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Microarchaeological Approaches to the Identification and Interpretation of Combustion Features in Prehistoric Archaeological Sites

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Abstract Combustion features inform archaeologists about the prehistoric use of space, subsistence behaviors, and tempo of site visitation. Their study in the field is difficult because burned sediments are susceptible to reworking and diagenesis. Microarchaeological analyses, including micromorphology, are essential for documenting the composition, preservation, and function of hearths and other burned residues. These investigations focus on the description of fuels, depositional fabrics and structures, and mineralogy. As evidenced by a literature review, microarchaeological analyses have much to offer Paleolithic archaeologists, while applications of the techniques to Late Pleistocene and Early Holocene sites and in ethnographic or experimental contexts are presently rare.

Keywords Hearth · Micromorphology · Ashes · Charcoal · Controlled use of fire

Introduction

Combustion features in archaeological sites take many forms. Intact combustion structures are commonly known as hearths. Although the term is widely used to describe a combustion feature that exhibits elements of intentional preparation, such as basal pavings or a rock-lined perimeter, Dibble *et al.* (2009, p. 187) define a "hearth" as "the remnants of a domestic fire feature that retains some or most of its

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original structural or compositional elements (e.g. organic matter and overlying ash)." Less intact features may be termed "hearth areas" or "combustion areas" to distinguish these fire traces from well-preserved hearths. Here, the terms "hearth" and "combustion structure" are employed in a similar sense, while the term "combustion feature" signifies a more general category that includes hearths and burned materials in secondary position due to human activities or natural processes.

Hearths and their numerous permutations may represent the remnants of (1) single events or short-lived activities (Berna and Goldberg 2008; Goldberg *et al.* 2012), forming in a matter of minutes or hours; (2) a central activity in a permanent or semipermanent occupation of a site, persisting for months when well-maintained (Mallol *et al.* 2007); or (3) repeated opportunistic use of the same space over many seasons or years. Moreover, a single hearth or horizontal hearth area usually defines an ancient surface that was used for a wider range of economic and social activities. The study of hearths and other combustion features can, therefore, contribute to the quest for the ever-elusive "living floor" (Dibble *et al.* 1997) or to the identification of communal spaces. Combustion features also permit relatively expedient evaluation of the impacts of postdepositional processes on the character of their sediments. For example, investigations of chemical alteration using the mineralogical or elemental composition of sediments can be carried out in the field (e.g., Eliyahu-Behar *et al.* 2009; Schiegl *et al.* 1996; Weiner 2010). Finally, hearths provide sources of material that can be dated using radiometric, paleomagnetic, and luminescence methods. Well-preserved charcoal can yield radiocarbon ages as old as 60 kyr BP (Bird *et al.* 2003); calcined bone may also be dated (Lanting *et al.* 2001). Thermoluminescence and optically stimulated luminescence techniques can be applied to even older materials, depending on the dose rates in and around the heated rocks and sediments (Aitken 1985, 1998). In sum, in an archaeological sequence, several meters thick combustion features and their contents are attractive sources of information about continuity and change in hominin behavior and sediment chemistry over time.

At the most basic level, the presence of a hearth in a site implies, first, an ability to acquire and/or produce and control fire and, second, a need for fire for cooking, light, heat, or a combination of these benefits. Therefore, a burning question in Paleolithic archaeology is when and where the controlled use of fire first appeared in the archaeological record. This question is key to the testing of the hypothesis proposed by Wrangham and colleagues (Carmody and Wrangham 2009; Wrangham and Carmody 2010; Wrangham 2007, 2010; Wrangham *et al.* 1999) that the cooking of food was a crucial behavioral development in the history of our genus. A recent literature review in search of the answer led Roebroeks and Villa (2011) to conclude that the first hominins to enter Europe did not possess fire technology. Although burned materials, such as heated flints or rubified[1] earth, are present in several Lower Paleolithic sites (e.g., Alperson-Afil *et al.* 2009; Goren-Inbar *et al.* 2004), James *et al.* (1989) insist that the best evidence for intentional burning in an archaeological site is the presence of an intact combustion structure.

An intact combustion structure is an archaeological feature that contains the by-products of burning in stratigraphic position within the original burning locality. The

[1] Also spelled "rubefied."

presence of an intact combustion structure implies that burning occurred *in situ*. The materials recovered within an intact combustion structure may also be termed *in situ*.

Following this possibly overstrict criterion for the existence of fire technology, some of the oldest intact combustion structures that have been described in the field and supported with micromorphological and geochemical identification of burned materials are the Amudian (400–200 ka BP) hearths in Qesem Cave, Israel (Barkai *et al.* 2003; Karkanas *et al.* 2007). In the upper deposits of this site, intact combustion structures composed of calcitic wood ashes are accompanied by burned bones and heated lithic artifacts. The recently reported burned materials in ~1.0 mya deposits in Wonderwerk Cave, South Africa (Berna *et al.* 2012) are significantly older than the combustion structures at Qesem Cave. However, the ash layers and burned bones identified in Wonderwerk Cave are not associated with intact structures.

The Qesem Cave and Wonderwerk Cave studies, like numerous other Paleolithic projects, utilize the technique of micromorphology to identify the by-products of burning and to determine whether these by-products are *in situ* or reworked by human activity or natural processes (Karkanas *et al.* 2007). Micromorphology is one of a number of analytical approaches that fall under the category of "microarchaeology" (*sensu* Weiner 2010). The most common of these approaches with applications in the study of combustion features are summarized in Table 1. In fact, a critique of the sparse evidence for controlled fire in the Lower Paleolithic (e.g., James *et al.* 1989), as well as more recent skepticism over the ubiquitous presence of intact hearths in Middle Paleolithic sites in Europe (e.g., Perlès 1981; Sandgathe *et al.* 2011), help to account for the development and growing adoption of microarchaeological techniques by the Paleolithic archaeological community. The impact of these investigations includes a proliferation in the types of combustion-related behaviors recognized in archaeological sites, a greater understanding of the different phenomena that influence the morphology and composition of combustion features (Table 2), and a strong bias in research efforts towards the earliest periods of human history.

The following text outlines the microarchaeological criteria that, in conjunction with field-based observations, are crucial to the identification of combustion structures and burned materials in secondary position. The aim of this paper is to highlight the types of information that can be generated when one applies a microarchaeological approach to Paleolithic and later archaeological records; these methods are currently underused in research on Epipaleolithic and Mesolithic sites and their African and New World equivalents. Discussion includes published observations from sites dating primarily to the Pleistocene and Early Holocene, as well as later periods, as appropriate; sites located in both the Old and New Worlds; and experimental and ethnographic studies. Examples from later periods are provided, as appropriate. Specialized fire technologies that become widespread in the Holocene in association with agriculture or urbanization, such as the regular burning of animal dung in caves, human cremations, metallurgy, ceramic production, lime processing, or the use of permanent constructed features ("fire installations"; *sensu* Crawford 1981) including kilns and ovens, are not included in this article. The large number of cited Middle Paleolithic or Middle Stone Age cases represents a concentration of interest in fire technology during these periods. The technique of micromorphology is also emphasized over other approaches due to its widespread use and versatility.

Table 1 Microarchaeological methods for the description and interpretation of combustion features and their contents

Analytical technique	Description	Purpose	Application to the study of combustion features	References
(Archaeological) micromorphology	The analysis of intact and oriented archaeological sediments mounted on thin sections using an optical petrographic microscope at low to moderate magnifications (×2–500). Additional types of equipment include flatbed scanners and fluorescence microscopes.	To study the composition, fabric and structure of archaeological sediments and features.	Useful for Identifying calcitic ashes, phytoliths and microcharcoal Determining whether ash and charcoal layers are *in situ* using microfacies analysis Identifying the mechanism and degree of postdepositional reworking of burned materials Identifying postdepositional chemical alteration of burned materials	Arpin *et al.* 2002; Courty *et al.* 1989; Goldberg *et al.* 2009
Grain mount analysis	The analysis of loose sediment samples mounted on glass slides using a mounting medium or liquid (e.g., Canada balsam, Entellan New®, or clove oil) and cover slip. Additional types of equipment include sieves, an optical petrographic microscope, and centrifuge (for processing phytolith samples).	To quickly determine the composition of a sediment or certain particle size fraction of a sediment. Analyses can be conducted in the field.	Useful for Identifying ashes Identifying phytoliths Identifying microscopic fragments of charcoal Observing the presence of secondary salts	Albert and Weiner 2001; Albert *et al.* 2000, 2012; Elbaum *et al.* 2003; Matthews 2010; Weiner 2010,
Reflectance petrography	Measurement of the percent reflectance of charred organic materials mounted on thin sections or in resin-impregnated and polished sample blocks.	To determine the temperature of burning of organic materials and to identify phases such as chars and gels.	Useful for Determining the temperature of combustion of charcoal Identifying alternative fuel sources such as coal	Braadbaart and Poole 2008; Ligouis 2006; Taylor *et al.* 1998

Table 1 (continued)

Analytical technique	Description	Purpose	Application to the study of combustion features	References
Scanning electron microscopy	The analysis of loose sediments, thin sections, or resin-impregnated sample blocks at moderate to high magnification (×50–5,000).	To observe grain morphologies and surface textures. Especially useful for viewing clay-sized sedimentary components. Basic elemental composition and compositional mapping.	Useful for Observing the grain morphologies of wood ashes and determining the degree of dissolution (surface etching) or recrystallization Observing the crystal habits of diagenetic minerals	Courty *et al.* 1989
Macrobotanical and microbotanical analyses and anthracology	The identification of botanical remains in archaeological sites. Additional types of equipment include a flotation device and a low-magnification stereomicro scope. Analyses may also be con ducted on materials in thin section.	To determine the genus and species of plant remains. To identify the plant parts that are present in a site or feature. To quantify diversity and fragmentation of plant assemblages.	Useful for Identifying the types of plants that were used as fuel or cooked in a fire Identifying deposits that derive from multiple burning events, reworked deposits, and weathered materials Identifying the conditions and temperature of burning	Asouti 2003; Boardman and Jones 1990; Goldberg *et al.* 1994; Théry-Parisot *et al.* 2010
Histomorphometry	The analysis of latitudinal cross-sections of bones using petrographic methods.	To identify and describe histological structures and color in thin section.	Useful for Determining the temperature of burning of bone	Squires *et al.* 2011
Carbonate equivalents	The analysis of weight percent calcium or magnesium carbonate using acid digestion and measurement of the volume of CO_2 produced. Requires a	To determine the abundance of calcium or magnesium carbonate in a sediment or sieved sedimentary grain size fraction.	Useful for Determining the abundance of the calcitic fraction of wood ashes that are present in a mixed deposit (barring	Dreimanis 1962

Table 1 (continued)

Analytical technique	Description	Purpose	Application to the study of combustion features	References
	Chittick apparatus or Dietrich-Früling calcimeter.		additional silt-sized sources of carbonate)	
FTIR and μ-FTIR	The identification of molecular bonds in powdered sediment samples, in sediments mounted on thin section, or in resin-impregnated sediment blocks.	To determine the mineralogical composition of archaeological sediments. To identify changes to the crystal structure of materials that result from heating. Analyses of loose samples can be conducted in the field.	Useful for Identifying the by-products of postdepositional chemical alteration of ash deposits Determining the mineralogy of materials identified in thin section (μ-FTIR) Distinguishing between stained and charred bone Determining the burning temperatures of bone fragments Determining the burning temperatures of clay minerals Distinguishing between ash and natural calcite	Berna *et al.* 2007; Chu *et al.* 2008; Goldberg and Berna 2010; Karkanas *et al.* 1999, 2002; Regev *et al.* 2010; Schiegl *et al.* 2003; Shahack-Gross *et al.* 1997; Thompson *et al.* 2009; Weiner *et al.* 1993
Electron microprobe, EDAX, and μ-XRF	The identification of major and trace elements present in sediments mounted on thin sections, or resin-impregnated sample blocks.	To determine the elemental composition of sediments or materials. To observe the distribution of individual elements within a defined 2-D area.	Useful for Determining the chemical composition of diagenetic minerals and sediments identified in thin section	Courty *et al.* 1989; Mentzer and Quade in press; Sherwood 2008

Table 1 (continued)

Analytical technique	Description	Purpose	Application to the study of combustion features	References
Stable oxygen and carbon isotope analysis	Measurement of the relative abundances of the isotopes of oxygen and carbon in loose sediments and samples drilled from resin-impregnated sediment blocks. Requires a mass spectrometer.	To calculate the ratios of ^{18}O to ^{16}O ($\delta^{18}O$; normalized to a standard) and ^{13}O to ^{12}O ($\delta^{13}C$; normalized to a standard).	Useful for Identifying of the calcitic fraction of ashes in highly altered or cemented deposits Identifying C3 and C4 plant ashes, temperature of burning and degree of recrystallization of ashes	Mentzer and Quade in press; Shahack-Gross *et al.* 2008; Shahack-Gross and Ayalon 2012
Magnetic susceptibility and magnetic mineralogy	Measurements of the relative degree of different types of magnetization of sediment are paired with mineralogical analysis to identify the magnetic phases.	To identify mineralogical changes within sediment that occur as a result of heating.	Useful for Identifying burned sediments Distinguishing between rubification due to heating and rubification due to other processes	Aitken 1978; Herries 2009; Herries and Fisher 2011; Herries *et al.* 2007; Latham and Herries 2004
Lipid analysis	Measurements of the lipid composition of sediment samples. Requires a gas chromatography mass spectrometer.	To identify fatty acids and their relative abundances.	Useful for Identifying organic residues derived from cooking or the burning of animal and plant tissues	Kedrowski *et al.* 2009; March *et al.* 1989, 1993

Table 2 Archaeological expression of combustion features—some factors that influence the morphology, composition, internal organization, and structuring

Factor	Archaeological expression
Phase 1: before combustion	
Location of combustion space	Position of the combustion area with respect to other activity areas, structures, or boundaries of the site (e.g., cave walls or entrance)
Substrate composition	Variably heat-altered anthropogenic materials, geogenic sediments, or bedrock
Substrate shape; modified or natural	Shape of the feature in profile and plan; nature of the contact between combustion by-products and substrate; exploitation of bedrock morphology
Size of combustion area	Shape of the feature in profile and plan
Fuel choice	Morphology and composition of charred and calcined combustible materials (plants, bone, coal), presence/absence of phytoliths, composition of noncombustible inclusions, production of charcoal *versus* ash
Phase 2: during combustion	
Hearth maintenance activities	Size, shape, and intensity of burning
Fuel additions	High volume of burned material
Tending/redistribution of fuel	Intensity of burning
	Shape of the feature in profile and plan
	Vertical and lateral distribution of burned elements
Combustion area function	Presence of nonfuel materials
Light/heat	Toss zone
Cooking	Food remains (bone, char, shell, seeds)
Refuse disposal	Heated lithic artifacts and debitage
Heat treatment/tool manufacture	
Oxygen availability	Ratio of charcoal to ash
Low	High ratio of charcoal to ash
High	Low ratio of charcoal to ash
Phase 3: extinction	
Loss of fuel	Complete combustion
	Low ratio of charcoal to ash
Extinction by water	Incomplete combustion
	High ratio of charcoal to ash
	Water-related redistribution
	Grain size sorting
	Cementation or dissolution
Loss of oxygen	Incomplete combustion
	High ratio of charcoal to ash
Smothering with sediment	Incomplete combustion
	High ratio of charcoal to ash
	Burned sediment on top of partially combusted materials with sharp contact?

