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The Anthropogenic Use of Firewood During the European Middle Pleistocene: Charcoal Evidence from Levels XIII and XI of Bolomor Cave, Eastern Iberia (230–160 ka)

Paloma Vidal-Matutano [a,b], Ruth Blasco[c], Pablo Sañudo[d] and Josep Fernández Peris[e]

[a]CEPAM, CNRS, Université Côte-d'Azur, France; [b]Departament de Prehistòria, Arqueologia i Història Antiga, PREMEDOC Research Group, Universitat de València, València, Spain; [c]Centro Nacional de Investigación en Evolución Humana (CENIEH), Burgos, Spain; [d]Àrea de Prehistòria, Universitat Rovira i Virgili (URV), Tarragona, Spain; [e]Servei d'Investigació Prehistòrica, Museu de Prehistòria, Diputació de València, Valencia, Spain

ABSTRACT

Human control of fire is a widely debated issue in the field of Palaeolithic archaeology, since it involved significant technological innovations for human subsistence. Although fire evidence has been the subject of intense debate regarding its natural or anthropogenic nature, most authors agree that combustion structures represent the most direct evidence of human control of fire. Wood charcoal fragments from these contexts represent the fuel remains that result from humans' collection of firewood, which means they can reveal significant behavioural and palaeoenvironmental information relevant to our understanding of Middle Palaeolithic societies. In this work, we present anthracological data derived from combustion structure 2 (level XIII, *ca.* 230 ka, MIS 7) and combustion structure 4 (level XI, *ca.* 160 ka, MIS 6) from Bolomor Cave, which are chronologically among the earliest combustion structures found in Europe. The present work discusses how the presence of black pine and / or scots pine in both levels sheds light on the characterisation of the local landscape. Additional analyses focussing on the pre- and post-depositional processes affecting charcoal preservation point to biodegradation patterns. The aim of this work is to provide the first discussion concerning the anthracological data derived from Bolomor Cave in order to contribute to the general debate regarding the use of fire during the European Middle Pleistocene.

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Bolomor Cave; Middle Pleistocene; charcoal analysis; combustion structure; *Pinus nigra-sylvestris*; taphonomy

Introduction

Pyrotechnology is considered to be one of the most significant technological achievements in human evolution (Berna and Goldberg 2007; Brown et al. 2009; Clark and Harris 1985; Courty et al. 2012; de la Rúa and Diez Martín 2011; Goldberg et al. 2012; Villa, Bon, and Castel 2002) although this statement is questioned by some authors based on the lack of direct evidence for human control of fire in northern latitudes (Dibble et al. 2017; Sandgathe 2017; Sandgathe et al. 2011a, 2011b; Stahlschmidt et al. 2015). The anthropogenic control of fire resulted in substantial changes in human subsistence, for example, providing a source of warmth and light, leading to the emergence of cooking practices (smoking, drying) and providing protection against predators (Blasco et al. 2016a; Carmody and Wrangham 2009; Clark and Harris 1985; Goldberg et al. 2012; Gowlett 2006; Gowlett et al. 1981; James et al. 1989; Preece et al. 2006; Wrangham 2009; Wrangham et al. 1999), as well as in socialisation and spatial organisation (Blasco et al. 2016a; Henry et al. 2004; Hietala 2003; Machado and Pérez 2015; Martínez-Moreno et al. 2016; Sañudo, Blasco, and Fernández Peris 2016; Vallverdú et al. 2010, 2012; Vaquero and Pastó 2001; Vaquero, Rando, and Chacón 2004; Vidal-Matutano 2017). The timing of human control of fire is one of the most widely debated topics in the field of Palaeolithic archaeology (Berna and Goldberg 2007; de Lumley 2006; Gowlett 2006; Gowlett et al. 1981; James et al. 1989; Karkanas et al. 2007; Roebroeks and Villa 2011; Stahlschmidt et al. 2015; Wrangham 2009), since such discussion is strongly related to the consideration of fire evidence as being of either natural or anthropogenic origin (Bellomo 1994; James et al. 1989; Roebroeks and Villa 2011). The most common fire evidence consists of archaeological features showing traces of having been subjected to heating, i.e. thermo-altered lithic artefacts, burnt bone fragments and, to a lesser extent, wood charcoal remains. However, this evidence is not exempt from controversy, since natural processes, for example, natural fires caused by lightning strikes, volcanic eruptions or spontaneous combustion, can also create such findings (Christian et al. 2003; Li 2000). Concerning the European context, the scientific community generally proposes that the controlled use of fire occurred from 400 to 300 ka onward and that the archaeological signal

CONTACT Paloma Vidal-Matutano paloma.vidal@uv.es; p.vidal.mat@gmail.com CEPAM, CNRS, Université Côte-d'Azur, France; Departament de Prehistòria, Arqueologia i Història Antiga, PREMEDOC Research Group, Universitat de València, Blasco Ibáñez 28, València 46010, Spain

became well established in sites younger than 100 ka (e.g. Roebroeks and Villa 2011). Burnt material at archaeological sites such as Vertesszöllös (Hungry), Menez-Dregan and Terra Amata (France), Bilzingsleben (Germany), Beeches Pit (England) and/or Maastricht-Belvedere (Netherlands) have often been reported as the earliest evidence of human control of fire in Europe; however, some researchers have warned of different problems relating to the chronological allocation and the taphonomic processes of some of these sites (e.g. Gowlett et al. 2005; Preece et al. 2006; Roebroeks and Villa 2011; Stahlschmidt et al. 2015). With this in mind, diagnostic evidence of the controlled use of fire is based on the presence of well-delimited combustion structures, thermo-altered sediment and burnt artefacts and ecofacts associated with human activity (Bellomo 1994; Mentzer 2014). Accordingly, Bolomor Cave (Eastern Iberia) is perhaps one of only a few European sites to record repeated evidence of fire along its stratigraphic sequence, with the presence of several hearths being identified in levels II, IV, XI, XII and XIII (Blasco et al. 2016b; Fernández Peris et al. 2012).

In light of the abovementioned debate, it is important to note that the use of firewood and, therefore, wood charcoal remains have long been an elusive issue. Whether due to the poor organic preservation at many sites or a lack of interest, the fact remains that the available data concerning firewood use for Middle Pleistocene chronologies is still scarce (e.g. Théry-Parisot, Chabal, and Chrzavzez 2010). In this regard, charcoal analysis focuses on the botanical identification of wood charcoal fragments in order to provide meaningful palaeoenvironmental data (Badal and Heinz 1989, 1991; Badal et al. 2012a; Badal, Villaverde, and Zilhão 2012b; Carrión, Ntinou, and Badal 2010; Chabal 1992; Figueiral and Terral 2002; Ntinou and Kyparissi-Apostolika 2016) and palaeoeconomical evidence regarding humans' strategies for collecting firewood (Allué, Solé, and Burguet-Coca 2016; Carrión and Badal 2004; Chrzavzez 2006; Chrzazvez et al. 2014; Henry and Théry-Parisot 2014; Théry-Parisot 2001, 2002; Théry-Parisot and Texier 2006; Théry-Parisot et al. 1995; Vidal-Matutano, Henry, and Théry-Parisot 2017). Indeed, significant archaeobotanical data have been derived from the Acheulian site of Gesher Benot Ya'aqov (Israel), where charcoal analyses have allowed the botanical identification of six taxa, which evidence the earliest anthracological data from an anthropogenic context published thus far (Goren-Inbar et al. 2004). Additionally, charcoal analyses from the sites of Terra Amata (Nice, France) and Torralba (Soria, Iberia) have also provided early data concerning firewood use among human groups (de Lumley et al. 2016; Postigo-Mijarra, Gómez-Manzaneque, and Morla 2017). Following anthracological data belonging to the MIS 5-4 chronologies have been conducted, wherein a few Middle Palaeolithic sites have provided new insights into past landscapes and human firewood management (Allué 2016; Arsuaga et al. 2012; Daura et al. 2015; Ntinou and Kyparissi-Apostolika 2016; Ronchitelli et al. 2011; Théry-Parisot 2001; Vidal-Matutano 2015; Vidal-Matutano et al. 2015; Zilhão et al. 2016), with a wider generalisation of charcoal analyses performed at MIS 3 sites (Allué, Solé, and Burguet-Coca 2016; Badal, Villaverde, and Zilhão 2012b; Théry-Parisot and Meignen 2000; Théry-Parisot and Texier 2006; Théry-Parisot et al. 1996; Uzquiano et al. 2012; Vidal-Matutano 2017; Vidal-Matutano, Henry, and Théry-Parisot 2017; Yravedra and Uzquiano 2013).

