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# FIRES IN CAVES: EFFECTS ON TEMPERATURE AND AIRFLOW

by

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ABSTRACT

Temperatures have been recorded in a cave at Creswell Crags, Nottinghamshire, to assess the effects of fire on the thermal micro-climate of a cave. The fires were located in the entrance and to the rear of the main cave chamber to examine how the positioning of the fire may affect the cave temperature pattern. Airflow and smoke movement were assessed qualitatively. It was concluded that fires near the cave entrance did not affect interior temperatures. A fire at the rear of the cave would generate warmth but excessive amounts of smoke, so only ember fires would be possible if the cave were to be suitable for habitation.

## INTRODUCTION

Archaeological and palaeontological remains found in cave sediments strongly suggest that caves have provided man with shelter and acted as burial sites for hundreds of thousands of years. The presence of man in caves in the Pleistocene and Holocene has often been indicated by evidence of fire such as charcoal, ash, hearths and burnt deposits (Campbell, 1977; Kitching, 1963; Pfeiffer, 1978). While it is possible that fire may arise due to spontaneous combustion of organic material, (a phenomenon which is believed to have formed the burnt material at Choukoutien (Binford, 1983)), the presence of charcoal and hearths associated with human remains, particularly lithic industries, is generally accepted as evidence for man's utilization of a cave (Laville *et al.*, 1980; Bramwell, 1973).

Human use of fire is evidenced strongly in many cave excavations, but what was its purpose? Hominid groups shared an interest in similar resources and occupation sites with large predators such as lion, leopard and hyaena during the Pleistocene (Campbell, 1977). Indeed it has been suggested that, before fire, man played a minor role in cave usage (Pfeiffer, 1978). With competition for suitable sites, it is probable that one of the main roles of fire was to provide protection against carnivores at night. Fire would also provide a source of light and warmth, especially in winter.

British and European archaeological evidence suggests that fires have been located in various types of caves and in several sites within them (Bordes, 1972; Bramwell, 1973). The location of the fire may be determined by its primary role; a fire within a cave is unlikely to provide much protection against marauding animals yet could provide considerable warmth. A further factor to be considered when choosing the site of the fire is the destination of the smoke. Wood fires, producing large quantities of smoke in a confined space, could be very uncomfortable unless the smoke was able to escape easily from the cave. This would