Table 2 (continued)

Factor	Archaeological expression
Wind	Incomplete or rapid combustion
	Aeolian reworking/textural sorting
	Winnowing
	High ratio of charcoal to ash
Removal of burning materials	Charred or calcined materials distributed over a wide area with contact heat alteration of other materials
Phase 4: after combustion	
Human activities	Reworking, alteration of feature morphology
New fire built directly atop old combustion structure	Stacked combustion features; thick, microlaminated ash layers
Hearth cleaning	Loose, unstratified ash deposits; rake-out deposits; truncation of combustion features in profile
Trampling	Compaction, planar voids, *in situ* breakage (crushing and snapping) of bone and charcoal
Construction of bedding areas	Dispersal of combustion by-products, mixture with bedding materials
Reworking/erosion	General mixing of burned and unburned materials, loss of combustion area morphology and internal stratigraphy
Water	Laminations, textural sorting, graded bedding, lag deposits, ash dissolution/cementation
Insect or animal bioturbation	Channel, chamber, crumb, or granular microstructures; fecal pellets; burrows and passage features
Wind	Winnowing/removal of silt-sized materials, lag deposits
Colluvial processes	Laminations, textural sorting, shearing
Cryoturbation	Fragmentation of burned materials; development of lenticular, platy, or granular microstructure
Burial	Combustion features or deposits buried by anthropogenic, geogenic, or biogenic materials
Plant growth	Development of channel microstructure, formation of calcitic hypocoatings
Moisture	Diagenesis
Low pH	Dissolution of carbonate, volume loss
High pH	Dissolution of silicates, ash recrystallization
Carbonate-saturated water	Petrification or cementation, loss of porosity due to development of void infillings
Phosphatic solutions	Isovolumetric replacement of ash by secondary phosphatic minerals and crusts

The first section describes the materials that are produced from the combustion of wood and other fuels and the types of information they may provide regarding fuel selection, temperature, and duration of burning. The second section explores the three most important lines of evidence that suggest that combustion occurred within an archaeological site: intact hearths, reworked burned materials, and indirect evidence

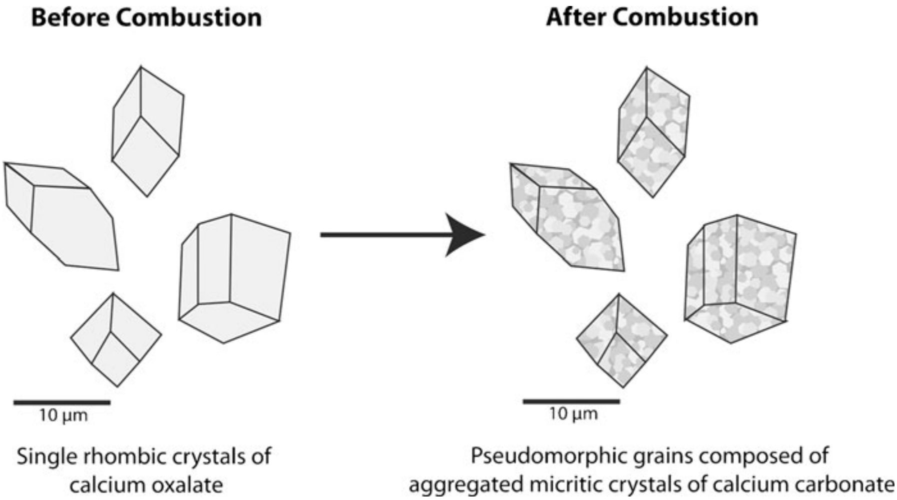

Fig. 1 Prior to combustion, plant tissues contain calcium oxalate crystals. Following combustion, ashes contain aggregates of micritic (<4 μm) calcite crystals that are pseudomorphic after the original calcium oxalates

for burning. The third section investigates the postdepositional chemical alterations that impact the three types of deposits in both open-air sites and cave environments. Differential impacts of postdepositional dissolution, as well as other taphonomic factors, result in a strong bias towards the recovery of burned materials in cave sites. Finally, the fourth section outlines the microscopic and geochemical features that, in well-preserved sites, are indicative of specific combustion-related hominin behaviors.

The By-Products of Combustion

At their most basic level, hearths arise from the interaction of a substrate (typically bedrock or sediment), a fuel source (typically wood or dry plant material), and a source of ignition. The by-products of burning shared by all combustion features are the heat-altered remnants of the original fuel source. In most hearths, these remnants consist of ash and charcoal.

According to Canti (2003), ash that forms as a result of burning dry plant material[2] contains three main components. The first component is calcium carbonate, which forms as pseudomorphic aggregates of micritic (<4 μm) crystals after the rhombic calcium oxalate and carbonate crystals that are naturally present in plant tissues (Fig. 1). The second component is siliceous phytoliths or slag. The third component is soluble salts, charcoal fragments, and other materials that were present on or in the plant tissues prior to burning. Rarely, other minerals, such as anhydrite, may be present in ash, depending on the nature of the fuel source (Shahack-Gross and Finkelstein 2008).

Fresh, pure ash is whitish in color when viewed in recent hearths. This white color is attributed to both the siliceous and calcitic components (Canti 2003). Other variations in color result from inclusions, such as fragments of charcoal, which

[2] Other types of ash, such as fly ash or volcanic ash, are not considered here.

contribute black particles and an overall grayish appearance to the sediment. According to experiments conducted by Wattez (1988, 1992), different burning intensities can produce color variations in fresh wood ash. Wattez reports that moderate-intensity burning produces yellow- or brown-colored ashes, while high-intensity heating produces more typical gray or white ashes. Wattez also notes that these color differences are not frequently reported in archaeological settings (Wattez 1992).

The three main components of ash are not visible to the naked eye. Consequently, methods of observing ash components include high-magnification analyses of loose samples. In the field, white sediments may be identified as ash using grain mounts viewed with a light microscope. In the laboratory, resin-impregnated or carbon-coated sediment samples can be viewed at low to high magnification using petrographic and scanning electron microscopes.

At magnifications of ×100–400, one can see that wood ash is composed primarily of silt-sized grains of calcite crystal aggregates that exhibit rhombic, triangular, or lozenge-like morphologies, depending on the orientation of the thin section (Fig. 2). These characteristic shapes and compositions result from the alteration of calcium oxalate druses present in plant tissues to micritic (<4 μm) calcite during burning (Fig. 1; see also Brochier and Thinon 2003, Figs. 1 and 2; Canti 2003, Fig. 3; and Shahack-Gross

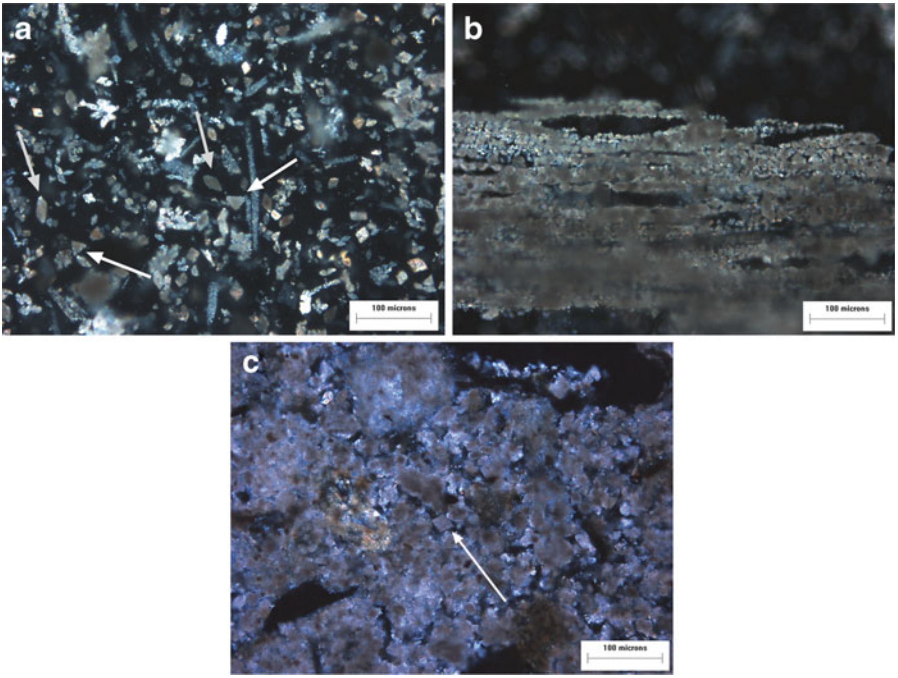

Fig. 2 Wood ash composition is dominated by calcium carbonate. **a** This grain mount of fresh wood ashes (Chilean mesquite; *Prosopis chilensis*) contains individual grains composed of aggregates of micritic calcite crystals with typical rhombic (*grey arrow*) or triangular (*white arrow*) morphologies. Experimental sample, cross-polarized light (XPL). **b** Individual calcitic druses aligned in anatomical position illustrate the relationship between the pseudomorphic crystal aggregates and the original oxalate-bearing plant structures. Experimental sample in grain mount, XPL. **c** In 30-μm-thick petrographic thin sections, two or more individual rhombs may be stacked in one position, although a single rhomb is visible here within a void (*white arrow*). Archaeological sample from Asıklı Höyük, Turkey in thin section, XPL

and Ayalon 2012, Fig. 2). In some studies, the rhombic grains composed of micritic crystal aggregates that are present in ashes are described using the acronym POCC for "pseudomorphose d'oxalate de calcium en calcite" (Brochier and Thinon 2003, p. 1212). Other grains may source from primary calcium carbonates present in plant tissues (Canti 2003). Grains or aggregates of micrite may be naturally present in archaeological sediments. For example, calcareous loess may be a primary component of the silt-sized particle fraction, while some forms of postdepositional precipitation can produce secondary silt-sized calcitic crystal aggregates. However, the morphologies described above and in Figs. 1 and 2 are unique to plant ashes. Ashes in archaeological sites are regarded as the most direct evidence of the use of fire by Schiegl *et al.* (1996, p. 764). The presence of rhombic micrite in archaeological sediments is frequently attributed to the burning of woody plants and shrubs. However, despite early attempts at classification (e.g., Wattez 1988), more specific correlations between ash morphology and different types of wood have not been found (Canti 2003; Simpson *et al.* 2003). Recent work by Shahack-Gross and Ayalon (2012) suggests that other properties of ashes, specifically their stable oxygen and carbon isotopic compositions, may be useful for distinguishing between C3 and C4 plant fuels.

The siliceous component of ashes, likewise visible only above ×100, is composed of phytoliths or their altered products (Fig. 3). Unlike rhombic micrite aggregates, phytoliths can provide information about the fuel source if they have not been significantly altered by heating or chemical degradation (Albert *et al.* 2000). Phytolith analyses may reveal not only the genus of the plant, but also the portion of the plant that was burned. In addition, certain types of plants—particularly grasses and sedges—produce significantly more phytoliths than calcite after burning (Albert and Weiner 2001; Miller and Sievers 2012). However, some plant species and tissue types, in particular woody tissues, do not contain phytoliths (Tsartsidou *et al.* 2007). When phytoliths are present in ashes, their analyses can be paired with micromorphology for a much better understanding of fuel choices over the short and long terms (Albert *et al.* 2012). Of course, phytoliths may enter archaeological sites as a result of hominin activities unrelated to combustion, such as in the form of decomposed mats or bedding (Wadley *et al.* 2011). Heated phytoliths are distinguished from unheated ones by measuring the refractive index of the silica (Elbaum *et al.* 2003). The analyses of Cabanes *et al.* (2010) of phytoliths in association with combustion features at Esquilleu Cave demonstrate the importance of using refractive index measurements to assess the degree of phytolith heating. In this example, the measurements revealed that wood and bark phytoliths in the combustion features were heated, while nearby grass phytoliths were not. This distinction suggested that there were at least two different cultural sources of phytoliths to the sediment—fuel and organic artifacts. Unfortunately, high temperatures can partly or completely melt phytoliths, although the resulting phytolith slags or glasses can be recognized by their negative relief in thin section, isotropy in cross-polarized light (XPL), white–gray color in oblique incident light, and the presence of internal vesicles (Fig. 3b, c; Canti 2003; Folk and Hoops 1982; Macphail and Crowther 2007; Zerboni 2011). Following postdepositional alteration of ashes, phytoliths may also weather into amorphous materials described as siliceous aggregates (Schiegl *et al.* 1996). These materials are also a component of fresh ashes (Schiegl *et al.* 1994). Although they can be by-

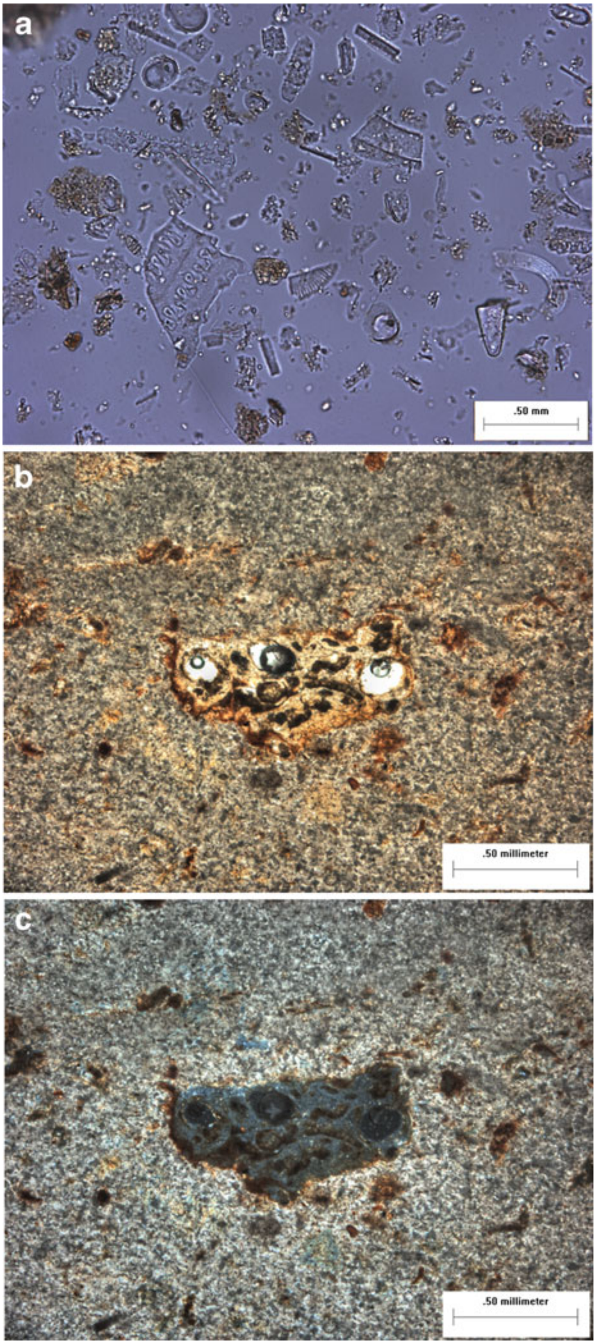

Fig. 3 Phytoliths comprise the siliceous fraction of ashes. Although visible in thin section, these materials are best identified in grain mounts of loose sediment. Burned phytoliths are identified by color (Parr 2006) and refractive index (Elbaum *et al.* 2003). **a** Grain mount of phytoliths in association with calcitic ashes at the Neolithic site of Aşıklı Höyük, Turkey; PPL. **b** Phytolith slag from the site of Üçağızlı I, Turkey in thin section. The vesicles in this material contain air bubbles; PPL. **c** Phytolith slag from the site of Üçağızlı I, Turkey in thin section (same view as above). The siliceous material is isotropic in XPL

products of burning, it is important to understand that siliceous aggregates alone are not reliable proxies for combustion activities.

Ash preservation in archaeological sites depends on both the depositional environment and postdepositional processes. Ashes are seldom preserved in open-air Paleolithic sites. They are most frequently encountered in the sheltered, alkaline environments typical of caves (Canti 2003). Loose, rhombic micrite aggregates and phytoliths are easily transported by water and wind. Thus, protected locations (such as caves), or rapid burial, contribute to ash recovery in excavation. Preservation of ashes also depends on the amount and chemistry of the water flowing through the sediments. In open-air sites, ashes near the ground surface may be dissolved by rainwater, which typically has a pH of 5.6 or lower (Drever 1997). At depth, the pH of infiltrating rainwater and groundwaters is variable and dependent on soil and sediment composition. The calcitic fraction of ashes preserves best in alkaline environments, while the siliceous fraction preserves best in neutral to slightly acidic environments. When very fresh ashes react with water, rapid dissolution of soluble salts produces highly concentrated localized groundwater solutions and soil pH as high as 9–13 and 11, respectively (Etiégni and Campbell 1991; Ulery *et al.* 1993). These conditions can contribute to the chemical breakdown of phytoliths and the preservation of the majority of the calcitic fraction of ashes (Albert *et al.* 2012; Karkanas *et al.* 2000). Extremely arid sedimentary environments are conducive to the preservation of both calcitic and siliceous components of ash because water is unavailable to act as a solvent on the materials.

Sediment texture also promotes or hinders the preservation of ashes. Because sand- or gravel-rich sediments are typically highly porous, they permit the rapid infiltration and throughflow of groundwater. Mechanical removal of ashes and, depending on the groundwater pH, dissolution may occur rapidly in these sediments. Clay-rich sediments tend to preserve ashes by preventing rapid water and particle movement. For example, the waterlogged and stagnant clay-rich sediments in the submerged Epipaleolithic campsite of Ohalo II are reported to contain preserved ashes (Tsatskin and Nadel 2003).

