization of the rock-mass.

It is possible to show that the critical tensile stress intensity factor (K_I) *can be in the same order of magnitude as fracture toughness* (K_{Ic}) *which can explain the fracture propagation. Some extension strain criterion (instead of stress criteria) could also be temporally reached due to temperature variations and could explain the fracture propagation.*

1 INTRODUCTION

Many recent observations have shown the role of positive temperature variations in the propagation of surface fractures. Rather than high temperatures, the recurrence of temperature variations (daily, or annual cycles) could contribute to a destabilization of the rock-mass. The phenomenon of thermal fatigue has been very little studied as far as rocks are concerned, whereas it is rather well characterized for other types of materials: Elsevier published a journal dedicated to fatigue (International Journal of fatigue). In the case of rocks, thermal phenomena and their impacts on mechanical behavior have been analyzed from a micro-structural point of view, for high temperatures and it is now well-known that an increase in temperature causes a dilatation of crystals (Arnould et al., 2004; Gasc-Barbier et al., 2017). This dilatation may lead to the development of inter-granular traction and compression stresses, and if those stresses are greater than fracture strength, inter-granular and intra-granular cracks may take place. Yet, the fatigue phenomenon (cyclic repetition of a temperature variation which is less extreme than the one that may lead to this inter-granular or intra-granular fracture) is a phenomenon which has not been much studied.

The principal studies on thermal fatigue on rocks come mainly from the field of geo-morphology, particularly in connection with the analysis of the evolutions of past climate that can explain the present shapes of those landforms: those studies remained essentially qualitative and not quantitative. Le Ber & Oter Duthoit (1987) proposed a thermal and thermodynamic approach to analyses the disaggregation of rock masses. This analysis is dedicated to the study of paleoclimates and was implemented to better understand the formation of slope deposits to propose transfer models permitting the reconstruction of the climactic conditions contemporary to their appearance. Since deterioration in the cliff only appears after several cycles, it means that it is a gradual and irreversible deterioration which leads to an increase of the « disorder ». Seen from a macroscopic system point of view, this irreversible evolution is quantified by the internal creation of entropy.

More recently, Hall (Hall, 1999), Hall & Thorn, (2014)) was one of the first to mention the importance of thermal fatigue in propagation of cracks, including in cold regions. He showed that, without neglecting the part played by freeze and thaw in the most arid regions, the impact of thermal stress could prevail in the destabilization of massifs. His studies, published in 1999, concentrate mainly on geomorphological considerations and thus are based on surface temperature recordings and on their in-depth variations in the massif as well as on the number of hours of sunshine. Yet, Hall does not propose a mechanical justification for cracks propagation; In 2011, Hall also constitutes an original experiment to measure temperatures inside a dry-brick construction (without cement) in order to record, along one full year, the temperatures of the different faces, according to the number of hours of sunshine and according to their depth. Those recordings showed that the freeze-thaw cycles not only occurred around 0°C but also that there is a coupling in the system that considers the exothermic reaction when the latent heat dissipates when the water freezes.

The idea that thermal fatigue can be at the origin of rock instabilities has also been discussed from the analysis of several Brazilian sites. Vargas and al. (2004, 2009) studied a number of rock falls that took place over a period of several years, more particularly in stone quarries situated in the area of Rio de Janeiro. Those fractures occurred mainly during dry periods, that is in June, July and August. Their papers present those different events and proposes a discussion on potential trigger mechanisms. The authors' proposition is that daily variations of temperature, particularly during the (dry) winter months can create thermal stresses with a magnitude sufficient to allow pre-existing fractures in the mass to propagate. A proposition of failure mechanism is then suggested.

Finally, in rock studies conducted in Valabres in the South of France, (Clément 2008, Gunzburger et al. 2005, Merrien et al., 2007), the authors underscored, both numerically and phenomenologically, the possibility that temperature variations, although very slight because of their daily periodicity, are enough to be a factor triggering instabilities. This site, and another French site are described below.