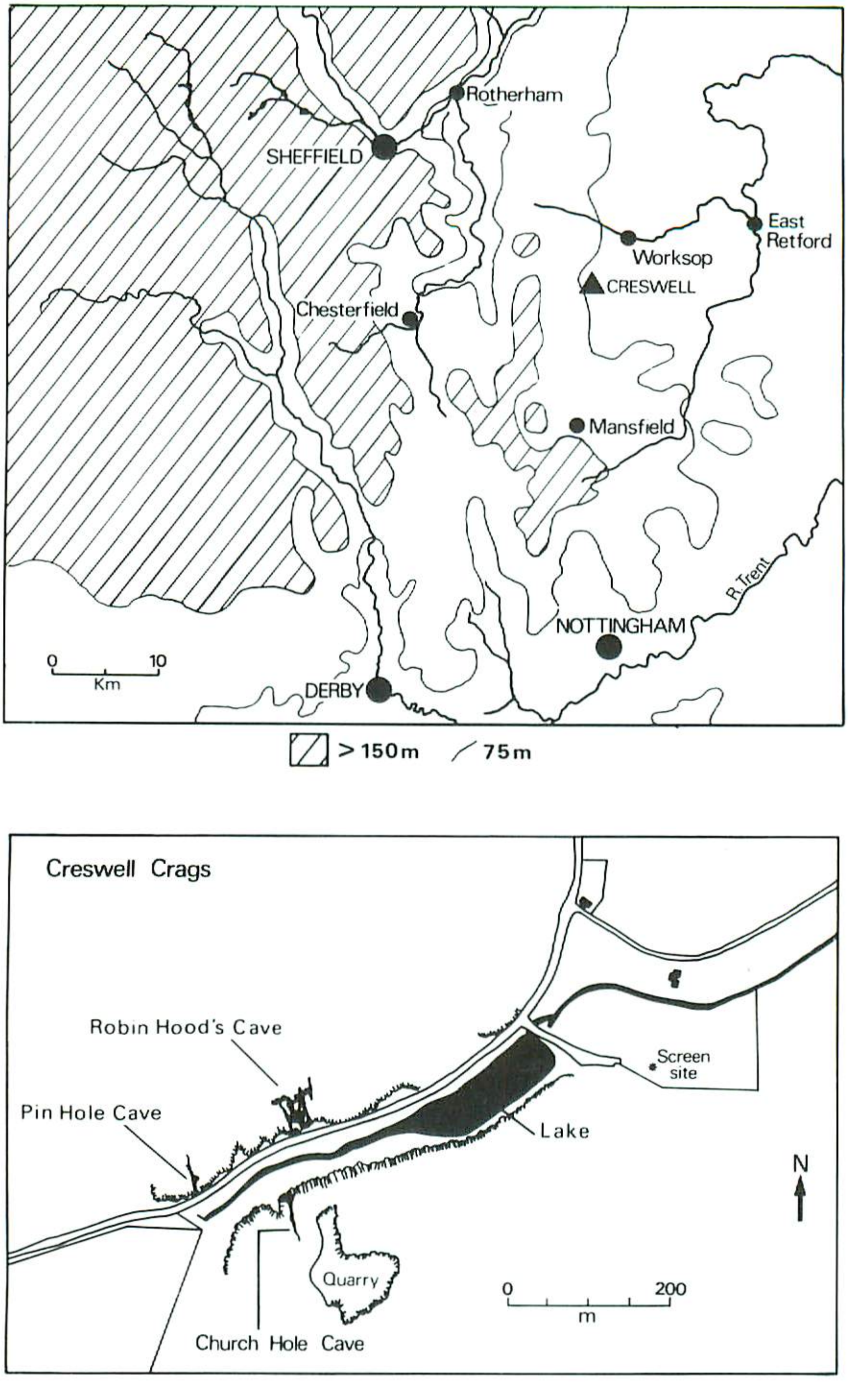


FIG. 1 — LOCATION MAP OF CRESWELL CRAGS AND ROBIN HOOD'S CAVE

only be possible if (1) the fire was completely outside the cave and the smoke rose vertically, or (2) the smoke was blown away from the cave entrance, or (3) the fire was inside and the smoke escaped through some ventilation hole or was carried out of the cave at roof level away from the habited area. Movement of the smoke if the fire was sited inside the cave would be determined by air circulation within the cave and by exchanges with the external air. The micro-climate within most caves responds to diurnal and seasonal changes in the external environment (Wigley and Brown, 1976; Smithson, 1982) and it seems certain that this also occurred during the Pleistocene epoch although the external temperatures would have been different (Lamb, 1977).

This paper reports an experiment into the main effects of a fire at two locations within a cave during the summer and winter, to gauge the importance of fire and seasonal changes in airflow on temperature distribution and smoke movement. The results are applied to a discussion of seasonal and locational siting preferences of the use of fire within caves under occupation in the Pleistocene. It is accepted that contemporary climate is different, but whatever outside conditions prevail, the relative differences between the climate in the cave interior and that outside are likely to have been similar.

## LOCATION OF THE EXPERIMENT

The experiment was conducted in Robin Hood's Cave (NGR SK535742) at Creswell Crags on the Derbyshire/Nottinghamshire border (Gentles, 1984). It is one of a group of caves situated on the northern side of a west to east orientated valley cutting through the Magnesian Limestone escarpment to give a relative relief of about 30 m (Fig. 1). Human and animal remains have been excavated in many of the caves and show a prolonged, though not necessarily continuous, period of human utilization (Jenkinson and Gilbertson, 1985).

Robin Hood's Cave has two main entrances which are interlinked into a complex of chambers (Fig. 2). The western or main chamber is higher than the eastern chamber and has a rather steeply sloping floor rising from the entrance to the rear of the chamber. Three minor entrances exist, one of which may have been more extensive in the past but has been largely blocked by rockfall. Although excavations have altered the topography within the cave, its present internal morphology is similar to that during the Pleistocene (Jenkinson, 1983). The work of Campbell (1977) suggests that a hearth was sited on the platform outside the western main entrance in the Late Devensian. Charcoal, burnt bone and flint assemblages have been found in the cave floor sediments dated between 40,000 and 10,000 bp. An experiment to elucidate the value of fire in Robin Hood's Cave as a means of warmth and comfort would seem relevant in view of its previous history and that of surrounding caves.

