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Processes of Formation and Alteration of Archaeological Fire Structures: Complexity Viewed in the Light of Experimental Approaches

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Abstract The aim of this article is to present an experimental approach for studying the formation and transformation processes of archaeological fire structures. We present a synthetic review of our experimental project, which was developed in many different natural archaeological contexts. We report the results and problems associated with experimental fires lit on different kinds of soils and in different environments, followed by the observation of natural and anthropic transformations. Finally, we analyse the nature and significance of these results for the archaeological interpretation

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process, while describing some general trends and showing the complexity of the approach.

Keywords Formation processes · Fire structures · Experimental approach · Taphonomy

Introduction

Hearth structures are one of the most important human structures yielding information on human behaviour related to the use of fire as well as the processes of control and application of thermal energy by humans. From the common point of view, a ″fire structure” is a real object that is perceived subjectively, and it is therefore important in the first place to establish objective knowledge concerning its study. From an archaeological point of view, the object being observed today is not the same as the one used in the past. In the same way as today's astronomers study stars that no longer exist, we are faced with ″pictures″ of the past that we need to reconstruct and understand. Moreover, we may consider that the different components studied in their present configuration suggest ″clues″ for interpreting the organization of these objects in the past, thus representing a residual image (understood in the broad sense) of the original object. However, the current arrangement of these indications is the result of human behaviour and taphonomic factors. Hence, each combination of traces corresponds to a particular history, ranging from the origin of the structure to the moment of its excavation. To reconstruct the process of evolution of human behaviour related to fire, the archaeological approach must first remove signs representing only ″background noise″ that blurs our vision of the past. Then, it is important to establish a method that improves both the understanding of the currently observable archaeological fire structure and what it really was, a source of thermal energy for human activities.

Understanding the signification of fire structures in terms of human behaviour and evolution leads us to address five fundamental questions

- What was the form of the hearths?
- What was their mode of functioning?
- What was their function?
- What was their duration of use?
- What were the taphonomic processes that transformed the structure after its abandonment?

To tackle these issues, we have developed a methodology based on a transdisciplinary approach (March and Ferreri 1989; March *et al*. 1989, 1991; March 1995a, b), linking various sciences such as physics of combustion and heat transfer, organic and inorganic chemistry and modelling studies. The aim of this methodology, based on an approach combining analytical techniques, experimental simulations and modelling, is to isolate and prioritise the various signs of human activities and their significant associations, in a meaningful reconstruction of the history of each fire structure studied, based on the study of their formation processes (March and Wünsch 2003).

The complexity of this kind of problem persists, despite great efforts to resolve the issues involved and construct different hypotheses about the history of each structure and their significance in their different archaeological contexts (March *et al*. 1989, 1991, 2003a, b, 2006; March and Ferreri 1989, 1991; March 1995a, b, 1999; March and Soler Mayor 1999; March and Lucquin 2007, 2012). Our experimental approach can open up an interesting perspective on the inherent complexity of fire structure formation and clarify ways of understanding the significance of each component as well as the structure as a whole. We consider that such data can be useful for other researchers working on the history of fire domestication and use, contributing to their efforts to address the questions and general issues presented above.

The goal of this study is to present a synthetic overview of the processes involved in the formation of archaeological fire structures, based on our experimental and analytical approach. Furthermore, we summarise the results of our taphonomic experiments, which can thus contribute to interpreting and assessing the significance of archaeological processes in this context

Some Remarks About Taphonomy and our Theoretical Approach

The concept of taphonomy is not new, since the term was coined back in the 1940s (Efremov 1940), but its history and significance seem to have evolved so that "taphonomy" has come to mean many different things and, in this sense, is now used in a general purpose way. While the study of taphonomy was first developed in palaeontology, archaeologists were obviously interested in understanding the natural transformation processes that have modified the archaeological record (for example: Isaac 1967; Hole and Heizer 1969; Ascher 1970; Coles 1973). Being closely related to the concepts used here, we should mention the pioneering work of M.B. Schiffer dealing with formation processes (cultural or natural), including c-transforms or n-transforms, in which n-transforms are defined as "post-depositional phenomena, especially the modification and destruction of artifacts and ecofacts by chemical and physical agents…" describing the interactions between culturally-deposited materials and environmental variables (Schiffer 1975).

Following these definitions, an extrapolation of the term taphonomy appeared in the American academic community in the early 1980s (Behrensmeyer and Hill 1980–1988; Shipman 1981; Brain 1981; Binford 1981). As such, this first involved understanding the formation and preservation of the palaeontological record and defining the limits of interpretation imposed by these processes. This approach was gradually extrapolated to other disciplines concerned with unravelling the recent or remote past, including geology as well as sciences related to forensic medicine (Pickering and Carlson 2004; Morton and Lord 2006), and even astronomy (Lipps and Rieboldt 2005). While at first limited to post-mortem processes, such as the burial and fossilisation of animal remains, the concept nowadays seems to be changing to cover a broader vision of the processes of formation, including the conditions prior to burial, while no longer being restricted only to living organisms. As has been pointed out by several authors (Sharer and Ashmore 1979; Schiffer 1972, 1975, 1976, 1987), humans themselves contribute to the transformation of the record deposited by their ancestors. In this way, it is easy to understand why and how this concept has been closely associated with the study of the processes of formation of *in vivo* sites, or the human systemic context. Thus, both the theoretical framework and the subject matter of taphonomy seem to be shifting. This change is accompanied by a certain confusion since, for the majority of authors, taphonomy retains its original meaning (Martinell *et al*. 2008), being instead related to the natural transformation of the context, which complicates the interpretation of the past. Other authors, however, consider that taphonomy is concerned with the study of the anthropic processes of formation and alteration, which are themselves the result of a cultural process. Taphonomy, by including all the processes of pre-burial formation, could even end up by merging with archaeology, as has already partly occurred in the case of palaeontology.

Because of all these considerations, we should point out that the studies presented here, in addition to the contribution of the above-mentioned theories, are inspired by the convergence of three theoretical principles (March 1995a, b, 1996, 1999): the observation theory as defined by Gandara (1982), the middle range theory as defined by Binford (1981, 1983) and the concept of equifinality as defined by Gardin (1987, 1990). Since 1983, in view of these principles, we have been developing an analytical and experimental approach in our research programme tending to reconstruct the processes of formation and alteration of the anthropic fire structures. We analyse the anthropic and natural processes, which lead to the formation of the archaeological record, and give an interpretative framework based on the development of evolving progessively adapted models of interpretation. The concept of taphonomy as used here is derived from evolutionary palaeoecology and, in particular, studies carried out on paleoenvironmental contexts and taphonomic processes (Behrensmeyer *et al*. 1992).

Our models of interpretation are based on data relating to three types of context: the archaeological context, realistic experimental simulations and analyses based on laboratory experiments.

The archaeological context is well defined and includes the whole range of archaeological and ethnographic data that are available for our samples.

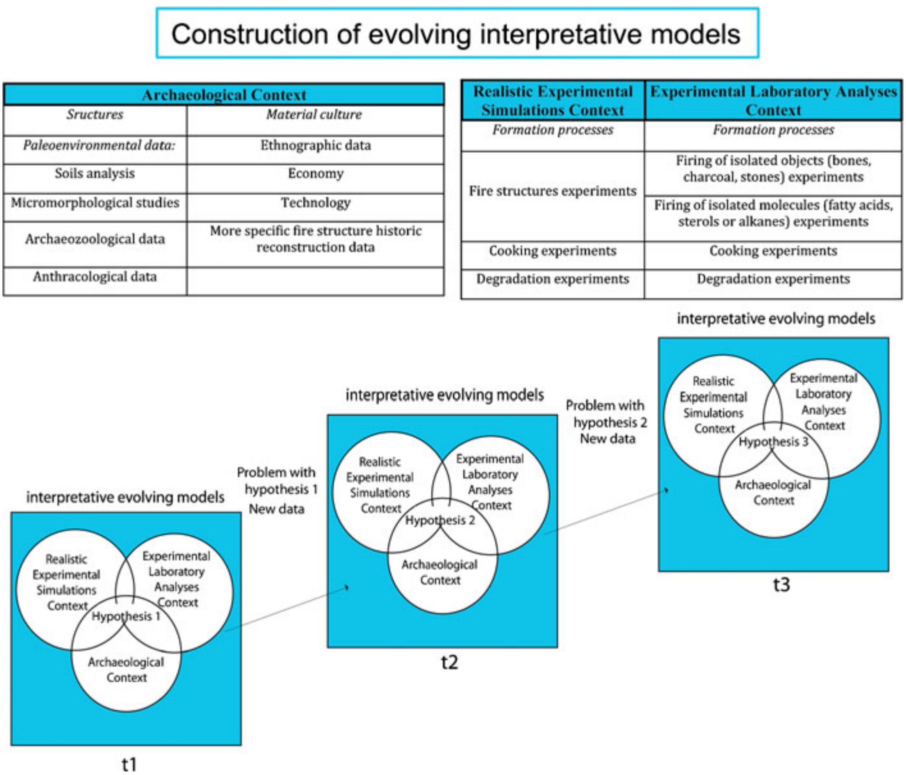
The realistic experimental simulations carried out in our study correspond to particular experimental contexts. Basically, we make a fire, which is used for different reasons such as cooking, heating or lighting, etc., or we perform degradation experiments under natural conditions. These kinds of experiments are highly complex because of the large number of variables that we must take into account, but such an approach is indispensable for understanding the interactions of many processes that are normally studied in an isolated way in the laboratory. A clear illustration is given by cooking experiments. We can cook different kinds of meat (sea mammals, sea birds, molluscs, fish, camelids and beef; March 1995a, 1996, 1999) according to ethnographic models or literary traditions frequently linked to the same locations as the archaeological sites. In these kinds of experiments, the organic matter to be analysed is often mixed with other constituents such as charcoal, soil or ash. We study the chemical reactions between these different materials and the taphonomic processes that can be inferred in each ecological context.

Finally, the laboratory experimental context is designed to study each variable separately. For example, we can study: (1) the influence of heat on different separate components of a fire structure, such as soils, stones, bones, wood, by analysing the physico-chemical transformations resulting from the effect of heat, which affect the elemental composition or crystallographic properties of each material; (2) the influence of certain processes such as boiling on different kinds of fats derived from meat or bone; (3) fats from different anatomical parts of an animal; or (4) the preservation of organic matter and fats in one kind of bone or plant after firing (March *et al.* 1989; March 1996, 1999; Joly and March 2003).

Our research is conditioned in the light of this reality, and our interpretations of the archaeological data are based on evolving interpretative models (Fig. 1). Such models are built on data obtained from these three contexts, which change frequently, and sometimes substantially, along with the acquisition of new data.

These interpretations contain analytical and experimental inferences about the form, functioning mode, thermal history and minimal time of burning and functions, which are then used as working assumptions to reconstruct each fire structure history. This historic reconstruction of fire structures, defined in an article published in 1995 (March 1995b), represents a hypothetical reconstruction of fire-related activities performed in each hearth at a given studied site, according to our evolving interpretative models at a given time (x), which can be re-expressed at a later time (x_1) when new data are acquired and our interpretative models are modified.

These interpretative models are confronted whenever possible with the reality of the archaeological data, thus providing a test of our preliminary interpretations, such as described by Chalmers (Chalmers 1982, 1990). Thus, acquiring knowledge about the real history of each fire structure can be regarded as a step-by-step process in our analytical and experimental approach.



Archaeological Context	
Sructures	*Material culture*
Paleoenvironmental data:	Ethnographic data
Soils analysis	Economy
Micromorphological studies	Technology
Archaeozoological data	More specific fire structure historic reconstruction data
Anthracological data	

Realistic Experimental Simulations Context	Experimental Laboratory Analyses Context
Formation processes	*Formation processes*
Fire structures experiments	Firing of isolated objects (bones, charcoal, stones) experiments
	Firing of isolated molecules (fatty acids, sterols or alkanes) experiments
Cooking experiments	Cooking experiments
Degradation experiments	Degradation experiments

Fig. 1 Reference framework for development of interpretative models and schematic evolution of the model

Our experimental work has led to the compilation of a corpus of 156 experiments concerning hearth structures used for domestic purposes, including 40 relating to the study of taphonomic processes (Table 1). These field experiments are accompanied by a large number of laboratory experiments intended to analyse the variables in an isolated and/or better controlled way, to test the hypotheses proposed from experimental work under .

We present here a short summary of our experimental data on the processes of formation and alteration of fire structures. We also perform an overall analysis of our experimental corpus on the shapes of domestic hearths, to identify trends in the processes of formation and alteration. This overview of the formation and transformation of fire structures is divided into two parts: the first part presents our experimental results concerning the processes involved in the formation of fire structures, and the second part is focused on the experimental approach used for the study of post-depositional processes.

In the following, we present some examples that may help to understand the complexity of processes involved in fire structure formation. These examples range from the transformation of hearth components to thermal alteration arising from different modes of functioning in relation to different fire structure forms. These data show some trends in the mode of functioning of fire structures, yielding information (on isolated or associated components) that allows us to reconstruct the functioning mode, function and minimal duration of burning of each fire, and even acquire some notions about the economy of fuel use. We also discuss some problems associated with the experimental approach and outline the development of a modelling approach

Table 1 Detailed experimental corpus

	Type of hearth						
Kind of substrate	Pit				hearths	Simple hearths	
Ovens	Stone				boiling	Including cooking	
Including taphonomic purposes	Total						
Shell midden		16			4	10	16
Flat stones or pebbles (Sandstone, Silex, Limestone)	5	4		32	10	1	41
Humus	1	8					9
Humus/carbonate	1	1					2
Silt	18	28			10	12	46
Volcanic ashes		3				2	3
Clayed silt	3					10	3
Lœss		8				2	8
Little pebbles under shell midden		1				1	1
Sand	2	15			4	2	17
Granitic sand		3	2		2		5
Silted sand	3	2					5
Total	33	89	2	32	30	40	156

that could facilitate the study of formation processes. This section is concluded by some brief remarks on processes of anthropic organic matter formation.

In "Post-Depositional Processes" we describe the experimental approach used to study the post- depositional processes that affect fire combustion structures, while focusing on the natural processes observed in the different ecological settings where our experiments were carried out. In the same way, we present some examples of anthropic and natural post-depositional processes to stress the importance of these factors and the inherent difficulties encountered during our work, due to the complexity of the data that needs to be taken into account to understand, unravel and model both natural and anthropic phenomena.

Finally, we conclude with a critical discussion about the problems faced by archaeologists and the implications for this kind of research.

Processes of Formation of Fire Structures

The processes of formation of fire structures involve physicochemical phenomena linked to human behaviour during the building of hearths and the activities related to their use. The numerous variables affecting these processes are analysed here, along with the relationships between the experimental and archaeological data, by interpreting the alteration of materials resulting from these processes. Table 2 describes shortly the variables taking into account for the 156 realistic experiments.

To address the five fundamental questions presented in the "Introduction", it is necessary to understand the significance of each component of a fire structure. This implies analysing the thermal transformation of each component, both in isolation and in relation to the other components of the structure. This helps us to identify the associations of components which might be preserved in a structure and which could be interpreted, for example, as isotherms, i.e. the position of different points in the structure attaining the same temperature during its functioning, or the distribution of oxidation or reduction conditions in different parts of the structure during combustion. Isolated thermally altered components found elsewhere at the site can also yield information about phenomena that are indirectly associated with the fire structure. For example, thermally altered stones, ashes, charcoal, etc. that were reused or discarded outside the structure can give some idea of the kind of fire structure, the fuel chosen and the combustion modes. By contrast, isolated elements can be used to rule out certain hypotheses such as the utilisation of bone as fuel. For example, certain components of a structure or site can sometimes have a thermally altered aspect, but have not actually been affected by heat, as is the case with bones stained by manganese oxides.

