Muséum national d'Histoire naturelle

International Master in

Quaternary and Prehistory

Burning Insights into Plant Remains: Archaeobotanical study of Neanderthal Occupations at Roca dels Bous (Sant Llorenç de Montgai, Spain)

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Année académique 2024/2025

First and foremost, I would like to express my gratitude to my supervisor, Ethel Allué, for her guidance, support, and patience throughout my internship as well as during the writing of this work. I am also deeply thankful to Aitor Burguet-Coca for supervising the section of this study dedicated to phytolith analysis and for introducing me to such a fascinating discipline. Both of you have greatly enriched my experience, not only through our work in the laboratory but also by taking me into the field in Burgos and on the visit to the site of Roca dels Bous. Thank you very much.

Many thanks to Rafael Mora and the team working at Roca dels Bous for allowing me to work on this fascinating site of Roca dels Bous.

I owe special thanks to Claudia Speciale for her invaluable help. Thank you for your assistance with carpological identification and for carrying out the challenging task of photographing material with HIROX. I am also grateful for your energy and contagious good spirit.

Many thanks as well to Isabel and Susagna for their patience with my modest Spanish skills and for the moments we shared in the laboratory.

I wish to extend my gratitude to the institutions that hosted me during this master's program, firstly the MNHN in Paris, as well as the URV and IPHES-CERCA. I have learned immensely from these experiences, and this training will remain of lasting benefit throughout my life.

I also wish to thank all my friends from IMQP and QPB, especially Devi Natusion, Félicie Beck, Flore Lucas, Juliette Elie, Léonard Botton, Lou Igier, Maïwenn Goyaux, and Sirikanya Chantarsi, for brightening my days, making me laugh until tears, and supporting me despite the distance. I am eternally grateful.

My heartfelt thanks also go to other pillars of my daily life, Léa Nuon Neava, Juliette Servais, and Ilona Coppens, for simply being there.

I am sincerely grateful to everyone who offered advice and support during this writing process, at last, it has come to an end.

And finally, I wish to acknowledge the generations of feminists who have fought, and continue to fight, to ensure that women have a rightful place at all levels of society, including within research and the sciences.

Abstract

Résumé

Le site de Roca dels Bous, situé dans les Pré-Pyrénées espagnoles, s'inscrit dans la dynamique des occupations néandertaliennes du nord-est de la péninsule Ibérique durant le MIS 3. Cinq niveaux d'occupation ont été fouillés et font l'objet d'une étude archéobotanique multiproxy portant sur l'anthracologie et la carpologie des niveaux N12, N14, N16 et N18, ainsi que sur l'analyse des phytolithes du niveau N10. Les résultats replacent Roca dels Bous dans les dynamiques locales de végétation en mosaïque, caractérisées par la coexistence d'environnements ouverts et de forêts de conifères stables malgré les oscillations climatiques. La prédominance du type *Pinus sylvestris* et la présence notable de *Juniperus* sp. mettent en évidence des stratégies d'approvisionnement en combustible fondées sur l'exploitation des essences les plus abondantes, tandis que la collecte de *Celtis australis* et de *Pistacia* sp. illustre l'exploitation opportuniste de ressources végétales locales.

Abstract

The site of Roca dels Bous, located in the Spanish Pre-Pyrenees, forms part of the broader dynamics of Neanderthal occupation in northeastern Iberia during MIS 3. Five occupational levels have been excavated and are the focus of a multiproxy archaeobotanical study, encompassing anthracological and carpological analyses from levels N12, N14, N16, and N18, as well as phytolith analysis from level N10. The results situate Roca dels Bous within the local dynamics of mosaic vegetation, characterized by the coexistence of open environments and coniferous forests that remained stable despite climatic oscillations. The predominance of *Pinus sylvestris*-type remains and the notable presence of *Juniperus* sp. highlight fuel procurement strategies based on the exploitation of the most abundant taxa, while the recovery of *Celtis australis* and *Pistacia* sp. reflects the opportunistic use of locally available plant resources.

Resum

El jaciment de Roca dels Bous, situat al Prepirineu català, s'inscriu en la dinàmica de les ocupacions de neandertals del nord-est de la península Ibèrica durant ell' MIS 3. Cinc nivells d'ocupació han estat excavats i constitueixen l'objecte d'un estudi arqueobotànic multiproxy que inclou l'antracologia i la carpologia dels nivells N12, N14, N16 i N18, així com l'anàlisi de fitòlits del nivell N10. Els resultats situen Roca dels Bous dins de les dinàmiques locals de vegetació en mosaic, caracteritzades per la coexistència d'ambients oberts i boscos de coníferes estables malgrat les oscil·lacions climàtiques. La predominança de *Pinus* tipus *sylvestris* i la presència notable de *Juniperus* sp. posen de manifest estratègies d'aprovisionament de combustible basades en l'explotació de les espècies més abundants, mentre que la recol·lecció de *Celtis australis* i *Pistacia* sp. reflecteix l'ús oportunista de recursos vegetals locals.

Table of Contents

Abstract **4**

Table of Figures **6**

Table of Tables **7**

List of abbreviations **8**

1. Introduction **9**

2. Biogeographic Setting **10**

- 2.1. Geographic Setting 10
- 2.2. Regional Geology 11
- 2.3. Present vegetation 13
- 2.4. Paleoclimatological context: the Marine Isotopic Stage 3 16

3. State of the Art **20**

- 3.1. Neanderthal's occupation in Iberia 20
- 3.2. Paleoecology 23
  - 3.2.1. Zooarchaeological record 23
  - 3.2.2. Paleovegetation records 24

4. Roca dels Bous archaeological site **30**

- 4.1. Technologies in use during current excavations 30
- 4.2. Chronological frame 31
- 4.3. Stratigraphic and archaeological record 32
  - 4.3.1. N10 34
  - 4.3.2. N12 34

5. Materials and Methods **35**

- 5.1. Anthracology 35
- 5.2. Carpology 36
- 5.3. Charcoal and Seed Taphonomy 37
- 5.4. Phytoliths 37

6. Results **39**

- 6.1. Results of the anthracological analyses 39
  - 6.1.1. *Pinus sylvestris* type 40
  - 6.1.2. *Juniperus sp* 42
  - 6.1.3. *Quercus sp. deciduous* 43
  - 6.1.4. *Buxus sempervirens* 44
- 6.2. Results of the carpological analyses 46
  - 6.2.1. *Celtis australis* 47

6.2.2. *Pistacia sp.* 48
6.2.3. Boraginaceae and Polygonaceae 49
6.3. Phytoliths 49
7. Discussion 49
7.1. Botanical significance of the taxonomic assemblage 49
7.2. Paleoenvironment during the MIS 3 in Northern Iberia 52
7.3. Formation process of the archaeobotanical record 55
7.3.1. Charcoal assemblage formation process 55
7.3.2. Seed assemblage formation process 61
7.3.3. Phytolith assemblage formation process 62
7.4. Neanderthals practices 66
8. Conclusion 67
References 68

Table of Figures

Figure 1: *Map showing the localisation of Roca dels Bous and the different terraces and samples in a 5km radius around RB. From: Roy Sunyer et al. 2017, p.51 ....* ***11***

Figure 2*: Geographical and Geological Context of Roca dels Bous. From: Benito-Calvo et al. 2020, p.3 ....* ***12***

Figure 3: *Schematic graph representing average heights of environmental belts present in the Pyrenees © Lachman 2025 ....* ***14***

Figure 4: *Pollen percentage diagram with selected taxa for the section 2200–1005 cm of core MD04-2845. From: Sánchez Goñi et al. 2008, p. 1139 ....* ***19***

Figure 5: *: Map showing the current natural distribution of Pinus sylvestris in Europe. From: Kelly & Connolly 2000, p.16. ....* ***25***

Figure 6: *Palynological diagramm of a sequence of Abric Romani. From: Burjachs et al.2012, p. 35 ....* ***28***

Figure *7: Stratigraphic sections of the Roca dels Bous (RB) site. From: Benito-Calvo et al. 2020, p.8 ....* ***33***

Figure 8: *Graph presenting the anthracological data of levels N12, N14, N16 and N18 of Roca dels Bous, Lleida, Spain © Lachman Noa ....* ***39***

Figure 9: *Environmental Scanning Electron Microscope (ESEM) images of Pinus sylvestris type © Lachman 2025.* **41**

Figure 10: *Environmental Scanning Electron Microscope (ESEM) images of Juniperus sp. ©Lachman 202* **43**

Figure 11*: Environmental Scanning Electron Microscope (ESEM) images of Quercus evergreen. ©Lachman 2025.* **44**

Figure 12: *Environmental Scanning Electron Microscope (ESEM) images of Buxus sempervirens. ©Lachman 2025* **45**

Figure 13: *Graph showing the distribution of Celtis australis seeds (and Pistacia sp. seeds for set S9) from the Roca dels Bous site, according to their colour and level of combustion. ©Lachman 2025* **47**

Figure 14: *Photos taken with HIROX of four Celtis australis seeds. ©Lachman 2025* **48**

Figure 15: *Photos of Pistacia sp. taken at HYROX. ©Lachman 2025* **49**

Figure 16: *Map showing the current distribution of Juniperus communis in Europe. From: Thomas et al. 2007, p. 1409* **50**

Figure 17: *Graph comparing de sites of El Castillo (Cabrera 1999), Cueva del Conde (Uzquiano et al. 2008), Cueva de Cobrante (Uzquiano 2009) and El Salt (Vidal-Matutano et al. 2017), with Roca dels Bous. © Lachman 2025* **54**

Figure 18: *Environmental Scanning Electron Microscope (ESEM) images of Juniperus sp. showing degradation in the form of large cracks. Magnification ×100 for the upper image and ×200 for the lower image.* **58**

Figure 19: *Environmental Scanning Electron Microscope (ESEM) images of Juniperus sp. showing degradation in the form of large cracks. ©Lachman 2025* **58**

Figure 20:*Environmental Scanning Electron Microscope (ESEM) images of Juniperus sp. showing degradation in the form of large cracks. © Lachman 2025.Erreur ! Signet non défini.*

Table of Tables

Table 1*: Sites and their distance (in km) between them and the nearest fluvial course. From: Eixea et al. 2020, p. 298* **22**

Table 2: *Summary of vegetation changes at Abric Romani through D-O cycles. From: Burjachs et al. 2012 p. 34* **29**

Table** 3: Dose rate data, single-grain equivalent doses, and quartz optically stimulated luminescence (OSL) ages for the Roca dels Bous (RB) samples. From: Benito-Calvo et al. 2020, p.6* ***31
Table 4** : Charcoal and bone series accelerator mass spectrometry the* 14C *ages from Roca dels Bous. From: Benito-Calvo et al. 2020, p. 16* ***32
Table 5**: Colour classification of Celtis australis according to the Munsell Soil Colour Book and attributed to phases of combustion.* ***37
Table 6:** Table presenting the number of identified taxa, unidentified charcoals fragments, bone fragments, and seed remains by archaeological levels, N12, N14, N16, N18 from Roca dels Bous, Sant Llorenç de Montgai, Spain* ***39
Table 7:** Table showing the number of carpological remains per taxon for levels N12, N14, 16 and N18 at the Roca dels Bous site* ***46
Table 8:** Number of Celtis australis and Pistacia remains in zone S9 of level N16 of Roca dels Bous* ***46
Table 9:** Number of Celtis australis (and Pistacia for S9) remains per colour category for the S9 assemblage and levels N12, N14, N16 and N18 of Roca dels Bous* ***46

List of abbreviations

A.s.l. : Above Sea Level
AMH: Anatomically Modern Humans
AMS: Accelerator Mass Spectrometry
DM: Data Matrix
D-O: Dansgaard-Oeschger
GS : Greenland Stadial
HE : Heinrich Event
IRD : Ice-rafted debris
MAP: Mean Annual Precipitation
MAT: Mean Annual Temperature
MIS : Marine Isotope Stages
NAO: North Atlantic Oscillation
NE : North East
OSL : Optically Stimulated Luminescence
PDAs : Personal Digital Assistants
RB : Roca dels Bous
SE : South East
SST: Sea Surface temperature
WMS: Western Mediterranean Sea

1. Introduction

Neanderthal occupations in the Iberian Peninsula represent a long-standing and particularly rich field of research, owing to the abundance of sites documented across the territory. The study of these occupations is especially relevant for the MIS 3 period, characterized by marked climatic oscillations and preceding the Last Glacial Maximum in Europe. The Iberian Peninsula also preserves the latest evidence of Neanderthal presence, prior to their progressive replacement by Homo sapiens (d'Errico & Sánchez Goñi 2003; Arsuaga et al. 2007; Martínez-Moreno 2010; Rey-Rodríguez et al. 2016). Analyses of Neanderthal occupations in this geographical framework are therefore central to understanding patterns of subsistence, mobility, and human adaptation to the environmental fluctuations of the Late Pleistocene (d'Errico & Sánchez Goñi 2003; Arsuaga et al. 2007; Martínez-Moreno 2010; Rey-Rodríguez et al. 2016).

Located in the Catalan Pre-Pyrenees, the site of Roca dels Bous offers a particularly favourable context for archaeobotanical investigation, due to the good preservation of macrobotanical remains such as charcoal and seeds. These materials are distributed across successive archaeological levels, forming a palimpsest that reflects the complexity of occupations at the site during MIS 3. The same levels (N10, N12, N14, N16, and N18) have also yielded lithic and faunal assemblages, enabling an integrated approach to site occupation dynamics. Within this framework, the pronounced climatic and environmental variability of MIS 3 continues to raise questions concerning the adaptive strategies and ecological relationships of Neanderthal groups.

Traditionally, archaeobotanical studies of Paleolithic sites have relied on a single-proxy approach (anthracology, carpology, or palynology) or, more rarely, a bi-proxy approach (pollen and phytoliths) (Burjachs et al. 2012; Moreno et al. 2012; Gómez-Orellana et al. 2013; Biltekin et al. 2019). The present study is distinguished by the integration of multiple proxies, combining anthracological, carpological, and phytolith analyses. These three paleoenvironmental records, shaped by distinct processes of formation and preservation, provide complementary datasets that make it possible to overcome the limitations inherent to each category of plant remain. Their combined study allows for a more refined reconstruction of the local environment and a better understanding of Neanderthal practices in relation to fuel procurement, food resource exploitation, and the use of vegetation.

This thesis therefore aims (1) to establish the taxonomic identification of the anthracological assemblage from levels N12, N14, N16, and N18, (2) to determine the taxonomic composition of the carpological remains, and (3) to analyse phytoliths extracted from sediments in level N10. Through this multiproxy approach, the study seeks to highlight the value of integrated archaeobotanical analysis for understanding conservation dynamics and taphonomic biases in rock shelter contexts during the Middle to Upper Paleolithic transition. It also aims to reconstruct the local vegetational landscape around Roca dels Bous and to shed light on Neanderthal subsistence strategies, particularly fuel procurement and the opportunistic exploitation of resources available in the immediate environment.

2. Biogeographic Setting

2.1. Geographic Setting

The site of Roca dels Bous (RB) is a Middle Palaeolithic rock shelter located in the southeastern (SE) Pyrenees. The landscape is characterised by narrow incised valleys carved by the Segre River, which is 265 km long, and its tributaries (Mora et al. 2012). Several other rock shelters with Middle Paleolithic evidence, have been identified in the region, (Polo-Díaz et al. 2016; Martínez et al. 2005; Benito-Calvo et al. 2020), including Cova Gran de Santa Linya (Martínez-Moreno et al. 2010), and Abric Pizarro (Samper Carro et al. 2024, Westbuy et al. 2024).

Roca dels Bous is situated along the middle course of the Segre River, on its right bank, at an elevation of approximately 400 m a.s.l. The rivers draining the Ebro basin generally follow a north-south orientation, connecting the Ebro Basin with the Pyrenees. In contrast, the interior basins of the Pre-Pyrenees exhibit an east-west orientation and run parallel to the axial mountain range. The Segre River serves as a natural corridor linking several key ecological biodiversity hotspots in the region and flows into the Lleida Plain about three kilometres downstream from the site, where it joins the Noguera Pallaresa River (see Figure 1 below) (Roy Sunyer et al. 2017; Benito-Calvo et al. 2020).

RB is situated on a sedimentary slope approximately 20 meters thick, which rests against an Eocene limestone wall (Pardo et al. 1994; Mora et al. 2014). The earliest occupations are found on the upper part of this slope, forming a horizontal platform measuring approximately 20 x 10 meters, situated about 30 meters above the current course of the Segre River (Martínez-Moreno and Mora 2004; Roy Sunyer et al. 2017; Martínez-Moreno et al. 2021).

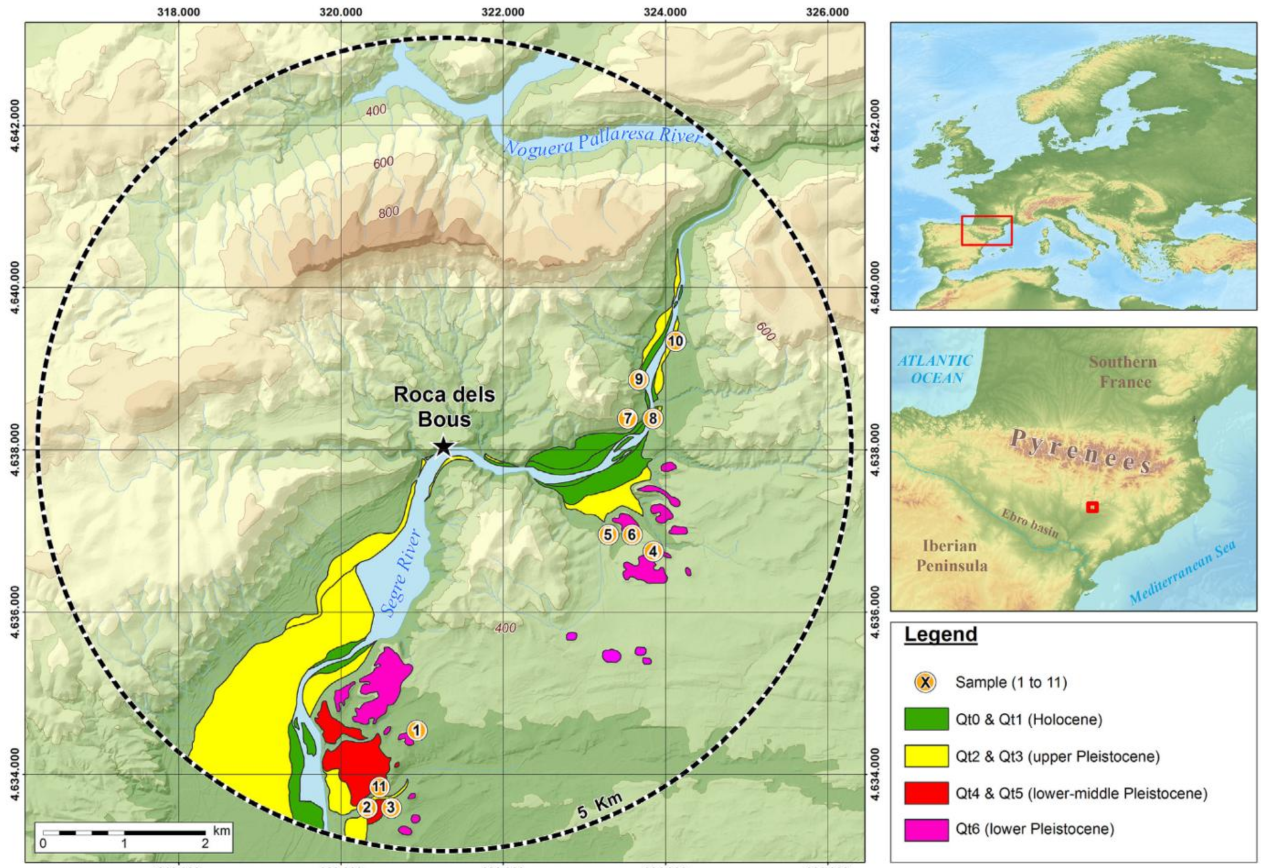


Figure 1: *Map showing the localisation of Roca dels Bous and the different terraces and samples in a 5km radius around RB. From: Roy Sunyer et al. 2017, p.51*

2.2. Regional Geology

The region is composed of several alluvial terraces (Figure 2), which have been thoroughly studied in terms of both their lithological composition and cobble morphology. The site of RB is situated on terraces at elevations of +16 m, +7 m, and +0 m above the water level (Benito-Calvo et al. 2020). These alluvial terraces were formed through cyclic fluvial incision processes that occurred throughout the Pleistocene and are still ongoing during the Holocene (Lewis et al. 2009; Jáuregui et al. 2016; Soria-Sancho et al. 2016; Roy Sunyer et al. 2017; Benito-Calvo et al. 2020; Peña-Monné et al. 2022). Between two incision phases, sedimentary infilling took place. These sediments originated from the dismantling of the axial zone of the Pyrenean mountain chain, namely, its central part where older rocks are exposed. These infillings are composed of granite, quartzite, and hornfels, as well as eroded materials from the Mesozoic and Cenozoic units of the Pre-Pyrenees (limestone, dolomite, conglomerates, sandstones, gneiss, schist) (Grüber 1979; Masiera 1982; Colombo & Cuevas 1993; Vera 2004). Eight Quaternary terraces have been identified on the current floodplain of the Segre River, and their study contributes to understanding the incision processes operating in the vicinity of the site (Roy Sunyer et al. 2017; Benito-Calvo et al. 2020).

