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The role of natural thermal cycles on a limestone cliff mechanical behaviour

M. Gasc-Barbier [a,*], V. Merrien-Soukatchoff [b], D. Virely [c]

[a] *Cerema, GeoCoD, avenue Albert Einstein, CS 70499, 13593 Aix-en-Provence, Cedex 3, France*
[b] *GeF, EPN01, Cnam, Paris, France*
[c] *Cerema, 31400 Toulouse, France*

Rock instabilities can represent major risks for local populations depending on their geographical location. Even if different mechanisms are known to trigger rockfalls such as precipitation, seismic activity and freezing, many rockfalls occur during periods when such trigger mechanisms are absent. Some recent studies have pointed out the role of thermal cycling in crack initiation or propagation. Here we use data from nearly five years of field monitoring of a French limestone cliff. Evolution of the aperture of joints were followed as well as displacements and temperature deep in the rock mass. We show that seasonal thermal variation affects the rock at depths of up to 6 m and subcritical cracking can probably appear even at this depth.

1. Introduction

Rockfall is one of the major risks that can occur not only in steep mountain terrain but also in plains when the rivers have dug hard rock and left cliffs. Various factors can explain rockfalls: in the Alps Gunzburger, Merrien-Soukatchoff, and Guglielmi (2005) cite sharp topographic contrasts, intensive previous tectonic deformations leading to a high degree of fracturing, seismic activity and precipitation profiles with rainfall concentration over time.

The causes of failure are diverse (Cloutier, Locat, Charbonneau, and Couture, 2015; Fell et al., 2008), and the triggering factor is often difficult to determine, but the action of weathering is significant in landscape evolution. In fact, many studies, based on site investigation, pointed out the importance different agents of weathering such as freezing (Deprez, De Kock, De Schutter, and Cnudde, 2020; Frayssines and Hantz, 2006; Matsuoka, 2008, 2001), rain (Galeandro, Doglioni, Simeone, and Šimůnek, 2014; Intrieri, Gigli, Mugnai, Fanti, and Casagli, 2012; Nguyen, Lee, and Kim, 2020; Regmi, Yoshida, Dhital, and Devkota, 2013; Stoffel, Tiranti, and Huggel, 2014) or thermal variations (Collins and Stock, 2016; Eppes, McFadden, Wegmann, and Scuderi, 2010; Eppes and Griffing, 2010; Eppes and Keanini, 2017; Gunzburger, Merrien-Soukatchoff, and Guglielmi, 2005; Hall, 2004, 1999; Hall, Thorn, and Sumner, 2012; Hall and Thorn, 2014; Holzhausen, 1989; Ravaji, Alí-Lagoa, Delbo, and Wilkerson, 2019; Vargas, Chavez, Gusmao, and Amaral, 2009; Vargas, Castro, Amaral, and Figueiredo, 2004). Changes in temperature are one of the agents of the alteration to which attention has been drawn due to several events where other causes could not be invoked (Gunzburger, Merrien-Soukatchoff, and Guglielmi, 2005; Vargas, Chavez, Gusmao, and Amaral, 2009; Gasc-Barbier and Merrien-Soukatchoff, 2019).

Studies focussing on thermal stress weathering were realised on different rock types: alluvial fans, boulders (Eppes, McFadden, Wegmann, and Scuderi, 2010; Eppes and Griffing, 2010), outcrops (Holzhausen, 1989) or quarry (Marmoni, Fiorucci, Grechi, and Martino, 2020), dome rock (Collins et al., 2018) or rock slopes (Gunzburger, Merrien-Soukatchoff, and Guglielmi, 2005; Vargas, Chavez, Gusmao, and Amaral, 2009) and different mineralogy: gneiss, granite, marble, … Most of those studies are based on surface observations with (Bakun-Mazor, Hatzor, Glaser, and Carlos Santamarina, 2013; Collins et al., 2018; Collins and Stock, 2016; Gasc-Barbier and Merrien-Soukatchoff, 2019; Gunzburger and Merrien-Soukatchoff, 2011; Holzhausen, 1989; Marmoni, Fiorucci, Grechi, and Martino, 2020) or without (Hall, Thorn, and Sumner, 2012; Hall and Thorn, 2014) instrumentation on the site. The two longest records are located in North America: an exfoliation sheet in the Yosemite Valley was monitored for 3.5 years (Collins and Stock, 2016) and temperature, light intensity, humidity and crack aperture have been recorded, and a small active rockslide in Gaspésie (Canada) was monitored with crackmeteers and other monitoring

* Corresponding author.
E-mail address: muriel.gasc@cerema.fr (M. Gasc-Barbier).

techniques for 4 years, to achieve sufficient spatial and temporal resolutions to characterise the displacements of the rockslide (Cloutier, Locat, Charbonneau, and Couture, 2015).

Both papers study the role of thermal stress weathering based on surface monitoring (crackmeters, surface extensometers, strain gauges, …) but thermal variation also affects the rock in depth. Dangerous rockfall hazard consists in rather larger rock blocks than "just" exfoliation sheets and the mechanisms of breakage, even if not completely understood is not only superficial. However, for larger blocks, the role of geology is predominant: and furthermore, the nature and location of structural joints, weak intercalation and natural stresses should be taken into account to understand the zones of weakness and the evolution over time of the rock mass, but a good knowledge of geometry in depth is difficult to achieve. Thus, it is interesting to understand the evolution of strain or temperature in the rock mass close to the surface. While many studies have been carried out around the evolution of temperatures in depth, they are generally carried out at the scale of the geothermal gradient and very few consider the very first metres behind a rockwall (Gasc-Barbier and Merrien-Soukatchoff, 2019; Gunzburger, Merrien-Soukatchoff, and Guglielmi, 2005) which is the case of the data recorded in La Roque-Gageac site that are described below.