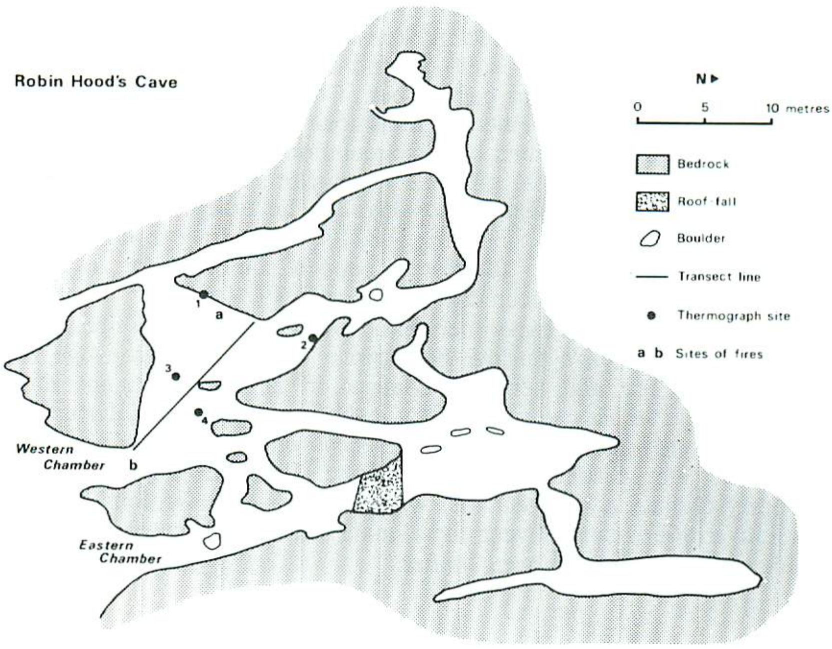


FIG. 2 — PLAN OF ROBIN HOOD'S CAVE WITH SITES OF FIRES, THERMOGRAPHS, AND TRANSECT

## RESEARCH DESIGN

In order to assess the influence of the fire on cave temperatures and airflow, information about the natural cave climate is necessary. Temperature observations have been made in Church Hole and Pin Hole caves (FIG. 1) for the summer period (Smithson, 1982) and in Robin Hood's Cave (Smithson, 1986) for a full year. This work suggested that temperatures within the caves were normally very stable, with diurnal temperature variations extending only a short distance into the cave. The nature of the temperature changes depends upon the diameter of the cave passages, the number of entrances, and speed of airflow (Wigley & Brown, 1971). However airflow is not an independent variable, but is partly controlled by temperature differences between the cave and the exterior. If temperatures are higher outside the cave than inside, then cool air will flow out at ground level with a return flow of warmer air near the roof. When outside temperatures are lower than inside, cold air will flow into the cave at floor level and out at higher levels (Smithson, 1982). The air flows generated by temperature gradients have important implications for smoke movement, though the presence of a fire, by affecting temperature patterns, could modify the inward and outward flow of air. A general conclusion from existing work on cave micro-climates is that most caves have their own individual micro-climates, making it difficult to predict the detailed distribution of cave temperatures without taking measurements.

The three-dimensional pattern of temperatures in Robin Hood's Cave was investigated by recording temperatures at varying distances into the cave and heights above the cave floor. Thermographs were placed on the cave floor of the western chamber at four sites (Fig. 2), at one site in the lower eastern chamber (not marked on the plan), and one in a Stevenson Screen (Fig. 1) 1 m above a horizontal grass-covered surface about 300 m down valley from the cave entrance in order to record external shade temperatures. The Creswell Crags lake prevented observations being taken on the valley floor immediately outside Robin Hood's Cave. These instruments provided the basic network for continuously recording temperatures. In addition, thermistor probes were used to record temperatures every 3 m along a transect from near the western cave entrance (0 m) to the back of the cave (12 m) and at 0.25 m, 0.5 m, 1 m, 1.5 m and 2 m from the cave floor. Cross-traverses to the cave walls were taken every three metres from the main traverse to produce a three-dimensional structure of cave temperatures as shown in Fig. 3. Ideally all observations should have been recorded synchronously. This was impossible with the equipment available so there is an inevitable time-lag between the first and last observation, though this should not be a severe problem in the stable temperature regime of the cave. Because of the time-consuming nature of the readings only four traverses were taken each day.