Charcoal (Fig. 4) is another major by-product of the combustion of plant material. Unlike ashes, large fragments of charcoal are visible to the naked eye and can be used to identify burned deposits encountered during excavation. At low and moderate magnification, charcoal is black in color, opaque in plane-polarized, cross-polarized,

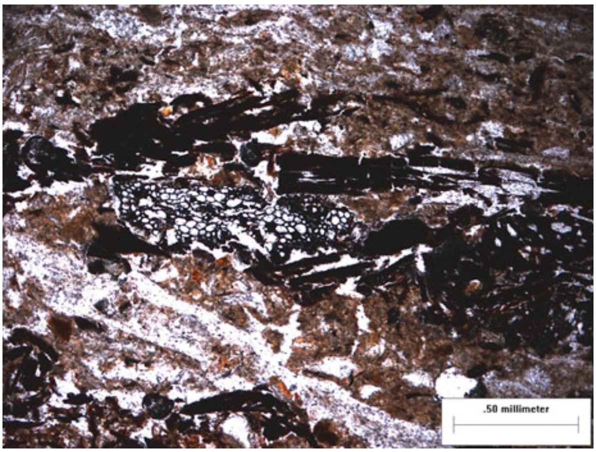

Fig. 4 Charcoal forms as a result of incomplete combustion of woody tissues. Microphotograph of charcoal in thin section from the Neolithic site of Aşıklı Höyük, Turkey. Visible orientations include cross-sections and the longitudinal plane; PPL

and oblique incident light, and morphologically resembles wood or plant tissue, although tissues and cells may be distorted. According to geochemical studies, archaeological wood charcoal is composed of carbon exhibiting a graphite-like organized phase and a nonorganized phase. The proportions of the two phases are determined by wood species, burning temperature, and diagenesis (Cohen-Ofri *et al.* 2006).

Under low oxygen conditions, the production of charcoal is favored over ash (Braadbaart and Poole 2008; Boardman and Jones 1990; Cohen-Ofri *et al.* 2006; Wattez 1988). Charcoal also dominates when wood combustion is halted by smothering or dousing with water (Braadbaart and Poole 2008; Wattez 1988). In experimental settings, well-ventilated hearths that are tended to ensure that all fuel reaches the center of the fire generally produce little charcoal and abundant ashes (Mentzer and Manne, unpublished data). Thus, one may regard abundant charcoal as evidence that combustion was less than complete.

The occurrence of charcoal in a feature or scattered within archaeological sites also depends on the fuel type and preservation conditions as well as the conditions of combustion (Boardman and Jones 1990; Cohen-Ofri *et al.* 2006; Théry-Parisot *et al.* 2010). Like phytoliths, well-preserved whole and sectioned charcoal fragments can be studied at low magnification to determine which types of plants were selected as fuel. Nonwoody plants, such as cereals, are composed of different tissues that carbonize at different rates, according to fire temperature (Boardman and Jones 1990). The burning temperature of wood charcoal of known taxonomy and tissue density may be estimated using reflectance petrology (Braadbaart and Poole 2008). Carbon reflectance, (%R) is measured on a resin-impregnated and polished sample block. If the species is unknown, the structural properties of the sample may be only generally suggestive of burning temperature since charcoal fragments with well-preserved wood structures are produced under low temperature (<1,000 °C) conditions (Braadbaart and Poole 2008). Reflectance petrology also distinguishes between decayed plant material and true charcoal and allows the identification of the charcoal type. For example, at Sibudu, this technique identified fusinite or inertodetrinite types of charcoal, which form as a result of incomplete burning (Taylor *et al.* 1998; Ligouis 2006; Goldberg *et al.* 2009), as well as secritinite, which possibly forms when plant-derived resins are heated (Ligouis 2006).

Charcoal can be susceptible to postdepositional factors. With time, the graphite-like phase of charcoal degrades via oxidation into humic substances, a process that is accelerated in alkaline environments (Cohen-Ofri *et al.* 2006). However, relative to wood ashes, charcoal is more chemically stable under a variety of archaeological settings. Thus, charcoal can become enriched relative to other combustion by-products under certain conditions of preservation, resulting in a bias in the interpretation of hearth function (Wattez 1988).

Less common archaeological by-products of burning may include plant-derived resins and gels (Berna and Goldberg 2008), as well as carbonaceous, phosphatic, or metallic compounds (Courty *et al.* 2010). Fuel was not necessarily limited to wood, even in Paleolithic times. Alternative or supplemental fuels are thought to include bone (Costamagno *et al.* 2005; Mentzer 2009; Théry-Parisot 2002; Théry-Parisot *et al.* 2005), coal (Théry *et al.* 1996), and possibly liquid hydrocarbon (Courty *et al.* 2010) in some cases. In the field, burned bone is identified by colors that range from black to white, depending on the intensity of burning (Stiner *et al.* 1995). Importantly,

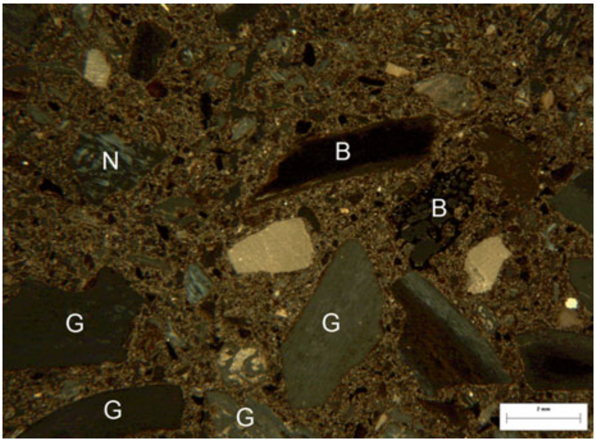

Fig. 5 Burned bones in a matrix of wood ashes from an open-air context at the Classical Greek site of Mt. Lykaion range in color from *black* (*B*) to *gray* (*G*) in XPL, indicating both charring and calcination. One bone fragment (*N*) is not burned. The groundmass of this sediment is comprised of the calcitic fraction of wood ashes; thin section

burned bone may persist in sediments long after all primary wood ash disintegrates. In thin section, lightly burned bone (Fig. 5) has an orange color in plane polarized light (PPL), fully charred bone has a black color in PPL (charred bone), and calcined bone is colorless in PPL paired with dulled interference colors in XPL (Courty *et al.* 1989, 2010; Karkanas *et al.* 2007; Schiegl *et al.* 2003; Squires *et al.* 2011). Burned bone fragments may be associated with a vitreous, vesicular substance termed "bone char" (Clark and Ligouis 2010; Goldberg *et al.* 2009) or "fat-derived char" (Miller, unpublished; Miller *et al.* 2009). The use of alternative fuels and rare by-products may be studied using a combination of zooarchaeological and statistical methods (e.g., Costamagno *et al.* 2009) or specialized microscopic, molecular, and elemental techniques, such as coal petrography, X-ray diffraction, and X-ray fluorescence (XRF) (e.g., Courty *et al.* 2010). Finally, the use of gas chromatography mass spectrometry to identify organic residues, including lipids, is more common in analyses of archaeological ceramics, but also has applications to the study of hearth sediments (e.g., Kedrowski *et al.* 2009; March *et al.* 1989, 1993).

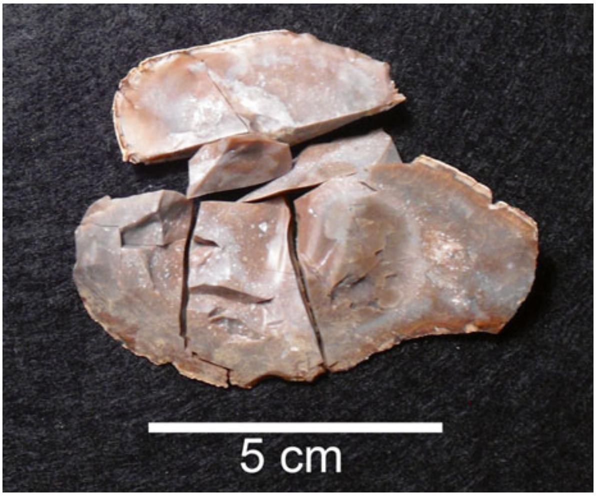

Fig. 6 A fragment of chert heated under experimental conditions. Heated flints and other types of fire-cracked rocks are sometimes used as indirect evidence for burning in archaeological sites. Fire-cracked rock fragments have also been reported in thin sections from archaeological deposits (Villagran et al. 2011a)

Rare compositional elements of combustion features include burned lithic artifacts or raw materials (Fig. 6), burned food residues (including bone and shell), burned discarded materials and other "casual fuels" (van der Veen 2007), burned soil aggregates, and rubified guano. Archaeological interpretations of such inclusions vary as to the degree intentionally attributed to their presence. Studies of rare hearth inclusions can nevertheless provide information about hearth function, age, fuel source, or temperature of burning. Burned lithic artifacts or bones may result from construction of a hearth atop or near knapping or butchery areas (e.g., Alperson-Afil *et al.* 2009; Stiner *et al.* 1995). Flints heated in this manner may be dated using the thermoluminescence technique. Construction of a hearth atop a biogenic substrate or beneath bat or bird roosts can likewise result in the production of rubified guano (e.g., Macphail and Goldberg 2000). Microarchaeological studies reveal that the minerals present in burned guano vary according to the temperature of heating. For example, in Gorham's Cave, the chemical state of organic matter within rubified guano found in association with burned sediments was used to evaluate the maximum temperature reached within the feature (Macphail and Goldberg 2000). Burned soil or sediment aggregates, like those found in sites such as Qesem and Sibudu (Karkanas *et al.* 2007; Goldberg *et al.* 2009), likely are produced when mineral matter enters fires with the fuel (Berna and Goldberg 2008). If radically different in texture or mineralogy from the geogenic sediments in the site, these aggregates may reveal information about the source of fuel brought to the site and its type (i.e., shrubby rather than woody vegetation). Identification of burned seeds can inform archaeologists about the types of plants growing near the site, the plants exploited as fuel, and in larger quantities, the plants that were consumed on-site during certain seasons or used for other purposes (see also Théry-Parisot *et al.* 2010). Lastly, burned food items may indicate the use of a fire for cooking (e.g., Gale and Carruthers 2000) or refuse disposal. Study of these burned materials may reveal information about subsistence and routine domestic activities that were conducted on-site (van der Veen 2007). Molecular changes that occur at certain temperatures in several types of food refuse can also provide additional information about hearth burning conditions. For example, the inorganic mineral component of bone tissue changes its molecular structure at known temperatures (Hiller *et al.* 2003; Rogers and Daniels 2002; Shipman *et al.* 1984), a phenomenon that has been exploited in archaeological samples from sites, such as Kebara Cave, Wonderwerk Cave, and Pech de l'Azé IV, to reconstruct temperature and degree of bone burning (e.g., Berna and Goldberg 2008; Berna *et al.* 2012; Dibble *et al.* 2009) (Fig. 7). Likewise, experimental studies indicate that the degree of calcination of burned mollusk shells and the presence of altered morphological features provide information about temperature of heating (Godino *et al.* 2011; Villagran *et al.* 2011a, b).

The Identification of Burning in the Archaeological Record

Intact Combustion Structures

In archaeological excavation, the presence of three primary components—rubified sediment or fire-cracked rock, charcoal, and ash—is used to identify intact combustion

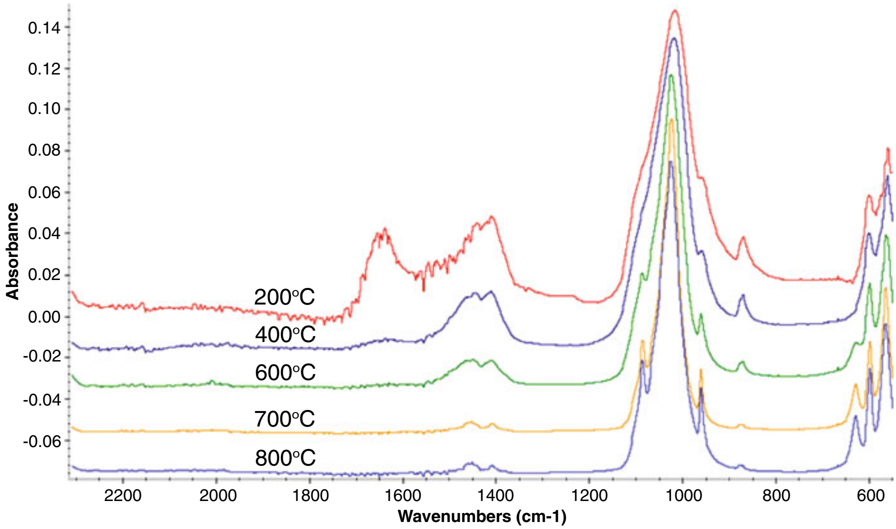

Fig. 7 Infrared analyses of burned bones yield information about burning temperature. Here, attenuated total reflectance FTIR spectra of bones heated at different temperatures exhibit characteristic peaks (see also Thompson *et al.* 2009). At 600 °C, peaks at 1,088 and 631 cm^{-1} appear. Experimental sample of pig bone (*Sus scrofa*) heated in a kiln and ground following a standardized procedure after Surovell and Stiner (2001)

structures or hearths (Fig. 8). The quantities of these three materials vary, depending on the nature of the substrate, the environment and duration of combustion, and the postdepositional alteration. The latter two materials, as discussed above, are direct by-products of burning, while rubified sediment or cracked rock are a consequence of substrate composition and exposure to heat.

Detailed and numerous macroscale and microscale descriptions of typical hearths come from the exceptionally well-studied site of Kebara Cave (Albert *et al.* 2012; Bar-Yosef *et al.* 1992; Goldberg 2001; Goldberg and Bar-Yosef 1998; Meignen *et al.* 2001, 2007; Schiegl *et al.* 1996). In Kebara, Middle Paleolithic combustion structures are generally lenticular in cross-section and located atop a flat or concave surface. When a geogenic substrate is present, the sediment is burned and rubified (Meignen *et al.* 2001, 2007; Schiegl *et al.* 1996). Charcoal-rich layers (3–5 cm in thickness) are generally found at the base of each individual feature, while ash-rich layers (5–15 cm thickness) are present at the top (Albert *et al.* 2012; Meignen *et al.* 2001, 2007). In thin section, the charcoal layers are composed of a mixture of charcoal and ash, while the ash layers are composed of rhombic micrite and phytoliths exhibiting variable states of preservation (discussed further in the succeeding paragraphs). In addition, many features contain multiple superimposed and paired layers of charcoal overlain by ash, resulting from several phases of reuse of the space (Meignen *et al.* 2001, 2007). Although single charcoal–ash couplets are typically interpreted as the remnants of one burning event (Goldberg and Sherwood 2006), some combustion structures in Kebara Cave contain very thick layers of ashes (up to 45 cm) above a comparably thick layer of charcoal. Meignen *et al.* (2007) interpret these features as evidence for multiple burning events within one feature.

