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Assessment of the influence of natural thermal cycles on dolomitic limestone rock columns: a 10-year monitoring study

1 INTRODUCTION

Geomorphology is focused on the explanation of the surface of the Earth. As explained by (Hall et al., 2012), “the Earth's landforms and landscapes express the integration of the balance between internal and external forces influencing that surface, as modulated by both a unique local history and the surface material”. Moreover, these authors precise that this balance is dynamic and that weathering is a fundamental topic as it is the “initial or primary expression of the transition from domination of material by internal forces to modification by external forces”. Therefore the action of weathering is significant in landscape evolution (Gasc-Barbier et al., 2021).

Rock fracturing plays a key role in the process of weathering (Eppes, 2022), because in the one hand it will increase the weathering as cracks are predisposing factors and, in the other hand, it is the consequence of weathering. Cracks modify the mechanical, chemical, and hydrological properties of the rock, and rock fracturing is the first step of erosion processes as it enables the development of isolated debris. When considering the failure of steep rock slopes, different agents of weathering should be considered as triggering factors, such as freezing (Deprez et al., 2020; Frayssines and Hantz, 2006; Matsuoka, 2008, 2001), rain (Balducci, 2007; Bernardie et al., 2014; Bezak and Mikoš, 2021; Chigira, 2009; Galeandro et al., 2014; Iverson, 2000; Regmi et al., 2013) or thermal variations (Alcaíno-Olivares et al., 2023; Breytenbach, 2022; Collins and Stock, 2016; Eppes et al., 2010; Eppes and Griffing, 2010; Eppes and Keanini, 2017; Gunzburger et al., 2005; Hall, 1999; Hall and Thorn, 2014; Marmoni et al., 2020; Mufundirwa et al., 2011; Ravaji et al., 2019; Vargas et al., 2004). More specifically, the influence of temperature as one of the agents of the alteration has been drawn due to several events where other causes could not be invoked (Collins et al., 2018; Gasc-Barbier et al., 2015; Gunzburger and Merrien-Soukatchoff, 2011; Vargas et al., 2009).

Merrien-Soukatchoff and Gasc-Barbier, (2023) have recently reviewed the accumulated knowledge on the effect of positive temperature cycles on rock slope stability. They offered a comprehensive summary on the site investigations conducted in the last 35 years, focusing on the effect of natural thermal cycles simultaneously at the surface and in the rock mass. Temperature is mostly measured at the surface (Alcaíno-Olivares et al., 2023; Guerin et al., 2021; Marmoni et al., 2020; McKay et al., 2009) but also in the rock mass (Breytenbach, 2022; Racek et al., 2021) up to 6 m (Gasc-Barbier et al., 2021). Displacements are sometimes registered (Bièvre et al., 2018; Guerin et al., 2021; Gunzburger et al., 2005; Krähenbühl, 2004) but in most cases it is fracture openings and closures that are recorded (Alcaíno-Olivares et al., 2023; Cloutier et al., 2015; Gischig et al., 2010; Grøneng et al., 2011; Mufundirwa et al., 2011; Racek et al., 2023).

Such thermomechanical measurements were observed in a wide range of lithologies (gneissic rock (Grøneng et al., 2011; Gunzburger et al., 2005; Krähenbühl, 2004), granite (Collins et al., 2018; Guerin et al., 2021) or different types of limestone (Bakun-Mazor et al., 2013; Gasc-Barbier et al., 2021; Marmoni et al., 2020; Taboada et al., 2017; Vlcko et al., 2009)) and climatic conditions (desertic areas, temperate climate, etc.). Different approaches to data processing and modelling can be used: in some cases, theoretical models are focused on rock mass deformations that result from continuous models of rock deformations, neglecting the presence of joints. Other approaches neglect the transient state of the environmental fluctuations.

48 Nevertheless, all authors agree on the importance of data acquisition during long timeframes to
49 better assess the time-dependent behaviour of the rock mass. As long-time measurements are
50 rare, the effect of climatic factors on rock weathering remains relatively poorly understood in
51 the long term, especially if we try to translate it into thermomechanical constitutive laws. As
52 mentioned, numerous papers show the influence of temperature, but most of the sites under
53 study are monitored during small periods, from a few days to a year. Those time laps are enough
54 to identify some thermomechanical behaviour but are not long enough to completely
55 characterise them especially when the mechanisms evolve with time. In the case of les
56 *chandelles de l'Escalette*, eleven fissurometers with temperature measurements were
57 positioned along 50-meter-high dolomitic columns and were monitored for 10 years. It enables
58 us to depict the long-term interaction between thermal sollicitation and displacements along
59 fractures and separated rock masses.

60 2 GEOMORPHOLOGICAL AND GEOLOGICAL SETTINGS

61 2.1 General description

62 *Les chandelles de l'Escalette* are located in the south of France (see insert in [Figure 1](#)) just
63 above an important highway and above the south heads of a tunnel ([Figure 1](#)). They are located
64 at the bottom of a *dead-end* valley of the Lergue River on the southern edge of the Larzac
65 plateau. A simplified geological log is given on the right part of [Figure 1a](#), [Figure 1b](#) presents
66 a top view of the site and [Figure 1c](#) is a geological map of the area (caution: scales are not the
67 same).

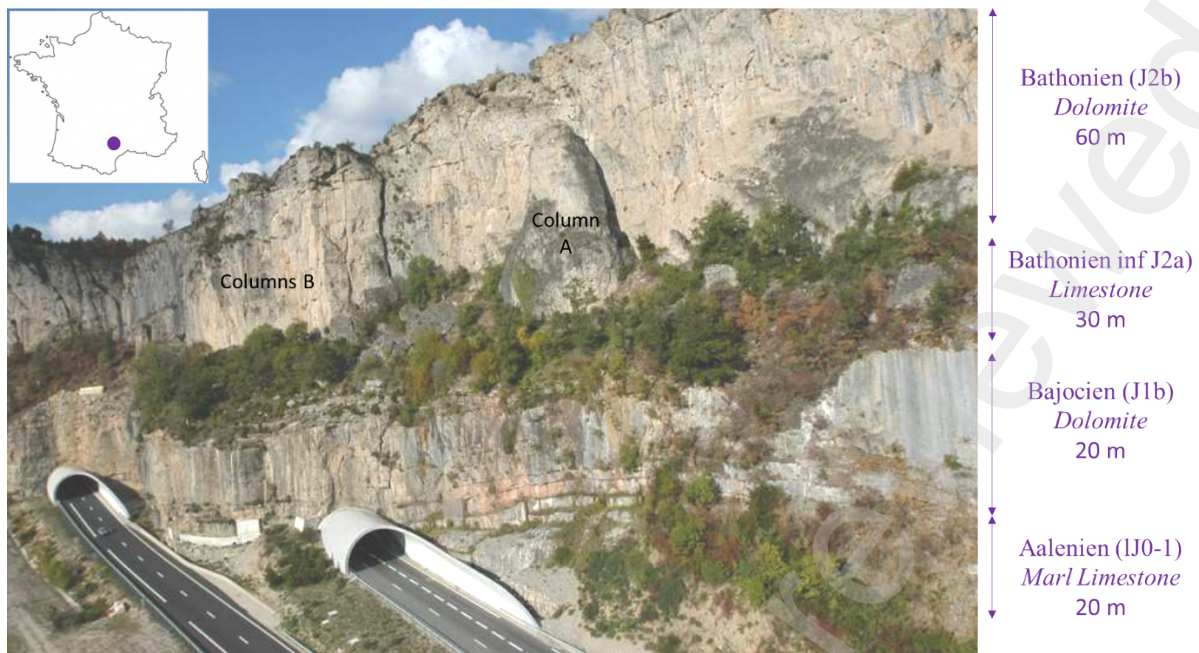
68 The rock columns are Bathonian (J2b¹) dolomitic limestone of approximately 60 m high. They
69 lie on about 30 m of infra-Bathonian (J2a), that are sub-lithographic limestones in small banks
70 and fetid marls with lignite debris around 30-m thick. This level forms the smoother slope
71 separating the two stiff cliffs (see [Figure 1a](#)). The underlying Bajocian (J1b) is characterised by
72 a rather massive light beige saccharoidal dolomite in large banks. Finally, a small thickness of
73 Aalanian (IJ0-1) marl -interlace limestone in small banks outcrops at the base of the topography.
74 Dolomite from Bathonian and Bajocian give steep cliffs whereas infra-Bathonian and Aalanian
75 limestone leads to gentler slopes. The local dip of the layers is about 5° to 6° to the north.

76 Wider, the southern edge of the Larzac plateau presents a relatively simple tabular and sub
77 horizontal structure made of Bathonian dolomite (light brown in fig 1c). The blind valley cut
78 by the Lergue River where the *chandelles* are located is easily observed on the geological map.
79 From a structural point of view, a major fault is located just at the north of the tunnel. An aerial
80 photointerpretation has shown a fairly dense fractures network oriented N30, N70, N100, N130,
81 N160. These directions are readable in the morphology of the cliffs.

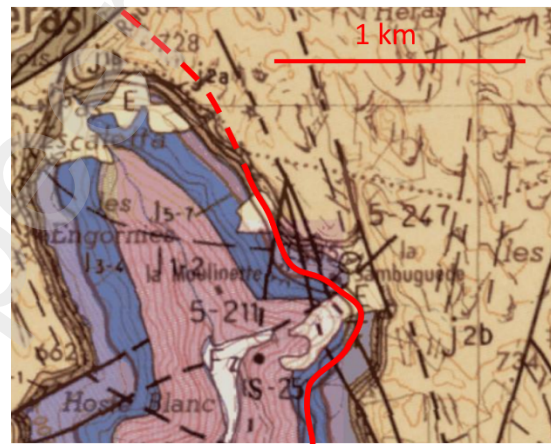
82 The nearest weather station was set up at Caylar in 2007 ([https://donneespubliques.
83 meteofrance.fr/?fond=contenu&id_contenu=37](https://donneespubliques.meteofrance.fr/?fond=contenu&id_contenu=37) - ID 34064003). This small village is located
84 on the Larzac plateau, about 5 km at the North of the *Chandelles*. French climate classification
85 made by (Joly et al. 2010) describe an Altered Mediterranean Climate: the average annual
86 temperature is high, with a small number of cold days and between 15 and 23 hot days per year.
87 Inter-annual variability in July temperatures is minimal: summer is repeatedly hot from one
88 year to the other. Annual rainfall is average (800-950 mm) but is not evenly distributed.

89

¹ J1b, IJ0-1, J2b, J2a are geological denominations that can be seen on [Figure 1c](#)



a



b

c

90 *Figure 1: Location of the site and geological clues. a- general view of the columns and*
 91 *simplified geological interpretation b-Top view of the site - red circles show the large*
 92 *fractures that separate the columns from the cliff; c- Geological map of the area, the highway*
 93 *is in red, the tunnel is in dotted line.*
 94

95 **2.2 Description of the columns**

96 **2.2.1 Description of column A**

97 Column A (see Figure 1a) is almost pyramidal and culminates at 659 m; its base is estimated at
 98 622 m according to the lowest point of the western face. Thus, the height of the column A is
 99 about 37 m. It should be noted that mining in 1993 (during road works) reduced its height by
 100 around 15 m. An estimation gives the roof of the infra-Bartonian between 619 and 621 m, which
 101 means that the column is entirely composed of the dolomitic Bathonian. More precisely, its top
 102 is about 7 m thick and 10 m long and its base is about 12 m thick and 30 m long. The back of
 103 the column is a well-defined crack oriented N150, with an opening ranging from 1.3 m to
 104 1.55 m. The bottom of the back crack is covered with earthy soil, with a large block in the
 105 centre. The column is very massive. The volume of the column is about 5000 m³. Its gravity

106 centre is anticipated at about 634 m high, that is 12 m above the base, 4.8 m of the back crack
107 and 7 m behind the front face.
108

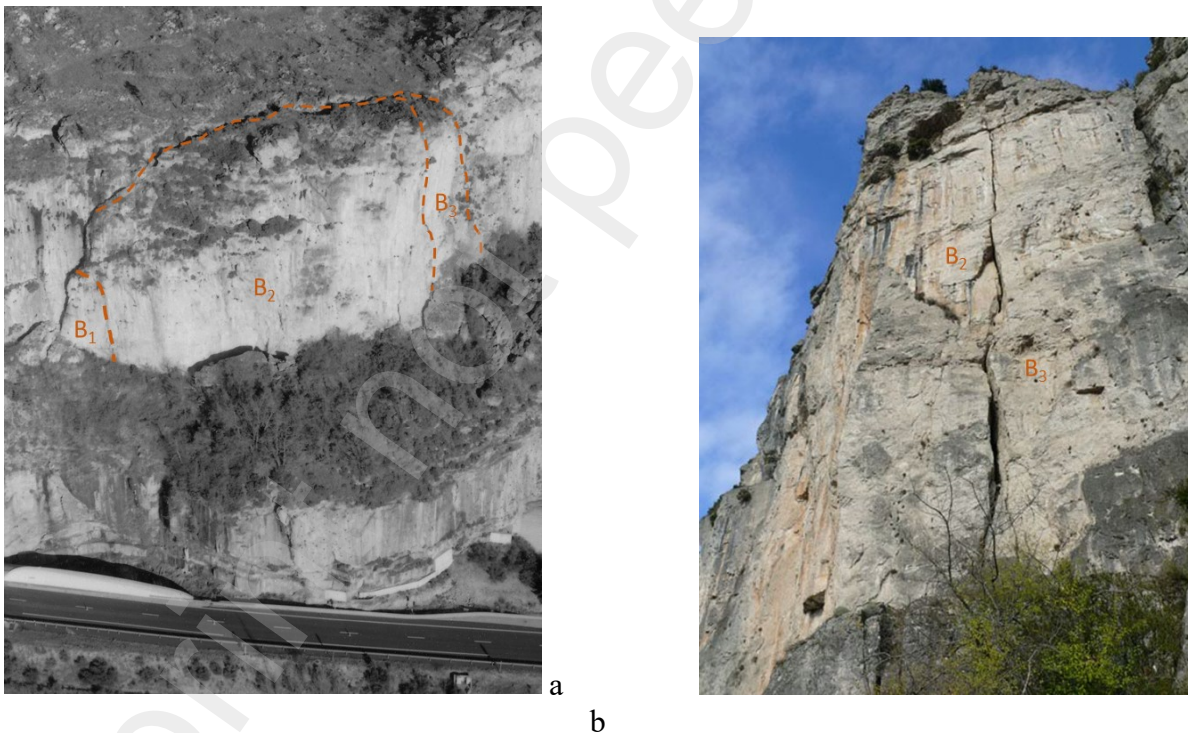
109 2.2.2 Description of column B

110 This column has a parallelepipedal shape. It culminates between 661 m and 665 m, its base is
111 estimated between 612 m and 620 m. Its height is about 45 to 49 m. At the top it has a
112 trapezoidal section of 80 and 45 m in length for a width of about 13 m. The area is almost
113 identical from the base to 645 m high, then decreases slightly on the north side. Its total volume
114 is about 34 000 m³.

