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## Did the charcoal-based iron industry really drive the forest cover decline in the Northern Pyrenees?

Léonel Fouedjeu Foumou, Sylvain Burri, Mélanie Saulnier, Laurent Larrieu,  
Sandrine Paradis- Grenouillet, Vanessa Py

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1 **Did the charcoal-based iron industry really drive the forest cover decline in the Northern Pyrenees?**

2

3 **Authors** : Léonel Fouédjeu<sup>1\*</sup>, Sylvain Burri<sup>2\*</sup>, Mélanie Saulnier<sup>1</sup>, Laurent Larrieu<sup>3,4</sup>, Sandrine Paradis-  
4 Grenouillet<sup>5,6</sup> and Vanessa Py-Saragaglia<sup>1</sup>

5 <sup>1</sup> GEODE UMR 5602 CNRS, Université de Toulouse Jean Jaurès, Maison de la recherche, 5 allées Antonio  
6 Machado 31058 Toulouse cedex 9, France.

7 <sup>2</sup> TRACES UMR 5608 CNRS, Université de Toulouse Jean Jaurès, Maison de la recherche, 5 allées Antonio  
8 Machado 31058 Toulouse cedex 9, France.

9 <sup>3</sup> INRAE, UMR DYNAFOR, Université de Toulouse, 24 Chemin de Borde Rouge - Auzeville CS 52627, 31326  
10 Castanet-Tolosan Cedex, France

11 <sup>4</sup> CRPF-Occitanie, antenne de Tarbes, place du foirail, 65000 Tarbes, France

12 <sup>5</sup> GEOLAB UMR 6042, Université de Limoges, 39 E rue Camille Guérin, 87000 Limoges, France.

13 <sup>6</sup> Eveha, bureau d'étude en archéologie préventive, 31 rue Soyouz, 87000 Limoges

14 \* Léonel Fouédjeu and Sylvain Burri are jointly first authors

15 **Abstract**

16 Through a reconstruction of the chronology and intensity of charcoal-making activities, this paper re-opens the  
17 debate about the supposed impact of the charcoal iron industry on forest cover in the French Pyrenees. This  
18 reappraisal focuses on the former territory of the communities of Haut-Vicdessos valley. This more refined  
19 chronology, based on the analyses of historical documents (n=617) and charcoal kiln remains (n=42), has  
20 highlighted the non-linear industrial development. The emergence of water-powered bloomeries during the early  
21 14th c. led to a brief expansion of the iron industry, but was followed by a slowdown in the 15th c. The combined  
22 effect of regulation and the outsourcing of a part of the charcoal supply on other territories, mitigated the impact  
23 of the iron industry on local forest, avoiding a forest crisis. The most significant industrial growth occurred from  
24 the mid-17th c. with development of the Catalan bloomery. Forests underwent major changes in structure and  
25 composition but cover was maintained to satisfy the local economy and people's needs. Charcoal production  
26 always occurred in well-stocked forests dominated by beech and fir. The increase of charcoal supply combined to  
27 the agro-pastoral growth led to the prohibition of charcoal-making in the mid-18th c. and to the exclusive recourse  
28 to an external fuel supply. Minimum forest cover was only reached in the mid-19th c. due to the demographic  
29 explosion resulting in the increase of daily needs and in the refocus on agro-pastoral economy. Conversely to the

30 common premise, the iron charcoal industry in European mountains did not necessarily induce forest depletion but  
31 rather its maintenance through sustainable management and policies.

32 **Key words:** charcoal iron industry, fuel supply, historical archives, charcoal kiln analysis, forest cover decline,  
33 Northern Pyrenees

34

35

## 36 **Introduction**

37 Starting in the mid-17th c., at a time when Navy officials, elites, urban and rural communities feared the exhaustion  
38 of forests and their wood supply, the impact of pre-industrial activities and common uses on forest cover was  
39 debated all around Europe (Warde, 2006; 2015). At this time, the growing charcoal iron industry was accused of  
40 sharply reducing forest cover (Devèze, 1964). Historical studies mostly deemed charcoal-based iron smelting as  
41 the most important driver of deforestation, leading to the mid-19th c. minimum forest cover in Western Europe  
42 (Mather, 1992), in addition to agro-pastoral uses and clearing (Ashton, 1924; Sclafert, 1926; Chevalier, 1956, pp.  
43 529–538; Houzard, 1983). Based on experimental fuel estimates, archaeologists have supported this assertion  
44 (Pleiner, 2000, pp. 126–129). However, some researchers have mitigated the impact of charcoal iron smelting  
45 considering forest management and social practices (Birrell, 1969; Hammersley, 1973; Lindsay, 1975; Belhoste,  
46 1990; Voss, 1995).

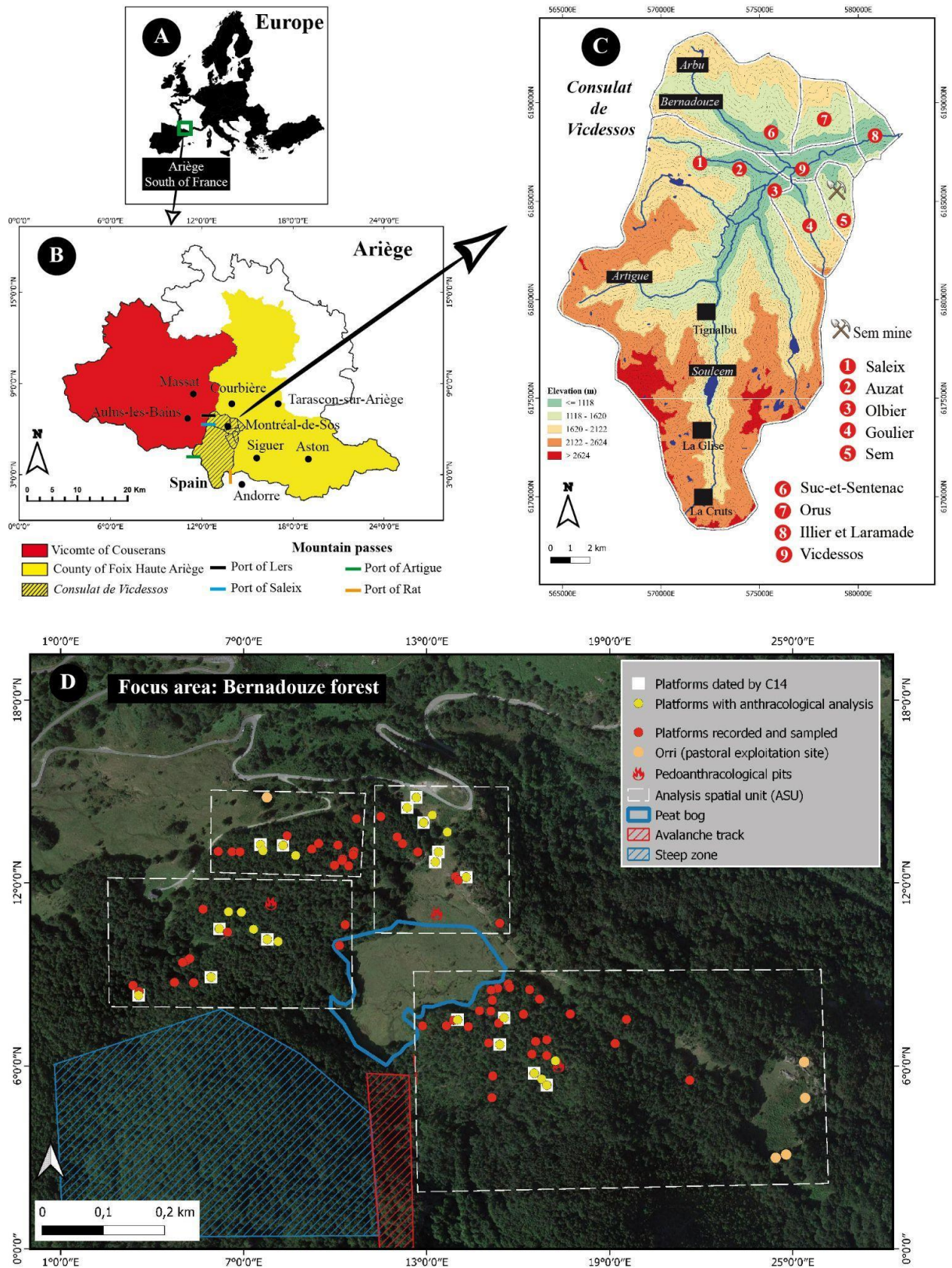
47 Studies of metallurgy-related remains combining archaeology and charcoal analysis have renewed our knowledge  
48 and deepened our understanding of forest-industry interactions in pre-industrial times (Backer et al., 1992;  
49 Bielenin, 1992; 1992; Bonhôte, 1998; Davasse, 2000; Montanari et al., 2002; Gale, 2003). In the 2000s, charcoal  
50 kiln remains (hereafter platforms) became privileged tools for assessing how charcoal metallurgy modified forest  
51 ecosystems, thanks to the improvement of charcoal analysis and remote-sensing methods (Ludemann and Nelle,  
52 2002; Paradis-Grenouillet et al., 2015; Hazell et al., 2017; Rassat et al., 2018; Gana and Malik, 2019; Deforce et  
53 al., 2020). Nevertheless, an improved characterisation of the impact of iron charcoal metallurgy on woodlands also  
54 requires an accurate assessment of the running time and productivity of ironworks, as well as an understanding of  
55 how users ensured their fuel supply and its sustainability (Woronoff, 1990; Baraldi, 1993; Horikoshi, 2008;  
56 Arribet-Deroin, 2013; 2018; Oury, 2020).