2 PRESENTATION OF THE SITES UNDER STUDY

2.1 A gneissic rock mass

For several years, geotechnical in situ measurements (including thermal quantities) have been collected at the “Rochers de Valabres” site (Figure 1), a gneissic rock mass, located in Southern French Alps. This site has been described in several papers (Gunzburger et al, 2005; Clement et al. 2009; Dünner et al. 2007; Gunzburger et al. 2011, Merrien-Soukatchoff et al. 2007; Merrien-Soukatchoff et al. 2010).

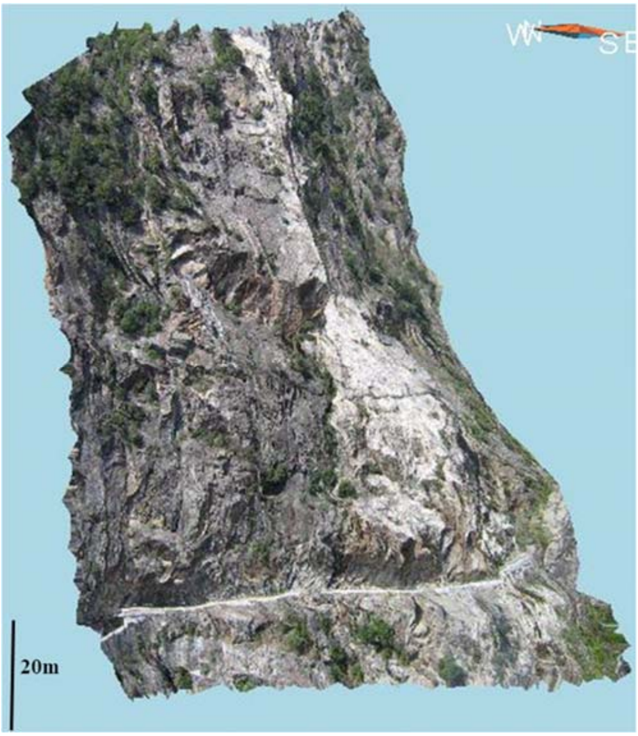

Figure 1 : 3D view of les Rochers de Valabres site AFTER Clement (2007)

The site, overhanging a busy road and a bridge, experienced two rock falls in May 2000 and October 2004 with volumes of 1000 m^3 and 40 m^3, respectively. Both periods did not coincide with any particular rain-fall event, seismic activity or freeze-thaw period occurrence and thermomechanical origin was suspected. The site was monitored with different thermometric and thermomechanical measurement devices apparatus to record the temperature variation in the rock-mass and the induced effects. The measured data were analyzed based on analytical thermo-elastic solutions and elastic numerical modelling showed the importance of strain or stress (according to the boundary conditions) variations at the surface.

Laboratory and in situ measurements have allowed to collect the parameters proposed in Table 2.

2.2 A limestone cliff

The village of la Roque Gageac (416 inhabitants) is situated in the North-East of the Aquitain Basin, on the right bank of the river Dordogne deep into what is called in French "le Périgord noir". It is a very touristic area near the Paleolithic famous place of Lascaux caves. La Roque-Gageac prides itself on the nearly 60 m-high limestone cliffs above the village. This limestone is mainly a bioclastic sandy limestone.

At least, four rockfalls have been referenced since 1920. Three of them, which were well documented were situated precisely. The 1920 rockfall is due to the collapse of a section of the rock cliff above the east of the village. In 1957, the collapse of a whole section of the cliff in the west caused the death of three persons. The collapse of 1994, at the center of the cliff could not be localized so precisely. Finally, the one in 2010, which led us to become interested in the site, correspond to the collapse of part of the roof of a perched cavity showed on Figure 2 which was turned into a troglodyte fort in the Middle Ages.

Figure 2 : Localization of the rockfall above La Roque-Gageac.

Table 1 : Thermo-elastic parameters of the gneissic rock of Valabres.

Parameter	From	Symbol	Value and Unit
Density	Laboratory	ρ	2698 $kg.m^{-3}$
Specific heat capacity	Laboratory	Cp	between 567 and 871 $J.kg^{-1}.K^{-1}$
Thermal diffusivity	In Situ	a	1.9 10^{-6} $m^2.s^{-1}$
Thermal conductivity		λ=a. (ρ.Cp)	2.91 to 2.26 $W.m^{-1}.K^{-1}$
Expansion coefficient	Literature	α	7.5 10^{-6} K^{-1}
Young's Modulus	Estimation	E	20.7 GPa
Poisson ratio	Estimation	ν	0.24

Table 2 : Thermo-elastic parameters of the limestone rock of La Roque-Gageac.