115 The global centre of gravity is estimated at 637 m (20 / 25 m above the base); at about 8.2 m
116 from the front face and 8.0 m from the back face, and 37.7 m from the foot of the fissure in the
117 South (40 m from the foot of the fissure in the North).

118 This large column is divided into 3 main masses (see Figure 2a).

- 119 - In the North a small column, B₁ is about 15 m long and 1 to 11 m thick for a height of
120 40 m.
- 121 - In the centre, the main mass B₂ is 55 m long and 12 to 15 m thick, for a height of 50 m.
122 A crack well defined delimited spalling C (see Figure 2b)
- 123 - In the south a much smaller column B₃ is about 15 m long and 6 m thick for a height of
124 50m (see Figure 2b).



135 found. The monitoring device is composed of eleven fissurometers, corresponding to the red
 136 points in Figure 3a, and also positioned on the simplified diagram represented in Figure 3b.
 137 Along each important fracture (see Figure 2) two pairs of sensors were located, one at the
 138 bottom (B sensors), one near the top (H sensors). More precisely: H1 and B2 are located
 139 between column A and the cliff; H3 and B4 are located between column B₃ and the cliff; H5
 140 and B6 between columns B₂ and B₃; H7 and H9 are located between column B₂ and the cliff
 141 and finally B8, V8 and B10 are located between column B₁ and the cliff (at the bottom of the
 142 large fracture), see Figure 3b.



143



○ Back side /inside ○ Front side

144

b



145
 146 *Figure 3: Instrumentation. a- general view, b, simplified diagram of the position of sensor in*
 147 *columns B, c, sensor H3 set-up, d- sensor B4*

148 All fissurometers are horizontal, except V8 which is vertical and located near B8 (only one red
 149 point corresponding to both B8 and V8 is displayed in [Figure 3](#)). Temperature is measured near
 150 each fissurometer.

151 Apart from H5 and B6, all the sensors are positioned on the back side of the columns, in screw-
 152 to-screw of the cliff (H3, B4, H9, B10), or inside, between parts of column B (H7, B8, V8).
 153 This point is important when considering the influence of temperature on the displacement and
 154 especially because they are not exposed to sunlight.

155 [Figure 3d](#) gives an example of a fissurometer in place and [Figure 3c](#) shows the set-up. Photos
 156 of all fissurometers are displayed in appendix 1.

157 3 RESULTS

158
 159 Temperature and displacement recording began in November 2012 (on the 7th). A measure is
 160 taken every hour, except for few periods due to measurement devices shutdown, depending on
 161 the sensors. Most fissurometers are still recording even if, after six or seven years of records,
 162 we observed more and more noise and some unexplained steps. Data up to October 2022 are
 163 available on sensors H3, B4, H5 and B6. Only part of the data (up to 2018 or 2021) is available
 164 on the other sensors.

165 3.1 Temperature recording

166 3.1.1 General observations

167 [Figure 4](#) presents temperature recording from November 2012 to October 2022 in H5 sensors.
 168 To make the data more readable, we only plotted the average weekly temperature (dots) and
 169 weekly maximum and minimum (error bar in blue). The seasonality is obvious and the 10 years
 170 can be recognized in [Figure 11](#) All temperature curves are given in appendix 2, presented 2 by
 171 2 on the same graph (H and B for the same global location).

172

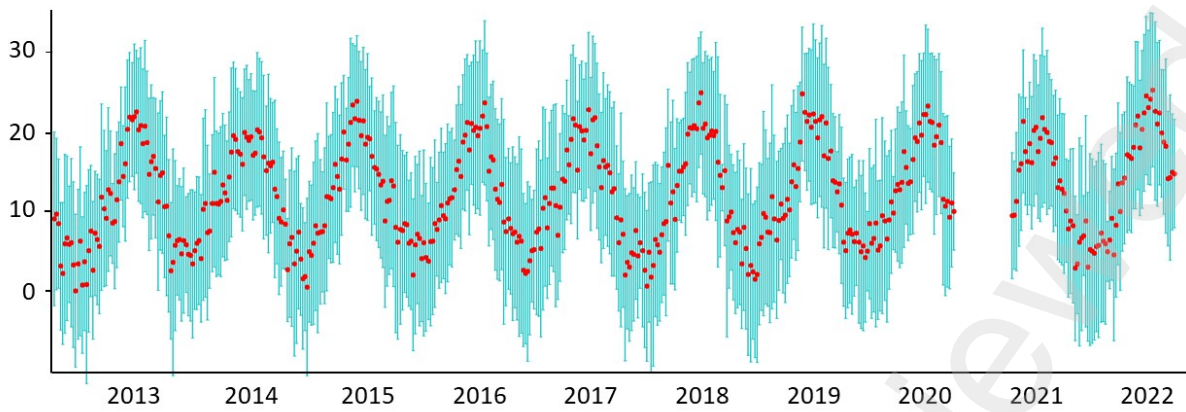


Figure 4: 10 years of temperature recordings on H5 sensor: dots: average weekly temperature, error bar: weekly minimum and maximum

The temperatures recorded are broadly the same in all the sensors, but a closer look reveals some local variations. Temperatures are more widely dispersed in the upper sensors than in the lower ones. (see also Figure 6).

Table 1 presents minimum and maximum temperature recorded for each sensor. The maximum temperature over the period is 37.67°C obtain on sensor H7 the 2017-06-17 at 8 p.m. On the 2nd of August 2018 at 9 p.m., we recorded the maximum temperature value for sensors B8 (36.93°C), H9 (36.92°C) and B10 (36.94°C). The minimum temperature over the period is -11.98°C obtained on sensor H3 the 2018-02-27 at 10 a.m. The same day, at the same hour, we have recorded the minimum values of B4 (-10.64°C), H5 (-9.08°C) and B6 (-11°C).

Max daily amplitude over the period is 30.18°C obtain on sensor B2 on the 03/12/2013 then 27.6 obtained on B6 on the 2017/01/19. The minimum daily amplitude is between 0°C and 1°C. It is obtained during the winter months, mostly in December, with no sunshine.

Table 1: Minimum and maximum temperature and maximum daily amplitude recorded.

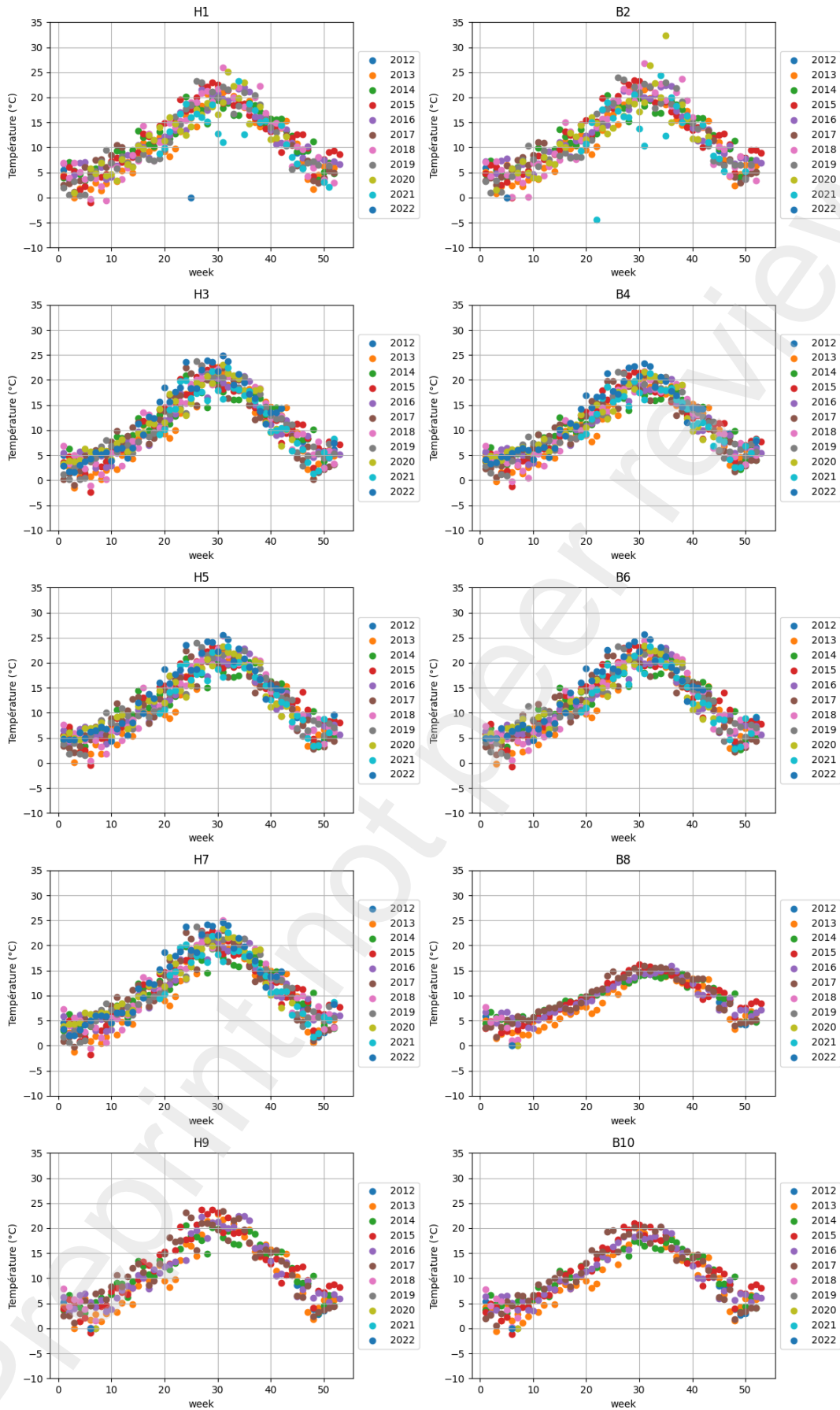
| | Min | | Max | | Amplitude max | |
|-----|----------|------------|---------|------------|---------------|-------------|
| | val | date | val | date | val | date |
| H1 | -8.8°C | 2018/02/27 | 33.84°C | 2022/08/04 | 24.15°C | 2022/07/31 |
| B2 | -6.81 | 2017/11/26 | 40.65°C | 2016/09/11 | 27.75°C | 2017/03/10 |
| H3 | -11.98°C | 2018/02/27 | 39.21°C | 2019/06/28 | 22.28°C | 2020/07/12 |
| B4 | -10.64°C | 2018/02/27 | 35.14°C | 2020/08/08 | 19.3°C | 2017/10/04 |
| H5 | -9.08°C | 2018/02/27 | 37.74°C | 2022/08/02 | 24.11°C | 2013/12/03 |
| B6 | -11°C | 2018/02/27 | 39.6°C | 2022/08/07 | 28.48°C | 2022/09/18 |
| H7 | -9.07°C | 2013/01/18 | 38.46°C | 2017/06/17 | 24.52°C | 2016/08/07 |
| B8 | -5.79°C | 2017/10/29 | 38.17°C | 2022/08/07 | 14.83°C | 2018/04/015 |
| H9 | -9.2°C | 2018/02/27 | 38.2°C | 2022/08/07 | 18.65°C | 2014/03/17 |
| B10 | -9.92°C | 2018/02/27 | 38.18°C | 2022/08/07 | 21.24°C | 2017/08/21 |

Figure 5 and Figure 6 present temperature recorded by all the sensors.

Similarly, data after March 2018 (respect. 2021) are not represented for sensors B8, H9 and B10 (respect. H1 and B2) because they are too scattered to be taken into account. The violins consider all the temperatures recorded (i.e. one per hour), and not just the averages.

197 To compare one year with another or one sensor with another we have chooses two different
198 types of graph. Figure 5 shows classical temperature data as a function of time (each point
199 corresponds to a weakly mean temperature) but year per year, with all plots having the same
200 scale, while Figure 6 represents the data in form of violin plots. Each violin corresponds to one-
201 year temperature. The larger the violin, the greater the temperature recorded over the year. The
202 bars represent the maximum, medium and minimum values recorded. Please remember that in
203 2012 recording began in November, thus this is not a full-year data, which is why the violin is
204 smaller (it only synthesises 2 months of winter). Similary, data after March 2018 (respect. 2021)
205 are not represented for sensors B8, H9 and B10 (respect. H1 and B2) as they are too scattered
206 to be taken into account. Violins consider all recorded temperatures (i.e. one per hour), and not
207 just the average.

208 Figure 5 illustrates the classical temperature recording in an Altered Mediterranean Climate
209 (see above the end of part 2.1). Highest temperature (weekly means between 20 and 25°C) are
210 recorded around July (weeks 26-32) and lowest (weekly means around 0°C) around the end of
211 January – beginning of February (weeks 1-8).



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Figure 5: Weekly Mean temperature recording on sensors

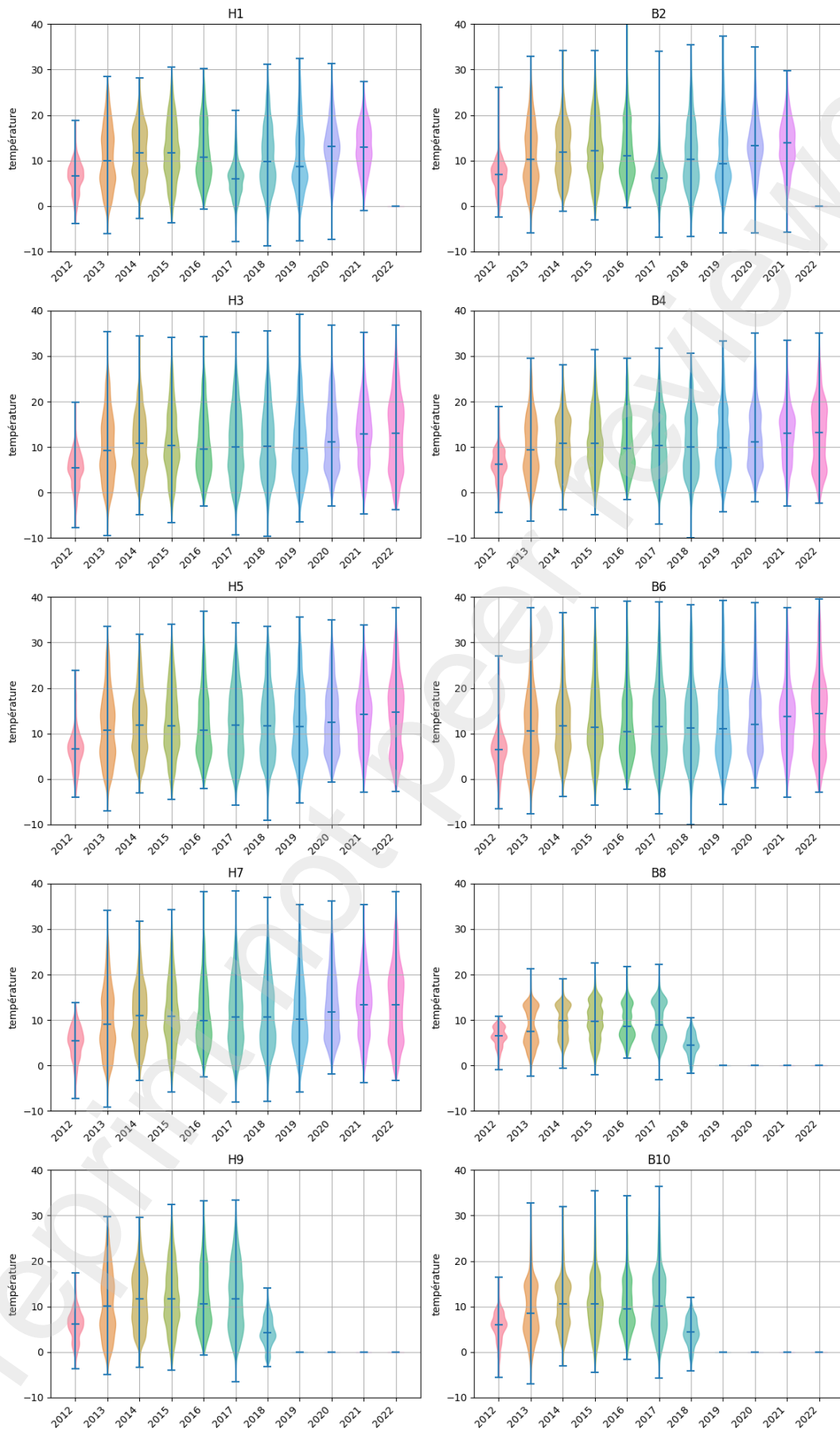


Figure 6: Temperature recording on sensors.

