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Hearths and bones: An experimental study to explore temporality in archaeological contexts based on taphonomical changes in burnt bones

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ABSTRACT

Although the occurrence of burned bones in the archeological record has been widely investigated, very few studies have focused on the distinction of temporality in burned bones assemblages, which would be useful in helping to identify human activity areas, as well as distinguishing combustion residues from those resulting from other activities.

In this work, we present the results of an experiment designed to characterize direct/indirect thermal alteration of rabbit bones, based on macroscopic and microscopic surface features. These results are then compared with an archeological burned bone assemblage associated with various Middle Paleolithic combustion structures from El Salt Stratigraphic Unit X (Alicante, Spain). In the experimental assemblage, we observed that rabbit bones tossed into a fire were strongly altered, while bones thrown on the cooled ashes and lying on the surface beneath the fire or slightly buried, were not. We observed a strong thermal surface alteration of fresh bone (color changes, high degrees of fragmentation, cracks and structural changes on the cortical surface), while dry bone showed only color changes. Taking this data into account when analyzing the archeological assemblage, we observed surface features corresponding to thermally altered fresh bone and others more like thermally altered dry bone. Crucially, the archaeological specimens are associated with black layers of combustion structures and exhibit signs of trampling. The results suggest that fresh bones were trampled into human occupation surfaces and were subsequently unintentionally or indirectly burned due to their position beneath hearths, along with other dry bones present there. Our study shows that investigating ways to distinguish temporality in burned bones may be a good tool for isolating different depositional events and thus contributing to archeological palimpsest dissection.

1. Introduction

The zooarcheological literature on thermally altered bone is relatively extensive. Even so, the source of burned bone in archeological contexts is an unresolved issue in both zooarcheology and taphonomy (Lyman, 1994; Reitz and Wing, 2008), mainly due to the high variability of events that may generate burned bone assemblages, including meat processing, bone discard, ritual and diagenetic processes (Cáceres et al., 2002; Costamagno et al., 1999, 2005, 2009; Joly et al., 2005; Outram, 2001; Sergant et al., 2006; Shahack-Gross et al., 1997; Stiner et al., 2001; Théry-Parisot et al., 2005, 2010; Théry-Parisot, 2002; Thompson, 2004; Villa et al., 2002; Yravedra and Uzquiano, 2013; Yravedra et al., 2005, 2016). For this reason, several researchers have carried out experiments to characterize the thermal alteration of bone associated with different activities (Bennett, 1999; Buikstra and Swegle, 1989; Castillo et al., 2013; Ellingham et al., 2015; Fernández et al., 2007; Hanson and Cain, 2007; Lloveras and Moreno-garcía, 2009; Nicholson, 1993; Sanchis and Fernández Peris, 2008; Shipman et al., 1984; Stiner et al., 1995; Whyte, 2001).

However, only a few studies have addressed the intentionality underlying thermally altered archeological bone (Asmussen, 2009; Cain, 2005; Spennemann and Colley, 1989; Bennett, 1999; Stiner et al., 1995). Previous studies have addressed of the variable of direct or indirect exposure of bones to fire (Bennett, 1999; Stiner et al., 1995), but without further investigation on the taphonomic origin of the affected bones.

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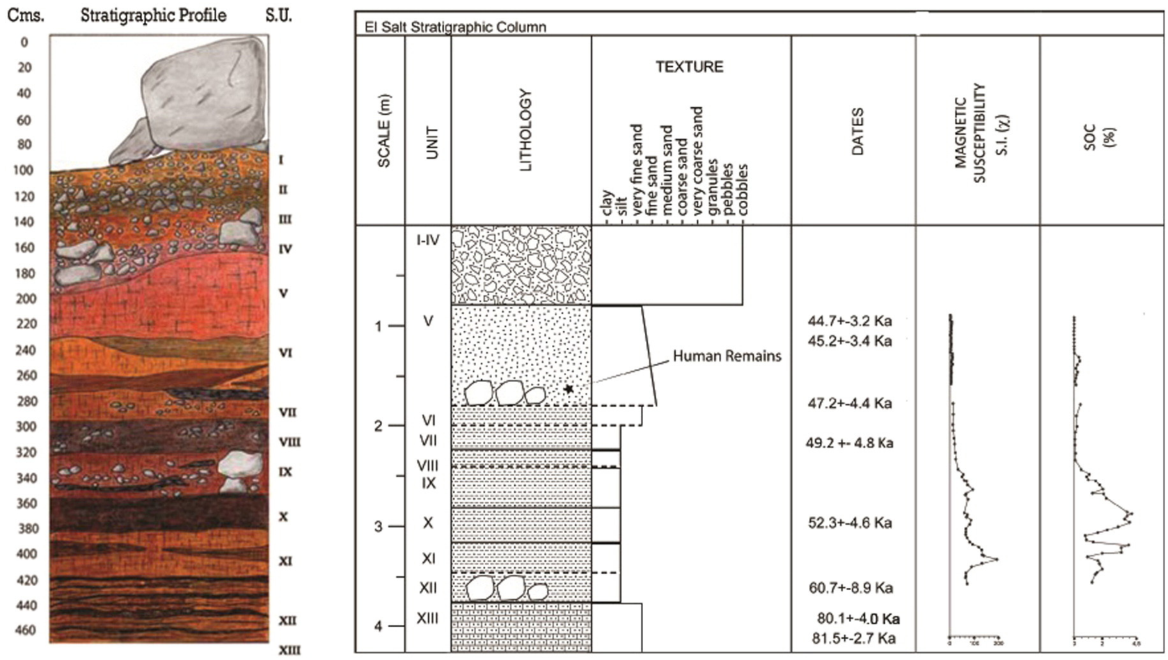

Fig. 1. Stratigraphic profiles of El Salt according to Fumanal (1994) and Galván et al. (2014b). Right picture show also the sedimentary features, position of human remains, average chronometric dates, magnetic susceptibility and soil organic carbon.

On the other hand, given the palimpsest condition of archeological contexts (Bailey, 2007, 2008; Henry, 2012a; Lucas, 2010; Machado and Pérez, 2016; Malinsky-Buller et al., 2011), it is not surprising that current theoretical and practical archeology is increasingly focused on: 1) the interplay between anthropogenic and natural site formation processes, and 2) the degree of temporal resolution that can be gleaned from archeological contexts. Both issues are central to our ability to understand past human behavior.

Recent experimental and archeological data on combustion structures from El Salt obtained from an interdisciplinary perspective has provided insight into the ways combustion features may be used as temporal markers to aid archeological palimpsest dissection (Mallol et al., 2013a, 2013b). The results of this work include an identification of the different sedimentary facies that one may find in a simple combustion structure, as well as its macroscopic and microscopic components and their arrangement according to the particular use and formation history of the combustion structure. A key result is the observation that the black layer of a simple combustion structure may represent the burned soils beneath a fire and that combustion residues contained in this black layer might have been unintentionally burned and therefore represent human activity preceding the fire (Mallol et al., 2013b). In contrast, remains within combustion structure ash layers have been shown to be associated with the fire itself. In this way, archeological combustion structures and their facies become crucial temporal markers in palimpsest dissection.

Further work along these lines involves looking for high temporal resolution analytical units and temporal markers in the Paleolithic archeological record (sediment, stone artifacts and bone remains) (Aldeias et al., 2016; Chacón et al., 2015; Eixea et al., 2014; Henry, 2012b; Hovers et al., 2011; Fernández-Laso, 2010; Machado et al., 2011, 2013, 2015, 2016; Mallol et al., 2013a, 2013b; Rosell et al., 2012; Sañudo et al., 2015; Stapert and Street, 1997; Vallverdú et al., 2005; Vaquero and Pastó, 2001; Vaquero, 2008; Vaquero et al., 2012; Villaverde et al., 2015). However, most studies related to sedimentology and archeostratigraphy and there are few zooarcheological works addressing temporal aspects (Bargalló et al., 2015; Gabucio, 2014; Gaudzinski and Roebroeks, 2000; Machado and Pérez, 2016; Pérez, 2015; Pérez et al., 2015; Rivals et al., 2009a, 2009b, 2014, 2015; Sánchez-Hernández et al., 2014; Gabucio et al., 2016). Moreover, none of these studies focus specifically on burned bones, which may appear *in situ*, concentrated inside, around or under combustion structures or scattered on an occupation surface (possibly in secondary position).

Most of the rabbit bone recovered from Middle Palaeolithic sites has been shown to be accumulated by raptors or small carnivores, with only rare cases of anthropogenic inputs. In many cases, such

Table 1
Principal features of experimental combustion structures. Note: Like fuel we only use *Pinys sylvestris* with different sizes, between 1.5 cm to >5 cm diameter.

Hearths ID	Combustion time	Fuel (kg)	Previous dimensions	Posterior dimensions	Burned soil thickness	Post-combustion events
H-I	4 h	39,75	63 × 40	75 × 58	3,5 cm	None
H-II	2 h	23,1	85 × 55	65 × 60	4 cm	None
H-III	6 h	51,1	60 × 32	77 × 68	3,5–4 cm	None
H-IV	8 h	57,75	62 × 33	77 × 68	3,5–4 cm	None
H-V	4 h	30	66 × 35	68 × 73	4 cm	
H-VI	8 h	53,5	62 × 50	66 × 70	5–5.5 cm	Small carnivore intervention (possible *Vulpes vulpes*): disturbed ash, consume bones located in embers.
H-VII	2 h	17,5	68 × 61	59 × 62	3,5–4 cm	
H-VIII	6 h	53,95	70 × 45	72 × 69	5–6 cm	

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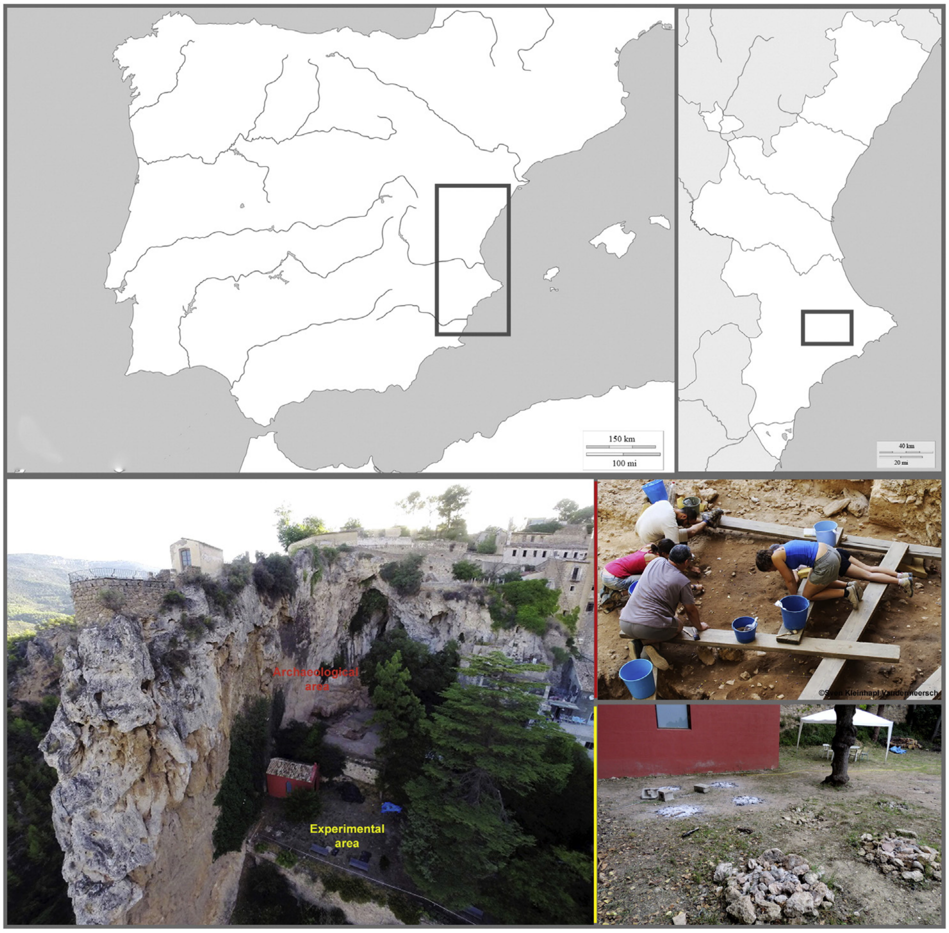

Fig. 2. Geographic location of El Salt in Iberian Peninsula (top pictures) and specific place of archaeological site and experimental area in Villa Vicenta – Alcoy, Spain – (bottom pictures).

as at the El Salt Middle Paleolithic site (Alcoy, Alicante, Spain), these assemblages contain a high proportion of burnt specimens (Pérez, 2014, 2015). Viewed from this perspective, burnt bone remain may prove to be a useful temporal marker, such as that of the sediment from the black layers of combustion features as proposed by Mallol et al. (2013b).

Following up on the observation that the burnt bone contained in anthropogenic combustion structure sediment might pre-date the combustion event, in this work we add the aspect of bone freshness. We assume that skeletal elements still containing fresh organic matter (fresh state bones) are likely to be directly burned or burned soon after deposition, while skeletal elements with little or no organic matter left (dry state bones) are likely to undergo indirect, post-burial burning. Thus, in our experiments we placed dry bones only in the substrate of hearths and fresh bones in the substrate as well as on the surface and flames.