In this paper, we present preliminary anthracological data derived from Bolomor Cave, specifically from two combustion structures from levels XIII (MIS 7) and XI (MIS 6) as well as from the scattered context of level XIII. Our charcoal analysis results are among the earliest published data for the European context, together with those obtained from Gesher Benot Ya'aqov, Terra Amata and Torralba. Hence, the aim of this paper is to provide palaeoecological data concerning this period in Eastern Iberia based on wood charcoal remains as well as to discuss the taphonomical processes affecting the preservation of this ancient charcoal assemblage.

Archaeological setting: Bolomor Cave

Bolomor Cave is an archaeological site located 2 km southeast of the town of Tavernes de la Valldigna, Valencia, Spain (30N 737919E 4329998N UTM Geolocation). The stratigraphic sequence is divided into 17 levels, which are numbered from the top of the deposit and have a maximum thickness of 14 m. Investigation of the magnetic susceptibility of the sediment shows a warm period related to MIS 9 (~ 350 ka) at the beginning of the stratigraphic deposit. For the top sequence, a single thermoluminiscence (TL) date exists, yielding an age of 121 ± 18 ka for level II (Figure 1) (Fernández Peris et al. 2012). The lithic industry found in Bolomor Cave is considered to be an early Middle Palaeolithic techno-complex, with the most retouched artefacts being scrapers and lateral denticulates. It is worth noting that it is characterised by intensive reuse and the recycling of lithics, especially in the upper levels (Fernández Peris et al. 2008). The Bolomor faunal assemblage shows high diversity, with more than 30 species belonging to the categories of Cercopithecinae, Carnivora and Ungulata being identified in addition to small prey such as Leporidae, Aves, Testudinidae, Amphibia and Salmonidae (Blasco et al. 2013a). Further, bone retouchers have been identified in several levels (XVII, XIII and XII) along the stratigraphic sequence (Blasco et al. 2013b; Rosell et al. 2015).

Currently, 14 hearths from levels II, IV, XI and XIII have been excavated. Although heat-altered material

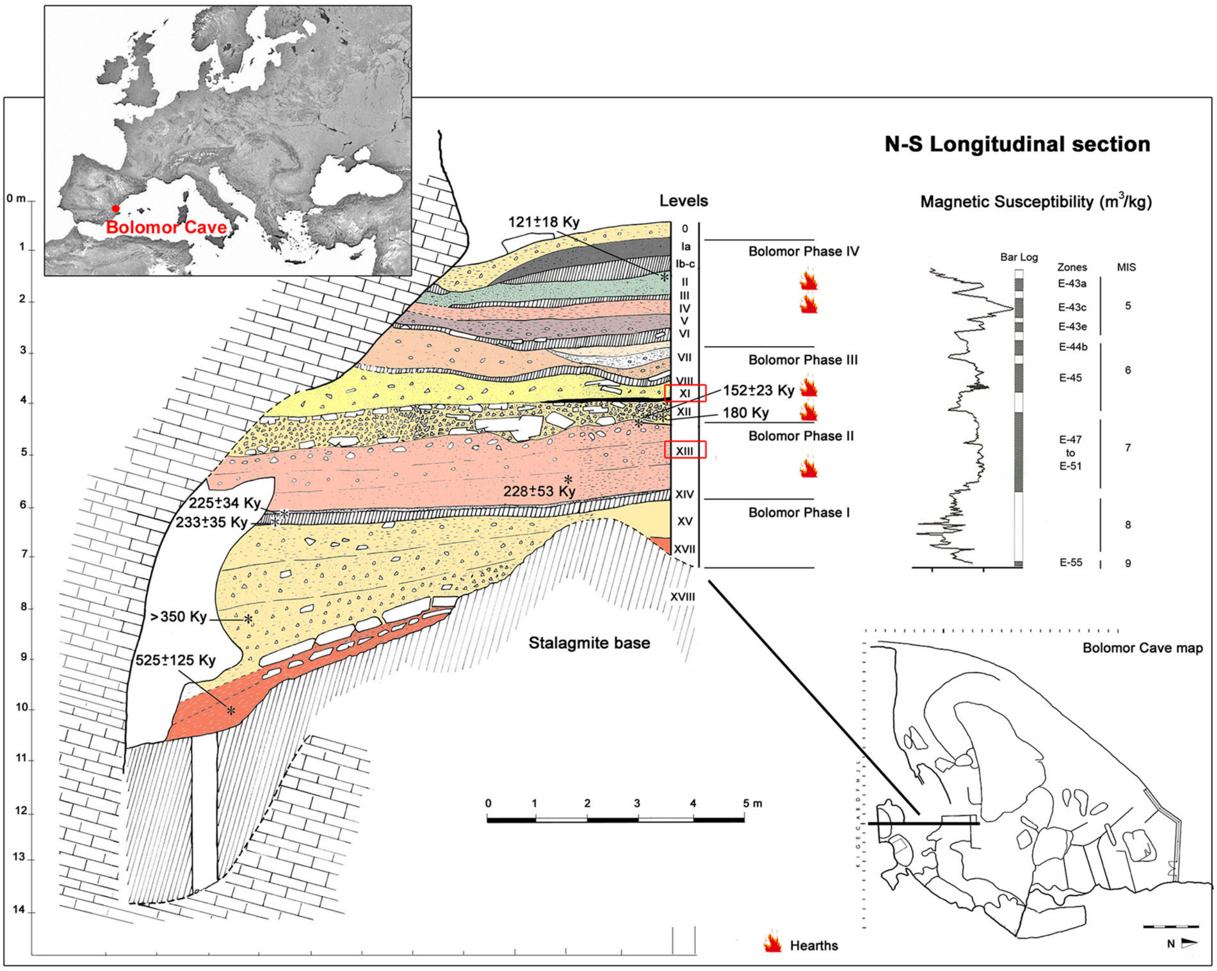

Figure 1. Location and stratigraphic profile of Bolomor Cave showing radiometric dates and positions of the hearths.

has been recovered from the lowest level of the sequence (XVII, 350 ka), the oldest combustion structures come from level XIII, with an age of 230 ka having been determined by amino acid racemisation (AAR) (Figure 2). The two hearths documented at this level both have a complex structure; one of them is basin-shaped, while the other shows preparation prior to ignition in the form of stone beds used to insulate it from the ground. At level XI, ~ 150 ka, seven simple oval-shaped hearths have been documented, which were aligned under the start of the cave's ledge (Figure 2). Around the hearths, a significant accumulation of archaeological material was documented. Levels II and IV, which have chronologies of 120-100 ka, have also provided evidence of the controlled use of fire. At level II, only ash accumulations have been recorded, while at level IV, four hearths were documented, which were also located under the line of the overhang on the west side of the cave mouth (Fernández Peris et al. 2012). Regarding the anthropic origin of the charcoal remains studied in this work, micromorphological analysis from combustion structures from levels XI and XIII allowed the observation of wood ashes and micro-charcoals with a clear distribution (Fernández Peris et al. 2012). These previous data led us to considering the presence of micro-charcoal remains, although they were not visible during the fieldwork.