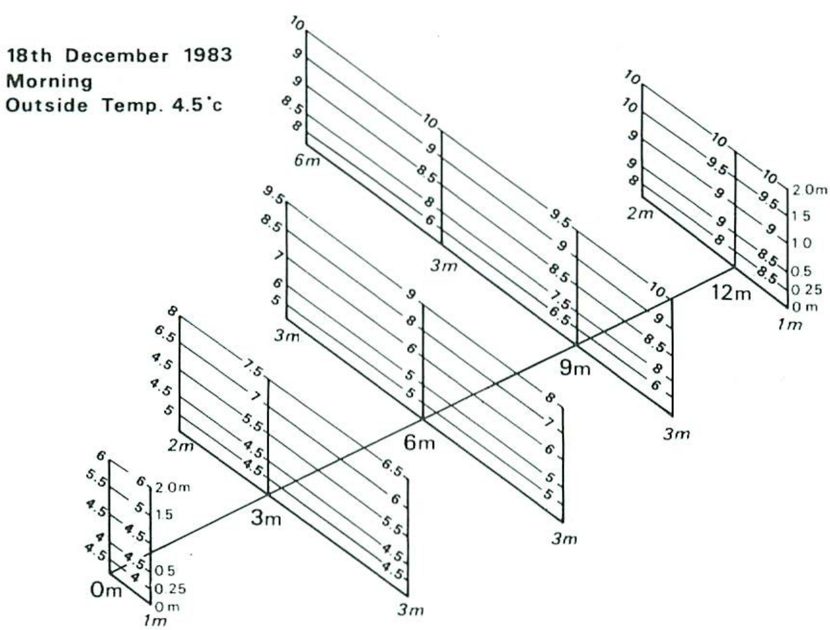


Fig. 3 — Temperature structure in the Western Chamber on December morning (Control situation)

Data collected in the western chamber before the fire was lit were used as a control, assuming external conditions remained constant. The temperature recordings in the eastern chamber could be used to see if there were any changes in temperature in an area well away from the fires, changes there being assumed to be the result of outside interactions rather than being connected with the fires in the western chamber. All instruments were calibrated and cross-checked against each other though the response time of the two types of instrument varied, thermistors responding much more rapidly to slight and/or sudden changes of temperature than thermographs.

Although archaeological evidence suggests that most fires were lit in the cave entrance area or even on a platform outside, it was decided to construct a fire at the rear of the chamber, where charcoal had been found, as well as in the front entrance area, to investigate the consequences on cave temperature, air movement and smoke production.

A final problem was to determine the kind of fire which would be most appropriate to simulate Palaeolithic conditions. During much of the Devensian, woodland would have been scarce or absent in the Creswell area. The Chelford Interstadial, about 60,000 bp, was dominated by pine, birch and spruce (Worsley, 1977) but during the Upton Warren Interstadial (42,000 bp) the landscape appears to have been largely open with no significant tree pollen preserved. Extensive woodland was absent until about 12,000 bp when birch reappeared, followed by the main migration of trees at the beginning of the Flandrian about 10,000 bp. Fires lit during this experiment inevitably relied on modern wood fuels – oak, ash, birch, maple and pine. Some of these, such as birch and pine, were recorded in the Chelfordian and Late-Devensian Interstadials. In Kent's Cavern, Devon, Pengelly's 'Black Band' contained oak, elm and poplar (Campbell, 1977), so the fuels in the following experiments bear some resemblance to fuels used in the past. It is quite possible, given the non-wooded nature of much of the Pleistocene, that dung and bone fuels may have been used; this might appear as charred bone and/or a phosphate deposit. In essence, this paper endeavours to monitor the effect of wood burning fires only, for which there is some evidence in the British Palaeolithic. The study of other kinds of fires would be valuable in terms of establishing differential smoke and heat output and ventilation values, thereby suggesting a possible preference for the type of fire used in a cave system.