Here, we present the results of an experimental study involving rabbit bone remains and fire and compare the results to an zooarcheological assemblage from El Salt Middle Paleolithic site. The study was designed to investigate ways in which we can identify the diagenetic phase in which a given bone is burned (e.g., bone deposited for a considerable amount of time before burning versus bone burnt at or near the time of meat processing). Thus, we focus on ways in which we can determine whether a given bone was fresh or dry when it was burned. Resolving this issue may contribute to resolve temporal relationships in archeological contexts and add to our understanding of the Neanderthal occupations from El Salt.

2. Materials and methods

2.1. El Salt

The open-air archeological site of El Salt is located in Alcoy (Alicante, Spain), at an altitude of 700 m.a.s.l. and situated under the protection of a 38 m-high Paleocene limestone wall covered by tufa and travertine. The 6.3 m-thick stratigraphic sequence has been divided into 13 lithostratigraphic units and five segments, according to macroscopic textural appearance and the archeological record (Fig. 1). The bulk of the sedimentary deposit was formed in the Middle Paleolithic (S.U. XIII-V), while the top part in the Upper Paleolithic and was later removed by karst reactivation during the Holocene. Radiometric dating (U-Th, TL, OSL) places the sequence from 81.5 ± 2.7 Ka (S.U. XIII) to 44.7 ± 3.2 Ka (S.U. V), with the presence of human activities being seen from 60.7 ± 8.9 Ka (S.U. XII). In this study, we focus on part of the S.U. X, dated to be around 52.3 ± 4.6 Ka (Afonso, 2013; Fumanal, 1994; Galván et al., 2014a, 2014b).

El Salt is a Late Pleistocene site with numerous lithic (Dorta et al., 2010; Galván, 1986; Galván et al., 2001; Machado et al., 2011; Rodríguez et al., 2002) and faunal remains (Morales and Sanchis, 2009; Morales et al., 2008; Pérez, 2015; Pérez et al., 2015; Sanchis et al., 2015) associated with a great quantity of simple, well-preserved combustion structures ranging in diameter between 0.20 and 1 m. The archaeological assemblages in S.U. X are hypothetically representative of recurrent short occupation based on the concept of hearth-related assemblages. There is a low rate of interaction among lithic and faunal assemblages around hearths, incomplete reduction sequences, scarce

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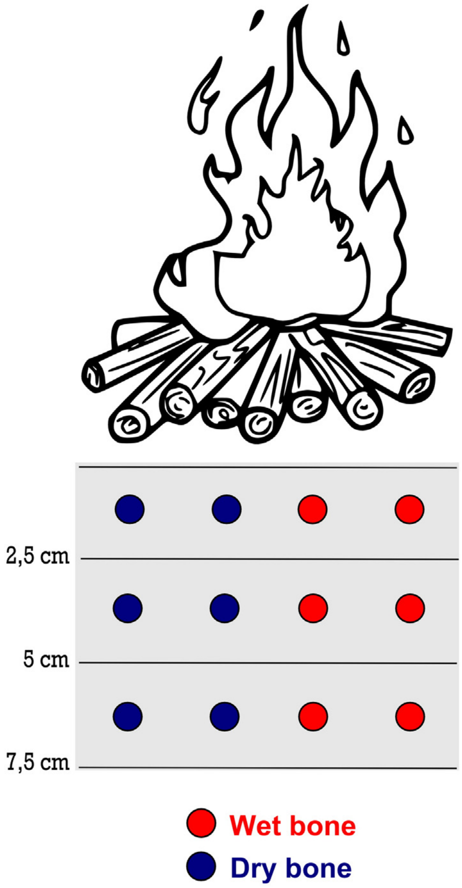

Fig. 3. Schematic distribution of experimental bones in hearth substrate. It is differentiated fresh and dry bones.

and unidirectional lithic refits, and distinct faunal processing tasks in archeostratigraphic units, as well as the presence of sterile geogenic facies as determined by archeostratigraphic (Machado et al., 2016), micromorphological and geochemical methods (Mallol et al., 2013b; Rodríguez-Cintas and Cabanes, 2015; Sistiaga et al., 2014).

The faunal remains identified in S.U. X are associated with the human exploitation of a recurring triad of ungulates present in the local environment (*Capra pyrenaica*, *Cervus elaphus*, *Equus ferus/hydruntinus*) together with other less well-represented animals (*Bos primigenius*, *Sus scrofa*, *Testudo hermanni*, *Alectoris* sp./*cf. rufa* and *Pyrrhocorax* sp.), and others for which there is no evidence of human manipulation (Rhinocerotidae, Carnivora, *Panthera pardus*, *Cuon* sp. and *Lynx* sp.). The consumption of small prey by raptors has also been ascertained; high numbers of rabbit bones are abundant throughout the sequence and this, together with preliminary results from their zooarcheological and taphonomical analys indicates that the S.U. X rabbit bone assemblages were accumulated by both humans and raptors (Pérez et al., 2015). This is the main reason for selecting rabbit bones for our experiments, as well as their ubiquitous presence throughout European Late Pleistocene archeological sequences.

2.2. Fire experiments

An experimental series consisting in the making of 8 open hearths of variable duration (2–8 h) was carried out adjacent to the El Salt site excavation area in 2013 (Table 1, Fig. 2). These experiments were designed according to: 1) Field observations made during the excavation of Stratigraphic Unit X at El Salt, 2) Observations from zooarcheological and taphonomic analyses of the faunal assemblage in this unit, and 3) Existing experimental data on simple combustion features (Mallol et al., 2013a, 2013b). Below, we describe the experimental protocol.

1) Prior to lighting each fire, a series of rabbit bones (*Oryctolagus cuniculus*) were buried at that same spot down to 7.5 cm deep (Fig. 3). A total of 148 rabbit bones from six individuals were introduced. These were farm animals with ages ranging between around five to more than nine months (subadult-adult). 96 pieces were located in the substrate or burned soil (four by level and hearth), 23 in the hearth base (three by hearth), 20 in the flames (three by hearth, except two in H-VII) and 5 in the embers (one in H-1, two in H-VII, two in H-VIII). The state of these bones was variable. There were 100 fresh bones, 18 dry-recent bones, 30 dry-archaeological. Only dry bones were put in the soil (Table 2, Appendix-Data). The archaeological specimens were uncontextualized findings recovered from the sieve, and were included under the assumption that on any given human occupation surface there might be very old bones lying on the surface or slightly beneath.
2) The sediment employed for burying the bone was obtained from nearby El Salt and contained sand, clasts and organic matter, similar to what has been described in micromorphological analyses carried out at the site (Mallol et al., 2013b). Thermocouples were inserted at each artificial burial level to control heat penetration. Subsequently, additional fresh rabbit bones were deposited on the ground surface.
2) The fires were lit and maintained using dry and fresh pine (*Pinus sylvestris*) wood due to its recurrent presence in Iberian Pleistocene deposits and specifically at El Salt (González-Sampériz et al., 2010), its good burning properties, and the fact that it is easily found in the surrounding area. Several variables were recorded including refueling events and their effects, environmental conditions and resulting combustion structure dimensions. Thermocouples were inserted in the embers and flames. Fresh rabbit bones were tossed into the embers and flames.
3) The combustion structures were excavated after 24 h applying the same method used in archeological contexts. Two facies were evidenced: a) A layer associated with combustion residues with calcitic ash and charcoal (the "white layer"); b) A layer representing the burned soil beneath of the hearths (the "black layer"). Bone remains were photographed in situ to control for possible displacements (Fig. 4).
4) The bone remains were cleaned with distilled water, except those with scraps of flesh, which were cleaned with a mixture of distilled water and acetone (50:50) for 8 h and with distilled water alone for 4 h.

2.3. The archaeological sample

The experimental bone assemblage resulting from the fire experiments was compared with selected archeological rabbit and very small sized bone specimens from El Salt *in situ* combustion structures H30, H32 and H33. These were previously excavated and belong to S.U. X, Subunit La8 (Figs. 5 and 6). We selected both piece-plotted and uncoordinated specimens recovered from the sieve (Table 3). The small size of the bones recovered from the sieve (<2 cm) precluded their taxonomic/anatomical identification with the exception of 82 rabbit bones fragments (*Oryctolagus cuniculus*). Besides the archeological bone specimens described above, we observed bone fragments present in existing sediment thin sections from combustion structures H30, H32, H33 and H44-1 and H44-3.

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Table 2
Stratigraphic location and original state of anatomical elements employed on the experimental combustion structures.

Hearth	Bone state	Artificial levels				
		Flames/embers	Fire base	2,5 cm	5, cm	7,5 cm
I	Fresh	Skull, tibia, metacarpals	Hemimandible, coxal, metatarsals	Radius-Ulna, cervical vertebrae	Tibia, thoracic vertebrae	Scapula, femur
	Dry (ext.)	–	–	–	–	Radius, lumbar vertebrae
	Dry (arch.)	–	–	Scapula, humerus,	Coxal, femur	–
II	Fresh	Skull, tibia, metacarpals	Hemimandible, coxal, metatarsals	Radius, cervical vertebrae	Tibia, thoracic vertebrae	Scapula, femur
	Dry (ext.)	–	–	Scapula, humerus	Coxa, femur	Radius, lumbar vertebrae
	Dry (arch.)	–	–	–	–	–
III	Fresh	Skull, humerus, thoracic vertebrae	Hemimandible, coxal, scapula	Radius, cervical vertebrae	Humerus, thoracic vertebrae	Scapula, femur
	Dry (ext.)	–	–	–	–	Ulna, lumbar vertebrae
	Dry (arch.)	–	–	Scapula, humerus	Coxal, femur	–
IV	Fresh	Skull, humerus, metacarpals	Hemimandible, coxal, metatarsals	Scapula, femur	Tibia, thoracic vertebrae	Radius-Ulna, cervical vertebrae
	Dry (ext.)	–	–	–	–	Ulna, thoracic vertebrae
	Dry (arch.)	–	–	Scapula, humerus	Coxal, femur	–
V	Fresh	Scapula, femur, humerus (×2)	Coxal, ribs, metatarsals	Scapula, femur	Tibia, thoracic vertebrae	Radio, cervical vertebrae
	Dry (ext.)	–	–	–	Tibia	Cervical vertebrae
	Dry (arch.)	–	–	Scapula, humerus	Coxal	Radio
VI	Fresh	Femur, radius-ulna, metatarsals, humerus (×2)	Coxal, ribs, metatarsals	Coxal, radius-ulna	Tibia, thoracic vertebrae	Scapula, femur
	Dry (ext.)	–	–	–	–	Maxilla
	Dry (arch.)	–	–	Scapula, humerus	Coxal, femur	Tibia
VII	Fresh	Skull, ribs	Coxal, humerus, hemimandible	Radius-ulna, cervical vertebrae	Tibia, cervical vertebrae	Scapula, femur
	Dry (ext.)	–	–	Lumbar vertebrae	–	–
	Dry (arch.)	–	–	Radius	Coxal, tibia	Hemimandible, humerus
VIII	Fresh	Humerus, ulna, thoracic vertebrae, ribs	Coxal, humerus, hemimandible	Radius-ulna, cervical vertebrae	Tibia, thoracic vertebrae	Scapula, femur
	Dry (ext.)	–	–	Humerus	–	Sacral vertebrae
	Dry (arch.)	–	–	Hemimandible	Coxal, tibia	Ulna

2.4. Analytical techniques

The experimental and archaeological bone assemblages were described and compared both macro and microscopically. First we employed existing macroscopic methods for burned bone characterization (Castillo et al., 2013; Ellingham et al., 2015; Hiller et al., 2003; Shahack-Gross et al., 1997; Stiner et al., 1995, 2001; Surovell and Stiner, 2001; Thompson et al., 2013; Weiner and Bar-Yosef, 1990). These are based on color changes, cracking, bone loss, weakness and shrinkage.

