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Abstract
The Chauvet-Pont d’Arc Cave (Ardèche, France), famous for its remarkable rock art, also contains unique thermal-alterations such as rock spalling and color changes on the walls. These alterations resulted from intense fires that have not been observed in the other decorated caves thus far discovered. The functions of these unusual fires challenge archaeologists. To characterize these combustions, we used a numerical tool, previously validated with experimental data, to study the thermo-alterations in the Megaceros Gallery. This unprecedented approach in cave art research enabled us to assess the wood quantities and locations of the hearths responsible for the thermo-alterations. We report here that at least ten fires took place in the Megaceros Gallery while burning more than 170 kg of wood. Both simulation and *in situ* observations suggest that the branches were arranged in a tepee shape and purposefully positioned, some distance from the walls. This method therefore enables further analysis of the functions of these fires.

Keywords Simulation · Fire · Chauvet-Pont d’Arc · Decorated cave · Aurignacian

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Introduction

In 1994, the discovery of the Chauvet-Pont d'Arc Cave (Ardèche, France) turned our perception of rock art upside down (Chauvet *et al.* 1995). On the one hand, the human activity in the cave extended from 37,000–36,200 cal B.P. to 34,400–33,500 cal B.P. (Aurignacian period) and from 31,400–30,700 to 29,700–27,900 cal B.P. (Gravettian period) (Quiles *et al.* 2014; Quiles *et al.* 2016). On the other hand, the skillful paintings and diversity of drawing techniques acutely challenged the so-called evolutionary scheme of rock art (Leroi-Gourhan 1965). These world-famous paintings (Clottes 2001), among the oldest known rock art, are accompanied by singular anthropogenic thermal-alterations on the upper part of some of the walls. The alterations are mostly observed (Fig. 2) in the Recess of the Bears (cumulative area of 3 m^2), the Entrance Chamber (11 m^2), the Chamber of the Bear Hollows (25 m^2), and the Megaceros Gallery (12 m^2). Their locations have already been thoroughly detailed (Ferrier *et al.* 2014).

These thermo-alterations correspond to (i) two limestone color changes (red and gray) (Chakrabarti *et al.* 1996; Liedgren *et al.* 2017) resulting from high-temperature chemical reactions and (ii) spalling caused by a coupled thermo-hydro-mechanical phenomenon (Mindeguia *et al.* 2015). The red color (rubification) is considered to appear after heating at 250 °C for 10 min (Walter *et al.* 2001; Ruan *et al.* 2002), while the gray color requires 350–400 °C for the same duration (Brodard *et al.* 2014). Each thermally altered area displays one or several types of thermo-alterations and soot deposits were often identified near them. Since the analysis of charcoal samples shows that *Pinus* sp. was used in the cave (Théry-Parisot *et al.* 2018), the thermo-alterations likely result from wood fires. Though fires occurred in other painted caves as well, only thermo-alterations on the floor (Medina-Alcaide *et al.* 2018) have been reported. The alterations of the walls in the Chauvet-Pont d'Arc Cave demonstrate that unparalleled intense fires burnt in this cave and their functions thus challenge archaeologists. At present, some explanations such as lighting, pigment production, sources to ignite torches, domestic fires, symbolic expressions, or protection against animals have been proposed (Ferrier *et al.* 2014; Medina-Alcaide *et al.* 2018). However, none of them is based on a quantitative analysis of the fires' characteristics.

To provide new clues, this investigation aims to characterize the hearths (mass, location, arrangement) that were burnt in the cave and to state the direct implications. Among all the altered areas (Ferrier *et al.* 2014), this paper specifically focuses on the Megaceros Gallery which is a narrow corridor located deep in the cavity (about 200 m from the Paleolithic entrance) containing rock art. This choice was instigated by the existence of photogrammetric surveys and the easy access to the thermo-alterations of the Megaceros Gallery. The thermo-alterations are particularly dense in this gallery, which varies in size from 3 to 6 m wide and around 2 m in height. Two large chambers (Hillaire Chamber and End Chamber), which host the two major panels of the cave, adjoin the Megaceros Gallery. The thermoluminescence dates (36,900 ± 2300 cal B.P.) of heated samples (Guibert *et al.* 2015), the radiocarbon dates of charcoal samples, and drawings in the Megaceros Gallery coincide with the first human occupation of the cave during the Aurignacian period (Valladas *et al.* 2005; Quiles *et al.* 2014).