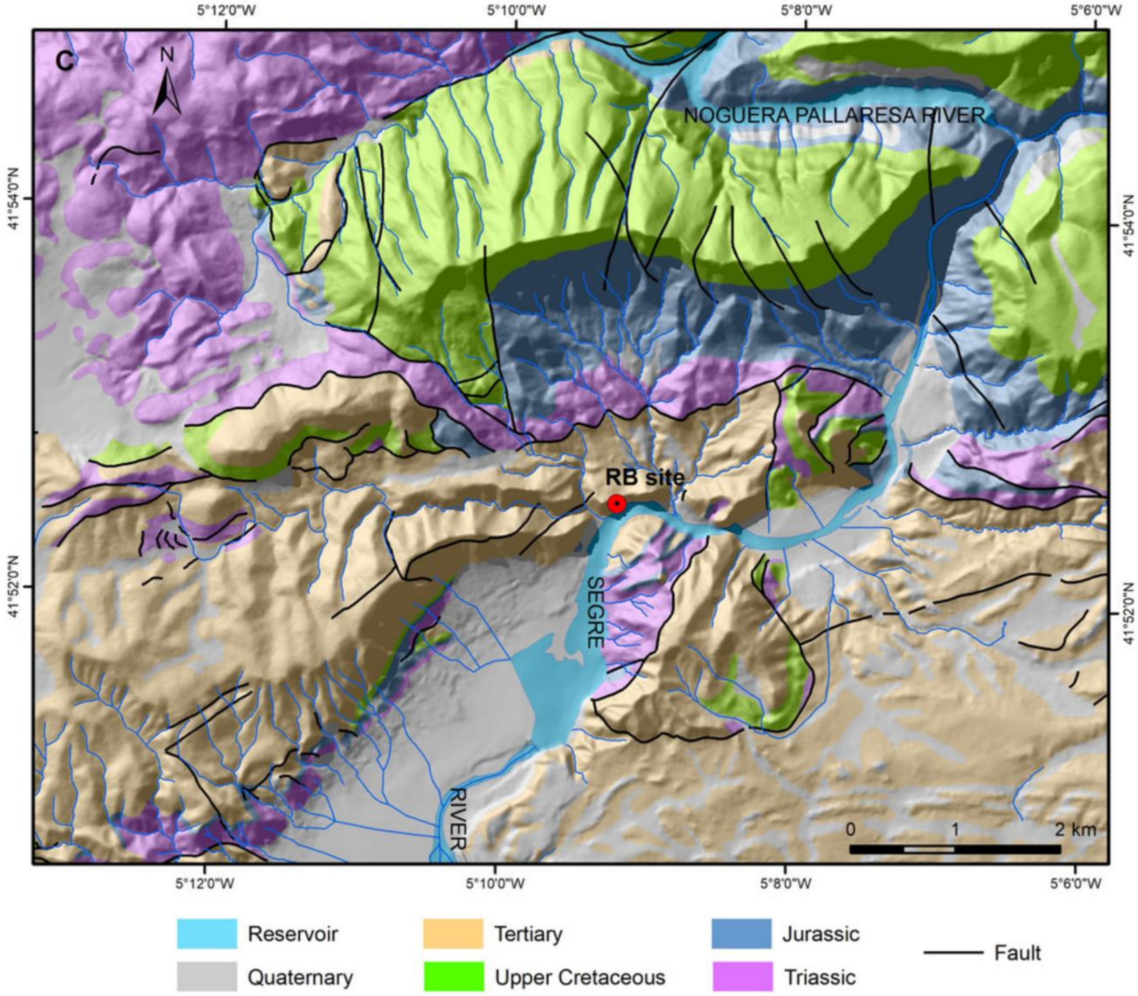


***Figure 2**: Geographical and Geological Context of Roca dels Bous. From: Benito-Calvo et al. 2020, p.3*

Several geomorphological studies have assessed the position of RB relative to the Segre River during Mousterian occupations. These studies have allowed for the characterization of the accumulation rate of deposits associated with the archaeological levels dated between 55 and 47 ka, corresponding to Marine Isotope Stage 3 (MIS 3). This sedimentation rate ranges from 0.16 to 0.44 m/ka. These data, combined with exposure dates obtained through ^{10}Be cosmogenic nuclide dating, indicate incision rates by the Segre River of 0.54 to 0.76 m/ka during the late Middle Pleistocene. According to these estimates, the site would have been much closer to the floodplains of the Segre and raw material sources during Mousterian occupations than it is today (Roy Sunyer et al. 2017; Benito-Calvo et al. 2020).

Several climatic phenomena shape the current climate of the Iberian Peninsula. Today, winter climate patterns in western Europe are strongly influenced by the North Atlantic Oscillation (NAO) index, which affects the strength and direction of north-westerly winds. A positive NAO phase leads to stronger westerly winds being displaced northward, causing drier winters in the Mediterranean and increased precipitation in northern Europe. Conversely, a negative NAO phase reverses this pattern (Sánchez Goñi et al. 2008). In summer, anticyclonic cells formed over the eastern tropical Atlantic contribute to the development of dry summer seasons in the western Mediterranean.

2.3. Present vegetation

To better understand forest dynamics in northeastern Catalonia, it is essential to consider the current state of vegetation in the Pyrenees and the Pre-Pyrenees and its altitudinal zonation. The Pyrenees are characterised by distinct altitudinal zones, each with specific characteristics on both the northern and southern slopes of the mountain range. The study of modern environmental belts, their key species, temperature and alluvial characteristics, enables us to better foresee the botanical assemblage during other periods, during which these belts might correspond to other altitudinal distributions.

Here, we provide a detailed overview of these zones (Figure 3), emphasising the southern slope, which is the focus of this study. Although the following descriptions concern the present-day vegetation of the Pyrenees and sub-Pyrenean areas, parallels can be drawn with arboreal formations that existed under similar climatic conditions during the Middle Pleistocene. The different vegetation belts and their descriptions are based on Grüber (1979, 1981), Bolòs (1954), Sánchez Goñi et al. (2008) and Rameau et al. (1994, 2008).

The mesomediterranean belt, ranging from 0 to 600 meters in altitude, is extensive and can be subdivided into two sublevels: the lower sublevel, extending up to approximately 500 meters, and the upper sublevel. The presence of *Pinus pinea*, *Pinus halepensis,* and *Quercus suber* characterises the lower sublevel. Additional indicator species include *Cneorum tricoccon*, Myrtus *communis*, *Phillyrea angustifolia*, and *Pistacia lentiscus*. In the upper sublevel*, Myrtus communis* and *Pistacia lentiscus* tend to disappear, while *Quercus ilex*, *Quercus rotundifolia*, and montane taxa such as *Viola willkommii*, *Quercus pubescens, Quercus faginea* (syn. *Quercus lentina*), and *Pinus nigra* become more prominent. Species such as *Arbutus unedo*, *Asparagus acutifolius*, and *Brachypodium retusum* are exclusive to this belt. Both sublevels generally receive less than 700 mm of annual precipitation and exhibit mean annual temperatures above 12°C.

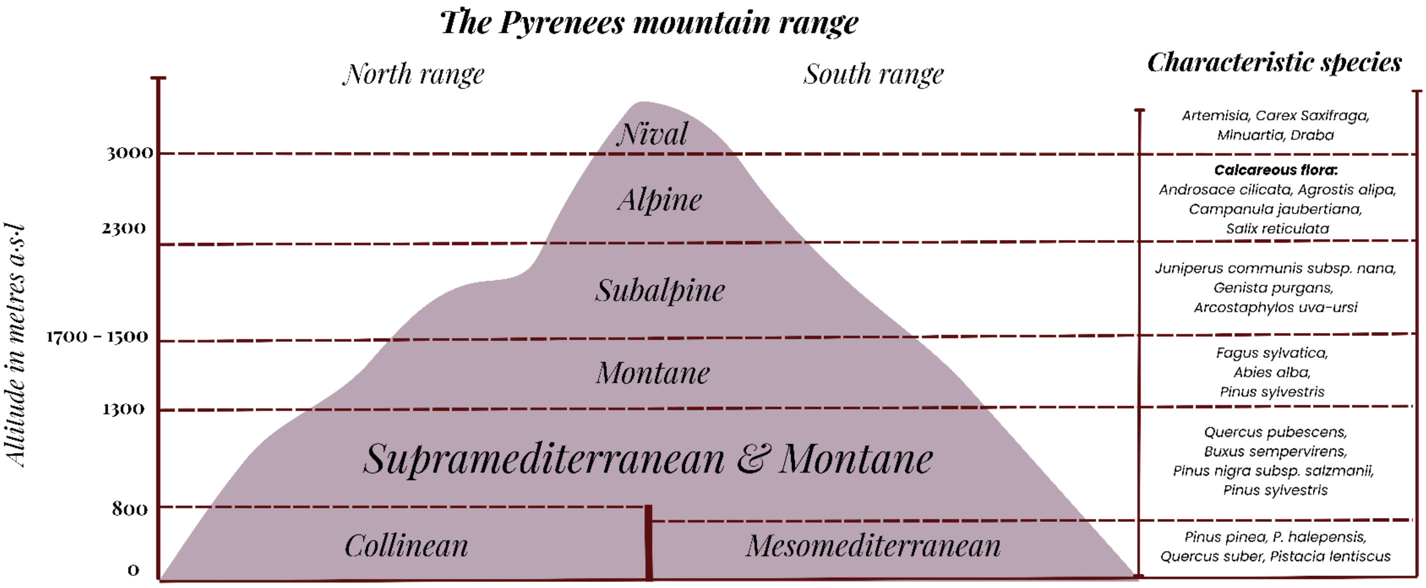


Figure 3: *Schematic graph representing average heights of environmental belts present in the Pyrenees © Lachman 2025*

The collinean belt, with Atlantic influences, extending from 0 to 800 meters in altitude, mainly concerns the northern slope of the Pyrenees.

The next zone is the supramediterranean belt, ranging from 600 to 1,300 meters, dominated by pubescent oak (*Quercus pubescens*) and boxwood (*Buxus sempervirens*) woodlands, as well as pine forests. This corresponds to the "Buxo-Quercion pubescentis" alliance, marking a transitional area between Mediterranean and Holarctic vegetation types. This belt is well-developed in the southern part of the range, with annual precipitation ranging from 700 to 1000 mm and a mean temperature of around 10°C. It is characterised by abundant *Quercus pubescens*, *Pinus nigra subsp. salzmannii*, *Quercus valentina*, *Pinus sylvestris,* and at the lower end of the zone, *Juniperus communis* and *Lavandula angustifolia subsp. pyrenaica*.

The southern slope can be further divided into subzones with distinct climatic influences. The first, between 600 and 700 meters, has a Mediterranean climate with a maximum of 800 mm of annual precipitation, a short dry summer, and dominance of *Quercus ilex* and *Quercus rotundifolia*.

The montane belt, spanning elevations from 800 to 1,700 meters, is primarily composed of beech forests (*Fagus sylvatica*), mixed beech-fir forests *(Fagus sylvatica* and *Abies alba*), pure fir forests, and Scots pine (*Pinus sylvestris*) stands. It can be divided based on the orientation of the slope, north or south range.

The northern slope features a humid climate, characterised by 1,300 to 2,000 mm of annual precipitation and frequent fog. The oceanic climate influence extends up to ~1000 m. Dominant forest types include *Abies* and *Fagus*, accompanied by other characteristic species such as *Acer pseudoplatanus, Salix caprea, Taxus baccata, Cardamine pentaphyllos,* and Atlantic taxa such as *Quercus robur, Quercus petraea*, *Quercus pyrenaica, Betula pendula, Castanea sativa, and Corylus avellana*.

The southern slope, more relevant to this study, has a drier climate, with annual precipitation of no more than 1400 mm. The xeric conditions favour the development of Scots pine and other species absent from the supramediterranean belt, such as *Deschampsia flexuosa, Galium rotundifolium, Lathyrus montanus, Sorbus aucuparia, Vaccinium myrtillus,* and *Valeriana montana*. Altitudes between 1300 and 1700 meters constitute the climatic optimum for natural Scots pine forests, which thrive in interior valleys between the "Quercus-Buxetum "domain and the subalpine forest belt.

A second climatic subzone of the southern Pyrenees, ranging from 600 to 1300 meters, is characterised by a sub-Mediterranean climate, also known as sub-Mediterranean–continental. Annual precipitation ranges from 800 to 1,200 mm, and the dry summer period disappears. Dominant taxa include *Quercus pubescens, Quercus valentina, Pinus nigra subsp. salzmannii, Pinus sylvestris,* and *Pinus uncinata*.

The subalpine belt extends from 1,500 to 2,300 meters in elevation. This zone exhibits marked asymmetry between the slopes: the northern slope receives more than 3,000 mm of precipitation annually, whereas the southern slope is drier, with a maximum of 2,000 mm. The southern slope is covered by forests of *Juniperus communis subsp. nana*, *Genista purgans*, and *Arctostaphylos uva-ursi*.

Next is the alpine belt, which begins at approximately 2,100 m or 2,300 m in the Catalan Pyrenees. This zone consists of alpine meadows, screes, and rock outcrops, with vegetation strongly dependent on the substrate, either calcareous or siliceous. Calcareous flora (e.g., *Androsace ciliata, Agrostis alpina, Antennaria carpathica, Campanula jaubertiana, Draba siliquosa, Salix reticulata,* etc.) often exhibits high levels of endemism. Siliceous vegetation can reach up to 3,000 meters. The mean annual temperature at 2500 m is 0°C, and precipitation can reach up to 4,000 mm per year. This belt is also referred to as "Festucion supinae".

Finally, the nival belt, above 3,000 meters, is minimal and only occurs on a few summits in the Catalan Pyrenees. This zone is characterised by permanent snow cover and a sparse presence of phanerogamic species adapted to rocky substrates, such as *Androsace, Carex, Saxifraga, Minuartia, Draba, Festuca,* and *Artemisia*.

Several climatic phenomena shape the current climate of the Iberian Peninsula. Today, winter climate patterns in western Europe are strongly influenced by the NAO index, which affects the strength and direction of northwesterly winds. A positive NAO phase leads to stronger westerly winds being displaced northward, causing drier winters in the Mediterranean and increased precipitation in northern Europe. Conversely, a negative NAO phase reverses this pattern (Sánchez Goñi et al. 2008). In summer, anticyclonic cells formed over the eastern tropical Atlantic contribute to the development of dry summer seasons in the western Mediterranean.

2.4. Paleoclimatological context: the Marine Isotopic Stage 3

Marine Isotopic Stage 3 (MIS 3), spanning from ~60 to 25 ka BP, represents a complex climatic interval characterized by substantial variability at orbital and suborbital scales (Imbrie et al. 1992; Rasmussen et al. 2003; Siddall et al. 2008). This section examines its defining features using marine and terrestrial proxies, focusing on abrupt climate oscillations and their environmental consequences in the Western Mediterranean and beyond. The study of those parameters is primordial in the understanding of the environment, in terms of paleovegetation and paleoecology, since they are directly linked to the living conditions of Neanderthals in NE Iberia and at Roca dels Bous.

Each marine isotopic stage is defined based on variations in the ratio of oxygen isotopes recorded in sediment cores (Rashid & Piper 2003; Lisiecki & Raymo 2005; Siddall et al. 2008). These variations reflect changes in global ice volume, influenced in turn by Milankovitch orbital parameters (Berger 1988; Pillans et al. 1998; Bard & Frank 2006; Ganopolski 2024). These parameters, also referred to as orbital forcing, operate cyclically and affect the distribution of insolation on Earth, ultimately modulating global climate patterns (Imbrie et al. 1992; Lisiecki & Raymo 2005; Siddall et al. 2008). Consequently, increases or decreases in global ice volume translate into corresponding decreases or increases in sea level (Rasmussen et al. 2003; Clark et al. 2007), which in turn influence the $\delta^{18}O$ values preserved in deep-sea benthic archives.

Within each MIS, fluctuations in the isotopic records are numbered and correspond to stadials and interstadials within an overarching glacial or interglacial cycle (Rasmussen et al. 2003; Lisiecki & Raymo 2005; Siddall et al. 2008). Odd-numbered stages generally represent interglacials, while even-numbered stages correspond to glacials. However, MIS 3 constitutes a particular case. Spanning approximately 35 ka, it deviates from the typical ~100 ka periodicity of glacial cycles (Lisiecki & Raymo 2005; Siddall et al. 2008). Sea level during this period fluctuated between 60 and 90 meters below present levels, values unusually low for a typical interglacial (Siddall et al. 2008).

This apparent paradox may be explained by the high-frequency climatic oscillations recorded in Greenland ice cores. These reveal abrupt warming events of 8 to 15°C occurring over just a few decades, followed by substantial cooling episodes. Such variability is characteristic of Dansgaard–Oeschger (D–O) events (Siddall et al. 2008; Rodríguez-Almagro et al. 2021; Malmierca-Vallet et al. 2023; Peltier et al. 2024). These events are often grouped into larger patterns termed "Bond cycles," which tend to culminate in particularly cold phases marked by increased ice-rafted debris (IRD), known as Heinrich events (HE) (Rasmussen et al. 2003; Rashid & Piper 2003; Siddall et al. 2008; Alvarez-Solas & Ramstein 2011; Andrews et al. 2018).

Climatic variability during MIS 3 has been reconstructed using a diverse set of terrestrial and marine proxies, including $\delta^{18}O$ from planktonic and benthic foraminifera, IRD content, pollen data, and sea surface temperature (SST) reconstructions. While the temporal resolution of pollen records is often insufficient to resolve individual D–O events, integrating them with high-resolution marine datasets allows for more refined reconstructions of vegetation dynamics and their correlation with abrupt climatic events (Rodríguez-Almagro et al. 2021).

In the context of MIS 3, all major datasets converge around a date of ~59 ka BP for the transition between MIS 4 and MIS 3 (Siddall et al. 2008). Within the initial phase of MIS 3, three D–O cycles, D–O 10, 11, and 12, are identified, along with two Heinrich events: H4 and H5 (Siddall et al. 2008; Rodríguez-Almagro et al. 2021). Following H5, a marked climatic deterioration is recorded in the Atlantic forest signal (e.g., core MD04-2845), which is then reversed during D–O 12 (Rasmussen et al. 2003; Sánchez Goñi et al. 2008; Rodríguez-Almagro et al. 2021). These recurring contractions and expansions of forest cover (see Fig. 4) are observable at both orbital and suborbital scales across numerous European terrestrial pollen records and are closely tied to changes in precipitation and temperature regimes (Tzedakis 2005).

Although limitations in pollen resolution complicate direct attribution of individual D–O cycles, the combination of palynological data with high-resolution marine indicators, such as $\delta^{18}O$ values, IRD content, Neogloboquadrina pachyderma (sinistral) abundance, and SST estimates, enables detailed reconstructions of Southern European vegetation dynamics that align with D–O climate variability (Rodríguez-Almagro et al. 2021).

One additional line of evidence for climatic variability during MIS 3 comes from marine productivity proxies. Jiménez-Espejo et al. (2007) analysed barium excess in core ODP 975B-1H and identified three distinct episodes of productivity change, designated BA1, BA2, and BA3. These events offer insight into the marine expression of D–O and Heinrich variability.

The BA3 event, dated to ~39–40 ka BP, is associated with Heinrich event 4. During this interval, SSTs fell to approximately 10°C. On land, a high degree of seasonality is inferred, with marked temperature differences between ~20°C in summer and 5–1°C in winter. This period also saw a pronounced decline in *Pinus* and *Quercus*, alongside an increase in Ericaceae (Jiménez-Espejo et al. 2007).

The BA2 event, dated to between 33.5 and 34.5 ka BP, may reflect the peak of climatic instability during MIS 3. Although IRD has not yet been reported for this phase along the Iberian margins, an influx of cold water into the Western Mediterranean Sea (WMS) likely reduced evaporation and consequently decreased regional precipitation. Pollen records document the near disappearance of oak at Monticchio and significant declines in Ericaceae and *Pinus* in northern Iberia. Nevertheless, Mediterranean forests appear to have persisted along the southwestern and southeastern Spanish coasts, as well as in North Africa during MIS 3.

The BA1 event, dated to 22.5–25.5 ka BP, is correlated with Heinrich event 2 and the transition from MIS 3 to MIS 2. This interval marks the onset of some of the most extreme climatic conditions recorded in the Western Mediterranean region (Jiménez-Espejo et al. 2007).

Together, these oscillations underscore the complex interplay between orbital forcing, oceanic circulation, and terrestrial vegetation dynamics during MIS 3, providing key insights into the sensitivity of the Mediterranean region to rapid climatic change.

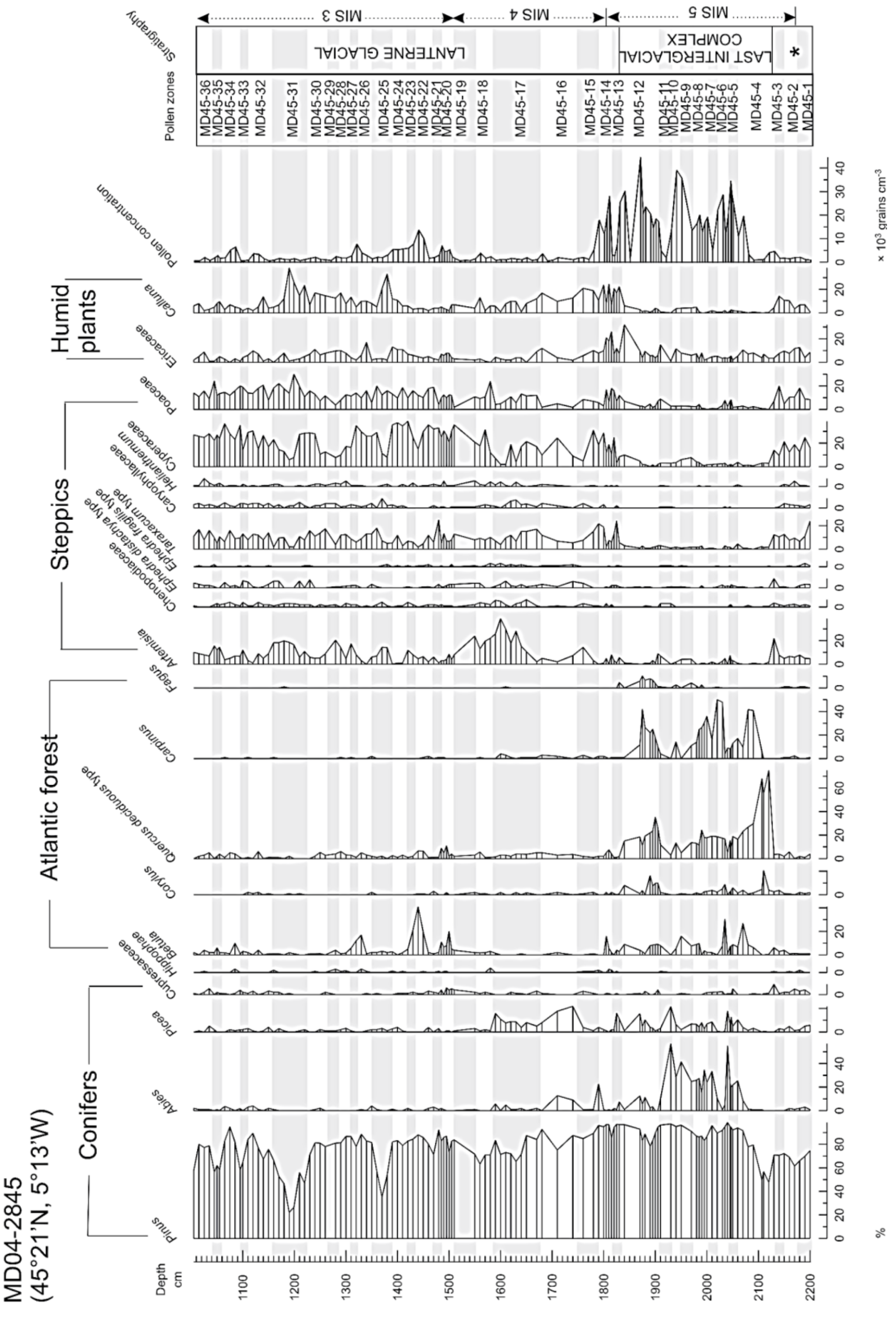


Figure 4: *Pollen percentage diagram with selected taxa for the section 2200–1005 cm of core MD04-2845. Grey intervals indicate cold episodes. The continental stratigraphy has been established by comparison of MD04-2845 pollen record with French and Iberian margin pollen sequences following Woillard (1978) and Sanchez Gon˜ i et al. (1999). *Linexert Glacial includes pollen zones MD45-1 (Stadial), MD45-2 (Zeifen Interstadial) and MD45-3 (post-Zeifen Stadial). The Last Interglacial complex encompasses the Eemian (MD45-4), Me´ lisey I (MD45-5), St-Germain Ia Interstadial (MD45-6), Montaigu Stadial (MD45-7), St-Germain Ic Interstadial (MD45-8, MD45-9, MD45-10), Me´ lisey II Stadial (MD45-11), St-Germain II Interstadial (MD45-12). The beginning of the Lanterne Glacial includes the Ognon Interstadial (MD45-14). From: Sánchez Goñi et al. 2008, p. 1139*

3. State of the Art

3.1. Neanderthal's occupation in Iberia

Various hypotheses have been proposed regarding the dynamics of Neanderthal colonization in Europe and their potential interactions with anatomically modern humans (AMHs). One such hypothesis suggests that AMH populations, bearers of Aurignacian technology (Anderson et al. 2019; Cortés-Sánchez et al. 2019; Paquin et al. 2023), which is widely recognized as a hallmark of their presence, expanded southward onto the plateau beyond the Ebro River during Greenland Interstadial 9 (GS-9)(corresponding to the onset of HE 4) (Rashid & Piper 2003; Rasmussen 2003). However, this expansion would have been significantly constrained by the persistence of relatively dense woodland, which was not conducive to the hunting of large game, a crucial component of AMH subsistence strategies. These modern human groups would only have ventured further south once the ongoing process of aridification made such territories more suitable. Consequently, the encounter between the two species may have occurred later than elsewhere, potentially delaying Neanderthal extinction. The strong climatic oscillations during this period would have disrupted Neanderthal territorial exploitation strategies, resulting in their isolation and weakening. The scarcity of anthropogenic remains in the archaeological record prevents this hypothesis from being empirically tested. Available data are based on a very small number of individuals per chronological phase, with insufficient evaluation of stratigraphic relationships between archaeological layers and dating, and general methodological limitations that hinder precise chronologies for the Middle to Upper Pleistocene transition (Sepulchre et al. 2007; Benito-Calvo et al. 2020; Eixea et al. 2020).