57 From the 1990s, the French Pyrenees is a pioneering multidisciplinary laboratory for the study of human-  
58 environment interactions, bringing together historians, geographers, archaeologists and palaeoecologists. Previous  
59 researches provided the first syntheses correlating the history of the charcoal iron industry to the evolution of  
60 woodland cover in the late Holocene in several Pyrenean valleys (Métailié and Jalut, 1991; Galop and Jalut, 1994;  
61 Bonhôte, 1998; Davasse, 2000; Bonhôte et al., 2002). The Haut-Vicdessos valley has received particular attention  
62 because of its long-lasting iron industry associated with the Sem mines (Verna, 2001; Cantelaube, 2005).  
63 Variations in the intensity of this activity through time, however, remained largely unknown (Py-Saragaglia et al.,  
64 2019). Despite the scarcity of written and archaeological data, the common working hypothesis was the continuity,

65 or even the increase, of iron production between Gallo-Roman times and the 14th c. AD (Dubois, 2000). Moreover,  
66 historical research has focused on the development of iron metallurgy made possible by the technical innovation  
67 of the water-powered direct bloomery, called *moulines*, at the turn of the 14th c. (Verna, 2001), while  
68 archaeological surveys carried out in some parts of the valley demonstrated that platforms became significantly  
69 abundant only from the 16th c. onwards (Bonhôte et al., 2000; Davasse, 2000; Dubois and Métailié, 2001). The  
70 strong fluctuations in the iron economy during the early modern era (Woronoff, 1984; Bonhôte, 1998; Davasse,  
71 2006) suggested a highly variable pressure on local forest resources.

72 At variance with the common assumption that it induced forest depletion due to intense harvesting (Galop and  
73 Jalut, 1994; Verna, 2001; Bonhôte et al., 2002; Galop et al., 2013), Davasse (2000) suggested that charcoal iron  
74 metallurgy was based on specific woodland management practices. Little is known, however, about the evolution  
75 of former silvicultural practices and how they drove forest ecosystem change. Moreover, silvopastoralism, wood-  
76 based crafts and domestic uses were likely considered in forest management strategies (Davasse, 2000).  
77 Consequently, a revision of the iron industry-induced forest depletion assumption is crucial to improved  
78 understanding of how this activity actually interacted with the formation of the mid-19th c. open dominated  
79 landscapes.

80 This paper proposes to reconsider the history of the iron-charcoal industry fuel supply and its impact on forest  
81 cover in the Haut-Videssos. The global and integrated study is based on (i) a review and original analysis of  
82 historical archives, (ii) previous historical ecology studies conducted in the Soulcem and Artigue valleys, and (iii)  
83 original data from archaeological and charcoal analysis produced in the Suc-et-Sentenac valley (hereafter Suc).  
84 On the basis of this data, we address the following research questions: (i) what were the variations of the iron  
85 industry over time? (ii) To what extent did the fuel demand involve specific forest management strategies? (iii) To  
86 what extent did fuel consumption drive environmental changes leading to a reduction in forest cover?



87

88 Fig.1: (A) European and national location; (B) *consulat de Vicdessos* location in Ariège administrative district;

89 (C) Mapping of the *consulat de Vicdessos* and locations of study areas (Bernadouze forest -focus area-, Arbu,

90 Artigue, Soulcem -Tignalbu, La Glise, La Cruts-), (D) Focus area with (i) platforms recorded and sampled (red

91 points), (ii) platforms dated by C14 (white squares), (iii) 28 platforms with charcoal analysis (yellow points), (iv)  
92 sampling points for pedoanthracological analysis (small fires) published in Saulnier et al. (2020), (v) pastoral sites  
93 (orange points). The focus area is divided into four Analysis Spatial Units (ASU) surrounded by white dotted lines.

## 94 **1. Material and methods**

### 95 **1.1. Study area**

96 The study area is a north-south oriented valley (a. 23,000 ha) located in the central French Pyrenees (Ariège) and  
97 connected with Spain and Andorra by several mountain passes that facilitated trade (Fig. 1 A, 1B). The Haut-  
98 Vicdessos was part of the early medieval Sabarthès which was progressively incorporated to the County of Foix  
99 between the 10th-12th c. (Pailhès, 2006; Guillot, 2009). Starting in the late 13th c., the local communities were  
100 grouped into the *consulat de Vicdessos*, an administrative district covering the Haut-Vicdessos valley (Fig. 1C).  
101 The ownership of ore, forest and water resources belonged to the earl of Foix before passing to the French crown  
102 in 1607. In 1786, the former *consulat de Vicdessos* and the neighboring *consulat de Siguer* merged into the *canton*  
103 *de Vicdessos*.

104 Since 2010, this area has comprised the Human-Environment Observatory of Haut-Vicdessos devoted to the  
105 interdisciplinary study of mountain socio-ecosystems. The Bernadouze forest in Suc, which is an  
106 Instrumented Site in Global Ecology, provides a focus area where several in-depth studies have already been  
107 implemented (Py-Saragaglia et al., 2019; Saulnier et al., 2020; Fouédjeu et al., 2021b; 2021a). Current vegetation  
108 around Bernadouze peat bog is almost exclusively composed of beech (*Fagus sylvatica* L.). Beech woods exist in  
109 three different forms: (i) high forest (between 130 and 160 years old) resulting from the conversion of former  
110 coppices with scattered young silver fir trees (*Abies alba* Mill.), (ii) on the edge of the bog, tall-grown coppices  
111 browsed in the past by livestock and (iii) in some places, tall-grown coppices of old trees resulting from historical  
112 silvicultural treatments. This forest composition and structure is representative of former mountain charcoal  
113 manufacturing forests in the Ariège Pyrenees (Davasse, 2000).

### 114 **1.2. Historical approach**

115 We performed a review of previous historical studies focusing on (i) iron metallurgy from medieval to  
116 contemporary times (Rouzaud, 1908; Cantelaube, 1992; 2005; 2009; Verna, 1994; 1996; 2001; 2003; Verna and  
117 Cantelaube, 2000; Cabau de Fauroune, 2021), (ii) Pyrenean economy and society (Barbe, 1900; Dufau de

118 Maluquer, 1910; Dengerma, 1934; Chevalier, 1956; Pailhès, 1992; 2006; Ruffié, 1997; 2003; Poujade, 2008;  
119 Guillot, 2009), (iii) historical ecology of forest ecosystems (Taillefer, 1939; Bonhôte and Fruhauf, 1990; Bonhôte  
120 et al., 2000; Dubois and Métailié, 2001). This literature review was supplemented by an original analysis of  
121 unpublished medieval and post-medieval documents (Supplementary file 1).

122 The synthesis comprises a total of 617 documents unequally distributed: 4 for the 13th c., 18 for the 14th c., 2 for  
123 the 15th c., 81 for the 16th c., 331 for the 17th c. and 181 for the 18th c.. Medieval and early modern written  
124 records are poorly preserved. Besides a few original Latin diplomas, a large part of the medieval documentation is  
125 composed of modern copies and/or French translations and brief summaries of the vanished acts. The 16th c.  
126 presents a few more documents thanks to several notarial deeds (purchases, debts, exploitation contracts, etc.) and  
127 the accounting registers of the County of Foix (from 1580s). These two types of sources constitute most of the  
128 17th c. material, in addition to the 1669 Forest Reformation archives. Data remains very qualitative until the second  
129 part of the 17th c. For the 18th c., we focused our original study on Vicdessos Council deliberations. We only used  
130 published data regarding the 19th c.

### 131 **1.3. Archaeological investigations**

132 While we only used published data concerning mining and iron ore smelting-related archaeological sites (Bonhôte  
133 and Cantelaube, 1986; Dubois and Métailié, 2001; Disser and Dubois, 2017; 2018; 2019; Dubois and Disser,  
134 2020); we performed an original systematic archaeological survey on 46-ha, i.e. in the Bernadouze peat bog buffer  
135 zone (Fouédjeu et al., 2021b) according to the methodology described in Py-Saragaglia et al. (2017, 2018) (Fig.  
136 1D). Platforms were sampled using a soil auger, preferably on the central part, with stepwise sampling at every  
137 20 cm of depth until the continuous mineral layer is reached. The focus area was divided into four “Analysis  
138 Spatial Units” (ASU) (Fig. 1D) according to their exposure and topography. In each ASU, we randomly selected  
139 4 to 9 platforms (n=28), i.e. about 35% of the total number of inventoried platforms, for charcoal analysis.

- 140 - ASU 1 includes tall-growing coppices, high forest and open grazing area, and is located on a gentle, north  
141 facing slope. We selected platforms 1, 4, 6, 7, 8, 9, 10 and 62.
- 142 - ASU 2 is located on the northwest part of the peat bog, within the high beech forest. The selected  
143 platforms (27, 34, 35 and 36) are located on a ridge line of a small relief overhanging the ASU.
- 144 - ASU 3 is located south of the peat bog, on a gentle north-facing slope within the high beech forest,  
145 overhung by a cliff and a very steep slope. We selected the platforms 11, 14, 17, 18, 19, 63, 64 and 65.



146 - ASU 4 corresponds to a relatively steep slope, facing northeast, in the western part of the focus area's  
147 watershed. We selected platforms 29, 31, 44, 47, 48, 49, 73, 74 and 79 located under the high beech forest.

148 These original data have been completed by a synthesis of previous studies performed in Arbu (Py-Saragaglia et  
149 al., 2019) and in the Artigue and Soulcem valleys (Davasse, 2000, pp. 155–157).

#### 150 **1.4. Laboratory analyses**

151 In the focus area, charcoal taxonomic determination was carried out using a reflected light microscope (Leica  
152 DM4) with magnifications of 100 - 1000 according to the three anatomical planes of wood (transverse, tangential  
153 and radial), xylological atlases (Schweingruber, 1990; Vernet et al., 2001) and the reference collection of the  
154 GEODE laboratory. Charcoals were identified at the level species, genus, family or sub-family. Moreover, we  
155 performed a multiproxy approach on charcoal, integrating the study of hyphae infestation of cells and radial cracks,  
156 allowing to assess the state of wood before carbonization and finally, wood diameter reconstruction, allowing to  
157 characterize the size of the wood used by the charcoal burners (Fouédjeu et al., 2021b). When charcoal has retained  
158 bark cells, we reconstruct the logging season based on the state of progress of the last ring's formation. Concerning  
159 Artigue and Soulcem, we used charcoal data published in Métailié and Jalut (1991) and Davasse (2000).

160 We randomly selected 17 platforms distributed in all ASUs and one sampling layer per platform, usually the  
161 deepest one, has been radiocarbon dated (Fig. 1D; Table 1). Due to the considerable depth of platform 17, we dated  
162 both the deepest and the uppermost layer. To avoid the “old tree effect” i.e. reducing the “inbuilt age” (Stouvenot  
163 et al., 2013), we selected young twigs with bark, and/or charcoal fragments with bark and/or, if such charcoal has  
164 not been preserved, bark fragments alone. Accelerator Mass Spectrometry (AMS) C14 dates were calibrated using  
165 OxCal (Reimer et al., 2013). To get a temporal overview of charcoal production activity at the *consulat de*  
166 *Vicdessos* level (Fig. 1C), we integrated former radiocarbon dates from Arbu (Py-Saragaglia et al., 2019), Artigue  
167 and Soulcem (Métailié and Jalut, 1991; Davasse, 2000).