For the sake of conservation, only numerical tools can reproduce fires in the Chauvet-Pont d'Arc Cave geometry. We thus developed a model to simulate the fires and the induced thermo-alterations on the walls (Salmon *et al.* 2019; Salmon *et al.* 2020). The numerical method is described in the following section. Using this innovative tool, this investigation corresponds to the resolution of an inverse problem without archaeological excavations: which hearths were the most prone to produce the observed thermo-alterations in the Megaceros Gallery? To achieve this goal, we tested several fire scenarios and compared both resulting color changes (red and gray) with the *in situ* observations for each fire. We then conducted a thermo-mechanical analysis of the most likely scenario to check whether the rock spalling that is observed in the cave can result from it.

Materials and Methods

Numerical Modeling

Numerical simulation corresponds to the theoretical reproduction of processes from the mathematical equations describing them. This field is becoming increasingly pervasive due to continual augmentation of computing capacity. This paper presents the results of fire simulations and their impacts on cave walls. The various physical mechanisms must then be considered: combustion, chemistry, gas production, toxicity, fluid mechanics, air circulation, thermal radiation, heat transfers, and thermo-mechanics. The interaction between these physical processes makes the predictions of fire characteristics complex and time-consuming. Before this investigation, no tool could directly manage the simulation of all these phenomena and it was necessary to build an appropriate multiphysics code. Moreover, the simulation of fires in a large irregular geometry, such as a cave, had never been achieved before since this particularity causes extra difficulty.

First, the open source code FireFOAM (FireFOAM 2019), which can manage the simulation of fires, was extended. The contributions are briefly itemized here since they have already been detailed (Salmon *et al.* 2019; Salmon *et al.* 2020). A thermal boundary condition, based on energy balance at walls, has been added. The model considers wet walls for the wall temperature calculation. The soot deposit calculation through the Beresnev-Chernyak model (Beresnev and Chernyak 1995) was implemented. A thorough investigation of dangers such as toxicity (Speitel 1996), radiation and temperature (Purser and McAllister 2016) can now give information about the living conditions. A mathematical assumption about horizontal velocity was developed to reach consistent thermal stratifications. Last, a thermocouple correction was implemented to the code to enable comparisons of the experimental data with the numerical temperatures. Indeed, a solid sensor does not directly measure the gas temperature because of heat fluxes at the boundary and a rectification is needed to get the gas temperature.

Second, FireFOAM was coupled with Cast3m (Cast3m 2019), which is usually employed for mechanical problems. This second code can estimate the mechanical stress in rock due to the thermal expansion of limestone and thus provide information about the spalling probability. The coupling corresponds to Python scripts, which are available online (Coupling 2019). The resulting tool enables the simulation of fires, danger assessment, soot deposit, color changes and spalling (Salmon *et al.* 2020).

Third, the designed code was validated with experimental wood fires in a quarry (Ferrier *et al.* 2017; Salmon *et al.* 2018; Salmon *et al.* 2019; Salmon *et al.* 2020). The L-shaped quarry consists of limestone. It is composed of two nine meters galleries and their dimensions are similar to those of the Megaceros Gallery: approximately 2 m in height and 2.5 m in width. The protocol involved 135 kg of *Pinus sylvestris* which were progressively brought in the flames by firemen with security equipment for 45 min. The initial hearth consisted of approximately 16 kg of wood and firemen supplied the fire with two 4.5 kg bundles step by step. This mass approximately corresponds to the quantity of branches that can be easily brought under one arm without being too cumbersome. The length of the branches was approximately 80 cm since this naturally corresponds to the length of the branches broken on knees. In addition, this makes the shipping of wood easier than with big branches. Their diameters were smaller than 4 cm because breaking bigger branches of *Pinus sylvestris* appeared difficult without modern tools. We chose tepee-shaped hearths since this appears the best way to alter the ceiling of the quarry according to preliminary tests. This configuration indeed leads to tall flames while the same wood mass in a “flat” arrangement leads to smaller and larger flames. This protocol was conducted three times over 3 days to challenge the reproducibility of such a fire. Moreover, the quarry was instrumented with thermocouples, velocity sensors, gas and particle concentration sensors, and plates for soot deposit. The experimental data allowed us to adjust several model constants to obtain consistent results (Salmon *et al.* 2019; Salmon *et al.* 2020).