Methods: charcoal analysis

The charcoal analysis presented here corresponds to a sampling from concentrated (combustion structures) and scattered contexts intended to determine the anthracological potential of Bolomor Cave. Dry sieving of the sediments from the hearths and the adjacent squares was conducted using a column of meshes of 2, 0.5, 0.250, 0.125 and 0.063 mm. Although the standard limitation of the botanical identification of charcoal is considered to be a size of 2 mm (Chabal 1988, 1992), extra effort was expended using this column of meshes to, at least, determine the charcoal remains at the angiosperms/conifers taxonomical rank. Each wood charcoal fragment was manually fractured to provide transversal, tangential and radial sections for microscopic observation, although the smallest fragments were not suitable for the observation of the three anatomical sections. The taxonomic identification was performed using a Nikon Optiphot-100 bright/dark-field incident light microscope with 50–500x magnification and by comparing the archaeological remains with specialised plant anatomy atlases (Jacquiot, Trenard, and Dirol 1973; Schweingruber 1976, 1990) as well as the reference collection of modern charred woody taxa of the Department of Prehistory,

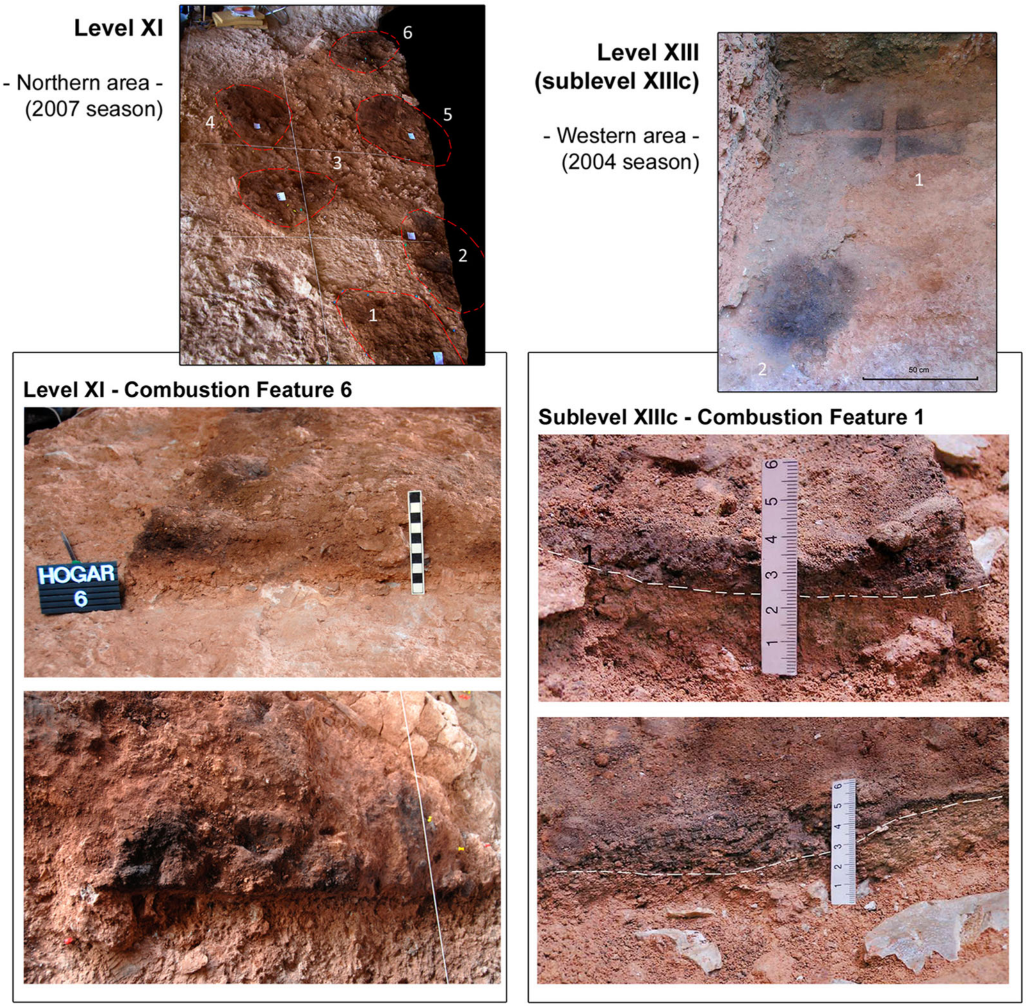

Figure 2. Hearths from Bolomor Cave during excavation process: hearths from level XI and detail of combustion structure 6 (left); level XIII during excavation and profile view of the combustion structure 1 (right). Artificial black area in the general view of excavation surface of level XI (top-left) corresponds to the significant shake-up of the cave's archaeological sediments produced by mining work in search of the cavity's thick basal stalagmite deposits during the 1930s.

Archaeology and Ancient History, University of Valencia. Photography and the detailed observation of the anatomical and taphonomic features were conducted using a Hitachi S-4100 scanning electron microscope (SEM) and the ESPRIT 1.8 software. The elemental analyses were performed using a Brucker 1110 CHNS X-ray spectroscopy device and the ESPRIT 1.9 software at the Central Service for the Support of Experimental Research (SCSIE, University of Valencia) in order to provide information about the chemical composition of the samples. For the SEM and energy dispersive X-ray spectroscopy (EDX) analyses, the samples were secured on aluminium stubs with adhesive tabs and then coated with gold/palladium.

Results

Botanical identification and degree of fragmentation

The charcoal analysis of the combustion structures and the adjacent squares provided a reduced anthracological assemblage (Table 1). The botanical identification has been strongly influenced by the small size of the wood charcoal remains, with a concentration of fragments in the 1–2 mm and 0.5–1 mm size classes. Combustion structure 4 (level XI) yielded a total of 23 charcoal remains that were dominated by undetermined conifers and *Pinus nigra-sylvestris* (black pine and / or scots pine) (Figure 3b). In terms of level XIII, one fragment of *Juniperus* sp. (juniper) (Figure 3a) was identified inside combustion structure 2, while a total of 30 wood

Table 1. Anthracological data from the combustion structures 4 and 2 and the scattered assemblage.