168 We performed statistical analyses using R software 3.5.1 (R Core Team, 2018) with “stats” and “graphics”  
169 packages. A hierarchical ascendant classification gathered the platform layers into clusters, based on the tree-  
170 species platforms composition similarity. We used the Ward's minimum variance criterion (ward.D2) to implement  
171 the hierarchical ascendant classification, in order to minimize the total within-cluster variance or, to be more  
172 precise, to minimize increase in the sum-of-squares (of errors) (Ward, 1963).

173 **2. Results**

174 **2.1. Variation of iron industry intensity according to historical data**

175 The first textual evidence of mining and iron ore smelting in this area only dates back to 1294<sup>1</sup>, but the charter  
176 recorded earlier activity that is impossible to date accurately. The first decades of the 14th c. are marked by the  
177 birth and development of water-powered direct iron metallurgy, supported by the Earl of Foix<sup>2</sup>. However, the first  
178 mention in the *consulat de Vicdessos* dates from 1390 with two running bloomeries reported and another already  
179 inactive<sup>3</sup> (Figs. 3, 5, 7). C. Verna assumed that these *moulines* were created before the second half of the 14th c.,  
180 and were preceded by unpowered bloomeries. Underground mining works were clearly established at Sem, as they  
181 required exploitation regulation in 1414. The 15th c. saw a decrease in the number of water-powered bloomeries,  
182 from two to one, caused by an economic crisis in the local iron trade and political instability<sup>4</sup> (Figs. 3, 7).

183 Our original study invalidates the former assumption of a considerable growth in the iron industry during the 16th  
184 c., based on (i) the economic recovery of the first half of 16th c., (ii) the French Wars of Religion-related iron  
185 demand boost, and iii) the emergence of the more productive “Genoa style” direct watered-bloomery. From the  
186 mid-15th to early 16th. c., the iron industry did not recover<sup>5</sup> (Fig. 3). A small revival occurred in the 1530s with  
187 one new bloomery<sup>6</sup> (Fig. 4). The same two *moulines* were still running in 1553<sup>7</sup> and 1560-61<sup>8</sup> (Figs. 3,4,7). During  
188 the second half of the century, while six new *moulines* were recorded in enfeoffment acts<sup>9</sup>, some of them were  
189 likely never built<sup>10</sup> or were only built later<sup>11</sup>. Other bloomeries were short lived, and sometimes rebuilt later<sup>12</sup>  
190 (Figs. 3-6). The success of these entrepreneurial initiatives faced repeated plague epidemics and insecurity. War  
191 did stimulate iron demand, but it restricted industrial development at the same time. Due to the return to relative  
192 security, the bloomeries number provisionally rose to three for the 1582-1595 period<sup>13</sup>, before decreasing to two  
193 in 1596<sup>14</sup> (Fig. 3,4,5, 7). Abandoned projects or the short life of some upper-valley bloomeries might also have

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<sup>1</sup> Supplementary file 1, doc n°3.

<sup>2</sup> Supplementary file 1, doc. n°8.

<sup>3</sup> Supplementary file 1, doc n°21.

<sup>4</sup> Supplementary file 1, doc n°23

<sup>5</sup> Supplementary file 1, docs n°24-25.

<sup>6</sup> Supplementary file 1, docs n°38-39; 43-44; 48.

<sup>7</sup> Supplementary file 1, doc n°53.

<sup>8</sup> Supplementary file 1, doc n°56.

<sup>9</sup> Supplementary file 1, docs n°57-62; 67-69; 71-73.

<sup>10</sup> Supplementary file 1, docs n°63-66; 71-72; 70; 74-78.

<sup>11</sup> Supplementary file 1, docs n° 57-60; 63-66; 68; 70; 74-78.

<sup>12</sup> Supplementary file 1, docs n°63-70; 73; 74-78; 80; 82; 85; 91; 94; 96; 99; 102.

<sup>13</sup> Supplementary file 1, docs n°77-78; 79; 82; 85; 91-94.

<sup>14</sup> Supplementary file 1, doc n°96.

194 resulted from harsh natural conditions, i.e. torrential flows, accessibility issues, significant snow cover and  
195 avalanche risk<sup>15</sup>.

196 A boom did occur briefly in the early 17th c., evidenced by the rebuilding of several former bloomeries and by  
197 new construction in the bottom valley, close to trade routes (Fig. 2-7). Between 1601 and 1642<sup>16</sup>, their numbers  
198 fluctuated but finished at the same level. Between 1630 and the 1650s, two new bloomeries were built in  
199 Vicdessos<sup>17</sup> and Suc<sup>18</sup> (Figs. 4, 5). Our results also mitigate the spread of the Genoa style bloomery because only  
200 Guilhe was successful in a long-term perspective (Fig. 5).

201 The mid-17th c. correspond to the birth and generalization of the Catalan direct water-powered bloomery. Between  
202 the 1640s and 1660s, the number of bloomeries increased from four to six and stabilized over the second part of  
203 the century<sup>19</sup>(Fig. 5; 7). An unlocated tilt hammer was also reported in 1669<sup>20</sup>.

204 The numerous economic and health crises did not significantly impact local iron industry, where five out of six  
205 bloomeries were still running in 1720<sup>21</sup> (Figs. 3-5, 7). While Ournac was no longer mentioned in 1720, the Forge-  
206 Neuve bloomery was created in c. 1722<sup>22</sup> (Fig. 3). In the 1750s, the functioning of some bloomeries was disrupted  
207 by ore supply problems<sup>23</sup> or floods<sup>24</sup>, but all of them were still running in 1772<sup>25</sup>. Cabre did close, however, in  
208 1775. In addition, two tilt hammers were illegally built<sup>26</sup>.

209 The first half of the 19th c. saw the rebuilding of Cabre in 1817-20 (Fig. 5) and the creation of two new bloomeries  
210 at Laramade in 1836-1837 and 1847. At the same time, Laprade closed (1846) (Fig. 3). The 1860-70s. saw the end  
211 of the iron industry, with the progressive closure of all the bloomeries of the area (Figs. 3,4).

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<sup>15</sup> Supplementary file 1, doc n°122.

<sup>16</sup> Supplementary file 1, docs n°103-109; 111-112; 116-129; 134-138; 140-144; 149-150.

<sup>17</sup> Supplementary file 1, doc n°150.

<sup>18</sup> Supplementary file 1, doc n°133.

<sup>19</sup> Capounta: Supplementary file 1, docs n°147-150; 182; 190-193; 198; 202; 206; 211; 229; 232; 240-241; 262-263; 275; 299; 301; 317; 328-330; 334; 349-351; 354-356; 359; 363; 365; 367; 377; 379-382; 387; 389; 391; 396-397; 400; 402-403; 410-412; 414; 420; 422-423; 429; 432-434; 436 / Ournac: Supplementary file 1, docs n°151-152; 154-156; 160-163; 167; 177; 187-188; 194; 197-200; 202; 212-214; 216; 220; 225; 227; 230; 239-241; 245; 255; 257; 262-263; 265-273; 281-282; 285-286; 291-295; 300-301; 310-311; 315; 323-327; 349; 351; 356; 361; 368; 374; 377; 383; 387; 389; 391; 396-397; 400 / Cabre: Supplementary file 1, docs n°150; 171-174; 179; 181; 222-223; 234; 236-238; 333; 335-336; 338-341; 348; 406; 413; 415; 417; 424; 431 / Guilhe: Supplementary file 1, docs n°150; 205; 207; 215; 218; 224; 226; 256; 259-261; 277-279; 282-284; 290; 297-299; 302-303; 306-309; 316-318; 320-321; 331; 362; 392; 426-427 / Laprade: Supplementary file 1, docs n°133; 139; 145; 215; 218; 221; 224; 226; 244; 247; 256; 264; 276-279; 282; 287; 290; 297-298; 302-304; 306-309; 316-318; 373 / Vexanelle: Supplementary file 1, docs n°183-185; 190; 205; 207-208; 210; 247; 278; 282; 287-288; 290; 297-298; 303-304; 306-309; 316; 318; 320-322; 331; 351; 357; 388; 416; 421; 425.

<sup>20</sup> Supplementary file 1, doc n°249.

<sup>21</sup> Supplementary file 1, doc n°451.