Parameter	From	Symbol	Value and Unit
Density	Laboratory	ρ	2382 $kg.m^{-3}$
Specific heat capacity	Literature	Cp	830 $J.kg^{-1}.K^{-1}$
Thermal diffusivity	In Situ	a	3.45 10^{-6} $m^2.s^{-1}$
Thermal conductivity	Literature	λ=a. (ρ.Cp)	2.5 to 4.0 $W.m^{-1}.K^{-1}$
Expansion coefficient	Laboratory	α	8.5 +/-2 10^{-6} K^{-1}
Young's Modulus	Laboratory	E	42.7 GPa
Poisson ratio	Laboratory	ν	0.15

This last event can neither be attributed to freeze-thaw which is extremely rare in the site, nor to water pressure as established by the absence of water percolation in the cave and the absence of movement in instrumented fractures (after the collapse) related to precipitation. Finally, in absence of other causes, temperature was suspected to have trigger the phenomena, but it’s not proven. In fact, they were no temperature measurement in the vicinity of the site before the collapse

In la Loire Valley, near Tours, another undermined cliff of limestone, where the temperatures were measured thereabouts, has also experimented collapse attributed to large temperature variation between the day and the night before the collapse.

In order to better understand phenomena able to trigger instabilities on the site, and to follow the evolution of the roof of the troglodyte fort, which was unstable as long as stabilization works was not carried on, instrumentation was implemented as described in Gasc-Barbier et al., (2015). The site was monitored during nearly 5 years during which deformation was recorded with fissurometers around natural cracks near the roof of the cavity and with 2 borehole extensometers drill on the cliff above the cave.

3 THERMAL CYCLIC DAMAGE IN LABORATORY

Experiments conducted by Gasc-Barbier et al. (2014) showed that the damage of lime-stone specimens subjected to more than 400 thermal cycles (varying between 10 and 50°C), significantly increase after about 300 cycles: a large decrease in the P-waves velocities is obtained on all tested samples. On those experiments macro-cracking was somehow observable after about 400 cycles.

Villarraga et al. (2018) conduct sets of laboratory experiments on the same limestone and even if the threshold of 400 thermal cycles to observe macrocracks cannot be con-firmed, they observed that when the number of thermal cycles increases the P-waves velocities decreases meaning that a damage occurs. Moreover, they were able to observe progression of natural microcracks during thermal cycles.

These experiments accredit the possibility of thermal fatigue causing significant damages.

4 *IN SITU* OBSERVATION AND POSSIBLE MECHANISMS

Several mechanisms can potentially be associated with temperature variations: Stress variation leading to reach the tensile strength of the rock mass, thermal shock, progressive snaking or ‘‘crawling motion’’ along a fracture (Gunzburger et al. 2005) due to an elastoplastic behavior of the fracture, viscoelasticity of fractures or rock mass, creep.

The possibility of cracks propagation is discussed below.

4.1 Theoretical approach of cracks propagation

According to fracture mechanics, a crack can propagate according to 3 possible modes or a combination of these 3 modes (Engerand, 1990). The analysis of the elastic stress field near a fracture lead Irwin (1926), quoted by Engerand, to the notion of stress concentration factor (K). The K factor, generally expressed in MPa.m$^{1/2}$, is function of the geometry of the cracked material, the dimensions of the crack and the loading mode. The ability of a fracture to propagate is controlled by a threshold named fracture toughness. When K exceeds fracture toughness, the crack propagates. The toughness is defined for each mode of rupture (K_{Ic}, K_{IIc} and K_{IIIc}).

The possible propagation of a crack is usually studied for a thin small crack of length 2a subjected to biaxial stress. The crack is considered to be small enough to assume that its environment is an infinite plane containing a line crack.