Level	XI	XIII	
Context	Combustion feature 4	Scattered	Combustion feature 2
Taxa	***n***	***n***	***n***
Angiosperm 1	1	7	
Angiosperm 2		1	
Coniferae	10	6	
Juniperus sp.		1	1
Pinus nigra-sylvestris	12	13	
Indeterminable		2	
Total remains	23	30	1
Min. taxa	1	2	1

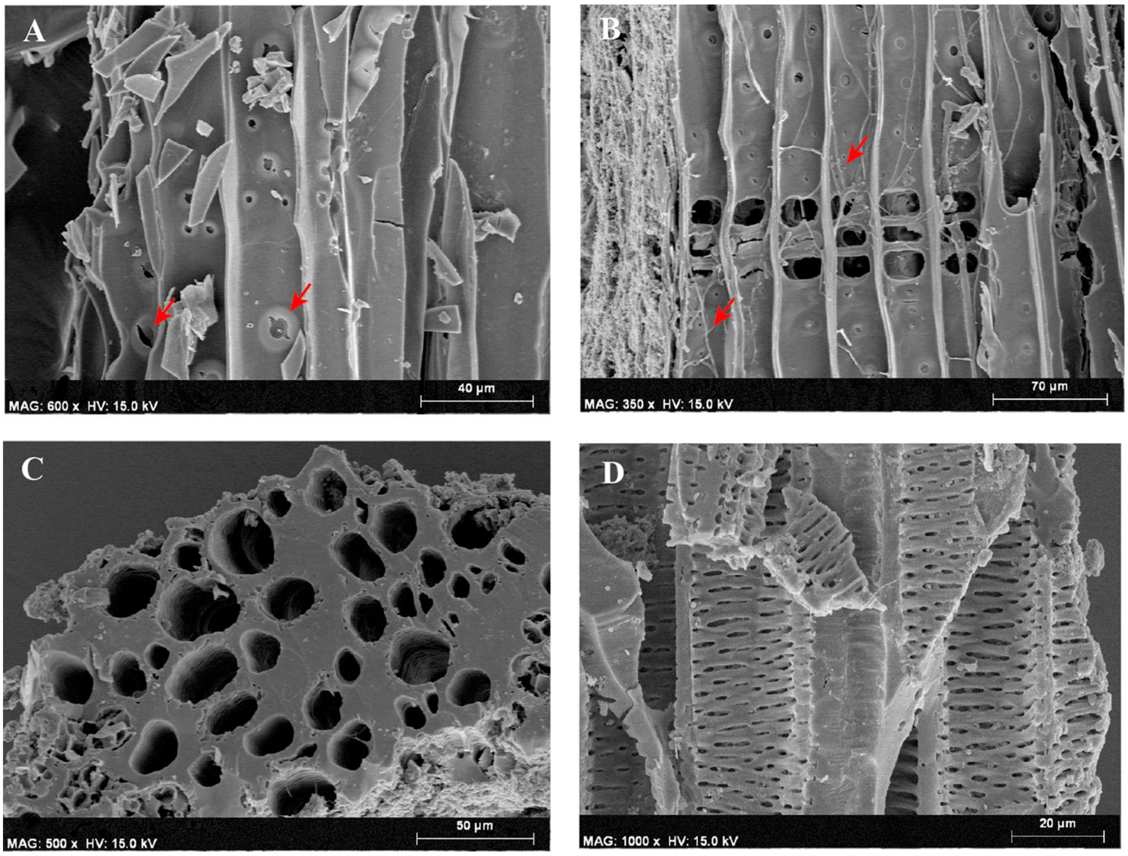

Figure 3. SEM images of the taxa identified at Bolomor Cave. A. Level XIII: *Juniperus* sp., radial section (×600). Note degraded tori (arrows) within bordered pits. B. Level XI: *Pinus nigra-sylvestris*, radial section (×350). Note the presence of fungal hyphae within the tracheids. C. Level XIII: Angiosperm 1, transversal section (×500). D. Level XIII: Angiosperm 1, tangential section (×1000).

charcoal remains were obtained from the scattered context, which indicated the presence of *Juniperus* sp., *Pinus nigra-sylvestris*, undetermined conifers and angiosperms, and indeterminable fragments. With regards to the angiosperm fragments, the degree of preservation hampered the botanical identification. Despite this, at least two different types of angiosperms are present in the record which are referred to in Table 1 as Angiosperm 1 and Angiosperm 2. Angiosperm 1, the most abundant in the anthracological assemblage, has diffuse porous wood and solitary vessels or in small clusters (Figure 3c), simple perforation plates, an absence of spiral thickenings and opposite inter-vessel pits (Figure 3d). Angiosperm 2, which presented worse preservation than Angiosperm 1, was only identified by the spiral thickenings present in the vessels (Figure 5g). Due to their degree of preservation and their relatively small size, it was not possible to distinguish the angiosperm fragments at the family or genus taxonomical rank.

Taphonomic remarks

The effects of several pre-depositional and post-depositional processes were observed during the charcoal analysis. In this sense, biogenic alterations caused by fungi, bacteria and insects are present in the recovered charcoal fragments, leading to the deterioration of the organic material. Additionally, mineralised cell walls together with the presence of mineral precipitates were observed in some fragments. Both types of degradation features, that is, the biogenic and the geologic ones, could have contributed to the degree of preservation of the anthracological assemblage.

Discussion

Palaeoecological inferences

Although the anthracological assemblage recovered from Bolomor Cave is quite limited, it constitutes the earliest known anthracological evidence based on humans' use of firewood in Iberia. Thus, the charcoal analysis presented here sheds light on the characterisation of the local landscape, with the presence of *Pinus nigra-sylvestris* in both levels pointing to the prevalence of meso-supramediterranean conditions (mean annual temperature [MAT] of 8–17°C) in Eastern Iberia during MIS 7 and MIS 6.

Pinus nigra-sylvestris constitutes the most abundant taxon within the wood charcoal remains recovered from Bolomor Cave. The identification of black pine and / or scots pine at this site represents the earliest evidence in Iberia of its use as fuel. While cryophilous pines (*Pinus nigra, P. sylvestris, P. mugo, P. uncinata*) are easily distinguishable from thermophilous pines (Schweingruber 1976), difficulties arise when attempting to

