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Wood and iron exploitation in the Pyrenean highlands during the Visigothic period: the case of the Puymorens pass and the Carol valley, France

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The Puymorens iron mine is located at an altitude of between 2,100 and 2,200 m at the western edge of the Pyrénées-Orientales department (France), which is bordered by the Ariège department in France and Andorra to the west and Spain to the south. It is the highest-altitude iron ore exploitation in the Pyrenees mountains. A major transportation corridor facilitating the north to south crossing of the Pyrenean massif passes by the foot of the mine, from the Ariège valley to the Carol valley. The mine is known to have been in operation from the seventeenth century to the end of the 1960’s, and it supplied ore to many modern smelting sites in Andorra, Catalonia and Ariège. New data acquired from the FEDER FERMAPYR and PCR FERAPO programs have enabled the identification of older ironworks in the neighboring Carol valley, which also used this ore and have been radiocarbon dated between the fourth and the sixth centuries. By placing this series of Visigothic smelting sites in their environmental context, we will be able to describe their technical specificities and the impetuses for the early exploitation of iron ore and wood at high altitudes in the Pyrenees. The study will be based as much on the results of archaeological excavations and surveys as well as on anthracology studies to understand the relation between iron ore smelting and the forest exploitation for charcoal production.

KEYWORDS

metallurgy, anthracology, mine, ore, iron, Pyrenees, charcoals, woody resources

1 Introduction

The process of smelting iron ore in a bloomery furnace (direct process) requires at least an equal mass of charcoal as of ore (Leroy et al., 2000). Several scholars have hypothesized significant environmental impacts resulting from agro-pastoral and also metallurgical practices in forest and mountainous regions such as the eastern Pyrenees (Schmider, 1978; Davasse et al., 1997; Galop, 1998, 1999; Guiter et al., 2005; Py-Saragaglia et al., 2017; Rendu, 1987; Rendu et al., 1995; Fouédjeu et al., 2022). However, very early claims have been substantially debated, because it is difficult to establish a geographical and chronological relationship between the metallurgical sites, the exploitation of the forest cover and the evolution of the natural environment. Iron metallurgy at high altitudes of above 1,500 m was first practiced in Pyrenees during the late Roman or Visigothic periods, as observed in relation to the Puymorens iron mine. There is no other previous metallurgical evidence in this area at this altitude (Meunier, 2023; Pagès, 2010; Pagès et al., 2022). The Visigothic iron metallurgy of Puymorens therefore provides an ideal setting for observing the exploitation of iron ore and wood in a limited area: the specific environment of high altitude and over a short chronological sequence. The objective of the study of smelting sites for Puymorens iron ore was to obtain ancient qualitative data on the flora composition of the mountain highland area and the changes that took place as a result of the exploitation of wood for metallurgy. More broadly, this paper aimed to understand how iron ore and wood mines were operated at high altitudes, in extreme environments. It first provides an overview of the context and the methodology used, which was adapted to specific circumstances. The ensuing section presents and analyzes the results, incorporating relevant published literature and micro-regional knowledge.

2 Research area and archaeological methods

2.1 Physiography, vegetation, and climate of the region

The investigation area is situated on the upper southern slopes of the Pyrenees massif, stretching from the head of the Carol valley to the Puymorens pass, in the far west of the Pyrénées-Orientales department (France). It is bounded by the Carlit massif to the east and the Font Negra massif to the west. This zone lies to the north of the Cerdanya high plain and is in close proximity to Andorra (Figure 1). On the other side of the Puymorens pass, to the north, lies the Ariège valley.

Now treeless, this area is located above the timberline, between montane and subalpine forest. The ecotone is still at its highest altitude acknowledged to be a zone that experiences constant change and that is vulnerable to various forms of disturbance, whether originating from climatic or human factors (such as the intensification of the erosion process and the challenge of reforestation at higher elevations).

Due to topographical effects and exposure to southerly winds, the Cerdagne region has a transitional climate that is predominantly continental. The climate is characterized by fairly low average annual temperatures (8.9°C in Villeneuve-les-Escaldes at 1,381 m, 7.7°C in Mont-Louis at 1,600 m and 6.1°C in Font-Romeu at 1,750 m). Freezing conditions occur during at least 7 months of the year. The annual number of frosty days is high (124 in Villeneuve-les-Escaldes and 156 in Font-Romeu). In winter, temperatures can fall below −20°C in the mountains and below −10°C on the plateau. In summer, it can reach 30°C during the day, but the nights are always cool. A further contrast is therefore a marked contrast between the plateau and the mountains. There is also a contrast between the south-facing slopes (“soulanes”) and the much colder north-facing slopes. Cerdanya has a dry climate. Annual rainfall shows a wide variation, low on the plateau (between 652 mm at Dorres at 1,450 m and Villeneuve-les-Escaldes at 1,381 m, 760 mm at Mont-Louis at 1,600 m, 823 mm at Font Romeu at 1,750 m and 879 mm at Valcebollère at 1,420 m), and probably a little higher (around 1,500 mm) on the mountains, for which there is a lack of meteorological data. This relative dryness is offset by a good distribution of rainfall throughout the year, with the wettest seasons being summer and autumn (Bagnouls and Gaussen, 1953).

Vegetation and climate differ between the head of the Carol valley at 1,444 m and the Puymorens pass at 1,915 m. The head of the Carol valley is humid and wooded, while the Puymorens pass is windy and situated at the upper limit of the forest. The study area consists of fir forests and Scots pine forests in the montane belt. As in the Alps, the subalpine zone is still forested, mainly with *Pinus uncinata* mixed with *Betula pubescens*, characteristic of the “subalpine belt” (Gaussen, 1925, 1938; Michel, 1951). *Pinus uncinata*, widespread in the subalpine forest in the eastern Pyrenean region, is associated with *Arctostaphylos uva-ursi* and *Juniperus communis* (Gaussen, 1925; Gruber, 1978). In places where the pine forest is sparse or has been disturbed, there is an increased presence of *Betula pubescens*. Three other species reach the base of the subalpine zone: *Betula pendula*, *B. pubescens*, and *Abies alba*. The climatic asymmetry between the two slopes of the Pyrenees means that the Pyrenean subalpine can be divided into humid and xeric types (Gruber, 1980).

2.2 Survey, samplings, materials, and method

Surveys in mountainous areas with significant erosion and extensive vegetation cover cannot be conducted in the same way as those in plains with cultivated areas, where plowing offers good visibility of deposits (Lallemand et al., 2022; Calastrenc et al., 2024). Because exhaustive observation of the territory is not possible, the surveys were conducted only in vegetation-free zones where archaeological remnants are visible on the sediment surface. Examples of such zones are paths and erosion cones. Special attention was given to soil sections, particularly those caused by river erosion (Figure 2). The assistance of people who frequently engage in such activities as farming, shepherding, hunting, walking, and forest wardening in these highlands was invaluable in making this work possible. This type of survey was carried out in the Carol valley and its tributaries, as well as on the Puymorens pass.

The identification of ancient iron ore smelting sites is dependent on the discovery of smelting slag. Large quantities of smelting slag are produced as a waste product during the direct iron ore smelting process. Smelting operations are carried out in a bloomery furnace, at a location that is separate from the place of extraction. Mining and iron production are therefore never carried out at the same site. In the technical context of the study (Pagès, 2010; Pagès et al., 2022), each smelting operation would generally produce more than 30–40 kg of slag, which would be accumulated in piles in front of the work area and the bloomery furnace.

Given the impact of erosion in mountainous regions, the surveys aimed to identify the concentrations of slag that make up the preserved waste heaps of iron ore smelting sites. The conservation of the slag remains was evaluated during the surveying on the surface thanks to slag density and, in some cases, the presence of coal. If a portion of the remains appeared to be well-preserved from erosion, excavations were conducted in the best-preserved part of the slag heap to