After the failure of a part of a limestone cliff in the village La Roque Gageac in France and because no other triggering factor could be demonstrated, temperature variations were suspected. There were no measurements on the site at the time of the event (08/01/2010), but afterwards the cliff was monitored to survey the remaining hazard and design the reinforcement. This allows to have a long chronicle of monitoring during almost 5 The temperatures and strains were recorded, along open fractures inside the rock mass, at depths of 2 m, 4 m and 6 m from the face of the cliff. These measurements allow analysing the role of temperature as potential failure factor.

2. Geological and geomorphological settings, *in situ* device, and mechanical properties

2.1. Geological and geomorphological settings

La Roque-Gageac is a small village in the south-west of France, just a few miles away of the famous prehistoric site of Lascaux. This small village (about 400 citizens) is sandwiched between a massive limestone cliff and the Dordogne River. It prides itself on the dramatic cliffs above the village, but it is also a source of hazards. Tourism, with about 2 million visitors a year, is a major asset for local economy. The climate of the site is temperate with an oceanic dominant influence. In winter, it may also undergo mountain influences which are consequences of the relative proximity to the Massif Central. Conversely, in summer, the region can undergo hot air flows from the Mediterranean. Over the period from December 1995 to January 2014, in Sarlat (less than 10 km near La Roque-Gageac), minimal negative temperatures are reached once a day for 50 days per year on average but only for 7.4 days/year under -5 °C.The mean temperature per month is between 5.7 °C (in December) and 20.9 (in July and August); maximum annual temperatures in the area are between 27° and 32 °C and minimum temperatures between -10°C and -15°C. Average annual rainfall is 855 mm, the maximum amount of precipitation recorded in one day was reached in April 2001 with 70 mm which is not such a high value. Precipitation greater than 10 mm occurs between 1.7 and 3.1-day/month, on average, over the period.

The cliffs above the village, about 60 m to 80 m high, are constituted of the middle and superior part of Coniacian limestone and subject to current or past karst phenomena. These networks, active or inactive, significantly weaken the rock-mass and are part of the aggravating factors in the overall susceptibility of the cliff to block fall hazards. The ubiquity of visible karsts on the cliffs facing La Roque Gageac and the presence of a paleo-polje not far away confirm the past intense activity. But the actual karst system is "perched" and it is now above its natural outlet, the Dordogne River because its vertical development was interrupted by an impermeable layer. Meteoric water on limestone plateaus is almost exclusively drained to deep karst systems by many dry valleys and sinkholes, resulting in the vertical surface of the cliff being dry. Anyway, the cavity under study belongs to an inactive part of the network also called paleo-karst but is dry. Indeed, in our survey, we found that all the observed upper karst system was, at various levels, blocked by rich sandy clay fillings iron oxides.

Around the studied cave described subsequently, the rock can be depicted as a bioclastic microcrystalline sandy limestone with important lateral variability. A more detailed description of the geology and a geological map are given in Gasc-Barbier, Merrien-Soukatchoff, and Villarraga-diaz (2020).

The tectonic phenomena affecting the region are small. We observed a wide undulation forming a faulty anticline fold and a synclinal fold from the north-west south-east axis (N120°) showing very weak dips. This undulation would be prior to the Santonian, so it affects the Coniacian. The tectonic accident closest to La Roque Gageac is about 30 km away, it is a fault, oriented N130°, which shifts the terrain from the Upper Cretaceous to the Santonian with a discharge of about 150 m. Thus, no major tectonic fracture affects the rock mass.

Four major rockfalls have been identified above the village at La Roque Gageac since the beginning of the 20th century (see Fig. 1).

- 1920: collapse of an eastern section of the village
- 17/01/1957: collapse of a large section of western part of the rock cliff; three people –and a donkey- died.
- 1994: small blocks collapse in the centre part of the cliff.
- 8/01/2010: in the morning collapse of a part of the roof of a perched cave. This cave was used in the Middle Ages as a small stronghold for the Bishop of Sarlat during the religious wars.

The mass that collapsed on the 8th of January 2010 was about 350 tons. The debris was removed few months after the collapse, but a part of the roof (about 350 tons as well), called "the unstable beam", remained in place. Some instrumentation was placed to survey the remaining hazard because of the village below the cave but we also took the opportunity to get more data on the behaviour of the rock mass.

Among author factors the possible role of temperature was invoked to explain this collapse leading, retrospectively, to investigative measurements on this issue. For this reason, the precise moment when the phenomenon started may be important, but the only information available is that the detachment of the block from the vault of the troglodyte cave took place on January 8 at 9 a.m., yet the previous day, during the night at 1.30 a.m., the closest neighbour heard an abnormal noise, without being able to determine its origin.

2.2. In situ device

Fig. 2 and Fig. 3 display the hazard zone while Fig. 4 presents a scheme of the cave where a part of the roof had collapsed, and the



Fig. 1-. Location of the rockfall above the village and location of the cave under study (2010 rockfall).