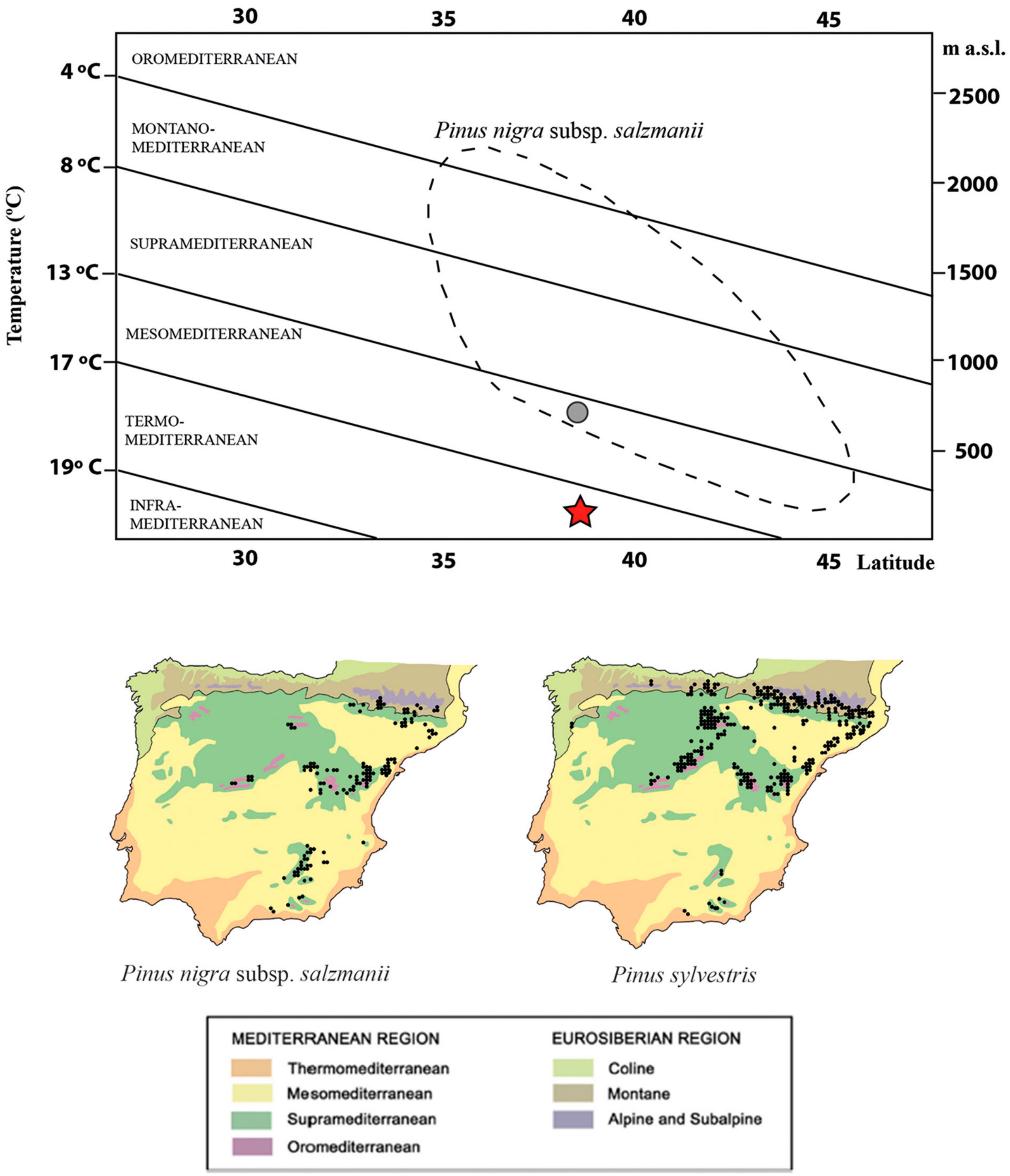

Figure 4. Current distribution of *Pinus nigra* subsp. *salzmanii* with *Pinus sylvestris* and *Pinus nigra* biogeographical data (after Costa, Morla, and Sainz 2005). Red star represents current biogeographical location of Bolomor Cave. Gray circle represents the minimal hypothetical biogeographical location of Bolomor Cave based on anthracological data. Current distribution maps drawn from the data obtained in www.anthos.es.

distinguish between the different species of highland pines (Allué, Solé, and Burguet-Coca 2016; Badal and Carrión 2001; Badal et al. 2012a; Badal, Villaverde, and Zilhão 2012b; Postigo-Mijarra, Gómez-Manzaneque, and Morla 2017; Vidal-Matutano et al. 2015). Taking into account the anatomy of the wood, the discrimination of these four species is barely feasible, although *Pinus mugo* and *Pinus uncinata* can be discarded based on the location of the site at a low altitude, since these two species are limited to higher elevations (above 1900–2000 m a.s.l.). When trying to differentiate *Pinus nigra* from *Pinus sylvestris*, some authors take into account the distribution of the resin ducts in the growth rings as well as the characteristics of the ray tracheid walls in mature specimens (Rubiales et al. 2007), whereas other researchers believe that current knowledge does not allow for the unequivocal distinction of these species (Allué, Solé, and Burguet-Coca 2016; Allué et al., in press; Badal and Carrión 2001; Roiron et al. 2013; Schweingruber 1976; Vidal-Matutano 2017; Vidal-

Matutano et al. 2015). This is why 'approximate' nomenclatures are used by different authors: *Pinus nigra-sylvestris* is favoured by some, while others prefer *Pinus* type *sylvestris*.

Pinus sylvestris mostly occurs in the oromediterranean belt above 800 m a.s.l. (Figure 4), although relict scots pine woodlands survive at low altitudes (down to 200 m a.s.l.) in Southern France (Quézel and Médail 2003). *Pinus nigra* represents a group of pine species (*P. nigra* subsp. *salzmanii, nigra, laricio, mauritanica, dalmatica* and *pallasiana*) that occupy a fragmented area in the mountains around the Mediterranean Basin. According to the current biogeographical distribution of the *Pinus nigra* subspecies in Europe, the *P. nigra* subsp. *salzmanii* is likely to be the only native subspecies found in Southern France and Iberia (Quézel and Médail 2003; Roiron et al. 2013). In Iberia, black pine is present between 500 and 2200 m a.s.l. on the supramediterranean or oromediterranean belt and it can become associated with the scots pine due to also being contained within the oromediterranean belt (Figure 4) (Costa, Morla, and Sainz 2005).

According to the available anthracological data, *Pinus nigra-sylvestris* previously had a significantly larger distribution than that seen today in the Mediterranean Basin. Indeed, anthracological data from Terra Amata and Torralba (*ca.* 400 ka) and many Middle Palaeolithic sites belonging to MIS 5-3 show the dominance of this taxon, indicating the widespread presence of cryophilous pine woodlands during the Middle-Upper Pleistocene (Allué et al., in press; Allué, Solé, and Burguet-Coca 2016; Arsuaga et al. 2012; Badal and Carrión 2001; Badal and Martínez 2017; Badal, Villaverde, and Zilhão 2012b; Daura et al. 2015; Postigo-Mijarra, Gómez-Manzaneque, and Morla 2017; Uzquiano et al. 2012, 2008; Vidal-Matutano 2017; Vidal-Matutano et al. 2015; Vidal-Matutano, Henry, and Théry-Parisot 2017; Zilhão et al. 2016). While scarce anthracological data is available for MIS 7-6 chronologies in Iberia, the black pine and / or scots pine record from Bolomor Cave constitutes the earliest evidence of its presence in Eastern Iberia based on humans' collection of firewood (charcoal fragments). Regarding this, the Auchelian site of Torralba also documents the preservation of *Pinus* cf. *sylvestris* wood fragments, although these non-charred material have no evidence of had been anthropically manipulated and, therefore, are not directly related with human practices (Postigo-Mijarra, Gómez-Manzaneque, and Morla 2017). According to current ecological and biogeographical data, *Pinus nigra* could probably have grown at low altitudes in coastal areas, as other Mediterranean sites have shown (Badal and Martínez 2017), while its presence at this site supports the descent of supramediterranean conditions by about 700–1000 m, since it has been observed at many later Mediterranean Palaeolithic sites in Iberia (Allué, Solé, and Burguet-Coca 2016; Allué et al., in press; Aura et al. 2005; Badal and Carrión 2001; Badal, Villaverde, and Zilhão 2012b; Daura et al. 2015; Esteban et al. 2017; Vidal-Matutano 2017; Vidal-Matutano et al. 2015; Zilhão et al. 2016), which implies a general decrease of 5°C in the MAT. Relatedly, further information obtained from other identified woody taxa would help to nuance the palaeoecological data derived from these levels. Unfortunately, the angiosperm fragments remain undetermined due to their small size and their degree of preservation. Only two fragments of *Juniperus* sp. are present in level XIII, although the homogenous anatomical structure of this genus hampers its identification at the species level (Schweingruber 1976). Thus, these fragments could be attributed to cryophilous junipers (*J. communis, J. thurifera*) or to thermophilous species (*J. oxycedrus, J. phoenicea*), whose present-day range extends from the thermomediterranean to the supramediterranean belt under dry or semi-arid bioclimatic conditions (Costa, Morla, and Sainz 2005). Despite this, given the fact that black pine and / or scots pine is present in the anthracological record of Bolomor Cave, it seems likely that the *Juniperus* wood charcoal fragments would correspond to cryophilous junipers rather than thermophilous ones.

Preservation of wood charcoal remains

Different processes affecting the anatomical structure of wood charcoal have been observed during the charcoal analysis at Bolomor Cave. These processes have been separated into those caused by biological agents (pre- and post-depositional processes) and those resulted from natural agents (post-depositional processes).