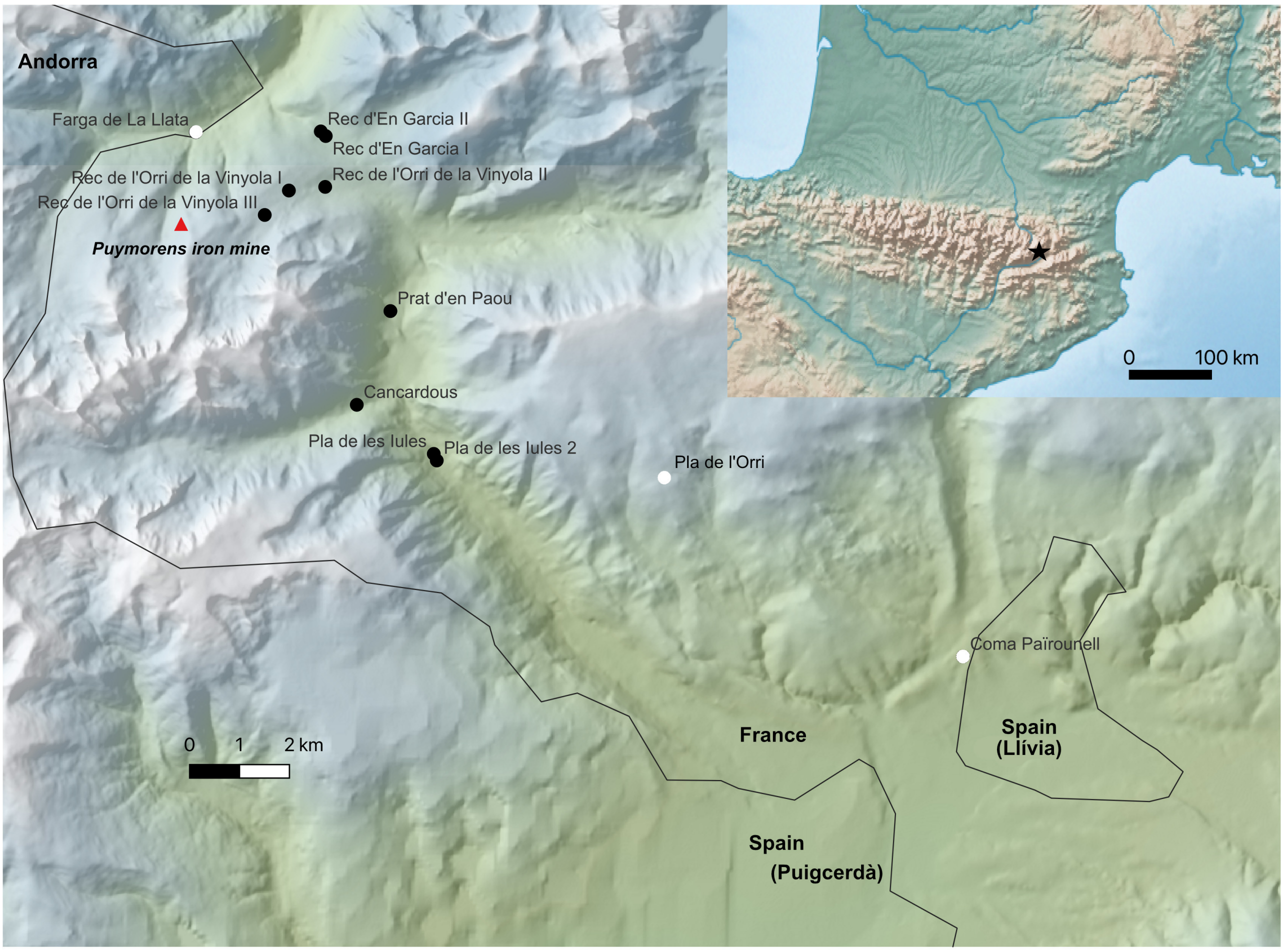

FIGURE 1
Area and sites studied (Pyrénées-Orientales, France). In black, the smelting sites; in red, the Puymorens mine; in white, the other places mentioned in the study.

eliminate the risk of contamination and prevent the excavation of reworked remains.

The objective of the archaeological excavations was to uncover artifacts such as ceramics (technical and consumption) and tools, as well as remains such as furnaces, pits, and grate spaces, which aid in dating the metallurgical site and understanding the operations carried out and the techniques that were used there. The excavations also served to calculate slag volume (thickness and density, with surface area being defined by the surveys), thereby helping to quantify the size of the exploitation and the volume of iron produced (Pagès, 2017). Smelting sites often lack archaeological evidence for dating purposes. Excavations can provide useful charcoal samples for carbon-14 dating and the anthracological analysis of the fuel used in ore smelting. The metallurgical sites in the study are small, each covering an area of <700 m^2, so test pit measuring 50 x 70 cm were used for the excavations (one test pit is carried out per site, but if the results are negative, a new test pit is carried out). This method gave a satisfactorily representative overview, allowing us to probe to a depth of 80–90 cm and to obtain distinct samples of the metallurgical layers (the depth is defined by the archaeological remains).

Numerous charcoals were collected during the archaeological excavations at the smelting sites. In some cases, they made up the majority of the sediment in which the slag was discovered. The methods used have been described in detail elsewhere (Chabal, 1997; Chabal et al., 1999; Figueiral and Mosbrugger, 2000; Puech et al., 2020; Kabukcu and Chabal, 2021) and are only briefly summarized herein. During the excavation of slag heaps, charcoal was recovered from standard volumes of 10 and 20 L of sediment, which was subjected to water flotation and then sieved (using a 1 mm mesh). The material was highly fragmented, so any fragments larger than 4 mm were collected from the sieves. The charcoal fragments were observed using an incident light microscope at magnifications ranging from 20 to 1,000 times after being sectioned into three diagnostic planes: transverse, tangential, and radial. The anatomical observations were compared to European wood anatomy atlases (Jacquiot, 1955; Schweingruber, 1982, 1990; Vernet et al., 2001) and online databases such as Insidewood (Wheeler et al., 1989). Identifications followed IAWA standards (Wheeler, 2011; Baas et al., 2004).

The qualitative and quantitative description of the coals was carried out for each charcoal mentioning dendrological features such as the presence of bark or pith, reaction wood,

FIGURE 2
Smelting slag exposed by water erosion at the Pla de les Iules site (arrow).

tyloses, fungal hyphae, and insect markings (xylophageous galleries, fecal pellets; Marguerie, 1992; Marguerie and Hunot, 2007; Marguerie et al., 2010). The caliber of the wood was also assessed based on growth ring curvature. For this, we chose to use a quick, easy-to-apply qualitative method that consisted in assigning a score based on the shape of the ring (weak curvature 1, intermediate curvature 2 and strong curvature 3 (Marguerie and Hunot, 2007; Marguerie et al., 2010). The occurrence of radial cracks (RC) is considered in charcoal analysis, but as demonstrated by Caruso Fermé and Théry-Parisot (2011) and Théry-Parisot and Henry (2012), their presence is not correlated with the moisture content of the wood or the differentiation between seasoned wood and green wood. According to these authors, calculating a ratio per mm^2 would be more accurate.

If taxonomic identifications of charcoal fragments do not present theoretical difficulties in European flora, the distinction between pine species namely *Pinus sylvestris* and *Pinus uncinata* can be challenging. In the case of *Pinus uncinata* the micro-anatomical characteristics taken into consideration are thiner growth rings with sharp demarcation from initial to final wood. The transverse walls of the parenchyma cells in the rays are lightly punctuated even in thick-walled cells. Tangential walls are thin with nodular aspects. Finally, thylloids are visible in canals (Jacquiot, 1955; Trouy-Jacquemet, 2023).

3 The smelting sites

Surveys in 2015 and 2017 led to the discovery of nine iron smelting sites in the Carol valley and Puymorens pass area (Pyrénées-Orientales department in France, Figure 1). The presence of dense concentration of slag, a sign of direct iron ore smelting, made the sites easy to recognize. Although four of the nine smelting sites have been significantly damaged by mountain erosion, the other five remain well-preserved are the focus of ongoing archaeological and anthracological new investigations (Pla de les Iules, Pra d'en Paou, Rec de la Vignola 1 and 2, Rec d'en Garcia 2).

The Puymorens iron mine, situated in the vicinity of the village of Porté-Puymorens is the highest-altitude iron mine in the eastern Pyrenees (Balent, 2005). It ranges between the elevations of 2,100 and 2,200 m and is located beneath the Pic de la Mine, which has an altitude of 2,683 m in the Font Negra massif. It is bordered by the Ariège valley to the north and west and the Carol valley to the south and east. The mine is situated in a remote location, due to its altitude and distance from other mines and iron deposits, which are situated more than 20 km away in a direct straight line.

The mine is known to have been in operation until 1964, by which time 1.3 million metric tons of hematite, carbonate, and magnetite had been extracted from Silurian schists (Besson, 1991). According to textual sources, ore had been mined here since the seventeenth century (Balent, 2005). The ore was used in Andorra and the Ariège valley, such as at the Farga de Llata smelting site, which was active from 1679 to 1772 (Balent, 2016). Sadly, this site was destroyed by flooding of the Ariège, and contemporary industrial operations have erased the remnants of most ancient mines.