For color, we used the scale proposed by Nicholson (1993) and Stiner et al. (1995), by which we classify burned bone according to simple, double and triple coloration. Surface alteration features considered include longitudinal and transverse fractures, cracks and general weakness of the bones caused by thermal impact (Asmussen, 2009), as well as shrinkage and weight loss (Shipman et al., 1984). Bone fragmentation

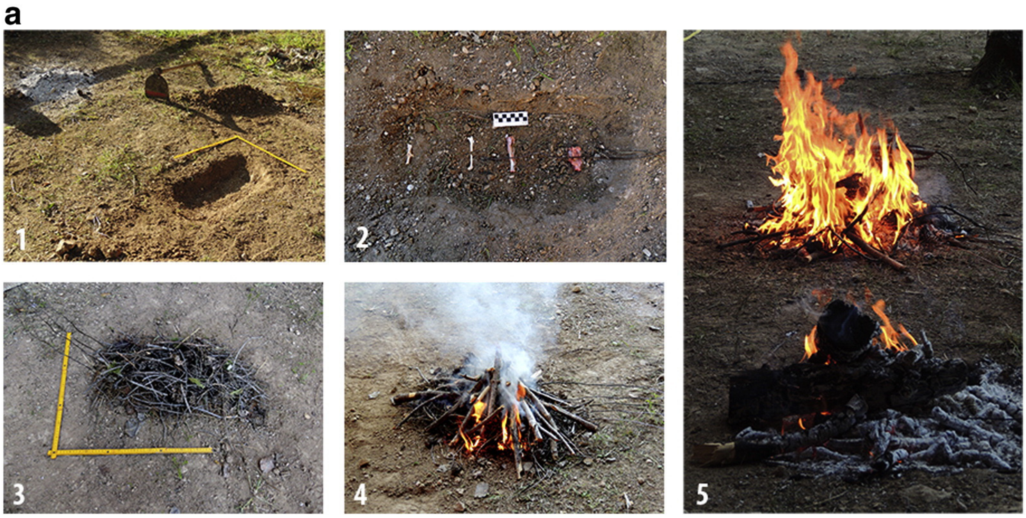

Fig. 4. A. Experimentation phases: 1) substrate excavation, 2) placement of experimental bones at different depth (2.5 cm, 5 cm, 7.5 cm), 3–5) combustion phases. B. Experimental hearth after combustion and different phases of excavation process: 1 and 2) Register dimensions of white layer and black layer, 3) profile of combustion with a red-line separate the white and black layer, 4–9) material recovery into white layer, hearth base and black layer. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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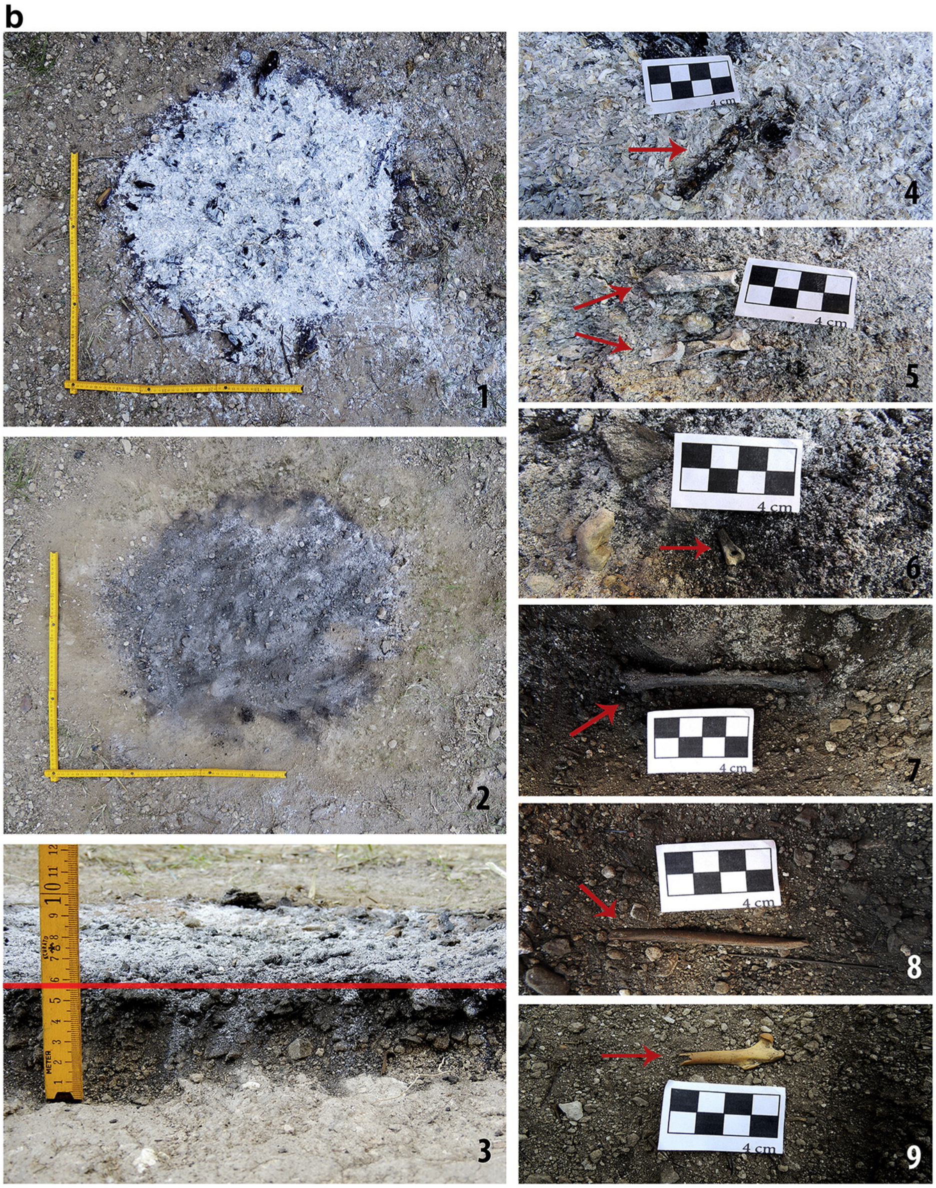

Fig. 4 (*continued*).

was assessed by comparing bone length before and after the combustion event, except for bone fragmented to an extent at which they could not be measured.

We are interested in exploring bone surface features through optical microscopy observation in the naked eye and using less expensive and faster methods than FTIR, X-Ray analysis or other such chemical techniques. Subsequently, optical microscopy was used to observe color changes and surface features. We followed criteria proposed by Asmussen (2009), Nicholson (1993), Shipman et al. (1984), Hanson and Cain (2007), and Castillo et al. (2013) to describe surface features such as fractures, cracking, shrinkage and possible changes in collagen fibers. We employed a Leica M165-C stereomicroscope coupled with a Leica MC170 HD camera to observe a selection of experimental and archeological bone specimens up to 10 magnifications and a Hirox KH8700 reflected light microscope to analyze a different set of experimental and archaeological bone specimens between 3.5 and 70 magnifications (Table 4). We also analyzed 2 unburnt bones as reference. Bone included in the sediment thin sections from the archaeological combustion structures was observed at 20–100 magnifications using a Nikon EPOL 600 petrographic microscope under plane and crossed polarized light.

Microscopic bone surface modifications are related with the occurrence of thermal alteration at a specific temperature range following the stages proposed by Thompson (2004) for heat-induced alteration: 1) dehydration, 2) decomposition, 3) inversion, and 4) fusion.

Finally, we carried out cluster analysis using *Past©* software to check relationships and generate groups from different variables. In all cases we used the Paired Group algorithm (UPGMA) and the Manhattan Similarity Index.

3. Results

3.1. Sediments and temperatures

Excavation of each experimental combustion structure was undertaken 24 h after its natural extinction. A common feature among the

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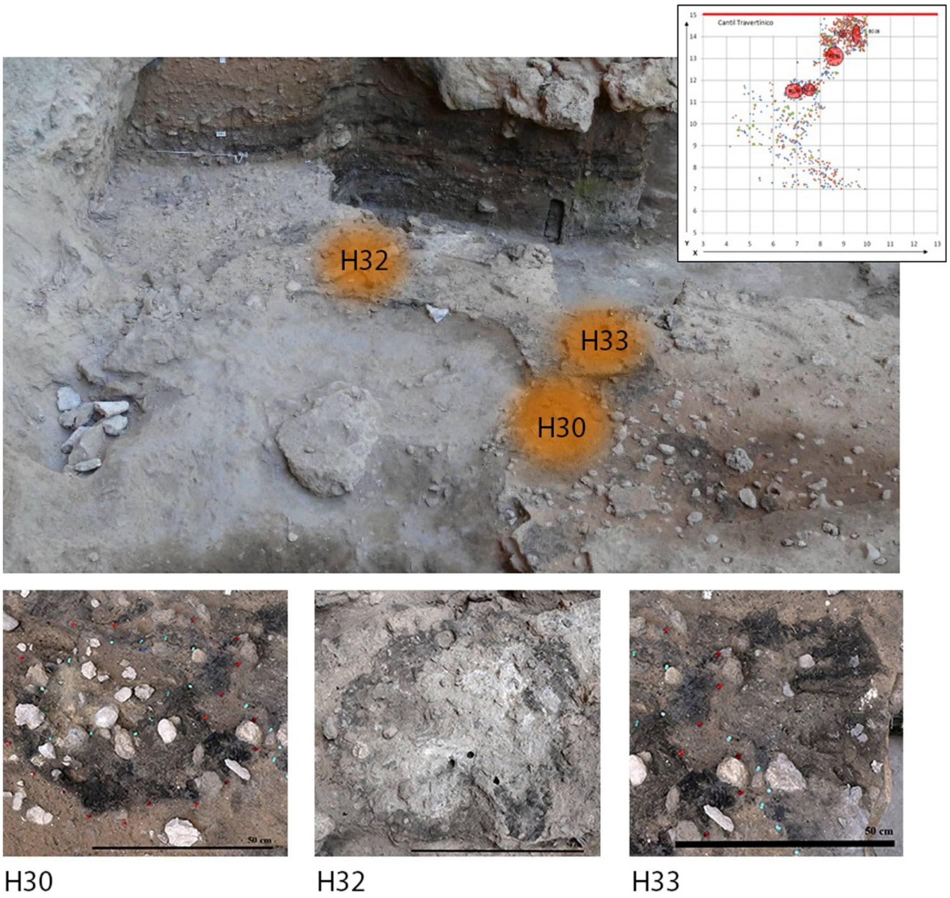

Fig. 5. Plot and real excavation surface of SU X showing distribution of hearths H30, H32, H33 and zenith photos of each one.

combustion structures was an increased size of the original diameter due to the ash deposit, being more pronounced in some compared to others, according to the quantities of fuel employed and the influence of the wind (Table 1).

The black layer, representing the burned organo-mineral horizon, varied between 2.5 and 4 cm in thickness thinning towards the edges (Fig. 4b.3, Table 1). In the archeological combustion structures, the thickness of the black layer did not exceed 2–3 cm.

For all the experimental hearths the maximum temperature recorded on the surface oscillated between 481 °C and 957 °C. Temperatures in the soil were more stable, decreasing proportionally to depth in each fire, although in experiment H-II the maximum temperature reached at 5 cm was higher than at 2.5 cm. On the other hand, experiments having had the same combustion time showed differences in the maximum temperatures recorded by facies (Fig. 7).

3.2. Macroscopic observations

3.2.1. Experimental series

85.8% of the experimental bones showed signs of burning (Table 5). Many of the buried bones showed only localized signs of burning along the cortical surface (8.4%) or isolated burned areas (9.2%), particularly articular ends of long bones and vertebrae. The rest of burned bones showed total color changes (82.3%).

Regarding color, the most thermally affected bones were the ones directly exposed to fire, particularly the ones that had been tossed in the flames. Nevertheless, bones lying on the surface and over the embers showed double colorations and a predominance of white, relating to the final phases of combustion (Fig. 8). In contrast, buried bones turned black (41%) and brown (28%), relating to the initial and intermediate phases of heat alteration (carbonization or dehydration/decomposition stages respectively, according to Thompson, 2004) and white bones were practically absent. Within the buried assemblage, bones at 2.5 cm depth were predominantly black and brown; bones at 5 cm depth were mostly unaltered, with some black and brown specimens; at 7.5 cm depth, the number of unaltered and brown bones prevailed (Table 6).

Besides color, we observed cracks (8.1%), fractures (15.5%), bone loss (33.8%) and weakness (35.8%) on fresh bones, while dry bones (both recent and archeological) showed low levels of polish (8.8%), weakness (0.7%) and bone loss (0.7%) (Table 5, Fig. 9). Cluster analysis confirms the thermal alteration relationship between dry-recent and dry-archaeological bone (Group 1) and their difference from fresh bone alteration (Group 2), showing a correlation coefficient of 0.93 (Fig. 19.1).

The observed differences between fresh and dry bone (Fig. 10) i.e., the incidence of surface alteration, including color, were found to be dependent on the position of the bones within the hearth and the intensity of the fire (a combination of temperature, duration and quantity of fuel employed). In this case, cluster analysis with a correlation coefficient of 0.67, shows the similarity of thermal alteration among bones located at 7.5 and 5 cm depths (Group 1) compared to bones placed at 2.5 cm depth or tossed in the flames and embers (Group 2), as well as bones located on hearth base (Group 3) (Fig. 19.2).

Finally, bone fragmentation was significantly higher in the combustion structures' white layer (the ash deposit), where bone fragments < 30 mm were more frequent than beneath (30.4% next to 1.3% on the surface and 9.5% in black layers, corresponding to buried bones). Among the buried bones > 30 mm-sized fragments were more frequent in the black layers (55.4%) than on the hearth surfaces (Table 7, Fig. 11).

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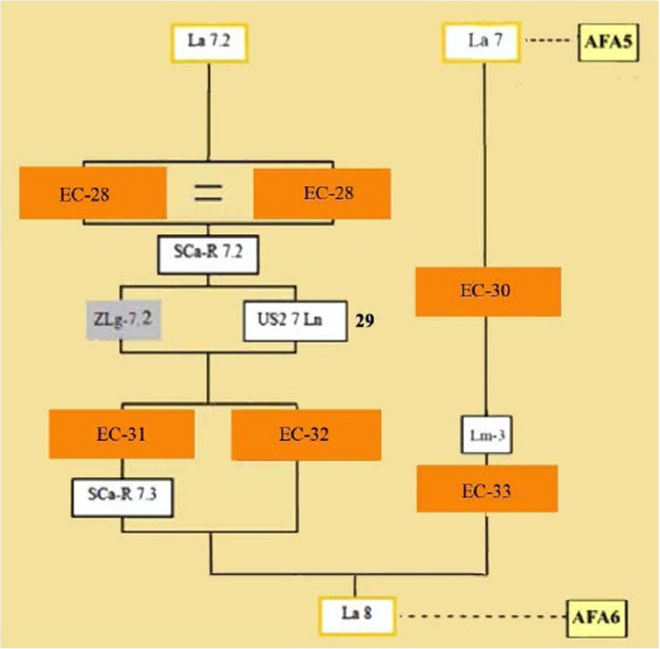

Fig. 6. Harris Matrix of Archaeosedimentary Facies (AFA) 5 with stratigraphic position and relations of the hearths employ in this study with other hearths and facies.