## RESULTS

### Control Conditions

From previous work in the cave (Smithson, 1986), control conditions would have been expected to show cooler temperatures in the cave than outside in July and the reverse in December. Diurnal temperature variations should be small and decrease away from the cave entrance. Summertime temperature changes away from the cave surface should be moderate with an increase in temperature towards the roof and higher parts of the cave system. In winter, when outside temperatures are low, the air temperature gradient from the cave floor will be smaller as the main source of heat is by contact with the cave walls. The western chamber in Robin Hood's Cave, with its rising cave floor, would be expected to trap any rising, less dense, warm air which will eventually cool through contact with the cave walls.

*July*

No detailed three-dimensional survey was made before the July fire but information from the thermograph network suggested that the expected temperature pattern had developed. The lowest daytime temperatures were found in the eastern chamber where 10°C. was recorded throughout the four day period, with only minor variations compared with 24° outside. In the western chamber a maximum temperature of 13° was recorded at site 4 (see Fig. 2 for locations), 12° at sites 1 and 2 at the rear of the cave, and 11° at site 3, demonstrating relatively small differences across the cave and much lower temperatures than outside. The higher value at site 4, compared with site 3, may have been because diffuse radiation could penetrate more easily to this point or because it was slightly nearer the cave entrance.

*December*

A similar pattern was obtained from the thermograph readings in December. Sites 1 and 2 experienced the highest temperatures of between 8° and 9° with 6° at site 3 and a lowest temperature of 4.5° at site 4, nearest the entrance. The eastern chamber had stable temperatures but was slightly warmer than at site 4, recording a constant 5°. Diurnal variation was negligible at all sites though the temperature range outside was from 3.8° to 6.2°. This pattern, with higher temperatures in the upper part of the cave and lowest temperature near the entrance, was supported by the thermistor readings. A consistent, stable pattern was observed with the highest temperatures being at 2 m above the ground at the 9 m and 12 m sample points (Fig. 3). Even in the upper part of the cave, the temperature decreased away from the floor, usually by about 2°. Near the cave entrance, at the 0 m sample point, the temperature gradient was almost zero. There was some indication of a small diurnal variation at 0 m.

## Thermal Effects of the Fires

In July, the external maximum temperature was higher by 3° on the control day compared with the day when fire 'a' was lit at the rear of the chamber. This makes precise comparisons difficult, especially at higher levels where warmer air, drawn in from outside, would be expected. It has already been shown (Smithson, 1982) that cave floor temperatures are very stable in summer, so the effects of warmer external temperatures should not be so marked at this level. In winter, outside temperatures varied only slightly, assisting comparison between the three days of the experiment.

Table I shows differences, for July and December at the five levels above the cave floor, between control temperatures and those when fires were present. Higher levels showed a general increase of temperature compared with the control conditions except for fire 'b' (at the entrance) in July. Near the cave floor, increases were not as large nor so consistent. On the summer nights it was slightly cooler with the fire than without it but the differences were not statistically significant. On the winter nights, even the 0.25 m level tended to be considerably warmer while the fires