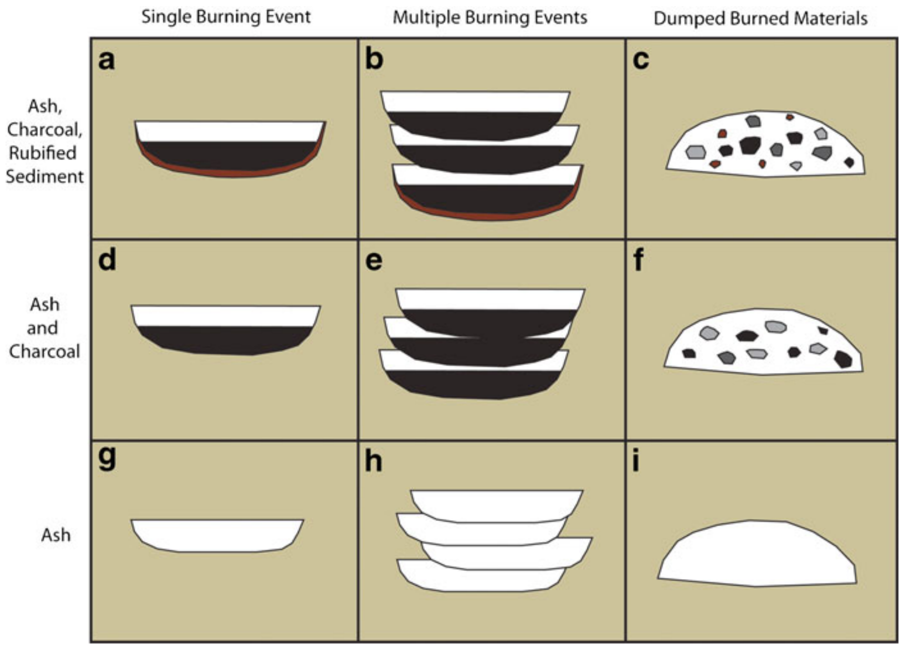

Fig. 8 A sequence of rubified sediment overlain by charcoal and ash visible in profile is indicative of an intact combustion structure (unprepared or lenticular substrate). Prehistoric archaeological sites contain many different types of combustion features that differ in morphology and composition from the typical structure illustrated in **a**. Depending on the composition of the substrate and the degree of burning, single events can produce combustion structures composed of rubified sediment overlain by charcoal and ash (**a**), charcoal overlain by ash (**b**), pure ash (**c**), or rubified sediment overlain by ash (not pictured). Multiple burning events in the same location result in stacked features containing superimposed lenses of rubified sediment, charcoal, and ash (**b**, **e**, **h**) or combinations thereof. Hearth cleaning activities produce ash dumping features that vary in composition from pure ash (**i**) to ash mixed with charcoal (**f**) to a mixture of ash, charcoal, and sediment (**c**). The identification of these features in the field is further complicated by postdepositional processes. Distinguishing between a laterally reworked or bioturbated stack of ashy hearths (**h**) and a dumped ash feature (**i**), for example, can be difficult in the field, as large pseudocarbonized plant structures and preserved plant tissues unique to (**h**) and high porosity more typical of (**i**) can only be observed at microscale

The typical sequence of rubified earth overlain by charcoal and ash has been replicated in some burning experiments (Miller *et al.* 2009; Wattez 1992). In partnership with microscopic confirmation of burned materials, this sequence has become the *fossil directeur* for a hearth. Hearths of this type have been documented in numerous archaeological sites ranging in age from Middle Paleolithic to recent (e.g., Bar-Yosef *et al.* 1992; Goldberg 2003; Goldberg and Bar-Yosef 1998; Goldberg *et al.* 2009, 2012; Homsey and Capo 2006; Karkanas 2001; Karkanas and Goldberg 2010; Macphail and Goldberg 2000; Mallol *et al.* 2010; Meignen *et al.* 2001; Rigaud *et al.* 1995; Wadley 2012; Wattez 1994; see also Tables 3, 4, 5, and 6). In some sites, rubified earth, charcoal, and ashes have been documented only in macroscale but are consistent with features that have been studied using microscopic techniques (e.g., Akazawa and Sakaguchi 1987). In other cases, the absence of these three materials in sequence, or in any context, has been used to argue against intentional combustion at certain archaeological sites (e.g., Zhoukoudian Cave; Goldberg *et al.* 2001; Weiner

Table 3 Middle Paleolithic and Middle Stone Age (Pleistocene) sites with evidence for combustion confirmed by micromorphological analyses

Site	Location	References
Type 1: Intact hearths		
Abric Romani (rockshelter)	Spain	Courty *et al.* 2010; Pastó *et al.* 2000; Vallverdú *et al.* 2005
Gorham's Cave	Spain	Macphail and Goldberg 2000
Grotte XVI (cave)	France	Karkanas *et al.* 2002; Rigaud *et al.* 1995
Hayonim Cave	Israel	Goldberg 1979; Goldberg and Bar-Yosef 1998
Kebara Cave	Israel	Albert *et al.* 2000; Bar-Yosef *et al.* 1992; Berna and Goldberg 2008; Meignen *et al.* 1989, 2001, 2007
Klissoura Cave	Greece	Karkanas *et al.* 2004
Lakonis Cave	Greece	Karkanas 2002
Melikane Shelter	Lesotho	Stewart *et al.* 2012
Pech de l'Azé IV (cave)	France	Dibble *et al.* 2009; Goldberg and Berna 2010
Pinnacle Point site PP13B (cave)	South Africa	Karkanas and Goldberg 2010
Qafzeh (Cave)	Israel	Berna and Goldberg 2008
Roc de Marsal (cave)	France	Goldberg *et al.* 2012
Sibudu (rockshelter)	South Africa	Goldberg *et al.* 2009; Schiegl and Conard 2006
Üçağızlı II Cave	Turkey	Mentzer 2011
Vanguard Cave	Spain	Macphail and Goldberg 2000
Type 2: Reworked combustion materials		
(A) Anthropogenic reworking		
Kebara Cave	Israel	Bar-Yosef *et al.* 1992; Goldberg 2001; Meignen *et al.* 2007
La Quina (rockshelter)	France	Mentzer, unpublished personal observation
Lakonis Cave	Greece	Elefanti *et al.* 2008
Pech de l'Azé IV (cave)	France	Dibble *et al.* 2009; Goldberg *et al.* 2012
Sibudu Rockshelter	South Africa	Goldberg *et al.* 2009
(B) Bioturbation		
Amud Cave	Israel	Madella *et al.* 2002
Grotte XVI (cave)	France	Rigaud *et al.* 1995
Hayonim Cave	Israel	Goldberg and Bar-Yosef 1998
Kebara Cave	Israel	Meignen *et al.* 2007
Sibudu (rockshelter)	South Africa	Goldberg *et al.* 2009
Tabun Cave	Israel	Albert *et al.* 1999
Üçağızlı II Cave	Turkey	Mentzer 2011
(C) Natural reworking (e.g., transport by water or wind, cryoturbation or pedoturbation)		
Die Kelders Cave	South Africa	Goldberg 2000
Esquilleu Cave	Spain	Mallol *et al.* 2010
Hohle Fels Cave	Germany	Goldberg *et al.* 2003; Miller, unpublished
Kebara Cave	Israel	Goldberg 2001
Obi-Rakhmat (rockshelter)	Uzbekistan	Mallol *et al.* 2009

Table 3 (continued)

Site	Location	References
Tabun Cave	Israel	Albert *et al.* 1999
Vanguard Cave	Spain	Macphail and Goldberg 2000
(D) Unspecified reworking		
Qafzeh Cave	Israel	Berna and Goldberg 2008
Type 3: Presence of combustion		
Pinnacle Point site PP13B (cave)	South Africa	Karkanas and Goldberg 2010
Tabun Cave	Israel	Albert *et al.* 1999

et al. 1998) or in favor of postdepositional modifications of the burned materials (see also Tables 3, 4, 5, and 6).

Of the three materials typical of intact hearths, the basal rubified sediment layer is most variable in its expression. "Oxidation of iron minerals" is an oft-cited cause of substrate rubification. According to Canti and Linford (2000) who described this process, brown- or yellow-colored iron oxide minerals, such as goethite, are typically present in sediments. Upon heating, these minerals transform to hematite, which is bright red in color. However, under certain burning conditions, iron oxides transform to other minerals. For example, under reducing conditions, brown or black maghemite can form. In addition, some substrates are composed of sediments or materials that do not contain iron. These substrates are theoretically unlikely to rubify upon heating.

Canti and Linford (2000) explored the process of sediment rubification and the effects of *in situ* burning on different types of substrates. They reviewed previously published experiments and observations of natural fires and found that, at several centimeters depth within an assortment of substrates, temperatures varied widely (from ~100 to ~500 °C), depending on the composition of the substrate and the duration of burning. In their own subsequent experiments, Canti and Linford documented substrate temperatures of more than 400 °C beneath fires exceeding 800 °C. Despite these high temperatures, only one of the three different test substrates exhibited rubification upon cooling. Within this substrate, Canti and Linford observed that the thickness of the red zone remained the same no matter the duration of burning (ranging from 6 h to 4 days). They hypothesize that rubification occurs only in sediments of a certain composition (determined in particular by the minerals present, organic material, and moisture content). However, when compositional requirements are met, the color change can be quite dramatic. Other experimental studies yield contradictory results. For example, following replication of the various types of prepared and unprepared burning surfaces at the site of Pincevent, March *et al.* (2010) observed visible differences in the rubified and blackened substrates, including a relationship between the thickness of the rubified zone and the duration of burning. Actualistic studies of prepared burning surfaces conducted by Homsey and Sherwood (2010) documented shifts in color in cave sediments following mixture with water and firing. In their experiments, four of five surfaces became darker and redder, while the fifth became lighter in color with no rubification. The archaeological significance of these findings is that reddening is

Table 4 Upper Paleolithic (Pleistocene) sites with evidence for combustion confirmed by micromorphological analyses

Site	Location	References
Type 1: Intact hearths		
Abric Romani (rockshelter)	Spain	Vallverdú 2002
Etoilles	France	Wattez 1994
Gorham's Cave	Spain	Macphail and Goldberg 2000
Kebara Cave	Israel	Bar-Yosef *et al.* 1992
Klissoura Cave	Greece	Karkanas 2010; Karkanas *et al.* 2004
Pincevent	France	Wattez 1994
Theopetra (cave)	Greece	Karkanas 2001
Üçağızlı I Cave	Turkey	Goldberg 2003; Mentzer 2011
Verberie	France	Wattez 1994
Type 2: Reworked combustion materials		
(A) Anthropogenic reworking		
Hohle Fels Cave	Germany	Goldberg *et al.* 2003; Miller, unpublished; Schiegl *et al.* 2003
Kebara Cave	Israel	Meignen *et al.* 2007
Klissoura Cave	Greece	Karkanas 2010
Üçağızlı I Cave	Turkey	Goldberg 2003; Mentzer 2011
(B) Bioturbation		
Gorham's Cave	Spain	Macphail and Goldberg 2000
Klissoura Cave	Greece	Karkanas 2010
Üçağızlı I Cave	Turkey	Goldberg 2003; Mentzer 2011
Verberie	France	Wattez 1994
(C) Natural reworking (e.g., transport by water or wind, cryoturbation or pedoturbation)		
Etoilles	France	Wattez 1994
Hohle Fels Cave	Germany	Miller, unpublished
Kebara Cave	Israel	Goldberg and Bar-Yosef 1998
Pincevent	France	Wattez 1994
Theopetra (cave)	Greece	Karkanas 2001
Üçağızlı I Cave	Turkey	Goldberg 2003; Mentzer 2011
(D) Unspecified reworking		
Geißenklösterle (cave)	Germany	Goldberg and Berna 2010; Miller, unpublished
Klissoura Cave	Greece	Karkanas *et al.* 2004

Micromorphological studies of Upper Paleolithic combustion features are not conducted as frequently as at Middle Paleolithic sites, perhaps due to the identification of hearths in these sites (e.g., the Abri Pataud) using visibly prepared substrates or rock linings that are readily observable in the field

dependent on both substrate composition and burning conditions and that the thickness of the rubified zone cannot be consistently correlated with hearth function.

At microscale, rubification and other heat-induced alterations to the substrate are also variable. According to experiments conducted by Wattez (1992), microscopic features, such as cracking of sedimentary aggregates and rock fragments, and

Table 5 Later Stone Age, Epipaleolithic, Natufian, Mesolithic, Paleoindian, and Archaic (Paleoamerican) sites with evidence for combustion confirmed by micromorphological analyses (these types of sites are generally Late Pleistocene to Early Holocene in age)

Site	Location	References
Type 1: Intact hearths		
Dust Cave	USA	Homsey and Capo 2006; Sherwood 2001, 2008; Sherwood and Chapman 2005
Mesolithic Site 16-D-4	Sudan	Zerboni 2011
Mesolithic Site 16-D-5	Sudan	Zerboni 2011
Type 2: Reworked combustion materials		
(A) Anthropogenic reworking		
Dust Cave	USA	Homsey and Capo 2006; Sherwood 2001, 2008
Lapa das Bolieras (rockshelter)	Brazil	Araujo *et al.* 2008
Mesolithic Site 16-D-4	Sudan	Zerboni 2011
(B) Bioturbation		
Dust Cave	USA	Sherwood 2001, 2008
Kitulgala Beli-lena (rockshelter)	Sri Lanka	Kourampas *et al.* 2009
Lapa das Bolieras (rockshelter)	Brazil	Araujo *et al.* 2008
Mesolithic Site 16-D-5	Sudan	Zerboni 2011
(C) Natural reworking (e.g. transport by water or wind, cryoturbation or pedoturbation)		
Dust Cave	USA	Sherwood 2001
Kitulgala Beli-lena (rockshelter)	Sri Lanka	Kourampas *et al.* 2009
Lapa das Bolieras (rockshelter)	Brazil	Araujo *et al.* 2008
Type 3: Presence of combustion		
Sierra Diablo Cave	USA	Mentzer, unpublished data

masking of clay birefringence occur only beneath moderate-intensity fires (350–500 °C). Rubification and development of a granular microstructure occur as a result of high-intensity fires (>500 °C). These features may or may not be present in archaeological sites. Mallol *et al.* (2007) reported both masked and higher clay birefringence beneath ethnographic fires, the former attributable to the presence of finely divided charcoal mixed into the sediment. Moreover, they also observed that hearth substrates that appeared rubified in the field were either indistinguishable from natural soils or only slightly rubified in thin section.

Finally, the identification of heat-induced rubification is controversial due to other processes that can produce red deposits within sites. For example, in Pech de l'Azé IV Layer 8, rubified sediments are present; however, Dibble *et al.* (2009) are cautious in their interpretation of these materials as burned due to the presence of hematite in unburned sediments within the cave. In the nearby site of Pech de l'Azé II, as well as the sites of Üçağızlı I and Zhoukoudian, red sediments naturally occur in deposits above the cave entrances (Goldberg 1979, 2003; Goldberg *et al.* 2001) and colluvial processes may contribute to their incorporation into the archaeological deposits.

Table 6 Ethnoarchaeological and experimental studies of combustion features paired with micromorphological analyses.

Site	Location	References
Type 1: Intact hearths		
Experimental wood fires	France	Wattez 1988
Experimental wood fires	Germany	Miller *et al.* 2009
Experimental wood fires	Argentina	Godino *et al.* 2011; Villagran *et al.* 2011b
Experimental burned bedding	South Africa	Miller and Sievers 2012
Hadza village fires	Tanzania	Mallol *et al.* 2007
Maasai village fires	Kenya	Shahack-Gross *et al.* 2004
Yamana fires associated with shellfish processing and consumption	Argentina	Villagran *et al.* 2011a
Type 2: Reworked combustion materials		
(A) Anthropogenic reworking		
Experimental dumped and trampled deposits	Germany	Miller *et al.* 2009
Yamana fires associated with shellfish processing and consumption	Argentina	Godino *et al.* 2011; Villagran *et al.* 2011a
(B) Bioturbation		
Yamana fires associated with shellfish processing and consumption	Argentina	Godino *et al.* 2011; Villagran *et al.* 2011a
Type 3: Presence of combustion		
Experimental ash production of different fuels at various temperatures using a muffle furnace	Iceland	Simpson *et al.* 2003
Experimental heating and petrography of shells and whale bone	Argentina	Godino *et al.* 2011; Villagran *et al.* 2011a, b

Lastly, rubified layers of postdepositional chemical origin have been documented at Grotte XVI (Karkanas 2010; Karkanas *et al.* 1999, 2002).

In some sites, an alternative to the basal rubified substrate is an intentionally prepared combustion surface or hearth lining. Middle Paleolithic hearths are typically built atop unmodified surfaces, although the shallow lenticular profiles observed in Mousterian layers of Kebara Cave may be indicative of limited surface preparation (Meignen *et al.* 2001, 2007). However, Mallol *et al.* (2007) observed that a similar profile results from ash removal during hearth maintenance. In the Middle Paleolithic of Europe, hearth preparation is likewise limited to the construction of a lenticular basin or exploitation of naturally flat or basin-shaped surfaces (e.g., Abric Romani; Pastó *et al.* 2000; Vallverdú *et al.* 2012). Abric Romani levels J and K contain the only examples of block-lined Middle Paleolithic hearths (Pastó *et al.* 2000) and levels J and O contain features interpreted as prepared hearth substrates (Courty *et al.* 2010). In the Middle Stone Age rockshelter site of Sibudu, hearths are constructed atop flat or concave surfaces or on roof block surfaces (Wadley 2010). Rock-lined or paved hearths (a.k.a. fireplaces) appear regularly in the Eurasian Upper Paleolithic and become especially common in later periods. These features allow the ready identification of burning areas in open-air sites such as Kostenki (Grigor'ev 1993), where other combustion by-products are not consistently preserved.