3.2.2. The archeological assemblage

When considering the rabbit and other very small sized bones recovered from archaeological combustion structures, there is a higher representation (28%) of archeological burned bone representing the hearth surface (immediately above the white ash layer). 20.5% of the burned bones are found in black layers and 10.9% in white ash layers. Regarding unburned bone remains, it is noteworthy that these are more frequent in white layers (15.1%) than beneath (Table 3).

With regard to color changes, the majority of bones show no visible thermal alteration (40.6%), followed by black (25.3%) and brown/black colorations (24.4%). The presence of white bones is very low, both among the coordinated and sieved remains, and they are almost totally absent from black layers (only 1 bone in H30). In general terms, this distribution is the same for each combustion structure, with simple and double coloration represented in all facies, predominantly in white layers and surface on white layer (Table 8, Fig. 12).

Bone surface alteration features are very scarce, mostly cracks (0.6%) and bone loss (0.08%) (Fig. 13).

Finally, fragmentation is prominent. First, most of the archaeological bone remains were recovered from the sieve due to their small size. One exception is H32, where the sieve yielded no bone remains, but these were relatively abundant among the coordinated remains found in the black layer and surface on the white layer of the combustion structure.

When comparing fragmentation levels among the different combustion structures (Table 7, Fig. 11), we observed clustering of <30 mm bone fragments surfaces and a very low or null representation of > 30 mm bone fragments in white layers at the base of white layers. Combustion structure H33 diverged from this trend, showing a relatively high number of <30 mm-sized remains in the black layer, an absence of > 30 mm-sized bone fragments, and an absence of bone at the surface on the white layer.

3.3. Microscopic observations

Microscopic analysis has enabled us to check further for bone cortical surface alteration features, including color changes, cracking, polish and structural changes.

3.3.1. Experimental series

For dry bone specimens, polish, weakness and bone loss observed at the macroscopic level was not identified microscopically (up to 70 magnifications). We only identified color changes as presented in Table 1, which correspond to the dehydration/decomposition stage (Thompson, 2004) (Fig. 14).

In contrast, the cortical surface of fresh bones showed significant heat alteration. We observed irregular polish corresponding to carbonization or decomposition stages, as well as loss of structure and surface regularization corresponding to calcination or inversion/fusion stages (Table 9, Fig. 15) (Castillo et al., 2013).

3.3.2. The archeological samples

Microscopic analysis of archeological bone from white and black layer facies showed no differences between the two (Table 9). In the first case, some bones display a regular surface suggesting incipient carbonization or decomposition stages, while others show a polished appearance characteristic of carbonization or decomposition stages (Fig. 16).

Some specimens from black layers present a homogeneous surfaces suggesting in a carbonization or decomposition stages. However, other specimens have a more irregular cortical surface, two of them displaying a melted surface (n° 663, 708) characteristic of carbonization and incipient calcinations or decomposition/inversion. The remaining bones have regular surfaces from calcinations or fusion stage (Fig. 17).

Regarding the bone fragments embedded in sediment thin sections from some of the combustion structures, although they are indeterminate small fragments, their small dimensions allow comparison with our experiments sample (Table 10). These show frequent fissures and display colors suggestive of low degrees of burning, never beyond the carbonization stage. One exception is a tooth fragment from a white-black layer contact in combustion structure H32 (Fig. 18.11).

4. Discussion

4.1. Archaeological and taphonomical implications

In any archeological context containing burned bones, we tend to think that their origin was linked to anthropogenic activities: processing, consumption and discard, as discussed in the introduction. However, some authors have proposed the possibility of indirect thermal

Table 3
Quantities of bone fragments recovered on archaeological combustion structure number 30, 32 and 33 in different stratigraphic locations: above white layer, white layer (hearth) and black layer (burned soil) in of S.U. X of El Salt. Differentiates between burned (B) and unburned (UB) bones and remains recovery in 3D or sieve.

Hearth ID	Above white layer (B)		Above white layer (UB)		White layer (B)		White layer (UB)		Black layer (B)		Black layer (UB)		Total 3D	Total sieve	% Total burned	% Total unburned	Total
	3D	Sieve	3D	Sieve	3D	Sieve	3D	Sieve	3D	Sieve	3D	Sieve					
H30	5	249	4	129	–	72	–	146	13	69	2	137	24	802	32,33	33,12	826
H32	8	92	8	–	2	–	–	–	12	–	30	–	60	92	9,03	3,01	152
H33	–	–	–	–	–	65	–	43	12	135	3	26	15	269	16,80	5,71	284

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Table 4
Macroscopic features of experimental and archaeological bones employ in microscopical analysis. Note: abbreviator "Ext" it refers to extant/recent bones, while "Arch" is refer to archaeological decontextualized bones. All abbreviators of color are specified in Table 1 (see above).

Origin	ID	Hearth	Deep/facies	Taxa/size	Bone	Age	Laterality	Previous state	Previous longitude	Posterior longitude	Color	Localization	Surface alterations
Experimental	I.A.3	I	2,5 cm	*O. cuniculus*	Radius-Ulna	Subadult	Right	Fresh	72 mm	50,74 mm (radius)	Bl	Total	Bone loss and weakness
	I.A.1	I	2,5 cm	O. cuniculus	Scapula	–	Left	Dry (arch)	24,1 mm	24,7 mm	Br	Total	–
	IV.A.2	IV	2,5 cm	O. cuniculus	Humerus	Subadult	Right	Dry (arch)	39,6 mm	39,25 mm	Br	Total	–
	IV.B.3	IV	5 cm	O. cuniculus	Tibia	Subadult	Left	Fresh	75,2 mm	75 mm	Br/Bl	Total	Cracks (distal epiphysis)
	V.B.2	V	5 cm	O. cuniculus	Tibia	Adult	Left	Dry (ext.)	88,1 mm	87,96 mm	Bl	Total	Polished
	V.B.1	V	5 cm	O. cuniculus	Coxal	–	Right	Dry (arch)	40,5 mm	40,39 mm	WT	–	–
	VI.C.2	VI	7,5 cm	O. cuniculus	Maxilla	–	–	Dry (ext.)	40,2 mm	36,85 mm	Br/Bl	Total	Fragmentation and weakness
	V.Bra.1	V	Embers	O. cuniculus	Humerus	Subadult	Left	Fresh	–	59,26 mm	Br/Bl/G	Total	Transversal fractures
	VI.Bra.2	VI	Embers	O. cuniculus	Radius-Ulna	Subadult	Left	Fresh	–	60,6 mm	Bl/G	Total	Bone loss, transversal fractures and weakness
	V.Ba.2	V	Hearth base	O. cuniculus	Coxal	Subadult	Left	Fresh	–	–	W/Bl	Total	Fragmentation, bones loss, cracks and weakness
	VI.Ba.2	VI	Hearth base	O. cuniculus	Coxal	Subadult	Left	Fresh	–	–	G/Bl	Total	Longitudinal and transversal fractures, bone loss and weakness
	VIII.Ba.0.3	VIII	Hearth base	O. cuniculus		Subadult		Fresh	–	–	Bl/G/W	Total	Fragmentation and weakness
Archaeological	N° 617	H30	White layer	Small size	Ribs	–	–	–	–	36,88 mm	Bl	Partial	Cracks
	N° 631	H30	Black layer	Cervinae	Falange 3th	–	Right	–	–	34,54 mm	Br/Bl	Partial	Cracks
	N° 635	H30	Black layer	Indeterminate	Trabecular	–	–	–	–	–	W	Total	Cracks
	N° 673	H32	White layer	Medium size	Large	–	–	–	–	34,65 mm	Br/Bl	Partial	–
	N° 675	H32	White layer	Medium size	Large	–	–	–	–	51,44 mm	Br/Bl	External points	–
	N° 678	H32	White layer	Medium size	Large	–	–	–	–	38,07 mm	Bl/G	Total	–
	N° 684	H32	Black layer	O. cuniculus	Femur	–	Left	–	–	32,09 mm	Bl	Total	–
	N° 686	H32	Black layer	O. cuniculus	Hemimandible	–	Left	–	–	37,25 mm	Bl	Total	–
	N° 708	H32	Black Layer	O. cuniculus	Tibia	–	Right	–	–	33,64 mm	Bl(G	Total	Cracks
	N° 715	H32	Black layer	O. cuniculus	Scapula	–	Right	–	–	22,67 mm	G	Total	–
	N° 726	H32	Black layer	Very small size	Mt5	–	–	–	–	22,14 mm	Bl/G	Total	–
	N° 653	H33	Black layer	O. cuniculus	Coxal	–	Left	–	–	27,4 mm	Bl	–	–
	N° 660	H33	Black layer	Small size	Large	–	–	–	–	55,25 mm	WT	–	–
	N° 663	H33	Black layer	Indeterminate	Flat	–	–	–	–	16,39 mm	G/W	Total	–

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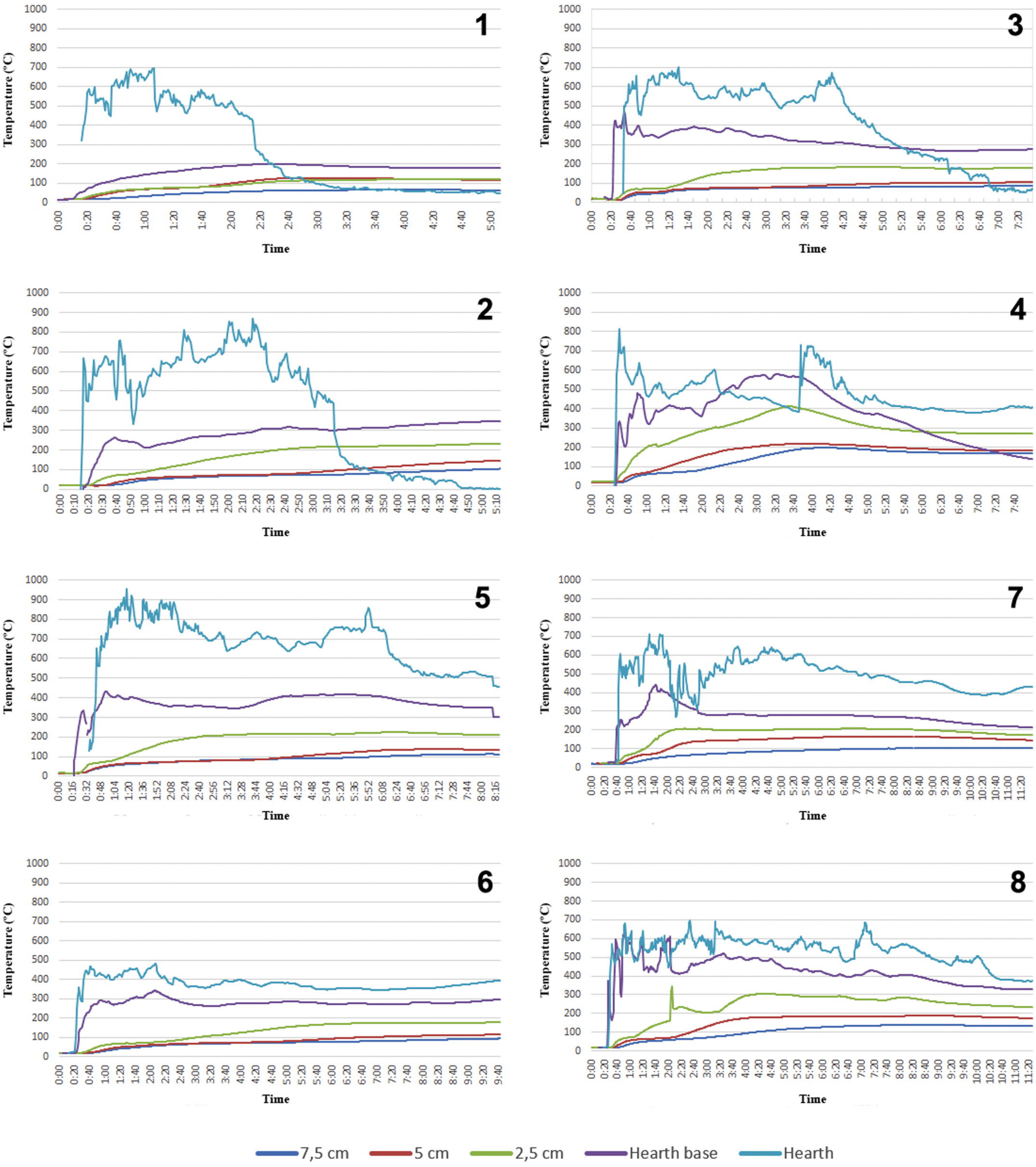

Facies	H-I	H-II	H-III	H-IV	H-V	H-VI	H-VII	H-VIII
Surface	701	694,3	957,2	713,9	830	695,7	902,1	481,2
2,5 cm	183	120,2	223,6	208,4	412,7	345	232,1	179
5 cm	104,7	127,8	137,5	165,4	219,5	198,7	146,7	115,4
7,5 cm	88,7	65,1	113,3	105,1	197,5	141,1	104,1	94,1

Fig. 7. Histograms with temperatures recorded during the combustion by hearth and table with maximum temperatures of them distinguish by facies: surface or hearth, 2.5 cm depth, 5 cm depth, 7.5 cm depth. 1, 2) H-II and H-VII of 2 h; 3, 4) H-I and H-V of 4 h; 5, 6) H-III and H-VIII of 6 h; 7, 8) H-IV and H-VI of 8 h. Interval time of 20 min. (Axis X).