3.1 Pla de les Iules (Porta, Pyrénées-Orientales, France)

The Pla de les Iules deposit is a dense slag heap of over 300 m^2 (located on a slight slope on the right bank of the Carol river, at an altitude of 1,441 m (Figure 1). It is the lowest-altitude deposit that was examined in the study area. Two excavations were conducted at this site in 2016 (Mach and Pagès, 2021). A first pit was excavated in the upper western part of the slag heap. However, the concentration of slag in the stratigraphic units (SU-3 and SU-4) was not very high and the sediment was not particularly carbonaceous. The slag heap could have been disturbed here by colluvium or alluvium. A second pit was dug 4 m further to the east. It revealed, below the humus layer (∼20 cm thick), a very dark or black sandy-loam layer with slag and charcoal and no dark cobbles or pebbles (SU-5). The next layer below (SU-6) consists mainly of slag and charcoals (Figure 3). These materials make up the slag heap, whose total depth is ∼50 cm. This waste heap is very large and dense and contains numerous kiln walls, slags and charcoals. Underlying the waste heap is a substratum consisting of a pile of large stone pebbles typically found at the bottom of Alpine valleys.

3.2 Prat d'en Paou (Porta, Pyrénées-Orientales, France)

The Prat d'en Paou deposit is located on the same bank of the Carol river (right), upstream, 3 km further north (Figure 1). It lies at the bottom of a northeastern-facing slope in a sensitive position similar to Iules, except for being located at a higher altitude, at 1,558 m above sea level. Although difficult to estimate because of the dense forest cover, its surface area probably does not exceed 700 m^2. A survey was conducted at the center of this site in 2021. Below 30 cm of humus and colluvium (SU-1), the upper layer of the waste heap was revealed (SU-2 and SU-3). It has probably been reworked and disturbed, because the sediment is not very carbonaceous. Intact pig iron lies 45 cm below the surface. This layer is composed of small slag and charcoal in a black sediment (SU-4) and is no more than 20 cm thick. It rests on granitic rock.

3.3 Rec de l'Orri de la Vinyola 2 (Porté-Puymorens, Pyrénées-Orientales, France)

The Rec de l'Orri de la Vinyola 2 deposit is located on the Puymorens pass, 2.8 km north of the Prat d'en Paou deposit (Figure 1). It is one of the highest site in altitude in this study (1,888 m). The site consists of a small mound measuring 540 m^2 which lies on a substrate of granite blocks bound by a light-brown sandy sediment. In 2021, the first survey pit was dug 5 m below the highest point of the butte (pit 1). The layers were very broken up and disturbed, so a second hole was excavated some 15 m below the first, at the foot of the mound (pit 2). After a 7 cm thick stripping operation (SU-5), a 10 cm thick metallurgical layer was discovered (SU-6). It is carbonaceous and contains numerous small fragments of roasted ore, a few burned stones and small slag.

3.4 Rec de l'Orri de la Vinyola 1 (Porté-Puymorens, Pyrénées-Orientales, France)

The Rec de l'Orri de la Vinyola 2 deposit is very close to the Rec de l'Orri de la Vinyola 1 deposit, only 700 m to the west and at a slightly higher elevation of 2,013 m (Figure 1). The deposit consists of 280 m^2 of a dense concentration of slag visible on the surface, on the left bank of the Rec de l'Orri stream. In 2021, a test pit was dug directly into the middle of the slag heap (Figure 4). A 10 cm layer was excavated to remove surface pollution (SU-1). The archaeological layers were excavated underneath to a depth of 18 cm (SU-2). This second level is composed almost entirely of small slag (<5 cm). The surrounding brown, silty sediment is rare and does not fill all the gaps between the slag. Many charcoals and fragments of roasted ore were collected. Excavation was halted at this layer, the bottom of which was not reached. It did not seem appropriate to purge this level, which may be linked to a kiln that probably lies above and would merit a more extensive archaeological exploration. The base of the slag heap was not reached.

3.5 Rec d'en Garcia I (Porté-Puymorens, Pyrénées-Orientales, France)

The Rec d'en Garcia I deposit is situated 1 km north of Rec de l'Orri de la Vinyola 1 and 2 (Figure 1). It lies at an altitude of 1,858 m on the southern slope of the Puymorens pass, on the Ariège valley side, along one of the river's tributaries (the Rec d'en Garcia). The site has suffered severe erosion and destruction by water torrents. Only 20 m^2 remain on the torrent-eroded left bank. In 2021, the site was excavated under 50 cm of a humus layer and a disturbed layer (SU-1 and SU-2). The 17 cm thick metallurgical layer (SU-3) was composed of a black, very carbonaceous sediment, rich in roasted ore and small slag (Figure 5).

4 Radiocarbon dating of smelting sites

No ceramics or other objects were available to determine the age of the sites through typology. Consequently, it was necessary to employ carbon dating. Charcoals similar to small twigs, or ideally originating from the secondary xylem tissues closest to the cambium were selected from intact metallurgical layers for dating. C14 analysis was performed

FIGURE 3
Pla de les Iules metallurgical layer (SU-6), under excavation.

at the Laboratoire de Mesure du Carbone 14 (Lyon, France) in 2016 and at the Pozan Radiocarbon Laboratory (Poland) in 2021 (Table 1).

In 2016, three C14 dates were obtained for the Iules site, from the same archaeological layer (SU-6). All have a consistent chronology (Table 2). In 2021, radiocarbon dating was conducted at four other sites, resulting in a total of seven dates (Tables 1, 2). There is a 95.4% probability that the correct dates fall between 254 and 605 AD (Figure 6).

This wide date range does not result from the date distribution, but rather from the calibration of dates using the IntCal20 reference curve and from plateau effects, which are well-established in Late Antiquity (Table 2). It is challenging to differentiate between the Late Roman Empire (spanning the third century up to 418 AD) and the Visigothic Kingdom (418–720 AD), which had its capital in Toulouse, just 150 km from the examined sites, from 418 to 507 AD. The plateau effects were slightly lessened by using multiple dates for the same location. Using the R_Combine function in

FIGURE 4
Slag heap of the Rec de l'Orri de la Vinyola 1, visible in the vegetation.

OxCal for Iules, the combination of the three dates shortened the sequence by 59 years: specifically, from between 367 and 548 AD to between 416 and 538 AD (Table 2). Ore smelting operations, indicated by the minimal waste volumes, were not persistent across the chronological range of the C14 dates for each location.

Based on the surface area of the slag heap (<700 m^2), each smelting site was operated for a maximum of 50 years, most likely for less than a generation, which covers 25 years (Pagès, 2010, 2017). Various parameters in addition to C14 dates must be considered to establish the sites' chronology. It is essential to determine whether the sites a) were part of a single continuous phase of occupation for iron smelting that occurred successively in different areas, or b) were entirely disconnected, with gaps spanning more than one generation. Can it be determined whether the Visigothic-era smelting sites were already in operation during the Late Empire? While the question remains open, several arguments suggest a Visigothic occupation sequence for iron smelting, at a time when the Cerdanya and Capcir regions were experiencing a restructuring

FIGURE 5
The metallurgical layer (in black, SU-3) preserved in the cross-section of the Rec d'en Garcia I site excavation.

of human settlements (particularly at Llívia and Coma Païrounell Figure 1) and mountain agropastoral exploitation (Luault, 2019, 2020). The sites are comparable and primarily date back to the Visigothic era, with no other acknowledged exploitation periods. Their morphology is considerably different from the production standards of the Roman period (Pagès et al., 2022).

Whether we adopt a narrow or a more dilated chronology, it is clear that not all sites were operational at the same time. Based on their dating, three phases of occupation can be distinguished: sites dated between 254 and 430 AD (Vinyola 1 and Garcia 1), sites dated between 413 and 538 AD (Iules and Vinyola 2), and the most recent site, dated between 435 and 605 AD (Paou). The oldest sites are therefore the closest to the mine (between 2 and 3 km), while the most recent is the farthest away (more than 6 km). This shift can be observed during an intermediate phase, when both the Puymorens pass and the Carol valley were occupied.

5 Fuelwood used in iron metallurgy

The anthracological diagram (Figure 7) is based on a selection of five metallurgical sites and eight stratigraphic units (SU), each containing between 51 and 300 charcoals (Table 1, Figure 1). The charcoals examined were debris of the fuelwood burnt in the metallurgical processes, which allows us to study the use of wood in relation to the area's activities. The process of smelting iron ore in a bloomery furnace requires at least an equal mass of charcoals as of ore (Leroy et al., 2000). The smelting sites vary in terms of their north-south topographical position and the distinct relief types found at the Carol valley summit and the Puymorens pass (Figure 1). There is a 569 m difference in altitude between the lowest (1,444 m) and highest (2,013 m) site studied. This study gives us the opportunity to describe the anthracological assemblages encountered at different altitudinal levels (montane, subalpine) and to determine whether or not they are of local origin. Three other non-metallurgical contexts in the Pla de les Iules (SU-3, SU-4, and SU-5) were analyzed for the purpose of comparison.

5.1 Charcoals from deposits in contact with the metallurgical layer

Fieldwork produced two groups: (1) metallurgical and (2) non-metallurgical contexts. Three stratigraphic units at Pla de les Iules (SU-3, SU-4, and SU-5) represent the non-metallurgical contexts. The second group is less rich in charcoal: only 51, 65, and 96 charcoals (<4 mm) samples were studied from these layers. Additionally, variations in brilliance (from bright to dull, not vitrification) across these samples suggest an heterogeneous assemblage with the presence of different sources of charcoals and reworked elements.