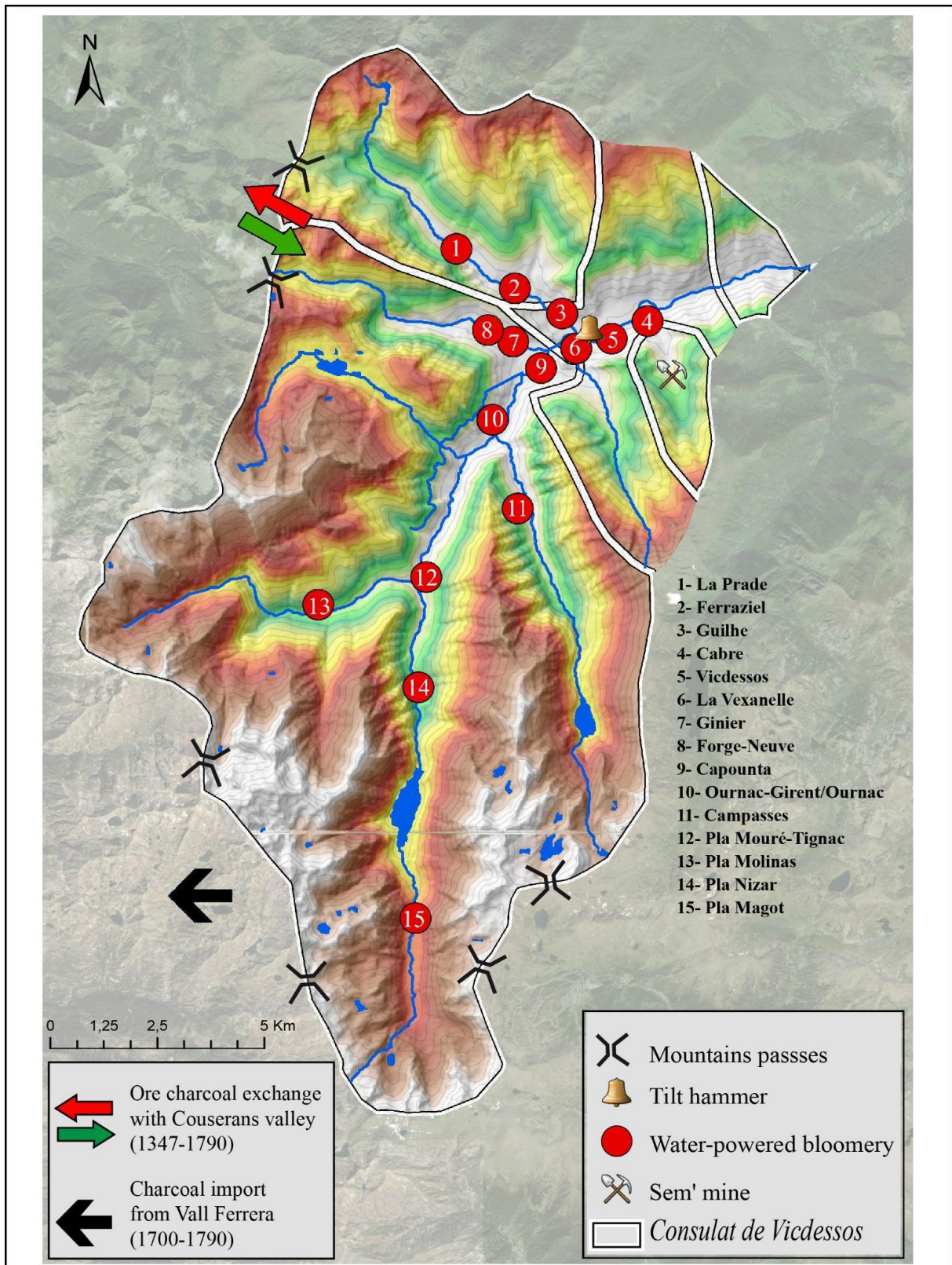
<sup>22</sup> Supplementary file 1, docs n°461; 465.

<sup>23</sup> Supplementary file 1, doc n°530.

<sup>24</sup> Supplementary file 1, doc n°525.

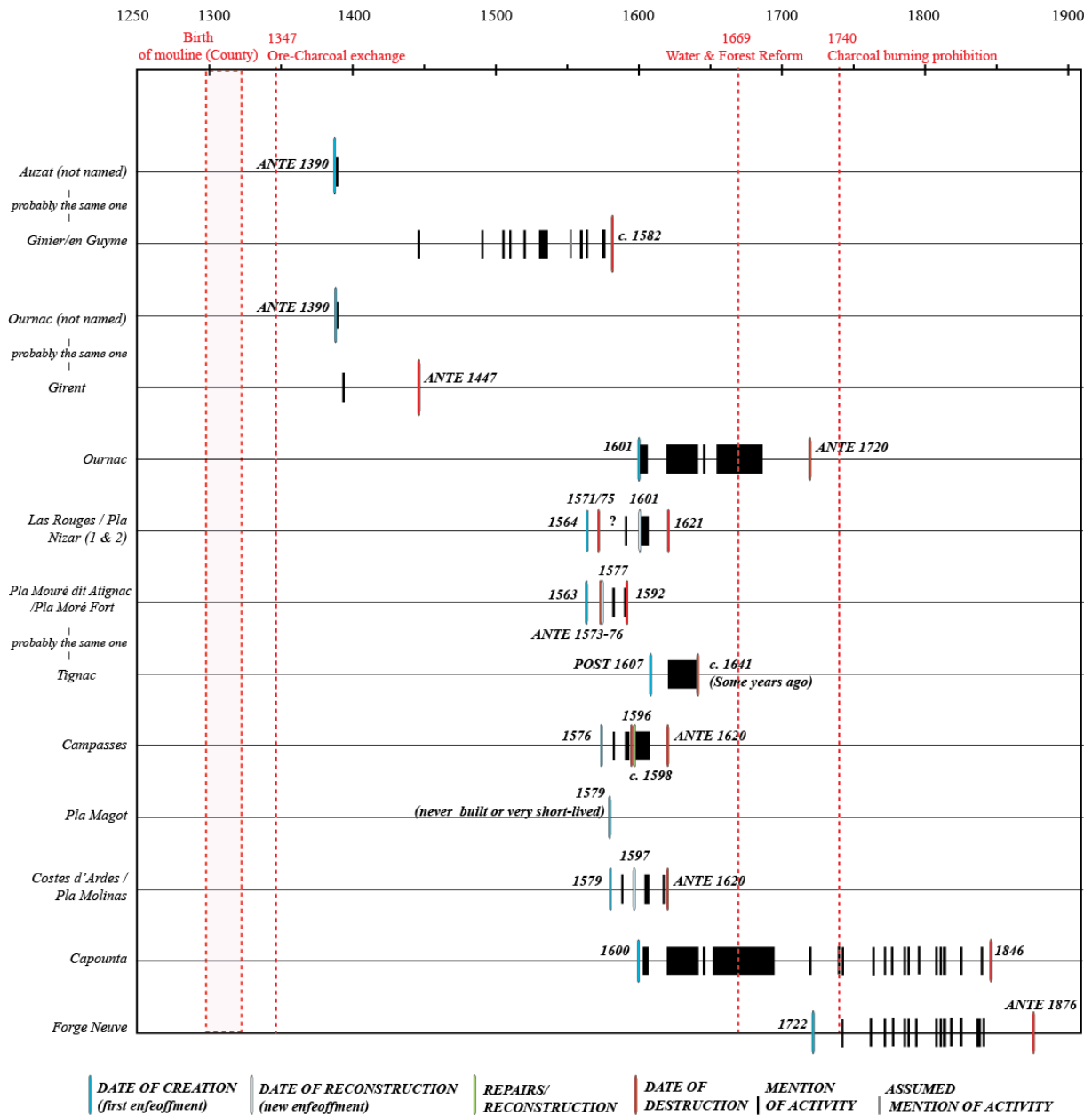
<sup>25</sup> Supplementary file 1, doc n°577.

<sup>26</sup> Supplementary file 1, docs n°539; 566.

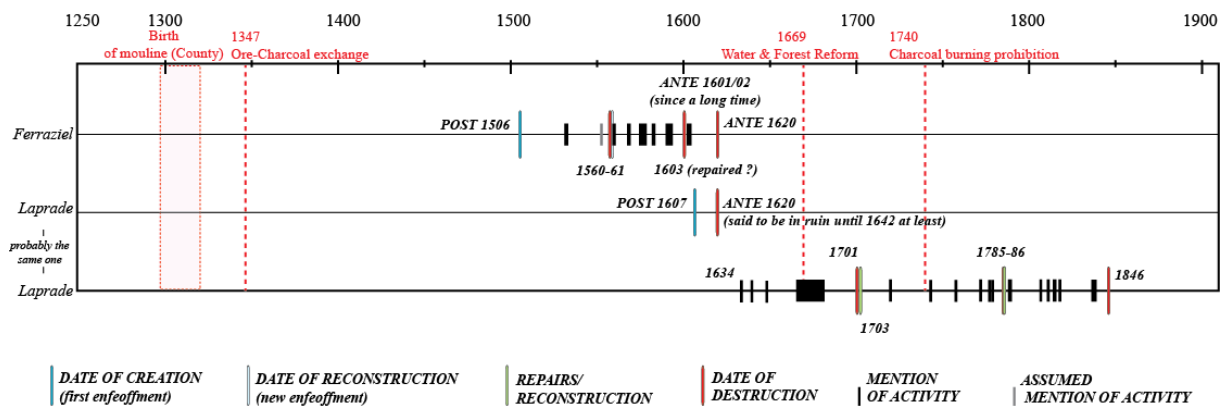


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213 Fig. 2: General location of the water-powered bloomery in the *consulat de Vicdessos*.