Using the notations of Figure 3 for the case of a two-dimensional stress field applied at infinity (σ_1, σ_2), in plane deformations and considering mode I (crack opening) and mode II (shear in the plane), the concentration factors are expressed by:

$$K_I = \sigma_n \sqrt{\pi a} \quad (1)$$

with $$\sigma_n = \sigma_1 \cdot cos\phi^2 + \sigma_2 \cdot sin\phi^2 \quad (2)$$

and if $\sigma_2 < 0$

$$K_{II} = \tau_{max} \cdot \sqrt{\pi a} \quad (3)$$

with $$\tau_{max} = \frac{1}{2}(\sigma_1 - \sigma_2) \cdot sin(2\phi) \quad (4)$$

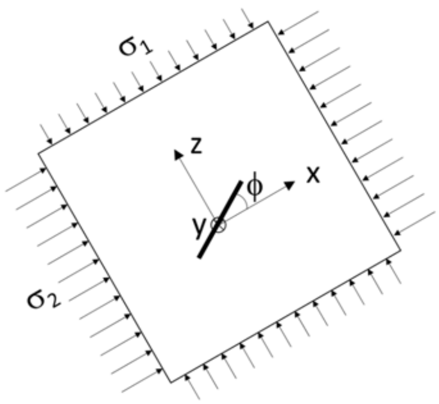

Figure 3 : Thin crack, placed in an infinite medium and subjected to a stress field (σ_1, σ_2) Φ the angle of the crack with the x-axis.

We can then compare these stress concentration factors to the toughness of the material. When the stress intensity factor (K_I) reaches the fracture toughness (K_{Ic}), a fracture can open according mode I. The tension needed to open a crack in mode I can be deduced from Equation 1:

$$\sigma_n = \frac{K_{Ic}}{\sqrt{\pi a}} \quad (5)$$

Alike, the shear stress needed to open a crack in mode II is, according Equation 2:

$$\tau_{max} = \frac{K_{IIc}}{\sqrt{\pi a}} \quad (6)$$

Let us now consider a semi-infinite sloping medium whose free surface is submitted to harmonic temperature variations Figure 4-a). In this configuration, Just below the surface the major principal stress (absolute value) is a compression parallel to the surface and the stress perpendicular to the surface is very low, zero at the surface.

Considering a thin crack, it will open if is normal or shear stress exceed the toughness i.e. :

$$\sigma_n = \sigma_{n(initial)} + \Delta\sigma_n = \frac{K_{Ic}}{\sqrt{\pi a}} \quad (7)$$

or

$$\tau = \tau_{(initial)} + \Delta\tau = \frac{K_{IIc}}{\sqrt{\pi a}} \quad (8)$$

Let z be the depth direction perpendicular to the surface (Figure 4-b). Using cylindrical coordinates, r and θ are the axis perpendicular to the z axis. Considering a semi-infinite medium, no strain is supposed to occur in this direction when temperature varied: the surface is free and temperature variations cause strain. It can be demonstrated from the thermo-elasticity relationships, that the strain (elongation for a positive variation of temperature) along the z axis is given by:

$$\varepsilon_z = \frac{1+\nu}{1-\nu} \cdot \alpha \cdot \Delta T \quad (9)$$

with ΔT standing for the temperature variation at the corresponding depth, α the linear thermal expansion coefficient and ν the Poisson' coefficient. The stress variations in the r and θ directions are:

$$\Delta\sigma_{rr} = \Delta\sigma_{\theta\theta} = -\frac{E}{1-\nu} \cdot \alpha \cdot \Delta T \quad (10)$$

with E representing the Young modulus. Compressive stresses are counted negatively. These thermal stresses added to the mechanical stresses due to the gravity and whose intensity and orientation are strongly linked to the topography (perpendicular to the surface there is no stress at the surface).