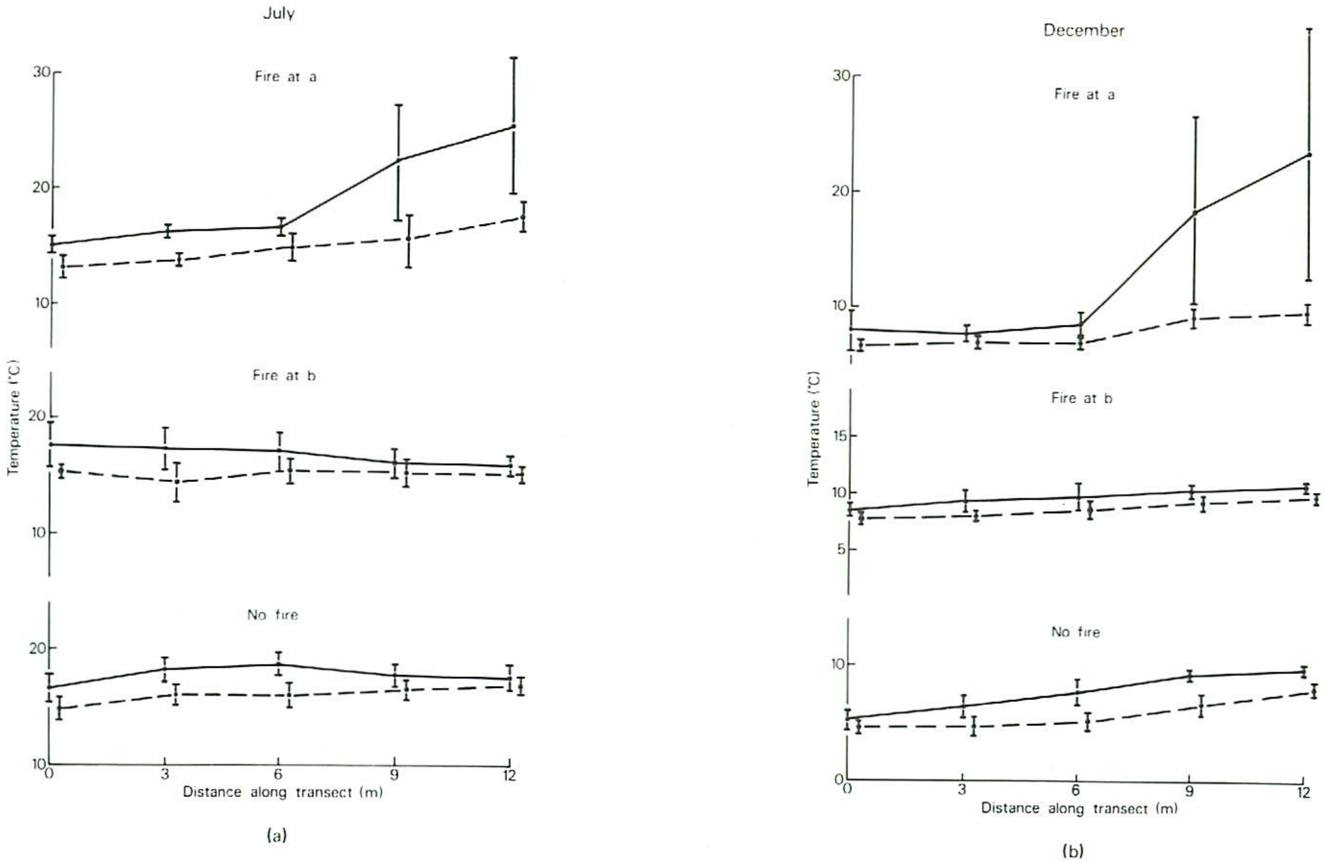


FIG. 4 — TEMPERATURE PROFILE INTO CAVE AT 2M (SOLID LINE) AND 0.25M (DASHED LINE) ABOVE CAVE FLOOR. BARS INDICATE THE RANGE OF TEMPERATURE (±1 STANDARD DEVIATION) FROM THE MEAN VALUE. FOR CLARITY, 0.25M TEMPERATURES HAVE BEEN OFF-SET SLIGHTLY ON THE HORIZONTAL SCALE.
(a) JULY (b) DECEMBER

were burning. Presumably this was because the warm air from the fire would be mixed with the cool air inflow to the cave at floor level. Smoke movement, which is to be discussed later, demonstrated this principle in operation.

TABLE I – *Temperature differentials between days with fire and control days (°C.)*

| | *Height above floor* (m) | *Afternoon* | | *Night* | |
|---|---|---|---|---|---|
| | | *a* | *b* | *a* | *b* |
| July | 2 | +2.8 | +1.1 | +3.8 | +0.1 |
| | 1.5 | +1.7 | +1.1 | +1.8 | −0.4 |
| | 1 | +0.6 | +1.0 | +0.8 | −0.4 |
| | 0.5 | +0.1 | +0.5 | +0.2 | −0.5 |
| | 0.25 | +0.6 | +0.8 | −0.2 | −0.2 |
| December | 2 | +3.5 | +1.8 | +3.3 | +1.5 |
| | 1.5 | +3.3 | +2.1 | +2.7 | +1.5 |
| | 1 | +2.9 | +2.0 | +2.4 | +1.7 |
| | 0.5 | +2.0 | +2.1 | +2.2 | +2.1 |
| | 0.25 | +1.5 | +1.9 | +1.9 | +2.1 |