The question of Neanderthal and AMH co-presence in the Iberian Peninsula during the Middle and Upper Pleistocene is inextricably linked to climatic conditions. The climatic variability of MIS 3, particularly the Heinrich 5 and 4 events, with a more pronounced impact from the latter, plays a central role in the various scenarios proposed to explain the extinction of Neanderthals in this region.

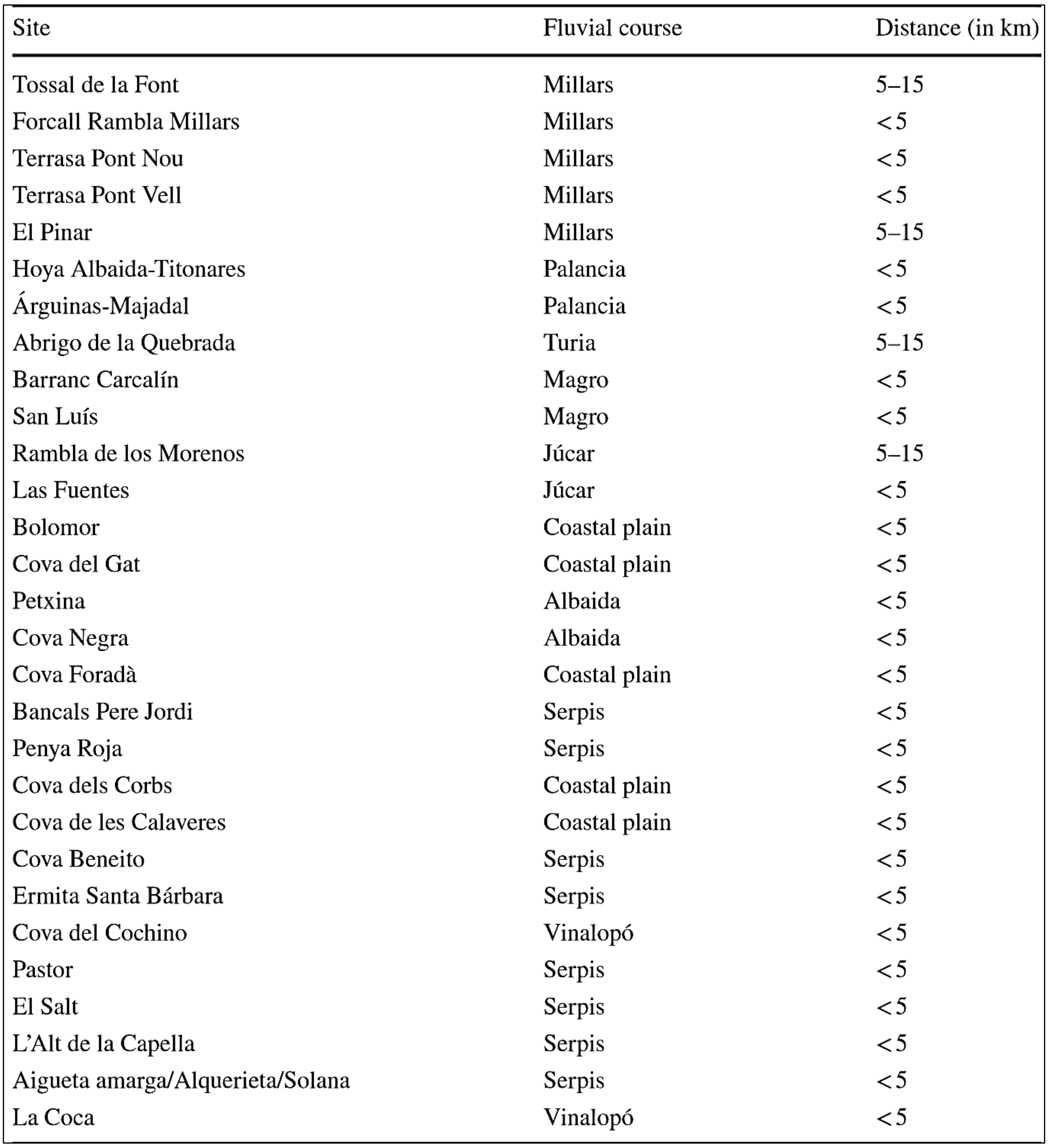
Many paleoclimatic studies focused on the western Mediterranean investigate the role and impact of climatic parameters in population replacement dynamics, particularly between Neanderthals and AMHs (Jiménez-Espejo et al. 2007; Wolf et al. 2018; Klein et al. 2023). Neanderthal extinction in Europe occurred during MIS 3, a phase characterized by intense climatic instability, as previously discussed. Several hypotheses have been advanced regarding the causes of this extinction and the extent to which climatic factors contributed (Wolf et al.

2018; Klein et al. 2023). Repeated and rapid climate fluctuations during MIS 3 severely disrupted ecosystems, which lacked the time needed to adapt to such abrupt changes. This disruption likely triggered increased aridity, which may have been detrimental to Neanderthal populations in the region (Jiménez-Espejo et al. 2007; Allard et al. 2021). Heinrich Event 4, is well documented in North Atlantic marine sediment records (Rashid & Piper 2003), and its climatic impact is clearly detectable in paleoclimatic models. The massive release of ice-rafted debris into the ocean around 39 ka BP led to a sharp drop in sea surface temperatures over a period of approximately 150 to 250 years. This cold water mass continued to circulate for another 400 years due to the persistence of oceanic thermohaline circulation cycles. This cooling episode triggered a marked increase in aridity in the Iberian Peninsula, accompanied by the replacement of arboreal vegetation with herbaceous taxa in the north. As noted earlier, this transformation is a significant factor in settlement scenarios involving AMHs and in the extinction processes of Neanderthal populations in the region (Sepulchre et al. 2007; Allard et al. 2021).

Despite these environmental constraints, Neanderthal groups were able to exploit a broad range of environments during MIS 3, showing a clear preference for natural corridors such as river systems, the edges of limestone massifs, transitional zones between biomes, plains, and, most notably, the southern Iberian Peninsula (Jiménez-Espejo et al. 2007; Jennings et al. 2011; Eixea et al. 2020). Multiproxy analyses from sites such as Peña Cabra and Peña Capón suggest that Neanderthals repeatedly occupied these highland areas during interstadial phases, when climatic conditions were milder and arboreal cover more extensive. These occupations seem to have coincided with warmer and more humid episodes, possibly enabling a temporary re-expansion of woodland biomes in central Iberia, which provided favourable conditions for Neanderthal subsistence. However, during colder stadial periods such as Heinrich Event 4, a marked contraction of these forest environments is observed, accompanied by increased aridity and steppe-like conditions. The alternation of such phases likely constrained the duration and intensity of Neanderthal presence in these interior regions, reinforcing the idea that central Iberia was a marginal and unstable habitat for them, used intermittently and in specific climatic windows (Jiménez-Espejo et al. 2007; Bhagwat 2008; Jennings et al. 2011; Vidal-Cordasco et al. 2022).

Intra-site spatial distribution analyses indicate that Neanderthal site exploitation was not influenced by altitudinal location (Pettitt 1997). Instead, these groups exploited a wide range of environments, demonstrating remarkable ecological adaptability, though with a consistent preference for proximity to watercourses or natural corridors (Table 1 below) (Eixea et al. 2020).

Table 1*: Sites and their distance (in km) between them and the nearest fluvial course. From: Eixea et al. 2020, p. 298*



Site	Fluvial course	Distance (in km)
Tossal de la Font	Millars	5–15
Forcall Rambla Millars	Millars	<5
Terrasa Pont Nou	Millars	<5
Terrasa Pont Vell	Millars	<5
El Pinar	Millars	5–15
Hoya Albaida-Titonares	Palancia	<5
Árguinas-Majadal	Palancia	<5
Abrigo de la Quebrada	Turia	5–15
Barranc Carcalín	Magro	<5
San Luís	Magro	<5
Rambla de los Morenos	Júcar	5–15
Las Fuentes	Júcar	<5
Bolomor	Coastal plain	<5
Cova del Gat	Coastal plain	<5
Petxina	Albaida	<5
Cova Negra	Albaida	<5
Cova Foradà	Coastal plain	<5
Bancals Pere Jordi	Serpis	<5
Penya Roja	Serpis	<5
Cova dels Corbs	Coastal plain	<5
Cova de les Calaveres	Coastal plain	<5
Cova Beneito	Serpis	<5
Ermita Santa Bárbara	Serpis	<5
Cova del Cochino	Vinalopó	<5
Pastor	Serpis	<5
El Salt	Serpis	<5
L'Alt de la Capella	Serpis	<5
Aigueta amarga/Alquerieta/Solana	Serpis	<5
La Coca	Vinalopó	<5

Lithic assemblage analysis allows a distinction between two main site types: (1) residential sites and (2) short-term or "stopover" sites, used occasionally or just once. In the case of residential sites, such as Quebrada, Pastor (Sossa-Ríos et al. 2022), Salt (Garralda et al. 2014), Cova Negra (Arsuaga et al. 2007), Beneito (Carrión & Munuera 1997), tool diversity is limited, consisting primarily of scrapers and denticulated tools. Retouch is minimal and non-invasive. On these sites, tools are clearly associated with anthropogenic activities, as also seen at Abric Romaní, Roca dels Bous, Cova Gran de Santa Linya and Cova del Estret de Tragó (Martínez-Moreno et al. 2010). The presence of hearths, often centrally located, reinforces their classification as residential. Conversely, at more ephemeral stopover sites, only small, lightly retouched lithic tools are found. These were likely transported from elsewhere to exploit specific hunting opportunities, such as the natural concentration of game due to topographic traps or carcasses abandoned by carnivores (Eixea et al. 2020).

The study of sites in the northeast of the Iberian Peninsula highlights the behavioral flexibility of Neanderthal groups. In the Pre-Pyrenees, Neanderthals exploited available resources in an opportunistic yet targeted manner, as demonstrated by the correlation between the abundance of faunal and floral taxa in the environment and the taxa most frequently exploited. Occupations of rock shelters and caves such as Abric Romaní, l'Arbreda, as well as other sites in NE Iberia mentioned above, reveal an alternation between seasonal camps and residential bases, integrated within diversified territorial strategies (Carbonell et al. 1996; Vaquero 1999; Martínez-Moreno et al. 2010). In a context marked by the rapid climatic fluctuations of MIS 3, these data point to a strong adaptive capacity and a detailed knowledge of local environments. In contrast to Mediterranean coastal sites such as El Salt or Cova Beneito, which often present evidence of more stable residential occupations in relatively buffered lowland settings (Villaverde et al. 1998; Galván et al. 2014), the Pre-Pyrenean record emphasizes greater seasonal mobility and the exploitation of rugged ecological niches, particularly through specialized hunting of ibex and other mountain-adapted taxa. Likewise, unlike the central Meseta, where climatic oscillations frequently resulted in discontinuities or reductions in occupation density (Carrión et al. 2008; Kehl et al. 2013), the Pre-Pyrenees appear to have functioned as both a resource-rich zone and a potential ecological refuge during the rapid climatic shifts of MIS 3.

3.2. Paleoecology

3.2.1. Zooarchaeological record

During the transition between the Middle and Upper Pleistocene in Iberia, the most frequently recovered fossils belong to cold-adapted megafauna such as the woolly mammoth (*Mammuthus primigenius*), the woolly rhinoceros (*Coelodonta antiquitatis*), and the reindeer (*Rangifer tarandus*). Other species also migrated through the less mountainous regions surrounding the Pyrenees and the Basque Country, including Catalonia. Among these were the wolverine (*Gulo gulo*), the arctic fox (*Vulpes lagopus*), the musk ox (*Ovibos moschatus*), and the saiga antelope (*Saiga tatarica*) (Rodríguez-Almagro et al. 2021).

The site of Aguilón P5, located in the Ebro Valley (NE Iberia) and dating to MIS 3, yielded a macromammal assemblage dominated by species associated with forested habitats, with *Cervus elaphus* and *Capreolus capreolus* accounting for half of the faunal record (Sauqué et al. 2014; Mazo & Alcolea, 2020). Evidence from micromammals indicates that wooded or rocky environments were less represented. Nevertheless, the presence of *Iberomys cabrerae*, an endemic species adapted to humid grasslands and Mediterranean climates, points to the persistence of more open environments (López-García & Cuenca 2012; Mazo & Alcolea 2020). Cold-adapted taxa are also present, including *Lagopus sp.*, *Chionomys nivalis*, *Rhinolophus hipposideros*, and *Myotis daubentonii* (Núñez-Lahuerta et al. 2016; Mazo & Alcolea 2020).

This faunal and environmental mosaic implies that Neanderthals living in NE Iberia during MIS 3 had to adapt their subsistence strategies to highly variable ecosystems. The coexistence of forest-adapted ungulates (*Cervus elaphus*, *Capreolus capreolus*) with cold-steppe taxa such as *Lagopus sp.* or *Chionomys nivalis* suggests a mixed strategy combining selective hunting of large herbivores in wooded habitats with opportunistic exploitation of species from open or colder environments (Maroto et al. 2012). The presence of both Mediterranean and cold-adapted faunal indicators further suggests that Neanderthals adjusted their mobility and site use according to shifting resource availability, alternating between forested valleys and more open steppe-like landscapes (Vaquero & Pastó 2001; Yravedra & Uzquiano 2013). Such flexibility highlights a strong capacity for planning and resilience, allowing groups to endure the rapid climatic oscillations characteristic of MIS 3.

3.2.2. Paleovegetation records

In most Upper Pleistocene sites of northeastern Iberia, *Pinus sylvestris* type is consistently overrepresented in both palynological and anthracological records. This taxonomic group dominates the assemblages attributed to MIS 3 and reflects the pronounced climatic oscillations of the period, which drove increasing aridification and cooling of the environment. Coniferous forests persisted under these conditions but were often associated with more open landscapes, including expanding steppe-like environments where shrub and herbaceous taxa developed. Among the latter, *Buxus sempervirens*, *Pistacia* sp., and *Juniperus sp.* are recurrently attested, occasionally accompanied by deciduous *Quercus*, pointing to the resilience of mixed woodland-shrubland mosaics even during the predominance of pine-dominated assemblages (Carrión et al. 2010; González-Sampériz et al. 2006; Sánchez Goñi et al. 2008).

The designation *Pinus sylvestris* type refers here to an identification group of montane pines encompassing at least four taxa, *Pinus nigra subsp. salzmanni*, *Pinus uncinata*, *Pinus mugo Turra*, and *Pinus sylvestris L*., the latter being the most widespread species at a global scale. These montane pines are currently distributed across the higher vegetation belts of the Iberian Peninsula (see Figure 3 and 5). *Pinus nigra* and *Pinus sylvestris* are most commonly found in the oromediterranean zones, i.e., at elevations above 800 m a.s.l., although they can also occur at much lower altitudes, below 200 m a.s.l., particularly in southern France.

These species may have been distributed in different biogeographical zones or may have coexisted in the same areas. *Pinus sylvestris* may have been distributed north of the 40th parallel, particularly in mountainous regions extending from the coastal zones to the Pyrenees, whereas *P. nigra* likely had a more extensive distribution south of the 40th parallel, particularly along the southeastern Mediterranean coast of the Iberian Peninsula and in southern France (Zilhão et al. 2016; Burjachs et al. 2012; Allué et al. 2018; Mazo & Alcolea, 2020).

Thus, *P. nigra* would be better adapted to the southeastern Mediterranean coast, *Pinus pinea/pinaster* to the southern Iberian regions, and P. *sylvestris* to the northeastern areas, above 300 m in altitude. The biogeographical distribution of these pines appears to have been driven by the ecological requirements of each species (Burjachs et al. 2012; Allué et al. 2018).

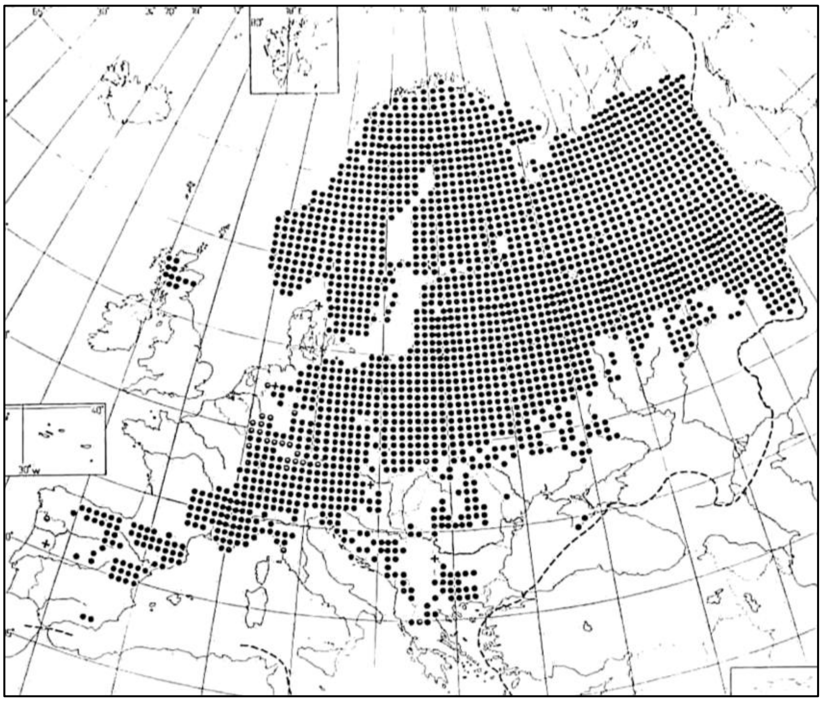


Figure 5: *: Map showing the current natural distribution of Pinus sylvestris in Europe. From: Kelly & Connolly 2000, p.16.*

The predominance of montane pines already plays a significant role from the Middle Pleistocene onwards, as demonstrated by numerous anthracological studies in the Iberian Peninsula, particularly in its northeastern sector. Indeed, anthracological analyses enable the reconstruction of local arboreal cover with high precision, as well as the associated environmental and climatic conditions. Moreover, these studies provide insights into the cultural factors associated with the presence of charcoal within Mousterian occupation contexts.

It is particularly relevant to examine the anthracological results from various sites in the northeastern Iberian Peninsula, such as Abric Romaní (Burjachs et al. 2012), Cova Gran de Santa Linya (Allué et al. 2018), and Aguilón P5 and P7 (Mazo & Alcolea 2020), whose occupations fall within the same chronological framework as that of Roca dels Bous, and which all show a similar trend in vegetation cover.

The anthracological and faunal analyses, particularly those based on the micromammal assemblages from Abric Romaní, provide essential insights into mean annual precipitation and temperature during Greenland Stadial 17 and GS 16. The beginning of MIS 3, coinciding with interstadial GI 17, is characterised by pine-dominated forests associated with ca. 25% warm-temperate taxa. This phase began under humid climatic conditions but concluded with a shift toward increased aridity. Following this warming phase, the cold period GS 17 is marked by a Mean Annual Temperature (MAT) approximately 7.5°C lower than today. At the same time, Mean Annual Precipitation (MAP) was 350 mm/year higher. The subsequent interstadial, GI 16 exhibits similar conditions. Anthracological data confirm the presence of pine forests in the region, firewood collected by Neanderthals consisted primarily of pine. Micromammals from GS 16 indicate a MAT 4.6°C lower and a MAP 75 mm/year higher than today (Burjachs et al. 2012).

The anthracological study of Cova Gran de Santa Linya (Allué et al. 2018) confirms the low taxonomic diversity of firewood assemblages and the predominance of *Pinus sylvestris* type. Comparative evidence from other sites in northeastern Iberia suggests that this taxon grew at altitudes 500 m lower than its current distribution range. Despite the numerous climatic oscillations documented in palaeoenvironmental proxies such as pollen and micromammals, woodland cover persisted, alternating with open mosaic landscapes composed of grasslands and arid steppes during the colder phases of MIS 3 (Burjachs et al. 2012; Allué et al. 2018). In contrast, much of Europe and other regions of the Iberian Peninsula exhibited extremely limited arboreal vegetation during these intervals, where alternative fuel resources such as bones were likely employed.