Manufactured hearth substrates are very rare in the Paleolithic but common in some later periods. Paleolithic examples are reported in the Aurignacian layers of Klissoura Cave, where dozens of hearths are lined with red clay that was collected and brought into the site (Karkanas *et al.* 2004). The clay linings were hardened by the fires built within them or by embers that were transferred into them from other fireplaces. Early prepared clay burning surfaces are reported in the Americas at Monte Verde (Quivira and Dillehay 1988) and at the Archaic sites of Ice House Bottom and Dust Cave, the latter studied at high resolution using micromorphology (Sherwood 2001, 2008; Sherwood and Chapman 2005). These features exhibit compositions and textures that distinguish them from the natural substrates in the archaeological layers of the same sites. In Dust Cave, the hardness of the clay appears to correlate with the temperature of the fire or the duration of burning, factors that may relate to the function of the combustion feature. Textile impressions and very thin ash crusts on the clay surfaces provide additional information on the mode of preparation and sweeping after or during use (Sherwood and Chapman 2005).

Micromorphological studies of the layers of charcoal and ash within hearths have also revealed variability in thickness and expression due to burning conditions and combustion-related activities. Experimental studies have produced different types of sequences. Burning experiments conducted by Miller *et al.* (2009) produced typical clear sequences of rubified sediment overlain by charcoal and ash. On the other hand, Wattez (1992) documented some variability in the morphology and color of the charcoal and ash layers that formed in experimental fires. This variability occurred as a function of burning intensity. In her experiments, moderate-intensity fires produced basal layers of carbonized organic material overlain by upper layers of charcoal mixed with ash, while high-intensity fires produced upper layers composed of pure ash.

Charcoal is not the only source of black material in archaeological sediments. Although combustion structures at some sites exhibit blackened basal layers, micromorphology reveals that these layers contain fine sediment that is enriched in plant-derived organic material (Mallol *et al.* 2007; Goldberg *et al.* 2012) or organic material mixed with blackened bone (Dibble *et al.* 2009). At Pinnacle Point site PP13B, Karkanas and Goldberg (2010) observe some black layers that contain charcoal and burned bones, while others contain only humified organic material. Finally, as described above, burning under reducing conditions can lead to the formation of brown or black iron-bearing minerals that in the field may be confused with charcoal.

Other studies suggest that the charcoal layers in hearths may be thin or, in some cases, absent. In Hayonim Cave, for example, some combustion structures are composed of bedded ashes atop bedded ashes mixed with burned terra rossa (Berna and Goldberg 2008, Fig. 2d). In Klissoura Cave, some Upper Paleolithic clay-lined hearths contain only ash (Karkanas 2010). At Pech de l'Azé IV, clear charcoal layers were not observed within the portions of the Layer 8 combustion sequence that were analyzed using micromorphology, despite the fact that charcoal layers were encountered during excavation and charcoal samples were analyzed using paleobotanical methods (Dibble *et al.* 2009). In ethnographic settings, development of charcoal beds beneath ash is also inconsistent. Mallol *et al.* (2007) reported that intact Hadza hearths contain only ashes mixed with variably carbonized materials exhibiting preserved cellular structures. Some archaeological sites contain exceptionally thick ash layers over comparatively thin layers of charcoal. Karkanas *et al.* (2004, 2007) speculated that such thick ash layers can form from the continuous use of fires, especially when coupled with low geogenic sedimentation rates. Based on experimental calculations, the substantial ash deposits that are present in some Near Eastern sites could form as a result of several years of continuous combustion of wood (Schiegl *et al.* 1996).

When rubified sediments and charcoal layers are absent, other characteristics present within ashes can confirm that combustion structures are intact. In Kebara Cave, for example, Meignen *et al.* (2001) used fragile layers of unbroken phytoliths within thick combustion sequences to identify individual structures that were not reworked. Stewart *et al.* (2012) also reported ashy deposits containing articulated phytoliths and intact leaf structures in the Middle Stone Age site of Melikane Rockshelter. Karkanas *et al.* (2007, p. 208) likewise used the “wavy internal fabric” of certain ash lenses in Qesem Cave to further support stratigraphic indications that they are intact. In Hadza hearths, Mallol *et al.* (2007) observed aligned clay intercalations within the intact ash layers, which they interpreted as undisturbed clays that were present within the plants prior to burning (Mallol *et al.* 2007, Fig. 10b). Other features present in intact ash layers include materials that Wattez (1988, p. 361 and Fig. 11) described as “residues brun noir” or “residues gris.” These materials, which exhibit morphologies consistent with plant tissue in thin section, preserve a stage of combustion during which charcoal is incompletely converted to ash. Mallol *et al.* (2007, pp. 2038–2039) described this stage of plant burning as “pseudocarbonization,” and the features visible in thin section as “pseudocarbonized wood.” In consideration of the fact that the term “pseudocarbonized” is misleading as to the dual calcitic and carbonized composition of the material, it is proposed here that the phrase “partially carbonized tissues” be used to describe such features in the future. In Dust Cave, plant tissue pseudomorphs are composed entirely of ash and are termed “articulated ash” (Sherwood 2001, p. 130; 2008). Like the pseudocarbonized wood structures of Mallol *et al.*, these features can exhibit the original fabric of the wood tissues. Courty *et al.* (1989, Figs. 34 and 35) observed similar structures in layer 9 of Grotte Vaufrey and interpreted them as burned fragments of plant stems or leaves. Here, these features will be described as “articulated ashes,” a phrase modified from Sherwood (2001, 2008) that acknowledges the presence of multiple micritic crystal aggregates in anatomical position.

Articulated ashes and partially carbonized tissues generated under experimental conditions (Fig. 9) are exceptionally fragile. These features are thus ideal for assessing the preservation of ash layers. Mallol *et al.* (2007) observe “pseudocarbonized wood,” “ash bundles,” and “carbonized and calcitic cells in anatomical position” in thin sections of intact Hadza hearths. In one hearth, they state that preservation is “excellent, as shown by the undisturbed position of the plant cells in the ash” (Mallol *et al.* 2007, p. 2041). These observations extend to archaeological settings. Homsey and Capo (2006) state that, in Dust Cave hearths, “calcitic pseudomorphs indicate minimal transport or disturbance.” Shahack-Gross *et al.* (2008, Fig. 6c) document “pseudomorphic cellular structures after woody tissue” that are present in cemented and laminated ash deposits at Amud Cave, later interpreted as intact hearths. Karkanas

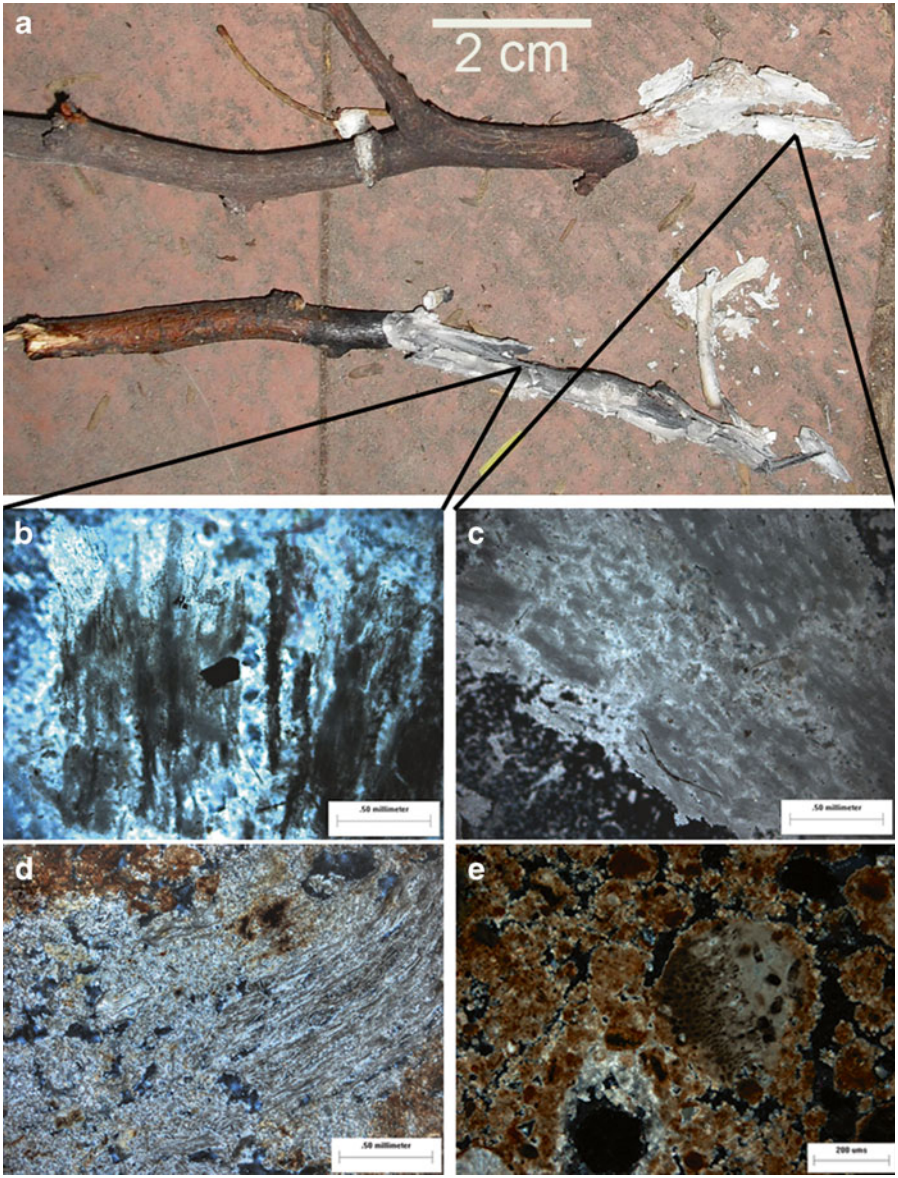

Fig. 9 Articulated ashes and carbonized tissues are indicative of intact ash deposits. **a** Photograph of two partially burned Chilean mesquite (*P. chilensis*) sticks that exhibit exceptionally fragile structures composed of charcoal, intermediate "pseudocarbonized"(*sensu* Mallol *et al.* 2007) or partially carbonized phases, and calcitic ash. **b** Photomicrograph of a grain mount of the partially carbonized phase from the lower stick; XPL. **c** Photomicrograph of a grain mount of articulated ashes from the upper stick. Informal agitation studies suggest that these multimillimeter structures would not frequently survive hearth sweeping or dumping episodes unless ash layers were previously cemented. Further work must be done to quantify these effects; XPL. **d** Articulated ashes and partially carbonized tissues in a thin section from a variably cemented ash layer in the archaeological site of Üçağızlı I; XPL. **e** Reworked and cemented articulated ashes and partially carbonized tissues in a thin section from the site of Üçağızlı II. The rounded edges of this sand-sized fragment are indicative of mechanical abrasion. The surrounding matrix is ashy material mixed with geogenic materials; XPL

(2010, Fig. 10) identifies "calcitic cellular pseudomorphs after plant tissues" in hearths in Klissoura Cave. Finally, these features are present in two early sites with evidence for burning. *In situ* ash lenses at Qesem Cave contain articulated ashes and partially carbonized tissues (Karkanas *et al.* 2007, Figs. 5b, 10, and 12b); not surprisingly, intact hearths are rare in relation to disturbed ash deposits in this early site. The ash deposits at Wonderwerk Cave also contain "ashed plant material" (Berna *et al.* 2012, Fig. 3). In sum, although archaeological, experimental, and ethnographic studies demonstrate that intact hearths are compositionally variable, many different types of microscopic features may be used to assess their degree of preservation.

Other microscopic features suggest partial erosion or alteration of otherwise intact structures. The most common types of alteration features, especially prevalent in caves, include discontinuous layers or secondary minerals formed *in situ* (Goldberg 2000). In Pinnacle Point site PP13B, Karkanas and Goldberg (2010) interpret layers of burned bone and charcoal without overlying ash as intact combustion structures. In this locality, secondary carbonate recrystallization and dissolution have negatively impacted the preservation of ashes. Similar sequences are present in Sibudu, although, here, ashes are sometimes locally preserved (Goldberg *et al.* 2009). At this site, charcoal layers are exceptionally thick, while rubified substrates are also present, but very thin. In Melikane Rockshelter, ashes are partially dissolved and locally recrystallized; however, articulated phytoliths observed within burned features suggests that they are intact (Stewart *et al.* 2012). The causes and types of postdepositional dissolution processes implicated by such sequences are discussed further in the succeeding paragraphs.

Reworked Combustion Materials

Some sites contain burned materials in secondary position ("type 2" of Tables 3, 4, 5, and 6). These materials indicate that burning likely took place somewhere within the site, either within a documented intact structure or elsewhere. The site of Tabun highlights the necessity of using microarchaeological techniques to assess the integrity of combustion features. In Tabun Level C, features composed of alternating layers of black, brown, and white sediment. At <50 cm diameter, these features resemble hearths in cross-section, but features visible at microscale indicate reworking to a degree that the original depositional mechanism is unknown (Albert *et al.* 1999). These results suggest that the presence of multicolored laminations in the field is not unambiguous evidence for intact hearths. Reworking of burned materials can range from movement on the order of millimeters to multiple meters and can occur as a result of geological processes, animal activity, or human activity. The macroscopic and micromorphological identification of naturally or biologically reworked deposits is discussed here, while case studies, in particular those concerning human modification during combustion-related activities, are detailed in later sections.

In the field, reworked combustion materials are identified primarily by the absence of the tripartite sequence of rubified sediment, charcoal, and ash described above, as well as by the mixing of burned and unburned materials (Fig. 10a; Schiegl *et al.* 2003). Other features indicative of reworking are visible only at the microscale (Fig. 10b). These include rounding or mechanical abrasion of burned materials or sedimentary fabrics such as laminations, long-axis alignment,

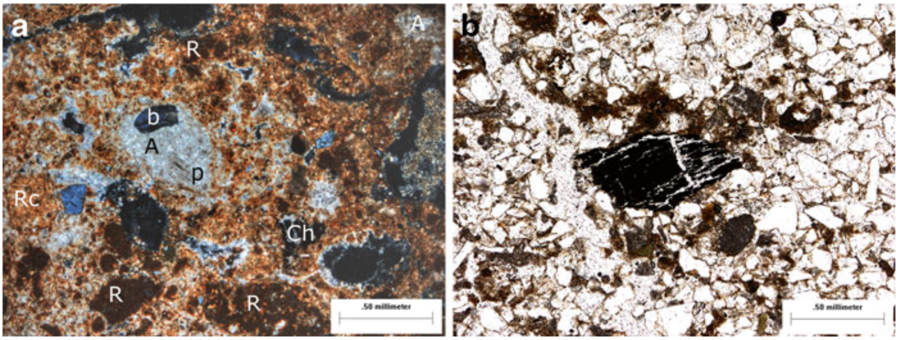

Fig. 10 Reworking by natural processes. **a** Reworked burned materials in a thin section from the Ahmarian layers at Üçağızlı I. This deposit contains rounded, reworked aggregates of geogenic materials, including red clay and silt (*R*) and cemented red clay and silt (*Rc*) mixed with materials sourced from combustion structures, including charcoal (*Ch*), and aggregates of ashes (*A*), one of which contains a fragment of bone (*b*) and partially carbonized wood tissue (*p*). The matrix of this sample is partially cemented red silt and clay mixed with wood ashes. Macroscale features of the layer are indicative of colluvial transport; XPL. **b** Reworked fragment of charcoal within a thin section from a water-lain deposit at the site of La Quina. The matrix is sorted and laminated quartz, carbonate, and glauconite sands sourced from the local limestone bedrock; PPL

and textural sorting, including microscopic graded bedding. Laminated burned materials have been reported from the site of Lapa das Bolieras, where they are interpreted as secondary reworking by water (Araujo *et al.* 2008). In Kebara Cave, sorted and rounded fragments of charcoal are present within laminated and sandy deposits (Goldberg 2001). In the field, such features are often termed "stringers." Stringers can be indicative of reworking by water or wind. Stringers of burned bone and/or charcoal have been identified within Die Kelders Layer 7 (Goldberg 2000). In Dust Cave, stringers of charcoal are sorted and graded. These textural features, in combination with ash depletion, suggest reworking by water (Homsey and Capo 2006; Sherwood 2001). Slight reworking of burned materials by low-energy water movement has also been documented experimentally by Villagran *et al.* (2011b) and at the Paleolithic sites of Etiolles and Pincevent (Wattez 1994). In the sites of Obi-Rakhmat and Esquilleau Cave, reworking of burned materials by local spring water is additionally evidenced by visible redoximorphic features and clotted calcite (Mallol *et al.* 2009, 2010).