Energy Source Modeling

The input parameter of the created tool is the power released by wood combustion as a function of time. A link between the wood mass, which is the archaeological input parameter, and the energy released by its combustion must be established. At present, this information remains unattainable by mathematical theories. Instead, an empirical approach is necessary to know how much energy combustion releases. The wood crib model (Babrauskas 2016) is based on experimental fires of wood crib structures. This provides the heat release rate of wood cribs depending on time. However, this kind of structure burns differently from tepee hearths even if the same trend is observed. We therefore conducted additional fire experiments in the same quarry to measure the heat release rate of pine tepee hearths. Several wood masses were successively tested: 16 kg, 32 kg, 40 kg, 60 kg, and 90 kg. The wood crib model constants were modified to fit the data acquired during the five fires. This modeling establishes the link between the mass of pine and the input parameter of the developed code.

Method of Investigation

The tool previously described has been applied to the thermo-alterations of the Megaceros Gallery. The 3D geometry of the Chauvet-Pont d’Arc Cave was obtained by lasergrammetry (MC, Perazio Engineering, Archéovision Production). The simulations are based on a mesh of the cave geometry (Fig. 1) achieved by the tool cfMesh (cfMesh 2019). The mesh consists of small cells (3 × 3 × 3 cm) in the flames, medium-sized cells (6 × 6 × 6 cm) in the area of interest, and then doubled in size as the distance increases. About 700,000 cells make up the cave mesh. For each thermally altered area,

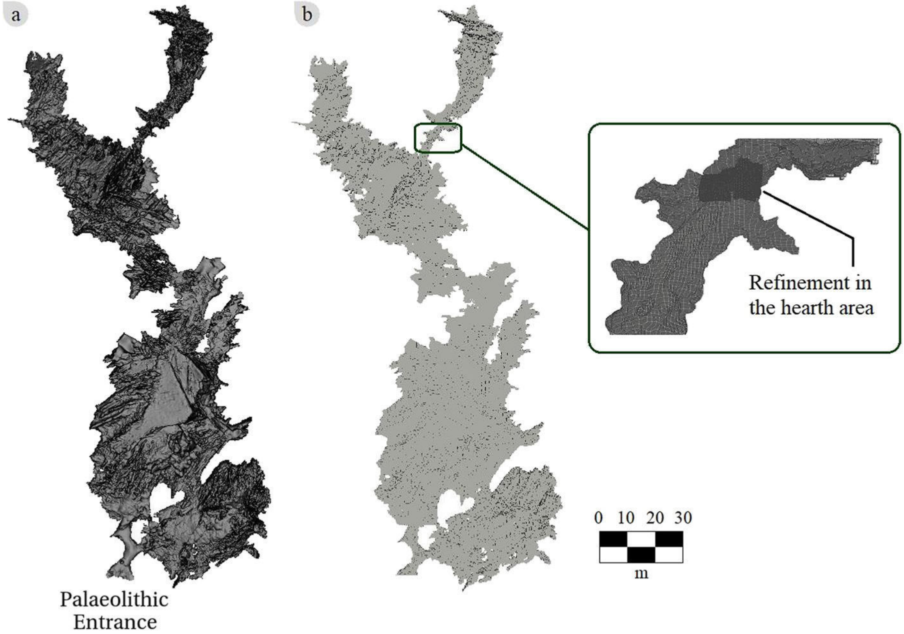

Fig. 1 a Geometry of the cave acquired by lasergrammetry (MC, Perazio, Archéovision Production). b Mesh of the cave achieved by version 1.1.2 of cfMesh

several fire scenarios were run. The more likely location of each hearth was first identified. From this fireplace, the color changes induced by the combustion of several wood masses were then tested. The wood mass, which yields color changes analogous to the observable ones, was then selected for the thermo-mechanical study. This analysis ensures that this mass leads to spalling similar to that observed in the cave. To assess the fire hazards, the air was assumed to be saturated since it is the most reliable hypothesis in a cave. The simulations were conducted on a supercomputer Bullx DLC with 10 × 24 cores Intel Haswell-EP Xeon 12-Cores E5-2690 V3 2.6 GHz. Each fire scenario required three days of calculation.