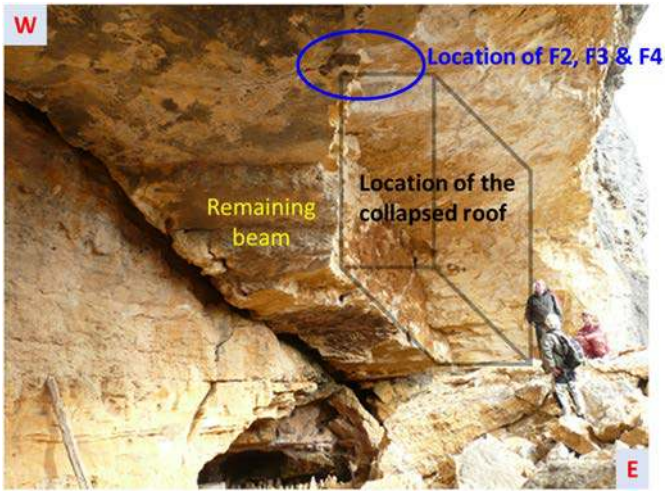


Fig. 2. – West view of the perched cave just after the collapse of the roof –the collapsed rock can be seen on the floor of the cave under the men standing who provide the scale- fissurometers were not in place at the time of the picture.

unstable beam. The remaining beam is delimited by a horizontal interlayer thinning from east to west, hanging to the roof of the cave at the west and east-clamped in the rock mass. Opened fractures can be observed all around the beam. In order to assess the remaining hazard, a monitoring of the joints opening around the beam was realised with 4 fissurometers (F1 to F4) that measure displacements, and a temperature probe was installed on the roof of the cave. In the meantime, borehole extensometers (D1 and D2) were drilled above the cave to understand the global behaviour of the rock mass. An extensive presentation of the monitoring device can be found in (Gasc-Barbier et al., 2020; Gasc-Barbier et al., 2015) and is summarised below.

The four fissurometers were positioned around the remaining beam to quantify the aperture (opening or closing) of the joints, in order to evaluate the relative movement of the blocks, according to changes in external conditions: F1 near the east-clamped end of the beam, and the three others on the west part (Fig. 3): Two of them (F3 and F4) were fixed across a horizontal joint and a vertical joint respectively, F2 is positioned across the vertical joint in a 45° angle. A thermal probe was also fixed on the roof of the cavity near the three fissurometers to register the evolution of the temperature in the cave. Fissurometers are LVDT strain gauges that measure displacements between their two extremes with a resolution of 1/10th mm. From July 2010 to April 2015, a value per hour was recorded except for a few periods.

The borehole extensometers (D1 & D2) are RockTest / Télémac distofor@ anchored in the rock mass at the end of the borehole at a depth of 8 m from the cliff wall. Both were prepared with three displacements measuring points at depths of 2 m, 4 m and 6 m from the cliff wall and temperature measuring points at 2 m and 6 m depth (see Fig. 5). Their positions above the cave are shown on Fig. 3.

The supplier gives a measuring range of 100 mm, a resolution lower than 0.01 mm. Given the length of the rods used (8 m), the precision is about 0.05 mm. The operating temperature must remain between 0° and 50 °C. The devices were placed perpendicular to the rock face, about 4 m and 7.5 m above the roof of the cave cavity (Fig. 4). From July 2010 to April 2015, a value per hour was recorded, except for some few periods.

Measurements were stopped in April 2015 because of reinforcement works in the cave in order to secure the village.

2.3. *Physical and mechanical properties of the limestone*

Physical characterisation of the limestone realised in our lab gives the following means (Villarraga, Gasc-Barbier, Vaunat, and Darrozes, 2018):

- Density $\rho = 2382$ (+/− 45) kg/m^3
- $V_p = 4651$ (+/− 545) m/s
- $V_s = 2671$ (+/− 174) m/s
- Total porosity $n_t = 17.9\%$
- Connected porosity $n_c = 11.2\%$
- Water ratio, $w = 4.7\%$

The uniaxial compression strength was measured on 10 samples (50 mm in diameter – 2 in slenderness). The mean value is 47.4 MPa with a standard deviation of 9.63 MPa. This standard deviation is quite high and characterises a heterogeneous rock. The heterogeneity can be

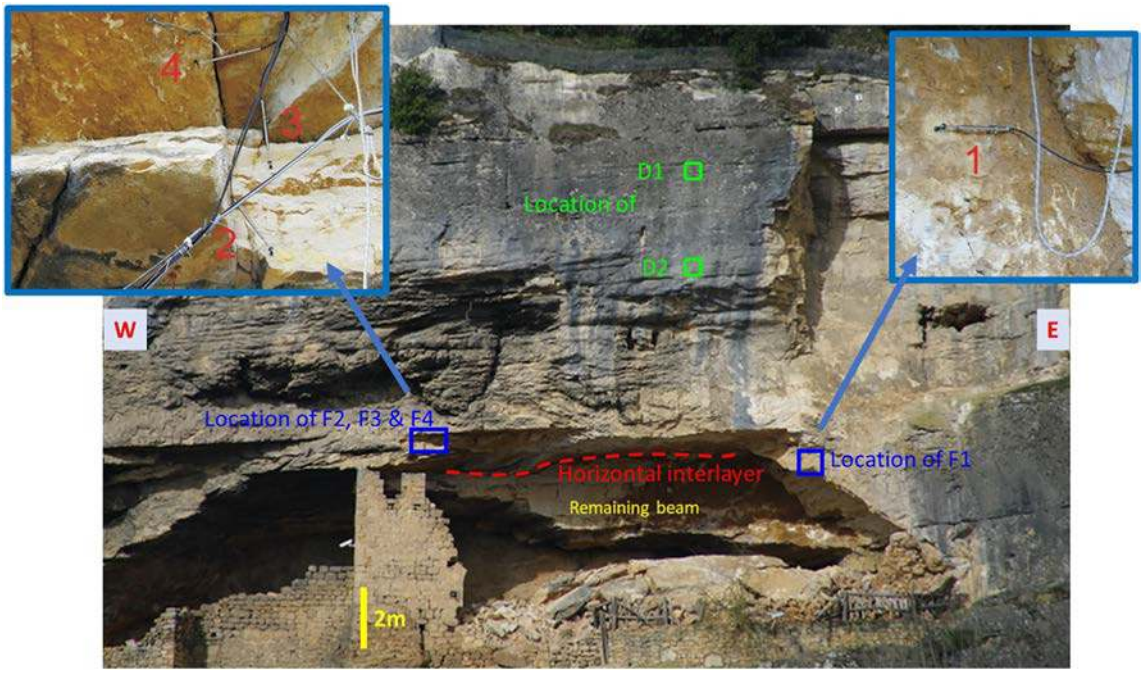


Fig. 3. – Front view of the perched cave just after the collapse of the roof.