To assess the nature of temperature change in the cave, mean temperatures were calculated for each height at each transect distance throughout the day. In July, without a fire, the temperature trend follows that predicted for summer by Wigley and Brown (1971), with the highest temperatures slightly inward of the cave entrance (FIG. 4a). Temperature differences between 0.25 m and 2 m are small everywhere. With the fire at site 'a', the temperature curve follows a similar pattern to that of the control day between 0 m and 6 m. Beyond 6 m temperatures rise markedly and the temperature gradient becomes very pronounced. With the fire at site 'b', a different pattern emerges. Temperatures at 2 m height decline steadily into the cave with a more erratic trend at 0.25 m. In general the temperature gradient decreases into the cave.

In December, the thermal pattern of the cave without the fire is different from that in July (FIG. 4b). Wigley and Brown (1971) suggested that there ought to be a temperature minimum near the entrance associated with evaporation from the cave walls. The December control day was very humid with evaporation unlikely. As a result the thermal pattern into the cave showed a steady increase of temperature and temperature gradients.

When the fire was burning at site 'a', an increase of temperature was apparent from the entrance area to 6 m into the cave. Beyond the 6 m point, mean temperatures rose dramatically. At 12 m, differences could be distinguished between the warmer, higher, left-hand sector of the cave and the cooler, lower, right-hand sector; hence the large standard deviation. The fire at site 'b' produced a reverse temperature gradient from that observed in July. Despite the fire burning in the entrance area, temperatures increased into the cave by about 2° with a similar temperature gradient at all levels, but variability was small. Temperatures at 12 m were a little warmer than those on the control day. Statistical tests showed that the differences were significant because of the low variability of the temperatures. Nearer the entrance the increase in temperature was more pronounced.

In conclusion, it can be stated that a fire at the back of the cave will lead to a marked increase in temperature of the inner and higher parts of the cave with only a slight effect in the cave entrance and near floor level. For a fire in the entrance the effects will be more subdued. There will be a slight increase in temperatures in the entrance zone but temperature changes resulting from the fire will not extend very far into the cave.

## Ventilation and Airflow

In the early stages of fire, smoke is released. If the fuel is moist and the fire temperature is low, large quantities of smoke may be involved. Subsequent movement of the smoke should be controlled by the initial buoyancy of the warm air from the fire and the air circulation of the cave generated by gravitational and pressure differences. The consequences of the fires being lit will be described and discussed in turn.

### *July 'a'*

Within twenty minutes of the fire being lit at site 'a', the whole upper area of the cave was filled with thick smoke between the roof and about 0.5 m from the floor. Nearer the cave entrance smoke density was less with a considerable movement of smoke outwards via the western entrance, mainly within 2 m of the floor, corresponding to the drainage of colder air out of the cave, the normal situation in summer. Smoke originating in the rear chamber of the cave could be seen to be incorporated into the outward drainage of cold air and so taken outside. When in contact with warmer external air near the entrance some smoke was observed to rise in the more turbulent flow and return into the cave at a level above 3 m.

For about seven hours, the area beyond the 9 m point continued to be greatly affected by smoke. Vision was reduced and running eyes, nose and hampered breathing made the use of this area very difficult. The only respite was to lie flat on the ground where the density of smoke was reduced. Condensation became a problem around the fire. The warm air containing moisture from the burning wood was able to condense on to the cooler walls and roof near the fire as well as on to bedding. The combination of thick smoke and condensation in this upper area meant that it became necessary to wait for the fire to burn down to embers before comfortable use was possible.

### *July 'b'*

On the following day, a fire was lit at site 'b'. After thirty minutes the cave became too uncomfortable for recordings to be made. Smoke rose from the fire and was carried into the cave by the inward flow of warm air at higher levels. The cool outflow took some smoke with it but this was then returned at higher levels as a result of turbulent mixing between warm and cool airflows in the entrance area.

In summer, therefore, neither fire allowed sufficient ventilation to enable comfortable activities to proceed unless reclining within about 1 m of the fire. Only at the ember stage was there minimal discomfort from smoke and an adequate level of heating.