Then, we study the effects of thermal alteration on the components of the hearths and their underlying soil, as well as the various types of fuels (wood and bone, among others) in a laboratory experimental context. This enables us to establish an experimental data base of the transformations affecting various materials (e.g. rocks, shells, bones and soils) following heat treatment under different conditions, some examples of which are shown on Fig. 2 (March 1988, 1989, 1990, 1992, 1996, 1999; Joly and March 2003; Lucquin and March 2003; March and Wunsch 2003; March *et al*. 1991, 1993; Joly *et al.* 2006; Dumarçay *et al.* 2008).

Table 2 Variables taken into account in realistic experiments (Measures were taken into XYZ coordinates with a total laser station)

General variables:

Ambient temperature, soil temperature (°C)

Precipitations (ml) Sun hours: exposition to sun of the experiment (hours)

Kind of soil (description, composition physicochemical characterisation and particle size characterisation)

Wind: two kind of measures: 1) subjective (absent, very weak, weak , strong), 2) speed (m/sec) Orientation (following cardinal points) at three different altitudes: 0 m 0.50 m and 1 m from soil

Form of fire structure:

Descriptive: simple hearths, pit hearths, with stones or without stones, stone position related to fire

Measurements of accumulations:

Fuel and fuel residues, depressions or pit forms long length thickness perimeter (cm) or surfaces (cm^2)

Measurements of stones employed:

Length, width and height or thickness (mm), volume (ml) , weight (g)

Variables about fire structures functioning:

Kind of fuel: (nature of fuel: wood , bone, dung, etc.)

Wood species: scientific name

Part of the plant employed: (branches, trunks, roots)

Dimensions of these parts: maximal lengths and maximum diameter in mm

Wood state: green/humid died/dry

Weight of fuel: kg

Kind of initiator for ignition: (description wood, mushrooms, straw, paper, matches); Frequency of feeding: quantity of fuel (kg) for each feed

Wood disposition on fire: radian, parallel or transversal to wind direction, position related to other parts of the structure, pits or stones used. (When it was practiced special forms of wood construction, wood on cross wood on tippy form etc.)

Weight of final charcoal and ashes: g (complete and selective with position on fire sampling)

Fire temperatures: K thermocouples for contact (sporadic use of other kinds of thermocouples as J for fluids)

Temperatures under and above the embers

Temperatures under the soil: trying to respect an axial position under the center of the embers distribution. In the most detailed experiments of flat hearths temperatures was taken in points drawn aside from axe but near the surface to study drying conditions. In pit hearths the same principle was respected but measurements were also performed in the soil under the pit walls

Temperatures at soil surface following an equidistance of 5, 10 and 20 cm from the centre of the embers concentration that was considered as the heat centre of the fire structure

Temperatures at stones surfaces: following the position of the stone (vertical, flat or inclined) the number of measurements was increased

For stones: temperatures into stones (at 3 cm of the surface), Temperatures under the stones and above the soil

These measurements were progressively accurate and were taken at each 5 min for short experiences (3 h) and at each 10 min (for longer experiences). With time and digital resources (digital inputs and outputs) these measurements are increased to one measure each 5 s and sometimes to 1 s into boiling experiments

Traces of thermal alteration and combustion residues

Dimensions of: charcoal and ashes accumulations; of dispersion zones of charcoal and ashes beyond the structure; of thermal altered soils: oxidations reductions, carbonisations; of organic deposits on soils; of

Table 2 (continued)

thermal altered surfaces on stones: oxidations reductions, smoked areas, all dimensions as follow [for long length thickness perimeter (cm) or surfaces (cm^2)]
Presence of thermal alterations: fissures, fractures (true, false, description)
Presence and formation of adherences: (true or false) organic matter from fuel, cooking or sediments (description, sampling and measures) cm^2
Organisation of traces of thermal alteration in sediment and organisation of traces on stones: description
Color of altered soils: following Cailleux or Munsell Atlas; sometimes we explored digital colour measurements (CIELAB Lab color space RGB or CMYB)
Organic residues sampling
Sampling of 300 g of sediment for each sample detailing position (perimeter and surface, XYZ) and nature (soils, fuel residues, stones, cooking residues, etc.)

For example, studies of the alteration of fresh or cooked bone, both ancient and modern and in various burial contexts, show that bones affected by heat exhibit small but nevertheless very regular variations in their behaviour during physicochemical alteration processes (e.g. carbon and phosphate). These variations depend on the preliminary state and context of burial of the bones, which are controlled by molecular and crystallographic transformations affecting their composition and aspect. Thus, according to the context of burial, we can observe changes in the carbon, nitrogen and hydrogen contents, or even the grain size of hydroxy-apatite. In addition, the colour of the bone may be altered or different types of deposit can be formed (manganese, iron,

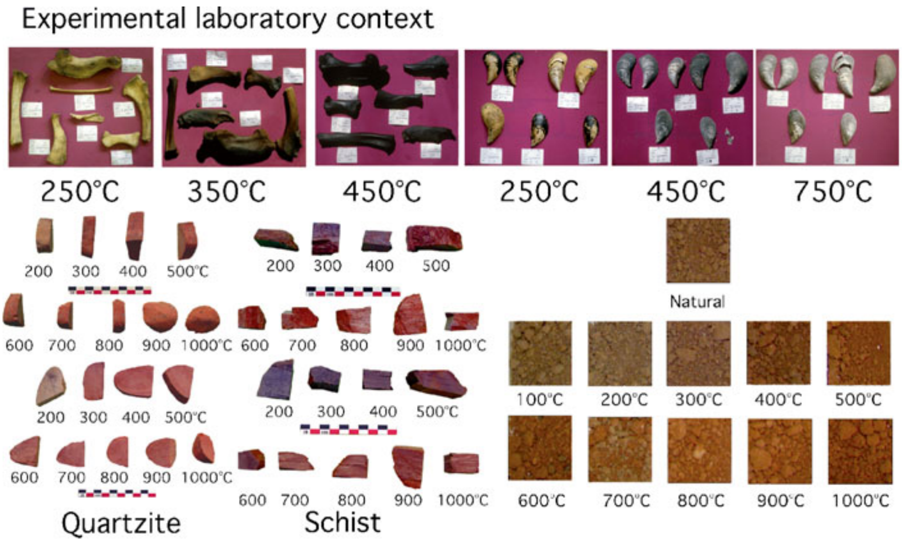


Fig. 2 Examples of laboratory experiments on thermal degradation of isolated components, providing information about fire structures: bones of ancient marine mammals (*Otaria flavescens*) and recent individual specimens of *Mytilus* sp. from the Beagle Channel, quartzite and micaschist pebbles from the Rhone valley region and clayey loam soils from the Lyons district in France. All of these materials were calcined in ovens at controlled temperatures under oxidising conditions

carbonates, etc.) (March 1988, 1989, 1990; March *et al.* 1991; Joly and March 2003; Joly *et al.* 2006; Joly 2008). We note that the bone colour—brownish, blackish, whitish, pink or bluish—depends not only on the temperature but also on the duration of combustion and the initial state of the bone. This contextual framework allows us to infer the conditions of thermal alteration of the bones, while opening up the possible identification of their initial state and post-depositional alteration (Joly et al. 2006; Joly 2008) (Fig. 3).

In the same way, we can study the formation of oxidation surfaces associated with fire structures in a realistic experimental context, as well as the areas of organic matter deposited in the hearths, resulting from combustion and culinary activities (Fig. 4). This type of study allows us to develop models for the formation of hearths according to their shape, functioning mode and duration of use. The various shapes correspond to characteristic signatures which reflect these parameters, but which can evidently be modified during re-use. When they are not disturbed by re-use, these signatures allow us to infer certain operating modes, as well as the anthropic processes which could modify them during the life of the structure. Thus, a pit hearth with a rim made up of vertical arrangement of flagstones will only leave traces on the soil in direct contact with the fuel at the base of the structure, while the flagstones will be affected instead of the soil; the oxidised sediment patch beneath a simple (or flat) hearth increases in thickness according to the time of burning in the

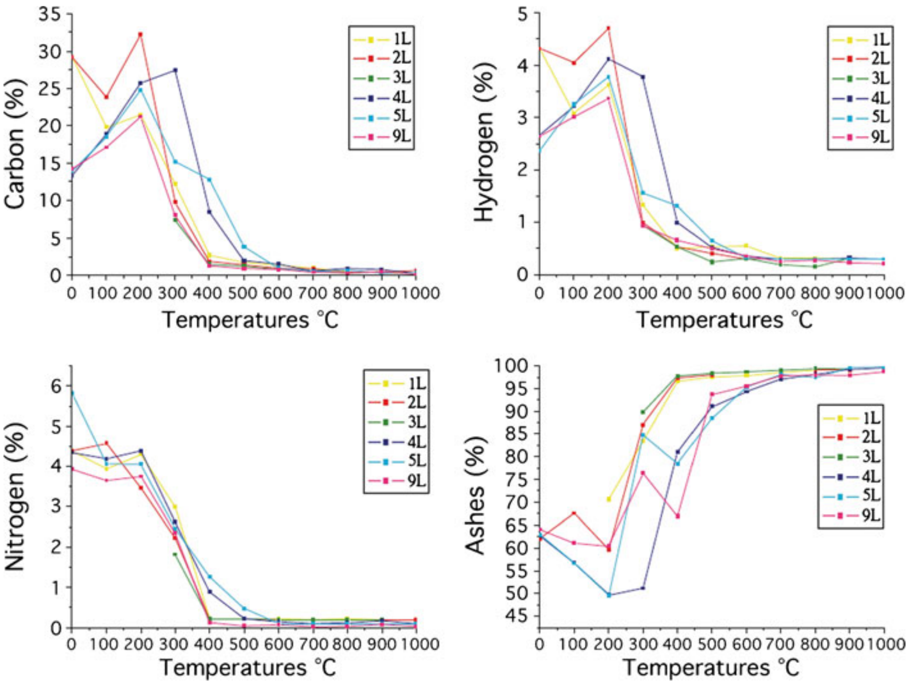


Fig. 3 Hydrogen, carbon and nitrogen contents of unburnt roe bones (1–9 L) after heat treatment for 1 h at constant temperature and at steps of 100 °C. Note that, after a short period of enrichment in C and H at 200 °C, the values of C and H decrease as a function of temperature of exposure, while nitrogen decreases steadily with temperature. When this method is cross-referenced with another, such as X-ray diffraction or SEM, it is possible to identify the thermal degradation of bone and their diagenetic transformations

Fig. 4 Examples of experiments of building hearths in realistic contexts, with distribution of the various zones of thermal degradation in rocks and soils (*reddish* and *blackened zones*) as a function of hearth shape and duration of use

hearth. Alternatively, the bottom of a hearth in a small pit may not be oxidised at all, since rapid filling of the depression by a layer of charcoal and ashes raises the centre of combustion, thus acting as an insulator rather than a fuel. In the same way, rocks forming a stone border can exhibit variable types of alteration according to their shape (flagstones, pebbles or blocks) and their arrangement in the rim or wall (bordering blocks set in rings, vertical or horizontal pavement, etc.) (March *et al.* 2010) (Fig. 4).

Heat not only affects the components of the hearth but also the soil, causing alteration of the various types of substrates. This leads, for example, to their oxidation, which varies according to the composition of the soil and the shape of the hearth. Thus, in our series of realistic experiments with simple hearths, the oxidised zones range in diameter from zero to more than 70 cm, with most of the values falling between 30 and 60 cm. These dimensions are related to the temperatures attained, the nature of the substrate, and the length of the branches or trunks used. The shape of the hearth, as well as its arrangement and thickness, varies according to the temperatures reached by the structure, the nature of the substrate and the time of burning for each hearth. For the same set of experiments, the thickness of oxidation of the soil varies between 0 and 8 cm, with a strong concentration of values between 1 and 2 cm (Fig. 5a). If we analyse this phenomenon in more detail, we observe that the oxidised zones on silty soil (reddish oxidation between 300° and 500 °C, according to type of soil) have diameters ranging mainly from 30 to 50 cm, irrespective of the firewood arrangement. This contrasts with shell middens, where the diameter of the oxidised zone varies according to the temperature (250, 475 or 750 °C) and exhibits three types of colour (brown, grey-blue or white) (March 1988, 1989; March and Ferreri 1989, 1991; Ferreri and March 1996). The white zones cover a smaller surface area than the blue and brown zones, which gives rise to three groups of different diameters (Fig. 5b). Finally, in our experimental investigation, we observe the appearance of blackish zones resulting from the degradation of organic matter contained in the soil (between 250° and 450 °C), or the deposition of organic matter coming from the fuel. These two phenomena most commonly give rise to the formation of blackish zones, whose thickness and diameter vary according to the origin of the fuel, but which are also controlled by the parameters mentioned above. Most frequently, the blackish colouration is derived from the organic matter used as fuel (relationship between surface areas of charcoal-ash and blackish zones shows a

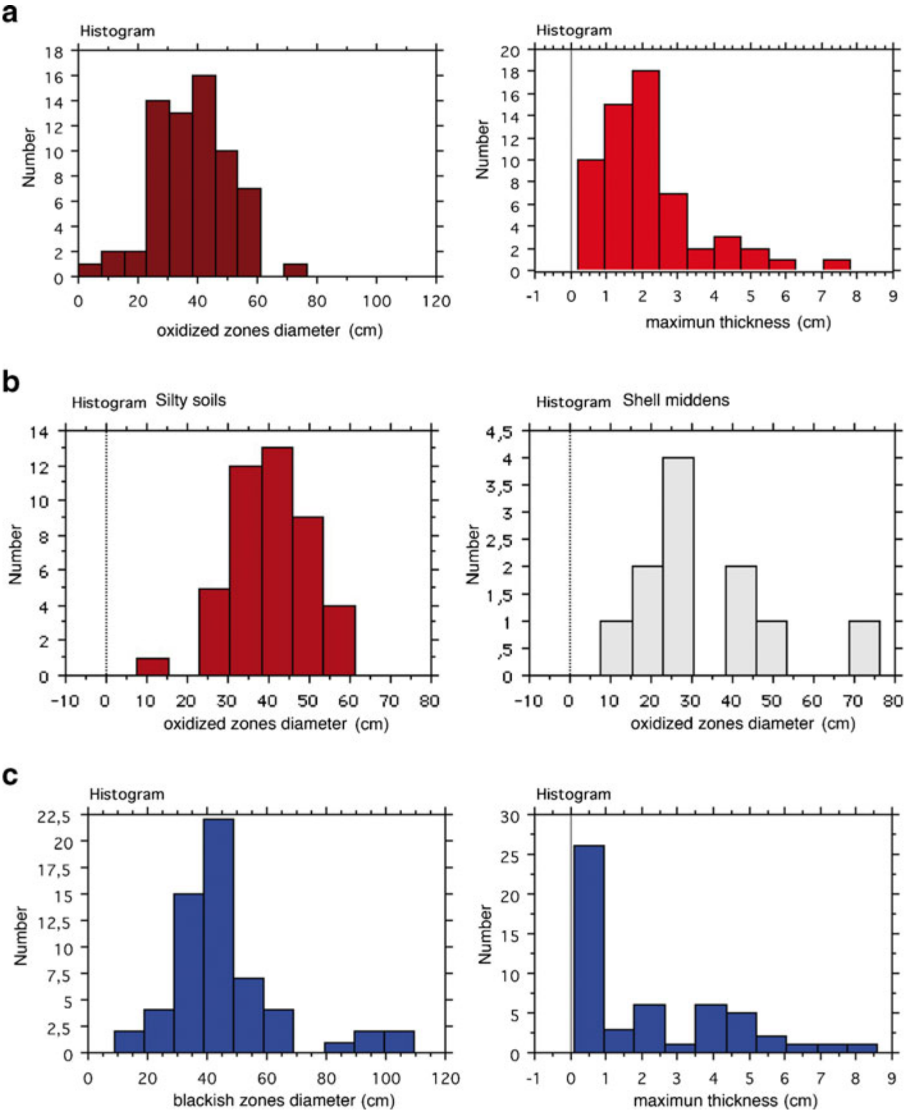


Fig. 5 Processes of hearth formation, and alteration of the underlying soil. **a** Diameters and thicknesses of oxidised zones on soils. **b** Diameters and thicknesses of oxidised zones on different kinds of soils: silts and shell middens. **c** Diameters and thicknesses of blackish zones of organic origin in different kinds of soils : silts, volcanic ashes, and humus

Table 3 Average temperature, in °C, of combustion phase (*TX*) for different hearth types

Descriptive statistics of TX by kind of structure	Total	Pit hearths	Small pit hearths	Simple hearths	Simple hearths (with draft)
Average	319.6	272.81	181	334.82	469
Standard deviation	111.9	91.25	41.01	111.71	60.81
Standard error	11.93	19.91	29	14.07	43
Number	88	21	2	63	2
Minimum	95	108	152	95	426
Maximum	538	413	210	538	512

correlation coefficient of 0.821). These blackish zones show a maximum diameter of between 30 and 50 cm, but can reach more than 100 cm according to the scattering of the charcoal layer and wood used. In the same way, their thickness is generally less than 1 cm. These zones rapidly disappear during re-use of the hearth, along with the appearance of ring shapes around a central greyish zone. The thicker blackish zones correspond to thermal alteration of the substrate; for example, humic soils, volcanic or aeolian silts are rich in organic matter, when the ground itself will be blackened under the action of heat (Fig. 5c). Finally, we should point out the existence of very localised blackish zones formed by indirect heating of the soil under the rocks, forming small isolated spots, which in all cases are smaller than the diameter of the rocks themselves.