Bacterial and fungal degradation features

Wood can be degraded by fungi as well as bacteria, which provides distinctive decay patterns. Fungi expand inside the ligneous structure by producing spores, which develop into hyphae that degrade the structure of carbohydrates (cellulose and hemicellulose) and lignin by means of depolymerisation (Baldrian and Valášková 2008; Blanchette 1991; Blanchette et al. 1991; Leonowicz et al. 1999; Tuor, Winterhalter, and Fiechter 1995). Fungal decay can be categorised into brown rot, white rot and soft rot according to the type of degradation affecting the wood's cell walls (Blanchette 2000). However, the identification of these types of fungal decay based on only micromorphological features remains unclear, since some studies have shown that there is a much greater diversity in the way different decay fungi challenge their hosts and substrates (Schwarze 2007). In addition, bacteria degrade lignified elements (namely tracheids, fibres and vessels) by first attaching to the lumen face of the cell wall and then penetrating into the wall, thereby producing tunnelling type bacterial

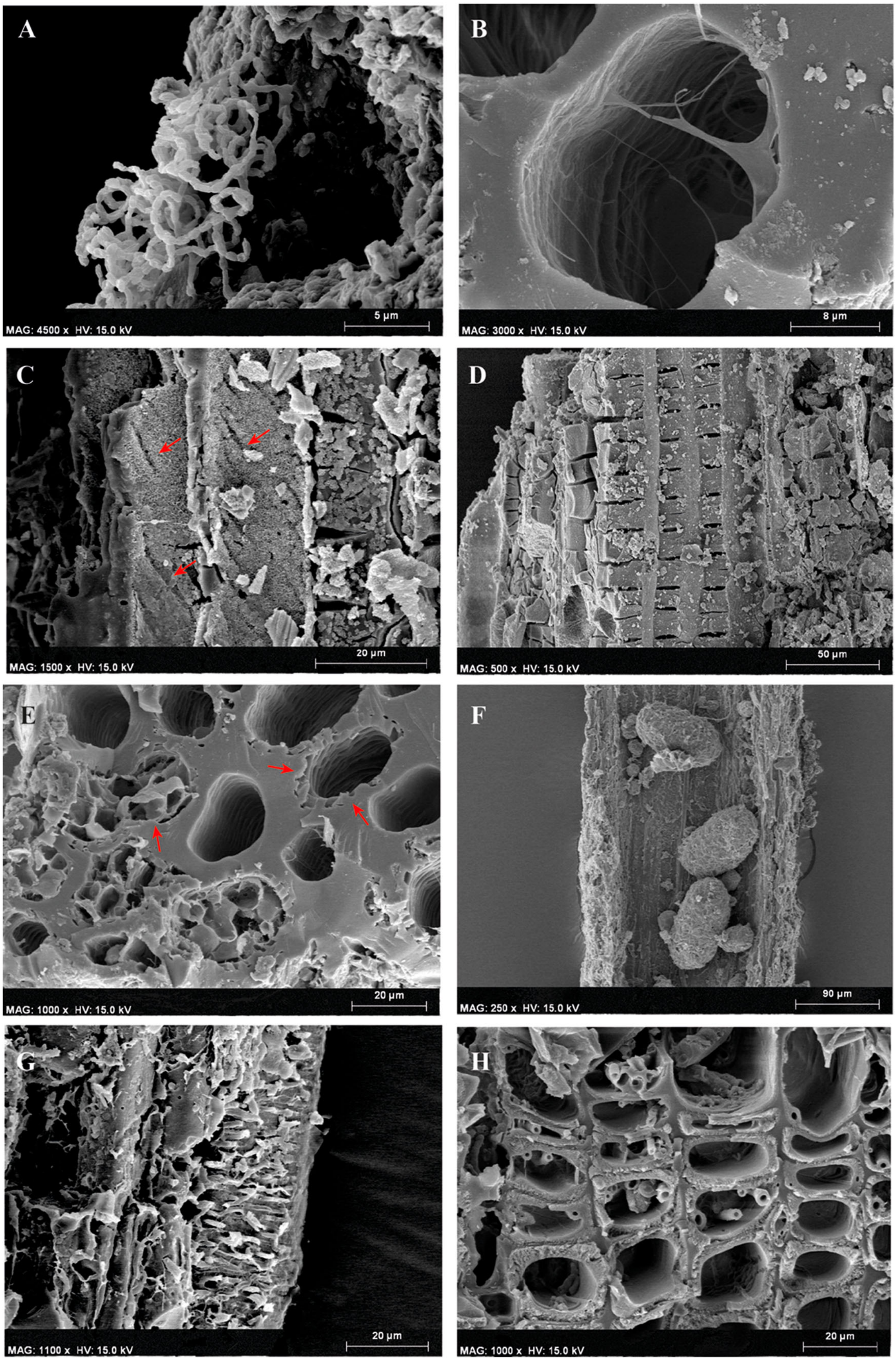

Figure 5. SEM images of bacterial and fungal decay features on wood charcoal from Bolomor Cave. A. Bacterial chains. Level XIII: Angiosperm, transversal section (×4500). B. Visible fungal hyphae within a vessel. Level XIII: Angiosperm, transversal section (×3000). C. Crystal features in a degraded tracheid. Note the lenticular cavities produced by bacterial and/or fungal activity (arrows). Level XI: Conifer, tangential section (×1500). D. Cubical cracks caused by brown-rot fungi. Level XI: Conifer, tangential section (×500). E. Degraded cell walls (arrows) and presence of lignin residues. Level XIII: Angiosperm, transversal section (×1000). F. Arthropod fecal pellets within a vessel. Level XIII: Angiosperm, tangential section (×250). G. Bacterial degradation of a vessel. Level XIII: Angiosperm, tangential section (×1100). H. Cellular deformation and calcium precipitates. Level XIII: *Pinus nigra-sylvestris*, transversal section (×1000).

decay (Kim and Singh 2000; Singh 2012). The degradation of the wood's components by bacterial and fungal activity leads to strength, weight and density losses, which are often observed in the 'wavy' appearance of the wood and the hyper-fragmentation of the wood's charcoal record (Allué, Solé, and Burguet-Coca 2016; Badal, Villaverde, and Zilhão 2012b; Henry and Théry-Parisot 2014; Moskal-del Hoyo, Wachowiak, and Blanchette 2010; Vidal-Matutano et al. 2015; Vidal-Matutano, Henry, and Théry-Parisot 2017).

The effects of biological activity on wood charcoal, together with other mechanical processes such as anthropogenic activities (trampling, re-working, sweeping), weathering, freeze/thaw cycles or dry/humidity cycles, should also be taken into account because these phenomena can lead to the fragmentation or even the disappearance of the material, thereby affecting our perception of the wood that was used as fuel in the past (Théry-Parisot, Chabal, and Chrzavzez 2010) and causing us to misinterpret the absence or scarcity of charcoal at archaeological sites (Chrzazvez et al. 2014; Marquer et al. 2012). Anthracologists have tried to understand if species did fragment differentially and how the charcoal record could be affected by fragmentation. According to this, the statistical analysis of different size classes from Le Marduel and Lattara (France) by Chabal (1992, 1997) and from Cova de les Cendres (Spain) by Badal (1988) indicated similar fragmentation patterns between all taxa. More recent experimental studies based on modern *Pinus sylvestris* wood have shown the important influence of the state of the wood prior to combustion on the mechanical properties of the charcoal: carbonised healthy wood was three to five times more resistant than carbonised degraded wood (Chrzazvez et al. 2014; Théry-Parisot 2001; Théry-Parisot, Chabal, and Chrzavzez 2010). Hence, the hyper-fragmentation and scarcity of the charcoal record recovered from Bolomor Cave could be linked to the pre- and post-depositional processes affecting its preservation. Indeed, some fungal degradation patterns have been recorded, i.e. cubical cracks caused by brown-rot fungi (Figure 5d), perforation of the cell walls (Figure 5e), degraded tori within the bordered pits (Figure 3a) or even cellular deformation of the tracheids and the presence of holes near the lumen surface (Figure 5h). The effect of fungal decay was especially evident on the angiosperm fragments, which evidenced great distortion of the plant tissue that caused a loss of strength. In addition, the fungal hyphae were well preserved and visible within the vessels and tracheids in all the recovered wood charcoal fragments (Figures 3b and 5b). Yet, the charcoal fragments obtained from Bolomor Cave were also highly degraded by bacterial activity, resulting in large losses of strength associated with the previously mentioned fungal attack. The features of this kind of decay (minute cavities and tunnels in the cell walls leaving residual wall material) are similar to those observed based on microscopic analysis of the 400 ka BP wooden spears found at Schöningen (Schmitt et al. 2005; Thieme 2000). Indeed, bacterial chains have been observed affecting mainly the angiosperm fragments (Figure 5a), together with chains of lenticular cavities produced by erosion bacteria or even soft-rot fungi (Figure 5c) and the presence of lignin residues mixed with bacterial slime located in degraded walls (Figure 5c, e and g). In addition, arthropod faecal pellets within a vessel have also been observed, which evidences the contribution of xylophagous insects to wood degradation (Figure 5f).