Results

Because no remains of fires have been observed on the floor of the gallery, the locations of the hearths are unknown *a priori*. Ferrier *et al.* (C. Ferrier *et al.* 2014) give potential explanations about the lack of hearths remnant (overlapping, erosion, displacement by humans or bears). Based on our *in situ* wall and ceiling observations, which suggest several thermally altered areas (C. Ferrier *et al.* 2014), the numerical study has allowed us to locate ten hearths (Fig. 2). The simulations enable us to estimate the wood mass associated with each area as well. The hearths were composed of approximately ten to thirty-five kilograms of pine depending on the location (Table 1). The combustion of these quantities leads to consistent color changes and relevant spalling probabilities (Fig. 3). Although successive smaller fires at the same locations could have produced analogous color changes, spalling would not likely have

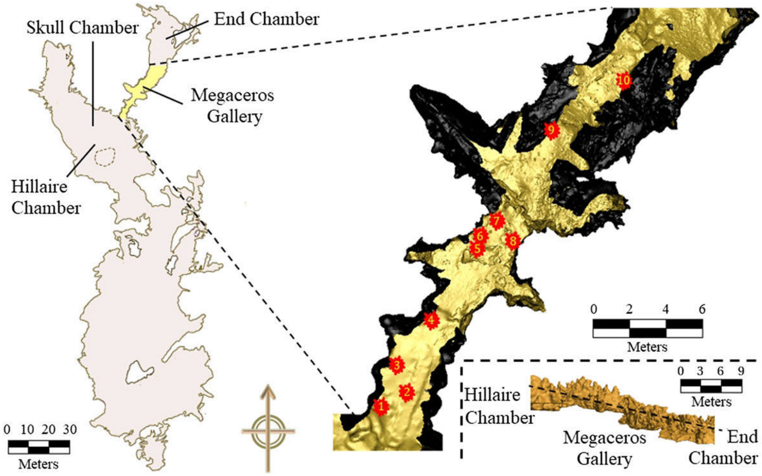

Fig. 2 Left: map of the Chauvet-Pont d'Arc Cave. Right: cutaway view of the Megaceros Gallery with the likely combustion sites from which the thermo-alterations were generated. The yellow part corresponds to the floor and the black part to the walls. The cutaway profile is shown in the lower right corner of the figure (extracted from the photogrammetry geometry by Archéovision Production)

occurred due to their low intensity. The scenario of single fires is thus more probable but not certain. Small-scale fires could also have been made outside the studied areas without leaving any traces. In total then, at least 170 kg of wood was burnt in the Megaceros Gallery according to the simulations.

Table 1 Characteristics of the thermo-alterations at each area. Likely order of magnitude of the wood masses which led to the thermo-alterations of each altered area in the Megaceros Gallery according to the simulations (in a single fire scenario). Minimum wood mass that had to be involved to generate the thermo-alterations in a scenario with several fires at each altered area (less wood could not induce mark)

Area	Thermo-alterations	Height (m) [min; max]	Approximated surface area (m^2)	Wood mass (kg) Single fire	Minimum mass (kg) Several fires
1	Red, gray, spalling	[0.9; 2.4]	1.1	[12–20]	< 10
2	Red, gray, spalling	[1.8; 3]	> 0.65	[25–32]	15
3	Red	[1; 1.7]	0.75	[16–21]	< 10
4	Red, spalling	[0.9; 1.5]	0.25	≤ 10	< 10
5	Red, gray, spalling	[1.7; 3.3]	1.15	[31–38]	20
6	Red, spalling	[1.3; 1.9]	0.15	[17–22]	< 10
7	Red, spalling	[1.1; 2.1]	0.45	[15–20]	< 10
8	Red, gray, spalling	[1.25; 2.8]	1.3	[22–27]	15
9	Red	[1.4; 1.9]	0.1	[14–17]	< 10
10	Red, spalling	[0.4; 2.2]	1	[12–15]	< 10