Palynological data from Abric Romaní illustrate the composition of open landscapes during the early MIS 3 (ca. 57–50 ka). The vegetation was dominated by Poaceae, *Artemisia*, and *Pinus,* the latter reaching up to 68.8% of the pollen assemblage (Burjachs et al. 2012). Climatic oscillations within MIS 3 are clearly reflected in the sequence (see Table 2 below). Warmer phases are marked by the appearance of Cupressaceae and mesothermophilous taxa such as *Quercus* spp., *Olea–Phillyrea*, *Rhamnus*, and several herbaceous families, including Fabaceae and Scrophulariaceae. These may be accompanied, albeit in low percentages, by more thermophilous species such as *Pistacia*, *Cistus*, *Syringa*, *Juglans*, *Hedera*, *Coriaria*, and *Erica*. By contrast, the interval between 50 and 47 ka BP, corresponding to Heinrich Stadial 5 (HS 5), records a sharp decline in arboreal taxa and a dominance of Asteraceae, Poaceae, and *Artemisia*, reflecting a cold, dry steppe-type vegetation. Despite these significant fluctuations, *Pinus* remains continuously represented throughout the sequence (see Figure 6) (Burjachs et al. 2012; Zilhão et al. 2016).

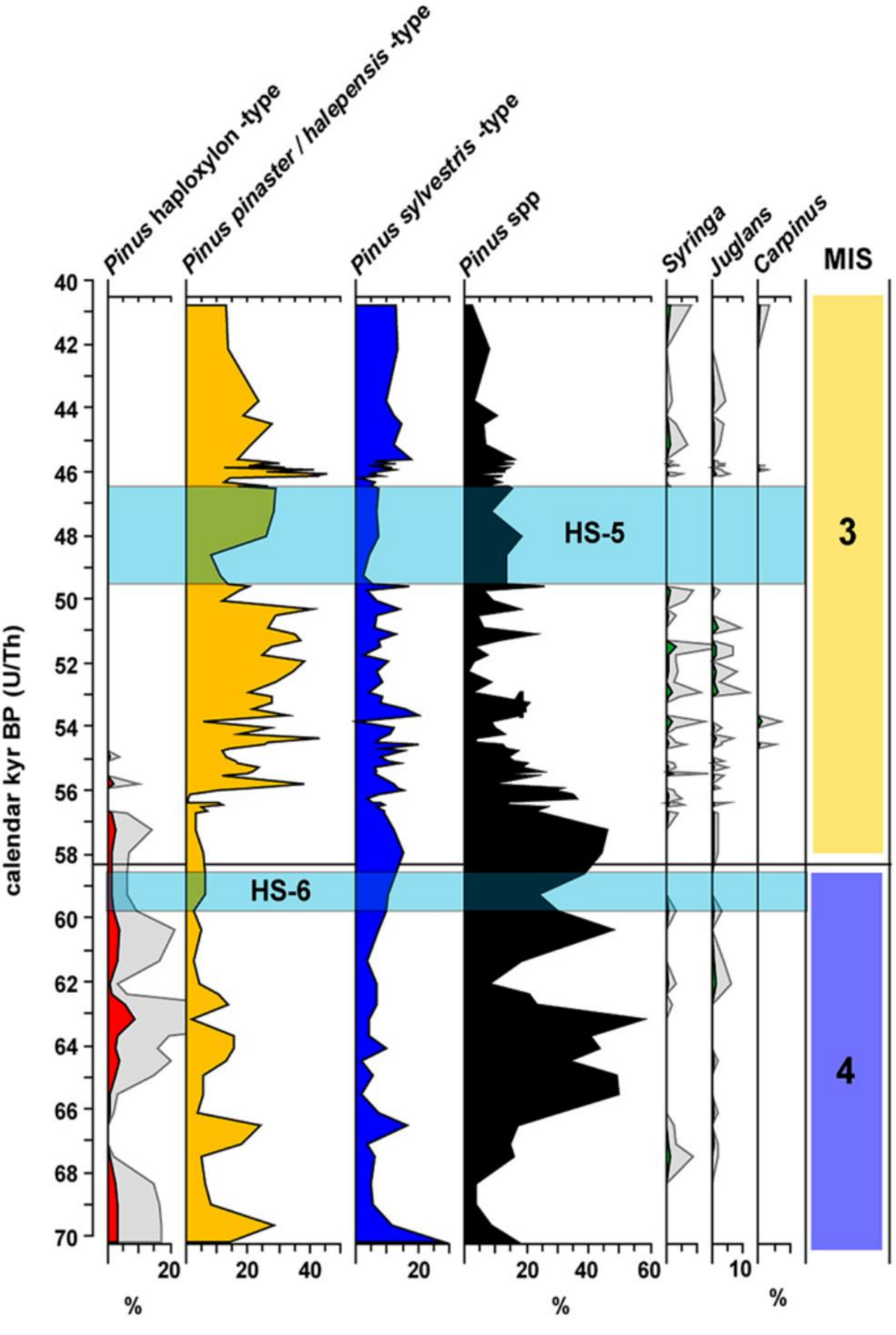
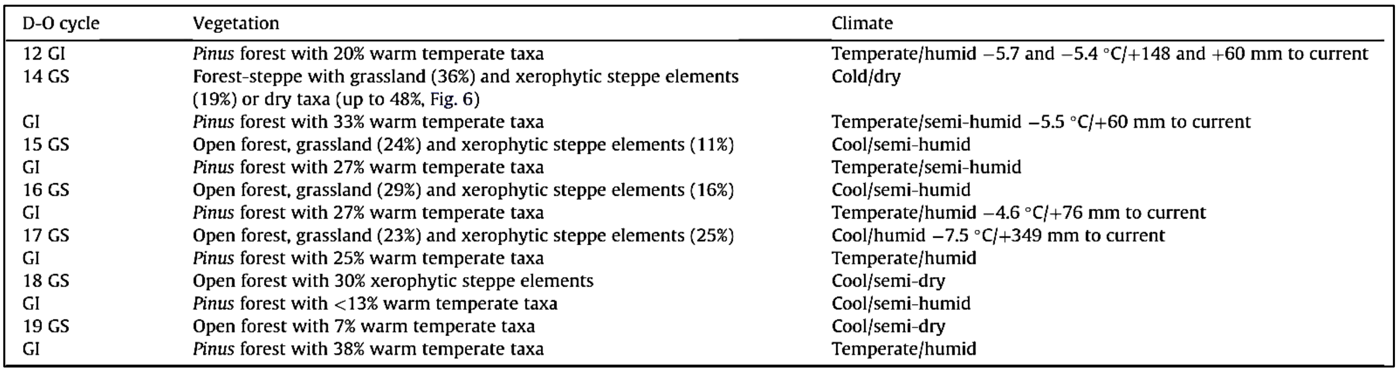


Figure 6: *Palynological diagramm of a sequence of Abric Romani site showing the diachronic progress of Pinys type and arboreal taxas during MIS 4 and MIS 3. From: Burjachs et al. 2012, p. 35*

Table 2: *Summary of vegetation changes at Abric Romani through D-O cycles. Interpretation of vegetation cover based on arboreal pollen (AP) percentages as follows : AP 20-40% = forest-steppe, AP 40-60%= open forest, AP> 60%=forest. From: Burjachs et al. 2012 p. 34*



D-O cycle	Vegetation	Climate
12 GI	*Pinus* forest with 20% warm temperate taxa	Temperate/humid −5.7 and −5.4 °C/+148 and +60 mm to current
14 GS	Forest-steppe with grassland (36%) and xerophytic steppe elements (19%) or dry taxa (up to 48%, Fig. 6)	Cold/dry
GI	*Pinus* forest with 33% warm temperate taxa	Temperate/semi-humid −5.5 °C/+60 mm to current
15 GS	Open forest, grassland (24%) and xerophytic steppe elements (11%)	Cool/semi-humid
GI	*Pinus* forest with 27% warm temperate taxa	Temperate/semi-humid
16 GS	Open forest, grassland (29%) and xerophytic steppe elements (16%)	Cool/semi-humid
GI	*Pinus* forest with 27% warm temperate taxa	Temperate/humid −4.6 °C/+76 mm to current
17 GS	Open forest, grassland (23%) and xerophytic steppe elements (25%)	Cool/humid −7.5 °C/+349 mm to current
GI	*Pinus* forest with 25% warm temperate taxa	Temperate/humid
18 GS	Open forest with 30% xerophytic steppe elements	Cool/semi-dry
GI	*Pinus* forest with <13% warm temperate taxa	Cool/semi-humid
19 GS	Open forest with 7% warm temperate taxa	Cool/semi-dry
GI	*Pinus* forest with 38% warm temperate taxa	Temperate/humid

Evidence from the sites of Aguilón P5 and P7 (AGP5 and AGP7) confirms the predominant use of *Pinus sylvestris* as firewood (Mazo & Alcolea, 2020). It is associated with shrub taxa such as *Prunus* sp., suggesting more open landscapes during colder phases. This evidence correlates well with the records from Cova Gran, Abric Romaní, and other sites in northeastern Iberia (Allué et al. 2017, 2018; Mazo & Alcolea 2020).

Taken together, these contemporaneous assemblages indicate that montane pines were exploited almost continuously as a fuel resource, regardless of climatic oscillations and abrupt cooling events during MIS 3. Alongside juniper-dominated open woodlands, pine forests thus constituted the most widespread forest formation in the Iberian Peninsula until the Late Pleistocene. Their gradual decline only began with the onset of more humid conditions at the beginning of the Holocene (Allué et al. 2018).

From an environmental perspective, these data highlight the coexistence of relatively closed conifer-dominated woodlands with increasingly open steppe-like habitats. During colder stadials, arid conditions favored the expansion of grasslands and xerophytic taxa such as *Artemisia*, whereas interstadial phases allowed for the temporary development of more humid and thermophilous vegetation, including *Quercus*, *Pistacia*, and other Mediterranean taxa. This alternation between dry, open landscapes and wetter, more forested settings reflects the pronounced climatic instability of MIS 3. For Neanderthal groups, this alternation between closed woodland and open steppe landscapes had direct implications for subsistence strategies. In colder and drier phases, the expansion of open habitats facilitated the availability of steppe-adapted prey such as ibex or horse, while also relying on conifer forest, particularly *Pinus sylvestris*, for firewood (Allué 2002; Yravedra & Uzquiano 2013). During warmer and more humid interstadials, the spread of deciduous and Mediterranean taxa such as *Quercus* or

Pistacia expanded the range of available resources, both for combustibles and for ungulate browsing niches, diversifying potential hunting opportunities (Carrión et al. 2010). These shifting ecological mosaics necessitated flexible mobility patterns and the ability to adapt site functions, alternating between logistical hunting camps in open environments and longer-term residential occupations in more sheltered, forested valleys (Vaquero & Pastó 2001). Overall, the persistence of *Pinus* as a dominant element throughout MIS 3 underscores its central role in both woodland ecology and human subsistence strategies, serving as a stable resource in otherwise highly variable environments.

4. Roca dels Bous archaeological site

In 1970, Emili Sunyer, an amateur archaeologist, reported the presence of Mousterian lithic tools in the cliff of Cingle de la Cascalda, near the village of Llorenç de Montgai, leading to the first excavations at the site (Sunyer 1973; Roy Sunyer et al. 2017). By the late 1980s, these preliminary investigations gave rise to the need for a systematic study of the site, which level N10 being the first archaeological unit to be excavated in extension (Martínez-Moreno et al. 2021). To date, the bedrock has not yet been reached, and the site's archaeological potential remains intact. Excavations carried out between 2001 and 2018 exposed an area of over 100 m² and a 2.5 m thick sequence of undisturbed deposits (Benito-Calvo et al. 2020). Excavations are taking place every year since 2001 and the fieldwork has been led by the UAB and the Centre for the Study of Prehistoric Archaeological Heritage.

4.1. Technologies in use during current excavations

The general excavation strategy aimed to reconstruct the original morphology of the surface used by Neanderthals. To achieve this, it was considered essential to record the complete three-dimensional spatial coordinates of every bone or lithic object found *in situ*, to identify potential spatial patterns corresponding to specific activity areas (Martínez-Moreno & Mora 2004; Mora Mora Torcal et al. 2015).

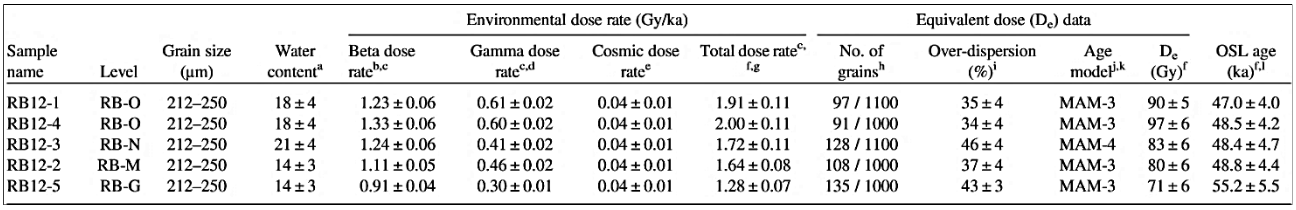
The software used to manage the site's spatial data includes Visual Basic 6 in conjunction with a MySQL (2014) database, as well as ArqueoUAB. The latter enables the management of geolocation data and facilitates its graphical representation, providing acquisition counts, statistical outputs, and inventory listings. These tools are particularly suited for optimised data recording in rock-shelter contexts or on large open-air sites.

When coordinates are captured using the total station, an alphanumeric identifier is generated based on contextual indicators, followed by a numeric sequence linked to an entry in the Data Matrix. The characteristics of each object are recorded using Personal Digital Assistants (PDAs). These digital notebooks are structured with hierarchical dictionaries, allowing the input of various data such as orientation, slope, width, thickness, and length of the item. All recorded information is stored in the PDA and transferred to a microcomputer, which generates a Data Matrix (DM) code placed in an individual bag containing the object's stratigraphic information. All information is thus centralised and can be continuously updated or corrected during the excavation. This systematic recording method is crucial, especially in contexts where the archaeological sequence is poorly visible or difficult to interpret (Martínez-Moreno et al. 2016; Mora Torcal et al. 2015)

4.2. Chronological frame

The chronology of RB was established through single-grain OSL dating of five sediment samples collected from stratigraphic units RB-G, RB-M, RB-N, and RB-O (see Figure 7). Between 9% and 13% of the quartz grains measured per sample were deemed suitable for optically stimulated luminescence (OSL) dating (see Table 3). The sedimentary layer RB-G is associated with archaeological level S9 (N16), RB-M with N14, RB-N with N12, RB-R with N10, and RB-O is not associated with any archaeological level (Benito-Calvo et al. 2020).

***Table 3**: Dose rate data, single-grain equivalent doses, and quartz optically stimulated luminescence (OSL) ages for the Roca dels Bous (RB) samples. Benito-Calvo et al., 2020, p.6*

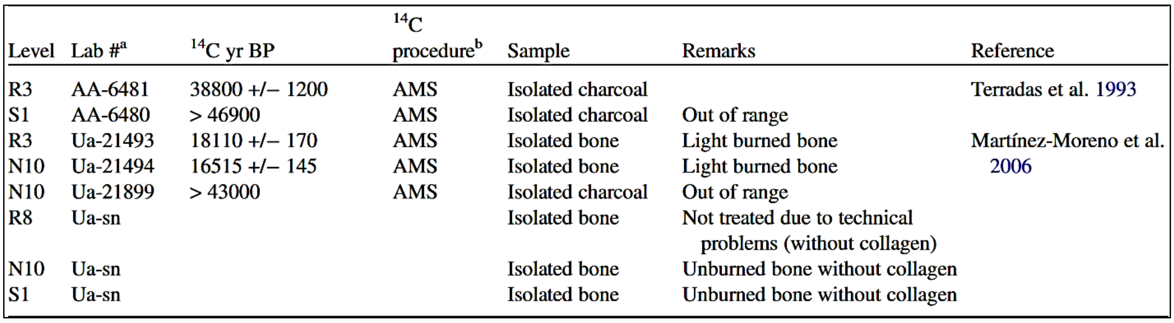


				Environmental dose rate (Gy/ka)				Equivalent dose (D_e) data				
Sample name	Level	Grain size (µm)	Water content[a]	Beta dose rate[b,c]	Gamma dose rate[c,d]	Cosmic dose rate[e]	Total dose rate[c,f,g]	No. of grains[h]	Over-dispersion (%)[i]	Age model[j,k]	D_e (Gy)[f]	OSL age (ka)[f,l]
RB12-1	RB-O	212–250	18 ± 4	1.23 ± 0.06	0.61 ± 0.02	0.04 ± 0.01	1.91 ± 0.11	97 / 1100	35 ± 4	MAM-3	90 ± 5	47.0 ± 4.0
RB12-4	RB-O	212–250	18 ± 4	1.33 ± 0.06	0.60 ± 0.02	0.04 ± 0.01	2.00 ± 0.11	91 / 1000	34 ± 4	MAM-3	97 ± 6	48.5 ± 4.2
RB12-3	RB-N	212–250	21 ± 4	1.24 ± 0.06	0.41 ± 0.02	0.04 ± 0.01	1.72 ± 0.11	128 / 1100	46 ± 4	MAM-4	83 ± 6	48.4 ± 4.7
RB12-2	RB-M	212–250	14 ± 3	1.11 ± 0.05	0.46 ± 0.02	0.04 ± 0.01	1.64 ± 0.08	108 / 1000	37 ± 4	MAM-3	80 ± 6	48.8 ± 4.4
RB12-5	RB-G	212–250	14 ± 3	0.91 ± 0.04	0.30 ± 0.01	0.04 ± 0.01	1.28 ± 0.07	135 / 1000	43 ± 3	MAM-3	71 ± 6	55.2 ± 5.5

Radiocarbon (^{14}C) dates on bones have been obtained, indicating an age range of >46 ka for the base of the sequence and 38 ka ± 1200 BP uncalibrated for the top of the sequence (Andrès & Chueca Cía 1998). However, the sources are unclear regarding the number of bones dated and their exact stratigraphic origin within the sequence. New AMS ^{14}C dates have been obtained (see Table 4 below), on charcoal and bone, highlighting several common issues in the radiocarbon dating of Mousterian sites. The difficulty in obtaining reliable ^{14}C dates between 50 and 30 ka arises from risks of contamination by recent carbon, poor preservation of the datable material itself, and the increasing uncertainty of the IntCal13 calibration curve during this period (Wood 2015). One of these issues was encountered in level S1 (AA-6480) and level N10 (Ua-21899), where the radiocarbon ages exceed the applicable range of the ^{14}C dating method. Other dates, by contrast, are incompatible with a Neanderthal occupation; these include AMS dates obtained on light-burned bones (R3: Ua-21493, N10: Ua-21494). Such anomalously young dates result from severe collagen degradation and do not provide reliable chronological information (Bocherens et al. 2005; Goldenberg et al. 2017; Talamo et al. 2021). Charcoal sample AA-6481, from level R3, which lies above levels N10, N12, N14, and N16, yielded a calibrated date of 44–42 cal ka BP at 68% confidence interval. This result is consistent with the OSL dates (Benito-Calvo et al. 2020).

The OSL dates provide a more reliable chronological framework for the Mousterian occupations at the site and can be correlated with specific, well-known climatic events. Level S9 (N16) can thus be associated with climatic event GS-15, levels N14 and N12 with GS-13, and level N10 with GS-12b/c (Rasmussen et al. 2014; Benito-Calvo et al. 2020).

***Table 4** : Charcoal and bone series accelerator mass spectrometry the ^{14}C ages from Roca dels Bous. [a]AA corresponds to Arizona Radiocarbon Laboratory, 'Ua' to Upsalla Radiocarbon Laboratory and [b]AMS is accelerator mass spectrometry, Benito-Calvo et al., 2020, p. 16*



Level	Lab #[a]	^{14}C yr BP	^{14}C procedure[b]	Sample	Remarks	Reference
R3	AA-6481	38800 +/– 1200	AMS	Isolated charcoal		Terradas et al. 1993
S1	AA-6480	> 46900	AMS	Isolated charcoal	Out of range	
R3	Ua-21493	18110 +/– 170	AMS	Isolated bone	Light burned bone	Martínez-Moreno et al. 2006
N10	Ua-21494	16515 +/– 145	AMS	Isolated bone	Light burned bone	
N10	Ua-21899	> 43000	AMS	Isolated charcoal	Out of range	
R8	Ua-sn			Isolated bone	Not treated due to technical problems (without collagen)	
N10	Ua-sn			Isolated bone	Unburned bone without collagen	
S1	Ua-sn			Isolated bone	Unburned bone without collagen	

4.3. *Stratigraphic and archaeological record*

Numerous faunal remains have been recovered from the various stratigraphic levels at Roca dels Bous.

Some species are associated with dry grassland environments, such as *Equus* sp. and *Stephanorhinus sp.,* found in association with *Cervus elaphus*, *Bos sp., Equus ferus, Capra pyrenaica*, and tortoises (Benito-Calvo *et al.* 2020). Although palaeoecological indicators for Roca dels Bous remain limited, they align with data from Marine Isotope Stage 3 at archaeological sites in the northeastern Iberian Peninsula, such as the site of Abric Romaní. At Abric Romaní, in NE Iberia, close to Barcelona, levels "Ja" and "Jb", dated to MIS 3, yielded two taxa also identified at Roca dels Bous: *Equus ferus* and *Stephanorhinus hemitoechus* (Rosell et al. 2012).