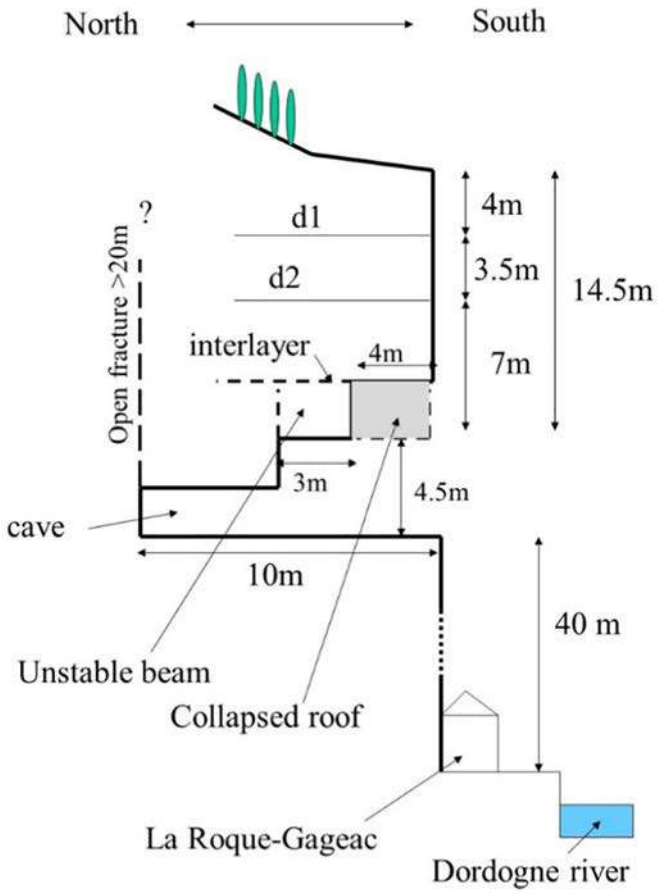


Fig. 4. – Schematic cross-section of the perched cave.

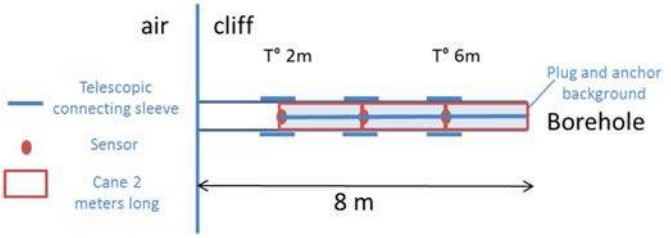


Fig. 5. - Schematic cross-section of a borehole extensometer.

attributed to the heterogeneous arrangement of elements (bioclasts) and/or variable cementation even on a centimetre level.

Indirect tensile strength was obtained using Brazilian tests on 11 samples. A mean value of 5.4 MPa and a standard deviation of 0.5 MPa was obtained. Triaxial tests were also performed on 50 mm-in diameter samples. Results are given in Table 1.

Following the European standard EN 14–581, linear thermal expansion coefficient (α) was measured at Toulouse Cerema laboratory on two cubic blocks (10*10*10 cm). It was also measured on two cylindrical samples (50 mm in diameter – 100 mm high) using the same thermal solicitation. Strain gauges were glued on the three opposite phases of the cubic blocs and thus gave three values of the linear thermal expansion coefficient for each sample whereas only two values, axial and circumferential, were obtained on cylindrical samples. We finally obtained nearly the same value whatever the shape of the sample: $\alpha = 6$ (+/− 3) 10^{-6} K^{-1}. The variability is due to heterogeneity and slight anisotropy of the rock. The role of anisotropy should be analysed more deeply, but our samples were drilled from one of the felled blocs as can be seen on Fig. 2 that we were not able to orient.

Table 1
Results of triaxial tests on La Roque-Gageac limestone.

σ_3(MPa)	σ_1(MPa)	E(GPa)	ν
0.0	47.4		
2.5	65.0	38.4	0.15
5.0	80.2	42.6	0.15
10.0	81.7	47.0	0.12

3. *In situ* measurements and recording

All temperature and displacement records are free of access, published in Mendeley Database under the name ThermoMechaLimestone (doi: 10.17632/wnt6thwzvp.1).

3.1. Temperature recording

3.1.1. Temperature recording in the cave

The temperature sensor hanging from the roof of the cave shows that the hourly variation of temperatures is often less than a degree. From time to time, much more significant hourly variations were measured: + 12.4° on 06/04/2011 between 12 and 13 p.m. and − 8,43 °C on 20/09/2014 between 4 and 6 p.m. The maximum temperature recorded on the site was 47.4° on 09/09/2001 (at 4 p.m.). Negative temperatures were occasionally recorded the first two winters, a minimum temperature of −6.5 °C was recorded on 02/09/2012 at 9:00. Between two consecutive measurements (1 h) the maximum temperature increase was +12.5 °C / h (on 04/04/2011 between 12:00 a.m. and 1:00 p.m.) and the maximum decrease was −7 °C / h (on 05/10/2012 between 6:00 and 7:00 p.m.).