Other natural postdepositional reworking processes that impact hearths include colluvial movement, cryoturbation, and pedoturbation. Colluvial deposits are distinguished from water- or wind-lain sediments by their heterogeneous compositions, erosive lower boundaries, and lack of textural sorting (see also Fig. 10a). In some depositional environments, colluvial reworking is also evidenced by grain rounding and coating (Miller, unpublished). Colluvial reworking of burned materials is a common occurrence throughout the sequence at Üçağızlı Cave I (Mentzer 2011). Within the Üçağızlı I deposits, colluvial layers in places truncate intact hearths and contain rounded aggregates of cemented ashes mixed with geogenic sediments.

Cryoturbated sediments are identified in thin section by several characteristic features. These include aggregated microstructures in which coarse materials are coated by clay and silt, platy microstructures, or postdepositional porosity increases relative to the original deposit, depending on the sediment texture. Cryoturbated combustion features have been identified at the sites of Hohle Fels and Esquilleau Cave. In Hohle Fels, cryoturbated layers are identified by the presence of coated bone fragments and rounded, sand- and silt-sized fragments of burned bone mixed with a small amount of ashes (Goldberg *et al.* 2003; Miller, unpublished; Schiegl *et al.* 2003). In Esquilleau Cave, Mallol *et al.* (2010) describe deposits that have been reworked by a combination of cryoturbation, spring activity, and carnivores.

Some postdepositional movements obscure the original fabrics but do not significantly impact the position of materials. For example, mild gravitational settling of fine burned materials is present in the thin sections of features from Pech de l'Azé IV with postdepositional movement occurring over distances of millimeters to centimeters (Dibble *et al.* 2009). In addition, Mallol *et al.* (2007) report that the dominant types of voids in well-preserved, intact hearths are packing voids, which are empty spaces between particles. Therefore, the presence of larger voids or higher sediment porosity within archaeological hearths may be indicative of some postdepositional disturbance. Sherwood (2008, p. 37) terms materials that have been reworked within the original locality of combustion as "mixed burned deposits."

Fine-scale, local reworking can also arise from the movements or feeding activities of insects and other small animals (Fig. 11). These processes have impacted combustion features at many archaeological sites. Bioturbation has locally dispersed burned materials in Amud Cave (Madella *et al.* 2002). At Verberie, postdepositional bioturbation resulted in excremental fabrics, fragmentation of burned materials, homogenization of formerly layered combustion by-products, and mixing of burned anthropogenic materials with natural materials (Wattez 1994). In Tabun Cave level C, bioturbation has resulted in channels, pellets, and very localized mixing of combustion materials (Albert *et al.* 1999). In Üçağızlı I Cave, insect activity has differentially impacted the ash and charcoal layers of intact, stacked combustion structures. While ash layers preserve internal laminated fabrics and contain articulated ashes and partially carbonized tissues, the charcoal layers exhibit crumb structures and high porosities that are indicative of postdepositional reworking. Identification of these

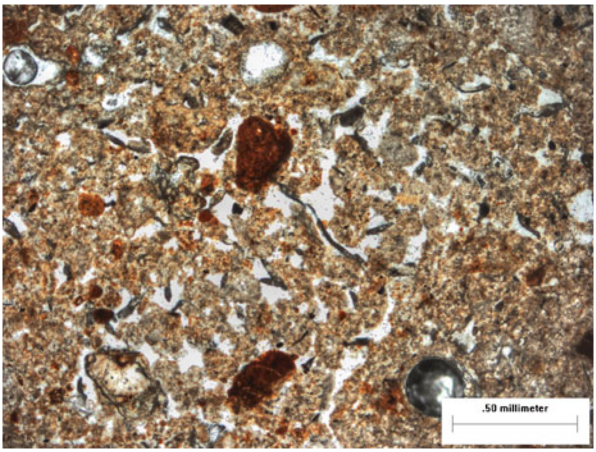

Fig. 11 A bioturbated anthropogenic layer from the site of Üçağızlı I contains welded, pellet-shaped microaggregates of ashes mixed with geogenic red clay and silt. The overall porosity is higher than intact ash layers, laminations are absent, and fragile structures such as partially carbonized tissues or articulated ashes are not preserved. Thin section, PPL

features as intact relies entirely on the microscopic characteristics of the ashes (Mentzer 2011).

Bioturbation may also cause extensive homogenization of burned materials. Mixing due to carnivore activity (e.g., the aforementioned deposits at Esquilleu Cave; Mallol *et al.* 2010) can be identified in the field and thin section by the presence of coprolites and digested bone fragments. Smaller mammals produce burrows as well as homogenized deposits. Infilled burrows may be visible in excavation profiles or identified in thin section by higher sedimentary porosity. Insects feed on organic material present in the sediment, as well as on other insects. Intense insect activity related to feeding can result in the obliteration of all primary depositional fabrics, an increase in porosity, and the development of a strong crumb to spongy microstructure. In the site of Üçağızlı II, a combination of insect and rodent bioturbation has obliterated all primary combustion features in the eastern half of the excavation trench, while in Üçağızlı I, insect activity within suspected ash dumps or middens prevents further archaeological interpretation (Mentzer 2011). Studies of intact hearths at both sites indicate that bioturbation by all types of organisms is hindered by postdepositional cementation.

Indirect Evidence for Burning

Finally, some archaeological sites or layers contain isolated burned materials; however, the exact locality of burning and relationship to human activity are unknown. At the macroscale, burned bones and heated lithic artifacts are the most recognizable indirect evidence for burning, although other rare types of burned materials have been documented (e.g., Vandiver *et al.* 1989). In one case study, Stiner *et al.* (2011) used the frequency and intensity of burned bones to identify the presence and horizontal distribution of combustion activities in the lowermost layers of Qesem Cave, where intact structures or preserved ash are lacking. A similar approach was utilized at the sites of Wallertheim A and Tönchesberg 2B (Conard *et al.* 1998; Adler *et al.* 2003). Likewise, Goren-Inbar *et al.* (2004) and Dibble *et al.* (2009) consider burned flints to be usable proxies for combustion at sites when postdepositional conditions may have negatively impacted the preservation of hearths (c.f. Roebroeks and Villa 2011). In the site of Pech de l'Azé IV, for example, intact and semi-intact combustion structures are present only in the lowest layers of the site in association with burned lithic materials. Above Layer 8, burned flints are present but decrease significantly in abundance towards the top of the archaeological sequence. Sandgathe *et al.* (2011) interpret this trend as evidence for a lack of hearths in the upper portion of the sequence. In some cases, chert may be intentionally heated in order to influence its fracture properties. Therefore, it may be possible to determine if the heating of the flints occurred at the site by identifying the stage in the reduction sequence of the heated materials. If only finished tools or blanks show evidence of heating, it could be argued that heating was intentional and that heat-treated artifacts were preferentially transported to the site. On the other hand, if unmodified waste flakes removed during the early stages of the reduction sequence have been heat-altered, the alteration is likely to have occurred in the vicinity of the knapping area. Refitting of burned and nonburned lithic materials may also indicate that heating occurred following knapping on site. Other macroscale heated materials that may be recovered out of primary context include isolated burned bones, heat-treated wood tools, fragments of charcoal, and faunal and heated rock assemblages associated with grease-rendering.

In thin section, indirect evidence for burning at or near an archaeological site most commonly occurs as microscopic fragments of charcoal (e.g., Angelucci 2003; Boschian 1997; Kourampas *et al.* 2009). In Tabun Cave Level B, charcoal present within terra rossa-derived sediments suggests that burning took place at the site during their deposition (Albert *et al.* 1999). However, microscopic charcoal fragments can enter archaeological sites and other types of deposits following non-anthropogenic burning events, such as forest fires (see, for example, Goldberg *et al.* 2001; Théry-Parisot *et al.* 2010). Heated debitage or bedrock fragments may also be identified in thin section. Under magnification, heated chert is identified by the presence of microfractures (Angelucci 2003). Similarly heated fragments of limestone bedrock may develop shrinkage cracks and reaction rims when exposed to water after burning (Karkanas 2007). Other lines of indirect evidence for combustion in thin section include burned bones or burned shell in otherwise unburned sediments (Angelucci 2003; Karkanas and Goldberg 2010). Rubified sediments, as discussed above, are ambiguous indicators of burning but are sometimes cited as indirect evidence of burning. These arguments may be compelling when the color, structure, or optical properties of the rubified sediments are significantly different from the natural sediment (Angelucci 2003; Courty *et al.* 1989; Wattez 1992). For example, in Kebara Cave, reworked aggregates of rubified terra rossa are distinguished from unaltered sediment by their characteristic color and the presence of internal cracks (Meignen *et al.* 2007, Fig. 4.30). In Tabun Level B, stronger birefringence at the edges of clay-rich soil aggregates is cited as possible evidence for heating of the sediment (Albert *et al.* 1999; Courty *et al.* 1989). These observations can be further supplemented by other microarchaeological studies. For example, magnetic susceptibility and mineralogy, when paired with micromorphology, have proved useful in the identification of heated sediments (e.g., Herries and Fisher 2011). Likewise, molecular analyses, such as Fourier transform infrared spectroscopy (FTIR), can be used to document the presence of structural changes within certain clay minerals that indicate heating to specific temperatures (e.g., Berna *et al.* 2007).

Postdepositional Chemical Alterations of Intact or Reworked Deposits

As evidenced by the dominance of cave sites in Tables 3, 4, and 5, most prehistoric sites with visible or well-preserved combustion structures are found in caves or rockshelters. This bias is due to the fact that hearths in open-air sites are susceptible to a greater range of postdepositional modifications such as winnowing by wind, transport and dissolution by water, and mechanical alteration by soil fauna. Ethnographic studies support these observations. Mallol *et al.* (2007) noted that the components of open-air fires break down rapidly following abandonment. In a study of Maasai hearths and trash pits of varying age, Shahack-Gross *et al.* (2004) documented vesicular structures indicative of ash dissolution. Their observations suggest that dissolution proceeds quickly in open-air sites, with some features appearing within a year of abandonment. However, hearths in caves are not immune to chemical alteration. Despite highly alkaline groundwater environments, ash dissolution may still occur within limestone cave deposits. In addition, caves are home to a number of unique chemical microenvironments that contribute to the alteration or obliteration of burned deposits. Finally, some cave systems and rockshelters are formed within noncalcareous rock formations, such as sandstone or basalt. In these settings, dissolution can occur rapidly.

Because wood ashes are composed almost entirely of calcite, decalcification can significantly undermine the preservation of ash layers in hearths and reworked deposits. Decalcification of ashes has been documented in Paleolithic sites, such as the sandstone rockshelter of Sibudu (Goldberg *et al.* 2009) and the open-air site of Verberie (Wattez 1994). Decalcification occurs as a result of acidic conditions or flushing of water with low amounts of dissolved calcium carbonate through porous sediments. Decalcification can be recognized in the field by loss of volume (Goldberg 2000) and in thin section by dissolution pedofeatures, such as mammilate edges on limestone fragments. Decalcification is a basic soil-forming process that occurs within the leached surface horizons of sedimentary deposits and is responsible for the breakdown of ashes in most open-air sites (Fig. 12).

Decalcification features are invaluable for understanding the ancient chemical environment in sediments or the conditions of site burial. According to Sherwood *et al.* (2004), decalcification in Dust Cave was more common during periods of less intense use of the site. This is because anthropogenic materials, particularly wood ash, raise sediment pH acting as primary buffering agents to sediment. Decalcification is further slowed by arid conditions or prevented when water entering the sediments is already saturated in calcite, as occurs in some limestone caves. Water becomes saturated in calcite by dissolving overlying bedrock or carbonate-bearing sediments. If such waters off-gas CO_2 or evaporate within the combustion deposit, secondary carbonate

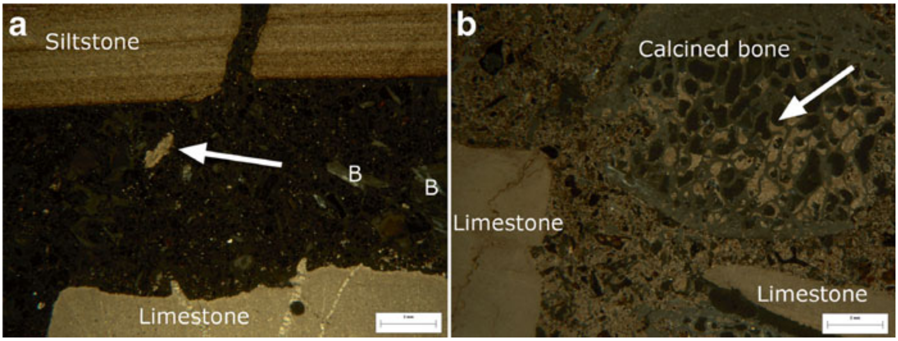

Fig. 12 Decalcification and ash dissolution are visible in thin sections from the open-air site of Mt. Lykaion (a ritual burned deposit that nevertheless illustrates the taphonomic principles discussed in this article). **a** Here, acidic rainwater infiltration has resulted in ash dissolution and decalcification of limestone fragments in the upper 30 cm of the sacrificial ash altar to Zeus. Ashes are only present within cemented aggregates (*arrow*) that have moved upward through the deposit as a result of bioturbation. The upper edge of the limestone fragment exhibits a mammilate morphology indicative of dissolution. Sparry calcitic veins within the fragment are more resistant to weathering. The remainder of the sediment is rich in sand- and silt-sized fragments of charcoal and fragments of calcined bone (*B*); XPL. **b** Below 30 cm depth, ashes are well preserved and present in association with pedogenic carbonates. This reworked deposit contains numerous fragments of limestone and fragments of calcined and burned bone—some containing ashes in their pores (*arrow*), in a matrix of ashes. The crescent shape of the ashes filling the spongy bone pores indicates that the bone fragment has not moved from its original place of deposition; XPL

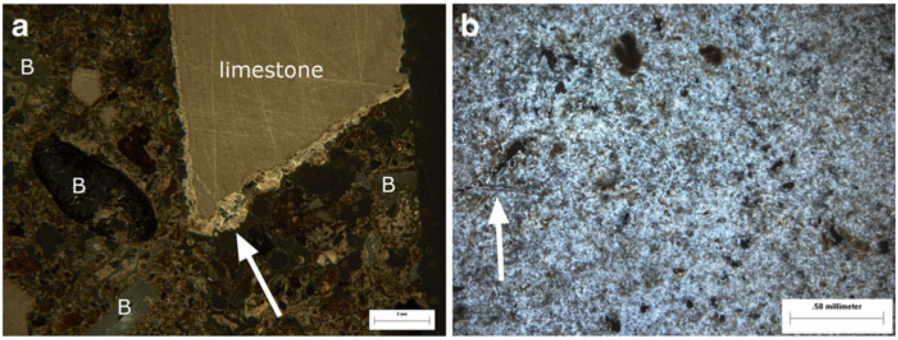

Fig. 13 Secondary carbonate in thin section. **a** Calcitic pedofeatures formed at depth within the sacrificial ash altar to Zeus on Mt. Lykaion include pendants (*arrow*) on limestone and bone fragments. The calcite sources from the dissolution of ash and limestone (see also Fig. 11). Burned bones are also present (*B*); XPL. **b** Cemented ashes from the site of Üçağızlı I exhibit preserved rhomb-shaped grains in a matrix of microsparry calcite. Secondary carbonate fills nearly all of the packing voids that were originally present between the ashes. A fragment of partially carbonized tissue is present (*arrow*). Highly recrystallized ashes (not pictured), when present in intact hearths, preserve only their original laminated fabrics, clay intercalations, and larger partially carbonized tissues; XPL

precipitation may also occur (Fig. 13); localized precipitation may result from water uptake by plant roots. In many cases, wood ashes are both the source of carbonate to the groundwater and loci for secondary carbonate precipitation. At Tabun Cave, for example, micromorphology reveals that secondary carbonate precipitation is greatest in the white, wood ash-rich layers of Level C (Albert *et al.* 1999). Calcite cementation and recrystallization of ash has been documented at microscale at several sites, including Qesem Cave (Karkanas *et al.* 2007), Sibudu (Goldberg *et al.* 2009), Mesolithic site 16-D-4 (Zerboni 2011), and Amud Cave (Madella *et al.* 2002), where secondary carbonates have replaced the original ash crystal rhombs (Shahack-Gross *et al.* 2008). In Amud Cave, cementation of ashes by secondary carbonate is corroborated by geochemical isotopic analyses (Shahack-Gross *et al.* 2008). In Qesem Cave, partially recrystallized wood ashes are identified by preserved micritic rhombs in a matrix of microspar and sparry calcite (Karkanas *et al.* 2007).