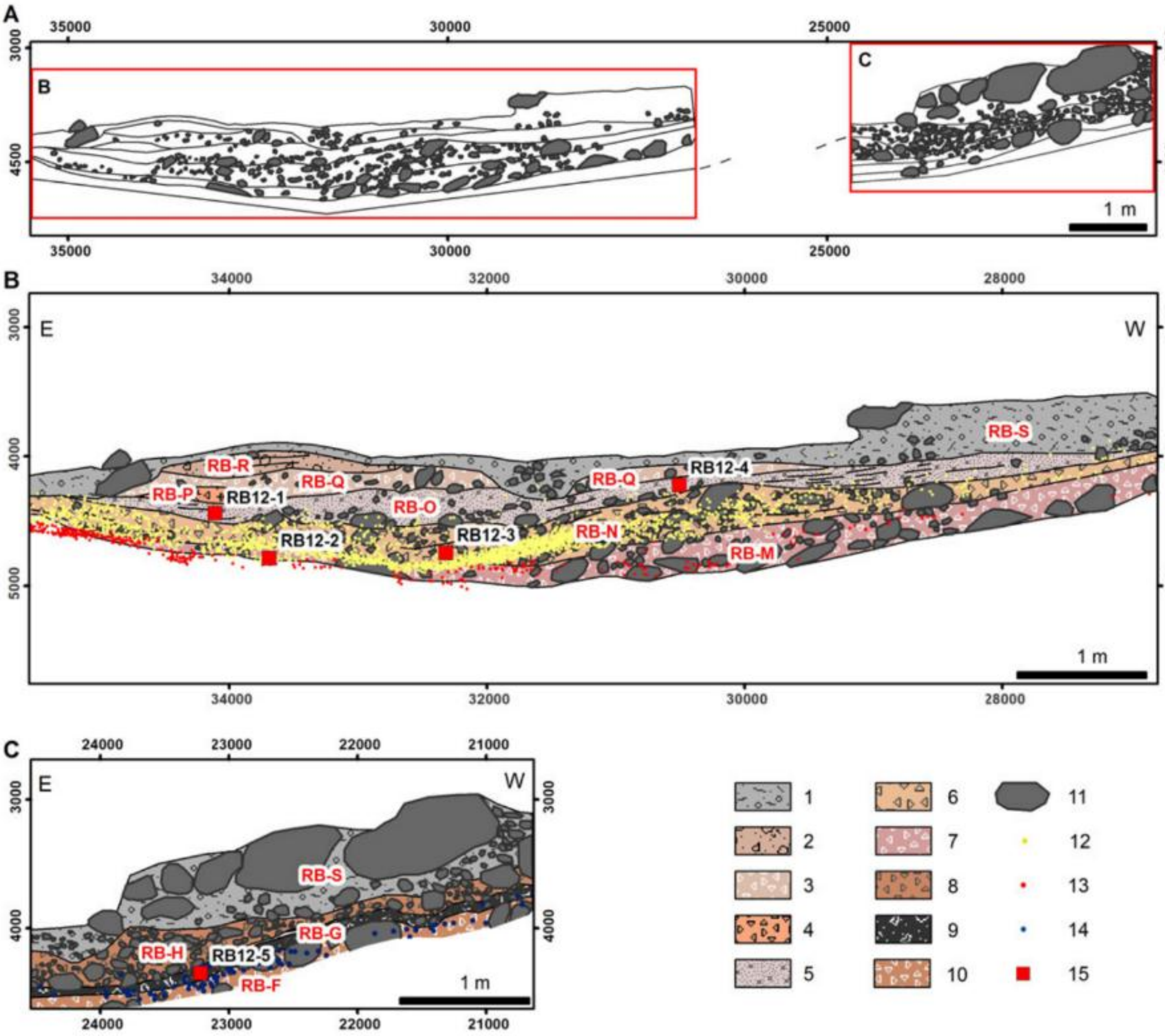


Figure 7: Stratigraphic sections of the Roca dels Bous (RB) site, digitalized in GIS from orthophotos georeferenced with a total station. Local cartesian coordinate system in mm. (A) E–W general section. (B) Sequence of the eastern and central areas. (C) Sequence of the western sector. Legend: 1, recent anthropic layer (RB-S); 2, coarse-bedded fining-upward angular pebbles, includes a pale yellow silty sandy matrix (RB-R) and the archaeological level N10; 3, angular and sub-angular coarse pebbles, scarce cobbles, and massive sands (RB-Q); 4, lens of moderately sorted sub-angular to sub-rounded medium pebbles with reddish sandy mud matrix (RB-P); 5, massive grey sands to the east, locally laminated and concreted, and bedded pebbles to the west (RB-O); 6, angular and sub-angular very coarse pebbles and some cobbles, showing fining-upward cycles (RB-N), contains archaeological level N12; 7, angular and sub-angular coarse to fine pebbles with grey sandy mud matrix (RB-M), contains archaeological level N14; 8, angular and sub-angular cobbles and very coarse pebbles with scarce red-brown sandy mud matrix (RB-H); 9, combustion ashes (RB-G); 10; angular pebbles, cobbles, and blocks with large interparticle voids and scarce sandy mud matrix (RB-F); 11, angular boulders and cobbles; 12, archaeological level N12; 13, archaeological level N14; 14, archaeological level S9; 15, OSL samples. Benito-Calvo et al., 2020, p.8

4.3.1. N10

In the studied area, more than 4,100 objects were recorded in three-dimensional spatial coordinates. These objects are associated with 8 hearths. The composition of the N10 assemblage does not appear to have been significantly affected by post-depositional processes that would have compromised its integrity.

Lithic artefacts account for approximately 880 items, representing about 45% of the total finds. The vast majority of the 2,000 bone fragments measure less than 2 cm in length, which rules out the action of taphonomic processes capable of clearing material from a sloped surface. The distribution of material across the surface is not homogeneous, with areas of high density contrasting with zones devoid of material. A spatial organization related to the hearths is clearly observable (Martínez-Moreno & Mora 2004).

4.3.2. N12

Layer N12, excavated over a surface area of 105 m² and to a depth of approximately 20 cm, includes a central depression located between two sedimentary cones. A total of 22 hearths have been recorded (Roy Sunyer et al. 2017).

A sterile layer measuring 30 cm in thickness and extending over more than 8 meters in length separates N10 and N12, clearly distinguishing these assemblages temporally and ruling out vertical migration as a source of artefact mixing. Inter-layer migration between N10 and N12 appears to be limited, as the layers themselves are relatively thin, ranging from 5 to 10 cm for N10 and up to 20–25 cm in some areas of N12. This sterile layer confirms a chronological discontinuity between the two levels. Nevertheless, both layers result from an undetermined number of short-term occupations occurring within an imprecise temporal range.

Some hearths from both levels overlap within an area of approximately 8 m², distributed along a parabolic surface. Certain hearths occur within similar contextual configurations, raising questions about possible synchronicity. The superposition of hearths, along with blocks and artefacts, within the same stratigraphic layer argues against a single occupation event. Rather, it points to multiple occupations distributed over an undefined period and of uncertain duration.

These two periods of frequent occupation are separated by a phase of site abandonment and are further distinguished by differences in raw material procurement strategies, knapping sequences, and settlement patterns in the Neanderthal landscape. However, these differences are only observable in the vertical stratigraphic profile and highlight the significance of spatial recording (Martínez-Moreno et al. 2016).

Quartzite fragments found in level N12 suggest that raw materials were sourced from the site's surrounding region, though not from its immediate vicinity. In the direct surroundings, only quartzite pebbles of approximately 10 cm are available. This selection reflects a clear Neanderthal preference for certain raw materials. Additionally, non-local stones such as flint, present in the Garumian Formation and the Serra Llarga, also appear in the assemblage, further supporting the idea of preferential material selection.

Metamorphic rocks constitute more than 80% of the lithic assemblage and were likely transported over distances of 14–20 km to the shelter, where they were subsequently retouched (Roy Sunyer *et al.* 2017).

Levels N14, N16, and N18 are currently under excavation, and the data have not yet been published.

5. Materials and Methods

This study presents an archaeobotanical analysis based on three complementary environmental proxies: anthracology, carpology, and the study of phytoliths. These botanical proxies provide information on different plant organs: wood, through the analysis of charcoal remains; fruits and seeds, through carpological evidence; and cellular morphology, through the study of phytoliths. Taken together, these approaches allow for a broader yet more detailed reconstruction of past environments, shedding light on soil composition, water availability, mean temperature, and other climatic parameters, as well as on the subsistence practices and acquisition strategies of the site's occupants.

5.1. Anthracology

The anthracological study of Roca dels Bous was primarily based on the taxonomic identification of charcoal fragments from the level N12, N14, N16 and N18 . The charcoal fragments analysed were hand-collected at the site of Roca dels Bous during the excavation campaigns conducted during 2001 and 2024. At most Paleolithic sites, charcoal remains require manual collection owing to their high degree of fragility. Flotation, while widely applied for the recovery of botanical remains, often induces mechanical stress and fragmentation that can alter the anatomical structures of charcoal. Manual retrieval therefore provides a more reliable method, minimizing post-recovery damage and preserving the integrity of sections intended for anthracological observation. A total of 355 charcoal fragments have been determined for 588 charcoals examined. With respectively, 15, 353, 134 and 86 charcoals for the layers N12, N14, N16 and N18. The charcoal remains were examined under a MOTIC PANTHERA TEC MATBD-T reflected light metallographic microscope, equipped with Brightfield (BF) and Darkfield (DK) illumination systems, and magnifications ranging between×50, ×100, ×200, ×500 to which the ×10 ocular magnification must be added. The fragments were manually fractured along the three observation planes commonly used in anthracology: transverse, tangential longitudinal, and radial longitudinal sections. Observing the arrangement of wood cells in these three planes allows identification at the family, genus, and, more rarely, species level. Taxonomic identification was achieved through comparison with the anthracological reference collection of the IPHES-CERCA, as well as consultation of various standard reference works, including Anatomy of European Woods by Schweingruber (1990).

To photograph the different sections of the identified taxa, selected fragments were mounted on metal stubs and fixed using conductive carbon cement. The images were subsequently obtained using an Environmental Scanning Electron Microscope (ESEM) with Backscattered Electron (BSE) imaging, operated through the xT Microscope Control software version 6.2.11 at the Serveis Cientifico Tècnics at the University Rovira i Virgili.

5.2. Carpology

The seeds examined and identified originate from the same stratigraphic levels as those analysed for anthracology, namely N12, N14, N16, and N18, and represent a total of 861 seeds. This total is divided into two subsets: carpological remains retrieved from the anthracological samples (NR: 44), and seeds recovered from a specific area designated as S9 within level N16 (NR: 817). The latter group was hand-collected and isolated, and was therefore studied separately from the seeds extracted from the anthracological samples, which were obtained during the fieldwork.

The observation of the seeds was carried out using a Euromex stereo microscope with magnification ranging from x0.65 to x5.5. Identification was conducted by consulting the carpological reference collection of the IPHES-CERCA, as well as reference works such as Atlas of Seeds and Fruits of the Mediterranean Basin (Sabato & Peña-Chocarro 2021), the Digital Seed Atlas of the Netherlands (Neef 2006), and the Digital Atlas of Economic Plants in Archaeology (Neef 2012).

5.3. *Charcoal and Seed Taphonomy*

Some of the seeds showed thermal impact, therefore a colour inventory of the seeds was also established using the Munsell Soil Colour Book. These colour references allowed the seeds to be classified into categories ranging from "unburnt" to "charred." The colour charts used correspond to the 10YR and 7.5R hue categories. The table below presents the colour classification; these categories are indicative and may be refined through experimental archaeology aimed at more precisely determining the combustion time and its impact on the coloration of *Celtis australis* seeds.

***Table 5**: Colour classification of Celtis australis according to the Munsell Soil Colour Book and attributed to phases of combustion.*

Description	Munsell Color
0: Not burned	7, 8 (Except : 7/1, 7/2, 8/1, 8/2)
1 : Lightly burned	6
2: Burned	5
3: Carbonised	2/2, 5/2, 3/2
4: Calcinated / Mineralized	7/1, 7/2 , 8/1, 8/2

No in-depth analysis of the morphological alterations of the charcoal (such as crack dimensions, frequency, and extent of vitrification) was conducted, with observations limited to a qualitative assessment presented in the Results section.

5.4. *Phytoliths*

Phytoliths were collected along with the sediments using a clean spoon. The coordinates of the samples extracted were then recorded with the information regarding the context from which they originated in terms of combustion structure. The phytoliths originate from sediments associated with hearth features, and only one sector was analysed in the present study: sector E38 of level N10, from which ten slides were prepared and examined. The extraction process was carried out using the rapid protocol proposed by Katz (2010), which enables the isolation and observation of phytoliths within a few hours.

The sediments were sieved to obtain a fraction no larger than 0.5 mm. Approximately 50 mg of this fine fraction was placed in a 0.5 ml conical plastic tube, to which 50 ml of 6N HCl were added in order to dissolve carbonate materials, such as carbonated minerals or small bone fragments. Once the reaction (evidenced by bubbling) ceased, the tube was vortexed (RSLAB-6PRO) for 3 seconds. Subsequently, 450 ml of a sodium polytungstate (SPT) solution was added, followed by another 3-second vortexing. The tube was then placed in an ultrasonic bath

(P-Selecta Ultrasons) for 10 minutes. After a final vortexing step, the tube was centrifuged using an Eppendorf Centrifuge MiniSpin for 10 minutes at 5000 rpm.

The resulting supernatants were transferred to another tube, from which 50 ml were extracted and mounted onto a microscope slide for observation. Ten slides were analysed using an Olympus reflected light microscope.

The identification of phytoliths is based on classifications of morphotypes that correspond to a taxonomic framework. Morphotypes are counted directly during observation and subsequently transcribed into taxonomic reality (Twist et al. 1969; Piperno 1987; Rapp & Mulholland 1992; Piperno 2006; Portillo et al. 2014). Morphotypes may also be compared with reference collections. The identification of phytolith morphotypes follows a precise nomenclature that is subject to periodic updates. This nomenclature ensures the rigorous and systematic attribution of a morphotype to a taxa. The terminology of this nomenclature derives from the *International Code for Phytolith Nomenclature (ICPN 2.0)* (Neumann et al. 2019).

6. Results

6.1. Results of the anthracological analyses

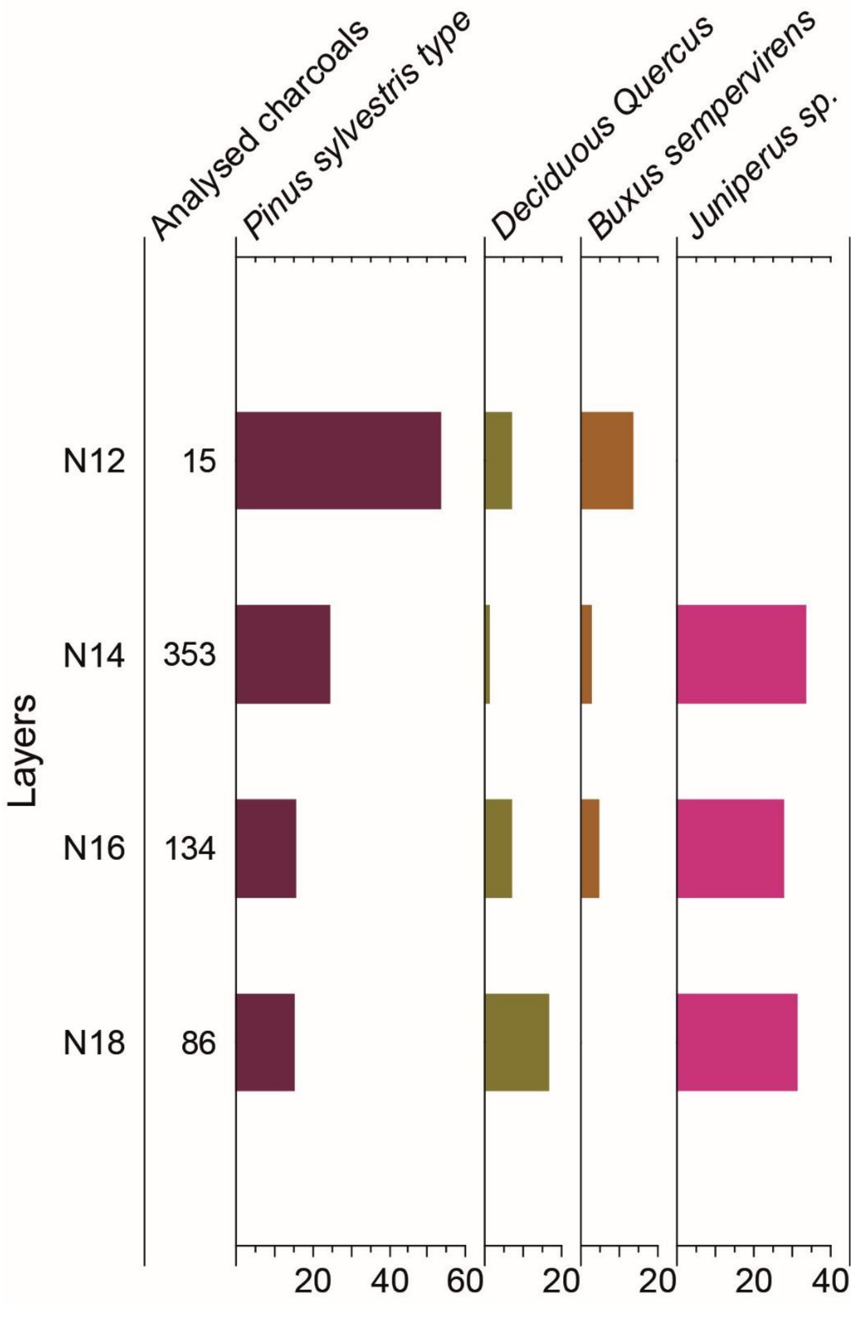


Figure 8: *Graph presenting the anthracological data of levels N12, N14, N16 and N18 of Roca dels Bous, Lleida, Spain © Lachman 2025*

A total of 588 charcoal fragments were examined; 233 of them (39.63%) remain undetermined, while 355 fragments were attributed to four taxa (see Figure 8), as detailed in Table 6.

Juniperus sp. is the most frequent taxon in the anthracological assemblage, representing 31.12% of the identified fragments. It is followed by *Pinus sylvestris* type, accounting for 21.77%. Deciduous oak makes up only 4.59% of the assemblage, and *Buxus sempervirens* represents

2.89%. The category of unidentified charcoal is the most substantial, comprising 39.63% of the total assemblage. Charcoal fragments grouped within this category are either too small for the full set of diagnostic anatomical features to be observed, or large enough but too poorly preserved for identification. This poor preservation is due to taphonomic processes such as compression, vitrification, or the formation of fractures within the plant tissue (see Discussion section).

Table 6: *Table presenting the number of identified taxa, unidentified charcoals fragments, bone fragments, and seed remains by archaeological levels, N12, N14, N16, N18 from Roca dels Bous, Sant Llorenç de Montgai, Spain*

Identifications	**N12**	**N14**	**N16**	**N18**
Pinus sylvestris type	8	86	21	13
Juniperus sp.	0	119	37	27
Quercus sp. deciduous	1	3	9	14
Buxus sempervirens	2	9	6	0
Undetermined	4	136	61	32
Total	15	353	134	86

6.1.1. *Pinus sylvestris type*

As explained in Section 3.2.2, the designation *Pinus sylvestris* type refers to a minimum of four montane pine species: *Pinus nigra* subsp. *salzmanni*, *Pinus uncinata*, *Pinus mugo* Turra, and *Pinus sylvestris* L. It is not possible to differentiate these taxa on the basis of wood anatomy, as they share highly similar structural features, occur in comparable environments, and are capable of interbreeding. Consequently, this group of montane pines is collectively designated as *Pinus sylvestris* type, with a high probability that the remains correspond to *Pinus sylvestris* L., as suggested by palynological evidence from other sites in northeastern Iberia (see Section 3.2.2).

The taxon *Pinus sylvestris* type accounts for 21.77% of the anthracological assemblage, with 128 charcoal fragments. It is most abundant in level N14 with 86 remains, followed by N16 with 21, N18 with 13, and finally 8 fragments in level N12.

The family of Pinaceae is part of the gymnosperms and, like other taxa within the conifers, *Pinus sylvestris* exhibits particular anatomical features observable in the three anatomical sections commonly used in archaeological charcoal analysis (see Figure 9).

The transverse section of the genus *Pinus* is characterized by the presence of distinct growth rings. These are marked by a difference between earlywood, where tracheids are larger and have thinner walls, and latewood, where tracheids are smaller, more compact, and have thicker walls. Mostly uniseriate, and occasionally biseriate, rays are present, along with isolated and scattered resin canals throughout the late wood tissue (see Figure 9, image B).

The tangential longitudinal section allows observation of the vertical elements of the wood along their length. The tracheids display numerous bordered pits arranged in uniseriate rows. These pits enable water and solute exchange between tracheids. Uniseriate, and more rarely biseriate, ray cells are also observable. The rays are heterogeneous, with marginal ray cells exhibiting a different shape from the body cells, for example, they may appear more elongated or smaller (see Figure 9, image A).

The radial longitudinal section enables the observation of the contact zone between tracheids and rays. At this interface, the pits facilitating exchanges between these two types of cells have a specific morphology that varies by genus. In the case of *Pinus sylvestris type*, the cross-field pits are of the fenestriform type: they are quadrangular in shape and fill the entire area of the so-called "cross-field" (see Figure 9, images C and D).

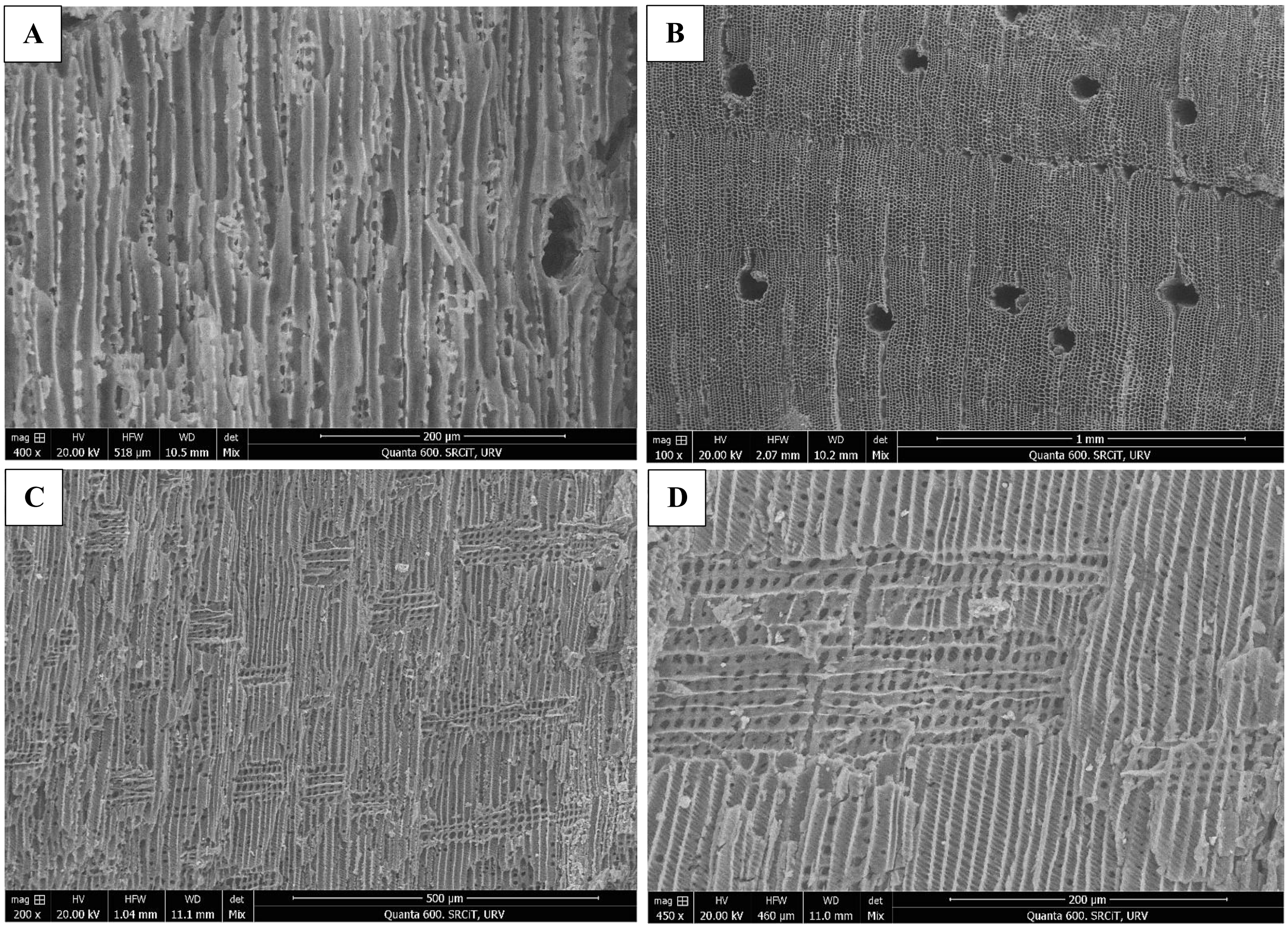


Figure 9: *Environnemental Scanning Electron Microscope (ESEM) images of Pinus sylvestris type: (A) tangential longitudinal section (×400), (B) transverse section (×100), (C) radial longitudinal section (×200), (D) radial longitudinal section (×450). ©Lachman 2025*

6.1.2. *Juniperus sp.*

Juniperus sp. represents 31.12% of the charcoal assemblage and is primarily present in level N14 with 119 fragments, followed by 37 in level N16 and 27 in N18. No juniper charcoal fragments were recorded in level N12. Like *Pinus sylvestris, Juniperus sp.* belongs to the gymnosperms and is part of the Cupressaceae family.