The maximum daily temperature variation in the cave was recorded on 14/03/2012 where the temperature varied between 9:00 a.m. and 4:00 p.m. from 9.44 °C to 41,19 °C, which is an increase of 32 °C in 7 h. This maximum increase was followed the next night by a decrease of 31 °C in 16 h.

The reported temperature variations were measured inside the cavity, while those at the surface of the rock mass could be more important on the faces exposed to sunlight (Gunzburger and Merrien-Soukatchoff, 2011).

3.1.2. Temperature recording in the rock mass

As explain in the experimental device, temperature was measured in the cave but also in the extensometers at 2 and 6 m depth. Fig. 5 presents the evolution of the temperature during the 5 instrumented years in the rock mass at 2 and 6 m depth (Fig. 6a) and in the cave (Fig. 6b). We can observe a decrease of the amplitude of the temperature variation when going deeper in the rock mass which is consistent with conduction phenomena.

The amplitudes of the temperature decrease with depth over the whole period which is consistent with the conduction hypothesis. To estimate conduction parameters, the rock mass is assimilated to a semi-infinite medium and the main wall to a free surface. A Fourier decomposition was performed to determine an *in situ* diffusivity "a".

Assuming only conductivity, for a semi-infinite ground, the temperature at depth z can be expressed as (Carslaw and Jaeger 1986):

$$T(z,t) = T_0 + \sum_{n=1}^{\infty} A_n(z) cos(n\omega t - \varphi_n(z))$$

with a mean temperature of T_0 and an angular frequency of $\omega = \frac{2\pi}{period}$ $rad.s^{-1}$.

$A_n(z)$ represents the half-amplitude of the n^{th} harmonic (n^{th} partial "temperature wave") at depth z, and $\varphi_n(z)$ represents its phase.

If the hypotheses are satisfied, the exponential amplitude of the harmonics are linked to the *in situ* thermal diffusivity "a" of the rock by the relation:

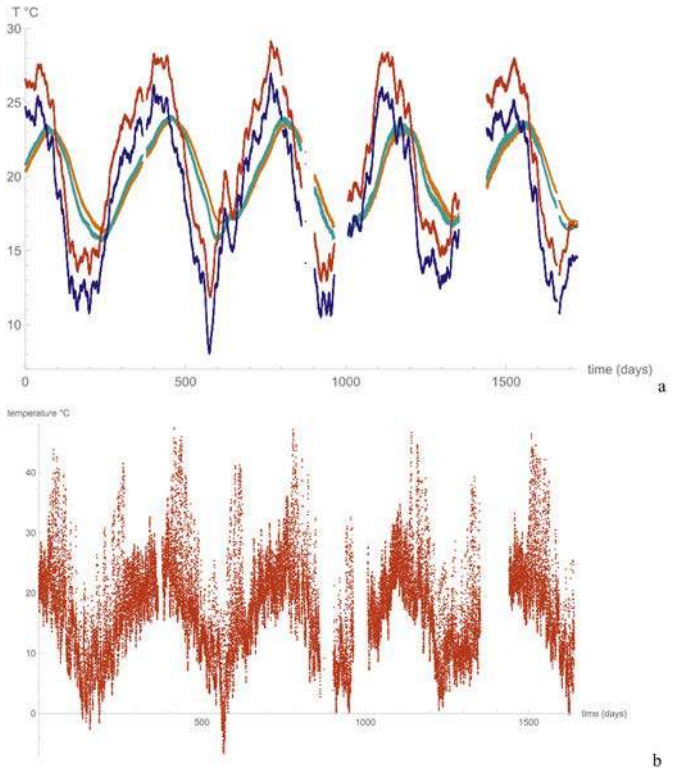


Fig. 6. - Temperature, a-in D1 (2 m: red, 6 m: orange) and D2 (2 m: dark blue, 6 m: light blue; b- in the cave (with the temperature probe) a point per hour. The series presented some gaps corresponding to some days to 2 weeks of lack of measurements. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$$\frac{lnA_n(z)}{\sqrt{n}} = \frac{lnA_n}{\sqrt{n}} - z\sqrt{\frac{\omega}{2a}}$$

The linear increase of the phase lag with depth is also linked to the *in situ* thermal diffusivity "a":

$$\frac{\varphi_n(z)}{\sqrt{n}} = \frac{\varphi_n}{\sqrt{n}} - z\sqrt{\frac{\omega}{2a}}$$

The thermal diffusivity "a" of the rock can then be obtained for the different harmonics from the decrease of amplitude or from the phase lag between the recording at two depths:

$$a = \frac{\pi}{\tau}\bullet\left[\frac{(z1 - z2)\bullet\sqrt{n}}{\ln A_n(z1) - \ln A_n(z2)}\right]^2$$

$$a = \frac{\pi}{\tau}\bullet\left[\frac{(z1 - z2)\bullet\sqrt{n}}{\varphi_n(z1) - \varphi_n(z2)}\right]^2$$

In our site we have temperature recordings at 2 and 6 m in the two extensometers. Although the means of temperatures are slightly different at 2 m and 6 m and for both extensometers and between the two extensometers, they can be fitted to a Fourier serie (Fig. 7) and we interpreted the amplitude decreasing and the phase lag for the two extensometers, for the consistent harmonics. The order of magnitude of the diffusivity is 2–3 10^{-6} $m^2.s^{-1}$ which is about the same order of magnitude as the value provided by Fortin, Gasc-barbier, and Merrien-soukatchoff (2018) for limestone that is 1.1 10^{-6} $m^2.s^{-1}$.