Table 5
Percentage of principal macroscopic alterations in different experimental bones in base at total number of remains ($n = 148$).

Bone nature	Total remains	% Termoalteration	% Cracks	% Fractures	% Bone loss	% Weakness	% Polished	% Total alterations
Fresh	100	62,84	8,11	15,54	33,78	35,81	–	167,57
Dry extant	18	16,22	–	–	0,68	0,68	6,08	23,65
Dry archaeological	30	6,76	–	–	–	–	2,70	9,46
Total	148	85,81	8,11	15,54	34,46	36,49	8,78	200,68

alteration in archeological bone assemblages (Asmussen, 2009; Bennett, 1999; De Graff, 1961; Lyman, 1994; Stiner et al., 1995, 2001). Bennett (1999) described several archeological bones that were burned by more recent fires at a depth of 10 cm. In the same way, Stiner et al. (1995) differentiated between bones that had had “indirect exposure” (located in the substrate) and bones with “direct exposure” (located on the hearth's surface). Due to the high number of burned bones recovered from the El Salt archeological site, this paper contributes new data evidencing the fact that there is not always a relationship between burned remains and human intentionality, and indirect thermal alteration may occur often.

Like Shipman et al. (1984: 321), we accept the fact that alterations in bones generated by fire are more related to organic-mineral or “substance” changes than anatomical factors. Therefore,

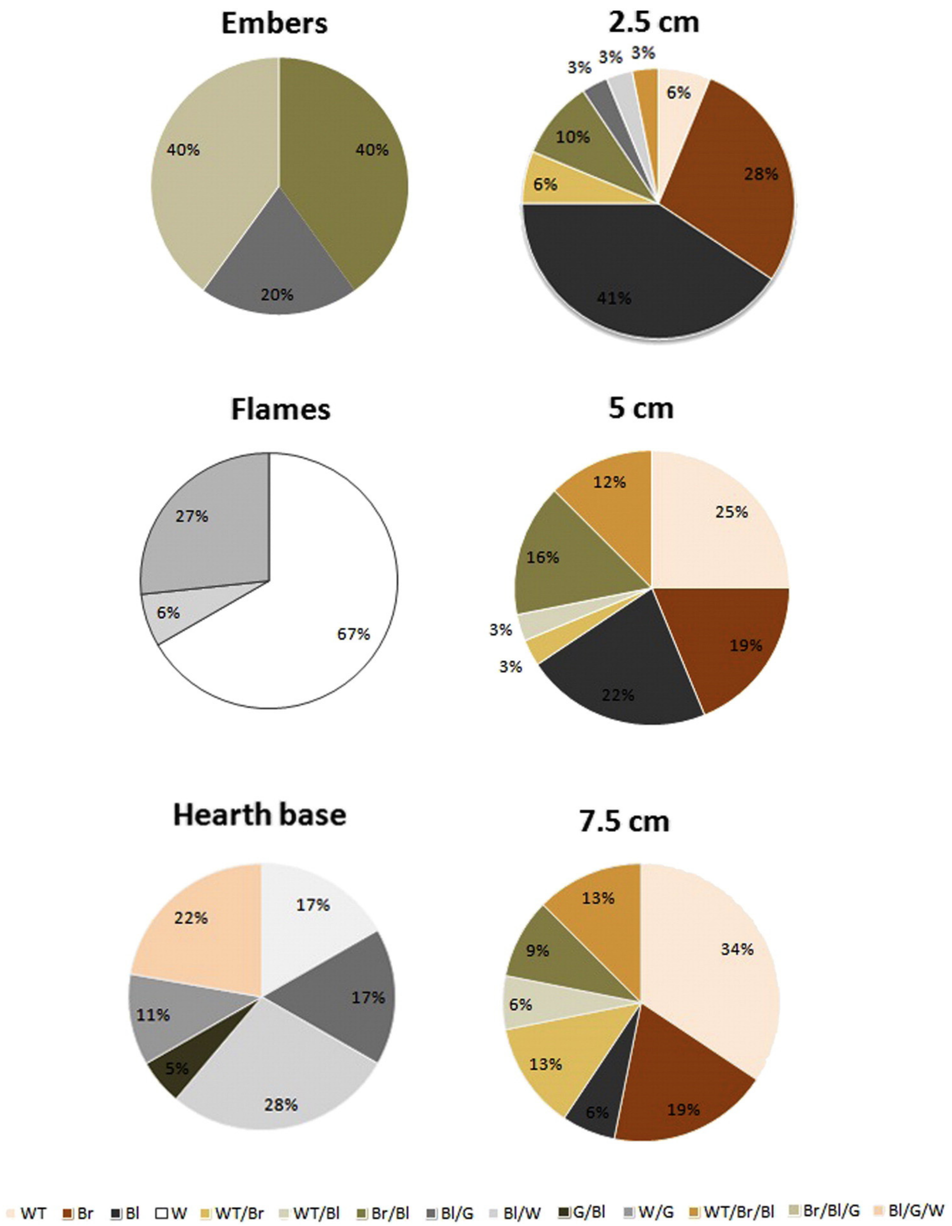

Fig. 8. Distribution of color changes in experimental bones located by facies: embers, flames, hearth base, 2.5 cm depth, 5 cm depth, 7.5 cm depth. Abbreviations: WT (without thermoalteration), Br (Brown), Bl (Black), G (Grey), W (White). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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Table 6
Quantities of bones with different color degrees in the experimental combustion structures (by time). Bones are classified according to their type of color modifications.

Combustion time	Depth	Bone state	Simple color				Double color							Tiple color			Loss/destroy
			WT	Br	Bl	W	WT/Br	WT/Bl	Br/Bl	Bl/W	G/Bl	W/Br	W/G	WT/Br/Bl	Br/Bl/G	Bl/G/W	
2 h (H-II y H-VII)	2,5 cm	Fresh			2						1			1			
		Dry arch.		1						1							
		Dry ext.					1		1								
	5 cm	Fresh	1		2									1			
		Dry arch.	1														
		Dry ext.	1	1	1												
	7,5 cm	Fresh		1				1						2			
		Dry arch.		1													
		Dry ext.	2				1										
	Hearth base	Fresh				1						1	1				3
	Embers	Fresh													1		
	Flames	Fresh				2							1				3
4 h (H-I y H-V)	2,5 cm	Fresh			3									1			
		Dry arch.		3													
		Dry ext.			1												
	5 cm	Fresh	1		1			1						1			
		Dry arch.	2				1		1								
	7,5 cm	Fresh	3				1										
		Dry arch.	1	1													
		Dry ext.	1				1										
	Hearth base	Fresh								2	2					1	1
	Flames	Fresh				3							2				
6 h (H-III y H-VIII)	2,5 cm	Fresh			4												
		Dry arch.		3													
		Dry ext.		1													
	5 cm	Fresh							3					1			
		Dry arch.	1	3													
	7,5 cm	Fresh		1			1	1						1			
		Dry arch.		1													
		Dry ext.	2				1										
	Hearth base	Fresh									1		1			3	1
	Embers	Fresh							2								
	Flames	Fresh				3				1							2
8 h (H-IV y H-VI)	2,5 cm	Fresh			3				1								
		Dry arch.		1	2				1								
	5 cm	Fresh			2				1								
		Dry arch.	1	2	1												
	7,5 cm	Fresh	2						2								
		Dry arch.		1													
		Dry ext.	2						1								
	Hearth base	Fresh				2				2	1						
	Embers	Fresh									1				1		
	Flames	Fresh				2							1				
Total	2,5 cm	Fresh			12				1		1			2			
		Dry arch.		8	2				1	1							
		Dry ext.		1	1		1		1								
	5 cm	Fresh	2		5			1	4					3			
		Dry arch.	5	5	1		1		1								
		Dry ext.	1	1	1												
	7,5 cm	Fresh	5	2			2	2	2					3			
		Dry arch.	1	4													
		Dry ext.	7				3		1								
	Hearth base	Fresh				3				4	4	1	2			4	5
	Embers	Fresh							2		1				2		
	Flames	Fresh				1				1			4				5

thermal alteration of fresh and dry bones produces different diagenetic signals, a fact that does not contradict the better preservation potential of larger anatomical elements (Von Endt and Ortner, 1984). In this work we show that fresh bones undergo color changes ranging from charring to calcination state, bone loss, weight loss, shrinkage/expansion, fractures, cracking and changes in cortical surfaces. Against the proposal of Spennemann and Colley (1989), we observed that cracks may appear only in fresh burned bones, while dry burned bones may undergo only color changes and become slightly weaker, yet seldom beyond the charring or decomposition stages. This is related to the small amounts of organic matter they preserve. These changes can be sought at a microscopic scale, allowing to establish differences according to the original state of the bone. Our experimental fresh bones showed polished cortical surfaces together with recurrent fractures, while no structural changes were identified on the cortical surfaces of dry bones beyond color modification.

Previous works have characterized histological modification of bone by fire (Castillo et al., 2013; Hanson and Cain, 2007; Herrmann, 1977; Nicholson, 1993; Shipman et al., 1984; Stiner et al., 1995; Surovell and Stiner, 2001, Gonçalves et al., 2011), mainly restructuring of collagen fibers and changes in the size of hydroxyapatite microcrystals. Our observed microscopic burned bone surface alteration features at 70 magnifications might correspond to the former, and their stronger

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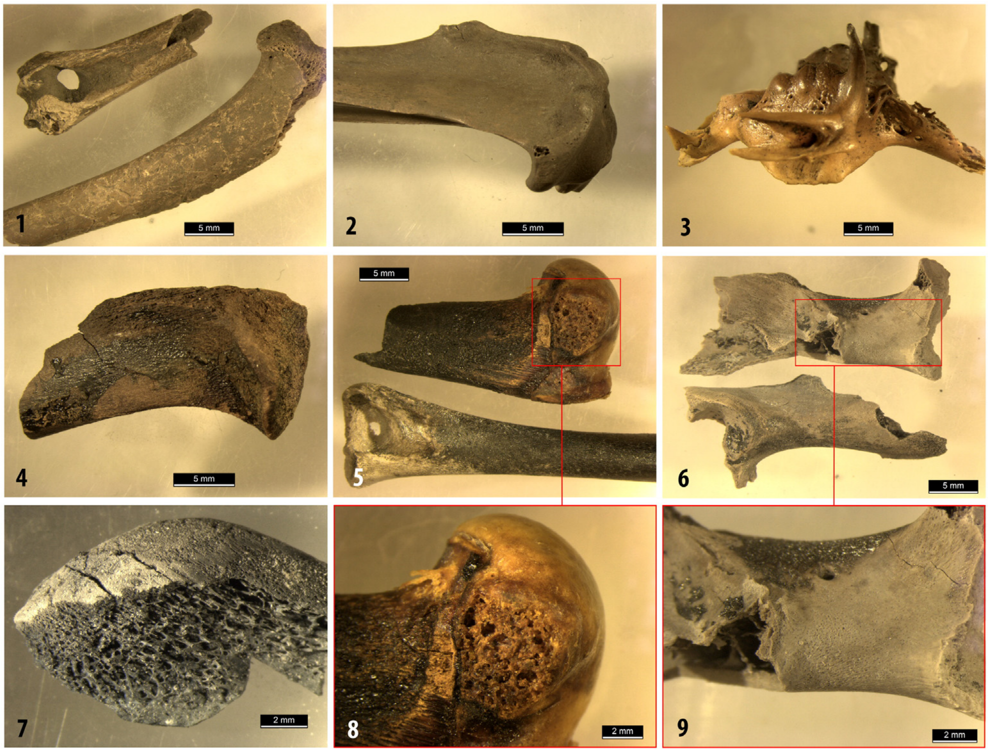

Fig. 9. Macroscopial alterations observed in experimental bones: All bones present color changes. 1–3) Dry bones; 4–9) Fresh bones. 2–3) Polish; 4,6,7,9) fragmentation and weakness with detail; 5.8) Bone loss and detail.

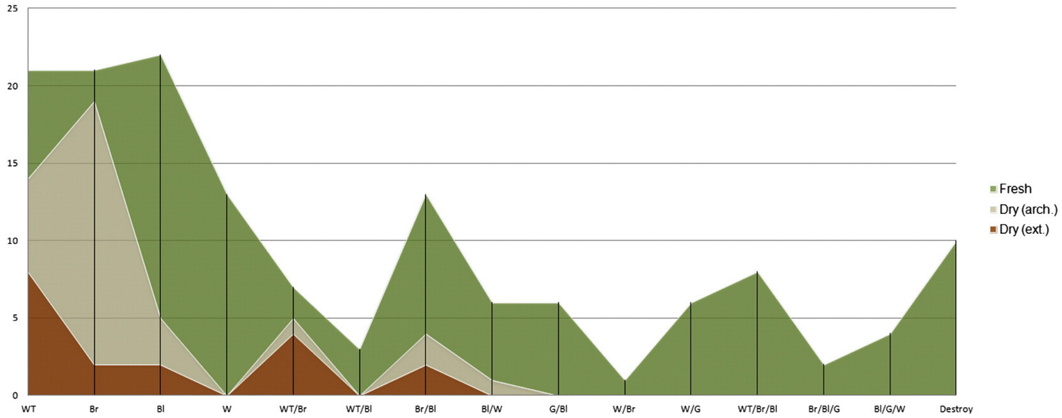

Fig. 10. Histogram with quantities of experimental bones classified by type of color changes and their previous state. Abbreviations: WT (without thermoalteration), Br (Brown), Bl (Black), G (Grey), W (White). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

incidence among fresh bone suggests a possible role of the amount of organic matter present in the bone at the time of burning. These results are in consonance with Gonçalves et al. (2011), who identify warping and thumbnail fractures in cremated dry human bones, conditioned by the small amount of collagen in them. Future research using higher resolution techniques should aim in this direction and explore the correlation between changes in collagen fibers and the freshness of bone.