Juniperus communis, like all species of the Cupressaceae family, has homoxylous wood, characterized by the following anatomical features.

In transverse section, growth ring boundaries are distinct and clearly marked, with a gradual transition between earlywood and latewood. Resin canals are absent, and the rays are predominantly uniseriate (see Figure 10, image C).

In tangential longitudinal section, the ray cells are heterogeneous, with marginal cells appearing slightly larger and fusiform. The rays are composed of two to five cells in height (see Figure 10, image A).

The radial longitudinal section reveals the presence of bordered pits on the tracheids, occurring either singly or in pairs, as well as the cross-field pits between tracheids and ray cells. These cross-fields typically contain two cupressoid pits, though up to eight may occur (rarely). The two pits are arranged irregularly, either side by side or one above the other (see Figure 10, image B). This type of pitting is diagnostic of the Cupressaceae family. These pits may also show a brownish coloration, still visible in some charcoal fragments, which is linked to organic deposits.

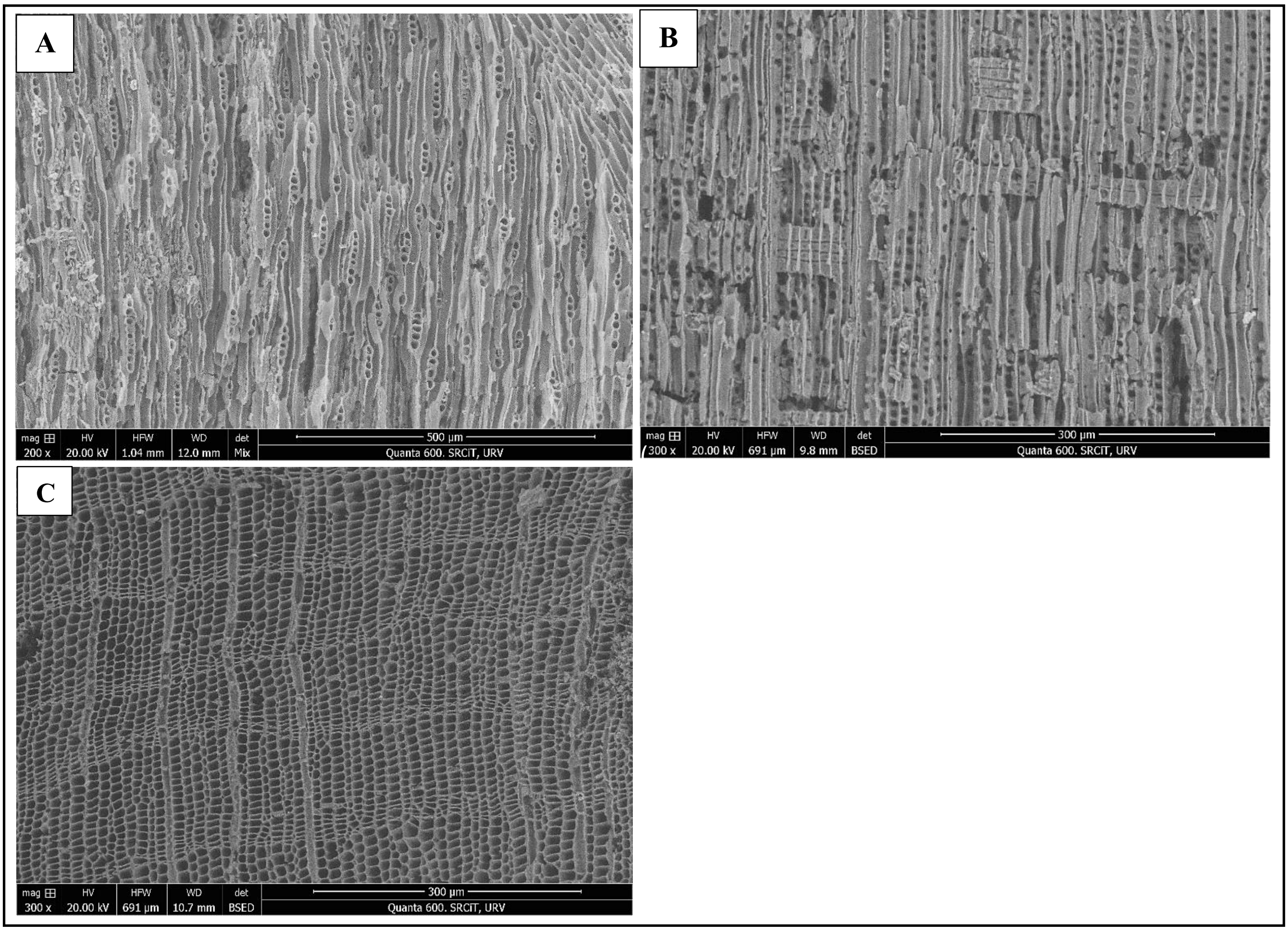


Figure 10: *Environnemental Scanning Electron Microscope (ESEM) images of Juniperus sp.: (A) tangential longitudinal section (×200), (B) radial longitudinal section (×300), (C) transverse section (×300). ©Lachman 2025*

6.1.3. Quercus sp. deciduous

Deciduous oak represents only 4.59% of the charcoal assemblage and is most abundant in level N18 with 14 fragments, followed by N16 with 9 fragments, N14 with 3 fragments, and a single fragment in level N12.

The transverse section is characterized by a ring-porous structure, with a marked size difference between earlywood vessels (larger, ranging from 100µm to 400µm) and latewood vessels (20-60µm). Latewood pores are solitary and arranged in a flame-like pattern. Earlywood pores are also solitary and display a radial, sometimes slightly diagonal or flame-like distribution. Growth rings are distinct and well-marked. Both uniseriate and multiseriate rays (≥10 ray cells) are present. Aggregated rays and paratracheal parenchyma are observable, and more rarely diffuse-in-aggregate parenchyma or vasicentric paratracheal parenchyma may also be present (see Figure 11, images A and B).

In the tangential longitudinal section, vessel elements are visible along with their simple perforation plates. Intervascular pits are alternate. The rays are heterogeneous, and the uniseriate rays typically contain 5 to 10 cells in height (see Figure 11, image D).

The radial longitudinal section shows alternate pitting in the longitudinal elements, as well as ray structures. Ray cells appear procumbent, with occasional upright or square marginal cells (see Figure 11, image C).

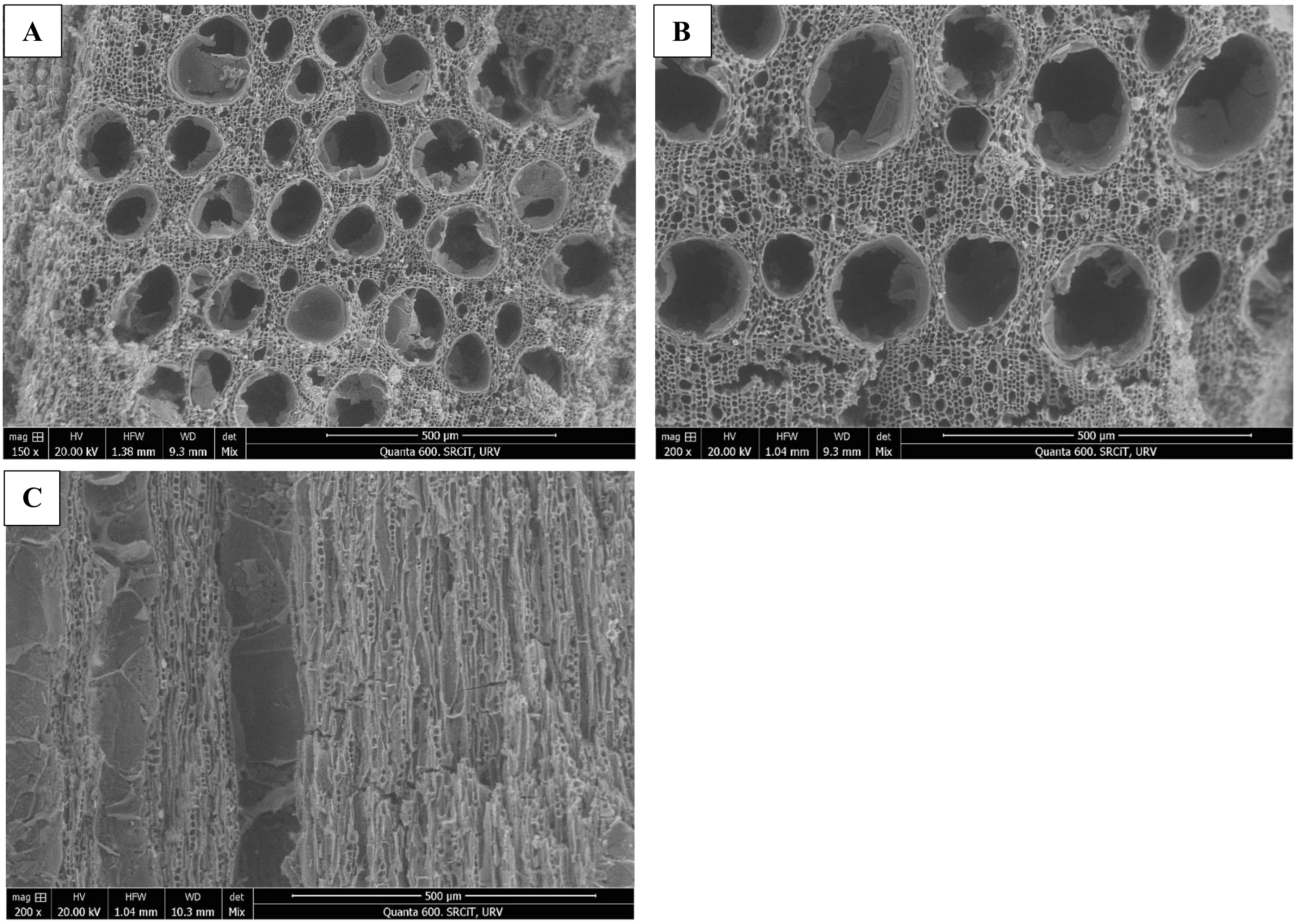


***Figure 11**: Environnemental Scanning Electron Microscope (ESEM) images of Quercus sp. deciduous: (A) transverse section (×150), (B) transverse section (×200), (C) tangential longitudinal section (×200).   ©Lachman 2025*

6.1.4. Buxus sempervirens

Buxus sempervirens is the least represented genus in the assemblage, accounting for 2.89%, with 9 fragments in level N14, 6 in N16, and 2 in N12.

In cross-section, distinct growth rings are visible, primarily marked by variation in pore size. The semi-porous wood of *Buxus* displays isolated pores throughout the tissue, with a high density of larger pores in the earlywood. Rays are uni- to triseriate. Paratracheal and apotracheal parenchyma can be observed, occurring in diffuse patterns, in bands, or in aggregates (see Figure 12, image C).

The tangential longitudinal section allows observation of vessel element perforation plates, which in *Buxus sempervirens* are consistently scalariform with approximately 10 bars. Rays are highly heterogeneous, with cells of varying sizes and reaching up to 15 cells in height. Intravascular pitting is small and alternate (see Figure 12, images B and D).

The radial longitudinal section shows these heterogeneous ray elements. Most of the cells form procumbent rays, separated by a row of square cells, with one or two rows of upright marginal cells (see Figure 12, image A).

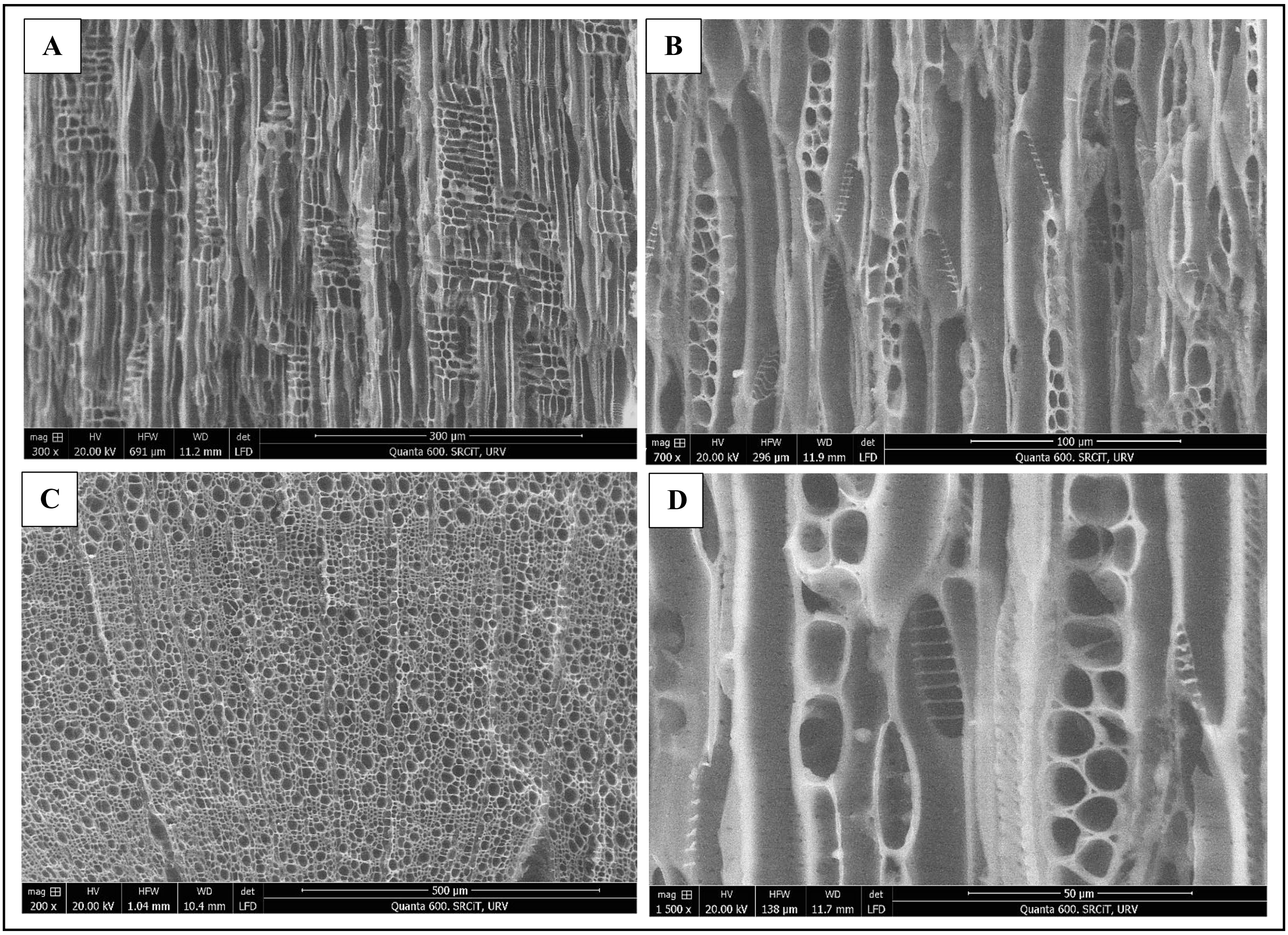


Figure 12: *Environnemental Scanning Electron Microscope (ESEM) images of Buxus sempervirens: (A) radial longitudinal section (×300), (B) tangential longitudinal section (×700), (C) transverse section (×200), (D) tangential longitudinal section (×1500) © Lachman 2025*

6.2. *Results of the carpological analyses*

The carpological study of the site of Roca dels Bous was carried for the four levels, N12, N14, N16 and N18 (see Table 7 below). The table reports the number of carpological remains, not the MNI. Level N14 yielded the highest number of remains, with *Celtis australis* dominating the overall assemblage. This pattern can be partly explained by the presence of an isolated area, S9, within level N16, which contains most of the site's carpological material (see Table 8). Only one remain of Polygonaceae was identified across the entire assemblage, along with six remains of Boraginaceae. Pistacia is the second most represented taxon, with nine remains in level N18, following *Celtis australis*, which has twenty remains in level N14. A total of 44 carpological remains, all taxa combined, were recovered from the four archaeological levels. The assemblage from S9 in level N16 includes 817 remains, composed predominantly (96.94%) of *Celtis australis*, and to a lesser extent of *Pistacia* (3.05%).

Table 7: *Table showing the number of carpological remains per taxon for levels N12, N14, 16 and N18 at the Roca dels Bous site*

Category	**N12**	**N14**	**N16**	**N18**	**Total**
Celtis australis	2	20	0	2	24
Boraginaceae (Echium)	4	0	2	0	6
Polygonaceae	1	0	0	0	1
Pistacia	0	1	0	9	10
Undetermined	0	3	0	0	3
Total	7	24	2	11	**44**

Table 8: *Number of Celtis australis and Pistacia remains in zone S9 of level N16 of Roca dels Bous*

Taxon	**S9**
Celtis australis	792
Pistacia sp.	25
Total	**817**

Table 9: *Number of Celtis australis (and Pistacia for S9) remains per colour category for the S9 assemblage and levels N12, N14, N16 and N18 of Roca dels Bous*

Category	**N12-N18**	**S9 (N16)**
0: Not burned	2	7
1 : Lightly burned	1	61
2: Burned	0	173
3: Carbonised	3	565
4: Calcined	18	10
Total	24	816

The number of *Celtis australis* remains is minimal in the various levels compared to the high concentration observed in area S9. The combustion conditions also differ between contexts. Levels N12 to N18 exhibit most of calcined seeds (75%), whereas carbonised seeds are the most abundant in area S9 (68.24%). Burnt seeds are the second most represented category in this area (21.20%). A clear difference in the state of carbonisation is therefore observable in area S9 compared to the other levels (see Table 9).

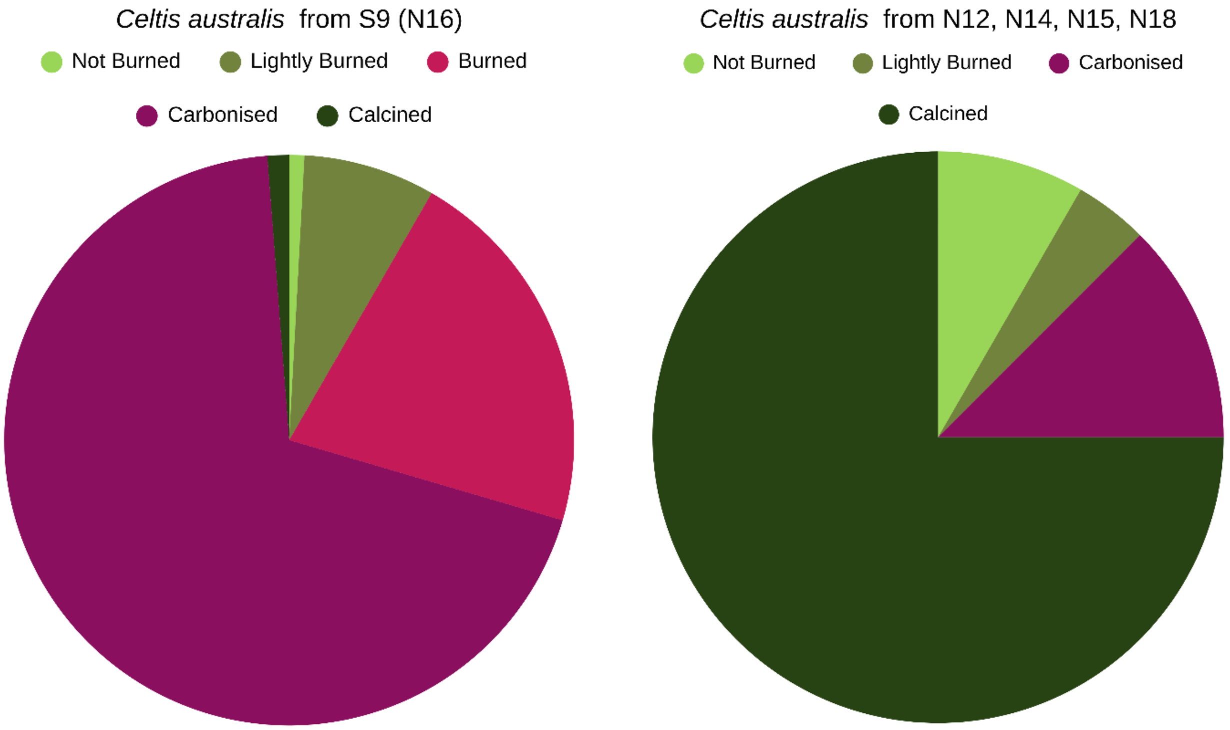


Figure 13: *Graph showing the distribution of Celtis australis seeds (and Pistacia sp. seeds for set S9) from the Roca dels Bous site, according to their colour and level of combustion. ©Lachman 2025*

6.2.1. *Celtis australis*

Celtis australis dominates the carpological assemblage of the Roca dels Bous site, being present in layer N14 with 20 remains, but primarily in sector S9 of layer N16, with 792 remains (96.94%).

Figure 14: *Photos taken with HIROX of four Celtis australis seeds, representing four categories: 0) Unburnt, 2) Burnt, 3) Charred, 4) Calcined. Category 1) Slightly burnt is not included, as its color shade is difficult to distinguish from category 2 in images. The scale is 1 mm. ©Lachman 2025*

6.2.2. Pistacia sp.

The total number of *Pistacia sp.* remains across the various archaeological layers, including S9, amounts to 35, representing 4% of the total number of remains (858). The vast majority of Pistacia sp. remains were recovered from area S9, accounting for 25 remains.

Figure 15: *Photos of Pistacia sp. taken at HIROX. Scale: 1 mm ©Lachman 2025*

6.2.3. Boraginaceae and Polygonaceae

A total of six Boraginaceae fragments and a single Polygonaceae fragment were recorded, representing 0.69% and 0.11% of the assemblage, respectively. These remains were found in levels N12 and N16, but not in area S9 of level N16.