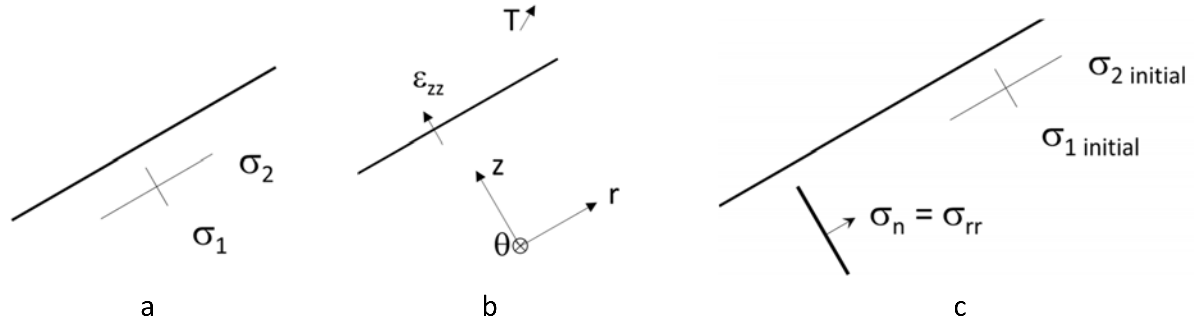

Figure 4 : Mechanical and thermo mechanical stresses: a - Mechanical stresses; b - Stresses / strain linked to thermal variations; c – Fracture perpendicular to the free surface submitted to tension and initial stresses

The previous equations consider rotational symmetry. For stress variations associated with temperature variations, however the initial stresses, in the plane parallel to the slope (σ_2 and σ_3), can be dissimilar. Subsequently we will only consider σ_2.

Because $\sigma_1 = 0$ at a free surface, σ_n will be maximum for a fracture perpendicular to the free surface (according equation [2]) and τ will be maximum for $\phi = 45°$.

Considering the fracture plotted in Figure 4-c and taking into account the initial stresses display in the figure: $\sigma_n = \sigma_{2(initial)} + \Delta\sigma_{rr}$. The tension needed to open a crack in Mode 1 is:

$$\sigma_n = \sigma_2 = \sigma_{2(initial)} + \Delta\sigma_{rr} = \frac{K_{Ic}}{\sqrt{\pi a}} \qquad (11)$$

Then, the temperature variation needed to open a crack in Mode 1 derived from:

$$\Delta T = \frac{\sigma_2(initial) - \frac{K_{Ic}}{\sqrt{\pi a}}}{\mathrm{E}\cdot\alpha} \cdot (1 - \nu) \qquad (12)$$

As $\sigma_1 = 0$ $\tau_{max} = \pm\frac{\sigma_2}{2}$

and $\sigma_2 = \sigma_{2(initial)} + \Delta\sigma_{rr}$

$$\tau_{max} = \pm\frac{\sigma_{2(initial)} + \Delta\sigma_{rr}}{2} = \frac{K_{IIc}}{\sqrt{\pi a}} \qquad (13)$$

$$\Delta T = \frac{\sigma_{2(initial)} \mp \frac{2\cdot K_{IIc}}{\sqrt{\pi a}}}{\mathrm{E}\cdot\alpha} \cdot (1 - \nu) \qquad (14)$$

The evaluation of the needed temperature to open a crack requires:

- crack length 2a;
- fracture toughness;
- $\sigma_{2(initial)}$.

Measurement of fracture toughness are rare, yet Vásárhelyi (1997) give value of K_{Ic} between 0.216 to 0.336 $MPa.m^{1/2}$, measured in a gneiss when Almeida et al. (1998) measured significantly higher values, approximately 1 $MPa.m^{1/2}$, in the Brazilian granite. Suhett-Helmer (2014) measured fracture toughness in several limestones, using various experimental protocols and she found K_{Ic} varying from 0.47 to 0.86 $MPa.m^{1/2}$ and K_{IIc} from 0.4 to 1.0 $MPa.m^{1/2}$.

In-situ stresses can be provided by field measurement, analytical solution, or a finite elements model.

4.2 Numerical application on Valabres case

In the case of les Rochers de Valabres site, field measurement, and finite elements model (Clément et al., 2009) provided order of magnitude of σ_2 just below the surface of the slope. We use a compression of 2 MPa in Table 3, below.

We keep Vásárhelyi measurements of toughness to evaluate temperature variation needed to open a fracture in mode I.

It is generally accepted that the microcracks of a rock are of the grain scale since cracks generally propagated along the grain boundaries. Thin sections observed under a micro-scope make it possible to evaluate the size of the grains, and the dimensions of the grains were comprised between 500 and 4000 μm. The minerals of the clear beds (quartz and feldspars) have larger dimensions than mica minerals. Yet, the most frequent mineral size is about 1000 μm. With the hypothesis adopted, and the parameter of Table 1, the variations of temperature needed to open fracture perpendicular to the surface in mode 1 are displayed in Table 2. Let us notice that the variation of temperature needed is negative.