Although recrystallization and cementation can lead to loss of ash morphology and fabric, these processes can also contribute to hearth preservation. In Pech de l'Azé IV, the thickest deposits of combustion structures are present along the former position of the cave's drip line (Dibble *et al.* 2009). This arrangement of features may reflect intentional positioning of the combustion structures close to the cave entrance. Alternatively, calcareous drip waters concentrated near the entrance may have aided in preservation of the features by cementing the ashes and preventing their erosion. In Üçağızlı II, intact hearths are situated beneath the highest point of the chamber ceiling. Whether this spatial arrangement is a consequence of hominin response to cave morphology or to a greater abundance of dripping water is presently unknown (Mentzer 2011). Finally, in the site of Sibudu, Middle Stone Age humans may have exploited certain properties of cemented ashy hearths. Wadley (2010a) postulates that gypsum-cemented ashes formed hard surfaces that were used as receptacles for powdered yellow and red ochre. This hypothesis is supported by micromorphological and geochemical analyses that indicate that the ochre fragments were not heated, and thus, their introduction to the hearths postdated their firing.

Secondary cementation by carbonates, although conducive to the preservation of ash layers, adversely impacts other burned materials. For example, secondary cementation has contributed to the fragmentation of charcoal in possible combustion structures in Pinnacle Point site PP13B (Karkanas and Goldberg 2010). In the site of Obi-Rakhmat, secondary carbonate precipitation within pores has contributed to the mechanical weathering of bone (Mallol *et al.* 2009). As mentioned above, chemical conditions that are favorable for the preservation of calcitic ashes may result in the dissolution of the siliceous phytolith component. Dissolution of silicates is evidenced in Qesem Cave by the lack of both phytoliths and siliceous aggregates and the active precipitation of secondary carbonates in the ash deposits (Karkanas *et al.* 2007).

Phosphate-induced dissolution or replacement of the original mineral phases in ash and bone by secondary minerals is a well-studied process in Paleolithic caves (Berna *et al.* 2004; Karkanas *et al.* 1999, 2000, 2002; Mallol *et al.* 2010; Schiegl *et al.* 1996; Weiner *et al.* 1993, 2002). The process was first documented in the sites of Hayonim and Kebara Caves, the latter of which contains at least 46 Middle Paleolithic hearths altered by secondary phosphatization (Schiegl *et al.* 1996). Similar features have since been identified at other sites using a combination of micromorphology and mineralogical analyses. For example, some alteration of ashes to dahllite is present in the combustion features of Roc de Marsal (Goldberg *et al.* 2012). This transformation is evidenced in thin section by ash layers containing domains of phosphate minerals that are characteristically yellow in PPL and isotropic in XPL. In some samples, these nodules also contain inclusions of amorphous silica identified using FTIR. Because concentrated phosphatic solutions typically come from materials such as bat guano, Goldberg *et al.* (2012) interpret these features, which overlie other, unaltered features, as evidence of temporary abandonment of the site. Similar sequences are present in Esquilleu Cave (Mallol *et al.* 2010) and Hohle Fels Cave, where periods of phosphatization appear to indicate not only abandonment of the site, but warm and wet climatic conditions (Miller, unpublished).

Unlike dissolution, secondary mineral replacement of ash helps maintain the original internal stratigraphy of the hearth or combustion feature. Therefore, when phosphatization occurs within a classic tripartite sequence of rubified sediment, charcoal, and ash, the intact nature of the original deposit can be established (Karkanas 2001). These sequences have been identified in sites such as Grotte XVI, Roc de Marsal, Esquilleu, Sibudu, Hayonim, and Kebara, where secondary phosphatic minerals (some pseudomorphic after ashes) are present within hearth-like structures containing other combustion by-products such as charcoal, burned lithic materials, and bone (Courty *et al.* 1989; Goldberg and Bar-Yosef 1998; Goldberg *et al.* 2009, 2012; Karkanas *et al.* 2002; Mallol *et al.* 2010). Gypsum, another secondary mineral that forms from guano, is precipitated into some intact hearth sequences at Sibudu (Goldberg *et al.* 2009). Formation of large crystals results in localized movement of charcoal fragments but otherwise preserves the original stratigraphy. In highly altered features, neither the original carbonate nor the secondary phosphate minerals are present, and *in situ* combustion is evidenced by the presence of siliceous aggregates (Schiegl *et al.* 1996), as well as other materials such as charcoal and burned bone (e.g., Karkanas and Goldberg 2010). Unfortunately, when the tripartite sequence is absent, it may be more difficult to determine the original depositional fabric from the altered deposit. For example, in Tabun Cave Level C, secondary phosphatization has replaced some of the calcitic ashes in the generally white stratigraphic units (Albert *et al.* 1999). As phosphatization has obliterated the original fabric of the ashes in this case, it is impossible to determine whether the ashes that lend the units their white color are *in situ* or reworked.

Finally, secondary chemical alteration can result in rubification of clay-sized materials or primary geogenic layers within the sequences. In Pech de l'Azé IV, some rubification may postdate the deposition of archaeological materials or sediments, as evidenced by the presence of both iron-stained bone fragments and hematite in reddish layers (Dibble *et al.* 2009). In Grotte XVI, rubified layers also result from the postdepositional concentration of hematite, perhaps as a result of microbial activity (Karkanas *et al.* 1999; Karkanas 2008, personal communication). These features highlight the importance of using additional tools, such as FTIR and FTIR microspectroscopy (μ-FTIR) (e.g., Dibble *et al.* 2009), to evaluate the composition of red sediments as well as molecular changes in clay minerals that result from heating.

Microarchaeological Evidence for Hearth Function and Related Behaviors

Consideration of combustion-related hominin behaviors often focuses on the spatial arrangement of hearths with respect to landforms, other archaeological features, and activity areas. For example, in Abric Romani, high-resolution study of numerous intact combustion structures reveals that the positioning of hearths relative to karstic features and other aspects of cave architecture changed through time. The "sleeping area" of level N contains few archaeological remains and is associated with wood preserved in travertine, which the researchers suggest may represent the remains of a structure (Vallverdú *et al.* 2012). They propose that regularly spaced hearths in this area near the wall of the cave were reused multiple times, although this hypothesis is supported only by the thickness of the rubified substrate and not by micromorphological evidence. In levels K and L, hearths were also situated in defined areas between the wall and drip line of the shelter (Pastó *et al.* 2000). In Abric Romani, intact combustion structures are identified by rubified sediment overlain by mixtures of ash and charcoal. Field-based measurements include the diameter of the structure and the thickness of the rubification zone. Micromorphological study of some combustion features confirms that the ash–charcoal layer results from burning *in situ*.

Micromorphology is the most reliable method of confirming the presence of intact hearths. However, the technique offers us much more than this, as it can be used to identify and study other combustion-related behaviors and materials. These human behaviors include choice of substrate and hearth preparation activities, hearth reuse and maintenance behavior, and abandonment behaviors, such as trampling. For example, the presence of a visible hearth lining generally defines a prepared surface in the field. Rock pavers may be identified and studied in hand sample; however, as demonstrated at the sites of Klissoura Cave and Dust Cave, clay surfaces are best characterized using petrographic methods (Karkanas *et al.* 2004; Sherwood and Chapman 2005) with heating confirmed by FTIR or differential thermal analysis (Karkanas 2010). On the basis of different hearth morphologies with or without clay lining, Karkanas *et al.* (2004) proposed a functional model for the Upper Paleolithic prepared hearths at Klissoura Cave involving a main burning area and satellite areas. They also suggest that the prepared clay burning surfaces at Klissoura were swept or cleaned prior to reuse. The Aurignacian deposits contain reworked burned materials that may be related to sweeping and cleaning behaviors. Meignen *et al.* (2001) discuss a similar model for hearth use at Kebara Cave. Supported by micromorphological evidence for repeated hearth reuse and movement of hot coals, Meignen *et al.* (2001) suggest that actively burning fuels were moved throughout the site for various purposes. Reuse of hearth features has been documented at other sites, such as Vanguard Cave (Macphail and Goldberg 2000). At Vanguard, micromorphology also contributed to the study of the unmodified substrate. The presence of intact combustion structures atop a variety of burned substrates at Vanguard Cave was indicative of a *lack* of substrate choice in situating combustion activities in the Middle Paleolithic (Macphail and Goldberg 2000).

Micromorphology is especially useful for identifying hearth maintenance behaviors such as sweeping and dumping or hearth rake-out. These and other activities, such as stirring and cooking, have been documented in ethnographic studies. For example, Mallol *et al.* (2007) observed Hadza villagers stirring coals in long-lived (3–4 months) sleeping and cooking fires in order to maintain heat and ensure that fuel burned to completion prior to renewal of the fire. Periodically, the Hadza would also scoop ashes out of long-lived hearths, a behavior that over time produced concave depressions at the base of the structures. Cooking fires, unlike fires built for other purposes (such as sleeping or tool manufacture), contained organic and inorganic residues from food. Although similar types of residues have yet to be recognized in archaeological hearths, raking, sweeping, and dumping deposits have been identified based on characteristic microscopic composition, fabric, and structure (Table 7); these deposits, like overthickened combustion structures, are associated with long-term reuse of activity areas.

Rake-out deposits (Fig. 14a) result from the lateral spreading of burned material during combustion (Homsey and Capo 2006) or after cooling (Meignen *et al.* 2007). Rake-out deposits are identified at microscale by the presence of charcoal, ash, rubified sediment (when present), and other materials arranged roughly horizontally (especially the larger fragments; see Meignen *et al.* 2007, Fig. 5.A.24), but not comprising distinct bands or beds of uniform composition. Nonburned materials may also be mixed into the unit. Rake-out deposits exhibit generally high porosity relative to intact combustion structures. Homsey and Capo (2006) identify the by-products of hearth rake-out as thin lenses of charcoal present in the sediments of Dust Cave. They state that, unlike ash dumping, the presence of charcoal in the stringers indicates that this behavior took place prior to the completion of combustion and produced sediments enriched in charcoal relative to ash. In Sibudu, Goldberg *et al.* (2009) identify a homogeneous, burned, and anthropogenic microfacies containing charcoal, bone, and phosphate (altered ashes) that they hypothesize formed as a result of rake-out or dumping of combusted materials. Indistinct ashy accumulations, bedded discontinuous deposits, or centimeter-sized aggregates of ashes mixed with charcoal are present in the combustion areas at Kebara Cave. These are likewise interpreted as combustion features that have been reworked by human activities such as hot coal displacement or cold hearth rake-out (Meignen *et al.* 2007). Rake-out is

Table 7 Micromorphological signatures of hearth-related behaviors

Behavior	Location	Features	Citations
Coal stirring	Within a fire	Complete combustion of fuel	Mallol *et al.* 2007
Cooking	Within or above a fire	Amorphous phosphatic particles; charred animal tissue and bone; higher amounts of amorphous organic material in the substrate	Mallol *et al.* 2007
Sweeping	Within a fire	Erosional surface within a hearth; development of a concave substrate; upward mixture of substrate aggregates into the hearth	Mallol *et al.* 2007
Rake-out	Within and around a fire	Horizontal beds (stringers) of unsorted burned materials; absence of or discontinuity/truncation in compositional layering; rounded aggregates of ashes and charcoal; blurring of combustion feature boundaries; alignment of large fragment long axes; mixture with unburned materials; high porosity	Dibble *et al.* 2009; Homsey and Capo 2006; Goldberg *et al.* 2009, 2012; Karkanas and Goldberg 2010; Meignen *et al.* 2007; Sherwood 2001, 2008
Trampling	Anywhere, often identified within or around a fire	Compression of burned materials; downward movement of large fragments into lower compositional units; *in situ* fracturing of burned bone, charcoal and shell	Balbo *et al.* 2010; Dibble *et al.* 2009; Goldberg *et al.* 2009, 2012; Karkanas 2010; Karkanas and Goldberg 2010; Mallol *et al.* 2010; Meignen *et al.* 2007; Miller *et al.* 2009; Schiegl *et al.* 2003; Zerboni 2011
Bedding	Above and around a fire	Layers of aligned or articulated phytoliths (burned or unburned) above combustion structures or rake-out deposits; often accompanied by trampling	Cabanes *et al.* 2010; Goldberg *et al.* 2009; Mallol *et al.* 2010; Wadley *et al.* 2011
Ash dumping	Away from the fire	Homogeneous deposit of nearly pure ashes with occasional inclusions of rubified or burned substrate aggregates; open or chaotic structure; absence of pseudocarbonized wood structures or laminations	Araujo *et al.* 2008; Homsey and Capo 2006; Goldberg 2001, 2003; Karkanas *et al.* 2004; Meignen *et al.* 2007; Mentzer 2011
Waste dumping	Away from the fire and activity areas	Heterogeneous deposit of burned materials mixed with other debris	Courty *et al.* 1989; Shahack-Gross *et al.* 2004; Villagran *et al.* 2009, 2011a

These behaviors have been observed in ethnographic and experimental settings or documented in multiple archaeological studies cited here and in the text. Behaviors are listed in order of proximity to the original hearth

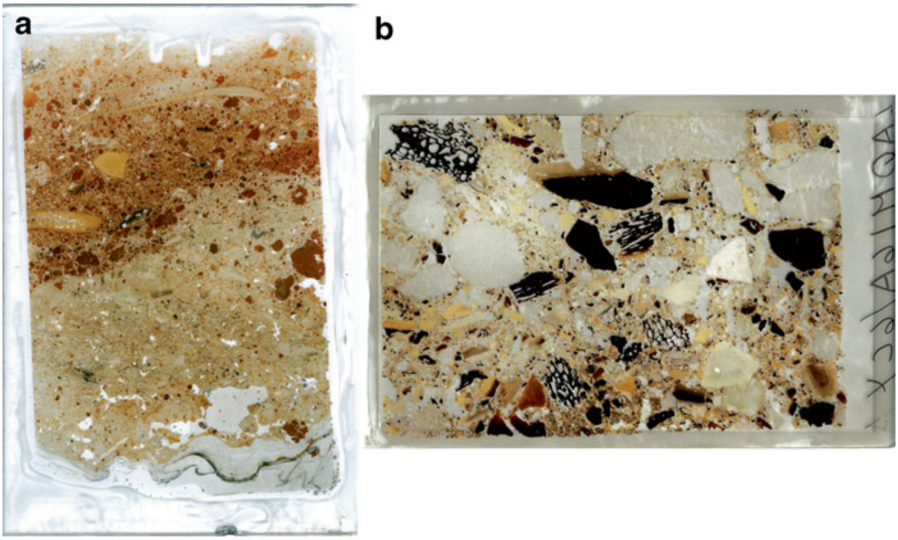

Fig. 14 Anthropogenically reworked burned materials are in secondary position due to the activities of hominins. **a** An intact ash layer from the site of Üçağızlı I is overlain by probable rake-out containing ashes mixed with aligned bone fragments and geogenic sediment; 5×7-cm petrographic thin section, incident light. **b** An incident light scan of a 5×7-cm petrographic thin section from the site of La Quina illustrates the loose structure and heterogeneous composition of a probable dumped deposit containing abundant burned bones mixed with ashes and limestone fragments

suggested as a cause of the diffuse appearance of combustion feature boundaries in the field, as well as the clear erosional surfaces visible within combustion sequences at Pech de l'Azé IV (Dibble *et al.* 2009; Goldberg *et al.* 2012) and Pinnacle Point site PP13B (Karkanas and Goldberg 2010).

Sweeping and dumping of ashes from hearths occurs after combustion (Fig. 14b). This process generates erosional surfaces and upward mixing of substrate aggregates within the combustion feature (Mallol *et al.* 2007) and also results in the formation of a midden when burned materials are mixed with other anthropogenic waste (Homsey and Capo 2006) or an ash dump when ashes are the sole component of the feature (Goldberg 2001, 2003). According to Schiegl *et al.* (2003), the paired processes of sweeping and dumping are likely responsible for the significant deposits of burned bone found in several German and French Paleolithic caves. Miller *et al.* (2009) report the inclusion of rubified clasts of sediment with experimentally swept and dumped hearth materials, as well as an open, chaotic microstructure in experimental material that was swept or dumped, although they question the preservation of this structure over archaeological timescales. An archaeological example of an ash dump comes from the rear of Kebara Cave. This feature is 90 cm thick and composed of ashes interbedded with thin layers of clay. Goldberg (2001) and Meignen *et al.* (2007) hypothesize that this deposit formed when ashes were repeatedly removed from hearths and dumped, with subsequent reworking of the dumped materials by water. Similar features have also been documented at Üçağızlı I Cave (Goldberg 2003; Mentzer 2011). Finally, incorporation of dumped burned materials with other discarded occupation debris yields heterogeneous midden deposits. Middens are identified in thin section by mixed burned and nonburned materials, high porosity, and decreased fragmentation of fragile materials such as coarse bones and shell (Courty *et al.* 1989; Villagran *et al.* 2009, 2011a).