TABLE 1 Charcoal samples for C14 dating.

Site	Layer	Taxa	Small twigs	Near cambium	Laboratory codes	Raw C14 date	Standard deviation
Iules	SU-6	*Juniperus* sp.	x	x	Lyon-13945 (SacA 48952)	1,635	30
Iules	SU-6	*Juniperus* sp.	x	x	Lyon-13946 (SacA 48953)	1,615	30
Iules	SU-6	*Juniperus* sp.		x	Lyon-13947 (SacA 48954)	1,590	30
Paou	SU-4	*Pinus* cf. *P. sylvestris*	x	x	Poz#2-150460	1,525	28
Vinyola 1	SU-2	*Pinus* sp.	x	x	Poz#2-150461	1,712	25
Vinyola 2	SU-6	*Pinus* cf. *sylvestris*	x	x	Poz#2-150379	1,613	28
Garcia 1	SU-3	*Pinus* cf. *sylvestris*	x	X	Poz#2-150380	1,671	28

TABLE 2 C14 dates calibrated using OxCal v4.4.4 Bronk Ramsey (2021).

	Unmodelled (BC/AD)			
Name	From_68.3%	To_68.3%	From_95.4%	To_95.4%
R_Date Paou_Poz#2-150460	540	595	435	605
R_Date Iules_Lyon-13945 (SacA 48952)	406	533	367	541
R_Date Iules_Lyon-13946 (SacA 48953)	417	534	410	542
R_Date Iules_Lyon-13947 (SacA 48954)	433	536	419	548
R_Combine Iules	419	531	416	538
R_Date Vinyola 2_Poz#2-150379	418	534	413	540
R_Date Garcia 1_Poz#2-150380	267	420	257	529
R_Date Vinyola 1_Poz#2-150461	262	401	254	412

The fewest charcoals were collected from SU-3 at Pla de les Iules, making this non-metallurgical context the least representative in this study. Only 51 charcoals were analyzed from this layer (Table 3). Six taxa were identified: *Abies alba* (62.7%), *Pinus* cf. *sylvestris*[1] (23.5%), *Juniperus* sp. (2.0%), *Fagus sylvatica* (2.0%), Angiosperms (3.9%), and unidentified taxa (5.9%). A homogeneous brilliant carbonization characterized 74.5% of the wood, while the remaining 25.5% was less well-preserved, suggesting the presence of reworked elements from post depositional processes and are therefore not contemporary with the age of deposits. Growth ring curvatures indicate the use of a majority of large wood pieces (94 vs. 6% for small wood with type 3 ring curvature). Sixty-five charcoals were analyzed from SU-4 (also in Pla de les Iules, below SU-3), and same taxa as in the upper horizon were found (Table 3): *Abies alba* (46.2%), *Pinus sylvestris* (38.5%), *Juniperus* (1.5%), *Fagus sylvatica* (1.5%), unidentifiable Angiosperms (4.6%), unidentifiable Gymnosperms (6.2%), and unidentified taxa (1.5%). Again, 74.5% of the wood had a homogeneous glossy carbonization (all coals have the same shiny appearance), with the other third very probably composed of reworked material. Growth ring curves indicate 51% of large wood pieces, but curvature could not be assessed for 21% of the samples, due to poor conservation. It is interesting to note the presence of two joinery elements, including a joint bar with notches, in these two layers (SU-3 and SU-4). Unfortunately, this artifact is too small to identify its source (infrastructure or tool).

SU-5 is the third non-metallurgical context studied, also from Pla de les Iules. It forms the interface between the humus and the metallurgical layers in the second pit. Ninety-six charcoals were examined, including *Abies alba* (31.3%), *Pinus sylvestris* (56.3%), *Juniperus* (2.1%), *Fagus sylvatica* (3.1%), unidentifiable Angiosperms (3.1%), unidentifiable Gymnosperms (1.0%), and unidentifiable taxa (3.1%) (Table 3). The unidentifiable wood tissues were vitrified. In this layer, carbonization resulted in only 68% of the material with a shiny appearance, the rest being composed of reworked elements. The wood's ring curvature are straight (the rays are almost parallel to each other) and suggests the use of large-diameter wood rather than small wood. When the rings the charcoal is considered to come from the most recent part of large-caliber wood.

5.2 Northeastern slope of the right bank of the Carol valley (Porta, France, 1,441–1,558 m)

SU-6 from Pla de les Iules (1,441 m) is the only intact metallurgical layer from the second excavation pit. In all,

1 *Pinus cf. P. sylvestris* is the correct identification for the period studied, *Pinus nigra* does not belong to the plant series of the montane and subalpine levels of the Eastern Pyrenees. It is possible that reforestation involving *Pinus nigra* and mixtures took place from the nineteenth century onwards.

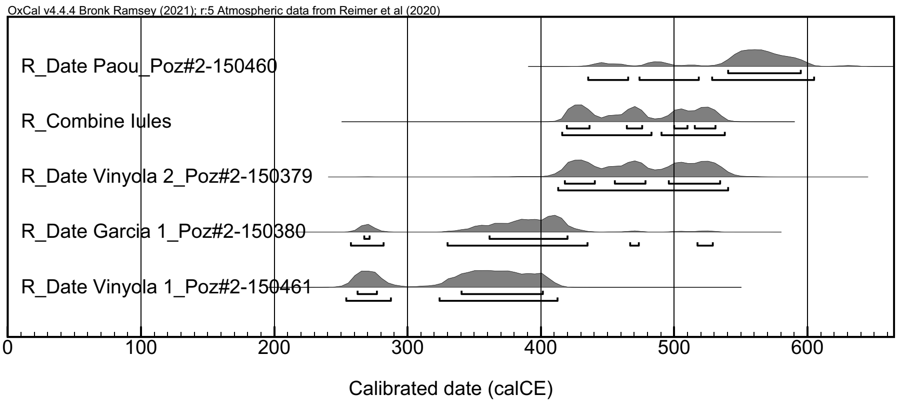

FIGURE 6
Diagram of C14 dates calibrated using OxCal v4.4.4 Bronk Ramsey (2021).

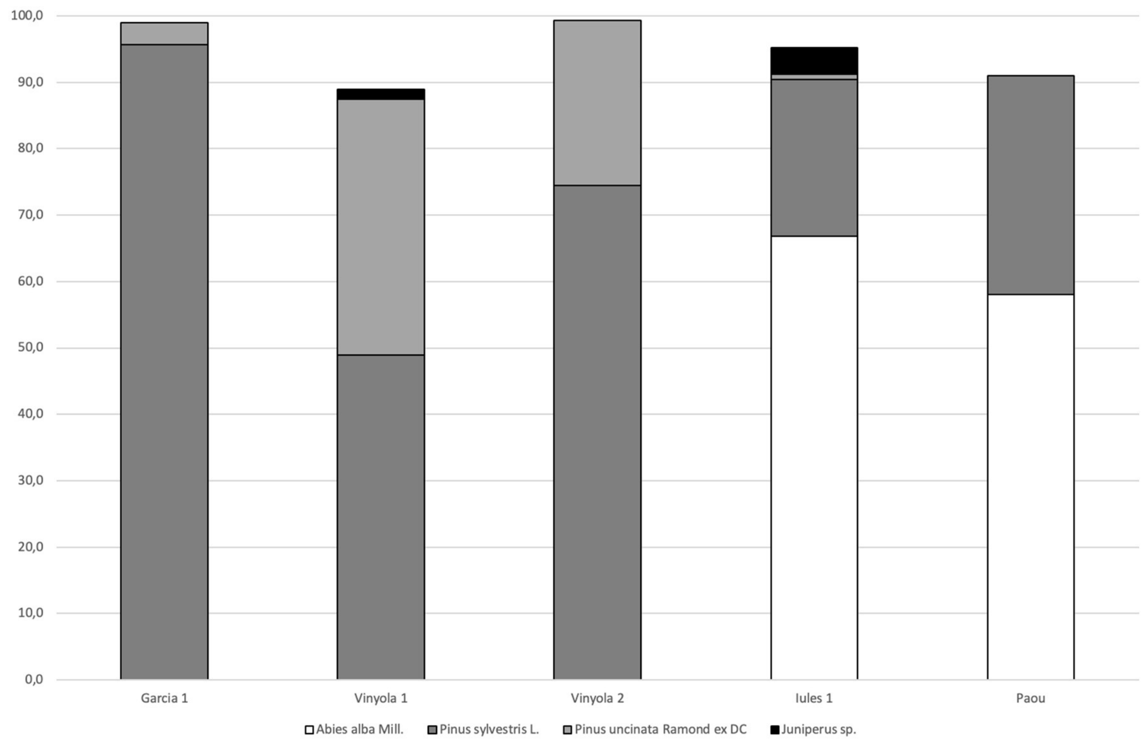

FIGURE 7
Anthracogram showing the relative frequencies (%) of dominant taxa in the metallurgical layers that were studied.