In addition, realistic experiments allow us to identify several trends in the functioning mode, as revealed by analysing the average temperature attained by hearths during the combustion stage, denoted as "TX" (March 1992). This temperature not only varies according to the shape of the structure but is also a function of the ventilation conditions. Thus, TX is higher in simple hearths than in pit hearths, where the fire is more sheltered from the wind. In the same way, TX can be higher if a draft is introduced for drawing air into the centre of the hearth, while it can be lower at the bottom of a small pit (diameter 30 cm, depth 7 cm) compared to a larger pit (diameter 60 cm, depth 12 cm) for the same reasons (Table 3). This relationship between air circulation and temperature attained not only explains the different modes of functioning but also accounts for the technical capacities of all types of structure ranging from simple hearths to metallurgical ovens (Andrieux 1996).

The Fuel

A large array of firewood types were included in our realistic experimental corpus, the most commonly used species being *Nothofagus betuloides* and *Pinus sylvestris*, followed by *Betula verruscosa*, *Berberis buxifolia*, *Salix alba* and *Carpinus betulus* (Fig. 6). We also carried out experiments with other fuels, sometimes with mixed fuel (wood), or by mixing wood and bone.

The use of fuel leads to the formation of areas covered with ashes and charcoal, but these are often absent in archaeological contexts because of taphonomic processes. Nevertheless, it is interesting to have some idea of the dimensions of the surface areas involved. In the case of simple experimental hearths (in a realistic experimental

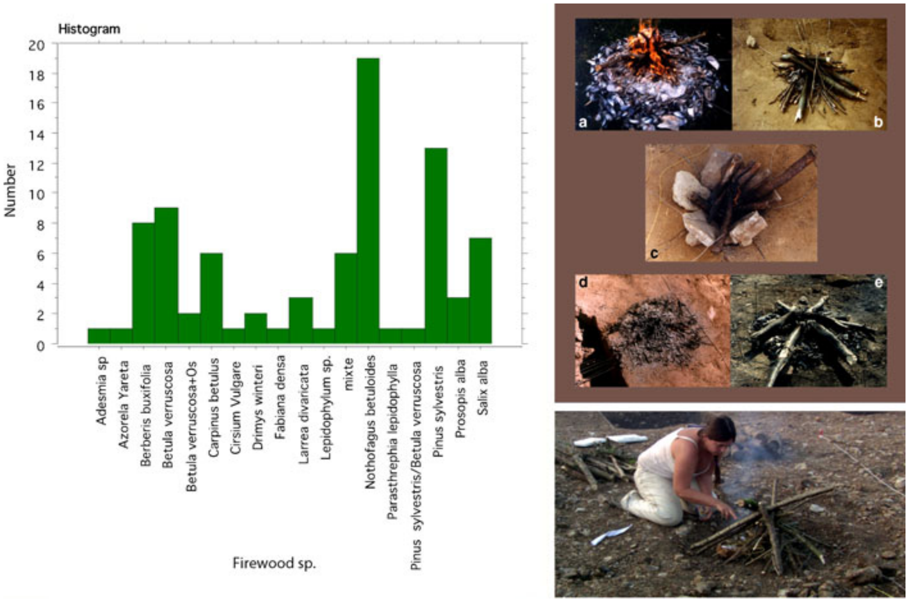


Fig. 6 Histogram of experiments according to fuel used; on the *right*, experiments with *Nothofagus betuloides* (**a**), *Carpinus betulus* (**b**), *Pinus sylvestris*, (**c**), *Larrea Divaricata*, (**d**), mixed *Betula verruscosa* and *Salix alba* and *Drimys winteri* (**e**)

context), the diameter of these surfaces can vary between 25 and 95 cm. Of 68 measured experiments, 40 have diameters ranging from 30 to 50 cm. Immediately after combustion, the ashes and charcoal make up a layer varying in thickness between 20 and 78 mm, most frequently lying between 20 and 30 mm. The thickest layers appear to be associated with pit hearths, but, in the case of simple hearths, they are linked to combustion incidents, for example, in experiments with natural dowsing (by rain) or deliberate interruptions for cooking (Fig. 7).

By plotting a histogram of charcoal weight recovered after the definitive cessation of combustion, we observe a very strong peak around a total weight of less than 500 g, with the best preservation associated with phenomena of incomplete combustion. Thus, in the majority of cases, the ashy and charred areas are no larger than 50 cm in diameter, and contain less than 500 g of charcoal (Fig. 7). In some exceptional experiments, we also observe a relationship between the degree of preservation of charcoal and other natural factors, such as the wind, which tend to disperse charcoal and ashes.

In economic terms, we note a considerable variation of wood consumption (TX), expressed in kg/h, even when considering the same technique of regular supply of fuel to the hearth. This consumption is calculated as a function of the time of burning in the hearth for each case (March 1992). Of 82 experiments (in realistic experimental contexts), where this variable was measured and where the skill of the craftsman did not influence the supply of wood, we note 64 experiments with a consumption ranging between 0.250 and 5 kg. In a context of strong winds and linked to obtaining high temperatures, certain experiments reached a wood consumption in the range of 12.5 to 22.5 kg. These experiments also showed that the average consumption TX is slightly higher in simple hearths (4.685 kg) than in pit hearths (3.642 kg). Pit hearths not only

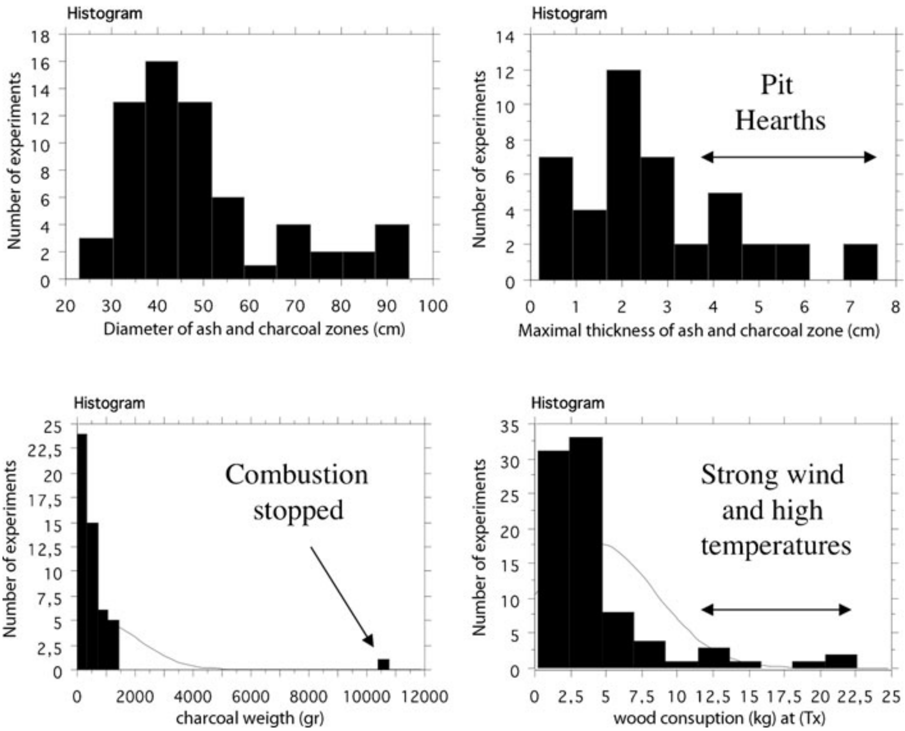


Fig. 7 Histograms of the diameter of areas covered by ashes and charcoal (cm), maximum thickness of carbonaceous layer (including ashes and charcoals) (cm), charcoal weight remaining after the experiment (g) and wood consumption TX (kg)

increase the thermal efficiency of the structure compared with simple hearths, since a larger surface-area is heated to the same temperature, but they also contribute to a saving in fuel. This difference is enhanced when the winds are stronger and in cases where simple hearths are slightly elevated from the ground surface. Although these variations can appear negligible, they are accentuated according to the duration of occupation and, in parallel, by the process of sedentarisation. However, this should be balanced against the fact that the larger the fire-pit, the greater the consumption of wood. This is because the users of the hearth tend to fill the pit and, as a result, this increases the amount of wood required for maintaining combustion over the same period of time. The reverse is also true, since small pits markedly restrict the fuel consumption in relation to their size. (Fig. 8).

descriptive statistics of Consumption TX (Kg) by kind of structure	Total	pit hearths	small pit hearths	simple (flat) hearths	simple hearths (with draft)
Average	4,295	3,642	1,29	4,685	2,643
Standard deviation	4,181	2,528	0,552	4,694	1,752
Standard erreur	0,456	0,552	0,39	0,611	1,239
Number of experiments	84	21	2	59	2
Minimum	0,25	1,44	0,9	0,25	1,404
Maximum	22,565	12,734	1,68	22,565	3,882
# Missing	7	0	0	6	0

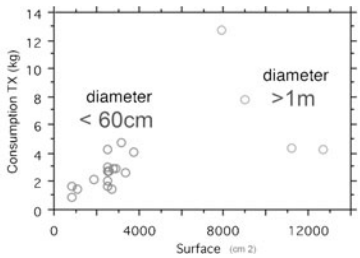


Fig. 8 Consumption TX of wood (kg) according to hearth type, with graph of consumption TX *versus* surface area of the pit hearth central depression

From Experimental to Modelling Approach

Theoretical Modelling based on Experimental Data

Our experimental study, involving both laboratory and realistic experiments, highlights the difficulty of recreating the multiple conditions that existed in the past in relation to the shapes and functioning of fire structures. Despite this drawback, we can establish models (sensu Popper) for the diffusion of heat in hearths and the various patterns of alteration induced by the shape of the fire structure. Indeed, the distribution of heat leaves traces on the environment of the hearth and its components, which change according to the shape of the hearth and nature of its components. An analysis of the distribution of thermal alteration thus allows us to infer the nature of the original hearths and their mode of functioning.

For example, hearths (March 1999) are often superimposed on for instance shell middens, in which case it is important to assess the probability of identifying the fire structure in order to predict the eventual impact of re-using the same area through the course of time. In addition, we model the thermal behaviour of fire structures in the case of simple hearths built on top of shell middens (Fig. 9). In Fig. 9, we can see

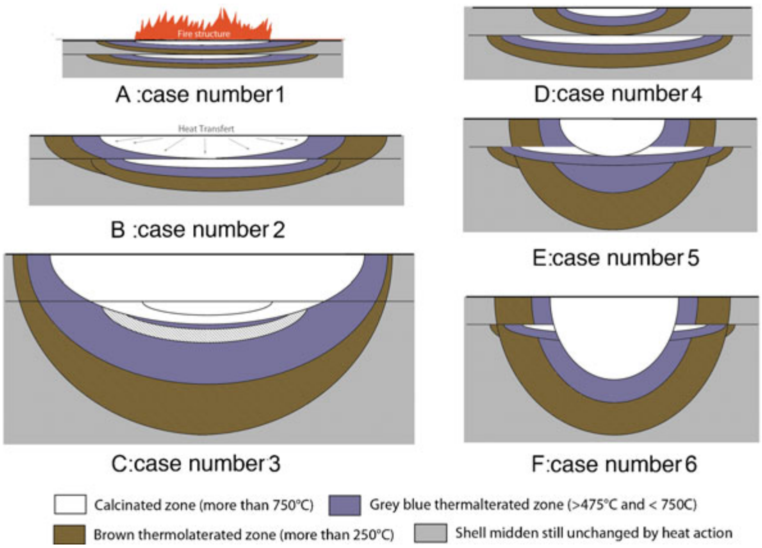


Fig. 9 Various examples of re-use of simple hearths built on shell middens, with the upper hearths always being used later. The colour coding corresponds to the three observed alteration zones according to temperature, indicated here in *white* (white-coloured zone between >750°C) *grey-blue* (grey-blue coloured zone >475 and <750 °C) and *brown* (brown-coloured zone >280 and <475 °C). **a** For hearths having a similar surface area, two different coloured zones come into contact, which were therefore produced at different temperatures. **b** Two zones of the same colour (*white*) come into contact, with the upper hearth having a larger surface-area and extending up to the boundary between two zones of the same colour. **c** The later hearth covers a larger area and was used over a considerable duration, thus masking the earlier hearth. Most frequently, the earlier hearth disappears when it does not contain a layer of ashes and charcoal on its surface. The estimated duration of use only applies to the upper hearth. **d** The later hearth covers a smaller area than the underlying hearth, with different coloured zones coming into contact. **e** The upper hearth covers a smaller area, with two similar coloured zones coming into contact; nevertheless, the outline of the underlying surface can still be picked out, which allows us to distinguish it from the first episode. **f** The later hearth still covers a smaller area, but has a longer duration of use; the *whitish zone* overlaps and extends beyond the previous whitish zone, but always remains distinguishable because of its size

different examples of superposition of simple hearths built on a shell midden surface as a function of their surface-area and their hypothetical duration of burning. Case A shows the contact of two different coloration zones caused by two simple hearths of equal size. Case B presents the contact of two areas of the same colour. Here, the action of the upper hearth, which occupies a larger area, extends right up to the contact with the calcined area of the lower hearth. In case C, the upper hearth has a larger area and extends over a considerable length, thus masking the underlying hearth. The previous hearth disappears if no area of ash and coals are present. If this lower layer persists, however, we can see that the fire came from an upper layer and the mode of functioning and the calculated burning time will therefore correspond only to the last episode. In case D, the surface area occupied by the upper fire structure is less than the underlying structure, while the time of burning is the same. Here, we find areas heated at different temperatures, which display differently coloured zones in contact. Case E represents a newer fire structure having a smaller surface area but burning for longer, with the two calcined areas coming into contact. Finally, case F corresponds to a similar situation as observed in case E, but the last fire structure continues burning for longer and extends beyond the earlier structure; nevertheless, despite the two episodes, the earlier structure can still be clearly distinguished.