Bedding, or the intentional spreading of leafy or grassy plant materials across an area to create a surface, has been identified in association with combustion features at several Paleolithic sites. In Esquilleu Cave, reworked combustion features are capped by layers of articulated grass phytoliths (Mallol *et al.* 2010). Because these phytoliths are unheated, the layers of bedding were likely laid down after the underlying burned materials were dispersed (Cabanes *et al.* 2010). Other sites that may preserve similar bedding areas containing combustion materials include Sibudu (Goldberg *et al.* 2009; Wadley *et al.* 2011) and the aforementioned "sleeping area" of Abric Romani (Vallverdú *et al.* 2012). At Sibudu, the multiple aligned layers of fibrous materials interbedded with combustion features are sometimes charred or fully burned. Goldberg *et al.* (2009) and Wadley *et al.* (2011) interpret these sequences as bedding that was accidentally or intentionally ignited.

Postdepositional anthropogenic modification of combustion features and deposits may result from unintentional behaviors such as trampling of the burned area following combustion or during later periods of occupation (e.g., Grotte XVI; Rigaud *et al.* 1995) (Fig. 15). Meignen *et al.* (2007) distinguish trampled burned features from nontrampled areas using a series of criteria including visible compaction, offsets in bedding, and localized downward movement of materials. Trampling has also been identified in archaeological settings by the compaction and *in situ* breakage of combustion materials or burned bones (Balbo *et al.* 2010; Dibble *et al.* 2009; Goldberg *et al.* 2009, 2012; Karkanas 2010; Karkanas and Goldberg 2010; Mallol *et al.* 2010; Schiegl *et al.* 2003; Zerboni 2011). This characteristic signature has been replicated in experimental settings (Miller *et al.* 2009). In Pech de l'Azé IV, postdepositional trampling identified using the above guidelines contributed to compaction of the deposits, which, along with rapid cementation, aided in the preservation of the combustion features (Dibble *et al.* 2009).

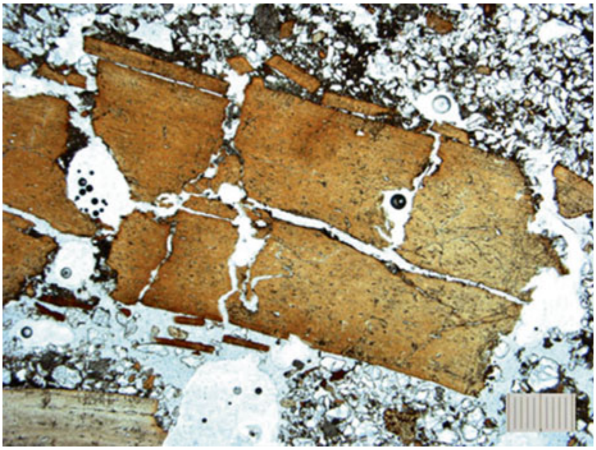

Fig. 15 Trampled materials are identified in thin section and in the field by *in situ* breakage. Burned bone from the site of Pech de l'Azé IV. Scale bar is 1 mm; PPL

In many sites, the combustion-related behaviors discussed above are combined in multicomponent sequences of repeated activities. In some cases, these sequences have also been impacted by natural postdepositional mixing or alteration processes. The deposits in Sibudu, for example, contain complex sequences of hearth construction, rake-out, trampling, and bedding, as well as postdepositional ash dissolution and phosphatic alteration (Goldberg *et al.* 2009). Similar sequences of trampling, rake-out, and bioturbation are proposed as processes that affected the homogeneous Middle Paleolithic ashy and burned materials excavated at Hayonim Cave (Goldberg and Bar-Yosef 1998).

The types of combustion features described above may be integrated with other archaeological and geological datasets to generate a more complete understanding of the use of space and tempo of occupation within prehistoric sites. The identification of intact hearths *versus* anthropogenically modified features can aid in the mapping of central and peripheral activity areas. Hearths are loci for many types of activities—some visible in the archaeological and ethnoarchaeological records (Audouze and Enloe 1997; Binford 1978; O'Connell 1987; Simms 1988; Stevenson 1985, 1991; Vaquero and Pastó 2001; Yellen 1977). On the other hand, ash dumps and middens occur in areas where people spend little time and their accurate identification can reveal as much as hearths about spatial planning in the site (Speth 2006; Speth *et al.* 2012). In several examples presented above, microarchaeological techniques were instrumental in distinguishing between primary and secondary refuse. For example, at a Mesolithic site in the Sudan, micromorphology allowed Zerboni (2011) to distinguish between trash pits containing burned materials and intact or partially reworked fireplace pits. Intermediate deposits, such as trampled materials, can contribute to the identification of occupation surfaces in ephemeral sites. Of course, spatial organization of all types of combustion features excavated in confined spaces, such as caves and rockshelters, can be influenced by the wall and ceiling morphology and micro-environments within the site. For example, archaeologists should consider hearth placement with respect to chimneys, natural vents, high and low ceilings, active drip centers, and entrances. Preference for dry areas within the site has been observed at Dust Cave (Sherwood 2001), while at Üçağızlı II, the situation of stacked hearths beneath the high point of the cave ceiling and active drip centers contributed to the preservation of the features (Mentzer 2011). Finally, some studies have revealed that hearths and secondary refuse can be used to understand repeated behaviors and seasonality (Meignen *et al.* 2007; Villagran *et al.* 2011a). In the ethnographic site of Tunel VII, for example, dumped materials from more intense fires are correlated with winter occupation of the site (Villagran *et al.* 2011a).

Summary and Future Directions

The discussion and case studies presented here demonstrate how archaeologists may effectively document and interpret combustion features in archaeological sites. A few key points are highlighted briefly below. First, high-resolution analytical advances, such as the techniques of archaeological micromorphology, phytolith studies, and *in situ* mineralogical analyses, have created a wealth of information regarding hearth construction, maintenance, and postdepositional sedimentary conditions. On the other hand, such advances have increased the number of specialists that work at sites, particularly Paleolithic sites, and force excavators to make decisions regarding the degree to which individual features should be studied. The discussion above has also highlighted some inconsistencies in the archaeological identification of combustion structures, specifically the poorly understood phenomenon of rubification, and the acceptable range in variability of compositional layers as a function of feature type. Finally, the review of archaeological sites containing combustion features that have been studied using micromorphology reveals biases towards cave sites and also against sites of late Upper Paleolithic, Epipaleolithic, Mesolithic, and Natufian ages, as well as their African and New World equivalents. These biases may be limiting important comparisons of pyrotechnology between time periods.

The technique of archaeological micromorphology has been instrumental in the identification and interpretation of hearth formation sequences, as well as burned materials that are not visible with the naked eye (i.e., wood ashes). The technique has allowed for the secure identification of controlled burning in sites as early as 400 kyr BP (Barkai *et al.* 2003; Karkanas *et al.* 2007), a period which, until very recently, has been only associated with indirect evidence for burning (see James *et al.* 1989). Micromorphological studies reveal that, because of the combined effects of hominin behaviors prior to, during, and after burning, as well as the numerous natural postdepositional modifications (see also Table 2), it is possible for combustion structures to appear intact in the field, yet exhibit features consistent with reworking at microscale (e.g., Tabun Layer C). Conversely, some structures that appear ambiguous in the field—lenses of ashes lacking underlying charcoal or rubification zones, for example—may in microscale exhibit fabrics that indicate little to no postdepositional movement. These possibilities highlight the fact that, in order to interpret the distribution(s) of combustion features within sites, it is necessary to document clearly when burned materials are *in situ* or reworked.

The success of micromorphology in the identification of intact and reworked features argues for its application at a wide variety of archaeological sites. Unfortunately, micromorphology can become ungainly when sites contain hundreds of hearths or burned deposits (e.g., Abric Romani, Kebara Cave, Hayonim Cave, El Salt). Here, other microarchaeological techniques can contribute to a triage system, of sorts, in the excavation and analysis of combustion features. As an example, at Abric Romani, Vallverdú *et al.* (2012) and Courty *et al.* (2010) have developed site-specific field methods that bridge the gap between excavation and laboratory analyses. Identification of intact combustion structures is made when rubified sediments are overlain by sediment that, according to expedient laboratory analyses, contains >40 % charcoal—termed "carbonaceous facies" (Vallverdú *et al.* 2010, 2012). The accuracy of these methods has been confirmed by paired micromorphological analyses that consistently reveal intact combustion structures containing ash, charcoal, and other compounds (Courty *et al.* 2010). Proposed future microstratigraphic sampling and excavation of sediments from combustion structures will be guided by findings from earlier thin sections and on-site loose sediment and microdebris analyses.

Other model excavations include the sites of Kebara Cave, Sibudu, Pinnacle Point site PP13B, and Dust Cave (Albert *et al.* 2000, 2012; Bar-Yosef *et al.* 1992; Goldberg 2003; Goldberg and Bar-Yosef 1998; Meignen *et al.* 1989, 2007; Schiegl *et al.* 1996;

Weiner *et al.* 1993; Goldberg and Berna 2010; Goldberg *et al.* 2009; Miller and Sievers 2012; Schiegl and Conard 2006; Speth 2006; Speth *et al.* 2012; Wadley 2010, 2012; Wadley *et al.* 2011; Herries and Fisher 2011; Karkanas and Goldberg 2010; Homsey and Capo 2006; Homsey and Sherwood 2010; Sherwood 2001, 2008; Sherwood and Chapman 2005; Sherwood *et al.* 2004). Each of these excavations utilizes numerous microarchaeological techniques to build site-specific classification systems for combustion features that consider differences in feature function and taphonomy. Several investigators (e.g., Homsey and Sherwood 2010) have gained further insight from experiments in burning and formation processes. All have contributed to methodological developments and further understanding of the range of behaviors of prehistoric peoples.

Future directions in the microarchaeological study of combustion features include further investigation into combustion processes, such as rubification and magnetization, increasing the volume of information that can be generated from intact sediment block and petrographic thin sections and expansion of these analyses outside of the earlier periods of the Paleolithic. Experimental and ethnographic microarchaeology are also promising avenues for exploring whether the functions of hearths can be deduced from their microscopic contents. Using the present methods, the question of hearth function is unresolvable in most sites.

Rubification, an understudied phenomenon associated with burning, suffers from the problem of equifinality. Some researchers have attempted to quantify the degree of rubification as a function of burning temperature and intensity (e.g., Canti and Linford 2000). Others (e.g., Vallverdú *et al.* 2012) use the thickness of rubified layers in combustion structures as a proxy for firing duration. However, unlike other materials, such as bones, wherein molecular changes in the mineral phase occur at known temperatures (Hiller *et al.* 2003; Rogers and Daniels 2002; Shipman *et al.* 1984; Stiner *et al.* 1995), rubified sediments do not behave predictably in response to certain temperatures or firing duration thresholds. Substrate response to heating, and the resulting the color and thickness of the altered zone can depend on a number of factors. In addition, hematite formation and associated color changes can occur postdepositionally as a side effect of the *in situ* breakdown of organic materials (Karkanas *et al.* 2002). Finally, rubification is not easily or consistently identified or described in thin section. Rubification, its presence and absence in a variety of substrates, and associated microarchaeological features are important avenues for future research.

Integrated, multidisciplinary studies of intact sediment blocks and petrographic thin sections or the "microcontextual approach" (Goldberg and Berna 2010) are developing quickly within the field of Paleolithic combustion feature research. When combined with traditional optical petrography and organic reflectance petrography, μ-FTIR analyses of clay and bone heating temperatures (e.g., Dibble *et al.* 2009; Goldberg and Berna 2010; Goldberg *et al.* 2009, 2012; Wadley *et al.* 2011; Berna *et al.* 2012) have the potential to significantly expand the types of information that can be used to compare multiple burning episodes within a single hearth or site. This approach should also be utilized when studying ethnographic and experimental features.

Finally, the case studies listed in Tables 3, 4, 5, and 6 indicate two main trends in combustion feature research. First, sites containing intact hearths are overwhelmingly situated within caves and rockshelters. Second, Upper Paleolithic and later combustion features are understudied in comparison to Middle Paleolithic combustion features, despite the fact that the former are more numerous. In fact, many micromorphological studies of Upper Paleolithic combustion features come from sites that contain both Middle and Upper Paleolithic components.

The bias towards cave and rockshelter sites is due to the superior preservation of burned materials, in particular ashes, in alkaline karstic environments. It is not a coincidence that the earliest secure evidence for controlled fire (Karkanas *et al.* 2007) comes from a cave. The deposits in Qesem Cave do indeed evidence significant hominin behavioral developments; however, these developments may be related to landscape exploitation rather than to fire activities *per se*. In later periods, a propensity towards the study of combustion features in caves may also result in biases in the association between hearths and other types of domestic features. Only recently and only with significant interdisciplinary and microarchaeological contributions have researchers begun to explore the environmental contexts and differences in archaeological assemblages with and without associated hearths (Sandgathe *et al.* 2011).

The focus on earlier periods in combustion feature research stems from the aforementioned, long-standing interest in the earliest controlled fire (e.g., James *et al.* 1989) and ongoing debates over the role of fire in the colonization of the northern latitudes (e.g., Roebroeks and Villa 2011; Sandgathe *et al.* 2011). The presence of well-controlled fires in later periods is less sensational and, therefore, receives less attention. In addition, Upper Paleolithic and later sites may not be sampled as frequently due to the presence of other markers of *in situ* combustion, such as constructed fireplaces with rock-lined edges and basal pavings. Constructed fireplaces are durable and are intended to be used repeatedly. These features are also most easily recognized during excavation. When archaeologists rely only on macroscopic markers to identify combustion areas, more expedient features may be ignored. Furthermore, as evidenced by the case studies presented above, the end goal in combustion feature research is not simply to document the presence and location of fires within sites. Microarchaeological techniques can be used to extract information about the diversity of pyrotechnologies and the formational histories of sites. Given the very detailed and valuable information that can be recovered from microlaminae within combustion features, it is likely that, due to a bias against research on Late Pleistocene and Early Holocene sites (see Table 5), the full range of modern human forager combustion-related behaviors have not been documented. The lack of studies of sites from these time periods, therefore, currently limits not only our ability to compare datasets within specific geographic areas, but also the development of nuanced understandings of site structure and human activities. The case study from Dust Cave in particular provides a tantalizing glimpse into the diversification of combustion activities that may be associated with plant processing and consumption during the late Paleoindian and Archaic periods in North America (Homsey and Capo 2006; Homsey and Sherwood 2010; Sherwood 2001; Sherwood and Chapman 2005; Sherwood *et al.* 2004).

Given the scholarly interest in intensification behaviors at the end of the Pleistocene and the early Holocene, higher-resolution analyses of combustion features within these sites may prove exceptionally valuable. Some key questions that may guide future archaeological and experimental research include:

1. What are the microarchaeological signatures of specialized combustion activities, such as food smoking, stone heating, roasting, and boiling?

2. What does it mean when prepared burning surfaces become more or less common in archaeological sites? If we only document these features (because they are most visible), what impact does this have on our interpretations of activity patterns, mobility, and spatial organization?
3. Do later developments in the form and function of combustion features used for materials processing, ritual purposes, cremations, or cleaning have their roots in earlier periods?
4. Can the study of combustion feature distributions, when integrated with paleoenvironmental and macroarchaeological data, contribute to reconstructions of occupation intensity on site-specific and regional scales?

The proliferation of microarchaeological techniques in combustion feature research has allowed an impressive variety of human behaviors and postdepositional processes to be documented in Paleolithic sites. However, there is still a tremendous amount left to learn about and from the use of fire by peoples in the past.

The information presented underscores the urgency for applying the techniques and synthetic approaches developed previously in research on Paleolithic sites to more recent periods. Microarchaeological approaches have assisted greatly in documenting the antiquity or geographical distribution of the controlled use of fire. However, systematic investigation of the pyrotechnologies of hunter–gatherers must be expanded to include sites dating to Late Pleistocene and Early Holocene, when the human pyrotechnic "footprint" increased both in scale and complexity. We also need more nuanced, accurate data on permanent and ephemeral burning localities, fuel sources for fires, and the organization of domestic spaces and activity areas. Expansion in the application of existing techniques to later cultural periods can, therefore, greatly improve our understanding of the dynamics of landscape changes brought about by humans, as well as the restructuring of occupation areas within sites that accompanied increases in sedentism.

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