Two subsurface thermometers placed at less than 1 cm deep, gave daily average temperature amplitudes of about 13°C. The variation of temperature computed in Table 2, are therefore compatible with the propagation of fracture of grain size, subjected to daily variations of temperature.

Yet, in the concept of toughness there is no notion of time. Laboratory tests used for measuring this parameter are faster than a day, and the variations of stresses likely to be caused by daily temperature variations are necessarily slower which may be a restriction to this analysis

In addition, we use a 2 MPa compression for the computation. If the compression is lower than that, the temperature needed to propagate a crack is lower. Notice that, the longer the fracture is, the lower the temperature variation required for propagation. A gradual increase of fracture length (fatigue) could be easier and easier.

Table 3: Temperature needed to propagate cracks.in mode I for Valabres case according the initial length 2a and the value of K_{Ic}

2a mm	σ_2* MPa	σ_n MPa	K_{Ic} MPa.m$^{1/2}$	ΔT K_{Ic} °C
4	-2	2.72	0.216	-11.1
4	-2	4.24	0.336	-14.6
1	-2	5.45	0.216	-17.4
1	-2	8.48	0.336	-24.5

*remember that compression is negative in the calculation.

4.3 Numerical application on the Limestone cliff

The geometry of the perched cave in La Roque-Gageac and moreover the part still unstable of its roof is quite complicated. However, a 3D Finite element modeling was performed with CESAR-LCPC code, with a simplified geometry of the cave. It has shown that around the cavern the major stress parallel to the edge of the cave is low, close to zero or could be in tension, unlike Valabres case. Table 4 gives an estimation of the stress variations induced by a given variation of temperature. For a negative variation of 15°C, $\Delta\sigma$ reaches 4.5 MPa which is close to the tensile strength of the rock mass and thus can explain a rupture.

We also explored the possibility of propagation of fractures, for temperatures lower than those which can lead to tensile rupture. As we had no data from La Roque-Gageac toughness we use data from Suhett-Helmer (2014) measured on the Pierre de Lens, a limestone quite similar to La Roque Gageac, that is K_{Ic} = 0.63 MPa.m$^{1/2}$ and K_{IIc} = 0.70 MPa.m$^{1/2}$.

On site different length of open fractures were observed, from 10 mm to 50 mm. Table 5 present the results of the parametric calculation. The maximum daily temperature variation on site recorded on summer are from 12 to 33°C that is 21°C. This variation is enough to propagate crack in mode I (when σ_2 is -0.5 MPa) but not or a 50 mm length crack in mode II.

Table 4: Stress variation due to temperature variation, considering E=42630 MPa (mean of value of Table 2ν = 0.15 and $\alpha = 6\ 10^{-6}$

ΔT(°)	$\Delta\sigma$(MPa)
-5	1.5
-10	3.0
-15	4.5

Table 5: Temperature needed to propagate cracks according different mode and function of the length propagation on La Roque-Gageac case.

2a (mm) mm	σ_2* MPa	σ_n MPa	ΔT K_{Ic} °C	ΔT K_{IIc} °C
15.8	-0.5	4.00	-15.0	-32.1
20	-0.5	0.55	-13.5	-27.9
30	-0.5	2.90	-11.3	-23.1
50	-0.5	2.25	-9.1	-18.3

*remember that compression is negative in the calculation.

5 DISCUSSION AND CONCLUSIONS

Several mechanisms may coexist to explain initiation and progressive failure due to temperature variation: thermal shock, creation and pervasion of fractures between minerals at the surface linked to differences in their light-transmissivity, recurrence of temperature variations (daily, or annual cycles) leading to thermal fatigue.

We show in this paper that this last phenomenon, could be explained cracks propagations in the two sites under study and is sustained by laboratory experiments.

Yet some assumptions, need complementary observations coupled with precise measurements (often difficult to obtain) to progress in the mechanical knowledge of these thermomechanical phenomena, which have been little studied in deep mechanical details. In addition, the transition from the propagation of fractures to larger collapses probably including failure of rock bridges is to be strictly established.

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