In the same way, we can make use of experimental observations to establish heat transfer and alteration models that can be applied to the various types of hearth (Fig. 10). Figure 10 illustrates the different kinds of heat transfer trend observed in our experiments. The red zones indicate the transfer (arrows) and intensity of heat in different kinds of fire structure, and the effect of this heat transfer on the soils and stones making up the fire structure. As we can see, beyond their material composition and state, soils and stones are altered in different ways according to the shape of the structure, the position and form of the stones, which conditions the position of the heat centre. For example, the fire in a pit hearth tends to be elevated, leading to the accumulation of ashes, charcoals and unburnt wood in the pit, thus producing alteration of the uppers parts of the pit, which are less affected when the pit is less filled. Following the same principles of heat transfer, flagstones are partially thermally altered , but in a different way, if they form the rim of the pit structure or are positioned under the fire in a horizontal position. At the same time, the walls of the pit are thermally altered in different ways depending on the presence or absence of a ring, since the

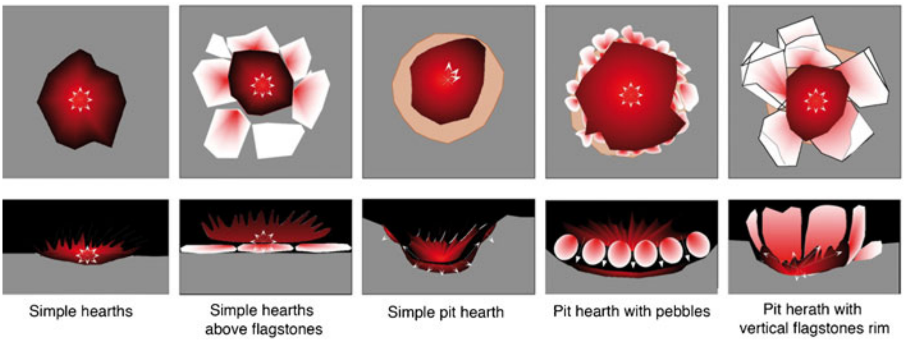


Fig. 10 Modelling the effect of heat transfer on the components of different types of hearth

flagstones create an insulating material between the charcoal, ashes and soil. By the same token, stone pebbles undergo different types of alteration according to whether they are below the fire or form the ring of a pit hearth. Even the re-use of stones and soil can sometimes mask their original position, and this observation helps us understand the mode of functioning of fire structures when studying in detail the thermal alteration of soils and stones (March and Soler 1999; March *et al.* 2003a, 2010).

While working with realistic experimental contexts provides clues to understanding the past reality of each studied structure, the enlargement of our experimental database forces us to change our interpretative hypothesis when we discover that two different forms or positions can lead to the same effect. Moreover, by exploring our experimental results, we discover that these different kinds of thermal alteration can be mathematically predicted, thus changing our hypothetical models into real simulations.

Mathematical Modelling of Hearth Activity

From our realistic experimental work, we note that substrates are increasingly degraded during prolonged combustion at constant or increasing temperature. In this way, an estimate of the minimal time of burning can thus be derived from an analysis of the substrate soils or other burnt materials (March and Ferreri 1989, 1991; March *et al.* 1991, 1993, 2010; Ferreri and March 1996; Muhieddine *et al.* 2011). However, a problem is posed by the variability of the environments that are likely to be degraded, while, in the same way, the behaviour of the hearth can vary throughout its functioning life. This implies the need to carry out innumerable experiments to understand the behaviour of these multiple scenarios. In our opinion, the only solution is to develop a mathematical approach to study the different possible behaviours, while at the same time continuing the field experiments on hearths. This approach enables us to vary the parameters mathematically, and hence determine the influence of each parameter. Thus, the experimentation plays a different role, which involves validation of the developed codes. In this study, we develop the modelling of thermal behaviour, initially with regard to the soils (shell middens, clayey loams and different types of silty soil), and then addressing the shapes of the hearths as well as the consumption and behaviour of the fuel.

For example, in the case of simple (or flat) hearths, we mathematically model the thermal behaviour of the soils to determine the distribution of temperatures that should be attained in each substrate, and thus predict the alteration to be expected according to each soil type and thermal history (March and Ferreri 1989, 1991; March *et al.* 1991, 1993, 2010; Muhieddine *et al.* 2011). For this purpose, we developed a program to simulate the thermal behaviour of the experimental hearths produced in our study. Figure 11 presents the results of modelling the thermal behaviour of a simple hearth by two-dimensional digital simulation. In this example, we can compare the values attained in experiments with the results of digital modelling to study silty soils under the action of heat in simple hearths.

Apart from the fact that we obtain an extremely faithful reproduction of the studied phenomena, the example referring to wet soil shows the appearance of a step at 100 ° C in the presence of water. The soil moisture content is one of the variables that plays a role in the alteration of the substrate, since it is a major factor influencing heat transfer.

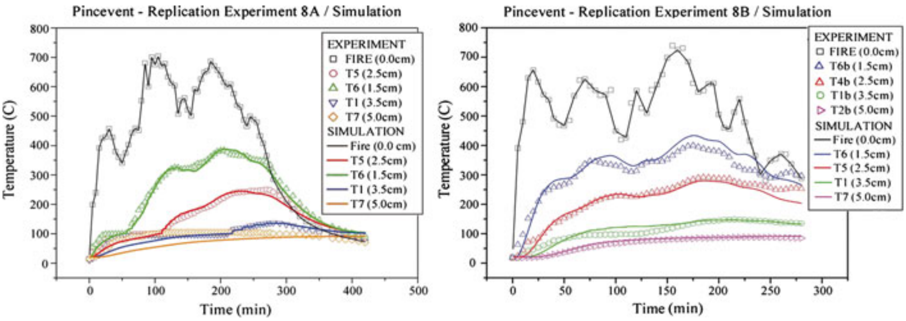


Fig. 11 Validation of mathematical modelling using a bidimensional code for the behaviour of clayey soils at Pincevent. Thermal behaviour of a hearth built on wet soil (*left*), and another hearth at exactly the same place and over the same soil, which is dry in this case (*right*). The *curves with symbols* represent the experimental values for wet and dry soils, while the other *curves* are obtained mathematically. *Black curve* indicates real temperature profile measured under the charcoals, and the other *curves* show soil temperatures along the central axis under the fire at different depths in the soil

By following this modelling strategy, we can study the impact of soil moisture separately by a parametric study. Figure 12 shows the thermal behaviour of a clayey soil and a sandy soil according to its initial moisture content, with the hearth functioning at a constant temperature of 600 °C for 5 h. The penetration of heat is slower when the soils are wet, considering that, for these two types of soil, the onset of perceptible alteration by oxidation is observed at 300 °C: hearths lit on wet soils will not leave visible traces on the ground following such a short time of burning. Since oxidation will only appear after a longer interval of time, we may conclude that, assuming the original soils were wet, the burning time of prehistoric hearths inferred from this alteration would have been necessarily longer. This leads us to grasp the importance of this factor (humidity) for correctly estimating the time of burning of archaeological structures (March *et al.* 2010; Muhieddine *et al.* 2011), which allows us to compare the inferred time of burning with the minimal time of burning.

Heat transfer between a body and a heating source may occur by heat conduction, radiation of heat or both. Depending on ambient temperature and boundary conditions one regime may prevail over the other. It may be asserted that thermal radiation does not have a major impact on the alteration of the substrates of simple hearths. On the other hand, radiated heat strongly influences the alteration of the walls of pit hearths. Therefore, we developed a computer code that takes this phenomenon into account, allowing us to reproduce the thermal behaviour of pit hearths in a more realistic way. Figure 13 shows the distribution of temperatures for a pit 44 cm in diameter and 25 cm deep, dug in a loamy soil, where the hearth structure reached temperatures of 270 or 350 °C during 3 h of burning. Alteration of the soil is only recorded when the temperatures reach 350 °C, while the depth of the alteration does not exceed a thickness of 1 cm, either at the base or on the walls.

Another issue is of interest here: we need to infer the time taken for the cooling of hearths, since this parameter is involved in calculating the time of burning as well as the heat output of the fuel, given that hearths continue to release heat once combustion has ceased. By analysing this phenomenon under similar climatic conditions, since the wind and rain have a considerable influence on cooling, we can consider that the cooling

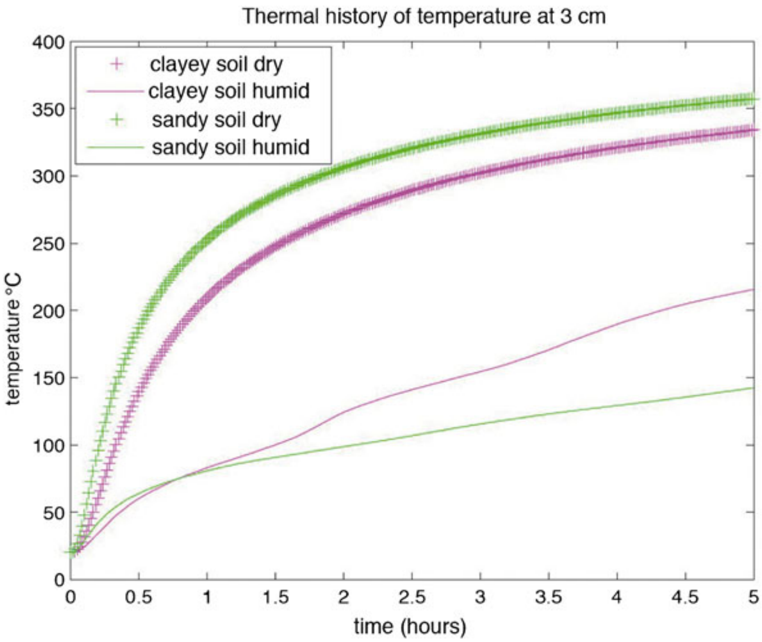


Fig. 12 Thermal behaviour of clayey and sandy soils subjected to a constant temperature of 600 °C at 3 cm depth

time obeys Newton's law of cooling, which states that the rate of change of the temperature of an object is proportional to the difference between its own temperature and the ambient temperature (i.e. the temperature of its surroundings). Therefore, without taking into account the type of soil, the fuel used or the temperature attained by the hearth, we can apply this law to obtain the cooling time (Fig. 14).

But modelling can be applied to other criteria apart from those presented above. Thus, we set out to use our experimental data derived from realistic experimental

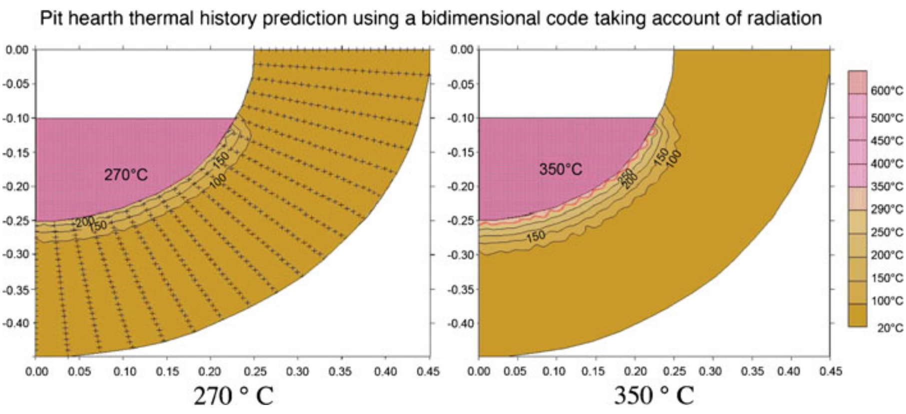


Fig. 13 Results of the predictive analysis of thermal degradation in a pit hearth according to its functioning temperature (270 and 350 °C), based on a bidimensional code taking account of heat radiation. The *brown zone* represents the soil of the pit hearth and the *red zone* the position of the heat source (fire). The distribution of colour zones is in accord with temperatures

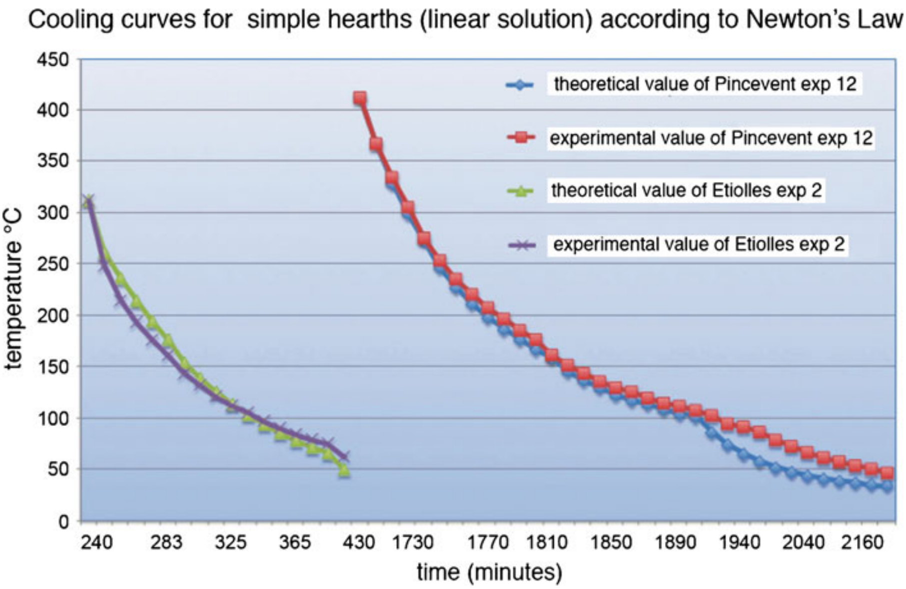


Fig. 14 Cooling curves from temperatures measured under the fire and above the soil for two experimental simple hearths (experiment performed at Pincevent and Etiolles Magdalenian sites in France) and linear solution of this curve according to Newton's Law

contexts to obtain information concerning fuel consumption (March 1992). With this approach, we can also use woodland pine to establish the average wood consumption for our experimental corpus. As already mentioned, consumption fluctuates on the short term between simple hearths and pit hearths, being higher for the former than for the latter. We wanted to find out if this relation remained constant with time, as well as assess its significance in terms of consumed mass in the case of hearths having a longer burning time.

We thus carried out a series of experiments of long duration to observe whether consumption is constant over time. Then, we took the average consumption per hour observed for the two types of hearths in our experiments, and applied a linear extrapolation of this consumption up to 24 h of continuous activity of the hearth. By comparing with our experimental data, we note that, while measured consumption approaches the theoretical calculations, pit hearths yield results that are even closer than those obtained from simple hearths (Fig. 15).