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We can observe on [Figure 6](#) that, even if temperature variations are observed from one year to the next, there is no overall trend to be drawn from these measurements in terms of warming over the past 10 years, nevertheless a slight increase of medium values is observed in 2021 and 2022 compared to 2015-2019. When comparing high (H) and Bottom (B) sensors located on the same fracture, we observe that the yearly amplitude is larger for top sensors than from bottom. As expected, deeper in the fracture, temperatures are more regulated since they are less exposed to sunlight.

Finally, we also computed mean temperature per month as displayed in [Table 2](#). As expected in the area, the coldest month for all sensors is January and the warmest is July for 6 sensors and August for the 4 remaining (remind that B8 and V8 have the same temperature sensor).

Table 2: Mean temperature per months

| | H1 | B2 | H3 | B4 | H5 | B6 | H7 | B8 | H9 | B10 |
|-----------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| January | 4.09 | 4.72 | 2.93 | 3.81 | 4.59 | 4.65 | 3.32 | 4.05 | 3.75 | 3.62 |
| February | 4.46 | 5.02 | 3.7 | 4.28 | 5.23 | 5.58 | 4.08 | 4.56 | 4.57 | 4.41 |
| March | 6.74 | 7.2 | 6.09 | 6.2 | 7.47 | 7.6 | 6.28 | 5.76 | 6.73 | 6.28 |
| April | 9.7 | 10.12 | 9.15 | 8.93 | 10.34 | 10.47 | 9.49 | 8.29 | 9.88 | 9.29 |
| May | 12.04 | 12.36 | 12.48 | 11.46 | 13.01 | 13.03 | 12.64 | 11 | 12.88 | 12.25 |
| June | 16.73 | 17.07 | 17.51 | 16.01 | 17.6 | 17.45 | 17.5 | 14.75 | 17.76 | 16.63 |
| July | 19.86 | 20.28 | 20.31 | 18.97 | 20.68 | 20.57 | 20.49 | 17.55 | 20.8 | 19.62 |
| August | 19.4 | 19.93 | 19.47 | 19.05 | 20.73 | 20.93 | 19.89 | 17.68 | 20.37 | 19.48 |
| September | 16.83 | 17.35 | 15.48 | 16.19 | 17.55 | 17.65 | 16.14 | 15.27 | 16.69 | 16.17 |
| October | 12.81 | 13.11 | 11.37 | 12.1 | 13.22 | 13.1 | 11.9 | 11.77 | 12.42 | 12.02 |
| November | 8.37 | 8.79 | 6.61 | 7.42 | 8.3 | 8.07 | 7.06 | 7.81 | 7.61 | 7.39 |
| December | 5.95 | 6.31 | 4.5 | 5.21 | 6.09 | 5.91 | 4.81 | 5.69 | 5.31 | 5.22 |

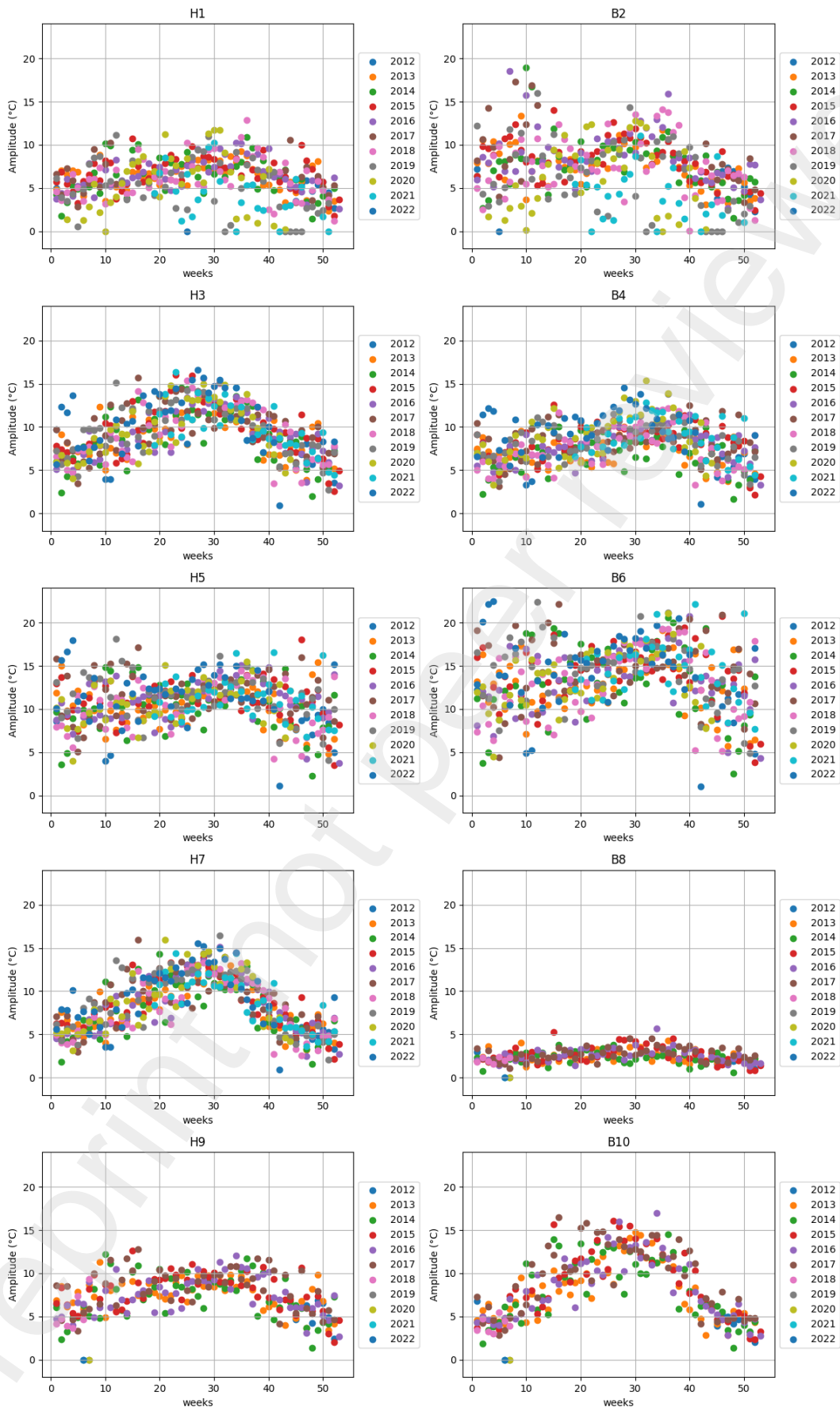
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230 3.1.2 Daily temperature amplitude

231 All daily temperature amplitudes were calculated. Maximum daily amplitude recorded on each
232 device is given in [Table 1](#). To be more readable, week means daily amplitudes are displayed in
233 [Figure 7](#) per year as a function of the considered week and [Figure 8](#) shows the mean temperature
234 as a function of the daily amplitude, values averaged over a week. Colours are kept the same
235 on all plots to be able to compare data from one year to another.

236 Considering both figures together we can say that, overall, when daily mean temperatures
237 increase, daily amplitude increase. It has been verified by statistical analysis of the data
238 (correlation, significance and variance analysis) not presented here. This trend is a general
239 trend, represented in [Figure 7](#) by bell-shaped curves and in [Figure 8](#) by a global linear positive
240 trend, easier to see on H3, H7, B10 sensors. Beyond this general trend, some more local
241 behaviour can also be observed:

- 242 • Very high daily amplitudes can occur even when the mean daily temperature is low
243 (winter periods). It probably occurs on sunny days, even if it cannot be proved with our
244 monitoring device.
- 245 • Even more, there is more variability in thermal amplitudes when the average
246 temperature is low than when it is high: daily amplitude values evolve more from one
247 week to another during winter months than summers. It can be easily observed in [Figure](#)
248 [8](#) on sensor H5 and B6 with cone-shaped curves, for instance.



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Figure 7: Distribution of daily amplitudes as a function of temperature - weekly means – scale and colours are kept the same for all plots.

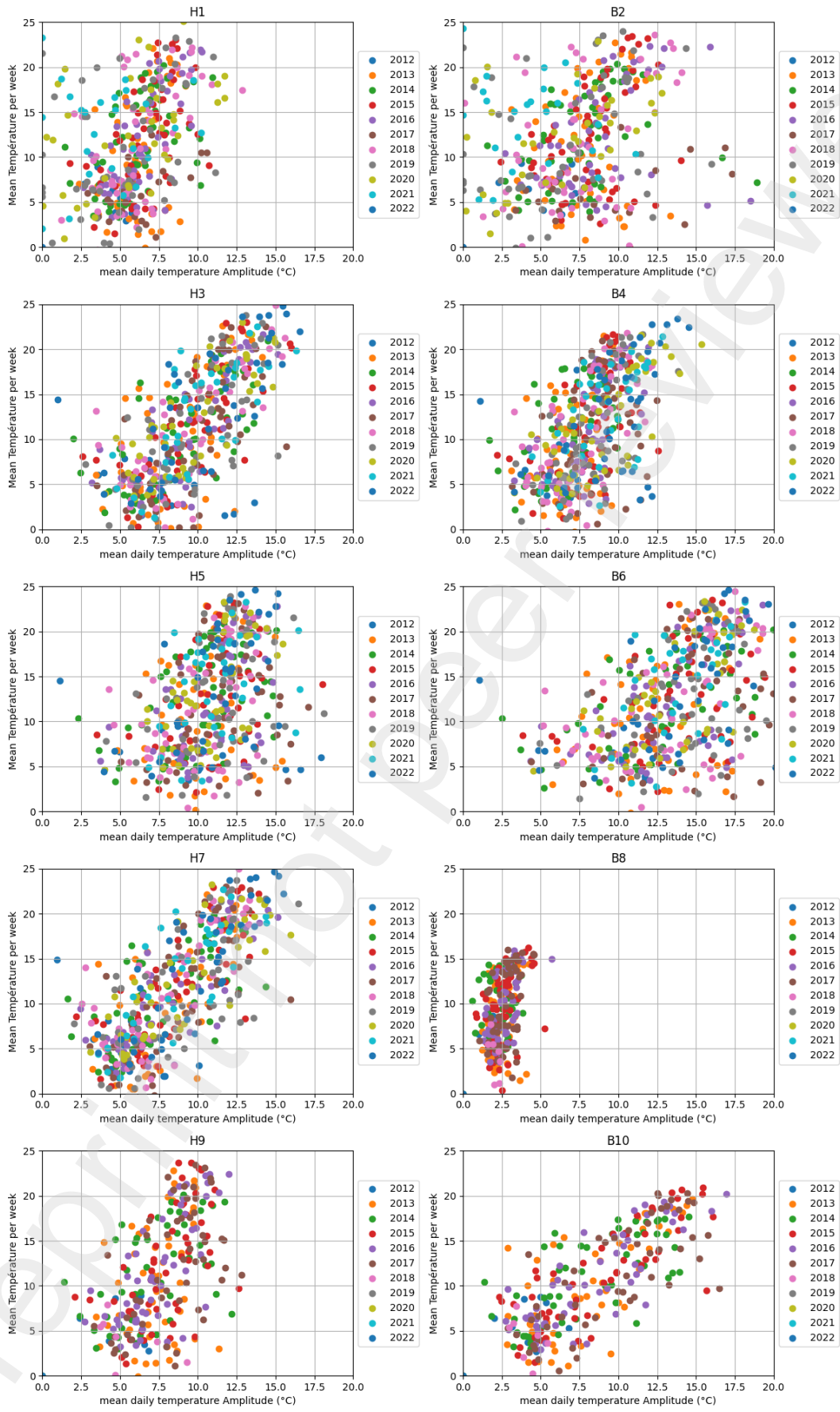
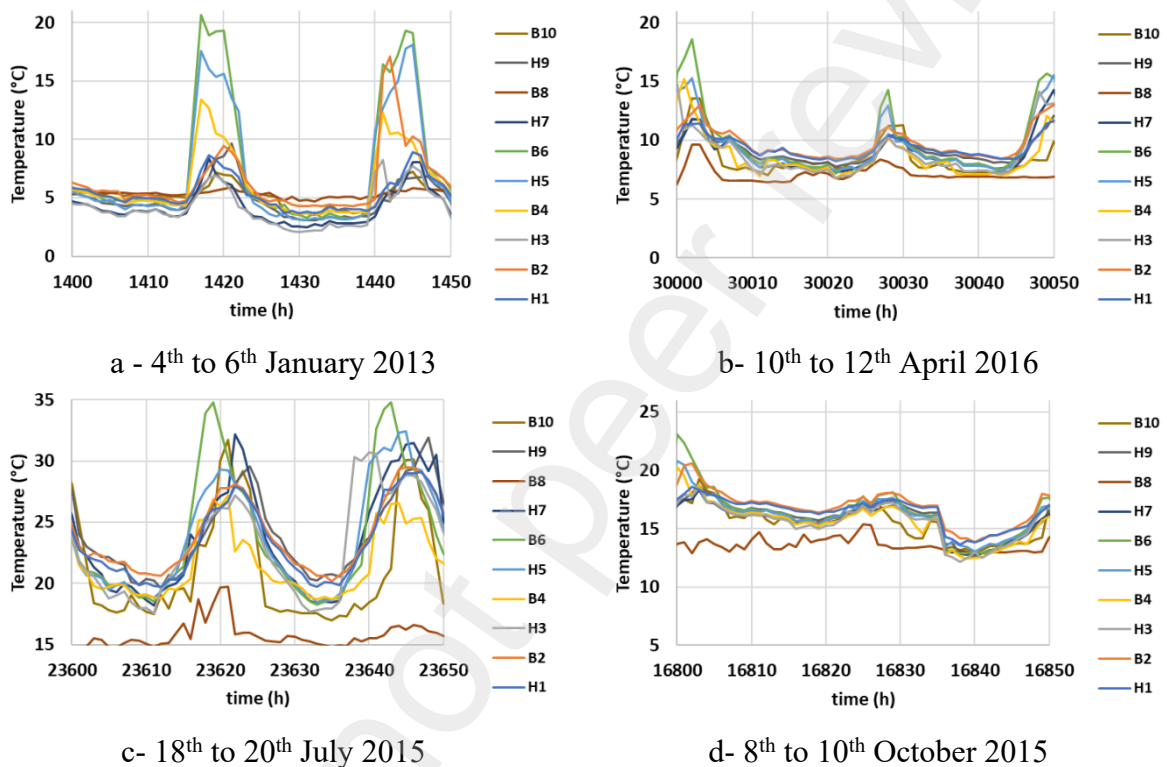


Figure 8: Distribution of weekly mean temperature as a function of daily temperature amplitude (one week average) – scale and colours are kept the same for all plots.