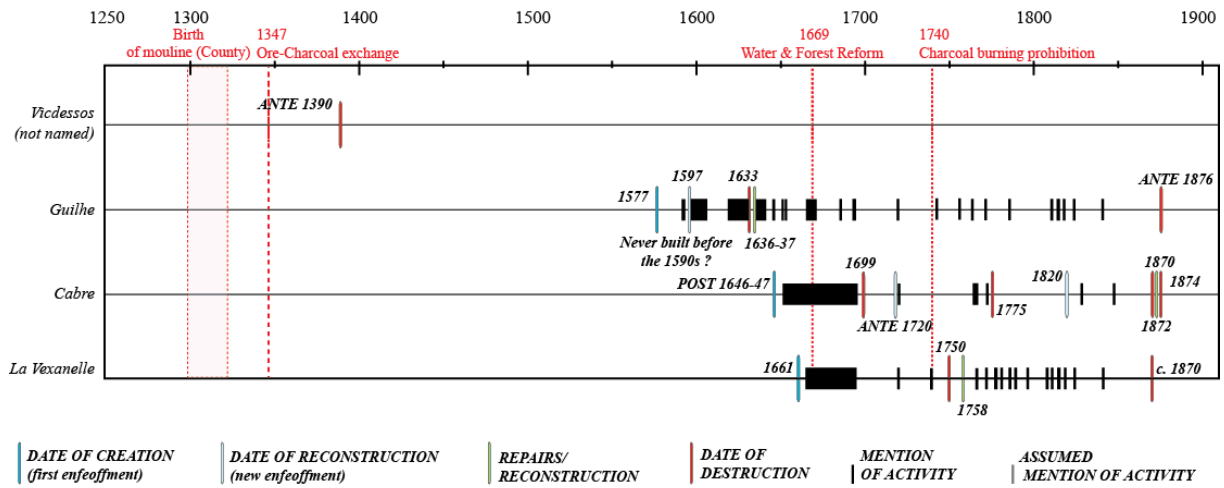


215 Fig. 3: Restitution of bloomery activity in Auzat territory.

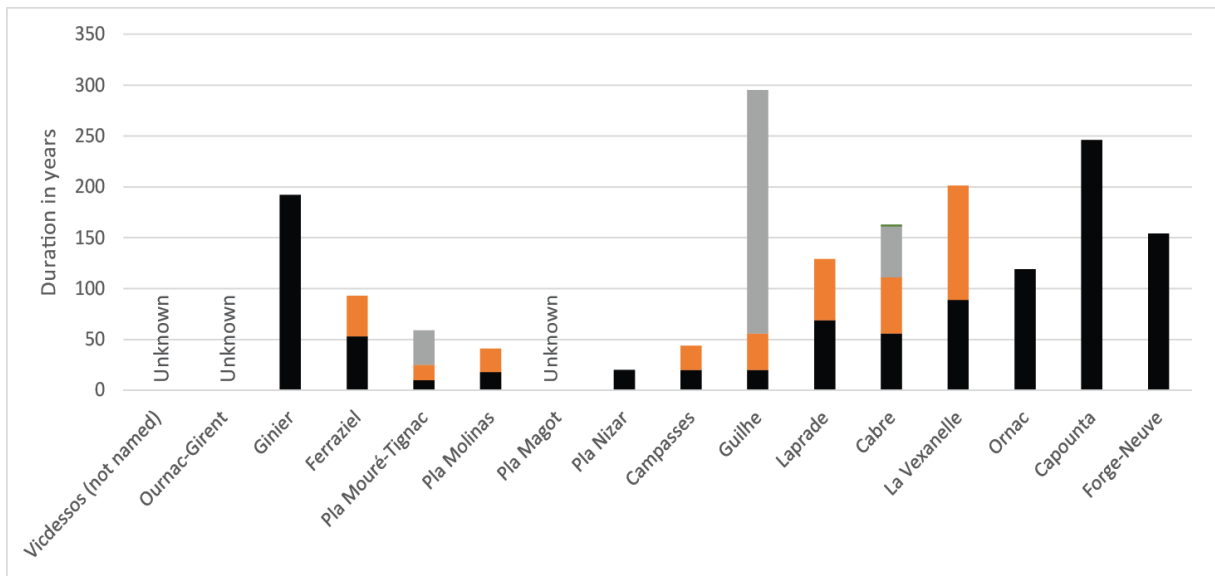


217 Fig. 4 : Restitution of bloomery activity in Suc territory.

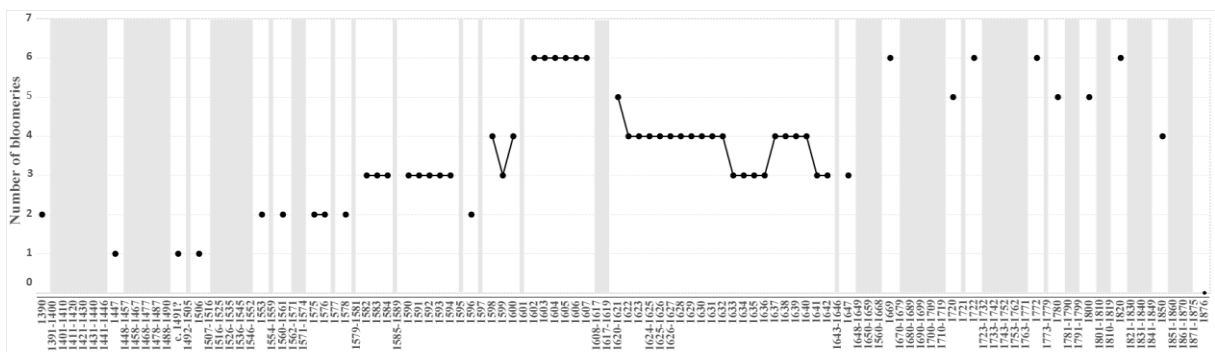




219 Fig. 5 : Restitution of bloomery activity in Vicdessos territory.



221 Fig. 6 : Evaluation of the maximum running duration for each bloomery (colors correspond to successive phases  
222 of activity).



224 Fig. 7 : Number of bloomeries over time in the *consulat de Vicdessos* according to written records (Only the years  
225 for which we have an overview of the total number of bloomeries are represented; contracted undocumented  
226 periods in grey).

## 227 2.2. Archaeological evidences

228 For now, in lack of archaeological excavations and radiocarbon dating, archaeology provides little information  
229 about ancient and medieval bloomeries in the former *consulat de Vicdessos*. While a couple of ironworks were  
230 radiocarbon dated to the 3rd-5th c. AD in the neighboring valleys of Siguer and Courbière, no evidence was found  
231 in the *consulat de Vicdessos*. Despite some textual evidence, for now, no medieval bloomeries remains have been  
232 recognized. Based on the scarcity of iron artifacts from the *castrum* site of Montréal-de-Sos, archeologists  
233 speculated on the existence of small-scale open-cast mining works between the late 12th c. and the late 13th c. But  
234 this hypothesis must be supported by iron isotope analyses to confirm their local provenance and manufacture.  
235 Thus, it is impossible to conclude that medieval iron making activity was continuous and intensive (Figs. 3,4,5).  
236 For the early modern era, only the Las Moulinas bloomery have been partially investigated but not radiocarbon  
237 dated. For late modern and contemporary times, all the bloomeries documented by archives were recognized.  
238 Recent surveys detected several undated ironwork evidence.

239 Concerning charcoal production, we detected a total of 80 platforms in the focus area. Platforms were distributed  
240 along slopes with 31% located on the steep slope (50 to 90%), 35% on medium-grade incline slopes (20 to 50%)  
241 and 33% on low to moderate slopes (low grade, up to 20%). Platforms recorded on steep slopes show visible signs  
242 of construction: excavation, overdeepening directly into the slope to prepare the location of the platform where  
243 charcoal kilns were settled. Smaller platforms with a moon shape are mainly found on steep slopes, while larger  
244 platforms (round shape) are located on gentle slopes. Almost all platforms are located within the current forest,  
245 except a dozen located in the current open grazing area (n° 1, 2, 3, 4, 6, 7, 8, 9, 10 et 62) (Fig. 1D). The past  
246 centuries had little effect on the conservation of platforms located in forest, unlike the platforms in open areas,  
247 which show weaker conservation, probably due to heavy human use and grazing by livestock. Almost all platforms  
248 show a homogeneous and regular black layer, more or less rich in charcoal, which usually extends to a depth of  
249 40 to 60 cm, sometimes to 80 cm (platforms 19, 74 and 79). Platform 17, which is the only one reaching 120 cm  
250 depth, is characterized by three charcoal deposits separated by two fine mineral layers suggesting three use phases.  
251 Platforms with 120 cm depth remain exceptional, because the thickness of the black layer usually ranges from 5  
252 and 30 cm on most of the platforms observed on different European sites. It could be a pit platform, the existence

253 of which has sometimes been mentioned by historical sources in the French Pyrenees (Gourbit valley, Pays de  
 254 Sault) and Catalan Pyrenees.

255 At the *consulat de Vicdessos* level, radiocarbon data from platforms cover a period ranging from the 6th c. to the  
 256 20th c. AD (with 95.4% of probability) (Table 1, Fig. 8). In the focus area, they bring 11 centuries of charcoal  
 257 production to light, beginning in the 9th c. AD. For platform 17, the deepest layer corresponds to the mid-15th-  
 258 mid-17th c. period, and the uppermost layer, to the mid-17th to the 19th c., confirming its use at different periods.

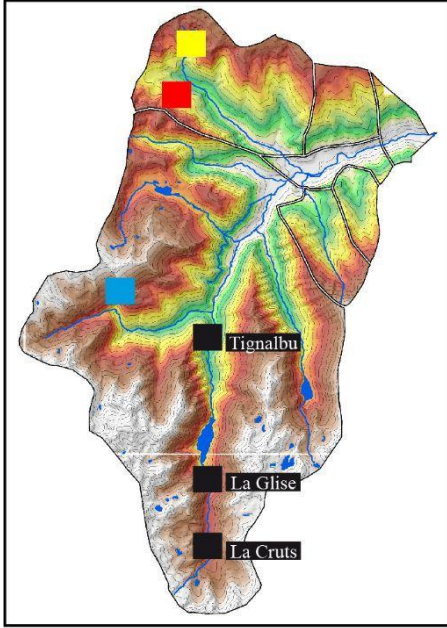
Study area	Platform	Depth (cm)	Age 14C BP	N° Lab	Tree-species	Cal BC-AD (95.4%)	Most probable dates (% probability)	Historical periods	Source
Focus area	4	0-40	65 ± 30	Poz-73024	Beech	1691-1921	1811-1921 (71.6%)	19th-20th c.	(Fouédjeu et al., 2021b)
Focus area	74	40-60	80 ± 30	Lyon-14958 (SacA-53114)	Beech	1690-1926	1810-1926 (70.6%)	19th-20th c.	(Fouédjeu et al., 2021b)
Soulcem (Tignalbu)	1	5-10	100 ± 50	Gif 8734	n/a	1676-1941	1799-1941 (61.4%)	19th-20th c.	(Davassee, 2000)
Focus area	17	0-20	185 ± 30	Lyon-14951 (SacA-53107)	Beech + bark	1650-present day	1726-1814 (52.5%)	Mid 17th-19th c.	(Fouédjeu et al., 2021b)
Soulcem (Tignalbu)	1	60-65	190 ± 40	Gif 8736	n/a	1644-present day	1720-1819 (47.9%)	Mid 17th-19th c.	(Davassee, 2000)
Focus area	14	0-40	130 ± 30	Lyon-14950 (SacA-53106)	Beech + bark	1675-1942	1675-1894 (80.5%)	Mid 17th-19th c.	(Fouédjeu et al., 2021b)
Focus area	29	20-40	140 ± 30	Lyon-14953 (SacA-53109)	Beech + bark	1669-1945	1669-1891 (80%)	Mid 17th-19th c.	(Fouédjeu et al., 2021b)
Focus area	63	20-40	140 ± 30	Lyon-14957 (SacA-53113)	Beech	1669-1945	1669-1891 (80%)	Mid 17th-19th c.	(Fouédjeu et al., 2021b)
Soulcem (La Glise)	5	25-30	160 ± 60	Gif 8733	n/a	1655-present day	1655-1894 (78.3%)	Mid 17th-19th c.	(Davassee, 2000)
Soulcem (Tignalbu)	2	20-25	220 ± 35	Gif 8738	n/a	1529-present day	1635-1810 (79.5%)	Mid 17th-19th c.	(Davassee, 2000)
Soulcem (Tignalbu)	3	35-40	220 ± 35	Gif 8737	n/a	1529-present day	1635-1810 (79.5%)	Mid 17th-19th c.	(Davassee, 2000)
Focus area	19	0-40	255 ± 30	Poz-73023	Beech + bark	1521-present day	1620-1675 (55%)	Mid 17th-19th c.	(Fouédjeu et al., 2021b)
Soulcem (Tignalbu)	1	30-35	250 ± 40	Gif 8735	n/a	1513-present day	1616-1684 (41.6%)	Mid 17th-19th c.	(Davassee, 2000)
Soulcem (La Glise)	1	30-35	240 ± 50	Gif 8530	n/a	1489-present day	1610-1813 (63.4%)	Mid 17th-19th c.	(Davassee, 2000)
Soulcem (Pla de la Crouts)	3	45-50	240 ± 50	Gif 8739	n/a	1489-present day	1610-1813 (63.4%)	Mid 17th-19th c.	(Davassee, 2000)
Arbu	6	40-60	260 ± 30	Poz-104699	n/a	1520 - present day	1520-1670 (53.1%)	Mid 15th-mid 17th c	(Py-Saragaglia et al., 2019)
Focus area	1	20-40	270 ± 30	Poz-73022	Beech + bark	1514-1799	1514-1669 (89.2%)	Mid 15th-mid 17th c	(Fouédjeu et al., 2021b)
Focus area	79	40-80	320 ± 30	Beta-480930	Beech + bark	1482-1646	1482-1646 (95.4%)	Mid 15th-mid 17th c	(Fouédjeu et al., 2021b)
Focus area	34	0-40	330 ± 30	Lyon-14954 (SacA-53110)	Beech	1477-1643	1477-1643 (95.4%)	Mid 15th-mid 17th c	(Fouédjeu et al., 2021b)
Arbu	14	0-20	335 ± 30	poz-104579	Beech	1475-1641	1475-1641 (95.4%)	Mid 15th-mid 17th c	Py-Saragaglia et al. (2019)
Arbu	16	20-40	340 ± 30	Poz-104580	Beech + pine + bark	1470-1640	1470-1640 (95.4%)	Mid 15th-mid 17th c	Py-Saragaglia et al. (2019)
Arbu	20	20-40	345 ± 30	Poz-104700	Fir + fir/juniper	1465-1638	1465-1638 (95.4%)	Mid 15th-mid 17th c	Py-Saragaglia et al. (2019)
Artigue (Pla Nouzère )	5	Lower layer	330 ± 50	Gif 8109	n/a	1454-1649	1454-1649 (95.4%)	Mid 15th-mid 17th c	(Métailié and Jalut, 1991)
Focus area	7	40-60	365 ± 30	Lyon-14949 (SacA-53105)	Beech	1449-1634	1449-1634 (95.4%)	Mid 15th-mid 17th c	(Fouédjeu et al., 2021b)
Focus area	6	20-40	375 ± 30	Poz-77095	Bark	1446 - 1633	1446 - 1527 (58.3%)	Mid 15th-mid 17th c	(Fouédjeu et al., 2021b)
Artigue (Bois de Fontanal)	n/a	n/a	360 ± 60	Gif 9433	n/a	1442-1646	1442-1646 (95.4%)	Mid 15th-mid 17th c	(Davassee, 2000)