These results not only show that consumption per hour is slightly higher when the activity of the hearths is prolonged but also that pits hearths are maintained for longer than simple hearths. Over the tested durations, the saving in fuel for the pit hearths can be estimated at nearly 40 kg. This difference in consumption, which may appear rather small in the short term, reaches significant proportions after 10 days of use. Thus, in the case of the species *Nothofagus betuloides*, we observe a significant difference in terms of impact on the forest environment (Fig. 16) over 90 days of continuous use. Such a level of consumption is equivalent to more than 6 tonnes in a season. It appears that, since the groups of hunter-gatherers prolonged the duration of their stay at the same locality, they were able to grasp the differences arising from the use of these two types of hearths

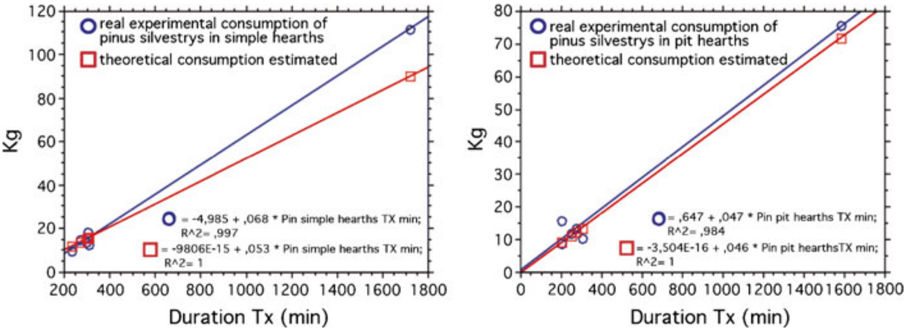


Fig. 15 Consumption of *Pinus sylvestris* wood in the case of simple and pit hearths (observed experimental consumption shown in *blue*; theoretical consumption estimated from these experimental data shown in *red*)

The same type of analysis of consumption can be carried out according to the wood species used. Thus, if we consider a set of five different species, *Berberis ilicifolia*, *Carpinus betulus*–*Nothofagus betuloides*–*Pinus sylvestris* and *Salix alba*, we observe that the difference in consumption between each species for the same type of hearth (simple) can only really be judged by a long-term use. *Nothofagus betuloides* and *Berberis ilicifolia* are less economic to use than the other species in our suite, while, among the remaining more economic wood fuels, willow is slightly more economic than pine and hornbeam (Fig. 16).

This analysis can be interpreted in another way, which leads to an interesting result: wood consumption appears to be clearly a function of the geographical localisation of the experiments. The highest consumption is observed in the procurement of firewood for simple hearths in windy areas of the Beagle Channel in Tierra del Fuego, where wind speeds are regularly much higher than in the Paris Basin. Moreover, most of the simple hearths are built on top of shell middens, and are slightly elevated compared to the ground surface. Hence, the shape of the hearth continues to play an important role, along with the presence or absence of wind, since improving the circulation of air has a major effect on consumption.

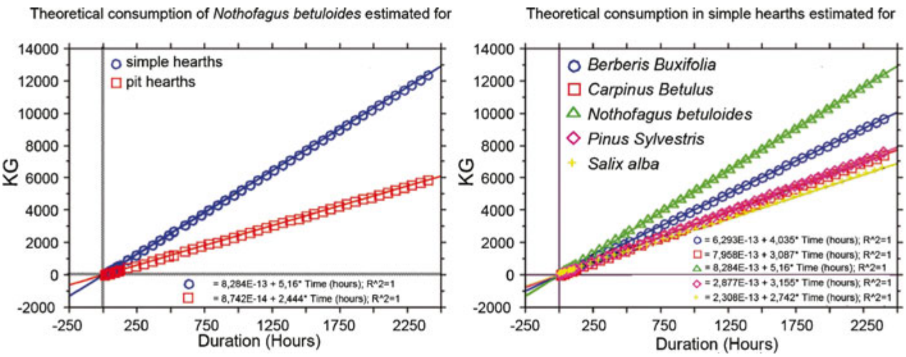


Fig. 16 *Left* consumption of *Nothofagus betuloides* wood in the case of simple and pit hearths (observed experimental consumption shown in *blue*; theoretical consumption estimated from these experimental data shown in *red*). *Right* theoretical consumption of various wood species in simple hearths

Alteration of Organic Matter

In the course of our research, we carried out a study of the processes of formation and deposition of organic matter during the use of the hearths. In this section, we only present the results concerning the lipidic fraction. During burning in the hearth, the organic matter present in the soil is altered by the effect of heat according to a process known as thermal alteration. This alteration modifies the natural chemical signature of the sediments and provides us with the possibility of identifying the organic matter resulting from anthropic inputs due to the construction and use of the hearths.

For example, by heating original soil for one hour at various temperatures, corresponding to steps of 100 °C between 0 and 600 °C, we observe a progressive loss of molecular species as a function of temperature (laboratory experimental context). The relative proportion of alkanes and fatty acids decreases very rapidly, starting from 100–200 °C. At this temperature, we observe a loss of the poly- and mono-unsaturated fatty acids, whereas the $C_{18:1}$ acids remain at trace levels. At temperatures around 300–400 °C, we observe the disappearance of other molecules such as alcohols, sterols, ketones, alkenes, diacids, etc.. At the same time, some changes occur in the relationship between the various molecules within the same group. Thus, we observe a reduction in the $C_{16:0}/C_{18:0}$ ratio starting from 100 °C (Fig. 17).

We can also notice a progressive smoothing out of the alkane distribution pattern, resulting in—among other things—a very marked reduction in the proportions of odd chain-length alkanes. Around 600 °C, we observe a disappearance of short-chain alkanes $<C_{19}$. (Fig. 18)

Beyond 600 °C, the soils only contain some almost imperceptible traces of organic matter.

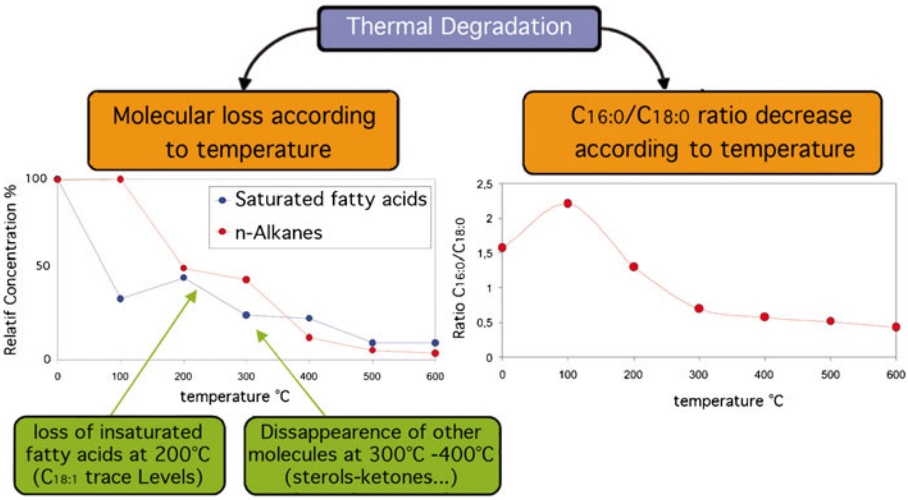


Fig. 17 Degradation of natural organic matter in sediments under the effect of heat, showing mass weight percent loss and modification of the $C_{16:0}/C_{18:0}$ (µg/g) ratio

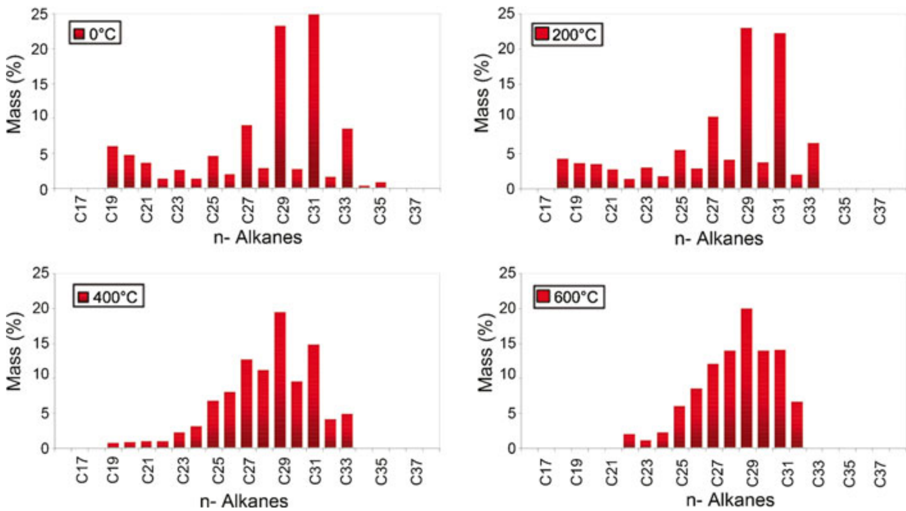


Fig. 18 Progressive smoothing of the distribution pattern of n-alkanes present in natural sediments under the effect of heat, expressed in mass percentage

Anthropic Inputs

Large quantities of organic matter derived from anthropic inputs are superimposed on the signature of thermally degraded soils, which are initially characterised by low concentrations and modified distributions of organic matter.

The first inputs usually come from the fuels. The organic matter associated with the residual material exhibits a strong alteration due to the process of combustion, in a similar way to that observed in the sediment (laboratory and realistic experimental contexts). This organic matter is characterised by the presence of charcoal, and has a lipidic composition showing predominant short-chain fatty acids, changing progressively to a bimodal and finally smoothed alkane distribution pattern (short- and long-chain), as well as a partial or total alteration of sterols and other molecules such as polycyclic aromatic hydrocarbons. Wood ashes give rise to strong concentrations of calcite in the hearth, and this residual material can still contain lipids. However, these ashes generally contain only alkanes, whose smoothed distribution pattern is dominated in this case by short-chain molecules. Moreover, pyrogenic policyclic aromatic hydrocarbons can be found into fire structures (Lozano *et al.* 1995), and we should note that wood smoke forms a deposit of organic matter on the rocks and walls of the pit hearths, as well as on the soil underlying the charcoal. This more or less volatile residual organic matter has a composition similar to that of charcoals (Fine *et al.* 2001, 2002; Simoneit 2002). However, it is not rare to observe charcoal residues after incomplete combustion that still preserves a readable vegetal signature. Bone fuel waste displays different characteristics, in particular, the absence of long-chain alkanes and very poor cholesterol preservation in cases of partial or incomplete thermal alteration, a ssociated with higher levels of phosphates (Joly 2008).

Then, when dealing with food cooking, whether in laboratory or realistic experimental contexts, this chemical composition is supplemented by the presence of culinary residues. The amount of this input is very large and can sometimes completely mask the signatures of fuels. During cooking, organic molecules appear within the lipidic fraction that are characteristic of the composition of the cooked animals and plants. Still others are formed during the culinary processes, including short-chain dicarboxylic acids, polycyclic aromatic hydrocarbons, the short 2-alcanones (2-K_{17}) or long 16-alcanones (14-K_{29}, 16-K_{31}, 16-K_{33}, 18-K_{35}), the γ-lactones, or certain short alkanes whose abundance can increase notably, as in the case of C_{17} (Lucquin 2007; Malainey *et al.* 1999; Buonassera 2005; March 1999; March and Soler 1999; March *et al.* 1989, 2003a, b, 2006; March and Lucquin 2007, 2012). These lipids are accompanied by various proteins primarily derived from meat and bone.

These substances are deposited on ashes and charcoal during combustion, as well as on the soils around the fuel residues and, finally, on cooking supports such as heated rocks (March and Soler 1999; Dumarçay *et al.* 2008). These latter sometimes remain inside the hearths and can even form part of the rims of the structures (March and Lucquin 2007). Thus, the original organic matter contained in the soil is replaced within the fire structure by substances coming from the hearths.

Post-Depositional Processes

A fire structure can be affected by a vast range of post-depositional processes, so we cannot claim by any means to treat all of them here. Such processes are of both anthropic and natural origin. Without going into further detail, we can accept that, in any archaeological context, some structures may be preserved after a single use, so any action of clearing out or reworking can be regarded as a post-depositional process following the cessation of the initial utilisation. Such actions are evidently extremely numerous during the functioning history of a hearth, with some occurring after a more or less long period of abandonment that is impossible to determine. Sweeping out of the hearth, for example, could be considered by some authors as a post-depositional process. However, according to Leroi-Gourhan and Brezillon (1972) or Leroi-Gourhan (1973), it also corresponds to a process—albeit of different type—associated with the formation of fire structures. In addition, we need to consider the innumerable situations related to natural phenomena that occur once the sites are abandoned. Then, we can affirm that archaeological context is dynamic as was proposed by Bate (1992). The following section does not attempt to provide more than a preliminary contribution to the study of these processes, representing to some extent a kind of summary of their complex nature.

Input and Alteration of Organic Matter

The data derived from realistic experimental contexts show that the inputs of organic matter from natural sources are of varied nature. For example, the sedimentary covering or filling is a function of the shape of the hearth (flat or pit). If the climatic conditions do not change appreciably, the sediments that cover or fill a hearth in most cases are similar to those surrounding the structures. All these different inputs have a similar chemical composition characterised by organic materials that are not thermally degraded, along with strong concentrations of unsaturated acids and a weak maturity of alkanes.

This sedimentary filling is followed by the growth of vegetation which, as discussed below, can develop at different rates according to the ecological context. This vegetation, which is characterised initially by the appearance of lichens, mosses, grass and roots of plants, is accompanied by a strong concentration of organic matter, which at the same time partly contributes to the organic matter deposited in the hearths. The organic matter has a chemical composition characterised by a vegetal-like profile and very good preservation, leading to the accumulation of polyunsaturated molecules in the soil, associated with a marked prevalence of odd-chain alkanes as well as many biomarkers of vegetal origin (sterols or ketones). However, this phenomenon is generally very localised within the layer of sediment covering the structure and, moreover, it only has a weak impact on the contents of the hearths which tend to be preserved. Once the hearth is filled or covered, the organic matter begins its process of degradation, which gives rise to a modification of the anthropogenic organic matter deposited in the hearth. This process of maturation leads gradually, by various mechanisms, to the disappearance of the unsaturated acids and alkenes, the maturation of the fatty acids and alkanes, as well as the formation of oxo- and hydroxy acids, dicarboxylic acids, branched-chain acids, alkanes and methyl ketones as shows many different studies realised in archaeological and in both kinds of experimental context by us and other colleagues (March *et al.* 1989; Evershed *et al.* 1992; Regert *et al.* 1998; Malainey *et al.* 1999; March 1999; Lalman 2000; Soltani 2004; Lucquin 2007; Heron *et al.* 2010).

However, as described more fully below, these phenomena are dependent on the burial environment. Accordingly, degradation by oxidation of the unsaturated acids in an aerobic medium leads to the formation of peroxide and other secondary derivatives, while bacterial degradation in an anaerobic medium brings about modifications of the profiles of saturated fatty acid. Although the process of degradation is complex, it can be summarised in terms of reactions involving β-oxidation and dehydrogenation. However, certain reactions will favour degradation more than others (Fig. 19). Indeed, some encourage the development of microorganisms: the production of palmitic acid from linoleic and oleic acid is energetically favourable, whereas stearic acid is not, unless there are changes in the pressure or pH conditions. In the same way, stearic acid, formed during the degradation of linoleic and oleic acids by dehydrogenation, does not appear to be an intermediate breakdown product. Moreover, during the degradation of stearic acid, no other saturated acids are formed as derived products. In the same way, while palmitic acid is a preferential derived product, myristic acid does not appear to exceed a certain maximum concentration, even when the concentration of palmitic acid decreases (Fig. 19) (Lalman 2000; Lalman and Bagley 2000, 2001; Lucquin 2007).