Based on our preliminary results, we think that it is worthwhile to discriminate between fresh and dry bone when analyzing archaeological combustion structure bone assemblages. Otherwise, there is a risk of misinterpretation in different ways: a) dry bones with few structural changes may be ascribed to low intensity fires, for example the first two stages established by Hanson and Cain (2007); b) we might find inconsistencies in prehistoric human management of faunal resources in hearth contexts; and c) we might mix diachronous depositional events, for instance by lumping together assemblages accumulated by humans with ones accumulated by raptors or carnivores.

On the other hand, unlike Stiner et al. (1995) and Bennett (1999) who conclude that there is "continuous color" in burned

Table 7
Percentage of experimental and archaeological bones located in several facies, classified by different levels of fragmentation.

Hearth	<30 mm			>30 mm		
	Black layer	White layer	Surface	Black layer	White layer	Surface
Experimental	9,46	30,41	1,35	55,41	1,35	2,03
H30	7,84	76,88	14,36	0,57	0,00	0,34
H32	0,00	0,00	60,53	27,63	1,32	10,53
H33	59,85	40,15	0,00	0,00	0,00	0,00

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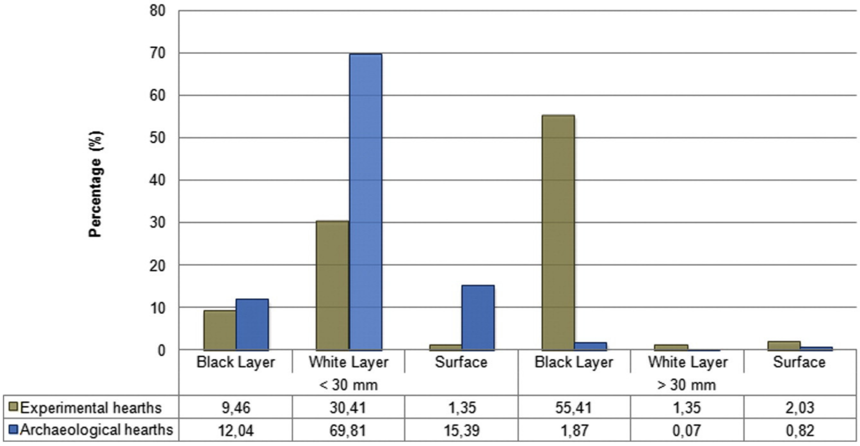

Fig. 11. Bar histogram with percentage of bones recovered in sieve (<30 mm) and coordinate (>3 mm) in experimental and archaeological hearth by facies: black layer, white layer and surface (over hearth). All data are normalized. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 8
Quantities of bones with different color degrees in archaeological combustion structures (by time). Bones are classified according to their type of color modifications.

		Coordinate (>3 cm)								Total	Sieve (<3 cm)								Total
Hearth	Facies	WT	Br	Bl	G	W	Br/Bl	Bl/G	Bl/W		WT	Br	Bl	G	W	Br/Bl	Bl/G	Bl/W	
	Surface	4	1	2	–	–	1	1	–	9	129	2	99	15	–	132	–	–	377
H30	White layer	–	–	–	–	–	–	–	–	0	146	1	37	8	2	17	3	5	219
	Black layer	2	1	5	–	1	6	–	–	15	137	7	32	10	–	20	–	–	206
	Surface	8	2	–	–	–	3	3	–	16	0	12	17	0	0	56	4	3	92
H32	White layer	2	–	–	–	–	–	–	–	2	–	–	–	–	–	–	–	–	0
	Black layer	12	6	9	2	–	12	1	–	42	–	–	–	–	–	–	–	–	0
H33	White layer	–	–	–	–	–	–	–	–	0	43	2	17	8	1	27	9	1	108
	Black layer	3	1	9	–	–	1	1	–	15	26	7	92	3	–	33	–	–	161

fresh bones, our experimental data suggests that both categories of bone (fresh and dry) can display double and triple colorations. This fact can be extended to the archeological record, where we found double colors in bones presumably altered in both fresh and dry states.

4.2. Combustion and sedimentary implications

Another significant issue relating to burned bones in archeology is combustion dynamics. Time and intensity are essential factors in the diagenetic alteration of bone (Von Endt and Ortner, 1984). However, our results show that this is not always the case and cluster analysis indicates similarity in bone alteration only between hearths II and VII. These hearths were both burning for two hours and had similar quantities of fuel (Fig. 19.3). On the other hand, in the substrate a steady temperature decrease with depth (Fig. 7) yielded a minor alteration of bones, except in H-II, where the temperature reached at 5 cm depth is higher than at 2.5 cm, but generate similar alterations in bones (Appendix Data). Therefore, bones in an oxidizing environment are strongly modified at 300–400 °C, whereas if they are buried

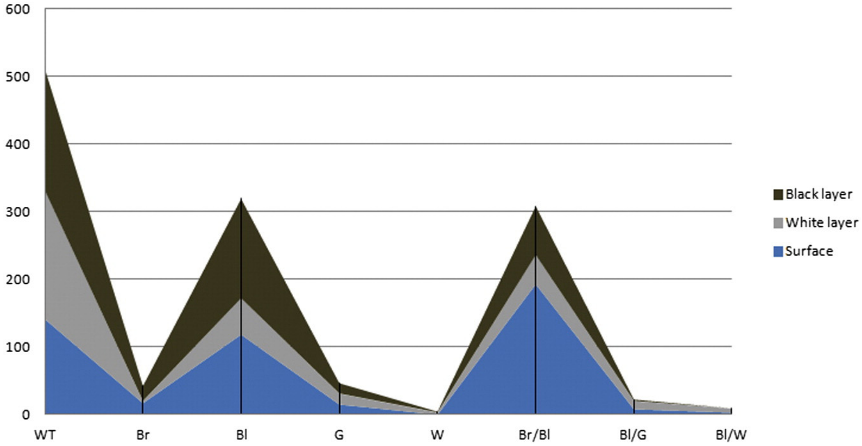

Fig. 12. Histogram with quantities of archaeological bones classified by type of color changes and position by facies: black layer, white layer and surface (over hearth). Abbreviations: WT (without thermoalteration), Br (Brown), Bl (Black), G (Grey), W (White). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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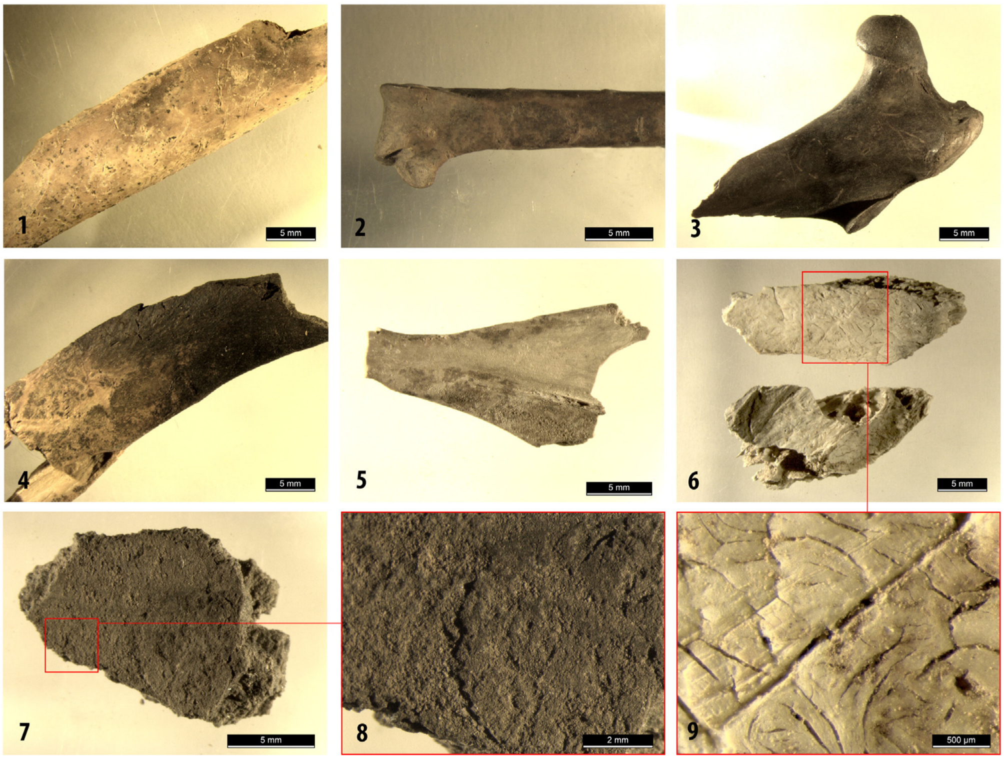

Fig. 13. Macroscopical alteration observed in archaeological bones of medium and small size specimens: All bones present color changes. 1–3) medium and very small size mammal bones burnt when were dry; 4–9) medium and very small size mammal bones together with indeterminate bones burnt when were fresh. 5–9) cracks, bone loss and cut marks with details. First line is related with dry bones. Second and third lines are related with fresh bones.

they do not exceed the level of charring and yield only few alterations (small fractures, weakness, shrinkage). This is the case of the remains located at 2.5 cm depth in experimental hearths V and VI (Fig. 7). These results are consistent with the work of Stiner et al. (1995), who claim they maintain that bones buried from 1 to 15 cm depth never exceed carbonization.

With respect to the thermal signal in the substrate, combustion time in the experimental hearths influenced the depth of the black layer, which had average thickness of 4 cm. This layer concentrates the majority of the potentially modifiable organic matter. Nonetheless, in other experiments and as seen in the archeological combustion structures this facies does not exceed 2 cm in thickness (Aldeias et al., 2016; Mallol et al., 2013b), although thermal alteration of buried bones may exceed the thickness of the sedimentary black layer. Also, in our experiment we tested the hearths by altering the combustion times and quantities of fuel, and observed that the temperature effect on buried bones not depend of fire duration, i.e. that in experimental hearth VIII the buried bones are more altered after 6 h than the bones in experimental hearth IV which burned for eight hours, both having similar quantities of fuel. Equally, hearths with the same combustion time and similar quantities of fuel did not reach the same maximum temperature in all facies (Fig. 7). Acorrelation coefficient of 0.73 supports this finding (Fig. 19.4). However, it is also true that hearths that have a short combustion time and low amounts of fuel still register high temperatures, i.e., hearth VII that burned for 2 h with only 17.5 kg of fuel, but reached temperatures of >900 °C in the surface layer and 230 °C in the immediate substrate. The best explanation for this has been suggested by Aldeias et al. (2016), who claim that the most significant changes occur in the first 2 to 3 h of combustion, as influenced by several variables including heat intensity and sedimentary features. We also include fuel quantity, log size and weather conditions among these variables.

4.3. Archaeostratigraphic interpretations

The archeostratigraphic results of this work are significant. Firstly, it is possible to differentiate between remains contained in the substrate, placed on the hearth surface and afterwards thrown to it. We can see how it was practically impossible to recover any bones from white layer without sieving due to the high levels of fragmentation. In contrast, bones located in black layer can be recovered manually. When we compare this data with archeological hearths we see that the pattern is repeated: a high density of bones smaller than 3 cm in length are recovered from the white layers, while bones located in black layers and the facies above the hearths are longer than 3 cm (Table 7, Fig. 11). The lack of remains in the white layers of archaeological combustion structures could be related to absence of bone in the original combustion-derived deposit. Alternatively, bone could be absent due to diagenetic processes involving ash dissolution in presence of highly fragmented burned bone or another phosphate source. This is supported by the presence of dahllite in white layer sediments from Stratigraphic Unit Xb (Mallol et al., 2013b; Rodríguez-Cintas and Cabanes, 2015). On the other hand, bone destruction in the white layer may explain the greater presence of large-sized bones in black layers, where the intensity of diagenetic processes is lower due to the absence of direct exposure to fire. All these data help us characterize different bone assemblage from different combustion facies and interpret their depositional times and thermal alterations from a genetic perspective.