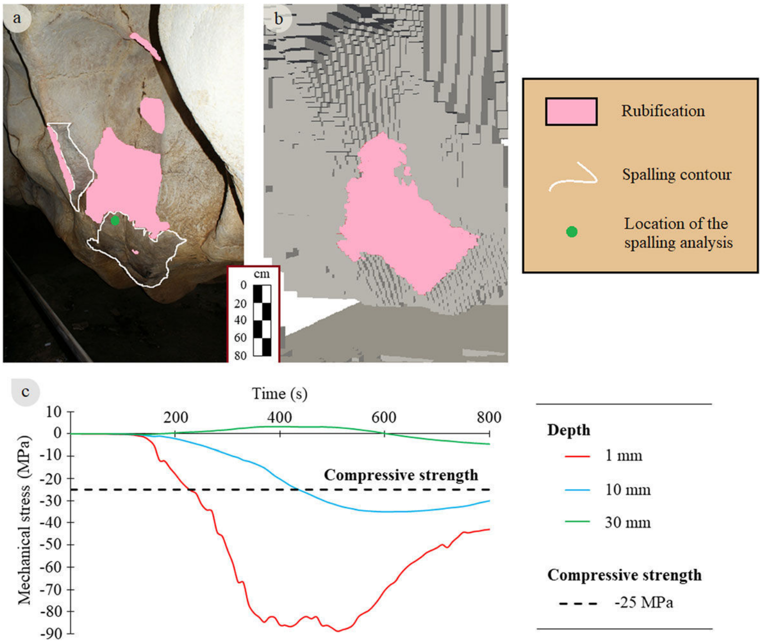

Fig. 3 As an example, this figure displays the comparison relating to the thermo-alterations of the 10th fire in the Megaceros Gallery. a Ground survey thermo-alterations of area 10 (MC–Chauvet Team). b Simulated rubification of area 10. Both the ground survey and simulation show similar color changes. c Evolution of the vertical compressive stress versus time at the green point (a) for several depths. Up to 10 mm, the compressive strength is exceeded, which means that spalling is likely to occur. This agrees with the ground survey (a)

Based on simulation, our analysis of the fire hazards in the Megaceros Gallery shows that the fires were not a barrier to human circulation. Indeed, all the toxic gases were expelled into the Hillaire Chamber while the End Chamber was left empty of any toxic gases (Fig. 4). The Aurignacians could have stayed in the End Chamber under standard conditions during the fires. In addition, due to the large volume of the Hillaire Chamber, the toxicity remained low enough to allow short stays. Finally, due to the

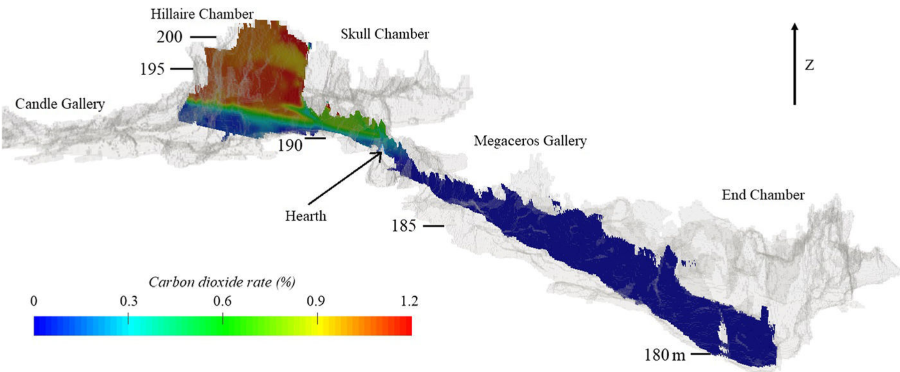

Fig. 4 Carbon dioxide rate (%) in the deep part of the Chauvet-Pont d'Arc Cave (Hillaire Chamber, Megaceros Gallery, and End Chamber) just after the combustion of 30 kg of wood at area 5 in the Megaceros Gallery. Like CO_2, carbon monoxide remains harmless

thermal stratification (Salmon *et al.* 2019) in the Megaceros Gallery, individuals in a squatting position (lower than 90–140 cm depending on the location) could have stayed near the hearths (from 1.5 m) in the cold layer (at ambient temperature) during the fires.