250 charcoals were analyzed and six taxa were identified, including *Abies alba* (66.8%), *Pinus sylvestris* (23.6%), *Pinus* cf. *P. uncinata* (0.8%), *Juniperus* (4.0%), and unidentified Angiosperms and Gymnosperms (1.6%) (Table 3, Figure 7). The material exhibited homogeneous carbonization, with 94.4% of glossy charcoals, suggesting that this assemblage is representative and devoid of reworked charcoals, not contemporaneous with the deposit. Many charcoals were collected from this metallurgical level, making them representative samples in this study.

The studied layer (SU-4) from Prat d'en Paou (1,558 m) has a depth of 55–60 cm. A total of 300 charcoal remains were examined and six taxa were identified (Table 3, Figure 7). The samples were made up of *Abies alba* at 58%, followed by *Pinus sylvestris* at 33%. The other taxa were *Alnus* sp. at 1% and Angiosperms (8%). The entire assemblage is homogeneous, with identical charring for all the coals. Few radial cracks were present. A small number of vitrification traces were also noted (2.6%). From horizon SU-3, a small number of centimeter-sized charcoal samples were collected ($n = 12$) comprising *Abies alba* and *Pinus sylvestris* species.

TABLE 3 Sites and stratigraphic dendro-anthracological summary.

Context	Garcia 1	Vinyola 1	Vinyola 2	Paou	Iules 1			
	Metallurgical layers					Non-metallurgical layers		
Stratigraphic Units (SU)	SU-3	SU-2	SU-4	SU-4	SU-6	SU-3	SU-4	SU-5
Number of charcoals	300	288	282	300	250	51	65	96
TAXA (%)								
Abies alba	0	0	0	58	66.8	62.7	46.2	31.3
Pinus cf. sylvestris	95.7	49	74.5	33	23.6	23.5	38.5	56.3
Pinus cf. P. uncinata	3.3	38.5	24.8	0	0.8	0	0	0
Juniperus sp.	0	1.4	0	0	4	2	1.5	2.1
Fagus sylvatica.	0.7	0	0.4	0	0	2	1.5	3.1
Alnus sp.	0	0	0	1	0	0	0	0
Rosaceae	0	0.7	0.4	0	0	0	0	0
Angiosperms	0	0	0	8	0.8	3.9	4.6	3.1
Gymnosperms	0	3.5	0	0	0.8	0	6.2	1
Unidentifiable taxa	0.3	6.9	0	0	3.2	5.9	1.5	3.1
Dendrological attributes (total)								
Bark	0	0	0	0	0	0	0	0
Pith	0	0	0	0	0	1	1	0
Fungi/fungal hyphae	0	0	0	0	0	0	0	0
Xylophagous galleries	0	0	0	0	0	0	0	0
Tyloses	0	0	0	0	0	0	0	0
Traumatic canals	1	0	0	0	0	0	0	0
Cutting season	ind.	ind.	ind.	ind.	ind.	ind.	ind.	ind.
Growth ring curvature type 1	291	282	280	173	236	48	50	87
Growth ring curvature type 2	4	4	1	114	20	2	1	10
Growth ring curvature type 3	5	2	1	13	3	1	0	3
Reaction wood	1	0	0	1	0	0	1	0
Carbonization type 1	2	0	0	1	8	8	8	30
Carbonization type 2	1	2	0	0	16	3	3	1
Carbonization type 3 (Bright carbonization)	297	286	282	299	225	40	49	66
Radial tracks	4	1	2	0	0	0	3	3
Vitrification type 1	8	14	18	2	6	0	2	2
Vitrification type 2	0	0	0	0	0	0	0	3
Vitrification type 3	0	0	0	0	0	3	1	3
Stained wood	18	0	0	0	0	0	0	0
Joinery elements	2	0	0	0	0	1	**1**	0

5.3 Puymorens pass (Porté-Puymorens, France, 1,858–2,013 m)

Two archaeological layers from surveys of two different smelting sites at the Rec de l'Orri location were analyzed: Vignola 1 SU-2 and Vignola 2 SU-4 (Table 3, Figure 7). A single layer from the neighboring Rec d'en Garcia 1 site (SU-3) was chosen for the examination.

From SU-2 at Rec de l'Orri Vignola 1 (2,013 m), 288 charcoals were studied (Table 3, Figure 7). The samples mostly comprised four precisely identified arboreal taxa, which included *Pinus* cf. *P. sylvestris* (49%), *Pinus* cf. *P. uncinata* (38.5%), *Juniperus* sp. (1.4%), and Rosaceae (0.7%). The other taxa were unidentifiable (6.9%). Carbonization was homogeneous, resulting in the charcoals' overall shiny appearance. Only 5% of the charcoals showed vitrification. In 23% of the samples, tension wood was observed. No radial tracks were found. The ring curvatures (type 1) suggest the use of wood with a large diameter.

From SU-4 at Rec de l'Orri de la Vignola 2 (1,888 m), 282 charcoals were studied (Table 3, Figure 7). This assemblage was mostly made up of seven arboreal taxa, with *Pinus sylvestris* (74.5%) and *Pinus uncinata* (24.8%)—the genus *Pinus* being the most prevalent among the Gymnosperms. The remaining taxa, including Rosaceae (0.4%), represent a small frequency. Homogeneous carbonization has resulted in an overall shiny appearance of the charcoals. Only 6.3% of the charcoals show vitrification. Charring is uniform throughout the assemblage and a strong gloss was observed. No compression or tension wood was found. A few of the charcoals (<1%) had split rays. In the survey, the charcoal samples indicated the use of large-diameter wood.

In the 300 charcoal samples analyzed in SU-3 from Rec d'en Garcia 1 (1,858 m), three taxa were identified (Table 3, Figure 7): *Pinus*, *Fagus*, and an unidentified species. *Pinus* was the dominant element, making up 98% of the assemblage with *Pinus sylvestris* at 95.7% and *Pinus uncinata* at 3.3%. *Fagus sylvatica* frequencies were <1%. Homogeneous carbonization of the charcoals and a shiny appearance were observed. Two-thirds of the fragments showed straight rings, indicating the use of bigger branches and fewer smaller ones. Vitrified wood was infrequently observed (in only eight charcoals). Remnants of manufactured components, such as quadrangular wood, off-cuts of small, beveled pieces, and quarter-sections and half-sections of stems, were evident. Some joinery elements (cleats) with bevels, showing the use of manufactured wood, were also found.

6 Discussion

6.1 Charcoals from forest exploitation used as fuelwood for the metallurgy

Three phases of timber and metallurgical exploitation were identified in the Puymorens pass and Carol valley area. The first phase, dating between 254 and 430 AD, included the Rec d'en Garcia and the Rec de l'Orri de la Vignola 1 sites, located at 1,858 and 2,013 m, respectively (Figure 1). These were the first of the sites to be exploited and were located in the immediate vicinity of the mine. The third and most recent smelting phase (435–605 AD) included Prat d'en Paou, situated at a lower altitude (1,558 m). The second, middle, phase included the Rec de l'Orri de la Vinyola 2 (1,890 m) and the Pla de les Iules (1,441 m) sites and represents an intermediate phase, with one site still at a high altitude and the other at a lower altitude. For the period under study, it perhaps marks the beginning of a shift in activity to lower altitudes.

The charcoal samples analyzed from all these locations and timeframes are dominated by a limited number of woody taxa, as shown in Table 3. Arboreal taxa prevail across all sites, with the following specific types identified: *Abies alba*, *Pinus* cf. *P. sylvestris*, *Pinus* cf. *P. uncinata*, *Juniperus* sp., *Alnus* sp., and Rosaceae. All these plants are only found in the montane and subalpine phytogeographic regions around the sites.

Fagus, a sciaphilous taxon that requires high atmospheric humidity, is excluded naturally from Cerdanya and can only be found in extant vegetation on a few hectares at the northern end of the Capcir (Gaussen, 1938). The discovery of a small number of *Fagus* charcoals in our analysis is most likely the result of material or tools having been brought to the site and later abandoned. *Abies,* which prefers moist soil and which is a heliophilous or half-shade species, can be found in Cerdanya in isolated stands depending on local microclimatic conditions. The Prat d'en Paou and Pla de les Iules sites, located on southern slope, offered some surprising results with the presence of *Abies*. However, due to the geographical and climatic particularities of Cerdagne, including continentality, altitude, and irregular precipitation distribution, the presence of this species may be limited to specific micro-habitats, favored by particular environmental conditions where the relative dryness is offset by a good distribution of rainfall throughout the year, which is very favorable for fir growth. Similarly, we can assume the opening of the Carol valley to the north brings humidity and fog, while the southerly and easterly winds bring clouds and abundant rainfall at higher altitude. Phytosociological studies would provide a better understanding of the dynamics of plant communities where the fir tree is present or absent. Additionally, more detailed climatic studies, particularly regarding local variations in temperature and humidity, would be crucial to assess the conditions that supported its past expansion in this region.