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255 3.1.3 Comparison of the kinetics of temperature variations

256 Figure 9 shows two consecutive days for each season. The temperature data are not smoothed,
257 and one measure per hour is displayed. The days are chosen at random to be as representative
258 as possible, although periods with missing data were not considered. As expected, given the
259 local climate, temperature amplitudes are greater in winter (when the sun shines) and in summer
260 than in spring or autumn. We decided here to focus on 2 consecutive days to compare
261 temperature trends. With such representation, it is difficult to propose general conclusions
262 because no systematic behaviour is observed. For instance, on the 4th of January 2013 (Figure
263 9a) the temperature of sensors B4, H5, B6 increase more quickly than the temperature of sensors
264 B2 and H3 whereas the following day B2, H3, B4 increase before H5 and B6.
265



266 Figure 9: Temperature recordings – zoom in 2 days per season. Scale is the same for all
267 figures
268

269 The evolution rates will be discussed deeper in the discussion part (4.3).

270 3.2 Displacement recording

271 All displacement curves are given in appendix 3. As done for temperature (Figure 4 and
272 appendix 2), to make the curves more readable, daily means and weekly means were computed,
273 and the data after February 2018 for B8, H9 and B10 and after 2021 for H1 and B2 are not
274 displayed as the records have too much noise. Displacements curves are presented 2 by 2 on
275 the same graph (H and B for the same global location). Weekly mean displacements are
276 represented by dots and weekly maximum and minimum are represented by an error bar.

277 3.2.1 Global analysis

278 Analysis of the curves show different results depending on the location of the sensors, but some
279 general trends can be observed (see displacement curves presented on appendix 3):

- annual cycles can easily be seen on the displacement curves (as for temperature curves),
- displacement curves seem to evolve more erratically than temperature curves,
- unlike the temperature curves which remain generally constant from one year to the next, the deformation curves show a drift with time,
- the drift can be positive or negative depending on the sensor under consideration,
- H and B sensors of the same location evolve in the same way: their drift has the same symbol (H1, B2, H3, B4 present negative drift and H5, B6, H9, B10 have positive drift). A negative drift means that rock faces tend to get closer to each other, a positive one means that both rock faces tend to separate from each other. This will be discussed later.

Comparing H and B sensors of the same location, we can add:

- Daily and weekly displacement amplitude is larger on B-sensors than on corresponding H-sensors except for H9 - B10. This is illustrated by the length of the bars in Annexe 3 figures.
- A larger drift is observed on H-sensors displacement than on B-sensors when the drift is negative and a smaller when the drift is positive, if we focus only on the first 6 sensors (H1 to B6) as H7 to B10 are more difficult to analyse 2 by 2.

3.2.2 Comparison of sensors placed at the same high but at the front or rear

Figure 10 compare displacements curves obtained at approximately the same height but at the front (H5, B6) or rear (H3, B4). The upper part of Figure 10 focuses on the H sensors (H5, dots in red, error bar in blue and H3, dots in green, error bar in yellow) and the lower part on B sensors (B6, dots in red, error bar in blue and B4, dots in green, error bar in yellow).

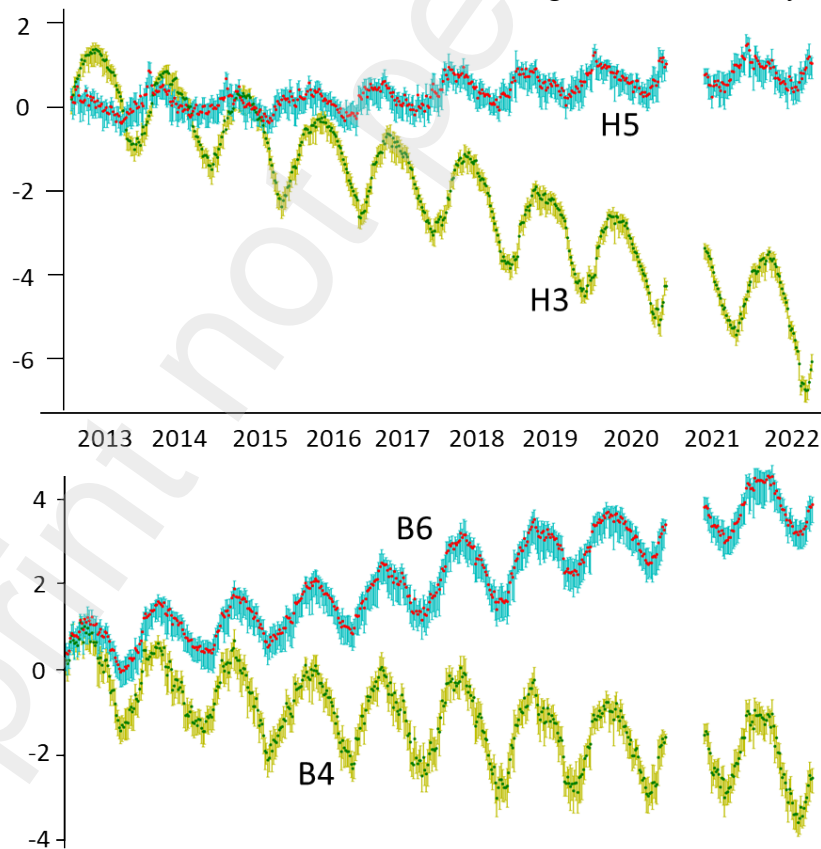
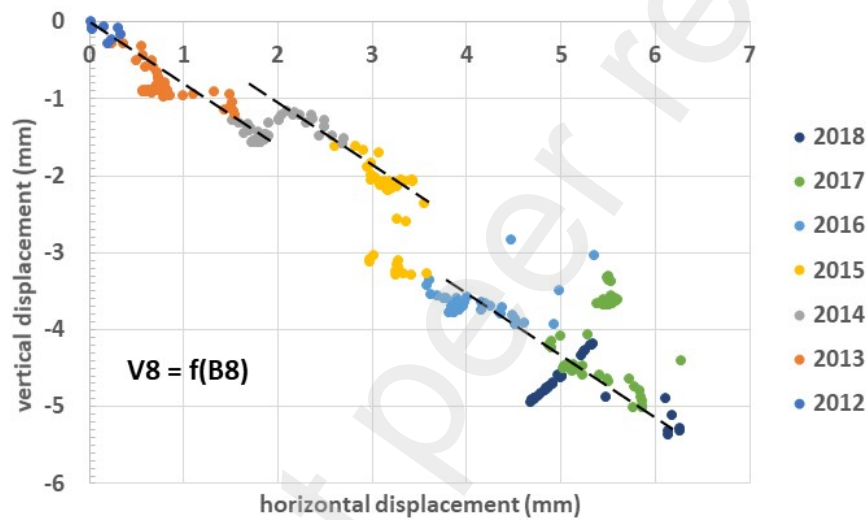


Figure 10. Comparison front face H5 and B6 (dots in red, error bar in blue) / backward face H3 and B4 (dots in green, error bar in yellow)

305 We can see that displacements are evolving simultaneously: on a yearly scale, a displacement
 306 peak on one sensor is mirrored on the others. In terms of weekly variations in displacement
 307 amplitude, H5 and B6 appear to be more dispersed than H3 and B4. On the other hand, if we
 308 look at annual displacement amplitudes, H5 and B6 are smaller than H3 and B4. Finally,
 309 regarding trends (drifts), sensors located at the same level show trends of opposite sign
 310 (displacements on H5 overall increase, while those on H3 tend to decrease; similarly,
 311 displacements on B6 increase, while those on B4 tend to decrease.

312 3.2.3 Oder of magnitude

313 **Figure 11** presents the comparison between horizontal and vertical displacement corresponding
 314 respectively to B8 and V8 sensors between 2012 and 2018. We can observe that a slope of -0.8
 315 can fit the curve from part to part. This observation will be discussed in the mechanical analysis
 316 part.
 317



318
 319 *Figure 11 : Comparison of horizontal (B8) and vertical displacements (V8)*

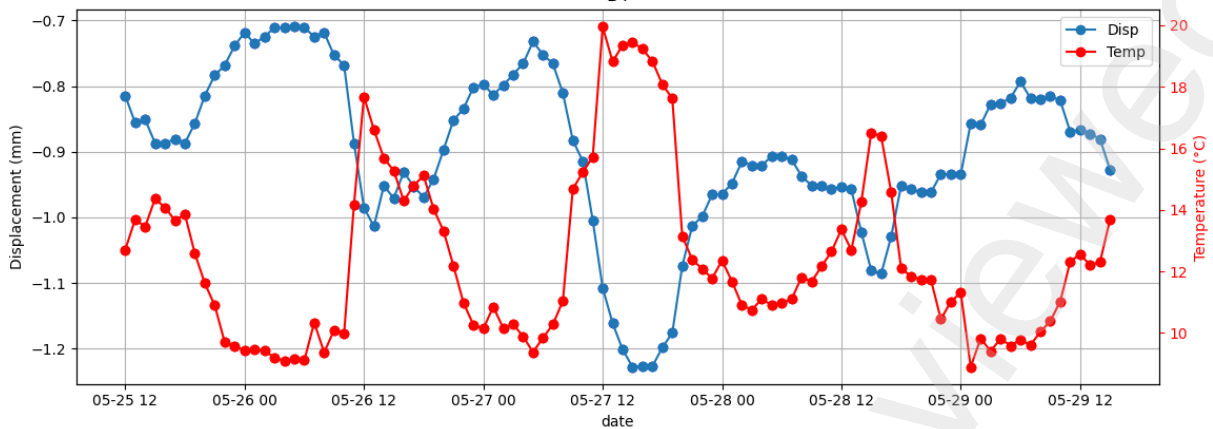
320 3.3 Displacement versus temperature curves

321 3.3.1 Daily / weekly comparison

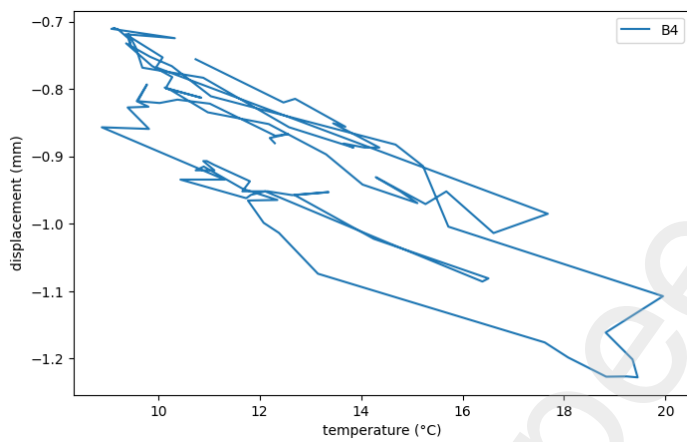
322 **Figure 12** presents displacements and temperature recorded on sensor B4. Displacement peaks
 323 correspond broadly to temperature peaks (see on **Figure 12a**), but in detail it is not quite as
 324 simple. In fact, the curve displacement = f(temperature) on **Figure 12b** is not a straight line even
 325 if the tendency is a linear behaviour. Overall, an increase (respectively decrease) in temperature
 326 leads to an increase (respectively decrease) in displacement. In most cases, this variation is
 327 concomitant. But, looking deeper in the data show that the same increase (or decrease) of
 328 temperature does not imply the same displacement variation depending on the mean
 329 temperature. For low temperatures, the temperature increment required to obtain a displacement
 330 increment is relatively small (1 or 2 degrees). If the temperature is higher, the same increment
 331 of 1 or 2 degrees will not lead to an increment in displacements - it may need 3 or 4°C to have
 332 one. This shows that the system is not purely elastic.

333 On a weekly scale, a moving 4-hour average is sufficient to smooth out some of the local
 334 variations, but on a monthly or yearly scale we need to enlarge the moving average to smooth
 335 the curves. Instead of a few days moving average, we choose to calculate weekly means and
 336 plot them together with weekly min and weekly max temperature (see curves on appendix A2).

337 Displacements are function of the temperature variations, the direction of variation (increase or
 338 decrease) and the average temperature over a week.