Although the analytical interpretation could be improved by an estimation of heat flux and solar radiation as proposed by Gunzburger and Merrien-Soukatchoff (2011), it was not realised because an accurate analytical estimation is difficult considering the morphology of the cliff and the cave.

3.2. *Displacements recordings*

Non-smoothed curves of displacement time for the four fissurometers and both extensometers are presented in Gasc-Barbier, Merrien-Soukatchoff, and Villarraga-diaz (2020). We only concentrate here on the main results. The records began in July 2010, when the temperature was about 24.5 °C in the cave and 20.5 °C at 6 m depth. Globally, the four fissurometers behave in a similar way, even if their displacement amplitude is different. We observed a total displacement amplitude ranging from 0.4 mm for F1 to almost 3.5 mm for F3 and F4 against 1.5 mm for F2 that will be detailed subsequently. Thanks to the long duration of the recordings, we were able to observe a seasonal variation of the crack openings when looking at the displacements *versus* time curves: as the recordings started in July, we could globally observe an opening of the cracks (positive strain slope) in the spring and in the summer and a closing of cracks (negative strain slope), in autumn. In winter we note a stagnation of the strain.

Both borehole extensometers have 3 measurement points, at 2, 4 m and 6 m from the cliff wall. Again, all the records are not presented here (see Gasc-Barbier, Merrien-Soukatchoff, and Villarraga-diaz (2020)), only the main results: D1 and D2 show that displacements are all the more important as they are measured near the external surface: the amplitude of the displacements measurement at 2 m depth is larger than the one recorded at 4 m depth, and both are also larger than the amplitude of the displacements recorded at 6 m depth; which is consistent with thermomechanical behaviour govern by external

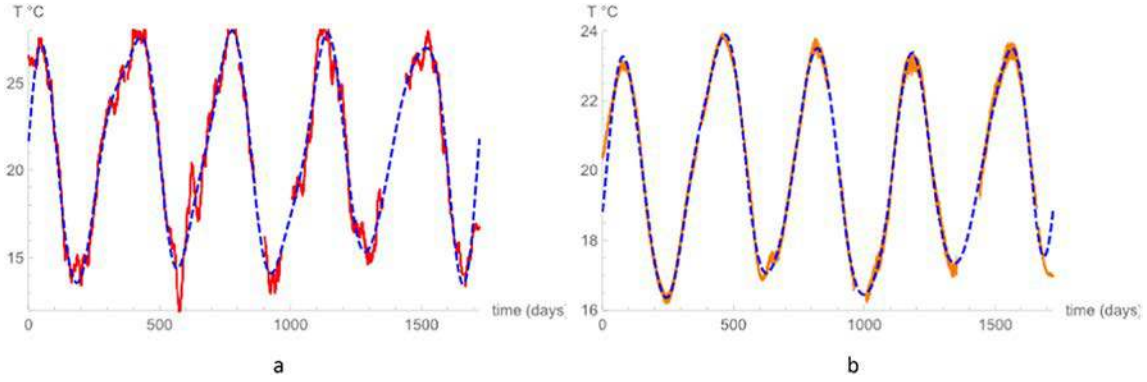


Fig. 7. - Temperatures measured in D1 a -*Red line* at two metres depth, b - Orange Line at six metres depth. *Blue dashed line*: Temperature estimated with Fourier series decomposition (please note the temperature scale is different on the 2 graphs to better show the adjustment). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

temperature. Temperature is inversely correlated to the displacements. Deformations recorded at a 6 m depth on both extensometers have very similar amplitudes, about 0.1 mm and the maximum amplitude (1.75 mm) is recorded on D1 at a 2 m depth.

3.3. Correlation between displacement and temperature

Another way to study the behaviour of the rock mass is to look at the displacement *versus* temperature curve. Fig. 8 and Fig. 9 display the relation between displacement and temperature on F2 and on D1 at 6 m depth. As can be seen on Fig. 6b, curves were smoothed to be more readable since a point per hour for both measurement points implied a lot of daily variations. On Fig. 8, when observing an annual cycle, we can see that overall displacements change little when temperature varies a lot and then an increase (or decrease) of displacements is observed with small global temperature variation. It behaved just as if the displacement was not caused by the variation of temperature alone, but that the cracks are open because of the accumulation of temperature. After 1-year recording, a hysteresis on the curve displacements/temperature is observed, and as plotted on Fig. 8, a permanent displacement of about 0.21 mm can be detected, then 0.42 during the year 2, 0.18 mm during year 3, and finally 0.07 mm during year 4. This gives about 0.88 mm after four years on F2. Similar behaviours can be observed on the other fissurometers even if permanent displacement is smaller. Similar observations can also be made on extensometer recording, even at 6 m depth: Fig. 9 shows the relation between displacement and temperature on D1 at 6 m depth. Over the whole recorded period, a slight permanent displacement of 0.015 mm after 5 years appears. At 2 m depth (not shown on the figures), it is more significant: 0.43 mm on D1 and 0.25 mm on D2.

As permanent displacements are observed in all equipment and on both depths, it cannot be attributed to instrumental drift or creep. Other explanations will be proposed below.

Dots correspond to each July 22nd that is one year of recording

4. Discussion

4.1. What is the driving force for the observed displacements?

The monitoring system and specially the fissurometers made it possible to understand the overall behaviour of the beam and to secure the site, while waiting for the reinforcement works which was the first priority.

The recorded data clearly show the role of temperature on the surface and in depth on displacements. Before discussing the possible role of temperature on crack initiation or propagation and thus to rocky instabilities, let us examine the possible liability of other factors.