These results suggest that during each time period, the forest's upper limit was higher than it is now, at least on a local level or very close to the sites where metallurgical exploitation took place. The arboreal species used were those that were present on the site and directly available, in accordance with the principle of least effort (Shackleton and Prinsh, 1992), which perhaps allows us to suggest the proximity of charcoal kilns for wood processing.

The smelting process in iron production requires a significant amount of fuel and the very probable presence of local coal production in the vicinity of the iron smelting site and consequently the existence of charcoal kilns. In reference to the examination of the Porta and Porté-Puymorens locations, the anthracological taxa results are consistent with the theoretical distribution of taxa (vegetation series; Gruber, 1981) which allows us to hypothesize that charcoal production took place nearby. The processing of wood might have taken place in coal pits, where all species were transformed on site, or a single wood species might have been used for more controlled burning, necessitating the use of multiple coalfields. However, no coal pits were identified during the surveys.

Similarly, the scarcity or absence of shrub species or heliophilous elements could suggest the immediate availability of woodland formations which offer more biomass. It is also likely that there were few clearings in the surrounding areas. Based on these observations, the hypothesis of a higher upper limit to the forest (at least locally) is plausible. Moreover, the absence of fungal spores and mycelium in the charcoals indicates a good phytosanitary status for the fossil specimens studied. The analyses revealed few ray tracks and low degree of vitrification, the anatomical features of the wood are visible allowing for its identification.

Two distinct anthracological sectors can be identified:

The metallurgical sites in the Carol valley are situated between 1,441 and 1,558 m in altitude, which corresponds to a montane zone range of 900–1,700 m. At Prat d'en Paou (dated 435–605 AD) and Pla de les Iules (dated 416–538 AD), *Abies alba* and *Pinus sylvestris* were identified, while *Pinus uncinata* was absent due to being outside of its habitat. *Fagus* and *Juniperus* were observed, although at low frequencies. Both sites exhibit low species diversity indicating marginal use of these species or solely used as kindling wood.

For the Puymorens pass area Rec de l'Orri de la Vinyola 1 sequence (dated 254–412 AD), the Rec de l'Orri de la Vinyola 2 sequence (dated 413–540 AD), and Rec d'en Garcia 1 (dated 257–430 AD), situated between the montane and subalpine zones at altitudes ranging from 1,858 to 2013 m, the anthracological evidence demonstrates that the main fuel sources were *Pinus* (*Pinus sylvestris* and *Pinus uncinata*), with a lesser, marginal use of *Juniperus*. For the periods and locations examined in the study, surveys excluded *Abies* and *Fagus*, which do not belong to this bioclimatic region and where the drier climatic conditions do not favor them. The pine trees, which are the local species, are the only ones being harvested in these areas.

6.2 Vegetation/anthropization history

The study area has been extensively researched over several decades by scientists in multiple disciplines (paleoecology, palynology, archaeology, and history). Archaeological data has revealed numerous pastoral and agricultural structures and remnants of metallurgical activities, indicating the prehistoric and historic use of highland resources (Davasse et al., 1997; Galop, 1999; Luault, 2020; Rendu, 1987; Rendu et al., 1995; Bal et al., 2010). Historical ecology, based on palynology, has provided long-term insight into the human activity and environmental history of the eastern Pyrenees, and more specifically, on the Cerdan plateau and in the higher altitudes, spanning almost 7,000 years, with a particular focus on fluctuations in the forest's upper limit (Galop, 1998; Guiter et al., 2005; Bal et al., 2010; Vannière et al., 2001).

Among the most prevalent publications, palynological and microcharcoal analyses from the peat bogs of the Pla de l'Orri, located in the high pastoral regions of Enveitg (southern slopes of the Carlit, 2,150 m, Figure 1; Galop, 1998), show a sequence beginning at 6,230+/- 6,000 BP (4,280 BC) with pine dominance. *Abies* is found at lower altitudes until 4,310 +/-60 BP (2,360 BC); at that time, human impact on the environment remained minimal. The *Abies* curve shows three periods of decline, the first in the Middle Neolithic and the second during the Middle Bronze Age, also attested by pedoanthracological studies (Bal et al., 2010). From the end of the Iron Age to the beginning of Antiquity, the pollen analysis indicates the recovery of land by the pine forest and a decline in high-altitude pastoral activities in the Pla de l'Orri area. The last major decline of *Abies* during the Middle Ages was recorded in 760+/60 AD, with a decrease of all arboreal pollen, apophytes having been at their peak during this period. The early Middle Ages marked the beginning of a new phase in the development of pastoral activities, with a significant anthropisation phase dating back to the eighth century (Vannière et al., 2001).

Pollen records from Racou lake (Guiter et al., 2005), situated at an altitude of 2,000 m above sea level on the right bank of the upper Têt river, 12 km northwest of Mont-Louis, show a similar pattern during the Late Holocene with a first decline of *Abies* curve at 2,515 +/- 35 BP and a second just before 1,215 +/-45 BP, suggestive of nearby pastoral activities. As for Pla de l'Orri, this confirms an increase in human pressure during the Middle to Late Neolithic, as evidenced by associated archaeological vestiges (Galop, 1998). Furthermore, the Racou lake pollen records lack sufficiently detailed dates for the last millennium. Generally, the documentation of vegetation dynamics during this period is insufficient, despite numerous palaeoecological studies conducted in the Pyrenees (Guiter et al., 2005). Further west, the Bosc dels Estanyons peat bog (Madriu, Andorra, 2,180 m; Miras et al., 2007) shows a similar vegetation dynamic to that of Pla de l'Orri and the Racou lake. The extension of *Abies* stands begins in around 7,100 BP. Between 7,000 and 6,300 BP (around 5,050 and 4,350 BC), pollen indices (AP/T 60%) show a trend toward a gradual reduction in montane and subalpine forest species (mean values of *Abies* are around 5%). As elsewhere, the Subboreal, which corresponds to the Late Neolithic, saw the first major human expansion in the Pyrenean Mountains. More significant anthropogenic pressures emerged around 2,600 BP (630 AD) including subalpine pine forests and oak and fir forest levels. From 2,050 to 1,800 BP (110–235 AD), all indicators of activity suggest an intensification of pastoral pressure during the Roman period. The subalpine forests are highly degraded, with an arboreal rate of around 20%, the lowest since the Late Glacial period. Site occupation during this period is also attested by the presence of a smithing activity from the first century AD until the first half of the third century AD. Note that smithing, which represents the final step in the metallurgical process, differs significantly from the reduction phase in terms of location, activity and wood requirements. Anthropogenic pressure in Cerdanya continued and intensified from the seventh century onwards (Miras et al., 2007), as it is generally known regionally.

The anthracological results from the Prat d'en Paou and Porté-Puymorens sites, obtained over a short historical period, have enabled us to gain a better understanding of the use of the environment by the population. *Pinus* and *Abies* were present in the montane and subalpine forests during the Visigothic period, but gradually disappeared almost completely from the highland area due to the intensification of human pressure and the modification of forest ecosystems.

Evidence from this study suggests that the records from the sites studied are earlier than the Racou lake records but later than those of Pla de l'Orri and Madriu, which include observations of subalpine forests from the Middle Bronze Age onwards, with different activities from one sector to another (Galop, 1998; Miras et al., 2007; Bal et al., 2010). Therefore, our findings and subsequent examinations highlight the challenge of making generalized assertions about human-environment interactions within a given regional geographic zone. The region's geography is intricate, due to its latitudinal position, diverse altitudes, opposing slopes, valley orientation, resources and timeframe, emphasizing the need to develop micro-regional aspects. As seen in this study, the mountain is a geosystem divided into parcels, with the eastern portion of the Carol valley being devoted to pastoralism, while metallurgical activity was concentrated in the western area.

6.3 Techniques and settlement

The mountain environment is widely acknowledged to be a constantly evolving region that is vulnerable to climate alterations and human influence and pressure. Additionally, the erosive processes in this area are aggressive, leading to the poor conservation of archaeological remains. Often partly destroyed, visible remains therefore only represent part of the reality. As a result, it is difficult to quantify iron mining and smelting activities in the Carol valley and on the Puymorens pass. Very early traces from the Visigothic period have been discovered and at least three phases have been identified. Based on our present knowledge, they are unconnected to any previous or subsequent activity. The nearest Roman remains are found at a straight-line distance of more than 35 km, at Vicdessos (Ariege, France) and Canigou (Pyrénées-Orientales, France).