339 a



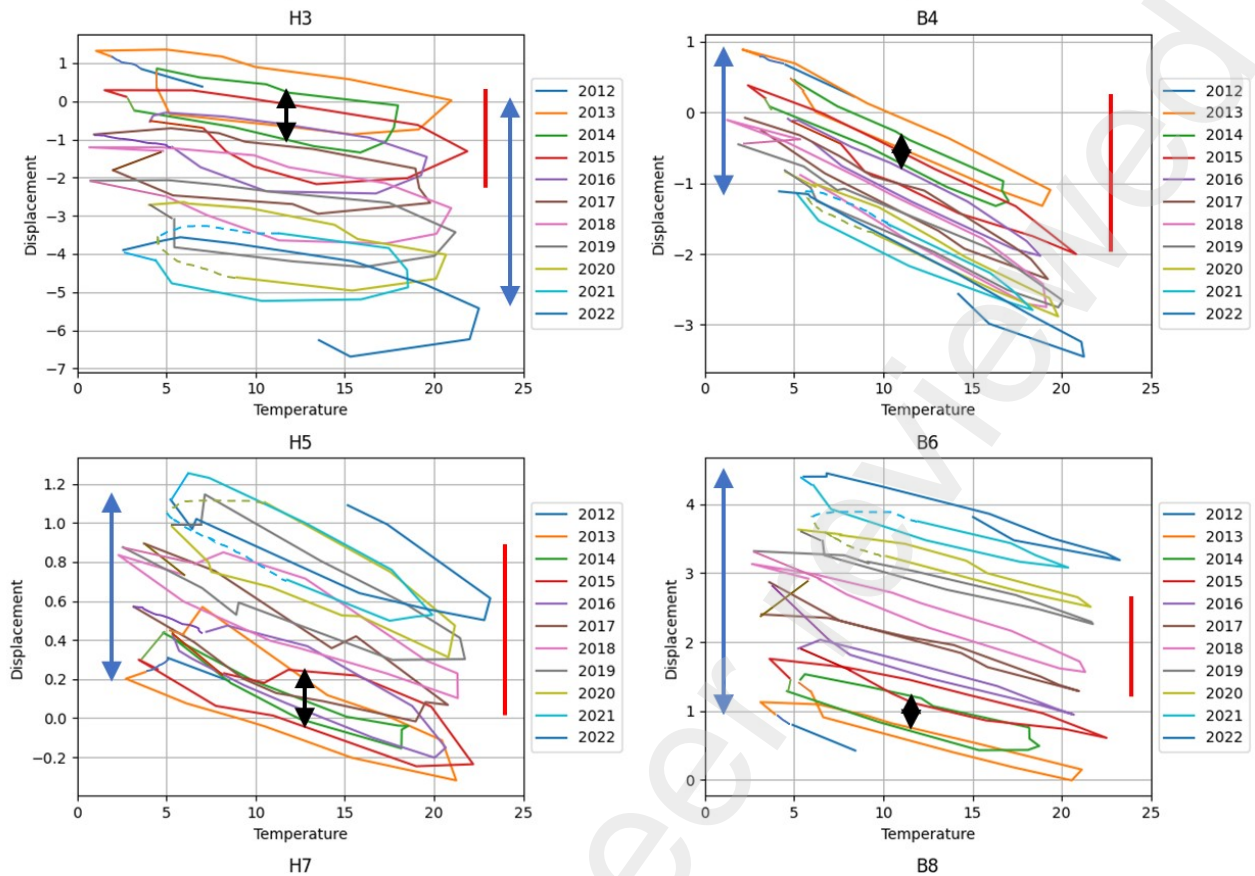
b

Figure 12 : Displacement and temperature recorded on B4 sensor between 2016/05/25 and 2016/05/29. a- as a function of time, b- displ = f(temp)

340 3.3.2 Evolution over 6 years

341 **Figure 13** presents recorded displacements versus recorded temperature in H3, B4, H5 and B6
 342 all sensors. On **Figure 13** smoothed curves plotted with monthly averages are shown over the
 343 10 years recorded. The cyclic behaviour is obvious. Appendix 4 presents all curves for the
 344 period 2012-2018, presented with weekly averages (dots are not linked to help to be more
 345 readable). Scales are kept the same for each H/B pairs, except for H5/B6 and H7/B8, and each
 346 colour corresponds to a year and year colours are the same for all sensors. On **Figure 13** and in
 347 Appendix 4 black arrows correspond to an annual hysteresis, red line is the annual displacement
 348 range between min and max temperature and blue arrows correspond to a 10-years drift on
 349 **Figure 13** and a 6 years-drift in appendix 4. Parameters measured on appendix 4 curves are
 350 given in **Table 3** (6 years drift) and parameters measured on **Figure 13** curves are given in **Table**
 351 **4**.

352 The vertical translation of the curves “displacement vs temperature”, means that displacements
 353 evolve even if the annual temperature range does not. This is a strong indication of the
 354 cumulative effect of the temperatures on displacements.



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Figure 13. Displacement versus temperature on High (left) and Bottom (right) sensors. Each dot corresponds to a week mean value. Colors are identical on all graph, but displacements scales are not the same. Blue arrows correspond to a 10-years drift, black arrows correspond to an annual hysteresis. Red line is the annual displacement range between min and max temperature.

Table 3: Measured parameters obtained on the curves presented in appendix 4 (2012-2018) – estimation of the parameter are based on weekly means.

| | Annual displacements range (mm) | annual hysteresis (mm) | 6-year drift (mm) | Comments |
|------------|---------------------------------|------------------------|-------------------|---|
| Appendix 4 | <i>Red line</i> | <i>black arrow</i> | <i>blue arrow</i> | |
| H1 | - 2.25* | 0.3 | -1.4 | *smaller in 2015 2017: Only partial data |
| B2 | - 2 | 0.3 to 0.4 | - 0.8 to -1 | 4-years drift Data after 2016 are not considered |
| H3 | -2.5 | 2 | -2.5 to 3 | |
| B4 | -2.5 | 0.5 | -1.1 to -1.5 | |
| H5 | 0.95 | 0.5 | 0.5 to 0.6 | |
| B6 | 1.7 | 0.3 | 2 | |
| H7 | -0.5 | 0.35 | -0.9 to -0.95 | |
| B8 | 1.1 | 1.1 | 4 to 5.5 | |
| V8 | 1.6 | 1.2 | 4 to 4.6 | |
| H9 | 2.1 | 1.3 | 1.5 | |
| B10 | 2.5 | 1.55 | 1.3 to 1.5 | |

364

365 *Table 4: Measured parameters obtained on the curves presented in Figure 13 (2012-2022) -*
 366 *estimation of the parameter are based on monthly means.*

| | Annual displacements range (mm) | annual hysteresis (mm) | 10-year drift (mm) |
|------------------|------------------------------------|---------------------------|-----------------------|
| <i>Figure 13</i> | <i>Red line</i> | <i>black arrow</i> | <i>blue arrow</i> |
| H3 | - 2.6 | 1.3 | - 5.5 |
| B4 | - 0.9 | 0.4 | - 2 |
| H5 | 2.15 | 0.3 | 1 |
| B6 | 1.5 | 0.5 | 3.6 |

367
 368 H3 and B4 behaviour have been already described in (Gasc-Barbier et al., 2023) only for the
 369 first 6 years of recording. After 10 years of recording, the total effect is a decrease in
 370 displacement of about 2 mm on B4 and of about 5.5 mm on H3, as illustrated with the blue
 371 arrows on *Figure 13* and values given on *Table 4*. They are consistent with values given on
 372 *Table 3* and (Gasc-Barbier et al., 2023) for a 6-year drift. In addition, there is a difference
 373 between the measured hysteresis of each annual D_p vs T curves. On the one hand, on both
 374 sensors the hysteresis is almost constant from year to year, but, on the other hand, the annual
 375 hysteresis (see black arrows) is nearly 3 to 4 times smaller on B4 (about 0.4, 0.5 mm) than on
 376 H3 (about 1.3 to 2 mm) depending on the representation by weekly means or monthly means.
 377 The choice of the way to represent data is emphasised by the annual displacement range (red
 378 lines): values obtained on 6 years curves and weakly means as presented in appendix 4 show
 379 that the amplitude of displacements between max and min temperatures is the same on both
 380 sensors, whereas 10 years curves and monthly means as presented in *Figure 13* does not show
 381 the same trend.

382 4 DISCUSSION

383 4.1 Displacements' seasonality

384 *Figure 14* presents a synthesis of the evolution of displacement during the year. Each dot
 385 corresponds one average weekly displacement, and graphs are plotted with a colour per year,
 386 to show the potential evolution. Most of the curves have a v-shape and present a minimum
 387 between week 20 (mid-May) and week 40 (end of September) and a maximum between week
 388 45 (early November) to week 10 (mid-March). To be more precise: B2 (except 2021), H3, B4
 389 (except 2021 and 2022) and H7 have their minimum in September (weeks 36-39), B1, B4, B6,
 390 H9 in August (weeks 31-34) and only H5 has its minimum at the end of July – beginning of
 391 August (weeks 29-32). On the opposite, maximum is obtained in December for H5, in January
 392 (weeks 1-4) for H1, B2, B4, H7, and in February for B6, H9. H3 has its maximum in early
 393 March (week 10).

394 If we compare these results with temperature recordings (see *Figure 5*), we can observe that
 395 maximum and minimum are not perfectly correlate. There is a slight time lag between peaks.
 396 This effect is particularly noticeable on H3, B4 and H9. Maximum temperature is respectively
 397 obtained weeks 29-31, 29-31 and 27-30 whereas minimum displacement is obtained weeks 35-
 398 38, 30-33 and 33-36. This slight time lag of 2 to 4 weeks is not as easily observed during winter
 399 months and seems to be reduced to only 1 or 2 weeks which is more difficult to see.

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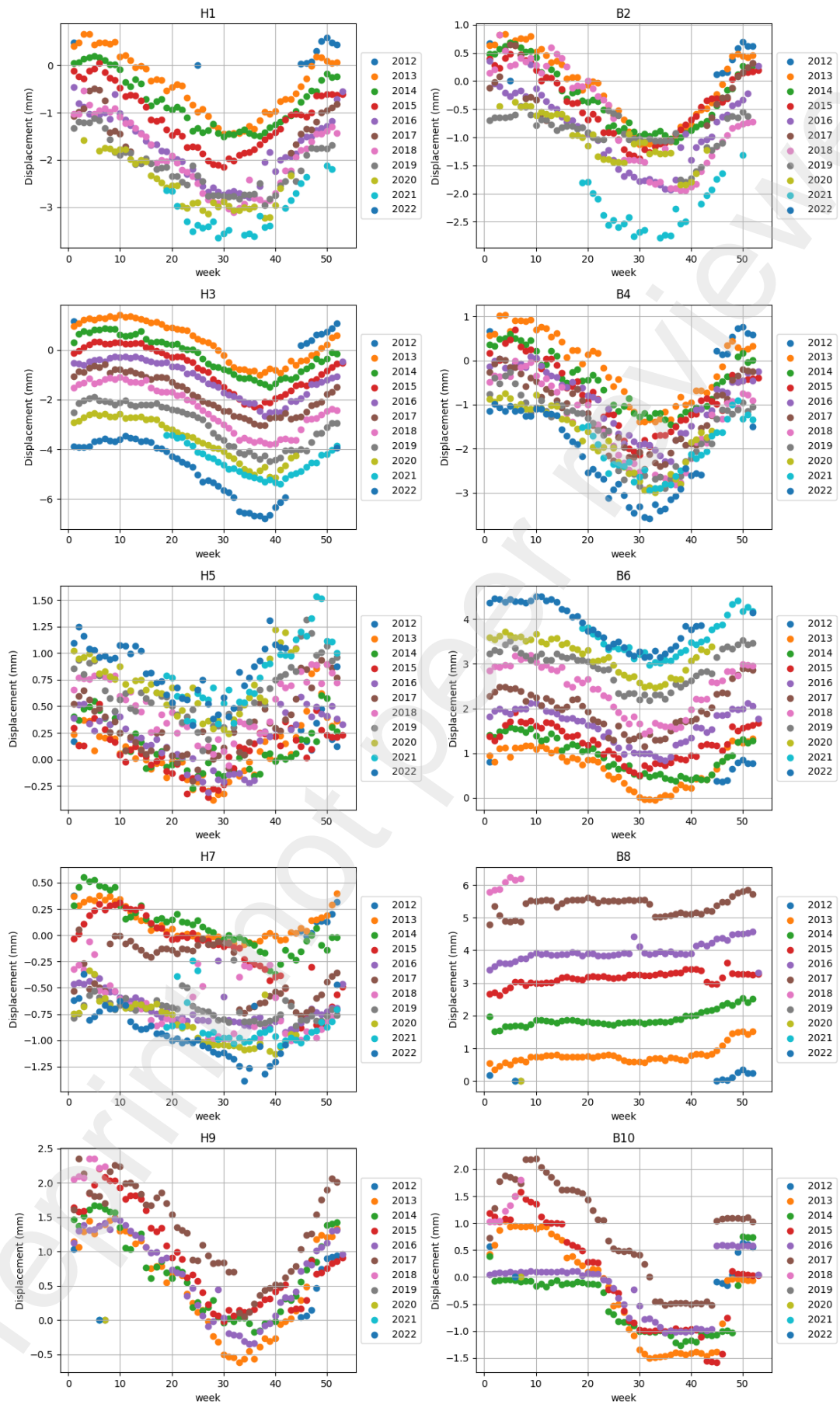
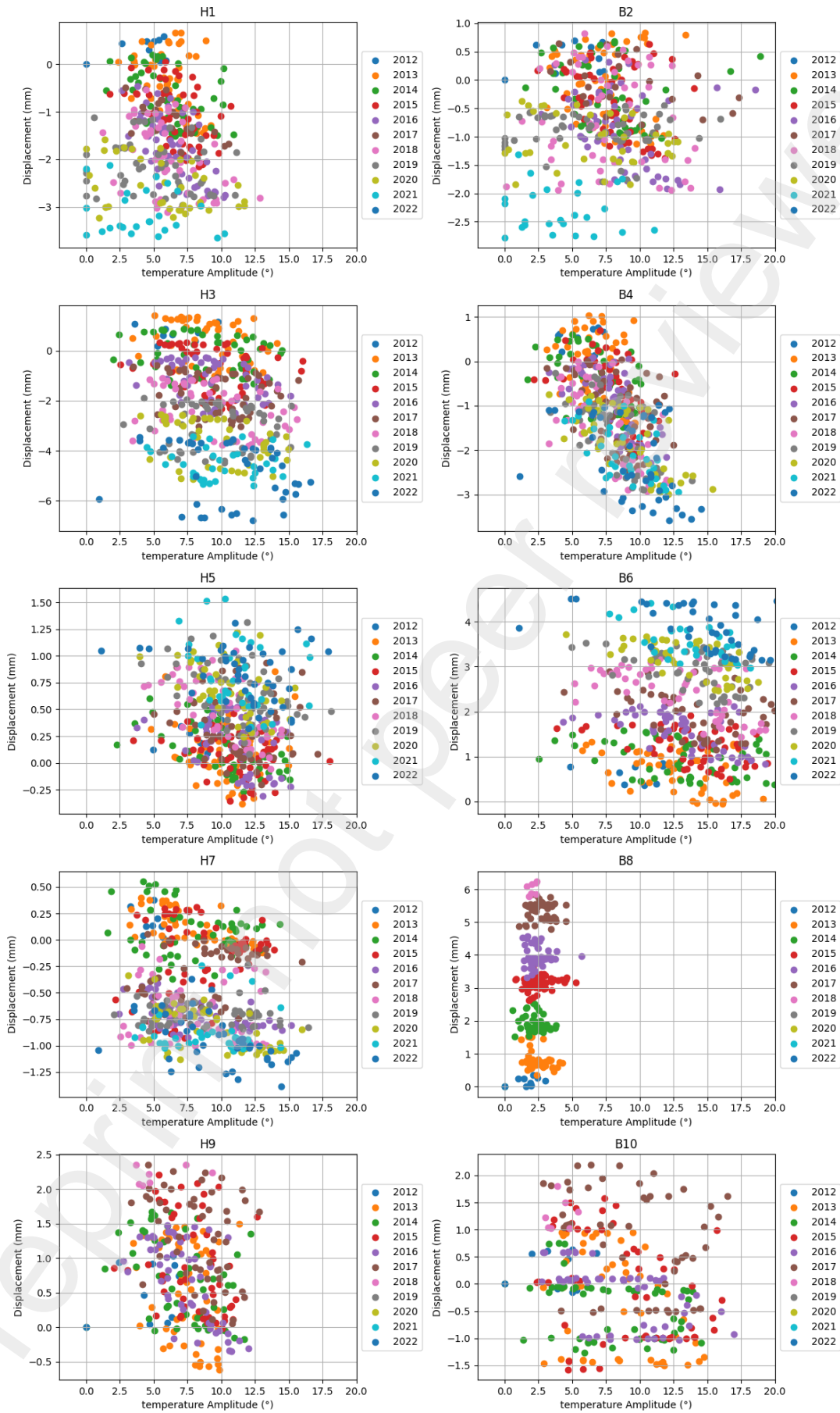