The anatomical alterations caused by fungal and insect activity on wood can provide meaningful data concerning the firewood acquisition strategies employed by past human groups, e.g. collection of green and healthy wood vs. dead and degraded wood. Accordingly, the microscopic characterisation of fungal decay patterns found on wood charcoal fragments from Palaeolithic and Mesolithic sites suggests the preferential use of degraded wood (Allué, Solé, and Burguet-Coca 2016; Chrzazvez 2006; Henry and Théry-Parisot 2014; Théry-Parisot 2001; Théry-Parisot and Texier 2006) or even half-rotten wood (Vidal-Matutano, Henry, and Théry-Parisot 2017) by hunter-gatherer groups. Unfortunately, the available anthracological assemblage obtained from Bolomor Cave up to now cannot provide us palaeoeconomical data regarding firewood selection criteria due to its reduced nature.

Mineralised wood charcoal: calcite precipitation or oxalate production by wood-rotting fungi?

The charcoal analysis from Bolomor Cave also documented the high presence of mineralised wood charcoal fragments (almost 96% of the total fragments recovered). Mineralised charcoal was evident due to cell structure deformations (Figure 5g and h) and the generalised presence of crystalline features within the wood tissue (Figure 5c and g), which raised a question regarding the taphonomical agent affecting wood charcoal fragments. The mineralisation of wood by silica or calcium precipitation within plant tissues has been widely studied in relation to the plant fossil record from petrified forests worldwide (Akahane et al. 2004; Dietrich, Lampke, and Rößler 2013; Hellawell et al. 2015). Since silica or calcium attraction by plant tissues prevents decay in an oxygenated environment, the petrification of wood is one of the most significant preservation processes in relation to trees (Hellawell et al. 2015; Mustoe 2015; Nowak et al. 2005). Indeed, the mineralisation of wood in these geological contexts involves the replacement of the organic cellular tissue by calcium, opal, chalcedony, moganite and/or quartz, thus even preserving the anatomical structure of the plants (Dietrich, Lampke, and Rößler 2013; Mustoe 2015). Yet, although physicochemical processes play a significant role in calcite formation and development (Ehrlich 1998), it is broadly recognised that

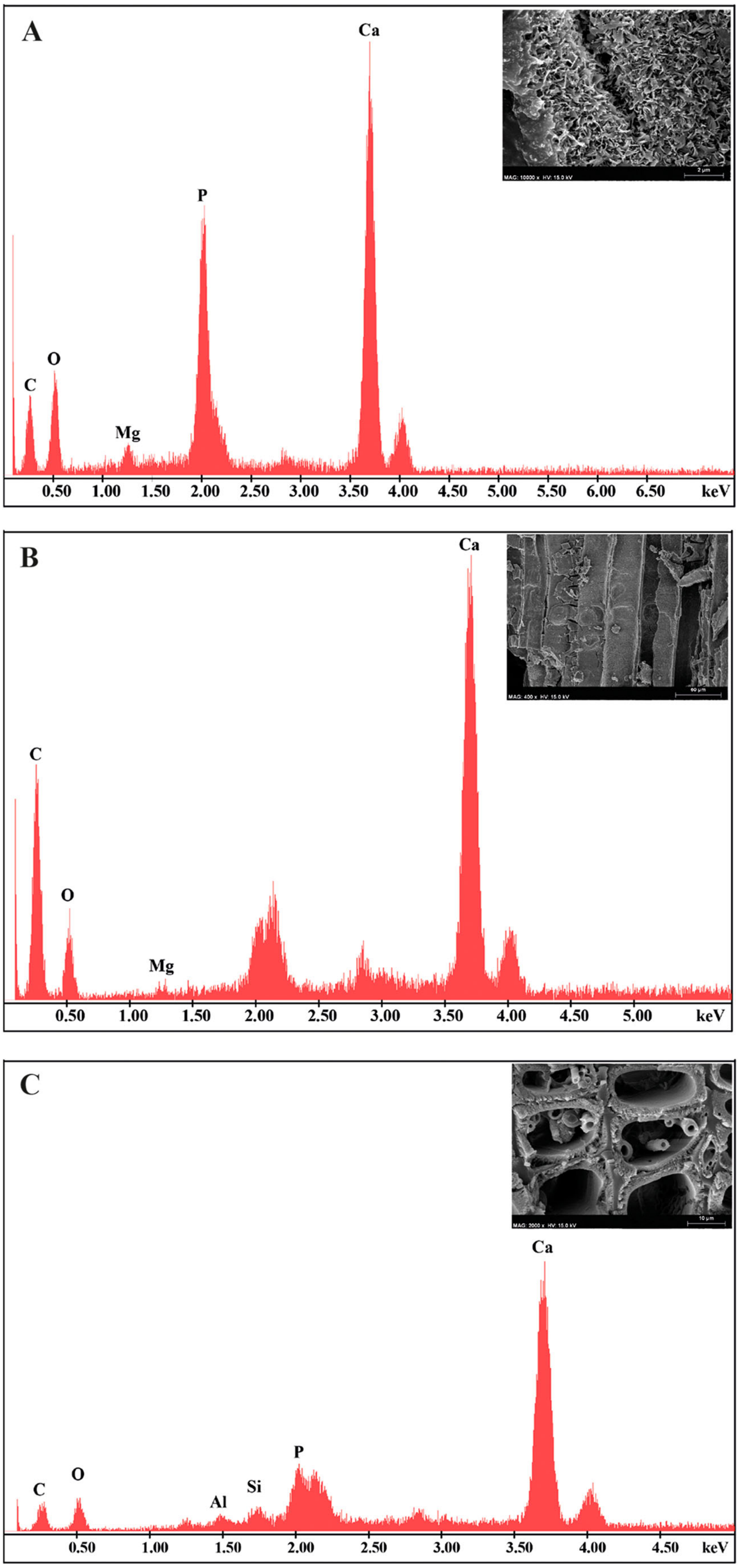

Figure 6. Energy-dispersive X-ray microanalysis on wood charcoal fragments from Bolomor Cave. A. Crystal features in a degraded tracheid. Level XI: Coniferae, tangential section (×10000). B. Mineralised cross-field. Level XI: *Pinus nigra-sylvestris*, radial section (×400). C. Calcium precipitates within the tracheids. Level XIII: *Pinus nigra-sylvestris,* transversal section (×2000).

Table 2. Chemical composition (SEM-EDX) from wood charcoal fragments. Sample letters correspond to those from Figure 6. The presence of gold (Au) and palladium (Pd) was not taken into account when drawing up the table of elemental composition as these elements were used for coating the samples prior to the SEM analysis.

