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Simulation of an experimental fire in an underground limestone quarry for the study of Paleolithic fires

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ABSTRACT

Numerous fire marks occur on the walls of the Chauvet-Pont d'Arc cave. Dating indicated that some of the fires were contemporary to the Aurignacian. Violent thermal shocks were observed in surprisingly narrow areas of the cave. This raises numerous archaeological questions about the function of the fires; the answers depend on the location of the hearths, and the intensity of the fires. Numerical simulation was used here to provide information about the behaviour of fires in such confined spaces. An underground non-archaeological site, in a limestone quarry, was equipped to monitor fires in an environment similar to that of the Megaceros gallery of the Chauvet-Pont d'Arc cave. The fire and the movement of heat and smoke in the quarry were simulated by the open source code "Fire Dynamics Simulator (FDS)". Results were validated on wall temperatures recorded behind and above the fire. The thermo-mechanical impact of the fire on the rock was simulated with CAST3M software, providing the most probable zones for limestone spalling due to thermal gradients. The validated approach will, in a forthcoming study, be applied to the Chauvet-Pont d'Arc cave, in which coupled simulations in the air and in the rock should indicate the location of the hearths and the intensity of the fires that generated the marks.

1. Introduction

1.1. Background

In the Chauvet-Pont d'Arc cave, from the earliest investigations, marks of rubification and shedding related to violent thermal shocks associated to combustion areas were noted on the walls and ceiling of the Megaceros gallery and the gallery of the Crosshatches [1] [2]. Research begun since 2008 on the taphonomy of the decorated walls allowed the identification of thermal alterations in the entrance sector, in the Chamber of the Bear Hollows and in several places of the Megaceros Gallery [3] [4]. They are revealed by a change of colour of the limestone and spalling of the rock surface [5]. The thermoluminescence study and the comparison with a thermal referential indicate a range of temperatures between 300 and 375 °C [6].

The dating of charcoal concentrations located close to walls or ceilings heated in the Entrance sectors and in the Gallery of Crosshatches [7] as well as the presence in the Chamber of the Bears and in the Megaceros Gallery of drawings related to the ancient phase of human frequentation [8] [9] and posterior to the thermal marks, indicates that some fires might have been contemporary to the Aurignacian. Recent thermoluminescence dating results obtained on heated calcite fragments sampled at the wall of the Megaceros gallery and at the ceiling of the Paleolithic entrance confirmed that fires were lit during the first paleolithic occupations of the cave [10]. Nevertheless, it cannot be totally excluded that others were the works of the Gravettians.

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The function of the fires has not yet been clearly identified but several hypotheses can be considered: lighting, beacons, torch rekindling, pigment production, protection from animals, heat or light production without practical need other than the one linked to the symbolism [11]. In the Chauvet-Pont d'Arc cave, few hearths have been found. They have been moved by bears or men, deliberately or not. Their absence leads to a lack of information, especially concerning their function. Locations of the fire marks in very narrow areas of the cave raises questions about lighting fires without being injured. Fires release large amounts of toxic gases into the atmosphere, and the evacuation of such gases constitutes a problem in confined areas. Simulations of a fire in a geometry similar to the Chauvet-Pont d'Arc cave may give additional information about the production of toxic gases, the temperatures close to the hearth and the temperature of the rock.

Various works on simulations of fires in underground or confined areas have provided valuable information on air flows and smoke evacuation. Computational Fluid Dynamics has been used to simulate spontaneous combustion of coal and evaluate oxygen levels in mines [12]. Catastrophic tunnel fires have placed a focus on fire safety issues concerning road and rail links, generating numerous simulation works [13] [14]. Fires occurring in subways have also been thoroughly studied from a numerical point of view [15]. The thermomechanical impact of fires on the structure of a car park has equally been studied [16].

Works on toxic levels of gases emitted during combustion have given valuable information about the toxicity of the fumes and the thermal hazards. Purser [17] proposed the definition of a dose (Fractional Effective Dose) to predict when an incapacitating or lethal quantity of fumes has been received. Following this research, the toxicology of the combustion gases in confined areas has been applied to aircraft [18] and more recently to tunnels [19].