Figure 14 : Average weekly displacements mean during the year

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Figure 15 : displacements as a function of the daily amplitude of temperature

406 4.2 Displacements as a function of the daily amplitude of temperature

407 Figure 15 presents recorded displacements as a function of the daily amplitude of temperatures
408 averaged over a week. The colours of the years are the same as those of the previous plots.
409 In contrast to the results shown in Figure 14, it is very difficult to find a trend on Figure 15. The
410 curves seem to have no characteristic shape. In the same way, if we compare Figure 15 with
411 Figure 13 or appendix 4 (displacements versus temperature) no global analysis can be proposed.
412 Thus, it is another clue to say that the value of the daily amplitude does not play a significant
413 role on displacements whereas the repetition of cycles does.
414

415 4.3 Influence of temperature increment on displacement increment

416 As mentioned earlier, the link between variation of temperature and evolution of displacement
417 is established (see 3.3 and figure 11), but the evolution is more complex than just a simple
418 proportional relation, which would have corresponded to a thermoelastic behaviour between
419 increment of temperature and increment of displacement. To look deeper how temperature
420 modifies displacement and, considering the previous observations (section 3.3), here we focus
421 on their incremental evolution and performed multiple linear regression. To avoid bias as far as
422 possible we decided to focus only on H3, H5, B4 and B6 which seems to be the more reliable
423 sensors. On those 4 sensors, data sorting was realised:

- 424 1. Incremental displacement (Δd_i) and incremental temperature (ΔT_i) were calculated only
425 if successive measurement were one hour apart.
- 426 2. Δd_i are kept for multiple linear regression analysis only if ΔT_i , ΔT_{i-1} , ΔT_{i-2} and ΔT_{i-3} are
427 available.

428 When using B6 as an example of data processing, from about 87600 measurements (which
429 correspond to a measure each hour for 10 years), only 76791 were used for all former analysis
430 (due to lack in measurements or not reliable values) and then 66452 were kept for multiple
431 linear analysis. Even if the exact number is not the same on all sensors, the proportion is similar.
432 Histograms of incremental values were prepared to verify the homogeneity and the repartition
433 of the measurements. All shows a Gaussian repartition which tends to show that no "erroneous"
434 values were kept.

435 Simple 2- by- 2 correlation between incremental displacements and incremental temperatures
436 were realised and the calculates correlation coefficients are presented on Table 5. For all
437 sensors, the best correlation is obtained with the corresponding temperature increment, but it
438 can be seen that previous increments also have a significant weight. It also appears that on B
439 sensors, the 2-hours previous increment (ΔT_{i-2}) plays a more important role (it has a higher
440 correlation coefficient) than the 1-hour previous increment (ΔT_{i-1}). This is not the case with H
441 sensors, where the order of importance follows the expected order (the further before, the less
442 significant).
443

444 *Table 5: Correlation coefficients between incremental displacement and incremental*
445 *temperature*
446

| R^2 | $\Delta d_i=f(\Delta T_i)$ | $\Delta d_i=f(\Delta T_{i-1})$ | $\Delta d_i=f(\Delta T_{i-2})$ | $\Delta d_i=f(\Delta T_{i-3})$ |
|-------|----------------------------|--------------------------------|--------------------------------|--------------------------------|
| B4 | 0.3671 | 0.0963 | 0.1874 | 0.057 |
| B6 | 0.3014 | 0.1688 | 0.206 | 0.1816 |
| H3 | 0.1336 | 0.0614 | 0.0149 | 0.006 |
| H5 | 0.6521 | 0.2572 | 0.1616 | 0.0979 |

447 Multiple linear regression analysis was then performed on the four sensors data. It consists in
 448 finding the coefficients a, b, c, d, e that give the best fit to the equation written as:

449
$$\Delta d_i = a * \Delta T_i + b * \Delta T_{i-1} + c * \Delta T_{i-2} + d * \Delta T_{i-3} + e$$

450 The values of the best-fitted coefficients and the correlation coefficients of the multiple linear
 451 regression are given in Table 6. Values are given with 6 digits for a better comparison. As
 452 expected, correlation coefficients of the multiple linear regression analysis are higher than those
 453 presented on Table 5 which emphasise the importance of not only the concomitant temperature
 454 increment but also the formers.

455
 456 *Table 6: Results of the multiple linear regression analysis*
 457

| | a | b | c | d | e | R ² |
|----|----------|----------|----------|----------|-----------|----------------|
| B4 | 0.014762 | 0.005392 | 0.010608 | 0.004118 | -0.000937 | 0.5505 |
| B6 | 0.009976 | 0.003625 | 0.005440 | 0.006379 | -0.001695 | 0.508 |
| H3 | 0.007247 | 0.003080 | 0.001372 | 0.000115 | -0.000331 | 0.1607 |
| H5 | 0.015766 | 0.005630 | 0.003675 | 0.003035 | -0.000577 | 0.7881 |

458

459 *4.4 Proposition of a mechanical interpretation*

460 *4.4.1 From a local point of view*

461 The previous observations on the influence of past temperature increments on the current
 462 displacement increment can be translated from a mechanical point of view with the rheological
 463 spring-sliding element. Further investigations are needed to be able to formalise properly such
 464 constitutive law, but our observations seem to show that to reproduce the thermomechanical
 465 coupling, thermoelasticity is no sufficient. Viscoplasticity with dashpot should at least be
 466 considered to reproduce the observed drift during years and, moreover, sliding element should
 467 also be used to better reproduce the in-situ observations.

468

469 Comparison of displacement recorded on B8 and V8 sensors give a -0.8 slope (see [Figure 11](#)).
 470 If the behaviour was isotropic, we should have a 1 slope. The difference between 0.8 and 1
 471 correspond to an angle of about 6° that be attributed to a local rotation of the rock mass, and
 472 more precisely considering the location of the sensors, between B₁ and B₂.

473

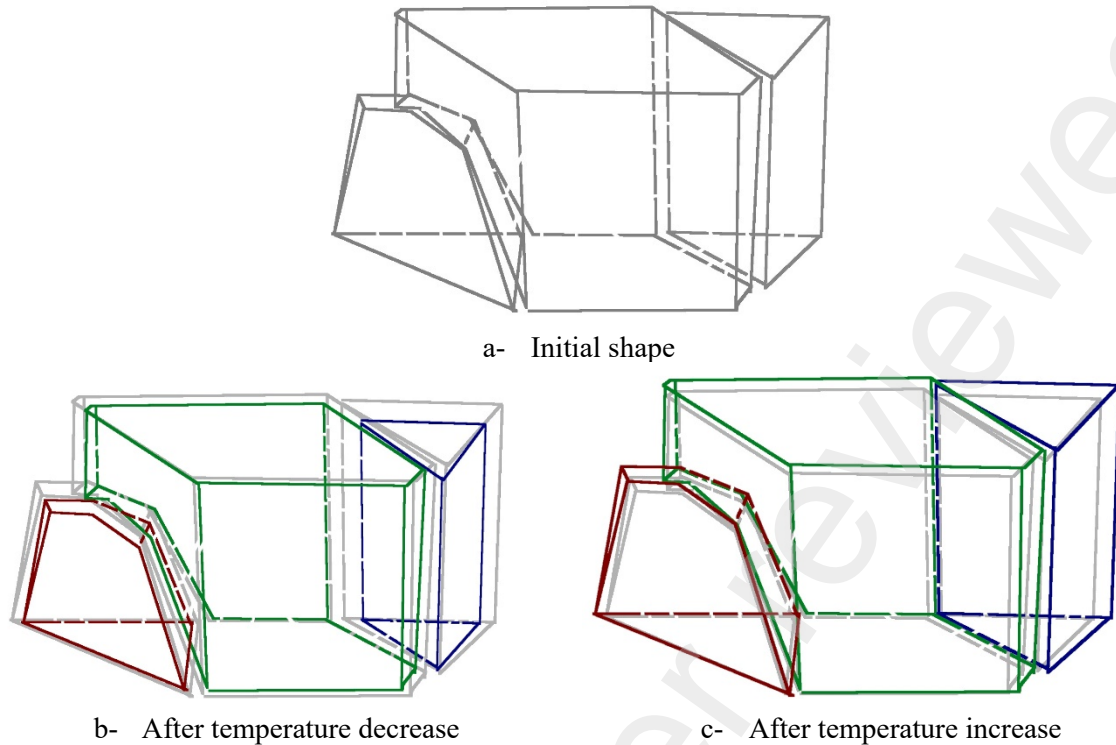
474

475 *4.4.2 From a global point of view*

476 Results presented above enable us to the propose schematic evolution of the shape of column
 477 B with temperature displayed in [Figure 16](#), in the short term: when temperature decrease rock
 478 mass globally shrinks, the rock faces move away from one another and displacements recorded
 479 on sensor (displayed between rock faces) are positive ([Figure 16b](#)). When temperature increase,
 480 the volume of the rock mass globally increases, the rock faces are getting closer and
 481 displacements recorded on sensor (displayed between rock faces) are negative ([Figure 16c](#)).
 482 This can be considered as the normal “breathing” of the rock mass, that is an elastic evolution
 483 in thermoelasticity.

484

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487 *Figure 16 : schematic evolution of the shape of column B with temperature. In grey: initial*
488 *shape, in red sub-column B1, in green: B2, in blue: B3*
489

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490 In the longer term, when considering the general evolution of displacements with temperature,
491 during the 10 years, between 2013 and 2022, we can measure a mean displacement drift twice
492 smaller on B4 than on H3. Considering the general movement of a column, which is an
493 oscillation, it is not surprising to observe that the movement of the top of the column is greater
494 than the movement of the base. What is more surprising is the global relative movement of the
495 column: a negative drift in displacement means that the column tends to move closer to the rock
496 wall, which is surprising. As mentioned earlier, the top of the column is farther from the cliff
497 than the bottom. Some assumption can be proposed:

- 498 • joint opening: if joints opened in the column itself or in the rock mass, it could lead to
499 bring opposite walls closer, a fracture exists on site (see B6 sensor) but this analysis
500 need to be investigated deeper to validate this assumption.
- 501 • iA rotation of the column, if its gravity centre is towards the rear. Even if an estimate of
502 the position iof the gravity centre was propose in § ?? the geometry of the column is not
503 precise enough (no laser scan for instance is available) to support this hypothesis
- 504 • B column could also punch the infra-bathonian interlayer limestone but no topographic
505 measurement was displayed in 2012 to validate or not this assumption.
- 506 • lateral interaction between the column and other rock masses that could limit and
507 constrain the movement of the column can also be evoked.
508

509 4.5 Comparison of observations with other sites

510 The observations and measurements realised on *les chandelles de l'Escalette*, are consistent
511 with those obtained on other sites. As mention formerly, (Merrien-Soukatchoff and Gasc-
512 Barbier, 2023) proposed a synthesis on the effects of natural thermal cycles on rock outcrops
513 and pointed out different studies. Most of the displacement's measurements realised along

514 fractures (Bakun-Mazor et al., 2020, 2013; Cloutier et al., 2015; Gischig et al., 2010; Grøneng
515 et al., 2011; Marmoni et al., 2020) show the same type of drift, but the range of the evolution
516 depends on the properties of the rocks under study. When comparing data only obtained under
517 positive temperature (Bakun-Mazor et al., 2013) measured in Massada (Israel) about 0.35 mm
518 of displacement amplitude (measurements last 25 months under 20 to 50°C) whereas (Guerin
519 et al., 2021) measured on granite exfoliation sheets, a 6 mm displacement amplitude
520 (measurements last 24 hours under 16 to 37°C) and (Virely et al., 2021) measured on a
521 limestone cliff a 1 mm displacement variation (measurements last 4 years under 5 to 35°C).

522 5 CONCLUSION

523 From an operational engineering point of view, the 10 years of recording have enabled us to
524 understand the overall functioning of the *chandelles de l'Escalette* as proposed in figure 16,
525 and to rule out the rock hazard for the road, even if questions remain concerning the very long-
526 term evolution of the massif.

527 From an understanding point of view, thanks to its sensors distributed in different positions,
528 and, above all, thanks to the duration of the measurements, the analysis of this site was able to
529 show the complex link between natural thermal variations and mechanical variations. If, in the
530 short term, looking at data over a few weeks for example, we observe a globally proportional
531 relationship between displacements and temperature, we can clearly see that when longer
532 recordings are available, this simple thermoelasticity hypothesis no longer works. To take
533 account of this drift, it is then necessary to propose mechanical models with damage, i.e. to
534 choose between viscoplastic or thermal fatigue behaviour laws.

535 Finally, an important contribution of this work is the identification of the inertia of the system.
536 Indeed, it seems that a given temperature increment will not lead to the same displacement
537 increment. The immediately preceding temperature history also plays a role in the recorded
538 displacement increment. This study is therefore a further step towards proposing a
539 phenomenological behaviour law to describe thermomechanical coupling in fractured massifs
540 subjected to natural temperature variations.