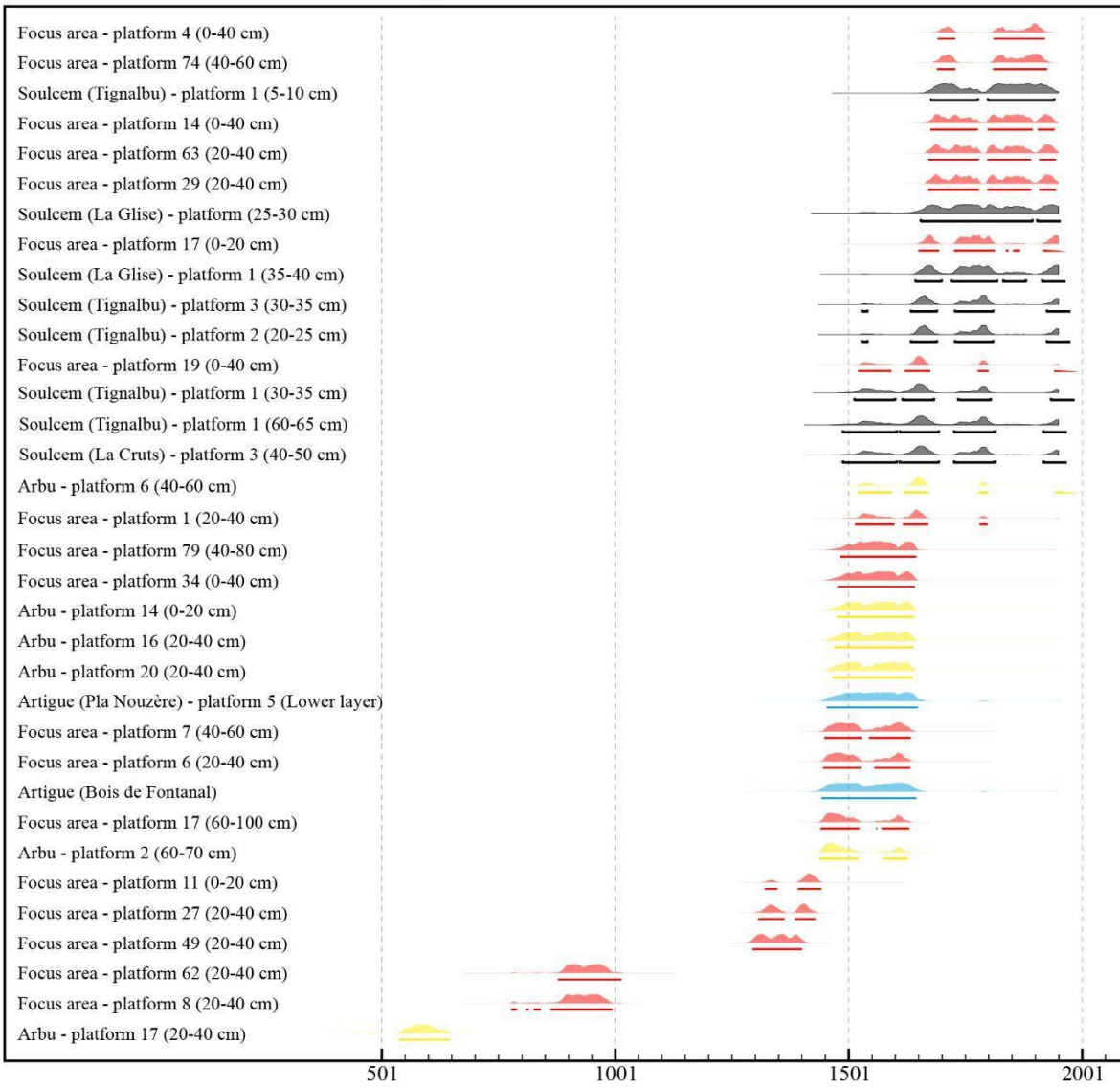
Focus area	17	60-100	390 ± 30	Lyon-14952 (SacA-53108)	Bark	1441-1631	1441-1524 (69.3%)	Mid 15th-mid 17th c	(Fouédjeu et al., 2021b)
Arbu	2	60-70	396 ± 30	Poz-104658	Beech + bark	1438-1628	1438-1523 (73.7%)	Mid 15th-mid 17th c	(Py-Saragaglia et al., 2019)
Focus area	11	0-20	525 ± 30	Poz-73025	Fir + beech + bark	1321 - 1442	1392-1442 (80.5%)	End 13th c.-early 15 th c.	(Fouédjeu et al., 2021b)
Focus area	27	20-40	560 ± 30	Poz-97774	Bark	1307 - 1429	1307 - 1429 (95.4%)	End 13th c.-early 15 th c.	(Fouédjeu et al., 2021b)
Focus area	49	20-40	615 ± 30	Lyon-14955 (SacA-53111)	Beech	1295-1401	1295-1401 (95.4%)	End 13th c.-early 15 th c.	(Fouédjeu et al., 2021b)
Focus area	62	20-40	1110 ± 30	Lyon-14956 (SacA-53112)	Fir + fir/juniper	878-1014	878-1014 (95.4%)	Early Middle Ages	(Fouédjeu et al., 2021b)
Focus area	8	20-40	1120 ± 30	Poz- 109062	n/a	778 - 995	863-995 (91.8%)	Early Middle Ages	(Fouédjeu et al., 2021b)
Arbu	17	20-40	1480 ± 30	Poz-104621	Beech	538-646	538-646 (95.4%)	Early Middle Ages	(Py-Saragaglia et al., 2019)

259

Table 1 Combine Accelerator Mass Spectrometry (AMS) dates of the focus area, Soulcem, Arbu and Artigue



Calibrated date (calBC/calAD), OxCal v4.4.2 Bronk Ramsey (2020);  
r:5 IntCal13 atmospheric curve (Reimer et al., 2013)