More generally, from experimental work carried out in Tierra del Fuego on the north coast of the Beagle Channel at the Tunel 1 site (54°49′13.75″S, 68°9′3.94″W) in Argentina—a hunter-gatherer type site with maritime adaptation dated between 6,980±110 BP and 450±60 BP—we find that the cold temperature of the soil at shallow depth during a large part of the year allows the preservation of certain molecules such as the mono- and poly-unsaturated acids, ketones, sterols and alcohols. These compounds are present in very high concentrations in the hearths because of the consumption of marine mammals and the use of grease for the production of pigments (March *et al.* 1991; March 1999) (Fig. 20). This good preservation of certain

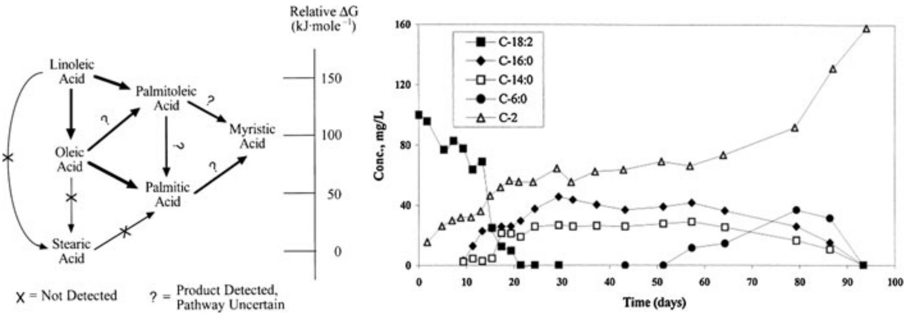


Fig. 19 *Left* anaerobic bacterial degradation of type-C_{18} fatty acids (Lalman and Bagley 2001); *right* degradation of linoleic acid (initial concentration of 100 mg l^{-1}) and derivative products (Lalman and Bagley 2000)

molecules, including the di- and tri-unsaturated fatty acids, sterols and alcohols, is also observed in very arid contexts in highland areas such as the puna of Jujuy province in Argentina, corresponding to the Late Holocene deposits of Tomayoc (23°12′30.27″S, 65°42′21.97″W) (Lavalle *et al.* 1997; March 1995a, b) a high-altitude shelter site (Sierra Aguilar at 4,170 m) related to pastoralism, which is dated at between 1,020±50 and 750±50 BP. Similar effects are observed in rocks used in hearth experiments for the indirect cooking of cattle, which even persist 1 year after their use. Lastly, some of these molecules, such as cholesterol, have been found in stones used for the cooking of food at level IV-0 of the Magdalenian site of Pincevent (48°22′5.41″N, 2°53′35.55″E) (Paris Basin, Montereau, Seine et Marne, France) , which is situated in a Tardiglacial context (ca. 14,000 years BP) (March *et al.* 2006).

Contamination can significantly affect the signatures of hearths. The most frequent phenomena involves the contamination of pit hearth fillings, whereby the pit is filled with sediments that cover the different sites owing to different geomorphological processes. Such cases have been observed in pit fire structures containing stones and occurring at different sites in France, such as the Neolithic sites of Z.A.C de Montauban at Carnac (Hinguant *et al.* 2010) and Gaillon La Garenne (late final Neolithic) Eure (TL 2,500 BC; 49°9′38.12″N, 1°22′8.35″E) (Prost *et al.* 2010, 2011).

Other examples, associated with the increasingly frequent use of fertilizers on agricultural soils, which are moreover mechanically reworked, can degrade the chemical signature of the sediments, affecting sites of various different ages, such as recorded at the Bronze Age site of Les Hauts de Feuilly (45°42′33.27″N, 4°56′ 21.99″E) (Lyon) (March and Lucquin 2012). In the same way, the presence of rodents in caves or open-air sites can lead to the contamination of certain structures by faeces-derived sterols or other substances (March *et al.* 2008). This latter process is still difficult to differentiate from the possible use of animal faecal matter as fuel (March *et al.* 2008; Sisitiaga *et al.* 2011; March 2012), considering the rarity of studies on understanding faecal deposition processes in archaeological contexts. Estuarine waters can also contaminate the composition of certain archaeological layers, as observed by our team working at the You–Hsian-Fan site in Taiwan (23° 0′ 21.23″ N, 120° 10′ 55.28″ E) (Yang 2002; Yang and March 2008). Thus, we consider the criteria chosen by Behrensmeyer *et al.* (1992) as a relevant framework for studying

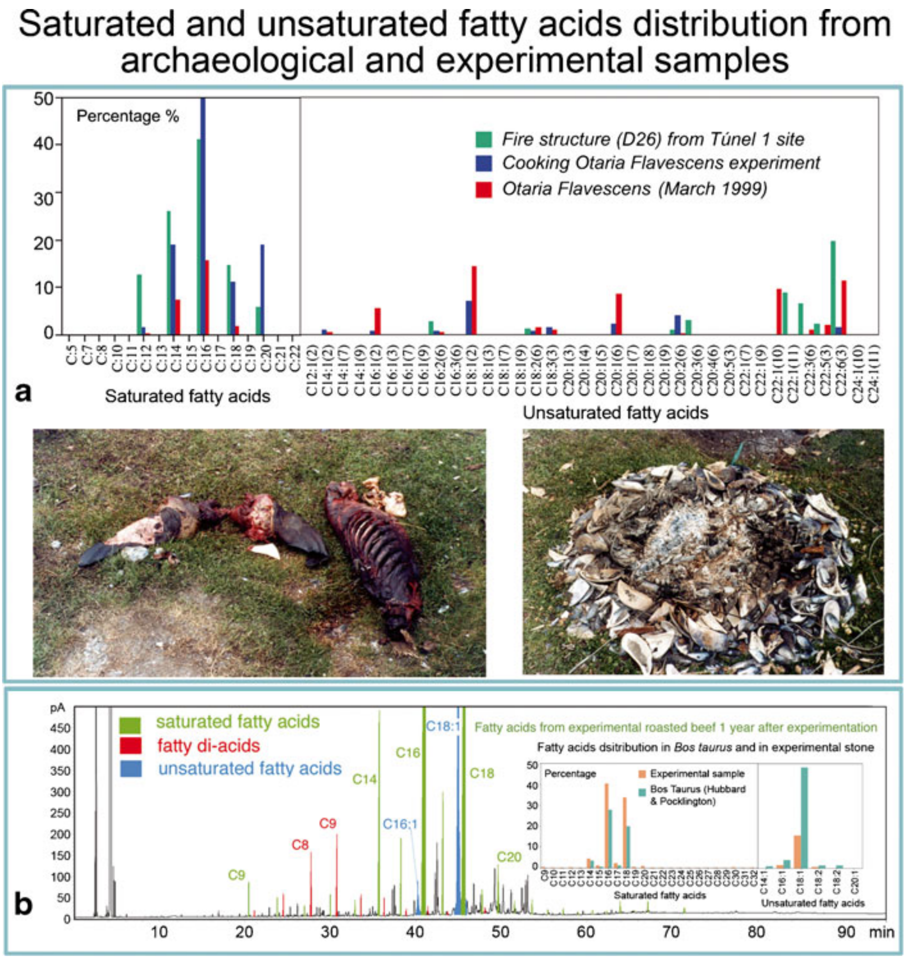


Fig. 20 Differential degradation depending on the burial setting as well as the climatic and environmental conditions. **a** Results of experiment with *Otaria flavescens* cooked on a shell midden (photos: *Otaria flavescences* before cooking and shell midden after cooking). **b** *Red*, fatty acid composition of animal meat and crude fat; *blue*, fatty acid composition of experimental fire structure after cooking (sample was taken in ashes); *green*, example of archaeological ashes from D26 episode 6 structure found at Tunel 1 site on the north coast of the Beagle Channel (March 1999). *Bottom histogram* shows results from experimental cooking of beef roasted on stones, saturated fatty acid composition of *Bos taurus* crude fat and cooked on stones, with GC-MS (gas chromatography–mass spectrometry) distribution pattern and conservation of total fatty acids after 1 year of open-air taphonomic experiment

post-depositional processes. Following on from this approach, we present here the results of our investigation of post-depositional processes in hearths.

Alteration of Fire Structures

During the course of research over the last 20 years, we carried out various experiments to study taphonomic processes on variable time scales and in very contrasted natural contexts. The observational protocol has changed over time, reflecting the evolution of our approach to addressing problems related to hearths. We present here an outline of this work, starting from two types of observations: first of all, natural phenomena observed in various geographical contexts; then, in a similar context, phenomena due to the joint action of anthropic and natural factors. The aim of this exercise is to show the diversity of problems and the difficulties encountered in following this approach.

Natural Phenomena Observed in Humid Sub-Antarctic Zones (Argentinian Tierra del Fuego)

Phenomena observed in the humid sub-antarctic zones of Tierra del Fuego in Argentina were studied by means of controlled experiments carried out on unoccupied soils of the town of Ushuaia (54°49′19.91″S, 68°19′24.15″W) and on the northern shore of the Beagle Channel, at or near the Túnel 1 site (54°49′13.75″S, 68°9′3.94″W) between 1983 and 1989.[1] Over this period, we carried out a large number of experiments on hearths: at the outset, the idea was to leave the hearths to evolve over time, making regular observations year over year, given that, at these high latitudes, it was impossible to carry out regular monitoring during the same year. Our observations were numerous and concerned several types of structure, including simple hearths on shell middens of varying heights (10, 20 and 30 cm), as well as flat hearths not only built on volcanic silty soils but also on the current vegetation cover called locally "champa".

To start with, the experiments allowed us to observe fire structures in the form of simple hearths on shell middens. First of all, regarding the hearth itself, we note a dispersion of ashes and charcoal due to the action of the wind (Fig. 21b), which is more marked when the hearths are elevated. Dispersion is sometimes very wide, reaching a distance of 2–3 m around the structures. Another interesting phenomenon occurs in the shell middens, which show a downward movement and sorting of fine-grained ashes and charcoal within the shelly material. Immediately after their formation, these shelly deposits are very porous structures containing more than 60 % voids. This porosity is due to the concave shape of the shells and the way in which they come into contact with each other. Even after compacting the shell deposits by trampling for prolonged periods, their porosity only falls to 20 %. Thus, ashes and charcoal of grain size less than 1 cm settle downward in the midden as the calcined upper layers are dispersed by the wind. Only the white calcined shells, transformed into small fragments of lime, are winnowed out by the action of the wind. As a result, certain large pieces of charcoal originally located in a calcined layer during the experiment are found later in a zone of less altered shells of bluish colour (Fig. 21g and h).

In the same way, the upper part of the bluish thermally degraded layer becomes filled with small whitish shells that eventually form a cement. This phenomenon is not observed in the lower layers, because the shells there are altered at lower temperature and are less weakened than shells whose carbonates are transformed into calcium oxide. The calcium oxide reacts with water to form calcium hydroxide, under the influence of the very abundant rain and melted snow in the area, which also

[1] Placed at our disposal by CONICET in the town of Ushuaia and on the northern shore of the Beagle Channel near the Túnel 1 site, in the framework of programmes developed at that time by the Asociacion de Investigaciones Antropológicas under the direction of L.A. Orquera and E.L. Piana. A DVD presenting this work, produced by CNRS-Audiovisuel, is available to readers on request.

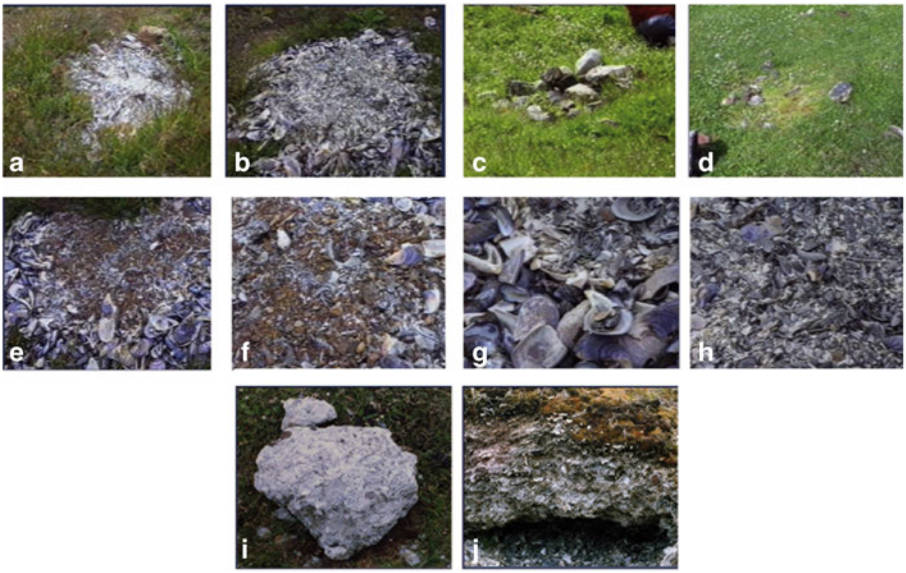


Fig. 21 Hearth experiments carried out in Tierra del Fuego (**a**–**h**), on an archaeological hearth (**j**) and archaeological fragments of "coquina" (**i**). **a**, **b** show fire structures on shell middens, as follows. **a** An example of a 10-cm-thick shell midden where the white zone of thermally altered shells was conserved for more than 2 years, while charcoals disappear under open-air conditions and grasses begin to colonise the shell midden; **b** another example of a thicker shell midden where white burnt shells with ashes and charcoals disappear under strong wind action. **c**, **d** Colonisation of grasses in a pit and a flat fire structure with stone rim; **e**, **f** small pebbles penetrating into a shell midden after combustion; **g**, **h** details of blue altered zones of shell middens where the white zone has disappeared due to wind action; **i**, **j** examples of coquina formation above two archaeological fire structures near the Túnel 1 site on the north coast of the Beagle Channel

plays a considerable role in the alteration of the hearths. This inflow of water contributes to the transport of ashes towards the inner part of the midden and also to the swelling of oxides contained in the middens, which gives rise to the formation of sedimentary rocks consisting of heat-altered conglomerates, or "coquinas" (Fig. 21i, j).

Cryoturbation also has an impact, but is difficult to detect since the structures remain buried under the snow during periods of cold weather. It is possible that infiltrating runoff waters could freeze within the shell midden, and then dilate during the thaw. However, we observe that these highly permeable deposits seldom retain any water, except when derived from the melting of snow in the less permeable surface layers.

In the same way, we observe the rapid formation of plant cover in the open areas around the middens on which the fire structures were built; this vegetation, primarily made up of herbaceous plants, rapidly surrounds the structures and covers them in a few years (Fig. 21a).

On other types of soil, outside the shell-middens we observe a slow recovery of the vegetation after thermal degradation; burial of the fire structures can take several years, remaining visible during the re-use of the camp ground. The hearths lit at ground level transform the surface vegetation layer, which is slowly restored by the growth of herbaceous formations from the rim towards the interior (Fig. 21c, d). The layers of fuel residue persist longer in this environment, being better preserved in pit hearths. These structures are generally filled in rapidly owing to runoff on the steep slopes of this zone bordering the Beagle Channel. The shell middens, located at low elevations on the terraces and shorelines of these steeply sloping zones, undergo the same process.

Experimental hearths built on volcanic silts and left exposed to the air are more slowly recolonised by the vegetation cover; after two years, they always become exposed to the open air. But in this case, this could be due to the experimental environment, which is made up of a container of silt set in an area relatively well cleared of vegetation.

Animal trampling also plays an important role, but our experiments use present-day animals (Bovinae) that show appreciably different behaviours, weight and anatomical features compared with ancient fauna (Camelidae), so extrapolations remain highly problematic.

Natural Phenomena Observed in Temperate zones (archaeological site of Pincevent, 48°22'5.41"N, 2°53'35.55"E, Paris Basin, France)

Since the 1990s, we have been carrying out a series of taphonomic experiments at the archeological site of Pincevent (Leroi-Gourhan and Brezillon 1972). These experiments are intended to observe taphonomic processes in a general way, since present-day conditions are considerably different from those prevalent during the Magdalenian occupation. However, we attempted to make use of old silts uncovered during the excavations of level IV20. These sediments, which were located by M. Orliac, enabled us to carry out experiments on soils that had undergone very little modification, apart from carbonate shrinkage cracks or traces of more or less contemporary roots. These clayey loam soils remained completely bare during the experiments.