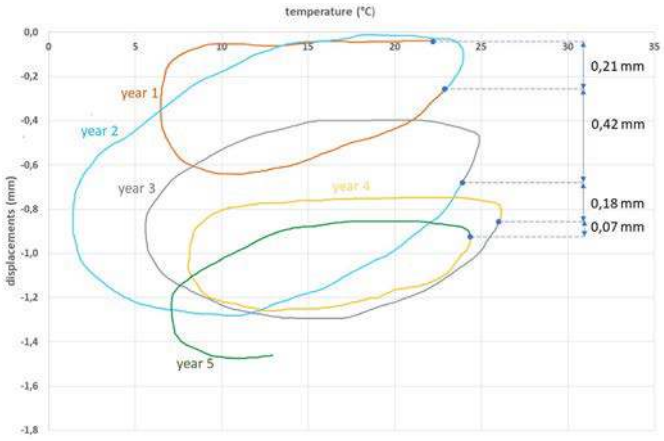


Fig. 8. – Correlation between length variation and temperature on F2.

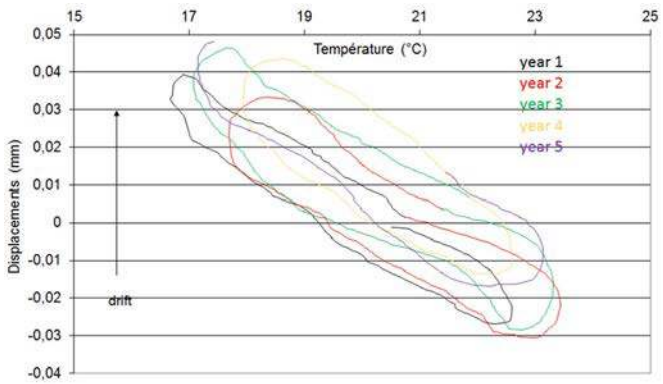


Fig. 9. –Length variation *versus* temperature for the D1–6 m depth extensometer– Colour change each July 22nd that is one year of recording. The resolution of the extensometer is less than 0.01 mm.

Main triggering factors considered for rockfall are seismic activity, frost and precipitation.

Seismic activity: the French government published in 2011 a seismic zoning of France. Our site is classified as "very low seismic hazard" that is the lowest possible class. That does not mean that no earthquake can occur, but that none was ever recorded in the area, and there was no seismic activity in January 2010.

Precipitation: The meteorological information was discussed in section 2.1 above, and no significant rain event was spotted prior to the January 2010 event. The cave belongs to an inactive part of a paleokarst. Whenever we went on the site when it rained, no water exuded from the monitored joint. However, some water was observed in larger discontinuities, such as the open fracture mentioned on Fig. 4. It seems more likely that water flows along the karst network. That does not mean that hydromechanics should not be explored but it seems that it is not the main point to be considered on the monitored fractures.

Frost: As seen on Fig. 6, at 2 m depth and, furthermore, at 6 m depth, recorded temperature is never less than 7.8 °C. No frost can occur in the rock mass. However, on the temperature probe in the cave, a few days nearly each year are recorded with subzero temperature. Again, we think that even if frost can locally induce fracture propagation it is not the main point to be considered.

The driving force of the recorded displacements is clearly temperature and, because other causes of failure were difficult to envisage, we detailed subsequently how thermal variations can influence stresses and lead to failure in the rock matrix or fracture propagation.

4.2. Thermomechanics approach

4.2.1. hermoelasticity and possible tensile failure of the rock matrix

Let us consider a semi-infinite medium submitted to temperature variations.

For a homogeneous and isotropic material, in thermoelasticity, the relationship between stress variation and associated strains are (Henry and Parsy, 1982):

$$\Delta\sigma_{ij} = \frac{E}{(1+\nu)}\bullet\varepsilon_{ij} + \frac{\nu\bullet E}{(1+\nu)\bullet(1-2\nu)}\bullet tr\varepsilon\bullet\delta_{ij} - \frac{E}{(1-2\nu)}\alpha\bullet\Delta T\bullet\delta_{ij}$$

$$\varepsilon_{ij} = \frac{1+\nu}{E}\bullet\Delta\sigma_{ij} - \frac{\nu}{E}\bullet tr\Delta\sigma_{ij}\bullet\delta_{ij} + \alpha\bullet\Delta T\bullet\delta_{ij}$$

E: Young modulus, ν Poisson's ratio and α linear thermal expansion coefficient.

Let z be the depth direction perpendicular to the surface. Using cylindrical coordinates, r and θ are the axis perpendicular to the z-axis. Considering a semi-infinite medium, no stress is supposed to occur along z when temperature varied. It can be demonstrated that the strain

(elongation for a positive variation of temperature) along the *z*-axis is given by:

$$\varepsilon_z = \frac{1+n}{1-n} \bullet \alpha \bullet \Delta T$$

And the corresponding stress variations in the (r,θ) plane are:

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

Which could be called $\Delta\sigma_{\perp z}$

$$\Delta\sigma_{\perp z} = -\frac{E}{1-n} \bullet \alpha \bullet \Delta T$$

ΔT is the temperature variation at the corresponding depth.

These thermal stresses, added to the mechanical stresses, increase the traction when temperatures decrease (bear in mind that tensile stresses are counted positively). Table 2 gives an estimation of the stress variations induced by a given variation of temperature in La Roque Gageac case, that is a 42.6 GPa Young modulus (E), a 0.15 Poisson's coefficient (ν) and a 6.10^{-6} linear thermal expansion coefficient (α).

If the stress modulus parallel to the surface is low, about zero (which have been confirmed by 3D modelling), 5,4 MPa, the tensile strength, is reached for a negative variation of about 18 °C and thus can explain a failure in the rock matrix. A decrease of temperature of 18,1 °C in 4 h was recorded the 20/09/2014 in the cave, which suggests this variation, or more, is feasible at the surface of the rock mass.