261 Fig. 8: Radiocarbon dates of platforms showing 15 centuries of charcoal manufacturing

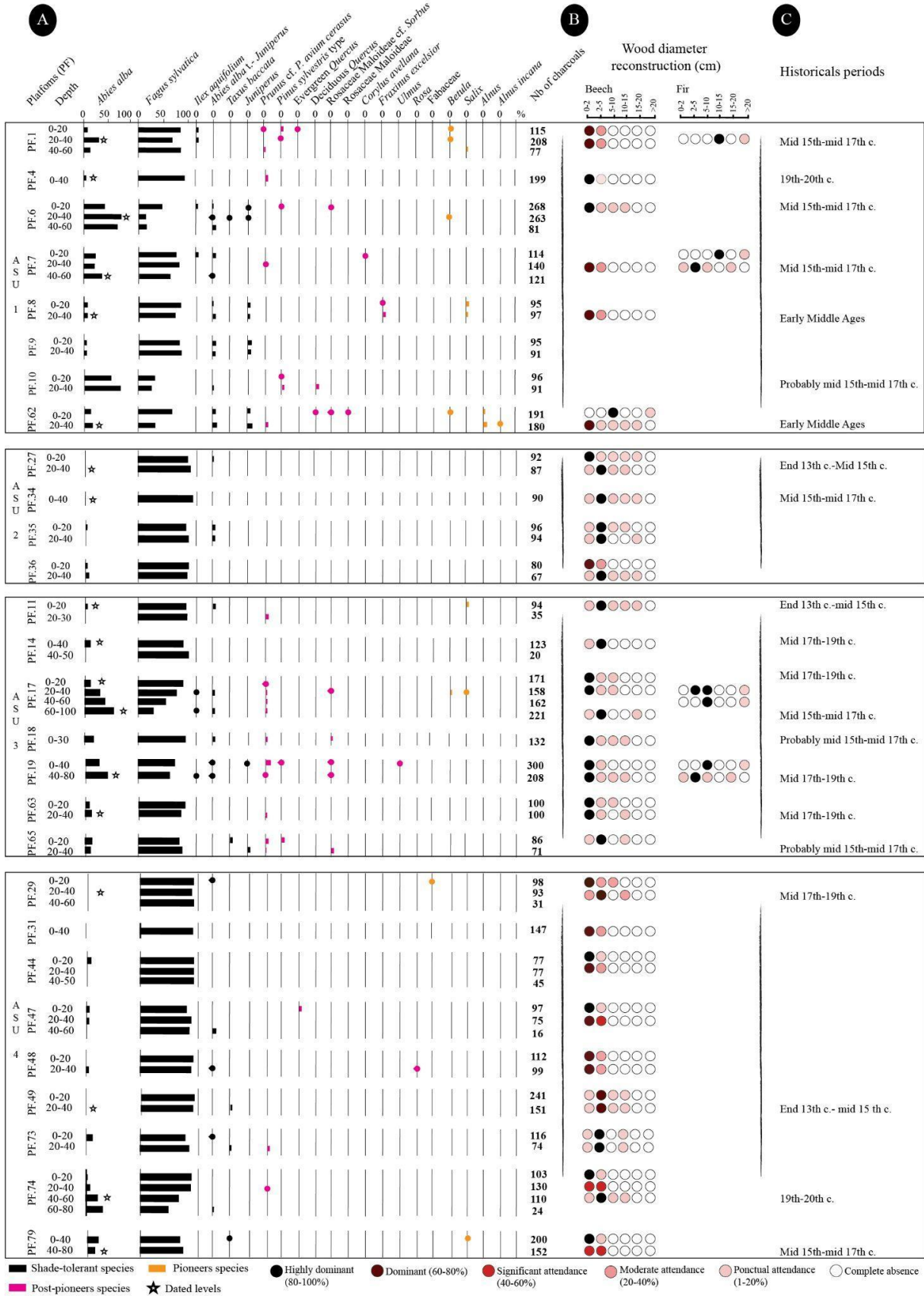
### 262 2.3. Results of charcoal analysis for the focus area

263 Among the 7990 charcoal samples analyzed, we identified 21 taxa classified into three main categories (Fig. 9A):

264 (i) shade-tolerant tree taxa so-called “dryads” including silver fir, beech, holly (*Ilex aquifolium* L.), common yew  
265 (*Taxus baccata* L.), fir/juniper (*Abies alba/Juniperus*); (ii) pioneer taxa, i.e. legume family (Fabaceae), birch  
266 (*Betula*), willow (*Salix*), grey alder (*Alnus incana* L.), alder (*Alnus*), juniper (*Juniperus*) and (iii) post-pioneer taxa  
267 including wild cherry (*Prunus*), scots/mountain pine (*Pinus*), evergreen and deciduous oak (*Quercus*), apple sub-  
268 family (Rosaceae, Maloideae), mountain ash (Rosaceae, Maloideae cf. *Sorbus*), hazel (*Corylus*), ash (*Fraxinus*),  
269 rose (*Rosa*), elm (*Ulmus*), wild cherry (*Prunus*). The corpus of charcoal is largely dominated by beech (81.2%),  
270 followed by silver fir (15.4%). The 19 other taxa had mean relative frequencies below 2% and were not identified  
271 in all platforms (Supplementary file 2).

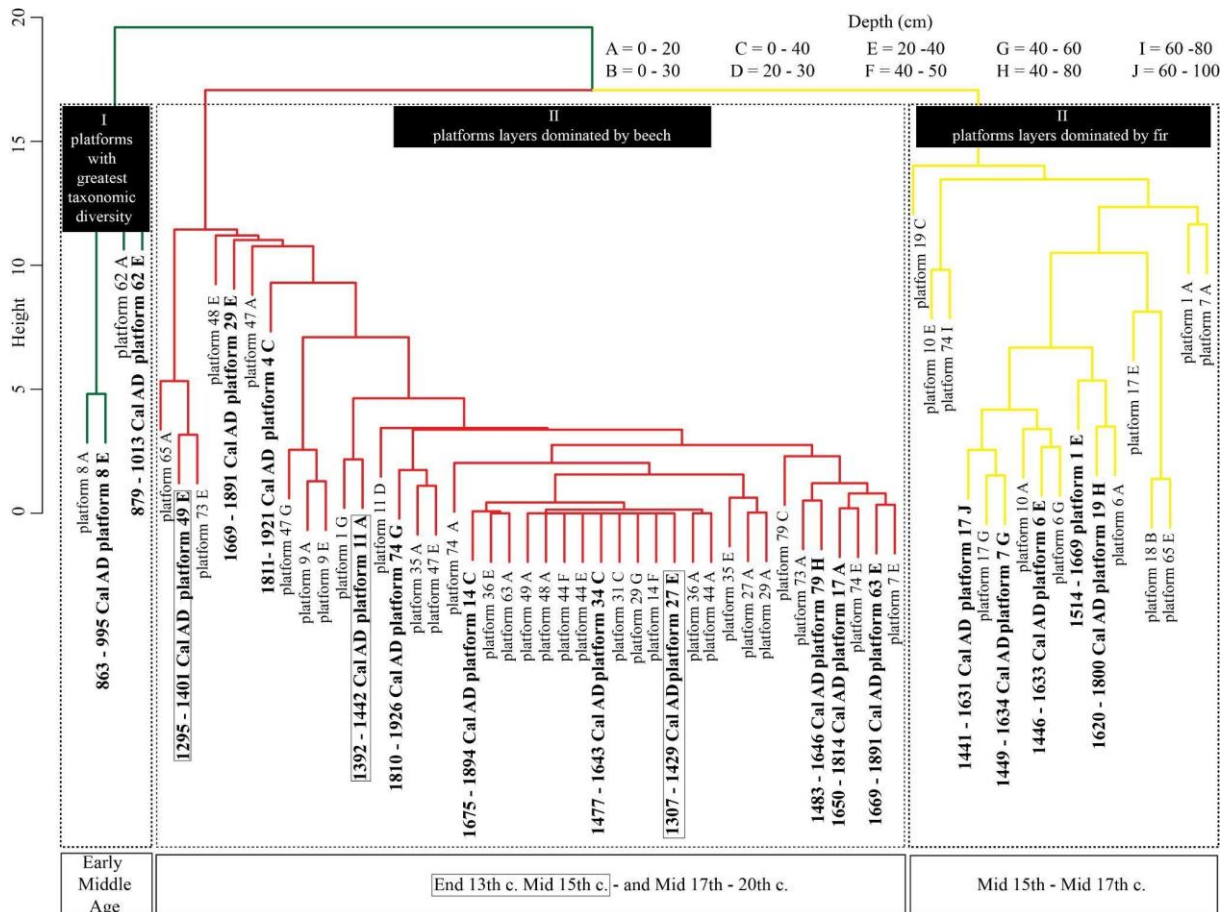
272 The anthracological spectra of platforms in the ASU 2 are characterized by very low taxonomic diversity (n=3)  
273 and a large predominance of beech. Nine taxa were recorded in platforms located in ASU 4. Beech is always  
274 predominant, but platforms 73 and 74 recorded high proportions of silver fir. The platform spectra in the ASUs 1  
275 and 3 show the greatest taxonomic diversity (n=18 and 12). They are characterized by significant frequencies of  
276 silver fir, even though beech is predominant overall (Fig. 9A).

277 Hierarchical clustering analysis grouped platforms into three main clusters according to their taxonomic  
278 composition and the relative frequencies of the taxa (Fig. 10). Cluster I included platforms (62 and 8) with the  
279 greatest taxonomic diversity (n=12), and the oldest dates, i.e. 9th-10th c. AD. C II included sampling layers  
280 dominated by beech and, in the deeper layers of the same platforms, rich in fir. Those platforms were dated for  
281 three different periods: end 13th- mid 15th c., mid 17th c.-19th c. and 19th-20th c. The oldest are composed of  
282 sampling layers in platforms 11, 27 and 49. The most recent are composed of most of the layers of platforms 4,  
283 14, 17 (except 20-40, 40-60 and 60-100 cm), 29, 63 and 74 (except 60-80 cm). Cluster III included platforms  
284 whose layers were dominated by fir. These platforms were dated between mid-15th to mid-17th c.



286 Fig. 9: (A) Anthracological diagram of the focus area showing the relative frequencies of taxa classified by  
 287 reference spatial unit. Points represent taxa with relative frequencies of lower than 1%; (B) Results of wood  
 288 diameter reconstruction carried on (Fouédjeu et al., 2021b); (C) Historicals periods

289



290

291 Fig.10: Hierarchical clustering conducted on the basis of the similar taxonomic composition of dated and undated  
 292 platforms highlighting three groups (green, red, yellow).

293 **3. Discussion**

294 **3.1. Fuel consumption for the iron industry and woodland management strategies over time**

295 Presently, no data is available to assess and characterize late antique and early medieval unpowered direct furnaces  
 296 charcoal consumption. Dubois' estimation (2000) is excessive as it was based on insufficient experiments and on  
 297 unrecognized hypotheses: the continuity of production and silvicultural practices over long periods (Arribet-

298 Deroin, 2013). Consequently, we assume low intensity iron production supplied by the local charcoal industry, as  
299 in Vall Ferrera (Pèlachs et al., 2009).

300 The first evidence of forest management dates from a. 1272 when the inhabitants of the *consulat de Vicdessos*  
301 were recognized in their customary right to freely use common natural resources<sup>27</sup> (Verna, 2001, pp. 115–116,  
302 167). Charcoal burning is attested as soon as 1281<sup>28</sup> and the right to make charcoal freely and without limitation  
303 is confirmed in 1294<sup>29</sup>. In 1301, the common rights of inhabitants were reconfirmed, but charcoal burning was  
304 forbidden<sup>30</sup>, probably because the earl sought to control the rising charcoal trade. In this sense, the 1303  
305 regulation<sup>31</sup> defined new rules for charcoal production, requiring producers to use dry and dead trees before using  
306 entirely green trees, but enforcement remains uncertain. In 1347–48, an iron-charcoal agreement was signed  
307 between the *consulat* and the Couserans viscount<sup>32</sup>. The former obtained the right to harvest timber and charcoal  
308 in the Couserans viscounty’s forest. In exchange, the Viscount was allowed to supply his bloomeries at Ercé and  
309 Massat with the iron ore from Sem mines. However, the Viscount excluded small-sized oaks and firs from the  
310 agreement (Verna, 2001, pp. 96–98). The regulation of local production<sup>33</sup> and the outsourcing of charcoal supply  
311 was intended to ensure forest resource sustainability in a long-term industrial development perspective.