Sample	A		B		C	
Element	Wt (%)	At (%)	Wt (%)	At (%)	Wt (%)	At (%)
Carbon (C)	32.69	47.89	49.68	65.78	26.77	43.53
Oxygen (O)	31.65	34.81	23.64	23.50	26.35	32.17
Magnesium (Mg)	1.16	0.84	0.53	0.35		
Aluminium (Al)					1.14	0.83
Calcium (Ca)	24.33	10.68	26.15	10.37	38.2	18.62
Phosphorus (P)	10.17	5.78			5.93	3.74
Silicon (Si)					1.61	1.12
Total	100	100	100	100	100	100

microorganisms (bacteria, fungi and algae) may also play an important role in these contexts (Goudie 1996). In this sense, the observation of calcified fungal filaments in limestone and calcareous soils suggests that fungi may play a crucial role in secondary calcite precipitation (Burford, Kierans, and Gadd 2003; Burford, Hillier, and Gadd 2006; Gadd 2007; Jarosz-Wilkolazka and Gadd 2003; Mäkelä et al. 2002). This phenomenon, which is referred to by many authors as 'geomycology' (Gadd 2007), refers to the impact of fungi on the geological processes that form biogenic micro-fabrics. Accordingly, calcium oxalates are commonly present in association with fungal hyphae and bacteria in soils and leaf litter (Burford, Kierans, and Gadd 2003; Burford, Hillier, and Gadd 2006; Gadd 2007), as well as within the wood tissue (Braissant et al. 2004; Mäkelä et al. 2002), and they play an important role in mineral formation through the precipitation of organic and inorganic secondary minerals and the deposition of crystalline material (mainly oxalates and carbonates) on and within cell walls (Gadd 2006). Indeed, experimental studies have evidenced the biomineralisation of fungal filaments with calcite modifying the local microenvironment (Burford, Hillier, and Gadd 2006; Jarosz-Wilkolazka and Gadd 2003; Lowenstam 1981).

At Bolomor Cave, analysis of the crystalline material and mineralised cells from the wood charcoal fragments using an X-ray microanalysis indicated that many samples were enriched with calcium (Ca), in addition to the presence of oxygen (O) and carbon (C), which is consistent with the chemical composition of charred wood (Young 1985). Hence, calcium peaks were detected when analysing the lignin residues and crystal features located in the degraded cell walls (Figure 6a and c) or mineralised *Pinus nigra-sylvestris* cross-fields (Figure 6b), together with the detection of some other elements in smaller amounts, including magnesium (Mg), aluminium (Al), phosphorus (P) and silicon (Si) (Table 2). Keeping in mind the degree of preservation of the wood charcoal found at this site due to both fungal and bacterial decay, the biomineralisation could be explained as a result of biogenic activity within the plant tissues. However, based on the current state of research, other possible taphonomical agents should not be overlooked. Indeed, taking into account the sediment matrix of Bolomor Cave, where calcite is predominant (Fernández Peris et al. 2012), the penetrating groundwater could possibly be saturated in Ca ions from the karst formation and the buried wood charcoal fragments would hence be likely penetrated by the Ca solution. Nevertheless, both taphonomic agents (Ca precipitation from the geological composition of the cave and the production of secondary minerals by fungi and bacteria) could jointly contribute to the mineralisation of plant anatomical elements in Bolomor Cave, thereby affecting, in many cases, the botanical determination of wood charcoal fragments.

Conclusions

The results presented here contribute to our understanding of Middle Pleistocene hominid subsistence based on the anthracological record recovered from Bolomor Cave. This site stands as a significant location recording archaeological evidence of the repeated use of fire in early chronologies. Preliminary charcoal data obtained from this site constitute the earliest known anthracological evidence based on humans' use of firewood in Iberia. Despite representing a scarce wood charcoal assemblage, Bolomor Cave constitutes an exception when compared to other early Palaeolithic sites, which have documented evidence of the use of fire, although no charcoal fragments have been recovered or published. The botanical identification of the fragments has allowed significant palaeoecological data to be obtained concerning the earliest evidence of *Pinus nigra-sylvestris* in Eastern Iberia based on humans' gathering of firewood. According to current ecological and biogeographical data, the presence of black pine and / or scots pine in both levels sheds light on the characterisation of the landscape during MIS 7 and MIS 6 (*ca.* 230-160 ka) occupations at Bolomor Cave. Hence, this charcoal assemblage is associated with meso-supramediterranean conditions that imply a considerable descent in the MAT. The hyperfragmentation of the charcoal assemblage, together with the presence of some degradation patterns, has been taken into consideration in order to extract possible inferences about pre- and post-depositional processes affecting the material. Indeed, fungal and bacterial degradation features have both been detected. The microscopic observation of the biodegradation patterns has been especially noted in relation to the angiosperm fragments, which remain undetermined due to their degree of preservation. Additionally, the chemical characterisation of the crystalline material and mineralised cells allowed the detection of calcium peaks, which could correspond to either the geological composition of the cave or the production of secondary minerals by fungi and bacteria. Further research on the charcoal analysis from this and other early Palaeolithic sites will contribute meaningful insights into past landscape dynamics and firewood collecting strategies among Middle Pleistocene human groups.

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ORCID

Paloma Vidal-Matutano http://orcid.org/0000-0002-5892-149X

Notes on contributor

Paloma Vidal-Matutano is a researcher at the Cultures et Environnements Préhistoire, Antiquité, Moyen Âge (CEPAM – UMR 7264), Nice, France, and at the Department of Prehistory, Archaeology and Ancient History (University of Valencia), Valencia, Spain. Her research focuses on charcoal analyses from Middle Palaeolithic sites located in Western Europe using experimental tools and spatial distribution software for a palaeoeconomical approach. She is involved in several archaeological projects, including El Salt, Abric del Pastor and Crvena Stijena in Montenegro. She is the author/co-author of several publications with impact factor and book chapters.

Ruth Blasco is a researcher at the National Research Centre on Human Evolution (CENIEH), Burgos, Spain. Her research focuses on the evolution of human behaviour during the Middle and early Late Pleistocene using the taphonomic and zooarchaeologic disciplines. She is involved in studies and fieldwork at several archaeological sites of Europe and the Levant, including Bolomor, Atapuerca, Toll and Teixoneres caves in Spain, Gorham's and Vanguard caves in Gibraltar and Qesem Cave in Israel. She is the author/co-author of 65 publications with impact factor and 15 book chapters. Currently, she is an editorial board member of Scientific Reports from the Nature Publishing Group. Her social and media impact has been discussed on several news blogs, including Nature News, John Hawks Weblog, Discovery Channel News and BBC News.

Pablo Sañudo is PhD student at Àrea de Prehistòria, Universitat Rovira i Virgili (URV), Tarragona, Spain, and Institut Català de Paleoecologia Humana i Evolució Social (IPHES), Tarragona, Spain. His research focuses on human behavior and occupation patterns during Middle and Upper Pleistocene using spatial analysis, Geographical Information Systems and lithic refits. His studies are mainly focused on Bolomor Cave (Valencia, Spain) and Abric Romaní (Barcelona, Spain). He is the author/co-author of several publications with impact factor and book chapters.

Josep Fernández Peris is a researcher associated to the Museum of Prehistory of Valencia and PhD by the University of Valencia. His professional career has focused on the study of the Neanderthal ways of life, especially in its technological aspects of lithics. Since 1989 he has been the director of the Bolomor Cave project and has participated into different projects and fieldwork. He has participated in 46 publications, including several books and numerous publications with impact factor.

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