### *December 'a'*

Again, large quantities of smoke were released when the fire was lit at site 'a'. Some of the smoke was liberated out of the western entrance at high levels – above 2 m, and some via the eastern entrance which is slightly higher than the western entrance. The greatest amount, however, remained near the fire in the upper area of the chamber. Ventilation was not effective and could not keep pace with the amount of smoke generated by the fire. By creating a source of rising air within the cave this fire intensified the influx of cooler air at floor level as shown by the absence of a temperature gradient between the entrance and 6 m on this day compared with the situation on the control day. Towards night the embers produced little smoke but considerable heat making the environment more pleasant but similar physiological effects to those experienced in July had occurred earlier in the day.

### *December 'b'*

On the following day, a fire was lit at site 'b'. The main pattern of smoke movement differed from those already described. Some smoke was drawn into the weak inward flow of cool air, but the majority rose vertically through the cool and weak surface inflow because of the heat of the fire. It then became incorporated into the warmer, outflowing current of air at higher levels. As a result, much more smoke was dispersed outside the cave. Temperature differences between cave and exterior were not large at this time so the gravitational and thermal inflow of air was weak. The comparative lack of smoke in the upper chamber was noticeable presumably because of the weak inflow. Unlike fire 'a', fire 'b' did not require a mask to enable readings to be taken. Towards evening the fire was subject to external wind eddies causing erratic changes in the direction of smoke movement in the immediate vicinity of the fire. Physiological effects on eyes, nose and breathing were not apparent at any stage.

In summary, the value of the fire depends upon its location within the cave, its physical state and the time of year. At site 'a', excessive smoke accumulation produced unpleasant conditions in both seasons unless the fire was in an ember state. The fire at site 'b' did not distribute heat very effectively apart from local radiant heat, but in winter smoke was removed by the air circulation keeping the interior of the cave largely smoke free.

## ARCHAEOLOGICAL IMPLICATIONS

These results suggest that fires placed on the platform area of a cave would have limited thermal value apart from localized radiant heat. However, they could act as a deterrent to predators as well as a source of embers for non-smoky fires further into the cave. It appears quite understandable, therefore, to find charcoal at positions 'a' and 'b' within Robin Hood's Cave, though for practical reasons it is suggested that the remains would be from embers at site 'a' and from a full fire at site 'b'. Because of the greater thermal benefit observed from an ember fire at site 'a' and a preferred sheltered location away from draughts, it is likely that its use would be of a domestic character. In support of this conclusion, Binford (1983) has noted that those areas in caves used for eating and sleeping in ethnographic contexts in various parts of the world are those where light is minimal, while those areas used for the production of tools and specialized goods are those nearest the light source. Campbell (1977) has suggested that there are lithic remains near the western main entrance of Robin Hood's Cave. Kitching (1963) has also noted evidence of fire and burnt bone at an intermediate distance between the vestibule area and the rear of the cave at Pin Hole.

In France, Bordes (1972) has noted that in the Pech de l'Azé cave there were three different types of fireplace in 'Rissian' layers. The more permanent types were situated at greater depth into this twin-entranced cave than the more frequent and less well-prepared fire sites near the entrance zone. Indeed, Bordes suggests that the permanent paved types, which can reach over 1 m in diameter, were used for cooking. The elementary hearths on the other hand were of similar size but do not appear to have been prepared for any special purpose, being set directly on to the ground. This idea is confirmed by our results.

## CONCLUSION

One of the most important aims of archaeology is to reconstruct, as far as possible, the behavioural context which produced the observed distribution of human remains recovered from ancient and prehistoric sites. One way in which archaeology can experience some parts of prehistoric life is through attempts to reproduce former circumstances by experimentation. By using some of the tools of the past we can often gain an insight into the meaning attached to high densities of artifacts and bone remains.

We have shown that a permanent, ember-based fire deeper in the cave would provide a suitable location for domestic usage, with a fire near the entrance to deter predators and act as a source of embers for the other fire.

These findings imply that the archaeological patterns of fire usage seen, for example, at Pech de l'Azé and Creswell Crags, may be related to the preference and practicalities of fire as demonstrated at Robin Hood's Cave. More detailed analyses of the composition and character of the fires used in caves during the Pleistocene would be helpful in enabling more realistic simulation experiments to be conducted. Once more is known of the nature of archaeological evidence for fires, i.e. how and why they were used, we would be in a stronger position to make more precise assertions about human living conditions in the Pleistocene.

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