The hearths produced during these experiments were left uncovered year after year during several years, so we could study the changes taking place. For example, in 1993, we were able to improve our understanding of phenomena related to cryoturbation of the hearths, due to the snowing up and extreme low temperatures (−18°C, with frozen banks of the Seine) (Fig. 22a, b). Various different processes are observed. First of all, the vegetation cover develops very little from one year to the following, apart from some lichens and mosses around the simple hearths (Fig. 22b), while oxidised zones formed during the previous year prevent the growth of plants (Fig. 22f, g). Some plants appear at the base of the fire pits, but this growth does not affect the walls. Gelifluxion considerably alters the substrates by the swelling of clays, which increases the volume and breaks up the zones beneath the hearths, whether or not they are degraded. This process is general and affects all the surface layers of the clayey loam soil over a thickness of up to 15 cm. In the dilated zones, small cracks are formed which are filled later with small particles of silt transported by surface waters (Fig. 22d–g). In the same way, due to melting of the snow and rains following the spring thaw, rills are formed draining the water away from the fire pits. In areas transected by the observation trench, we observe truly detached blocks of clayey loam soil forming patches bounded by cracks (Fig. 22e–g). This phenomenon sometimes also affects the walls of pits, though in a less marked way. Once the soil is drained,

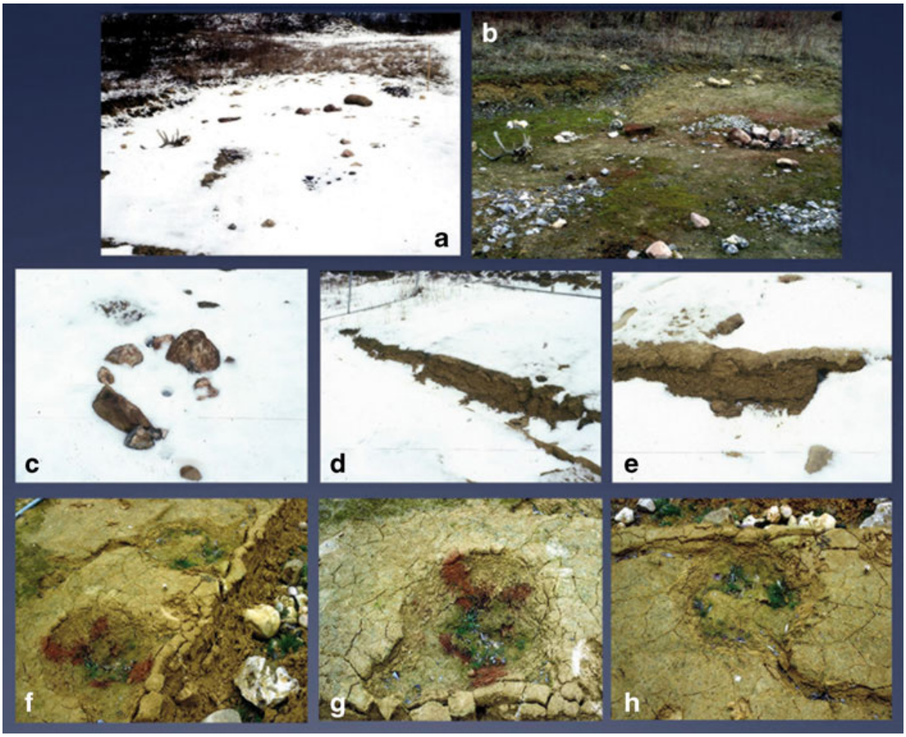


Fig. 22 Taphonomic transformations affecting structures at Pincevent during periods of extreme cold, snowing up, dilation of swelling clays and formation of mudcracks and rills in pit hearths

and with the return of warmer weather, shrinkage cracks are formed on the ground surface, giving rise to a criss-cross type pattern (Fig. 22e–g).

During temperate years, we observe other types of processes. First of all, the poor development of vegetation is a constant feature: on this type of soil, plant growth is generally slow and can be even slower during cold weather periods. A sparse ground cover is thus formed, accompanied by some lichens. Under these humid conditions, human and other animal footprints can also be observed. The vegetation cover changes over the years, giving way to grasses, thistles, nettles and other plants associated with sands overlying the sediments at Pincevent. During the summer, the pits can be very rapidly filled in: a single rainfall event can lead to the formation of a layer of sediments 1 cm thick. Silts then become mixed with the charcoal, forming a carbonaceous mud which dries very quickly. Although charcoal is seldom transported beyond the pits, this can easily occur during the flooding and over-bank flows of summer, such as observed in hearths located on the river bank. Pit hearths offer a favourable environment for plant seeds, since the depression acts as a natural pot that is well supplied with water and sediments. In this way, plants tend to develop more quickly at the bottom of the pit, with the walls forming a more sterile and well-defined rim (Fig. 23). Organic matter of vegetal origin accumulates more readily in pits than in simple hearths. The pits are quickly filled in, and the sedimentary layers show the development of plant roots from one year to another. Such a phenomenon could be observed in certain old hearths at Pincevent. All this tends to disturb the zones of oxidised or blackish colour underneath the hearth. During dry years, the development of plant cover is attenuated. Despite everything, the slow rate of covering of the hearths means that they remain visible from one year to another and even over some years. However, at the end of 2 or 3 years, these features tend to disappear and only the stony structures remain visible at the surface. In pit hearths close to the river, muddy layers are laid down by floods year after year, followed by the growth of lichens and mosses. During temperate years, no cracks or rills are observed in areas where the soils are not frozen (Fig. 23).

This description of the observed phenomena stresses the eventual disturbances, but should not disguise the fact that most of the hearths are extremely well preserved as described below.

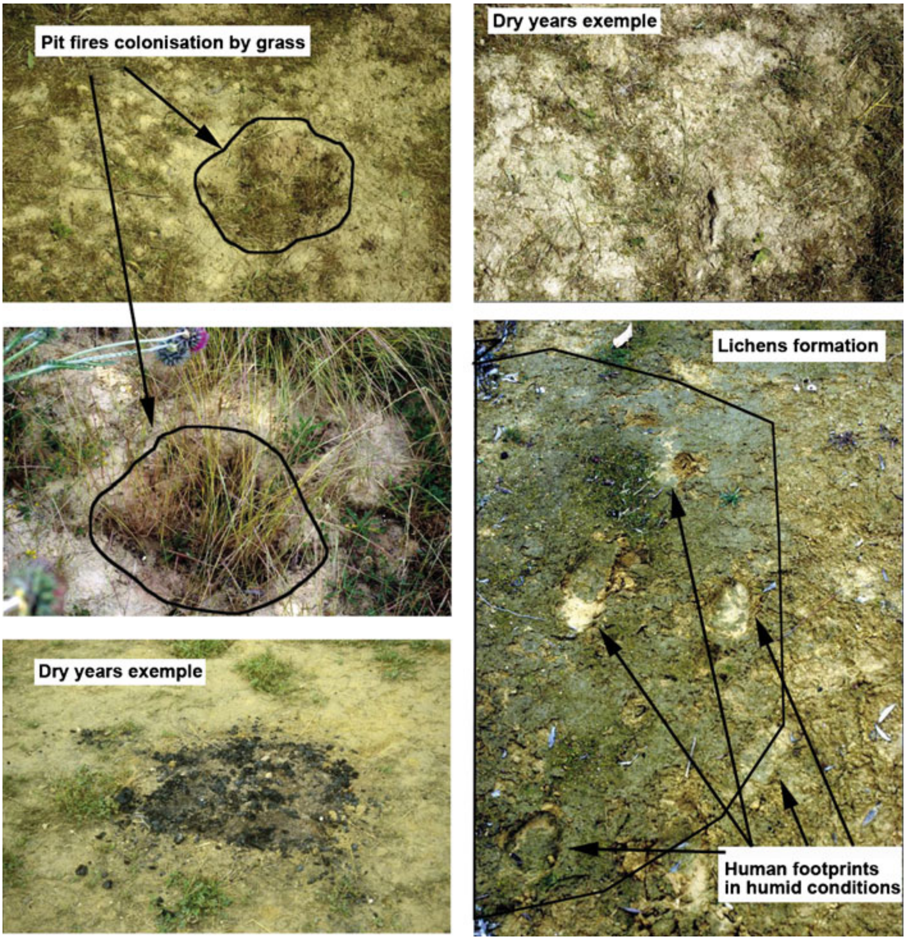


Fig. 23 Different examples of pit hearths (*top left*) and simple hearths (*middle left* and *right*) exposed to temperate climate conditions at the Pincevent site. We can observe pit hearths colonised by grass, the recurrent growth of sparse vegetation around and within the fire structures as well as lichen formation and human footprints. Under dry conditions, the aspect of the simple hearths is preserved both with and without charcoal

In forested zones, that are more humid and conducive to rapid lichen formation on soil, a carpet of leaves covers the old hearths from one year to another. The ashy and charcoal accumulation is flattened and the cover became imperceptible after 2 years. Again, the pits tend to accumulate more leaves, which favours a concentration of cuticular organic matter (waxes) from plants. This results in a higher concentration of waxes and alkanes than recorded in unforested areas (Fig. 24). Similarly, fire pits at the present day appear to contain accumulations of rabbit droppings, which are found at sites where the hearths are little affected by digging. This is an interesting observation, because certain traces of hormones or sterols, derived from animal faecal matter found in old hearths, may reflect this type of behaviour.

We also observe the fire-related behaviour of flat hearths situated on the banks of the Loire, near Orleans (47°53′43.92″N, 1°53′29.93″E), in deposits made up of flint gravel and calcareous rocks. Hearths lit during the winter or summer are quickly washed out and the charcoal carried away by floods, leaving almost no trace of fuel at the site from one year to another. The only remaining trace of these hearths is represented by thermal alteration of the soil (pebbles substrate).

Natural Phenomena Observed in Arid Temperate zones (Andálgala Catamarca, Argentina, 27°32'44.10"S, 66°20'29.64"W)

We also studied hearths in the area of Andalgalá, a part of the Piedmont of the Andes cordillera situated in the Prepuna of Argentina. This rather arid area is characterised by a flora made up of trees such as the Algarrobo (*Propsopis nigra* or *P. alba*), the Chañar (*Geoffrea decorticans*) as well as shrubs including the Jarilla (*Larrea divaricata*), cactuses and some herbaceous plants (Joly 2008). Here, we observed the behaviour of flat hearths built in stony enclosures dating from the INCA period and left uncovered from one year to the next (Fig. 25a–f). These arid regions are characterised by aeolian and overbank fluviatile deposits. In our case, the hearths were built far away from the nearest brooks and rivers, our idea being to test the influence of arid conditions at this site. Hence, the hearths were primarily affected by the presence of silty soils.

The example presented here consists of a hearth produced using Jarilla wood, which, once the combustion had finished, was left with its unburnt charcoal and wood still in place (Fig. 25a, b). From one year to the next, this hearth is covered by a 1-cm-thick layer of sediment (Fig. 25c). This covering is characterised by the formation of micro-layers of sediment which are very easily detached from each other, and which

Fig. 24 Simple hearth under forested conditions. **a** Hearth functioning; **b** hearth condition after 4 weeks, when we can clearly seen the ashy and charcoal zone; **c** hearth condition after 2 years, with accumulation of leaves above the fire structure, completely covering the fire structure, along with lichens growing in this more humid environment

also display shrinkage cracks resulting from desiccation following the low rainfall at this site over the year. No development of vegetation is observed. The charcoal and wood remains are dispersed by animals around the zone of combustion. Except for this dispersion, the structure is very well preserved, and even ashes are present (Fig. 25c). The black- and red-coloured zones beneath the sediment cover also show an excellent state of preservation and no disturbance is observed in the thermally degraded sediment (Fig. 25d to f).

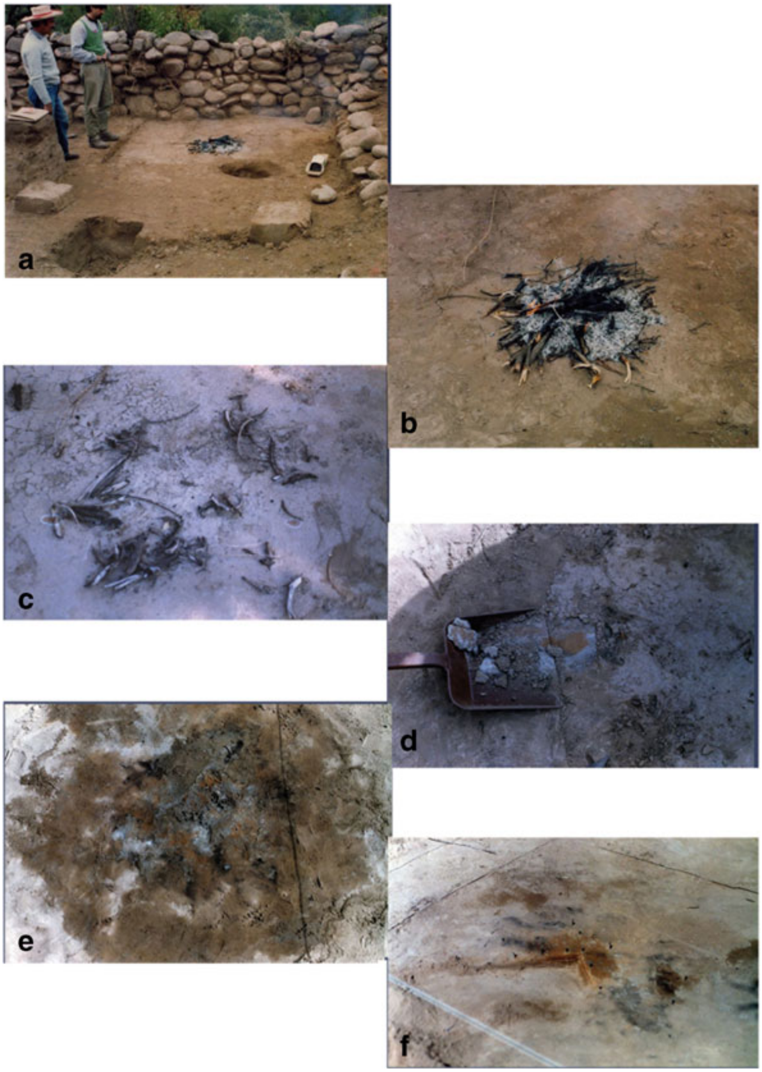


Fig. 25 Experimental sequence of simple hearths at Andalgalá. **a** Hearth functioning; **b** hearth condition after 2 days, when we can clearly seen the ashy and charcoal zone and partially unburnt woody remains; **c** hearth condition 1 year later, with accumulation of soil partially covering the fire structure and natural scattering of burnt wood; **d**–**f** excavation of the fire structure after 1 year of exposure, revealing well-preserved ashes, blackened and oxidised zones. Experimental sequence of simple hearths at Andalgalá

Anthropic and Natural Phenomena Observed in Temperate-Zone Hearths. Examples of Hearths at Pincevent

Our aim at Pincevent was to supplement studies on exclusively natural phenomena by also working on examples of re-used hearths. For this purpose, we carried out detailed excavations and monitoring of hearths reproduced on the site, as part of group entertainment activities and while setting up reconstructions open to the public. While first of all not appearing very scientific, this approach very quickly provided us with abundant information, otherwise difficult to obtain, on the interaction between natural phenomena, human activities and hearths. Once abandoned, or after several years of re-use, the hearths were excavated according to the usual archaeological methods. Evidently, the excavation of a fire structure cannot reveal the complete succession of phenomena that take place over the years, and which change during the history of the hearth. However, the information obtained in this way allows us to replicate types of actions and processes that even the users of the hearth may sometimes have even forgotten.