6.3. Phytoliths

The analysis of phytolith thin sections did not yield enough identifiable phytoliths to be considered in this archaeobotanical study. It is commonly accepted that a minimum of 200 phytoliths per thin section is required to achieve statistical significance (Barboni et al. 1999; Katz et al. 2010; Zurro et al. 2016), and this lower threshold was far from being reached, with a total of only three phytoliths observed across ten thin sections. The slides contained various inorganic elements and fibres that were not identified.

7. Discussion

7.1. Botanical significance of the taxonomic assemblage

The charcoal assemblage from Roca dels Bous revealed the presence of four taxa, including both coniferous and broadleaved species. The following section outlines the ecological and biogeographic characteristics of the main taxa identified.

Pinus sylvestris (Pinaceae) is one of the most widely distributed conifers worldwide, thriving across a broad range of environments, soils, and climates (Mason & Alía 2000; Pyhäjärvi et al. 2008). This species can establish in habitats generally unsuitable for most others, owing to its high tolerance of stress, low temperatures, and variable soil pH. However, Scots pine is less competitive in favourable environments, where other species dominate (Mason &Alía 2000; Kelly & Connolly 2000; Pyhäjärvi et al. 2008; Tóth et al. 2017) (see Figure 5 for its current distribution in Europe).

The genus *Juniperus* comprises 68 species and 36 subspecies (or varieties). *Juniperus communis* is the only species occurring in both hemispheres and has one of the widest distributions among gymnosperms across the Holarctic (García et al. 1999; Adams and Pandey 2003) (see Figure 16 below for its distribution in Europe). Under harsh climatic conditions, such as extremely low winter temperatures or increasing aridity, *Juniperus* populations may experience reproductive decline, which can resume when conditions improve, due to the species' longevity (Thomas et al. 2007).

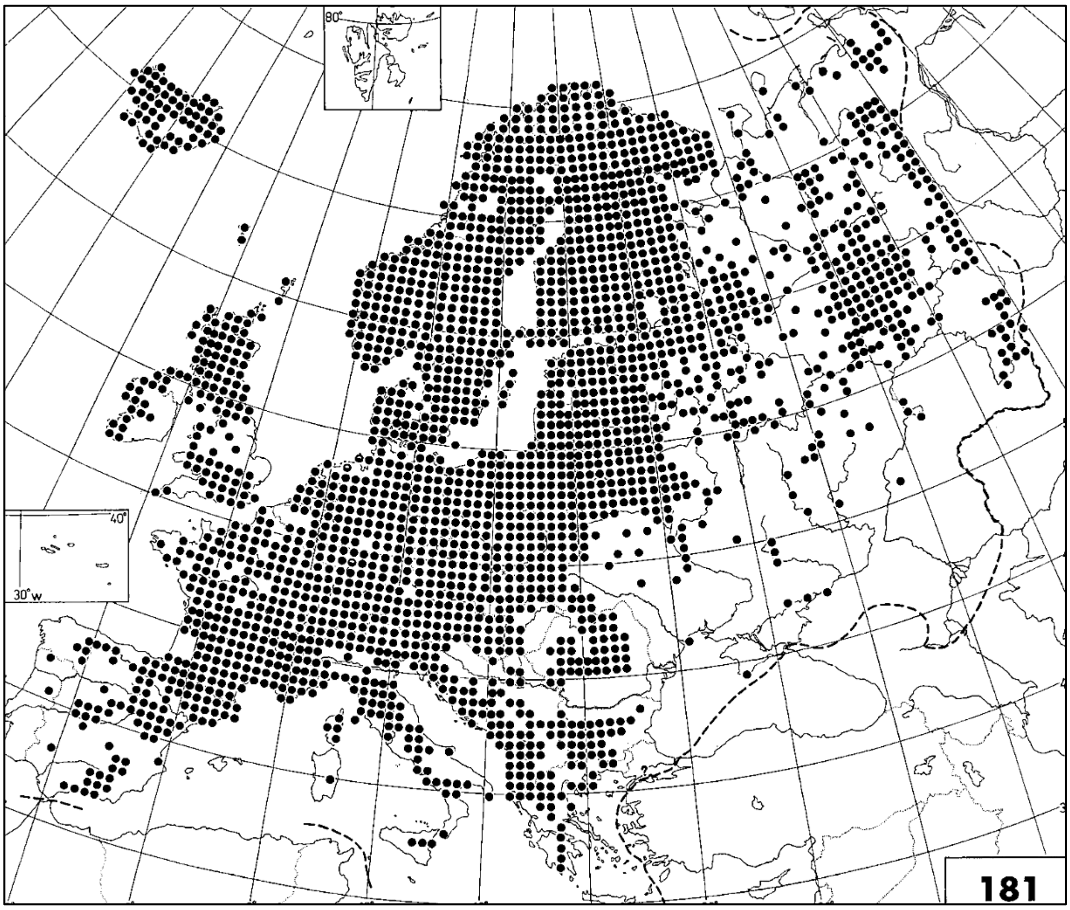


Figure 16: *Map showing the current distribution of Juniperus communis in Europe, Thomas et al., 2007, p. 1409*

Quercus (Fagaceae) includes heteroxylous woods within the angiosperm clade. Because of the limitations of anthracological identification, species-level attribution is not possible; it is standard practice to distinguish between deciduous and evergreen oaks. The genus includes more than 400 species distributed across North America, Europe, Asia, and Mexico. In the Iberian Peninsula, deciduous oak forests belong to the *Querco-Fagetea* class. Their extent was greatly reduced after the Last Glacial Maximum, persisting mainly in southern and coastal refugia (Brewer et al. 2002; Díaz-Maroto & Vila-Lameiro 2007; Čarni et al. 2009).

Buxus sempervirens (Buxaceae) belongs to a family comprising five genera (*Buxus, Notobuxus, Sarcococca, Pachysandra,* and *Styloceras*) and approximately 130 species distributed across all continents except Australia (Von Balthazar and Endress 2002). Within the Iberian Peninsula, two species occur: *B. sempervirens L.*, which extends from the Cantabrian region and eastern Iberia to the northeast (with a very limited presence in Portugal), and *B. balearica*, which thrives in warmer, more humid areas such as the Baetic region, the Balearic Islands, Sardinia, northern Morocco, and southern Turkey. Both species grow mainly on calcareous soils but may also occur on volcanic tuffs or ophiolitic substrates. Their divergence likely took place in the Mediterranean basin during the Miocene as an adaptive response to increasing aridity (Von Balthazar and Endress 2002; Rosselló et al. 2007; Di Domenico et al. 2012; Carvalho et al. 2016).

Buxus sempervirens L. currently extends across the western Mediterranean basin, typically as a shrub not exceeding 5 m in height. Both species are monoecious, bearing inflorescences with one female flower surrounded by four male flowers. Pollination occurs via both insects and wind. Fruits consist of dehiscent capsules with small black seeds dispersed by gravity upon capsule opening. Buxus leaves exhibit remarkable adaptations to low light and freezing conditions, enabling persistence in cold and shaded habitats (Von Balthazar and Endress 2002; Di Domenico et al. 2012; Carvalho et al. 2016).

Celtis (Cannabaceae) comprises 66 species distributed across the Americas, Asia, Europe, and Africa. In the Mediterranean basin, *C. australis, C. occidentalis, C. glabrata*, and *C. tournefortii* are present, with *C. australis* being the only species occurring exclusively in the Iberian Peninsula. Celtis is a heliophilous genus that avoids cold and frost, and today it is mainly cultivated as an ornamental tree in public spaces. In natural environments, it commonly grows with *Quercus halepensis*, *Fraxinus ornus*, *Corylus avellana,* as well as evergreen oaks and *Pinus halepensis*. It is also found in riparian forests alongside *Salix*, *Populus*, and *Ulmus* (Allué et al. 2015; Martínez-Varea et al. 2023).

Celtis australis occupies a particular place in the Roca dels Bous assemblage, being especially abundant in unit S9 (N16). Understanding its presence and significance is key to reconstructing site dynamics and resource management strategies. The genus is well attested in association with Neanderthal occupations at numerous Middle Pleistocene sites across Eurasia. *Celtis* appears as early as the Lower Pleistocene at Dmanisi in Georgia (*Celtis cf. tournefortii*) and at Zhoukoudian in China (*Celtis cf. barbouri*) (Chaney, 1935). During the Middle Pleistocene, it is recorded at Vallonet and Caune de l'Arago in France, and at Achalkalakai in Georgia, among others (Allué et al. 2015).

The rigid endocarp of *Celtis* contains the seed and exhibits four prominent ridges originating at the apex: two of them encircle the endocarp, while the two others, situated opposite each other, are located on its upper half. The inter-ridge spaces are covered by a markedly reticulated surface. Although taxonomic differentiation within the genus can be challenging, it may rely on the density of the reticulate network and the more or less pronounced relief of the ridges. The fruit is an elliptical drupe containing a stony endocarp, characterized by its four ridges and a surface that is both reticulate and rugulose (Cowan et al. 1997; Allué et al. 2015; Martínez-Varea et al. 2023).

The genus *Pistacia* (Anacardiaceae) comprises evergreen or deciduous shrubs and small trees, many of which produce resin. The family includes about 70 genera and 600 species. *Pistacia* species are dioecious and wind-pollinated. Seven species occur across the Mediterranean and Central Asia: *P. atlantica, P. integerrima, P. khinjuk, P. palaestina, P. lentiscus, P. terebinthus,* and *P. vera*, the latter being the only one cultivated for commercial purposes. Other species have been traditionally exploited for their resin and fruits, both as fuel and for medicinal use (Al-Saghir et al. 2012; Bozorgi et al. 2013; Koca-Çalışkan 2024; Kole 2011; Loidi 2017; Rodríguez-Sánchez et al. 2010). *Pistacia lentiscus* has been widely documented at Mesolithic and Neolithic sites in northeastern Spain, where its fruits were collected. However, evidence for *Pistacia* during earlier periods such as the Middle Paleolithic remains scarce. At Roca dels Bous, 35 charred *Pistacia* remains were identified—a significant quantity given the overall low diversity of carpological material. Further analysis of stratigraphic disturbances will be required to assess whether these remains are genuinely ancient (Antolín and Jacomet 2015; Carrión et al., n.d.; López-Dóriga 2015).

7.2. Paleoenvironment during the MIS 3 in Northern Iberia

In order to better understand the ecological significance of the taxa identified at Roca dels Bous, comparisons were made with anthracological data from other sites in the NE Iberia, North and East Iberia. The sites are, El Castillo (Cabrera 1999), Cueva del Conde (Uzquiano et al. 2008), Cueva de Cobrante (Uzquiano 2009), El Salt (Vidal-Matutano et al. 2017), Cova Gran (Allué et al. 2018) and Abric Romaní (Allué et al. 2017). These sites cover a similar chronology with

Roca dels Bous in a similar geographical and geological setting and the comparison allows for the evaluation of local specificities versus broader regional patterns in woodland composition and human wood-use strategies.

The comparison of the different sites highlights the importance of the *Pinus sylvestris* type in the majority of them, a trend also observed at Roca dels Bous. A notable presence of *Juniperus sp*. is recorded at Roca dels Bous, whereas this taxon is only very weakly represented at El Salt, nearly absent at Cueva de Cobrante, and completely absent at El Castillo, Cova Gran de Santa Linya and Abric Romani. In contrast*, Juniperus sp.* is the dominant taxon in Level 10 of Cueva del Conde. Its position as the second most represented taxon at Roca dels Bous therefore appears relatively unique.

Another taxonomic group that proves to be prevalent at several of the studied sites is the genus *Betula*, although it was not identified at Roca dels Bous. The taxa *Quercus sp., Quercus evergreen,* and *Quercus deciduous* are generally poorly represented across most assemblages, yet their distribution remains relatively consistent across the sites where they do occur.

Finally, a number of other taxa appear sporadically at certain sites, in very low quantities. This scarcity may reflect local specificities, particular wood exploitation strategies, or environmental conditions specific to a given location and time.

It is therefore evident that coniferous forests were well established in the northeastern Iberian Peninsula, persisting from MIS 4 through the oscillations of MIS 3. Despite short-term fluctuations and episodes of increased humidity, pine remained an abundant resource, consistently selected by Neanderthal groups for fuel. The widespread availability of this resource facilitated the establishment of campsites at different locations, including Roca dels Bous, and enabled repeated occupation without the risk of resource scarcity, thereby supporting greater mobility. Only a limited number of charcoal fragments have been recovered from the studied sites, a fact directly related to their relatively poor state of preservation and comparable to other sites dated to the same period. Nevertheless, this limited assemblage is sufficient to reveal a consistent trend observable across several sites in the region. This point will be further developed in the following section.

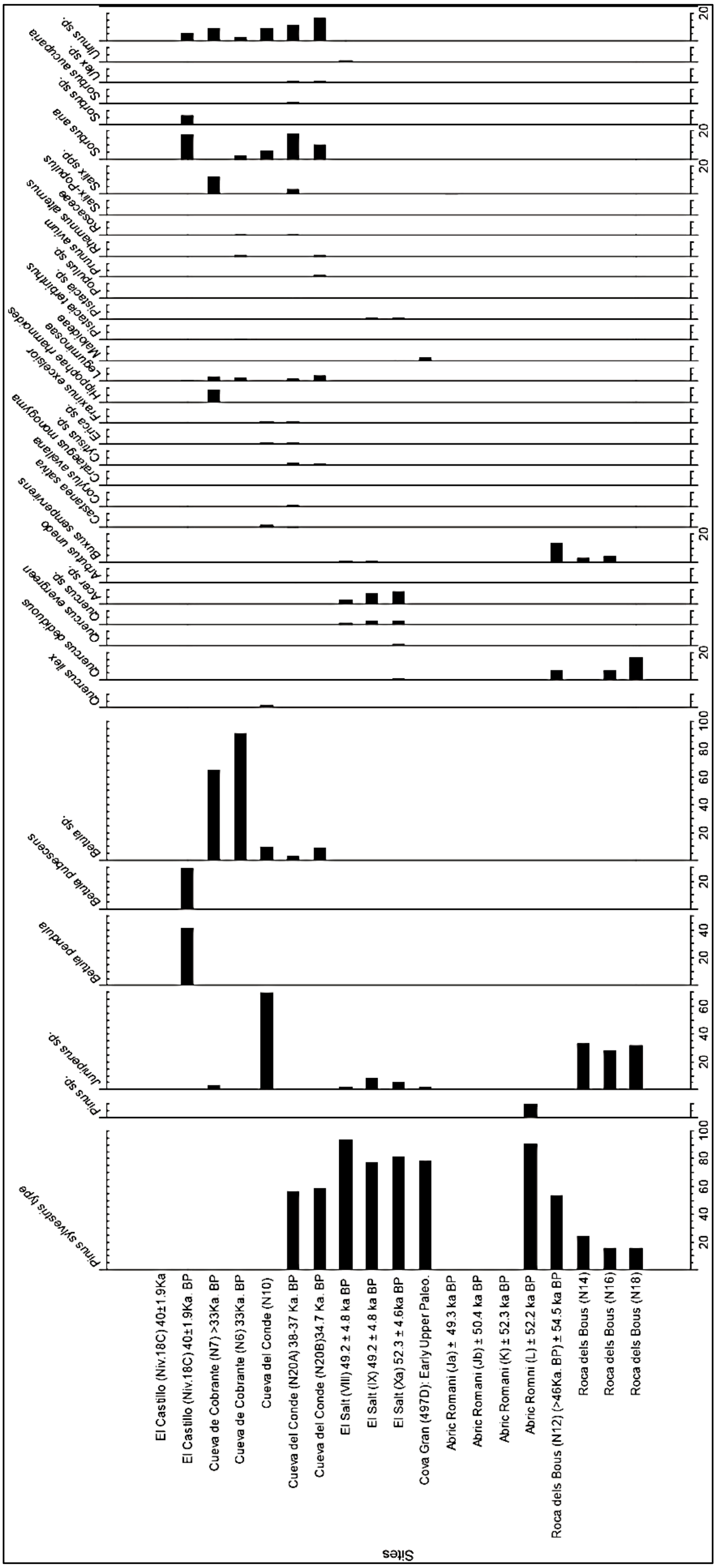


Figure 17: *Graph comparing de sites of El Castillo (Cabrera 1999), Cueva del Conde (Uzquiano et al. 2008), Cueva de Cobrante (Uzquiano 2009) and El Salt (Vidal-Matutano et al. 2017), with Roca dels Bous. © Lachman*

7.3. Formation process of the archaeobotanical record

Numerous debates persist within the scientific community regarding the definition and scope of taphonomic studies. The term “taphonomy” was first introduced by Efremov in 1940, deriving from the Greek words *taphos* (burial) and *nomos* (law), to mean the “laws of burial”. In its original sense, taphonomy encompasses the processes that occur after the death of an organism until its fossilization. However, in archaeological contexts, the definition differs: when applied to charcoal, it concerns the processes that act upon the material before and during combustion, as well as those related to its burial. Taphonomy, in archaeological contexts, therefore includes the range of cultural selection choices and sequences of actions that have impacted the material under study (Efremov 1940 ; Allué 2009; Lyman 2010; Théry-Parisot et al. 2010; Madella & Lancelotti 2012).

The specificity of this analysis lies in the study of three distinct categories of botanical remains recovered from the archaeological record. The combined examination of charcoal, seeds and fruits, together with phytoliths, provides a more comprehensive understanding of the occupational and environmental history of Roca dels Bous than a single-proxy approach. Each of these proxies results from different depositional processes, is subject to distinct pathways of alteration, and therefore serves as an indicator of targeted practices and environmental trends at local or broader regional scales.

Accordingly, Neanderthal occupation at Roca dels Bous is examined through both macroscopic and microscopic perspectives. While the joint study of pollen and phytoliths is relatively common, the integration of anthracological, carpological, and phytolith analyses is innovative and essential for advancing archaeobotanical and paleoenvironmental interpretations of past practices. In the following section, we will therefore outline the specific characteristics of each proxy, with particular attention to their depositional processes and the potential post-depositional alterations affecting the studied materials.

7.3.1. Charcoal assemblage formation process

Studies dedicated to the taphonomic processes affecting charcoal examine, among other aspects, the cellular deformations that may occur during combustion or through post-depositional processes. It is important to note that from the perspective of wood anatomy, it is currently not possible to distinguish anthropogenic from natural sources of combustion, as the resulting alterations depend on the condition of the wood and the combustion style (Allué 2009). Although not the only source of wood degradation, combustion causes several types of alterations, such as fragmentation, fissuring, shrinkage, vitrification, and changes in cellular integrity and morphology. These aspects will be reviewed in the following section and discussed in relation to the integrity of the charcoal remains from Roca dels Bous.

Roca dels Bous, we study charcoal remains originating from hearths as well as from other deposits dispersed across several archaeological levels ranging from N12 to N18. These are identified as palimpsests, reflecting multiple occupations of varying duration accumulated over a long period. However, the current lack of radiocarbon dates for each structure precludes any precise assessment of occupation duration or whether the same group revisited the site. It is mostly the case of Paleolithic sites, in which a very limited number of charcoals are found and without very clear dispersion patterns allowing for a scenario between “last fire” and “synthetic deposits” to be considered (Chabal 1992).

The study of archaeological charcoal assemblages begins, as is the case in this work, with the taxonomic identification of charcoal fragments of varying sizes. Counting the number of fragments identified per taxon then allows the establishment of relative proportions, which in turn form the basis for interpreting key environmental characteristics of the site. This is the approach taken in the results of section 6. According to Lucie Chabal, a minimum of 250 to 400 charcoal fragments per archaeological level is required to approach environmental representativeness. This criterion is not fully met in the present study, which totals 588 charcoal fragments across four archaeological levels. This minimum should be adjusted according to the site chronology; a site such as Roca dels Bous, dated to MIS 3, cannot be expected to yield the same amount of material as a medieval domestic site. Indeed as many works have now demonstrated 100 charcoal fragments for Paleolithic sites is sufficient to make inferences about landscape composition and selection patterns (Allué et al. 2017, 2018, 2020). Nevertheless, it is essential to pause and reflect on questions regarding the role and objectivity of charcoal fragments in such studies.

Do all taxa fragment at the same rate? What are the factors driving such fragmentation? Should fragments of different sizes be counted equally? These questions are crucial, as they raise methodological issues that may significantly affect the statistical validity of the results.

Fragmentation, mass loss, and cracks

Fragmentation occurs during combustion, post-depositional processes, and sampling. Statistical studies have investigated fragmentation differences between charcoals from different taxa. When total charcoal mass is known, it is possible to determine relative quantities of small (2–4 mm) and large fragments (>4 mm); however, this provides no information on actual mass loss. A taxon that undergoes limited mass loss may yield more fragments, and vice versa. Mass loss and fragmentation must therefore be considered together: they occur simultaneously but represent distinct phenomena (Chabal 1992).

Experimental procedures on modern wood samples have attempted to determine mass loss indices for selected taxa, but results vary between authors. These indices likely depend more on combustion conditions than on inter-taxonomic differences (Chabal 1992; Chrzazvez et al. 2014). Chrzazvez (2014) indicates that fragmentation intensity is related to wood porosity: taxa with porous zones are more prone to fragmentation, whereas homoxylous or diffuse-porous woods produce fewer fragments. The anatomical composition of wood directly influences fragmentation and fragment size. For instance, *Quercus sp*. may be more vulnerable due to its multiseriate rays, which represent structurally weak zones. These observations, however, remain to be confirmed and are relatively unique in the literature (Knight 2025).

The lack of consensus regarding both fragmentation rates and mass loss indices calls for caution when interpreting anthracological diagrams. The proportions they present should not be viewed as a direct reflection of absolute values present in past environments. Additionally, the number of charcoal fragments recorded is affected by the sampling method: sieving and flotation may increase the fragmentation of charcoal and damage its integrity in case of highly fragile materials such as it is often the case for Paleolithic sites. Whereas hand-picking contains its own risks, it limits post-sampling breakages. Interpretations are therefore multiple, and different analytical pathways may lead to similar conclusions (Chabal 1992; Lancelotti et al. 2010; Chrzazvez et al. 2014; Paradis-Grenouillet & Dufraisse, 2018: Allué & Mas 2020).

Beyond fragmentation, charcoal often displays alterations visible under the microscope, such as cracks. These are mostly observable in transverse sections and can be explained by physical phenomena, with some taxa being more affected than others. Cracks typically form at the cellular level during the early stages of combustion, as a result of gas and water evaporation within the wood. They are more frequently observed in the combustion of green wood, which contains a higher water content that is expelled more abruptly. However, the presence of cracks is not systematically linked to the burning of green wood and may also result from other factors (Allué 2009; Théry-Parisot & Henry 2012; Chrzazvez et al. 2014).

The site of Roca dels Bous has yielded some fragments of heteroxylous wood showing large cracks, mainly observable in the transverse plane. In most cases, these cracks did not hinder taxonomic identification (see Figure 19 below).