The hearths were composed of up to a few dozen kilograms of wood (Table 1). Just a few individuals would thus have been necessary to gather and carry the branches deep into the cave. Personal tests made while gathering wood for the experimental fires (Ferrier *et al.* 2017) show that one single tree can supply about 10 kg of wood which can be collected by one person in about 12 min. This does not encompass the shipping of wood from trees to the cave. These tests were achieved with the same possibilities as Aurignacians so only branches smaller than 4 cm in diameter and less than 2 m above the ground were broken by hand.

Some clues suggest that the hearths were shaped like tepees. The surface areas of all the thermally altered areas except 2, 5, and 8 are very small, indicating that the flames were very narrow and concentrated. For instance, in area 1 (Fig. 5), the color changes indicate that the wall was hotter in the gray zone (> 350 °C for 10 min) than outside of it. Therefore, the flame would have impacted only the gray zone (< 50 cm in diameter) before spreading out along the wall with less impact. Given that the wood mass was between 15 and 20 kg (Table 1), the hearth was necessarily very compact. Otherwise, the affected surface would have been larger or nonexistent because the released power would have been less concentrated. Experiments (Dréan *et al.* 2017) showed that tepee-shaped hearths naturally produce high narrow flames (Fig. 6). On the contrary, flat carelessly entangled hearths lead to smallest and largest flames than tepee hearths with the same wood mass. Therefore, it seems very probable that the localized thermo-alterations were generated by tepee-like hearths. The thermo-alterations in areas 2, 5,

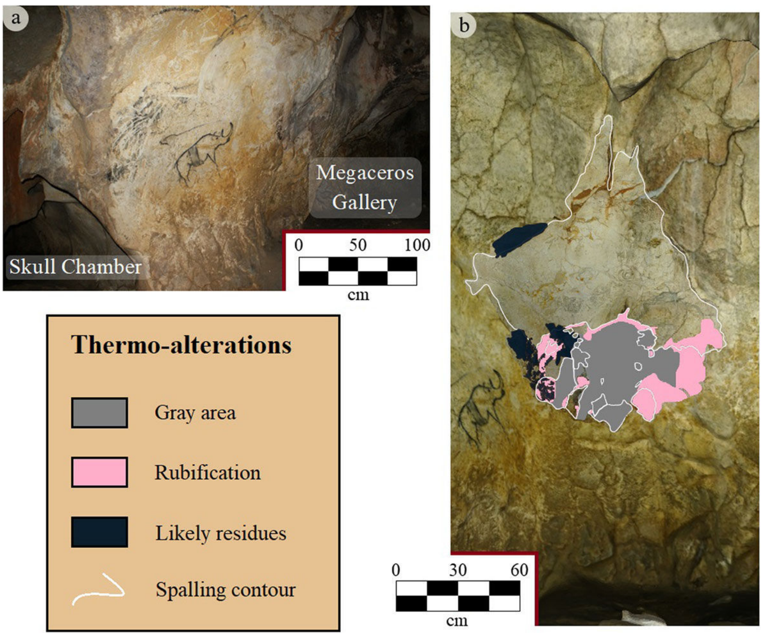

Fig. 5 a Thermo-alterations of area 1 at the entrance of the Megaceros Gallery (MC–Chauvet Team). b Thermo-alterations map of area 1 (front view)

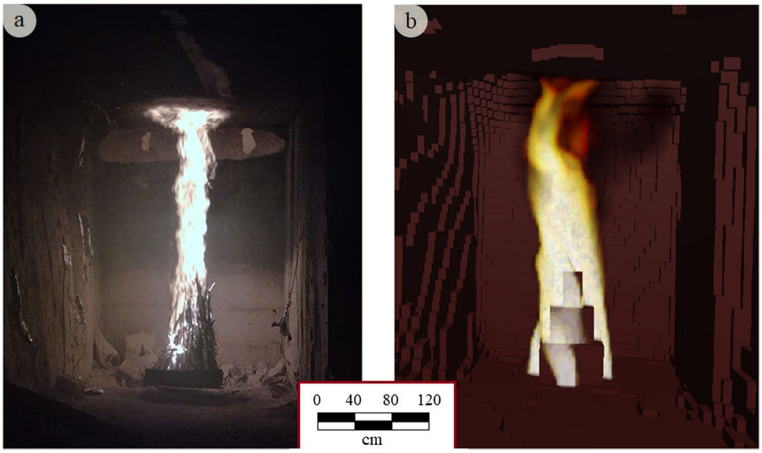

Fig. 6 a Combustion of a hearth in a tepee configuration composed of 16.8 kg of branches measuring approximately 80 cm long. The hearth diameter is approximately 80 cm. The combustion process produced narrow flames 5 min after its ignition (MC–Chauvet Team). b Simulation of the fire 5 min after its ignition