Re-Use of Simple Hearths

In 1987, we studied a series of simple hearths that had been lit at Pincevent for several years for the purpose of public demonstrations. This work enabled us to observe the consequences of re-using the same space over the course of time, while performing these demonstrations. After being re-used for 4 years, the structure was abandoned for 1 year. The final hearth (Fig. 26a) corresponds to a simple hearth with a rim of stones, which appears to resemble certain hearths of level IV20 at Pincevent, such as 36-R126 (March 1995a, b; March *et al.* 2010). It was partially surrounded by grass of medium height and, once cleared out, still contained some clearly visible charcoal remains, unburnt wood, burned stone fragments and an ochreous zone (Fig. 26b, c) made up intentionally to resemble the ochreous zones of level IV20. We also observed seedlings growing in the soil around the zone of heated rocks. By removing the stones belonging to the last use of the hearth, we found an ochreous zone in the south-western sector, and an oxidised central zone partially covered with charcoal that belongs to a previous episode (Fig. 26d). By removing the ochreous zone, we found a blackish zone underneath (Fig. 26e), and, in the central part of the hearth, the remains of charcoal and ashes lying directly on a layer of oxidised silts (Fig. 26f). The upper layer of oxidised sediment overlies a zone of blackish material extending under the hearth sediments. However, this blackish deposit does not reach the centre of the structure, which is characterised by the appearance of a second layer of oxidised sediment. Outside this younger layer, we observe an old zone of sweeping out, where large-sized charcoal is completely absent (Fig. 26g, h). This sweeping-out zone, which was last used 2 years before, has become naturally covered with muddy sediments, but still preserves its oval shape. Another hearth was lit on top of sediments that covered the earlier sweeping-out zone. Over the central red zone of this later hearth, we could observe only a thin whitish ashy layer, still accompanied by fine-grained charcoal remains without any fragments larger than 1 cm (Fig. 26f).

Once the surface had been well cleared, by removing the oxidised sediments of the first episode, we could observe that many roots had grown within this layer. These

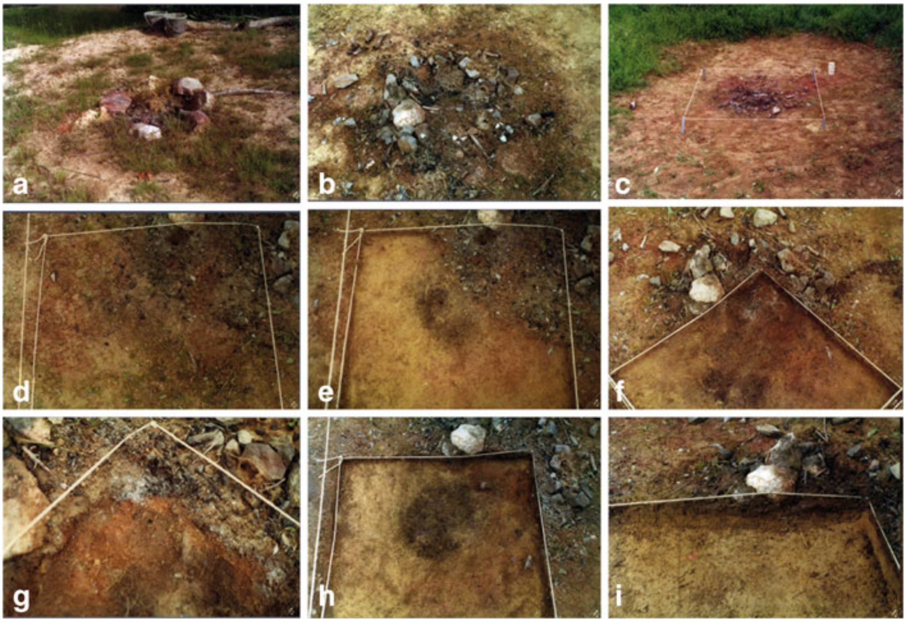


Fig. 26 Sequence of excavation of a zone selected for building several simple hearths at the Pincevent site. **a** Final simple hearth with a rim of stones; **b**, **c** charcoal remains, unburnt wood, burned stone fragments and an ochreous zone from the final hearth; **d** ochreous zone in the south-western sector of the last fire structure, and an oxidised central zone partially covered with charcoal belonging to a previous simple fire; **e** blackish zone underneath and slightly displaced from the two last fires; **f** central part of previous hearth, with remains of charcoal and ashes lying directly on a layer of oxidised silts belonging to the last fire structure; **g**, **h** oxidation produced by the third fire and blackish material extending under oxidised sediments of this hearth; **i** final profile and natural soil without traces of fire structures

roots belonged to a former plant cover obliterated by the activity of the last hearth. Then, under the layer of oxidised sediment, we found a new ochreous zone located around the accumulation of charcoal, still containing some remains of knapped flint. Under the oxidised sediment in the centre of the structure, we could see a new layer of blackened sediments, but this time without any trace of charcoal.

At the end of this excavation, we were able to determine the existence of at least three successive hearths that had attained different temperatures, since the last accumulation of charcoal (Fig. 26h) had not caused oxidation of the substrate.

In this way, we note that the fire structures are superimposed one above the other. Layers of silts are formed between the building of each structure, partially covering over the hearths from one year to another. The different layers of silt vary in thickness, since they are formed by precipitation and erosion on the ground slope. In addition, the activity of the last structure completely oxidises the underlying layer of silt. The red layer of the last hearth comes into contact with the earlier red layer, but can be differentiated due to the preservation of ashes and charcoal between the two oxidised zones.

Our study indicates a good preservation of the coloured zones and ashes during the 5 years prior to excavation of the structure. The preservation of charcoal remains is distinctly different from top to bottom: in the upper layers, the charcoal remaining from the previous year is in good condition and of normal size, while the preceding hearth lacks any visible layer of charcoal, containing only some small fragments of charcoal associated with ashes. The uppermost blackened layers of sediment are rich in organic matter. Given the thickness of the layer (more than 1 cm), this could be interpreted as resulting from the alteration of charcoal. This experimental excavation shows that the superposition of simple hearths can be clearly identified provided that no digging out operations have taken place. In this example, we were unable to assess the bioturbation of animals or ants.

Re-Use of Pit Hearths

Later on, we applied the same approach to a pit hearth used by the Pincevent team for entertainment and performing experiments such as the preparation of glues and pastes. In this example, we used a pit hearth with a stone rim. It was built near two trees, contrary to the simple hearth described above, which was located in a completely cleared zone. The studied hearth was used for 4 years, with its shape changing over this period (Fig. 27a, b). Although subject to cold weather conditions and being completely covered by snow (Fig. 27b), it always kept the same shape of a pit with bordering stones. The firewood collected for our experiments generally consisted of logs of woodland pine or birch, as well as branches of woodland pine, birch and willow. Then, after 4 years of use, it was abandoned and replaced by another hearth set up elsewhere. When we began excavation, the hearth was almost completely covered with grass, and large rocks piled on top of each other filled the centre of the pit. The rocks arranged around the rim showed traces of oxidation and blackening, leading us to consider that they are not in place, but have been moved since the thermal alteration. When abandoning the hearth, we took out the stones from this first filling, and then removed the grass in and around the structure to observe more clearly the coloured zones in the soil. A very recent layer of silt without vegetation, evidently representing the last year, covered part of the rocks, charcoal and underlying oxidised sediment (Fig. 27c). After this first layer of silts was stripped away, we removed the underlying charcoal, which lay on top of stones belonging to the old structure. Under the pit and its final filling, we could pick out the shape of an even older pit, completely filled in by sediment, charcoal and rocks belonging to the last use. This pit is smaller in size, becoming completely filled in and even extending beyond the initial hearth during the construction and activity of the last hearth excavated here. The oxidised sediment patches revealed here (Fig. 27d) represent the addition of several episodes of combustion prior to the current form of the hearth, but which post-date the older pit. We could observe several zones of overlapping hearths, marking the position of large logs arranged radially on top of the structure once it was filled. These zones are superimposed onto the oxidised zones of previous hearths present at the edge of the structure. However, these zones do not cover all the ground surface, since they locally highlight the presence of rocks protecting the underlying silts from oxidation. Therefore, we proceeded to remove rocks from the western wall of the structure and detected the presence of a large anthill located just on top of the rocks forming the edge (Fig. 27e–g). The rocks cover the charcoal produced by an earlier phase of use, as well as oxidised walls that clearly belong to a previous state of the hearth. During this previous activity of the hearth, the walls of the pit were oxidised at the rim, which shows that the rocks filling the structure are not in a position corresponding to this earlier phase of use. The ants built galleries under the stones, producing small pellets of oxidised red sediment that they displaced towards another part of the hearth. In this way, the oxidised sediments were buried under rocks near silty deposits that show no sign of alteration. In the same way, the ants avoid the pieces of charcoal, which thus remain unfragmented under the stones that we removed during the excavation. Under other rocks, we observe very fragile charcoal enclosed in a network of roots and rootlets (Fig. 27h). A small flint pebble separates an oxidised silt layer from a filling of undegraded silt covering the charcoal (Fig. 27h). The oxidised sediment represents an episode when the hearth was lit on the rock surface. By contrast, the sediments and charcoal located in the inner part of the pit depression (3 cm thick) belong to a later hearth, protected from oxidation by a rock forming part of the upper filling. Once the stones and charcoal were removed from the central part of the structure, we uncovered a new underlying layer of silt—the fourth in this hearth—which overlies yet another layer of greyish and blackened sediment consisting of charcoal microparticles and ashes mixed with fine roots resembling mycelium. These sediments and roots fill the base of the structure, sometimes forming a layer up to 4 cm thick, but no charcoal could be identified at first sight (Fig. 27i, j). Finally, by carrying out a transect through half of the structure, we revealed a rodent burrow under the edge of the last pit, located underneath oxidised as well as undegraded sediments (Fig. 27j).

Thus, although this fire structure has been disturbed by several taphonomic phenomena, we can nevertheless read its complex history, since they highlight several modifications of form and phases of re-use. The layers of undegraded and oxidised silt that make up the filling clearly reflect the periods of abandonment or rapid filling of the structure between several phases of use. Even if these fillings do not show a clear periodicity, they suggest that the structure remained unused for a certain period of time. However, we know that this structure was used every year, implying that the layers of silts could have been formed during the same year and even during the same season owing to summer rains. The structure has evolved and increased in size as a result of this natural process, which is accompanied by anthropic filling consistent with our phases of abandonment and filling of the hearth. Grasses have completely filled the structure while masking the rocks, but without significantly altering the oxidised sediments or our interpretation of the earlier episodes. The activity of ants has modified the walls of the fire-pit under the stones, while also moving oxidised sediments from one wall to another. Then, roots have apparently reworked the remains of ashes and charcoal, rodents have altered part of a structure building a gallery under the walls of the pit in its final state.

The experiments like those described above are still continuing today, with the aim of studying hearths left undisturbed at various sites for more than 10 years; some of these structures have existed for up to 20 years, without being disturbed by any human intervention.

Conclusion

The results presented here show that studying natural and anthropic processes of formation and alteration of an archaeological context approaches the analysis of

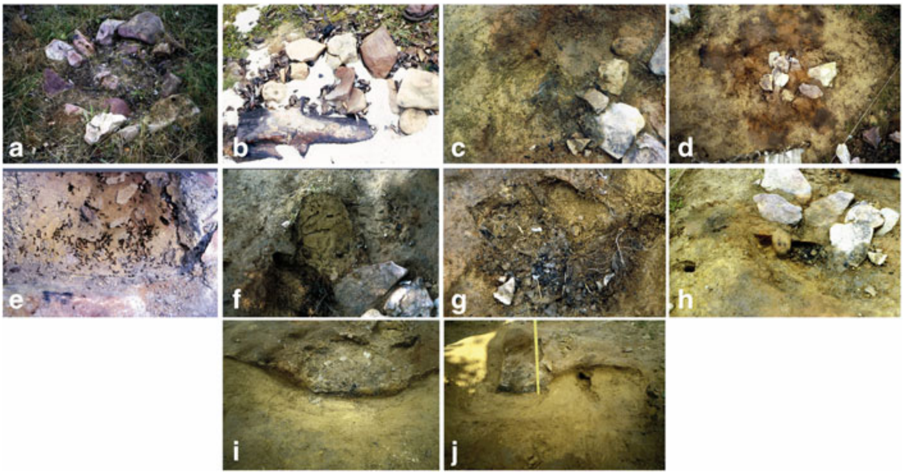


Fig. 27 Sequence of excavations of a pit hearth with stone rim at Pincevent, to study mixed anthropic and natural transformations. **a** Final state of the last hearth, which corresponds to a simple hearth with a rim of stones; **b** the same hearth under cold conditions covered by snow; **c** recent layer of silt without vegetation, evidently representing the last year, covering part of the rocks, charcoal and underlying oxidised sediment; **d** oxidised sediment patches representing the superposition of several episodes of combustion prior to the current form of the hearth, overlapping the oxidised zones of previous hearths present at the edge of the structure; **e–g** anthill located under rocks from the western wall; **h** very fragile charcoal enclosed in a network of roots and rootlets under some rocks, and oxidised silt layer from a filling of undegraded silt covering the charcoal of the first utilisations of these fire structure; **i**, **j** fourth underlying layer of silt, which overlies yet another layer of greyish and blackened sediment consisting of charcoal microparticles and ashes mixed with fine roots resembling mycelium

accessible complex systems by modelling. In the same way, this highlights the fact that understanding the processes of formation is a prerequisite to carry out taphonomic studies. While the modelling of hearths is already within our scope, it would be necessary to overcome a certain number of limitations to model taphonomic processes. Taphonomic studies pose problems of a practical nature, primarily the monitoring and recording of experiments, owing to the number of variables that need to be taken into account. Moreover, by accepting that the various ecological contexts will condition and determine the natural processes of alteration, we also acknowledge the need to work in these different contexts. In this study, we attempt to show that there are regular patterns or at least trends in the processes of formation. We also present some examples of experiments conducted in various ecological contexts. This leads us to determine the variables that need to be studied to specify these processes, and we attempt to monitor the variables analysed during our study of the processes of formation. However, the measurement of these phenomena still escapes us, and our presentation deliberately emphasises the narrative aspect of the events in order to highlight the difficulties of quantification. For example, this involves calculating the quantities of sediment transported by the wind in Catamarca or the annual rainfall in Tierra del Fuego or Pincevent, at the same place where the experiments were carried out. In addition, we need to assess the force of the Loire river currents, the exact temperature reached by the soil during the year or the number of insects present, as well as the moisture of the sediments or growth rate of plants within the structures, or the method for weighing ashes and charcoal in a realistic experiment that is left undisturbed after burial of the structure. Moreover, extreme or remote conditions pose problems of a practical nature that are difficult to resolve without an automatic observation system for recording the natural processes affecting fire structures such as, for example, the activity of animals. Certain variables and their associated processes of alteration are better known than others, for example, improvements in the applications of organic chemistry have led to advances in this field.

Despite there are alternatives to carrying out studies in the natural context to simulate natural alteration over short time intervals, we still need to investigate these same processes as a function of time. However, these alternatives are not yet very well developed.

It remains to address the transformations brought about by anthropic activities, which we can see as multiple and varied, and which can modify the structures much more markedly that natural processes.

Even though we are just beginning to reconstruct the history of each fire structure, their signification for understanding human behaviour and the history of the whole process of control and application of thermal energy, we still require further research into these different aspects.

Despite everything, our hearths are still there and have been waiting our attention for 20 years now!!!

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