In this sense, it is noteworthy that both, the experimental and archeological black layers contain a mix of strongly altered and unaltered bones. These results agree with archeological data from several hearths in El Salt Stratigraphic Unit X, where there are mixes of burned and unburned bones from medium and small mammals, including rabbits (Mallol et al., 2013b). White layers have also yielded unburned

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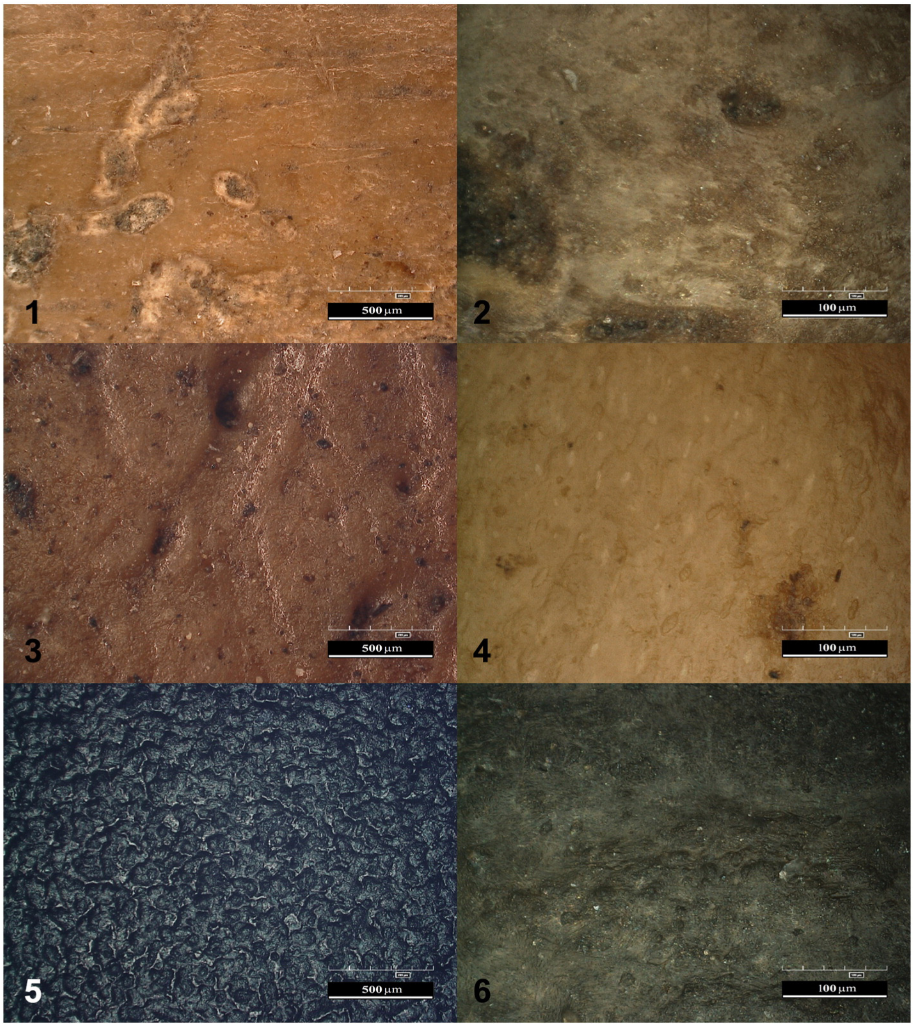

Fig. 14. Microscopical surface of experimental dry bones at ×140 (left) and ×700 (right), classified by color levels: 1–2) brown, 3–4) brown-black, 5–6) black. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 9
Microscopic features of experimental and archaeological bones at ×700.

Origin	ID	Hearth	Deep/facies	Color	Localization	Macroscopical surface alterations (×35)	Microscopical surface alterations (×700)	Stage of bone transformation
Experimental	I.A.3	I	2,5 cm	Bl	Total	Bone loss and weakness	Melted appearance	Decomposition
	IV.A.2	IV	2,5 cm	Br	Total	–	Color changes	Decomposition
	V.B.2	V	5 cm	Bl	Total	Polished	Color changes	Decomposition
	V.Ba.2	V	Hearth base	W/Bl	Total	Fragmentation, bones loss, craks and weakness	Irregular surface structure	Inversion
	V.Bra.1.	V	Embers	B/Bl/G	–	–	Regular surface structure	Inversion/Fusion
	VI.C.2	VI	7,5 cm	Br/Bl	Total	Fragmentation and weakness	Color changes	Decomposition
	VI.Bra.2	VI	Embers	Bl/G	Total	Bone loss, transversal fractures and weakness	Melted appearance	Decomposition
	VI.Ba.2	VI	Hearth base	G/Bl	Total	Longitudinal and transversal fractures, bone loss and weakness	Regular surface structure	Inversion
Archaeological	N° 617	H30	White layer	Bl	Partial	Cracks	Melted appearance	Decomposition
	N° 635	H30	Black layer	W	Total	Cracks	Regular surface structure	Fusion level
	N° 673	H32	White layer	Br/Bl	Partial	–	Color changes	Decomposition
	N° 708	H32	Black Layer	Bl(G	Total	Cracks	Melted appearance and irregular surface	Decomposition/inversion
	N° 715	H32	Black layer	G	Total	–	Color changes	Decomposition
	N° 660	H33	Black layer	WT	–	–	Color changes	Decomposition
	N° 663	H33	Black layer	G/W	Total	–	Melted appearance	Decomposition

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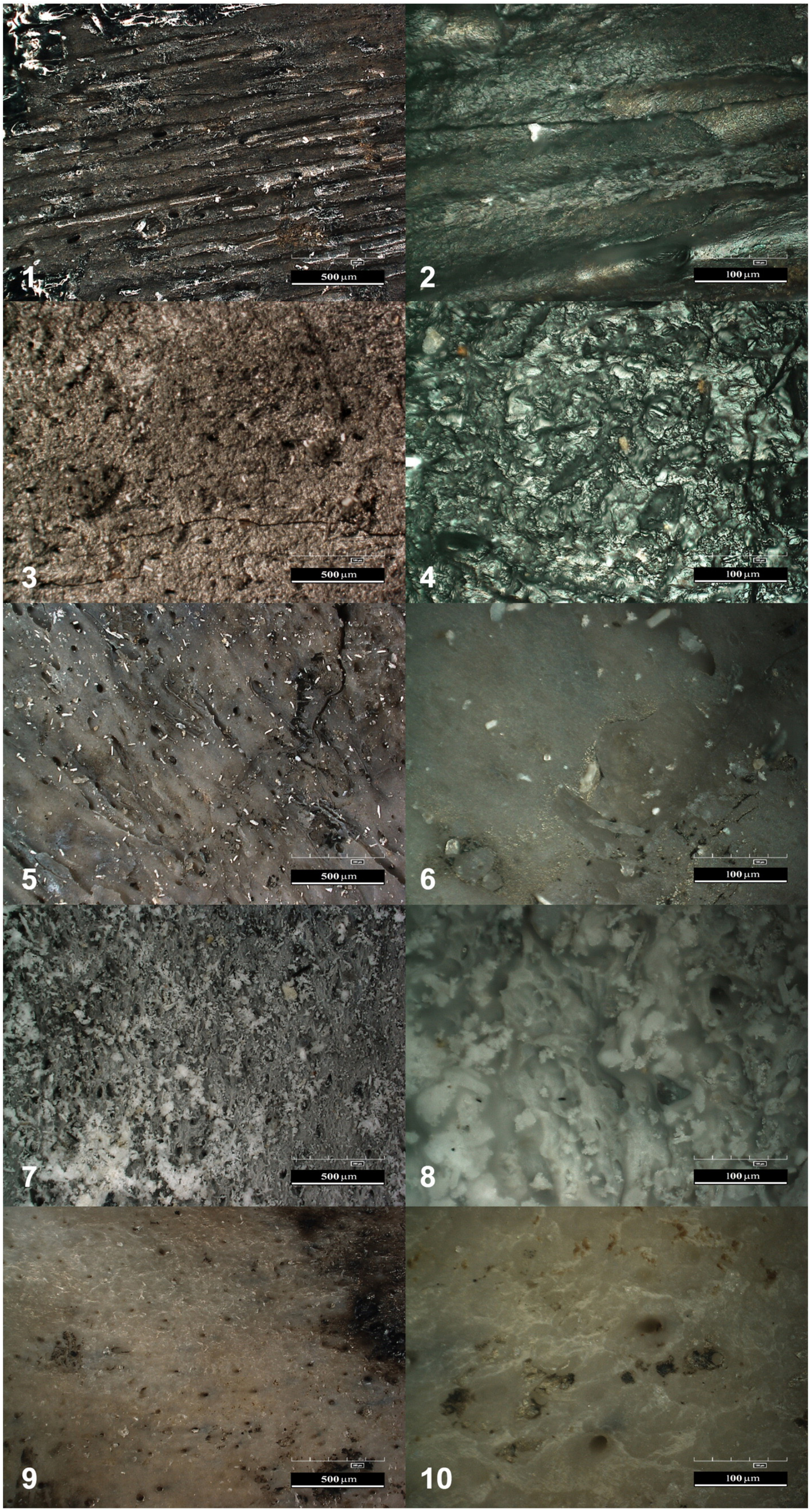

Fig. 15. Microscopical surface of experimental fresh bones at × 140 (left) and × 700 (right), classified by color levels: 1–2) black, 3–4) black-grey, 5–6) grey-black, 7–8) white-black, 9–10) brown-black-grey. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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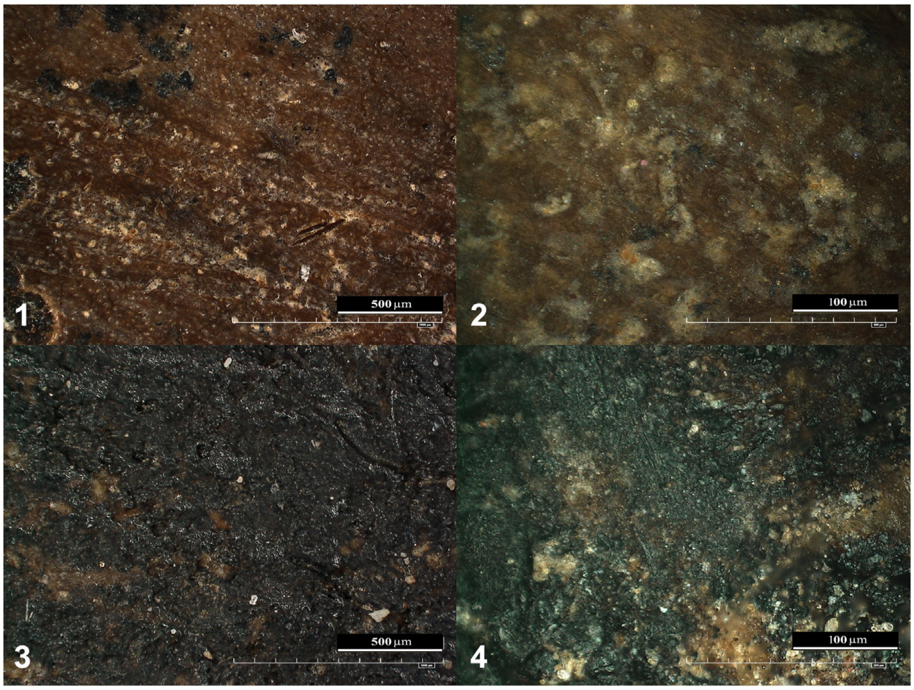

Fig. 16. Microscopical surface of archaeological bones located in white layer at × 140 (left) and × 700 (right), classified by color levels: 1–2) brown-black, 3–4) black. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

bones, which are associated to post-combustion events, related with the recurrent use of the site by raptors in the case of rabbit bones, as well as more recent human occupations.

The analysis of several archaeological bone fragments contained in sediment thin sections has enabled us to identify compression and vertical displacement features in black layer facies. On the one hand, the presence of weakly burned with frequentfractures in the basal sedimentary layers is not consistent with our microscopic observation of dry bone hand specimens. Possibly, the bones in thin sections represent trampled dry bones contained in the sediment during the combustion event (Fig. 18.2, .9). On the other hand, strongly burnt and calcined bones contained in black layers show the same features as experimental fresh burned bones tossed in the flames or placed on the hearth surface. Their presence in the black layers may be related to postdepositional vertical displacement, as has been documented in other archeological sites with high quantities of burned bones, e.g., the Mousterian levels of Hayonim Cave (Stiner et al., 2001). At El Salt, this phenomenon is particularly evident in the thin sections from combustion structure H44-3, in which a calcined tooth fragment was identified at the contact zone between the white and black layers (Fig. 18.11, Table 10).

Finally, we must take into account that the bones recovered from the site have multiple origins. Hoofed animal bones were accumulated by humans, while rabbit bones were mainly accumulated by raptors, with minor instances of Neanderthal input (Pérez et al., 2015). This pattern has been checked against other sites with the aim of determining the degree of intentionality in the thermal alteration of bones: at Wanderer's Cave, dingos accumulated bones, which were subsequently burned by humans (Asmussen, 2009). Ongoing zooarcheological analyses at El Salt show that a large proportion of the rabbit remains were accumulated by raptors as evidenced by digestion features, beak impacts, fragmentation categories and skeletal parts present, together with occasional inputs by humans as shown by notches, scrapings, incisions and peeling fractures) (Pérez, 2014). These bones were affected by postdepositional burning from overlying combustion events. Therefore, the significant presence of rabbit bones in the sequence, the mix of burned and unburned anatomical elements in black layers and the evidence of raptors as depositional agents leads us to considerer that a large part of the burned rabbit bone assemblages are not a result of intentional burning.

This kind of mixed deposit, involving several agents and mixed burned and unburned bones is common in combustion structure black layers. This observation offers temporal information on the timing of combustion activities and bone assemblage accumulation, providing and aid to archaeological dissection. Likewise, it provides a basis for identifying combustion substrate facies in cases where combustion residues or associated sedimentary features are not well preserved.

5. Conclusion

In this paper, we present macroscopic and microscopic bone surface alteration features produced by direct and indirect exposure to fire as criteria for identifying temporality in archeological deposit formation. The results obtained from analysis of bone from experimental fires and archeological bone specimens from El Salt Middle Paleolithic site combustion structures; highlight the possibility that a high number of bones in hearth contexts may have been burned long after their original deposition.