and 8 extend across a broader surface since they correspond to the largest fires in the gallery (Table 1). However, our simulations suggest that the flames impacted a very restricted gray zone for these areas. The extension of these thermo-alterations would thus originate from the circulation of hot gases, not from the flame itself. Therefore, it is rather probable that the thermal-alterations of all the areas are the result of tepee-type hearths.

As stated in the introduction, the bottom of the walls of each area never displays thermo-alterations (at least 90 cm high). The numerical model reproduces this observation with hearths located a bit away from the walls (a few dozen centimeters at most). This matter was also noticed during some experiments in the abovementioned experimental quarry (Lacanette *et al.* 2017). The combustion of branches leaned against a wall necessarily generates color changes from the bottom or nothing if the fire is not enough powerful. Therefore, the most likely scenario that could have led to such thermal marks seems to be the combustion of tepee hearths, not in direct contact with the walls while being close to them.

The probable tepee arrangement of the hearths created tall and narrow flames that concentrated the energy and maximized the wall impact. Moreover, the location of the hearths away from the walls ensured a beneficial oxygenation all around the burning branches. On the contrary, a hearth leaned against a wall, which is an easier construction, would block out a part of oxygen supply since air would not be able to circulate between the branches and the wall. Since a greater oxygenation necessarily enhances the combustion process, both location and tepee arrangement optimized the release of energy which augmented the alteration of the vaulted ceilings. The similar characteristics of all the fires show that those who managed them shared the same skills and goals, whatever the time interval between each fire.

This kind of combustion does not foster charcoal production, even if some quantities are still generated. Instead, a poor combustion of a lighter random tangle of branches would have been more efficient at making charcoal. Given that these choices seem intentional, the main purpose of these fires could not have been to produce charcoal.

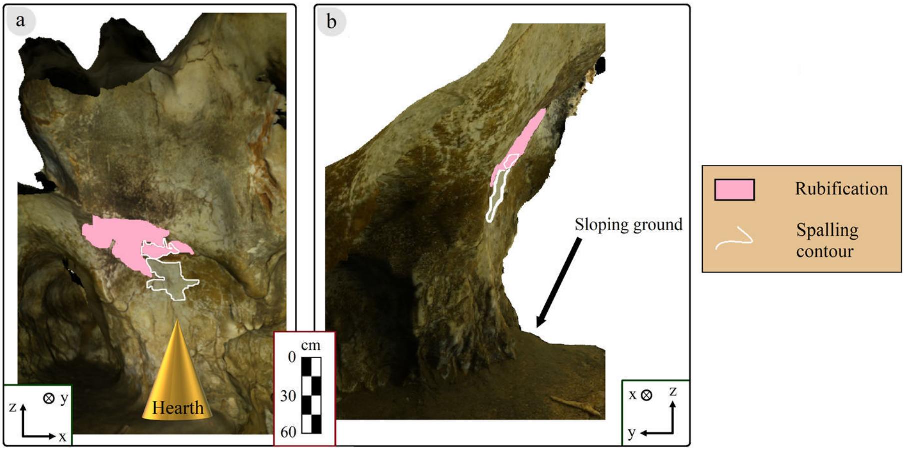

Fig. 7 Ground survey thermo-alterations of area 4 observed from two vantage points. a Front view. b Lateral view. The hearth (symbolized by the yellow cone) was located on the sloping ground but the flames had to impact the spalling zone without altering the bottom of the wall

One can wonder whether the locations of the hearths in the Megaceros Gallery (Fig. 2) have been rationally chosen. First, as already noted, the branches did not touch the walls. Second, the hearths were sometimes placed at inconvenient locations, such as in areas 4 (Fig. 7) and 9 (Fig. 8), whereas effortless positions were available just a few meters away. In area 4, the hearth was placed on sloping ground while, just 1 m away, a recess could have hosted the fire (Fig. 2). In area 9 (Figs. 2 and 8), a fire altered a rocky ledge at half height without altering the space underneath it. This means that the wood burnt exactly below the ledge boundary. Making the fire beneath the ledge or in the recess a few meters away (Fig. 2) would have made the living conditions less inconvenient around the fire.