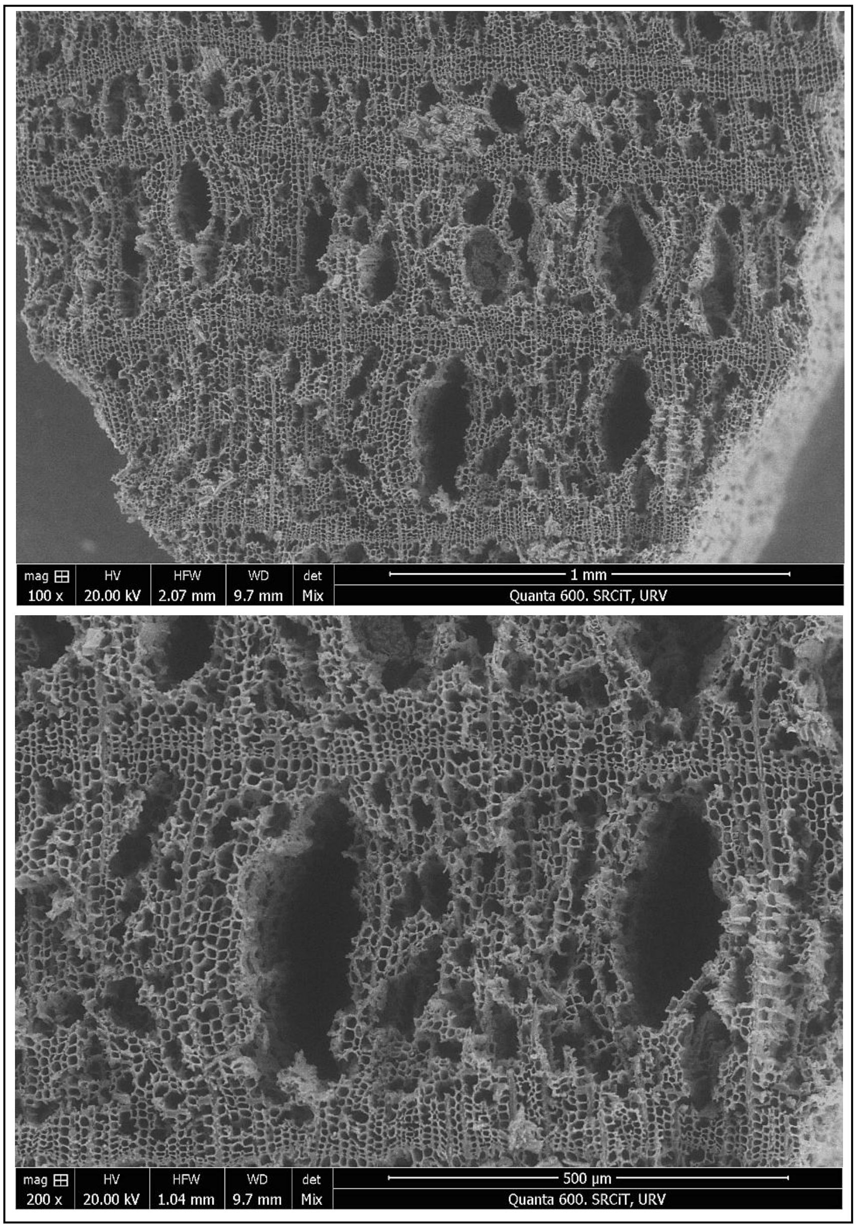


Figure 19: *Environmental Scanning Electron Microscope (ESEM) images of Juniperus sp. showing degradation in the form of large cracks. Magnification ×100 for the upper image and ×200 for the lower image. © Lachman 2025*

Shrinkage and vitrification

It is well documented that the carbonization process affects wood volume, which undergoes shrinkage It is generally accepted that approximately two-thirds of the original mass is lost between 200°C and 400°C. The maximum volume reduction can reach up to 80% of the original mass. Shrinkage does not necessarily imply systematic changes to the cellular structure. In the context of this anthracological study of Roca dels Bous, the mass of charcoal fragments was not recorded, and it is therefore not possible to estimate the shrinkage index. Such measurements, however, could prove useful when combined with studies on combustion features or dendro-anthracology, which were beyond the scope of this research (Slocum 1978; Cutter 1980; Paradis-Grenouillet & Dufraisse 2018).

An experimental archaeology project is currently underway, focusing on the question of combustion-related variation. This project, based in the northeastern Iberian Peninsula, seeks to better understand combustion dynamics across several sites dated to the same period in the region.

Several charcoal fragments from Roca dels Bous, recovered from different stratigraphic levels, exhibited vitrified areas. These vitrified portions are rare and do not cover the entire fragment. It is often mistakenly assumed that vitrification results from extremely high combustion temperatures, based on analogies with metallurgy or ceramic production. However, numerous studies have shown that increasing temperature does not necessarily lead to vitrification (Courty et al. 2020).

It is important to distinguish between vitrification in archaeological charcoal and vitrification in coal petrology, where lignin transforms into vitrinite (Prior & Alvin 1983; Thinon 1992; Kaelin et al. 2006; McParland et al. 2010). In archaeology, vitrification is relatively frequent, yet its mechanism remains unclear. Hypotheses include the combustion of green wood, re-burning, rapid cooling, or the presence of siliceous compounds, though the latter has been rejected due to the high melting point of silica (>1720°C) (Thy et al. 1999; McParland et al. 2010). While laboratory conditions have failed to reproduce the phenomenon, field experiments have generated vitrified charcoal in resinous Pinaceae (McParland et al. 2010). Vitrification therefore likely results from a combination of physical and chemical factors acting before, during, or after combustion (Lingens 2005; Braadbaart & Poole 2008), and its precise causes remain unresolved. Consequently, the presence of vitrified charcoal at Roca dels Bous cannot be attributed to a single process but can at best be interpreted as the result of multiple physico-chemical factors affecting the wood before, during, and after combustion.

Another type of alteration, absent from the Roca dels Bous assemblage but of particular relevance, is microbial or biological activity in wood, including fungi, bacteria, insects, and nematodes, which can modify its cellular structure. Such traces provide insights into the condition of the wood prior to carbonization. For instance, insect damage indicates infestation of green wood, while bacterial activity in moist or dry contexts reflects its state immediately before or after burning (Gilbertson 1984; Rayner & Boddy 1988; Eriksson 1990; Schwarze 2007; Moskal-del Hoyo et al. 2010). Although such observation were not systematically recorded at Roca dels Bous, some charcoal fragments showed these alterations.

Anthropic factors: from the accumulation to the study of the material

The role of human agency in shaping the condition of wood and charcoal must be fully integrated into the *chaîne opératoire* of taphonomic processes affecting the preservation of archaeological charcoal. Numerous authors have long discussed this impact (Salisbury & Jane 1940; Godwin & Tansley 1941).

As outlined at the beginning of this section, the fragmentation of archaeological material can occur during sampling or analysis, and these processes are integral components of the taphonomic framework affecting the artefact. Fragmentation related to sampling is a well-understood and observable phenomenon, and generally not debated, except in discussions concerning the development of gentler sampling methodologies (Brossier et al. 2020). In contrast, processes related to wood selection or the structuring of specific combustion features can only be hypothesized, despite the significant body of research on fire-use strategies.

Théry-Parisot (2010) highlights several key considerations in the reconstruction of past combustion dynamics. Notably, she argues that assuming ancient populations, distant from us both temporally and culturally, perceived tree species in the same way we do today introduces a modern interpretive bias. Ethnobotanical studies have shown that many human groups do not classify plant species according to modern taxonomic categories; rather, they group plants based on shared properties or uses, sometimes associating taxonomically distinct species as a single utilitarian category (Solari 1992; Alix 1998; Théry-Parisot 2001; Asouti & Austin 2005; Henry 2009).

It is therefore problematic to project our own species distinctions onto potential selection preferences in the past. Moreover, the formation of these functional groups is not only culturally specific but also situational, varying with the availability and condition of the wood. The selection of wood for cooking fires, for instance, may have shifted based on whether certain species were available, dry, of sufficient size, etc. Multiple selection parameters may be involved—parameters that remain archaeologically invisible in anthracological records (Nicholson 1981; Smart & Hoffman 1988; Garcia 1992; Joly et al. 2009).

Dendro-anthracological techniques provide a much broader range of information on the life history of wood, both before and after felling. Advanced analyses can detect features such as stress indicators, the formation of double or false rings, among others. However, such analyses were not undertaken in this study due to the very small size of the charcoal fragments, which does not allow for this type of observation and makes its application particularly challenging in contexts of such antiquity (Moskal-del Hoyo et al. 2010; Théry-Parisot et al. 2010).

7.3.2. Seed assemblage formation process

In this section, we focus exclusively on the depositional and post-depositional processes affecting *Celtis*, as it is both the most abundant taxon at Roca dels Bous and one of the best documented in Neanderthal occupation contexts at Paleolithic sites.

Macroscopic plant remains are extremely rare at Lower Pleistocene sites but become more frequent in the Middle and Upper Pleistocene. These remains are mostly charred or (bio)mineralised. The latter type of preservation requires very specific conditions and is therefore less common. At Roca dels Bous, both preservation modes are present. Charred material is explained by the documented presence of hearths and associated charcoal remains, while mineralisation may be attributed to the composition of the *Celtis australis* endocarp itself. This endocarp is rich in calcium carbonate and minerals, which allows it to mineralise without the intervention of external agents, unlike many other seeds (Cowan et al. 1997).

The distribution of *Celtis* fluctuated during the Middle Pleistocene, depending on glacial and interglacial phases, expanding into northern Europe during warmer periods and retracting into the Iberian Peninsula during cooling phases (Martínez-Varea et al. 2023).

If the presence of *Celtis* in archaeological layers is accepted as being contemporaneous with the formation of those layers, rather than resulting from post-depositional vertical disturbances, then it is worth examining the mechanisms by which *Celtis* seeds were deposited. In nature, birds disperse *Celtis* seeds and may therefore act as depositional agents. If a *Celtis* tree was located near the site, seeds may also have been deposited by gravity or wind. Finally, humans could have transported the seeds themselves (Allué et al. 2015; Martínez-Varea et al. 2023). Given that *Celtis* seeds are systematically associated with archaeological occupations and other occupation-related remains, not only at Roca dels Bous but also at other sites, anthropogenic accumulation is the most likely scenario.

To quantify the potential nutritional contribution of *Celtis australis* fruits, an experimental archaeology protocol was developed by the team of Martínez-Varea et al. (2023). In this study, manual collection of 2 kg of fruit required 3 hours. The fruit, which is bitter-sweet, ripens in summer and can remain on the tree until winter, making it attractive to humans. The stone is edible and can yield oil. Various uses of *Celtis* fruits and wood are documented throughout history. Notably, *Celtis* wood is not very often identified archaeologically, whether associated with seeds or not. This may suggest intentional collection of the fruit alone, but also highlights the difficulty of wood identification, as *Celtis* is often confused with and difficult to distinguish from *Ulmus spp*. (Demır et al. 2002; Badoni et al. 2010 ; Martínez-Varea et al. 2023).

Without drawing overly conclusive interpretations, it is possible that *Celtis australis* seeds were brought to the site for consumption by a Neanderthal group that remained in the region long enough to gather such a quantity. Most of the seeds from unit S9 are charred, whereas those from other levels are predominantly calcined or mineralised. The function of the S9 area remains open to interpretation; however, its use appears to be specifically associated with *Celtis* seeds, which underwent a different type of processing compared to those found elsewhere on the site. The study of spatial distribution is still ongoing and was therefore not available at the time of writing this research. Once completed, it will provide valuable insights into the use of Sector S9, as well as into the occupation areas and activity zones within the rockshelter.

The recording of the different seed colours of *Celtis* was carried out with the aim of distinguishing categories useful for analytical purposes. These colour-based categories could be employed in an experimental archaeobotanical study. Such a study could involve the controlled heating of *Celtis australis* fruits and seeds alone at various temperatures, under both oxidizing and reducing atmospheres. The outcomes of these experiments may provide insights into the uses of *Celtis australis* at Roca dels Bous, as well as at the many other sites in northeastern Iberia where this taxon is present.

7.3.3. Phytolith assemblage formation process

Phytoliths are microscopic opaline bodies ($SiO_2 \cdot nH_2O$), particularly abundant in the Poaceae family. They are composed of hydrated silica, absorbed by plant roots as monosilicic acid and deposited in intercellular spaces during transpiration (Piperno 2006; Cabanes & Shahack-Gross 2015; Jenkins 2009). Their production is controlled by both genetic and environmental mechanisms. Some cells are genetically programmed to deposit silica depending on their tissue function, while others become silicified due to high evapotranspiration rates (Madella & Lancelotti 2012). Phytoliths, composed of porous opal-A, may occasionally form incompletely, especially if the plant dies prematurely, resulting in morphologies that can be mistaken for taphonomic damage (Madella & Lancelotti 2012).

Due to their resistance and taxonomic significance, phytoliths are excellent palaeoecological indicators, enabling reconstruction of past vegetation and the study of prehistoric plant exploitation practices (Albert et al. 2006; Jenkins 2009; Cabanes et al. 2010; Madella & Lancelotti 2012).

Taphonomic Vulnerability and Methodological Considerations

Contrary to earlier assumptions, opaline phytoliths are relatively unstable in soils and sediments. They are subject to complex taphonomic processes including necrolysis, biostratinomy, and fossil diagenesis (Jenkins 2009; Madella & Lancelotti 2012; Cabanes & Shahack-Gross 2015). Although the combination of FTIR spectroscopy and phytolith analysis represents a promising approach for the study of combustion structures, methodological gaps persist in sampling, counting protocols, and interpretative criteria. Phytolith taphonomy remains understudied despite its significant impact on archaeological interpretation (Jenkins 2009; Rodríguez-Cintas & Cabanes 2017).

Counting and sampling strategies are closely tied to the question of representativity. A common benchmark is the identification of at least 250 phytoliths per sample. However, few publications provide a justification for this threshold. Zurro (2018) conducted experiments to assess whether exceeding 250 counted phytoliths significantly altered assemblage composition. Results showed stabilization between 200 and 350 counted phytoliths.

Deposition Constraints and Early Taphonomic Processes

The taphonomic process begins with the death of the plant and the onset of necrolysis. As organic matter decomposes, phytoliths are released into the environment and become exposed to potential mechanical transport by wind or water, something that does not affect phytoliths still embedded in living tissue. This transport can impact preservation: fragile parts of the phytolith, such as the narrow ends of bilobate morphotypes, may break, and entire bodies may become damaged. Anatomical connections between phytoliths are rarely preserved. These alterations can already affect morphotype identification.

Phytoliths, being heavier than pollen, are generally not transported over long distances. However, in desert environments with strong wind regimes or areas subject to heavy rainfall, such transport is possible (Albert et al. 2006; Jenkins 2009; Madella & Lancelotti 2012).

Differential Preservation and Post-Depositional Alteration

Before even considering natural post-depositional factors, it is crucial to understand that phytolith preservation varies between plant species. Silicification intensity and the diversity of produced morphotypes differ greatly. Some morphotypes are produced in large quantities but are poorly preserved, while others are rare but more stable in sediments. In addition, plant parts like leaves or grasses, more frequently consumed by herbivores, may be underrepresented in assemblages (Albert et al. 2006; Tsartsidou et al. 2007).

Once phytoliths enter the sediment, a series of post-depositional processes may affect their integrity. These processes are closely tied to soil chemistry. Phytoliths are known to dissolve under alkaline conditions ($pH > 9$), particularly in water-rich environments that sustain high pH over time. This is often the case in karstic settings, where the presence of limestone leads to alkaline conditions (Albert et al. 2006; Tsartsidou et al. 2007; Jenkins 2009).

Dissolution Processes and FTIR Analysis

In waterlogged environments, phytoliths are especially susceptible to post-depositional dissolution. Once incorporated into the sediment, they may be affected by pedogenesis and fossil diagenesis. These physical, chemical, and biological processes transform soil composition and can alter the phytoliths it contains.

The vertical translocation of phytoliths through soil horizons by water infiltration remains debated. While studies yield contrasting results, Fishkis et al. (2010) demonstrated that vertical movement of up to 4 cm per year is possible via bioturbation and water percolation.

Phytoliths play a significant role in the soil silica cycle: their contribution to the dissolved silica flux is estimated to be three times that of other mineral compounds. Interestingly, dissolution rates appear to be independent of phytolith morphotype size. Studies suggest that phytoliths can undergo multiple erosion and alteration cycles, such as in loess deposits. The question of which morphotypes are more resistant to degradation remains unresolved. Some researchers have proposed that aluminum content in phytolith silica increases stability, but this hypothesis remains unconfirmed (Jenkins 2009; Osterrieth et al. 2009; Madella & Lancelotti 2012; Cabanes and Shahack-Gross 2015).

A more reliable predictor of phytolith stability appears to be their anatomical origin. Phytoliths from deciduous tree leaves are 10 to 15 times more soluble than those produced by grasses. Preservation is not necessarily age-dependent but is influenced by burial conditions, depth, and water accessibility. Rapid and deep burial significantly enhances phytolith preservation by isolating them from surface disturbances (Albert et al. 2006; Osterrieth et al. 2009; Cornelis et al. 2010; Cabanes & Shahack-Gross 2015).

Studying poorly preserved assemblages may lead to biased palaeoecological interpretations. Bulliform morphotypes, for instance, may be overrepresented due to their greater stability, potentially leading to inaccurate reconstructions of water availability or palaeoclimatic conditions. FTIR spectroscopy is a valuable tool for assessing sediment conditions affecting phytolith preservation. For example, the detection of calcite in association with water activity may explain reduced phytolith integrity (Albert et al. 2006).

Anthropic Factors in Phytolith Deposition and Preservation

Human activity plays a major role in phytolith deposition and preservation. The presence and nature of anthropogenic practices, such as plant use for food, construction, or fuel affect the accumulation of phytolith-rich plant residues. These residues are then subject to the same degradation processes previously described.

However, human behaviour also influences phytolith spatial distribution. Activities such as cleaning, storage, or the creation of designated areas for plant processing can result in concentrated phytolith deposits in places where natural accumulation would not occur (Madella & Lancelotti 2012). Once integrated into the sediment, phytoliths become vulnerable to trampling or thermal alteration from domestic fires.

Understanding these human-related factors is essential for reconstructing site formation processes. Integrating taphonomic phenomena into interpretations of occupation sequences and sediment use enhances our understanding of human activity. This becomes especially important at sites where occupation layers are not clearly stratified, as is the case at Roca dels Bous (Henry 2012; Madella & Lancelotti 2012).

The phytoliths analyzed derive from a single hearth and from the zone of thermal impact, rather than from the ashes, which may account for their absence. Soil alteration caused by combustion has a significant effect on phytolith preservation, which, in combination with soil pH, may have contributed to the poor preservation of these siliceous remains. Furthermore, the anthracological results indicate a clear arboreal concentration, and arboreal phytoliths are generally less abundant than those produced by grasses (Rapp & Mulholland 1992; Piperno 2006; Portillo et al. 2014; Strömberg et al. 2018; An & Xie 2022). Since this study focuses on a single hearth, it is not representative of the overall preservation at the site. It is therefore essential to continue phytolith analysis from hearths across different stratigraphic levels.

7.4. Neanderthals practices

The zooarchaeological remains recovered at the site reflect a steppe-like, open environment, with *Equus* sp. and *Stephanorhinus* sp. found in association with *Cervus elaphus* and *Bos* sp. In parallel, the anthracological record indicates the persistent presence of coniferous woodland in the vicinity of the site. These paleoenvironmental indicators are consistent with data obtained from other contemporaneous sites in the Iberian Peninsula, such as Cova Gran de Santz Linya, Abric Romaní, Cueva del Conde, and El Salt, and mirror the climatic oscillations characteristic of MIS 3.

The evidence points to a highly variable environment, marked by strong fluctuations and the coexistence of multiple ecological niches. Such conditions made northeastern Iberia a particularly favorable landscape for Neanderthal groups, who practiced opportunistic hunting strategies while sourcing fuel from more wooded areas, such as those surrounding Roca dels Bous. It is therefore plausible that the Neanderthals who occupied the site used the rockshelter as a temporary camp between residential bases, from which they could exploit local faunal and plant resources. This pattern suggests a degree of planning in mobility and resource management, as reflected in both the anthracological assemblage and the study of seed remains.

In particular, *Celtis australis* seeds were recovered in notable abundance at Roca dels Bous, as well as at other Neanderthal occupation sites in the region and beyond. Their presence suggests that they were harvested in large quantities during autumn, when the fruits ripen and become edible, highlighting how mobile groups took advantage of seasonally abundant resources in the landscape.

When integrated with zooarchaeological and anthracological data, these botanical remains underscore the flexibility of Neanderthal settlement strategies in northeastern Iberia. Instead of a purely residential mobility pattern, the evidence suggests a more logistical form of land use, where rockshelters such as Roca dels Bous functioned as specialized or task-specific sites embedded within broader foraging territories. This interpretation aligns with regional evidence for short-term occupations linked to hunting and resource processing, and implies that Neanderthals engaged in deliberate planning of their movements across diverse ecological settings.

Thus, the archaeological record from Roca dels Bous contributes to a growing body of evidence indicating that Neanderthal mobility in northern Iberia was dynamic, seasonally structured, and responsive to the heterogeneous environments of MIS 3.

8. Conclusion

The multiproxy archaeobotanical study conducted at Roca dels Bous highlights the richness and complexity of interactions between Neanderthals and their environment during MIS 3 in northeastern Iberia. Anthracological results confirm the predominance of coniferous formations, particularly the *Pinus sylvestris* type, as a stable fuel resource despite pronounced climatic oscillations. The notable presence of *Juniperus* sp. stands out from the data obtained at neighboring sites, suggesting a local specificity that merits further investigation, particularly through palynological studies capable of reflecting vegetation composition at a broader territorial scale.

Carpological analysis revealed the importance of *Celtis* seeds, likely collected seasonally and in large quantities, reflecting a flexible and opportunistic management of plant food resources. Although limited, the phytolith analysis provided additional evidence on local vegetation composition and fire-related practices. The presence of *Celtis australis* as well as *Pistacia sp*. underscores the exploitation of varied ecological niches and reveals opportunistic strategies in the use of plant resources.

These datasets converge towards the interpretation that Roca dels Bous functioned as a temporary campsite, integrated within strategies of planned mobility. The Neanderthals who occupied the shelter appear to have adjusted their movements and resource-gathering practices according to local and seasonal availability, complementarily exploiting the resources of a mosaic landscape shaped by MIS 3 climatic variability. The persistence of coniferous woodland throughout these fluctuations provided a reliable source of fuel, while simultaneously allowing groups to take advantage of more open environments, particularly for hunting small- and medium-sized game.

Finally, this study demonstrates the essential contribution of a multiproxy archaeobotanical approach, which enables researchers to move beyond the intrinsic limits of individual plant remain categories. It confirms the relevance of integrating anthracology, carpology, and phytolith analysis in order to reconstruct both past environments and the cultural strategies of the human groups who inhabited them.

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