541

542

543 [Supplementary material](#)

544 Data are available on request. Please contact the authors

545

546

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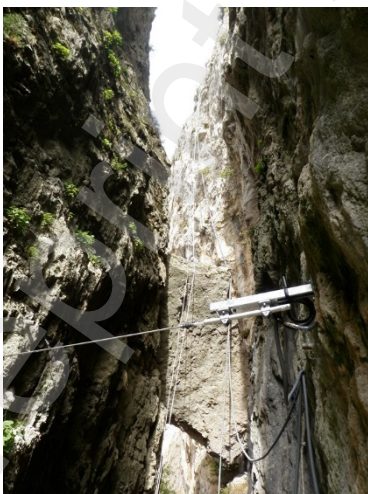
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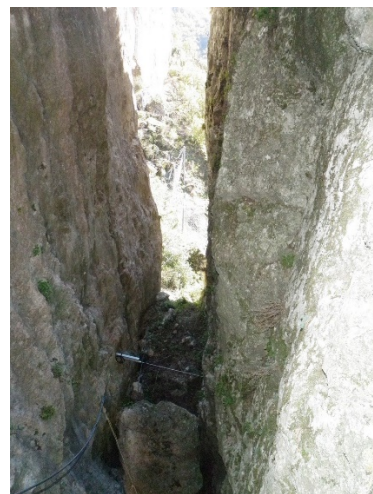
687 Annexes

688 A1- photos of all sensors on site.

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H1



B2



H3



B4



H5



B6



H7



B8-V8



H9 (upper view)

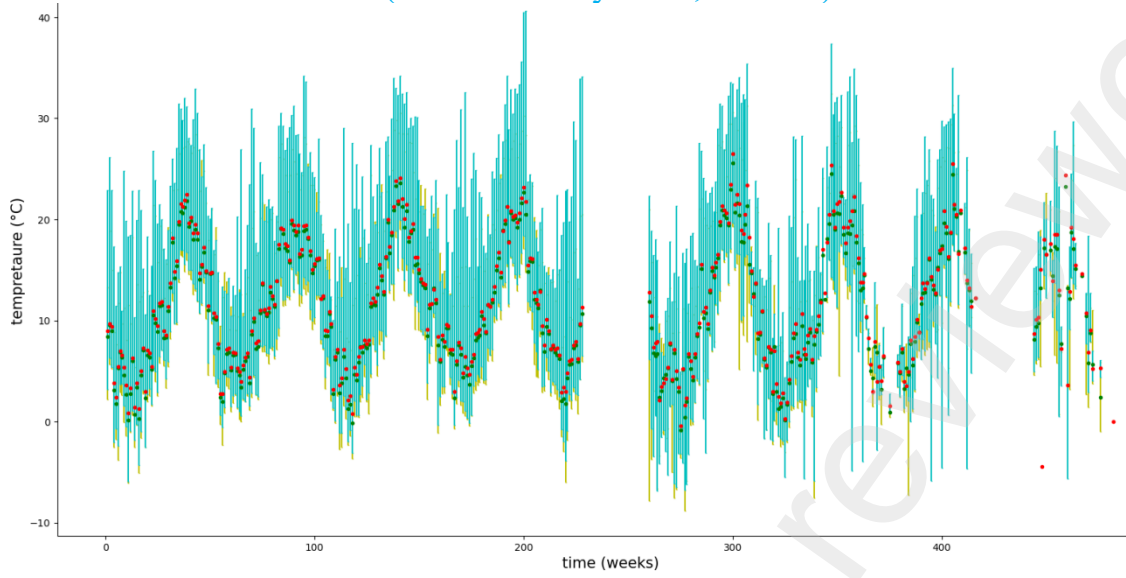


B10

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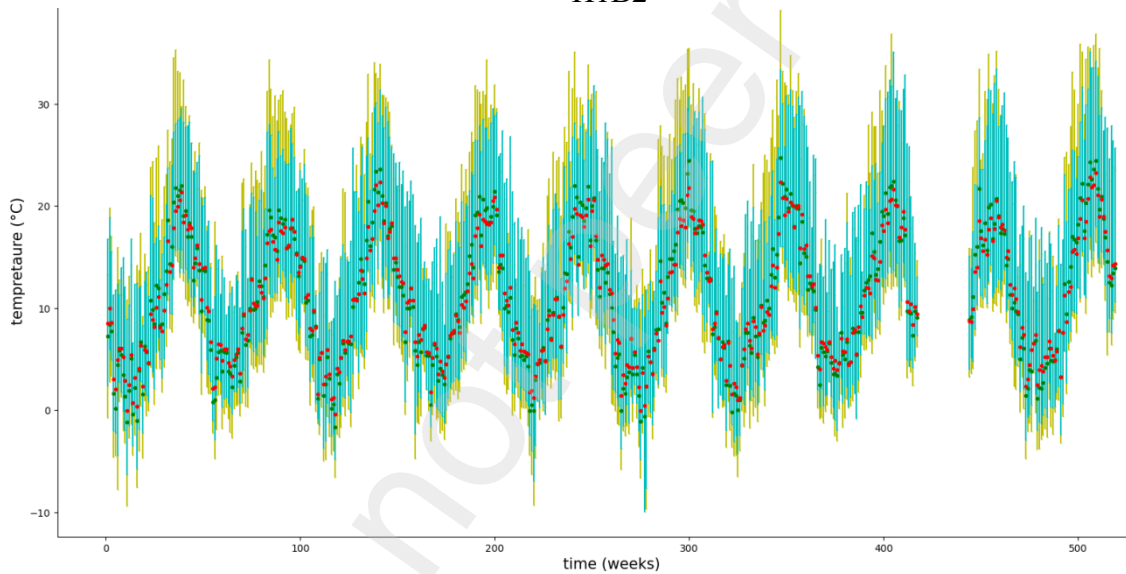
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694 A2- Temperature recording on all sensors. Weeks' mean (dots: H: green, B: red),
695 maximum and minimum (error bar: H: yellow, B: blue).



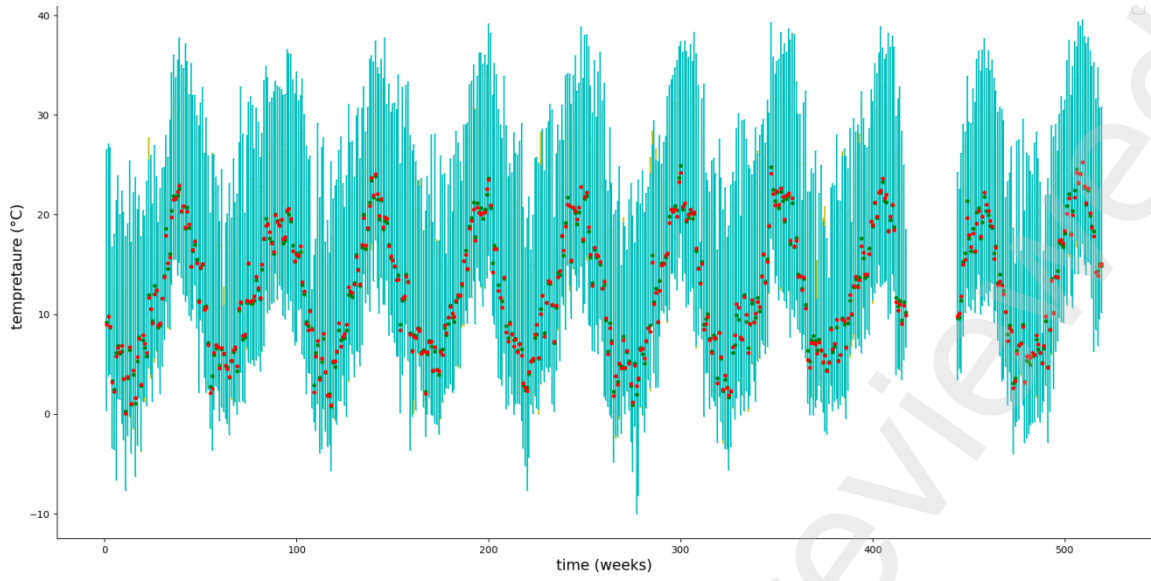
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H1B2



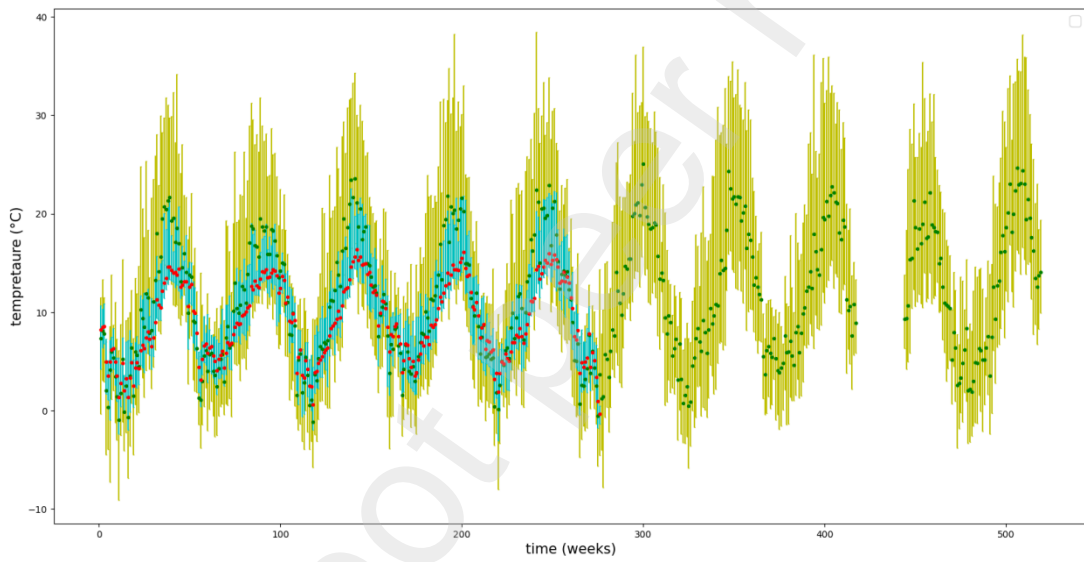
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H3B4



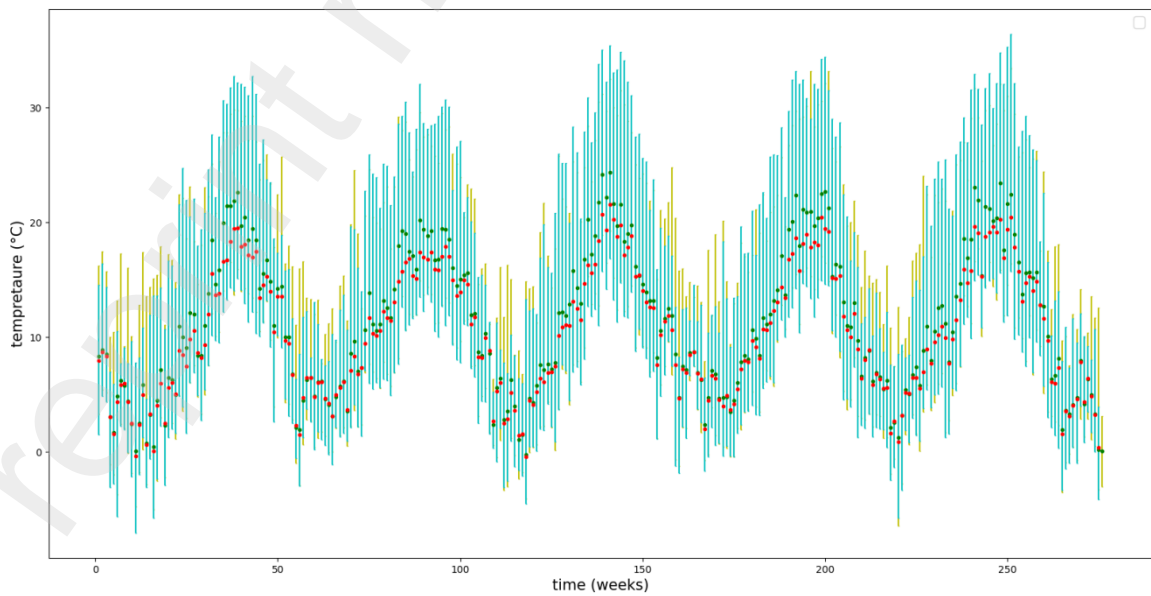
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H5B6



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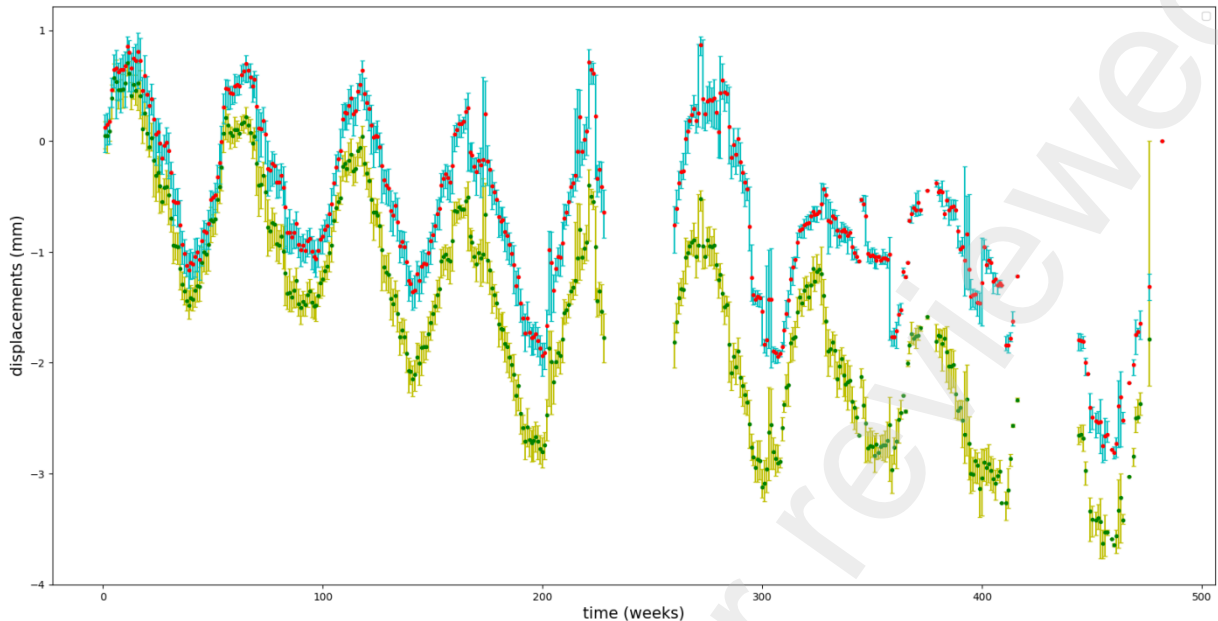
H7B8



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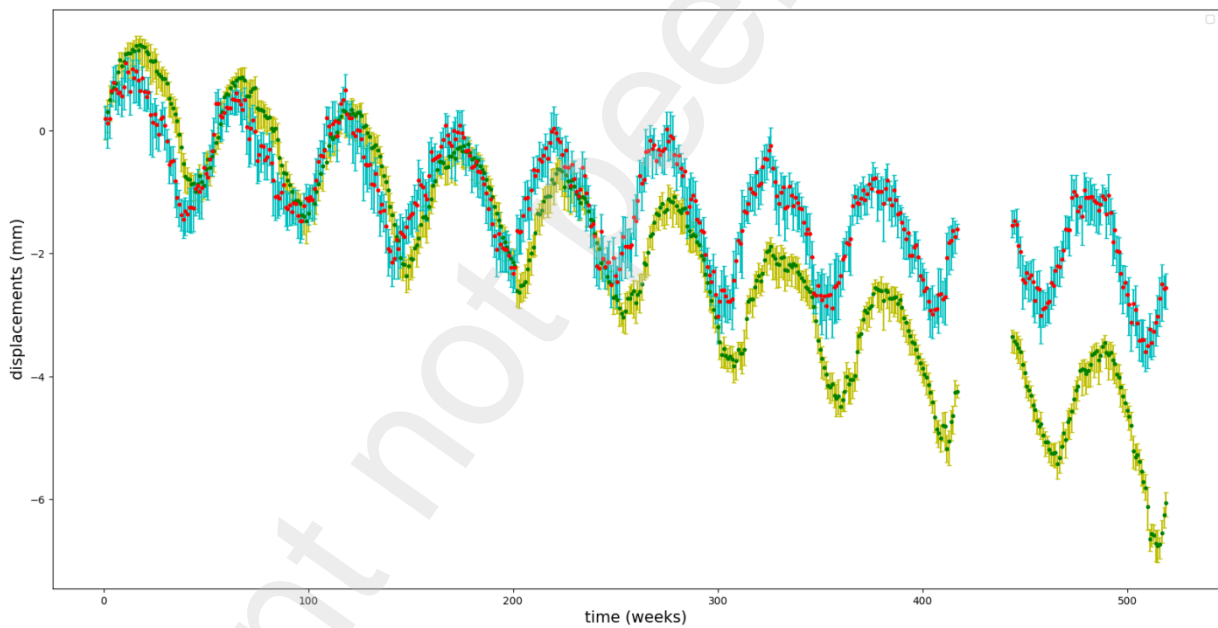
H9B10

706 A3- displacement recording on all sensors. Weeks' mean (dots: H: green, B: red),
707 maximum and minimum (error bar: H: yellow, B: blue).