Excluding smithing as a separate activity, iron production necessitates specialized techniques and was split into at least three distinct activities demanding different skill sets (mining, smelting, and forging). In the Roman and medieval world in western Europe, mining, charcoal burning and iron ore smelting were carried out by different specialists (Pagès, 2010). These activities were not performed by the same people, due to the advanced skills required for each.

The extraction and smelting of iron ore in the Carol Valley and on the Puymorens pass would have required the arrival and settlement of people proficient in both mining and metallurgy. Coal production may have been a native activity, but it experienced significant growth in the region due to the influence of metallurgy, possibly utilizing local expertise. The presence of metallurgists — but also of miners as a consequence — therefore implies that the area was frequently occupied for metallurgical activity during the Visigothic period. Metallurgical infrastructure was assimilated into the pre-existing network of settlements and activities, potentially enhancing the forestry "industry" in the Carol valley and on the Puymorens pass (Luault, 2019, 2020). Nonetheless, all operations took place only during the summer months, after the snow had thawed.

It is challenging to determine precisely why metallurgists and miners operated the Puymorens mine, with the assistance of the local population, on a consistent seasonal basis during the Visigothic period. Multiple factors must be considered to answer this question. Studies conducted since 2010 have shown that such exploitations are prevalent in the northwestern Mediterranean. From the decline of the Roman Empire onwards, metallurgists increasingly operated in steeper and higher-altitude areas, in both the Alps and the Pyrenees (Pagès, 2010, 2017; Pagès et al., 2022). Was this due to a shortage of wood at lower altitudes, due to heavy forest exploitation during the Roman era? Or was it a result of the exploitation of new territories that were more conducive to new economic models? The explanation is undoubtedly multifactorial. It is essential to carry out an increased number of high-resolution interdisciplinary investigations of metallurgical contexts, while placing the discussion in a micro-regional framework.

7 Conclusion

Thanks to an integrated archaeological and anthracological investigation conducted over a region covering 400 km^2, it is now possible to reconstruct partially early iron exploitation at the Puymorens mine in the Pyrenees mountains, which is the highest-altitude mine in the region, at more than 2,100 m above sea level. At the end of the Roman Empire and especially during the Visigothic period, a population of miners and metallurgists settled in the area to exploit the mine on a regular seasonal basis. They went on to produce iron nearby at workshops situated at lower altitudes, between 1,400 and 2,000 m, making use of the available forest resources. This industry was likely part of a preexisting network of settlements and land usage in the mountains, especially for farming and pasturing activities, which flourished in the fifth and sixth centuries. Consequently, this metallurgical industry was part of an active economic framework. Woodland and fuel resources were exploited near the smelting sites. The anthracological spectra are characterized by very low taxonomic diversity and a large predominance of *Pinus* and *Abies* which corresponds to the low diversity of species in the montane and subalpine environment of this montane area. There was no selection of species; the supply was simply based on the availability of local wood. According to this analysis, it is likely that the forest's upper limit was higher in the past. Subalpine *Pinus* forests were exploited first, followed by montane *Abies* and *Pinus* forests. Smelting site locations followed this pattern, moving lower and lower during the Visigothic period. This shift could indicate that the significant need for wood for iron smelting has contributed, at least in part, to the forest's decline in this area.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

Author contributions

GP: Writing – original draft, Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization. M-CJ-S: Writing – original draft, Conceptualization, Data curation, Formal analysis, Methodology, Resources, Visualization.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Baas, P., Blokhina, N., Fujii, T., Gasson, P., Grosser, D., Heinz, I., et al. (2004). IAWA list of microscopic features for softwood identification. *IAWA J.* 25, 1–70. doi: 10.1163/22941932-90000349

Bagnouls, F., and Gaussen, H. (1953). Saison sèche et indice xérothermique. *Documents Cartographiques de la Production Végétale des Services Généraux* 8:47.

Bal, M.-C., Rendu, C., Ruas, M.-P., and Campmajo, P. (2010). Paleosol charcoals: reconstructing vegetation history in relation to agro-pastoral activities since the Neolithic. *A case study in the Eastern French Pyrenees. J. Archaeol. Sci.* 37, 1785–1797. doi: 10.1016/j.jas.2010.01.035

Balent, A. (2005). "La mine de fer de Puymorens (Cerdagne) : conflits de propriété et d'usage (XVIIe-XXe s.)," in *Les ressources naturelles des Pyrénées du Moyen Âge à l'Epoque Moderne (Actes du congrès international Resopyr 1)*, ed. A. Catafau (Perpignan: Presses Universitaires de Perpignan), 423–452.

Balent, A. (2016). La farga de La Llata, Vall de Querol (Cerdanya). *Records de l'Aravó* 12, 12–20.

Besson, M. (1991). *Carte géologique de la France à 1/50000—Fontargente—Notice explicative*. Orléans: Editions du BRGM.

Calastrenc, C., Baleux, F., Laurent, A., Poirier, N., Llubes, M., Philippe, M., et al. (2024). Inspecter les zones d'altitude : programme TAHMM ou le développement d'une procédure multi-source pour la prospection archéologique des terrains d'altitude. *ArcheoSciences, revue d'archéométrie* 47, 105–122. doi: 10.4000/archeosciences.12009

Caruso Fermé, L., and Théry-Parisot, I. (2011). Experimentation and combustion properties of Patagonian Andean wood. *Sagvntvm Extra* 11, 39–40.

Chabal, L. (1997). Forêts et sociétés en Languedoc (Néolithique final Antiquité tardive): L'anthracologie, méthode et paléoécologie. *Éditions de la Maison des sciences de l'homme* 1997:43380. doi: 10.4000/books.editionsmsh.43380

Chabal, L., Fabre, L., Terral, J.-F., and Théry-Parisot, I. (1999). "L'anthracologie," in *La Botanique*, eds. C. Bourquin-Mignot, J.-E. Brochier, L. Chabal, S. Crozat, L. Fabre, F. Guibal, et al. (Paris: Collection "Archéologiques"), 43–104.

Davasse, B., Galop, D., and Rendu, C. (1997). "Paysages du Néolithique à nos jours dans les Pyrénées de l'est d'après l'écologie historique et l'archéologie pastorale," in *La dynamique des paysages protohistoriques, antiques,médiévaux et modernes, XVIIe Rencontres internationales d'archéologie et d'histoire d'Antibes, Antibes 1996* (Sophia-Antipolis: A.P.D.C.A. ed.), 577–599.

Figueiral, I., and Mosbrugger, V. (2000). A review of charcoal analysis as a tool for assessing Quaternary and Tertiary environments: achievements and limits. *Palaeogeogr. Palaeoclimatol. Palaeoecol. Fire Palaeoenviron.* 164, 397–407. doi: 10.1016/S0031-0182(00)00195-4

Fouédjeu, L., Burri, S., Saulnier, M., Larrieu, L., Paradis-Grenouillet, S., and Py-Saragaglia, V. (2022). Did the charcoal-based iron industry really drive the forest cover decline in the Northern Pyrenees? *Anthropocene* 38:100333. doi: 10.1016/j.ancene.2022.100333

Galop, D. (1998). *La forêt, l'homme et le troupeau dans les Pyrénées. 6000 ans d'histoire de l'environnement entre Garonne et Méditerranée*. Toulouse: Geode-Université de Toulouse Le Mirail.

Galop, D. (1999). "Le parchemin et le pollen: la Cerdagne médiévale, de l'archive écrite à l'archive naturelle," in *Les sociétés méridionales à l'âge féodal (Espagne, Italie et sud de la France Xe-XIIIe siècle): Hommage à Pierre Bonnassie* (Toulouse: Presses universitaires du Midi), 3.

Gaussen, H. (1925). Le pin à crochets dans les Pyrénées. *Bulletin de la société d'histoire naturelle de Toulouse* 3, 150–157.

Gaussen, H. (1938). Les forêts de l'Aude et de la Cerdagne. *Revue géographique des Pyrénées et du Sud-Ouest, tome 9, fascicule 3* 1938, 293–302. doi: 10.3406/rgpso.1938.1100

Gruber, M. (1978). *La végétation des Pyrénées ariègeoises et catalanes occidentales.* Marseille: Université de Marseille I, 305.

Gruber, M. (1980). Le Hêtre et le Sapin dans la chaîne pyrénéenne. *Revue forestière française* 32, 364–372. doi: 10.4267/2042/21419

Gruber, M. (1981). Espèces indicatrices des différents étages de végétation dans les Pyrénées. *Bulletin de la Société Botanique de France Lettres Botaniques* 128, 295–302. doi: 10.1080/01811797.1981.10824515

Guiter, F., Andrieu-Ponel, V., Digerfeldt, G., Reille, M., de Beaulieu, J.-L., and Ponel, P. (2005). Vegetation history and lake-level changes from the Younger Dryas to the present in Eastern Pyrenees (France): pollen, plant macrofossils and lithostratigraphy from Lake Racou (2000 m a.s.l.). *Veget. Hist. Archaeobot.* 14, 99–118. doi: 10.1007/s00334-005-0065-z

Jacquiot, C. (1955). *Atlas d'anatomie des bois de conifers* (Paris: CTB), 133.