4.2.2. Fracture mechanics

If tensile strength can explain some rupture in the rock matrix in specific configurations, fracture mechanics could also be explored. According to fracture mechanics, a crack can propagate according to three possible modes or a combination of these three modes. The analysis of the elastic stress field near a fracture lead (Griffith, 1924) to the notion of stress concentration factor (K). The K factor, generally expressed in $MPa.m^{1/2}$, is a 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 in a single load at a low speed, the crack propagates. Toughness is defined for each mode of rupture (K_{IC}, K_{IIC} and K_{IIC}). Analytical developments not presented here (Merrien-soukatchoff and Gasc-barbier, 2021) show that as soon as the joint aperture reaches 4.4 mm, fracture can propagate in mode I. And the larger the aperture, the easier the chance of a fracture to propagate in mode I and in mode II. If the decrease of temperature is greater than 18 °C, tensile failure in the rock matrix is the predominant phenomenon compared to crack propagation.

Yet crack can propagate due to fatigue at a stress concentration factor (K) lower than toughness (Atkinson, 1982), up to 10% of Kc according to Putot, Chastanet, Cacas, and Daniel (2001) especially when the fracture is subjected to cycling loading. The subcritical crack growth has been studied in rocks since the 80′ by Atkinson (Atkinson, 1982; Meredith and Atkinson, 1985). According to Eppes and Keanini (2017) "terms including "environmentally assisted cracking," "stress corrosion," "time-dependent crack growth," "progressive failure," "microcracking" or "static fatigue" are commonly synonymously employed to describe combined subcritical cracking processes"

Table 2
Stress variation due to temperature variation, considering E = 42,630 MPa (mean of value of Table 1, $\nu = 0.15$ and $\alpha = 6\ 10^{-6}$.

ΔT (°C)	$\Delta\sigma_{\perp z}$ (MPa)
−5	1.5
−10	3.0
−15	4.5
−14.6	4.4
−17.9	5.4
−21.2	6.4

4.3. Thermal stress weathering

Due to temperature variation, matrix failure can happen (for a decrease of temperature greater than 18 °C in our case) or cracks can grow quickly when fracture toughness is reached or slowly and steadily at stresses much lower than critical stresses. In this last case fatigue due to subcritical fracturing, need long-term exposure (10–10^6 years). Temperature variation could induce such fatigue that is generate thermal stress weathering.

Some recent paper proposed mathematical formulation of thermal stress weathering (Eppes and Keanini, 2017; Ravaji, Alí-Lagoa, Delbo, and Wilkerson, 2019). Eppes and Keanini (2017) formulation is based on kinetic laws: cracking rates are dependent on many factors including stress magnitude and the length of the crack for instance.

In addition, from a micro-structural point of view, it is well known that an increase in temperature induces a dilation of crystals (Fortin, Gasc-barbier, and Merrien-soukatchoff, 2018). This expansion can lead to the development of intergranular tensile compression stresses and, if they exceed the tensile strength, intragranular and intergranular cracking may occur. In the case of thermal fatigue (*i.e.* repetition of small temperature cycles just as daily temperature variation, this crack propagation can exist even for smaller stresses: that is subcritical crack growth (Atkinson, 1982; Meredith and Atkinson, 1985). According Eppes and Keanini (2017) "terms including "environmentally assisted cracking," "stress corrosion," "time-dependent crack growth," "progressive failure," "microcracking" or "static fatigue" are commonly synonymously employed to describe combined subcritical cracking processes".

Nevertheless, the majority of studies that highlight sub-critical crack propagation focus on subsurface cracking and can explain exfoliation phenomena (Collins et al., 2018; Collins and Stock, 2016; Holzhausen, 1989).

The data collected at la Roque Gageac the shows the possibility of skin phenomena, on the surface, leading to the propagation of cracks due to thermal fatigue, but the mechanism of failure of the large blocks certainly involves some sizable fractures as those due to paleo-karst.

The geometry as well as the thermal and mechanical behaviour of such fractures involves too many uncertainties for their comportment under thermal stresses to be able to be calculated, but they generally have a lower tensile strength than the rock matrix, the predisposition of which we have shown to failure.

5. Conclusion

The roof of a limestone perched cave subjected to partial collapse and presenting a residual hazard was monitored during more than five years (after the collapse) until reinforcement works. A body of evidence, detailed in this paper, led us to suspect that temperature variations play a role in crack propagation and possible failures. The first one is that no evidence of other triggering factors for rock fall such as raining, freeze/thaw cycles or seismic events was identified. Secondly, extensometers in boreholes above the cave, show temperature and displacement decreasing with depth, but they also make it possible to detect an increase in displacements over time. This increase was also detected on the fissurometers placed in the cave and was larger than deep in the rock mass. Finally, analytical consideration computation reinforced this opinion.

As the shape of the cave is simplified, numerical results cannot be precisely compared to the recordings, they can only give orders of magnitude. Nevertheless, it shows that the stress variation in planes parallel to the topographic surface can be close to the tensile strength of the rock matrix and can thus explain a rupture in tensile mode. Moreover, fracture mechanics also show that the registered thermal

variations can lead to subcritical crack propagation and probably even in the rock mass at a depth of 6 m.

The whole phenomenon of failure mechanism that occurs in La Roque-Gageac limestone cliff is not completely understood because it certainly involves large fractures with undetermined mechanical behaviour. However, a network of observations, measurements and computation led to incriminate natural thermal cycles as one of the potential triggering mechanisms for the rock mass instability in this site.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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