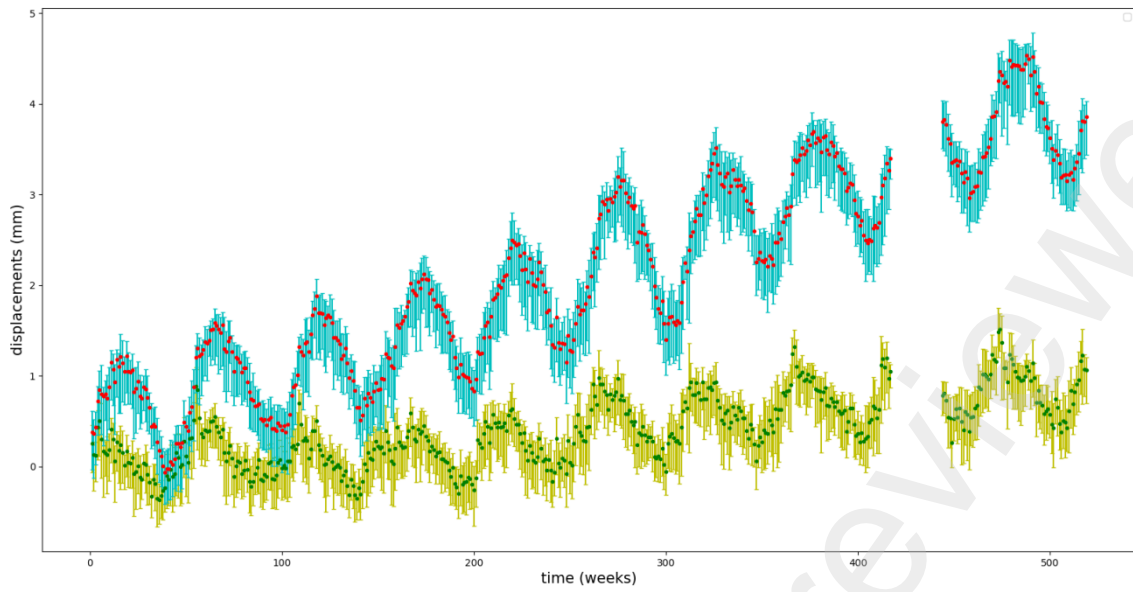
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H1B2



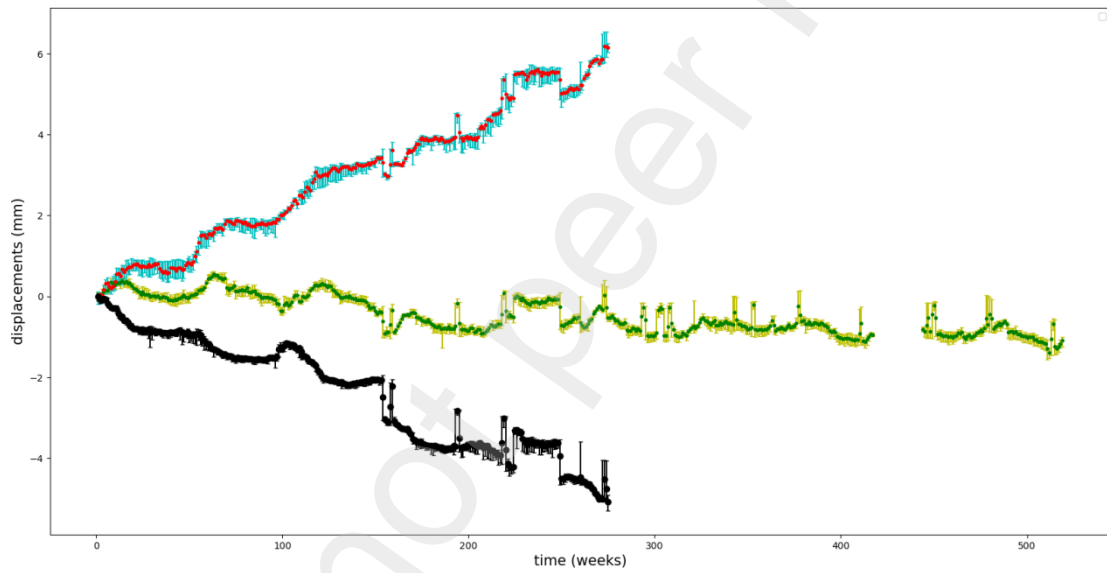
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H3B4



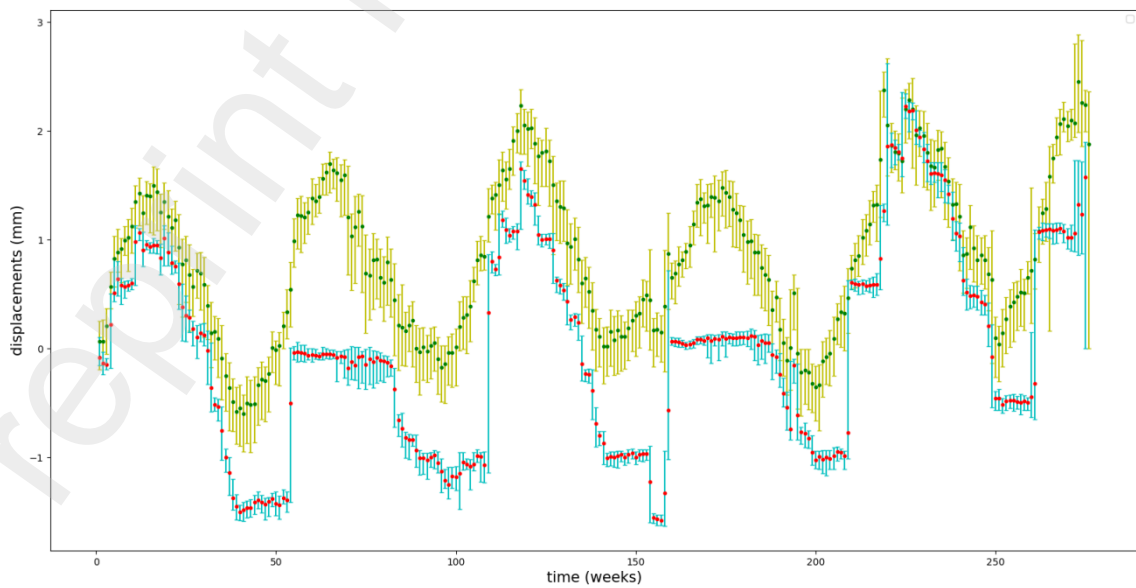
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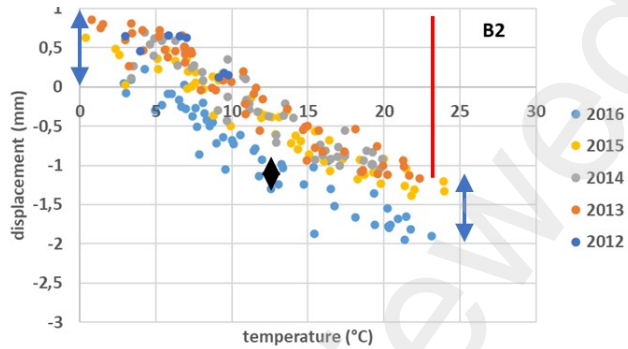
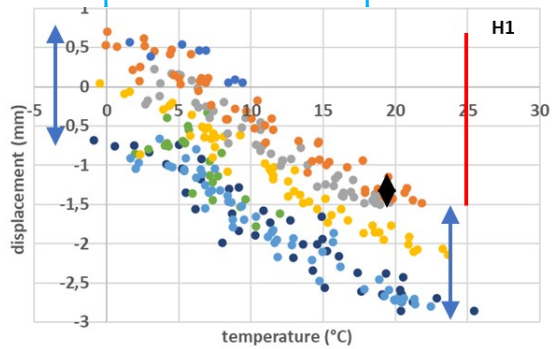
H7B8V8



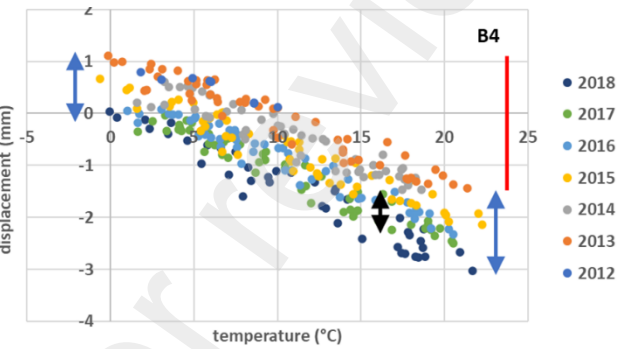
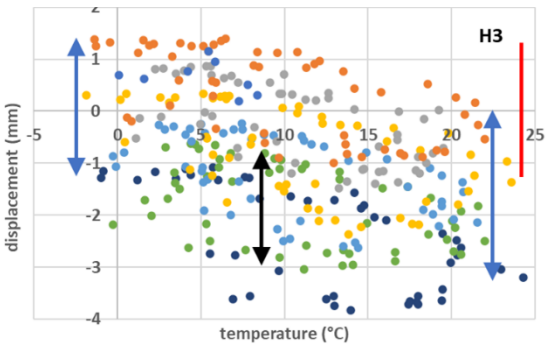
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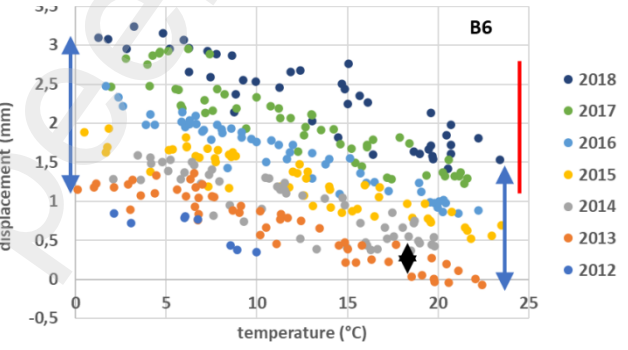
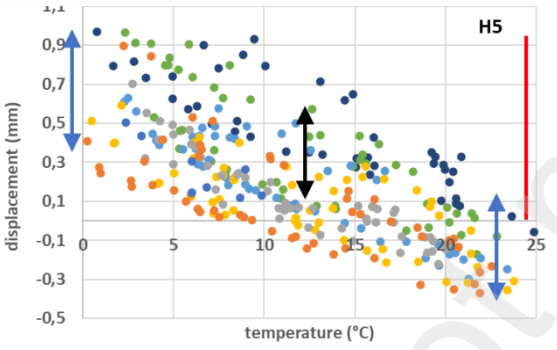
718 A4- displacement vs temperature curves



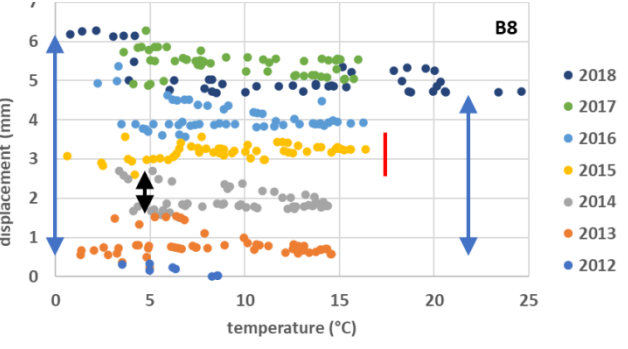
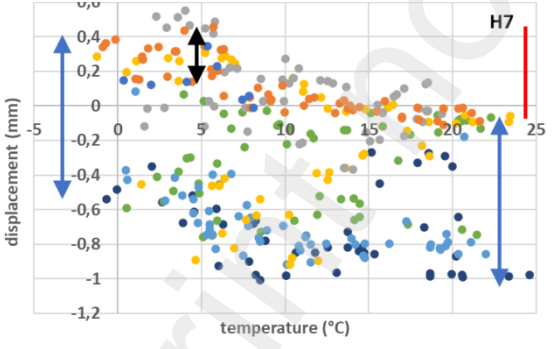
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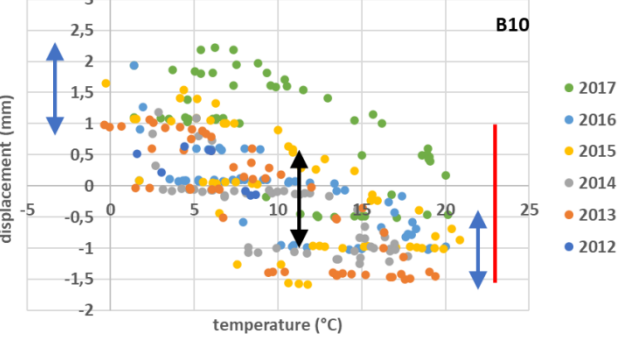
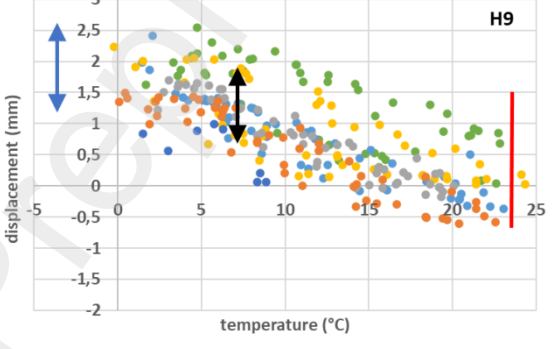
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