Kabukcu, C., and Chabal, L. (2021). Sampling and quantitative analysis methods in anthracology from archaeological contexts: achievements and prospects. *Quater. Int.* 593–594, 6–18. doi: 10.1016/j.quaint.2020.11.004

Lallemand, V., Kotarba, J., and Rendu, C. (2022). Archéologie préventive et programmée en montagne Le haut bassin de la Cerdagne (Pyrénées-Orientales). *Archéopages- Archéologie nationale Recherche Expertise Patrimoine* HS06, 170–176. doi: 10.4000/archeopages.12531

Leroy, M., Merluzzo, P., Fluzin, P., Leclere, D., Aubert, M., and Ploquin, A. (2000). "La restitution des savoir-faire pour comprendre un procédé technique: l'apport de l'expérimentation en archéologie du fer," in *Arts du feu et productions artisanales, XXe Rencontre Internationale d'Archéologie et d'Histoire d'Antibes, Antibes, 21–23 octobre 1999,* eds. P. Pétrequin, P. Fluzin, and J. Thiriot (Antibes: A.P.D.C.A. ed.), 37–52.

Luault, N. (2019). Entre ville et montagne : premiers jalons pour une étude de l'habitat de hauteur en Cerdagne (Pyrénées-Orientales, Ve-VIe siècle). *Archéologie du Midi Médiéval* 37–38, 291–310.

Luault, N. (2020). *Entre ville et montagne: habitat, peuplement et terroirs dans les Pyrénées de l'Est de l'Antiquité tardive au Moyen Âge (Cerdagne, IIIe-XIIe siècle)*. Toulouse: Université Toulouse le Mirail - Toulouse II, 306, 228.

Mach, J., and Pagès, G. (2021). Le Pla de les Iules 1 : premier jalon sur la production du fer ancienne dans la haute vallée de Carol. *Records de l'Aravó* 17, 6–12.

Marguerie, D. (1992). *Évolution de la végétation sous l'impact humain en Armorique du Mésolithique aux périodes historiques: études palynologiques et anthracologiques des sites archéologiques et des tourbières associées. Travaux du Laboratoire d'Anthropologie, Préhistoire, Protohistoire et Quaternaire armoricains 40* (Rennes: Université Rennes 1), 313.

Marguerie, D., Bernard, V., Begin, Y., and Terral, J.-F. (2010). "Anthracologie et dendrologie," in *La dendroécologie: principes, méthodes et applications*, eds. S. Payette and L. Filion (Québec, QC: Presses de l'Université Laval), 311–350.

Marguerie, D., and Hunot, J.-Y. (2007). Charcoal analysis and dendrology: data from archaeological sites in north-western France. *J. Archaeol. Sc.* 34, 1417–1433. doi: 10.1016/j.jas.2006.10.032

Meunier, E. (2023). *L'exploitation minière dans le sud-ouest de la Gaule entre le second âge du Fer et la période romaine le district de l'Arize dans le contexte régional.* Bordeaux: Ausonius éditions.

Michel, A. (1951). La limite altitudinale de la végétation forestière dans les Pyrénées-Orientales. *Revue forestière française* 4, 274–280. doi: 10.4267/2042/27773

Miras, Y., Ejarque, A., Riera, S., Palet, J. M., Orengo, H., and Euba, I. (2007). Dynamique holocène de la végétation et occu- pation des Pyrénées andorranes depuis le Néolithique ancien d'après l'analyse pollinique de la tourbière de Bosc dels Estanyons (2180 m, Vall del Madriu, Andorre). *Comptes-Rendus Palevol* 6, 291–300. doi: 10.1016/j.crpv.200702.005

Pagès, G. (2010). *Artisanat et économie du fer en France méditerranéenne de l'Antiquité au début du Moyen Âge : une approche interdisciplinaire*. Montagnac: Monique Mergoil.

Pagès, G. (2017). "Des tas de déchets petits et grands : vers des critères d'enregistrements communs nécessaires aux bases de données pour étudier dans la diachronie les productions sidérurgiques," in *ArqueoPyrenae "L'explotació dels recursos naturals al Pirineu oriental en època antiga", Acta di primer colloqui (Blovir, 2015) Trebals d'Arqueologia*, eds. O. Olesti i Vila, J. Oller Guzmán, and J. Morera Camprudí (Barcelone: Universitat Autònoma de Barcelona), 247–262.

Pagès, G., Dillmann, P., Vega, E., Berranger, M., Bauvais, S., Long, L., et al. (2022). Vice-versa: the iron trade in the western Roman Empire between Gaul and the Mediterranean. *PLoS One* 17:5. doi: 10.1371/journal.pone.0268209

Puech, E., Bamford, M., Porraz, G. E., Val, A., and Théry-Parisot, I. (2020). Evaluating sampling methods in charcoal-rich layers and high diversity environment: a case study from the Later Stone Age of Bushman Rock Shelter, South Africa. *Quater. Int.* 11:18. doi: 10.1016/j.quaint.2020.11.018

Py-Saragaglia, V., Cunill-Artigas, R., Métailié, J.-P., Ancel, B., Baron, S., Paradis-Grenouillet, S., et al. (2017). Late Holocene history of woodland dynamics and wood use in an ancient mining area of the Pyrenees (Ariege, France). *Quater. Int.* 458, 141–157. doi: 10.1016/j.quaint.2017.01.012

Rendu, C. (1987). "Quelques jalons pour une histoire des forêts en Cerdagne: le massif d'Osseja entre 1030 et 143," in *Études roussillonnaises offertes à Pierre Ponsich*, eds. M. Grau and O. Poisson (Perpignan: Le Publicateur), 245–251.

Rendu, C., Campmajo, P., Davasse, B., and Galop, G. (1995). "*Habitat, environnement et systèmes pastoraux en montagne*. Acquis et perspectives de recherches à partir de l'étude du territoire d'Enveig," in *Cultures i medi de la prehistòria a l'edat mitjana. Xe Colloqui internacional d'arqueólogia de Puigcerda. Homenatge al Professor Jean Guilaine* (Puigcerdà: Institut d'Estudis ceretans), 661–673.

Schmider, B. (1978). L'industrie lithique de la grotte de La Vache, commune d'Alliat (Ariège). *Bull.Soc. Préhist. De l'Ariège* 33, 13–56.

Schweingruber, F. H. (1982). *Microscopic Wood Anatomy: Structural Variability of Stems and Twigs in Recent and Subfossil Woods From Central Europe, 2nd Edn* (Teufe: F. Flück-Wirth), 226.

Schweingruber, F. H. (1990). *Anatomy of European Woods: An Atlas for the Identification of European Trees, Shrubs and Dwarf Shrubs* (Bern; Stuttgart: Eidgenössische Forschungsanstalt für Wald, Schnee und Landschaft, Paul Haupt), 800.

Shackleton, C. M., and Prinsh, F. (1992). Charcoal analysis and the "Principle of Least Effort"—a conceptual model. *J. Archaeol. Sci.* 19, 631–637. doi: 10.1016/0305-4403(92)90033-Y

Théry-Parisot, I., and Henry, A. A. (2012). Seasoned or green? Radial cracks analysis as a method for identifying the use of green wood as fuel in archaeological charcoal. *J. Archaeol. Sci.* 39, 381–388. doi: 10.1016/j.jas.2011.09.024

Trouy-Jacquemet, M.-C. (2023). *Atlas des bois résineux de France: Outil d'identification multi-échelles.* Versailles: éditions Quæ; Collection Guide pratique, 240.

Vannière, B., Galop, D., Rendu, C., and Davasse, B. (2001). ≪ Feu et pratiques agro-pastorales dans les Pyrénées Orientales: le cas de la montagne d'Enveitg (Cerdagne, France). *Sud-Ouest européen* 11, 29–42. doi: 10.3406/rgpso.2001.2765

Vernet, J.-L., Ogereau, P., Figueiral, I., Machado Yanes, C., and Uzquiano, P. (2001). *Guide d'identification des charbons de bois préhistoriques et récents: Sud-Ouest de l'Europe: France, Péninsule ibérique et îles Canaries*. Paris: Editions du Centre National de la Recherche Scientifique.

Wheeler, E., Baas, P., and Gasson, P. (1989). IAWA list of microcopic features for hardwood identification. *IAWA J.* 10, 219–332. doi: 10.1002/fedr.19901011106

Wheeler, E. A. (2011). Inside Wood—a Web resource for hardwood anatomy. *IAWA J.* 32, 199–211. doi: 10.1163/22941932-90000051