The main conclusions of our study are:

1. Bones burned in a fresh state and containing significant amounts of organic matter can be distinguished both macroscopically and microscopically from bones burned in a dry state with small amounts of organic matter.
2. Optical microscopy at 70 magnifications provides sufficient resolution to observe changes in bone cortical surfaces and differentiate burning stages. This is a fast method of checking the original state (fresh or dry) of bones at the time of without resorting to more expensive and slower analytical techniques.
3. Using macroscopic and microscopic methods to identify bones burned at low temperatures is problematic due to the scarcity of

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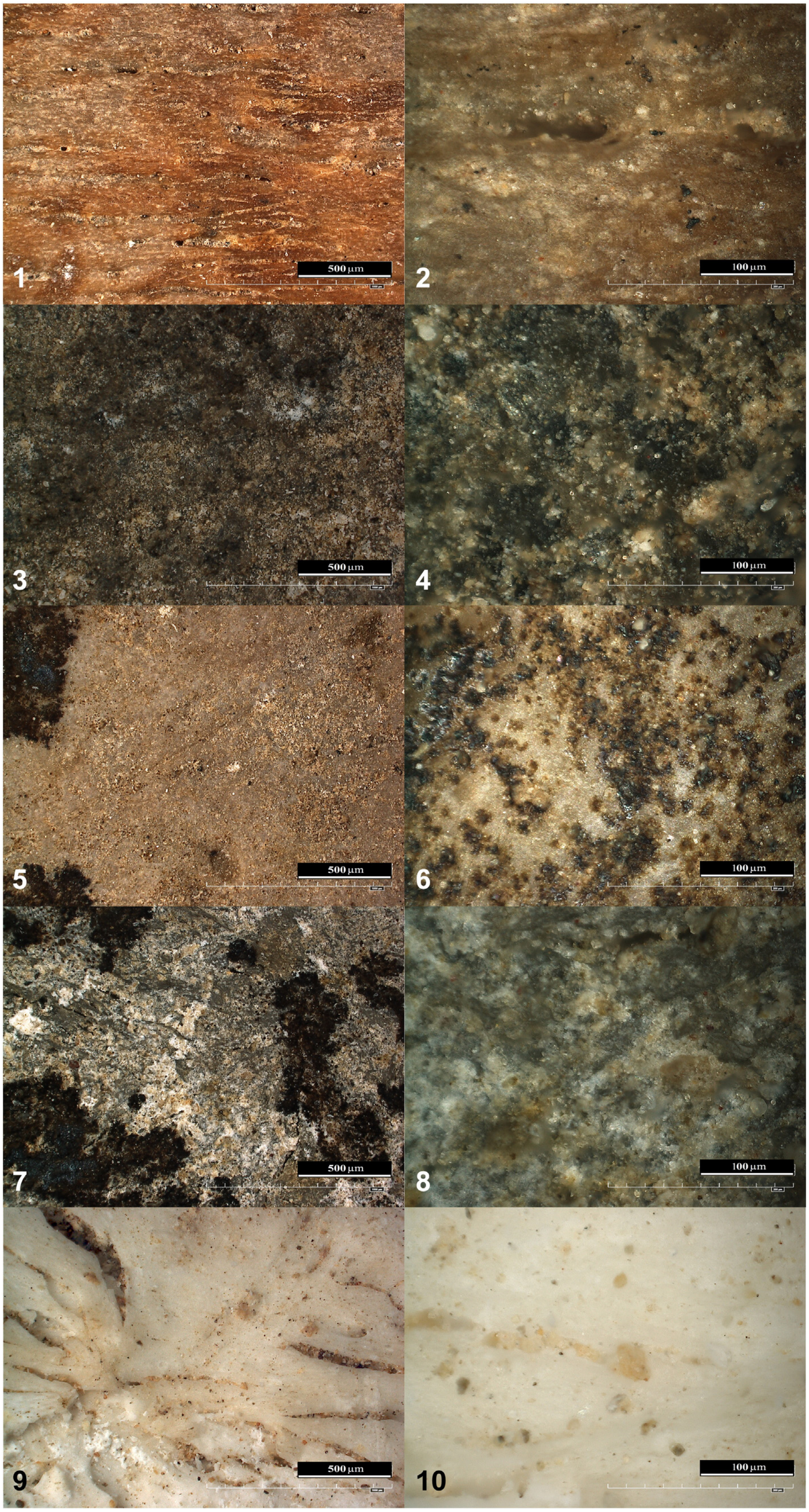

Fig. 17. Microscopical surface of archaeological bones located in black layer at ×140 (left) and ×700 (right), classified by color levels: 1–2) without thermoalteration, 3–4) black-grey, 5–6) grey, 7–8) grey-white, 9–10) white. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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Table 10
Micromorphological features observed in archaeological bone and sediment associated to combustion structures from El Salt Stratigraphic Unit X (Specimens interpreted as burnt in dry state are highlighted with an asterisk).

Thin section	Provenience	Sedimentary features	Bone surface features	
			Color	Structural alteration
1 - Salt 10-3-a*	Base of black layer (H44-1)	Loose, organic-rich sandy clays	Soft brown	Few fractures
2 - Salt 10-3-a	Base of black layer (H44-3)	Loose, organic-rich sandy clays	Yellow-brown	Abundant fractures
3 - Salt 10-4-c	Center of black layer (H32)	Loose, organic-rich sandy clays	Pale yellow	Abundant fractures
4 - Salt 10-4-c	Center of black layer (H32)	Loose, organic-rich sandy clays	Brown	Few fractures
5 - Salt 10-6-a	Center of black layer (H30)	No sediment	Yellow	Few fractures in edges
6 - Salt 10-11-b	Base of black layer (H33)	Channeled,sandy clayey sediment	Brown-Black (burnt edges)	Trabecular bone, without changes
7 - Salt 10-11-b*	Base of black layer (H33)	No sediment	Brown-Black (burnt edges and osteons)	Without changes
8 - Salt 10-11-c*	Base of black layer (H33)	Loose, organic-rich sandy clays	Pale yellow	Few fractures
9 - Salt 10-4-b*	Base of black layer (H32)	Loose, granular, organic-rich sandy clays	Brown	High fractures
10 - Salt 10-4-b*	Center of black layer (H32)	Loose, organic-rich sandy clays	Brown	Without changes
11 - Salt 10-4-b	Black layer – white Layer contact (H32)	Loose, granular, sandy clays	White-Black (carbonized enamel and calcined dentine)	Few fractures in dentine
12 - Salt 10-4-b*	Top of black layer (H32)	Loose, organic-rich sandy clays	Yellow	Longitudinal fractures

structural cortical changes. In this case it is necessary to employ spectrometric techniques.

4. Temperature reached, type and quantity of fuel employed in a hearth and sedimentary conditions are the main variables in the formation of burned soil deposits. Combustion duration is not a relevant parameter on its own.
5. Combustion structure white layers yield low quantities of bone when compared to black layers and facies above white ash layer. This provides information on three depositional times: T1) pre-combustion bones unrelated to human combustion activities; T2) bones related to anthropogenic combustion activities during combustion; T3) post-combustion bones unrelated to preceding combustion event.
6. Black layers are characterized by the presence of burned bones in the carbonization stage together with unburned bones.
7. Our method makes it possible to identify trampling, providing information on the possible postdepositional mixing of remains from different times.
8. The relationship between dry burned bone, taphonomic agent marks and stratigraphic position can help identify non-intentional burning in bones.

We hope these results will serve to inspire future explanations for other archeological burned bone assemblages with which they can be compared, leading the way to new discussions on a fundamental topic relating to human behavior in the past: the importance of fire in prehistory and its archeological interpretation.

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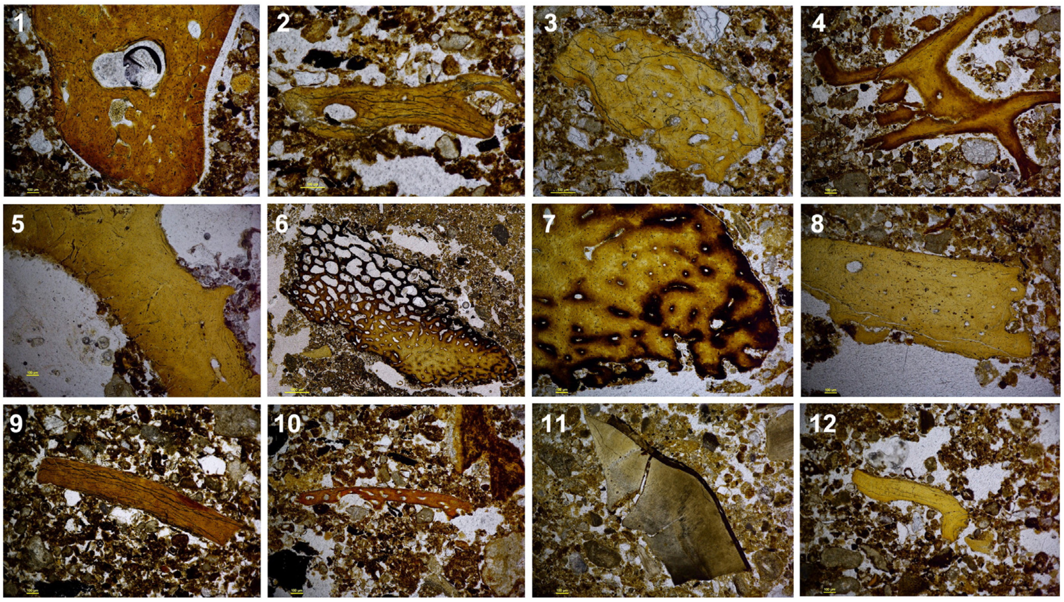

Fig. 18. Micromorphological captures of bones located in black layer of H44-3 and H33. Figure order follows the order established in Table 10.

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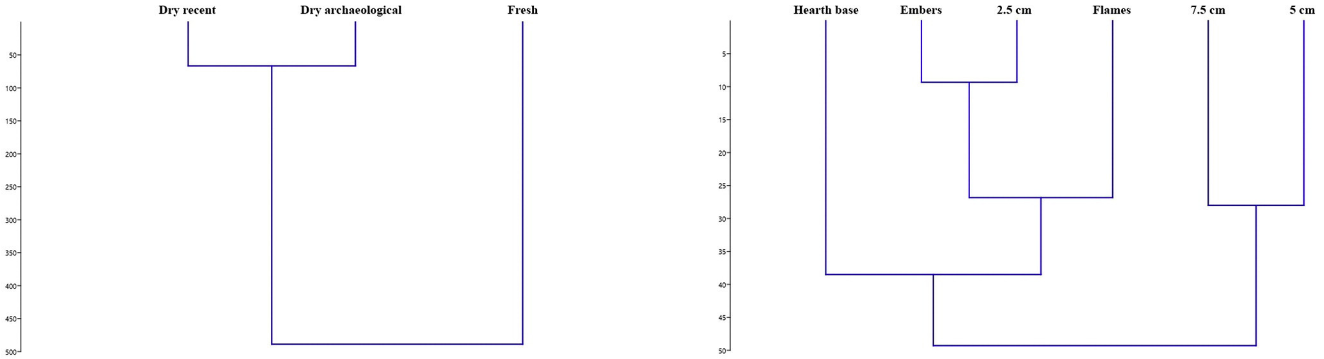
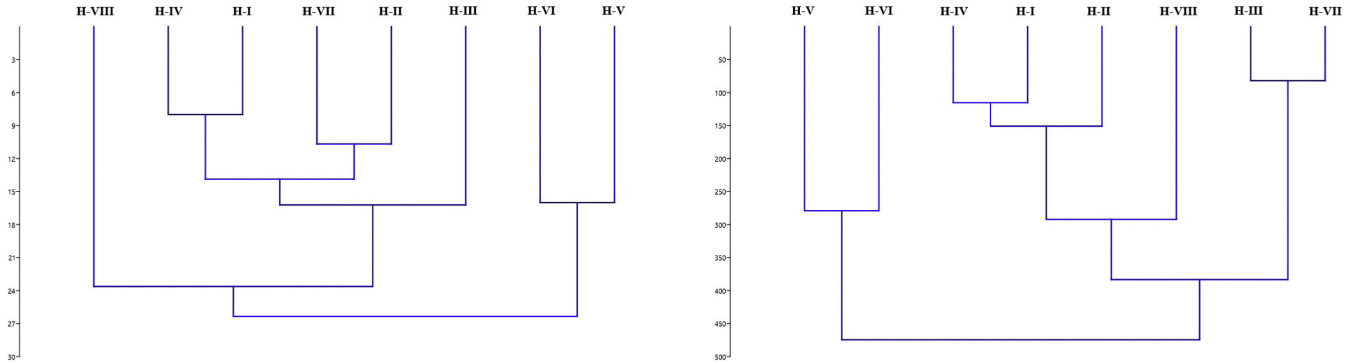


1. Coef. corr. = 0.9371

2. Coef. corr. = 0.6659



3. Coef. corr. = 0.6716

4. Coef. corr. = 0.7337

Fig. 19. Cluster analysis and coefficient of correlation. 1) groups by macroscopic post-thermal alterations in different experimental bone state; 2) groups by levels of color changes on bones at different facies of all experimental hearths; 3) groups by levels of color changes on bones in different hearths; 4) groups by maximal temperatures reached in different facies by hearth. Axis Y represent de "Distance" between variables.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.jasrep.2016.11.036.

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