Simulations of fires in an archaeological context have so far focused on the ground supporting the fire. 3D simulations of the impact of outdoor fires on the ground have given information about fire duration or for instance reuse of archaeological hearths (Pincevent, Seine-et-Marne, France) [20]. More recently, heat transfer simulations on the ground of an experimental fire gave information on the duration of the fire starting from the temperature of the sediment [21] [22].

As far as the authors know, no works have simulated fires in the archaeological context of a rock art cave.

1.2. General objectives

The simulation of the impact of a fire in the air and on the rock of an underground area is a part of a project dedicated to studying fire in a monitored underground area. We aim to reach a better understanding of the phenomena involved in the combustion in such confined areas.

The project originates from archaeological observations of the walls of the Chauvet-Pont d'Arc cave. From the very first scientific studies of these caves, areas on the walls affected by a rubification due to heat from fires were identified in various zones. Arguments based on relative chronology and indirect dating suggested Aurignacian frequentation was responsible for the state of the walls. Thermoluminescence analysis of rubified rock (limestone) samples indicated that temperatures of at least 300 °C were reached [5].

Starting from these archaeological observations, several questions arose. What types of hearths can produce marks (rubification, flakes, soot deposit) similar to those observed on the Chauvet-Pont d'Arc walls? How hot were their flames? What were the functions of the fires? Did the hearths occupy any particular positions? To answer these questions, several research objectives had to be defined. First of all, the marks observed in Chauvet-Pont d'Arc had to be experimentally reproduced by calibrating the fire correctly. The marks result from the acquisition of a pink to grey colour, flaking of the limestone, a temperature at the surface of the wall of at least 250 °C, or soot deposit on the walls. Secondly, our aim was to characterize the effect of heat on the walls by a transformation gradient approach at macroscopic and microscopic scales. To achieve this, thermal and hygrometric measurements on the surface and in the rock were made. Also the different textures were studied as a function of the thermal history and the depth from the surface. Thirdly, the residues resulting from combustion for each type of experimental hearth were studied. Residues include charcoal, ash, or solid particles ejected into the atmosphere of the cave. Finally, the consequences of fires on the environment of the cavity were estimated by simulation taking a narrow gallery with dimensions similar to those of the Megaceros Gallery of the Chauvet-Pont d'Arc cave. Heat balance (distribution and variation of the temperatures), smoke flow, and air renewal were calculated and compared to experimental data. Once the model had been validated, it was used to simulate the impact of fires in archaeological sites such as the Chauvet-Pont d'Arc cave.

We aimed to be able to provide an accurate description of a fire in an archaeological context underground. For obvious reasons, the site chosen for the experiments was free of archaeological interest. We used an underground limestone quarry presenting morphological similarities with the burned galleries in Chauvet-Pont d'Arc cave.

The archaeological objective of the project was to obtain indications on the position of the paleolithic population in the caves near the fires. From the position of the fire, simulation should indicate the zones in which it would be impossible to remain without serious intoxication from the combustion gases.

The experimental process is detailed first. A description is given of the experimental site, the instrumentation used, and the way the fire burned. Then, fire simulations are presented in the site. An open source code (Fire Dynamics Simulation – FDS) was used to calculate the temperatures in the air and on the wall surface, as well as the level of toxic gases. Finally, we discuss the thermo-mechanical impact of the fire on the wall.

2. Implementation of the experimentations

2.1. The experimental site

The experimental fires were set up in an abandoned underground limestone quarry situated in Lugasson in the Gironde district, France. The quarry presents several advantages: it is located far from any site of archaeological interest so fires would not cause any damage, its shape and volume are relatively easy to simulate (to mesh) and it is located close to the project members' laboratories.

The fires were made in an L shaped chamber with only one of the extremities open to the outside. They were placed against a wall located at the back of the chamber. The opening of the room was tall enough to enable us to maintain the fire. A photogrammetry technique was used to visualize the inner volume of the experimental room with a resolution of 1 cm. A view of the opening as seen from outside and a 3D representation of the volume are presented in Fig. 1.

2.2. Metrology

Numerous instruments were set up in the experimental cave during the fire tests. In this article we only present the temperatures of the chamber atmosphere, of the surface of the wall directly exposed to the fire and of the bulk of the limestone at various depths. Measurements of air velocity in the upper part of the