Except for areas 5 and 8 (Fig. 2), all the thermo-alterations look alike, despite different ceiling heights. First, when a gray surface is observable, it is always small. Second, the red color extension often remains limited since, in most areas, it is caused by the flame impact rather than by the hot gases according to the simulations. This

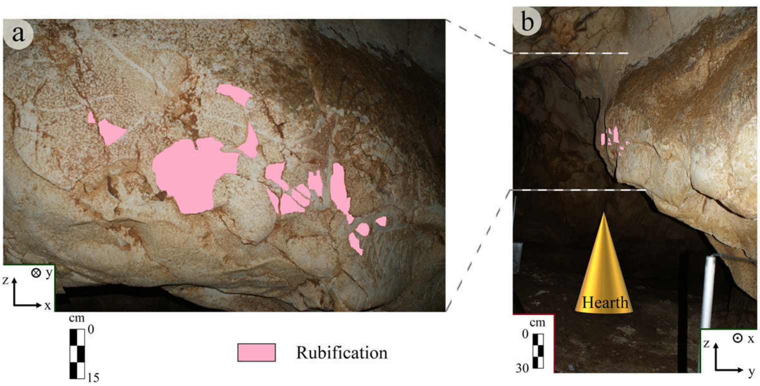

Fig. 8 Ground survey thermo-alterations of area 9 observed from two vantage points (MC–Chauvet Team). a Front view. b Lateral view. The hearth (symbolized by the yellow cone) had to be located just below the ledge boundary, which seems to be a very particular location

similarity between the areas necessarily means that the hearths were tailored according to the ceiling height: the higher the impacted area, the larger the wood mass. For instance, in area 2 which is more than 2 m high, the simulation shows that about 30 kg of wood was burnt. In the other areas, the hearths always consisted of between 10 and 20 kg disposed under surfaces between 40 cm and 1.5 m high. As previously mentioned for area 9, the combustion of about 15 kg of wood affected a rocky ledge, while the fire spared the ceiling. According to the simulation, a larger amount of wood (≥ 20 kg) would have turned the ceiling red, whereas a smaller fire would not have transformed the rocky ledge. In short, the Aurignacians used a wood quantity that was adequate to turn the wall red without altering the ceiling. In addition to the particular location of the hearth (see prior paragraph), the fire characteristics might have been planned.

Conclusion

For conservation reasons, we developed a numerical tool that solves the equations governing the involved physical phenomena (combustion, heat transfer, fluid and solid mechanics). This consists of a coupling of two codes which was validated on fire experiments that we performed in a former quarry. The measurement of the energy released by the combustion of tepee hearths against time was also carried out since the developed approach needs it. With access to high-performance computing, we have run many fire scenarios in the Chauvet-Pont d'Arc Cave. In particular, we have tested different masses of wood and positions in the Megaceros Gallery. Our simulations and *in situ* observations enabled us to determine the main characteristics of the hearths (location, wood mass, configuration). At least ten separate fires burnt in the Megaceros Gallery (Fig. 2).

The configuration of the hearths was likely similar for all of them. The Aurignacians seem to have chosen tepee-shaped hearths. The latter were systematically positioned close to walls without touching them. The structure and position of the hearths optimized the release of energy. These characteristics suggest that charcoal production was not the only objective since they are not conducive to it. The large amount of burnt wood (at least 170 kg) and the care taken to make the fires in the Megaceros Gallery below vaulted ceilings could rather suggest other functions. It is worth noting that these fires are located between two of the main painted areas (Panel of the Horses and End Chamber). The thermo-alterations of area 9 are associated with the Feline Panel (Fig. 8), which might have been drawn with fingers. Does this association result from intentionality? If so, a symbolic link between rock art and fire could thus exist. To better understand the functions attributed to these fires, the physical clues generated by this study must be confronted with archaeological knowledge. At the very least, the Aurignacians seem to have followed a rational plan that has never been reported in other caves.

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