312 Medieval and modern charcoal consumption also remains largely unknown. Generally water-powered bloomeries  
313 allowed a higher iron production rate and involved higher charcoal consumption (Arribet-Deroin, 2018). However,  
314 without local information on the rhythm and duration of smelting operations, it is impossible to estimate the annual  
315 consumption of each bloomery.

316 In the context of industrial variability (Fig. 7), charcoal supply was both locally sourced and imported from  
317 Couserans<sup>34</sup>, through the Port de Lers, probably in the framework of the iron-charcoal exchange, but their  
318 respective shares are unknown. Local charcoal was generally supplied by the rights granted in bloomeries  
319 enfeoffment<sup>35</sup> and secondarily by purchases and debt repayments<sup>36</sup>. This local production is confirmed by nine  
320 platforms in the focus area, four in Arbu and two in Artigue (Davasse, 2000, pp. 163–164) (Fig. 8, 10). The low

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<sup>27</sup> Supplementary file 1, doc n°1.

<sup>28</sup> Supplementary file 1, doc n°2.

<sup>29</sup> Supplementary file 1, doc n°3.

<sup>30</sup> Supplementary file 1, doc n°5.

<sup>31</sup> Supplementary file 1, doc n°6.

<sup>32</sup> Supplementary file 1, doc. n°16; 17.

<sup>33</sup> Supplementary file 1, doc n°20.

<sup>34</sup> Supplementary file 1, doc n°41.

<sup>35</sup> Supplementary file 1, doc n°48; 57; 60.

<sup>36</sup> Supplementary file 1, docs n°36-37; 41; 130-133.



321 accuracy of radiocarbon probability ranges does not allow us to relate them to the individual bloomeries running  
322 phases.

323 While only the use of beech is mentioned in written records<sup>37</sup>, charcoal analysis revealed a large variety of species.  
324 Las Moulinas bloomery (Artiès, late 16th-early 17th c.) was mainly fueled with beech, fir and birch (*Betula*) with  
325 numerous other broadleaved trees and conifers (Métailié and Jalut, 1991; Dubois, 1995; Davasse, 2000, pp. 163–  
326 164). In Artigue, fir was almost exclusively charred. Indeed, while fir was expected to be used primarily as a  
327 building material<sup>38</sup> (Barbe, 1900; Ruffié, 1997), it was also significantly identified among charcoal. Wood  
328 diameters of fir charcoal raise issues about the charring of logging slash (Fouédjeu et al., 2021b). The  
329 contemporaneous intensification of anthropogenic canopy removal (Saulnier et al., 2020) suggests the harvesting  
330 of a large number of fir standards. The combination of charcoal and timber productions is also suggested by the  
331 ownership of sawmill by ironmasters and the spatial proximity of both activities<sup>39</sup>.

332 During the 17th c. industrial intensification (Fig. 7), forest administration reports emphasized the role of charcoal  
333 imports from Couserans<sup>40</sup> (Davasse, 2000, p. 135; Cantelaube, 2005, pp. 224–228; Poublanc, 2019, p. 54).  
334 Although charcoal delivered at the Port de Lers were partly produced in Massat, Ustou<sup>41</sup> and in the Earl of Rabat's  
335 forests<sup>42</sup>, the sourcing of imported charcoal is often unknown<sup>43</sup>. However, charcoal was also locally manufactured  
336 as stated by historical<sup>44</sup> and archaeological evidence (Fig. 8). Forest court condemned bloomery owners for  
337 “abusive use” but maintained their rights<sup>45</sup>. While beech was considered to produce better charcoal than fir<sup>46</sup>,  
338 charcoal analysis still evidences a combined use of conifers (pine, fir, juniper) and broadleaved trees (hazel, birch,  
339 alder, etc.) (Davasse, 2000, pp. 175–180).

340 Improving technical processes led to a 30-50% reduction in charcoal consumption between 1667-1868  
341 (Cantelaube, 2005, p. 245). The charcoal/iron ratio was around 6/1 or 4/1 according to François (1837, p. 588;  
342 1843, p. 321). However, the annual consumption of each bloomery remains unknown for the reasons previously  
343 exposed (e.g. the Guilhe only ran 2-3 months per year<sup>47</sup>).

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<sup>37</sup> Supplementary file 1, doc n°130.

<sup>38</sup> Supplementary file 1, doc n°39; 49.

<sup>39</sup> Supplementary file 1, doc n°29; 56-58; 67-71; 82.

<sup>40</sup> Supplementary file 1, doc n°231, fol. 418 (1667); 249, fol. 136 (1669).

<sup>41</sup> Supplementary file 1, doc n°170.

<sup>42</sup> Supplementary file 1, doc n°215.

<sup>43</sup> Supplementary file 1, doc n°165; 175; 230; 242; 254; 289.

<sup>44</sup> Supplementary file 1, doc n°36-37; 41; 48; 57; 60; 130-133; 149-176; 178-182; 187-195; 197-210; 212-230; 232-248; 254-274; 276-312; 315-351; 353-368; 371-378; 387-394; 396-403; 410-413; 415; 418-419; 423-425; 427.

<sup>45</sup> Supplementary file 1, doc n°251-253.

<sup>46</sup> Supplementary file 1, doc n°150; 152; 165; 167; 170; 176; 180; 187-188; 201; 207; n°249, fol. 140 ; 296-297; 302; 305; 308; 319-321; 367; 373-375.

<sup>47</sup> Supplementary file 1, doc n°249.

344 Despite strong control, illicit charcoal burning occasionally occurred in woodland reserves during the 18th c.<sup>48</sup>. In  
345 1740, the fear of timber shortages led authorities to create new reserves to ensure timber supply for mining and  
346 construction, and to prohibit charcoal burning in the entire *consulat*<sup>49</sup>. This prohibition was globally respected<sup>50</sup>  
347 (Picot de Lapeyrouse, 1786, p. 64; Davasse, 2000, pp. 106–110), but was renewed after the French Revolution due  
348 to new offenses<sup>51</sup>. Charcoal making continued in private woodland away from commons (Davasse, 2000, p. 117).  
349 The 1740 prohibition led the *consulat* council to enforce the respect of the iron-charcoal exchange with  
350 Couserans<sup>52</sup>. Due to rising charcoal prices, the lords of Massat and Ercé tried to end it (Davasse, 2000, pp. 135–  
351 143; Cantelaube, 2005, pp. 224–233). In response, the *consulat* signed new exchange agreements with other  
352 Couserans lords<sup>53</sup>, then with the Donnezan (1770)<sup>54</sup> and Vall Ferrera communities<sup>55</sup> (until the prohibition of  
353 charcoal exportation in 1773)<sup>56</sup>. The iron-charcoal exchange ultimately stopped in the 1780-1790s (Davasse, 2000,  
354 p. 137; Cantelaube, 2005, pp. 224–233). In the 1780s, about 1.706 t. of outsourced charcoal per day were consumed  
355 by the six bloomeries of the *consulat*<sup>57</sup> (François, 1837, p. 585; Cantelaube, 2005, pp. 206–209).

356 Iron production no longer drove mountain woodland exploitation. Several decrees leading to the 1810 law required  
357 those who wanted to create a bloomery to indicate the sourcing of charcoal supply to the Waters and Forests  
358 administration to demonstrate the absence of impact on local woodland. Most charcoal supplies came from external  
359 purchases or from the bloomery owner's private woodlands outside the *consulat* (Bonhôte, 1986; Davasse, 2000;  
360 Cantelaube, 2005, pp. 505–519).

361 Later, the development of an agro-pastoral-based economy led to a global wood shortage resulting in tensions  
362 between local communities and state forestry administration. The fuelwood and timber supply of each commune  
363 was restricted to its own territory and required legal authorization. It was problematic because the spatial  
364 distribution of fir high woodlands was unequal as it resulted from former common organization (Davasse, 2000,  
365 pp. 123–125). The 1827 Forest Code, again restraining common rights, and the Mountain Lands Restoration  
366 plantation of exotic conifers, initiated in the 1820s, caused an increasing conflictuality (e.g. War of the  
367 Demoiselles) (Chevalier, 1956, pp. 873–877; Baby, 1972; Whited, 2000).

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<sup>48</sup> Supplementary file 1, doc n°446; 456; 460; 477-478; 497; 501-502.

<sup>49</sup> Supplementary file 1, doc n°506.

<sup>50</sup> Supplementary file 1, doc n°587; 592; ; 601-604; 609.

<sup>51</sup> Supplementary file 1, doc n°614-615; 617.

<sup>52</sup> Supplementary file 1, doc n°428; 430; 443-445; 447-448; 452-455; 457-459; 467-468; 479-486; 488-490; 496; 498; 503; 505; 508-511; 514; 516-521; 523-524; 516; 528-529; 531-536; 538; 547; 549-551; 553; 560; 567-573; 579-580; 587; 591-592; 594-601; 605.

<sup>53</sup> Supplementary file 1, doc n°455; 457; 480; 4826-485.

<sup>54</sup> Supplementary file 1, doc n°567-572.

<sup>55</sup> Supplementary file 1, doc n°539-542; 561.

<sup>56</sup> Supplementary file 1, doc n°575; 578; 583.

<sup>57</sup> Supplementary file 1, doc n° 598.



### 368 3.2. Long-term forest evolution driven by human practices

369 Previous studies have highlighted the early medieval altitudinal rising of agrarian lands and clearing of pine forest  
370 for pasture in subalpine areas (Galop, 2000; Galop et al., 2003; 2013; Rendu, 2003). Until now, there has been  
371 little evidence of local high-altitude pasture occupancy (Guillot, 2014). While agro-sylvo-pastoral activities were  
372 the main driver of woodland clearings, charcoal manufacturing was usually considered to have contributed to  
373 landscape opening (Galop, 1998; Galop et al., 2013).

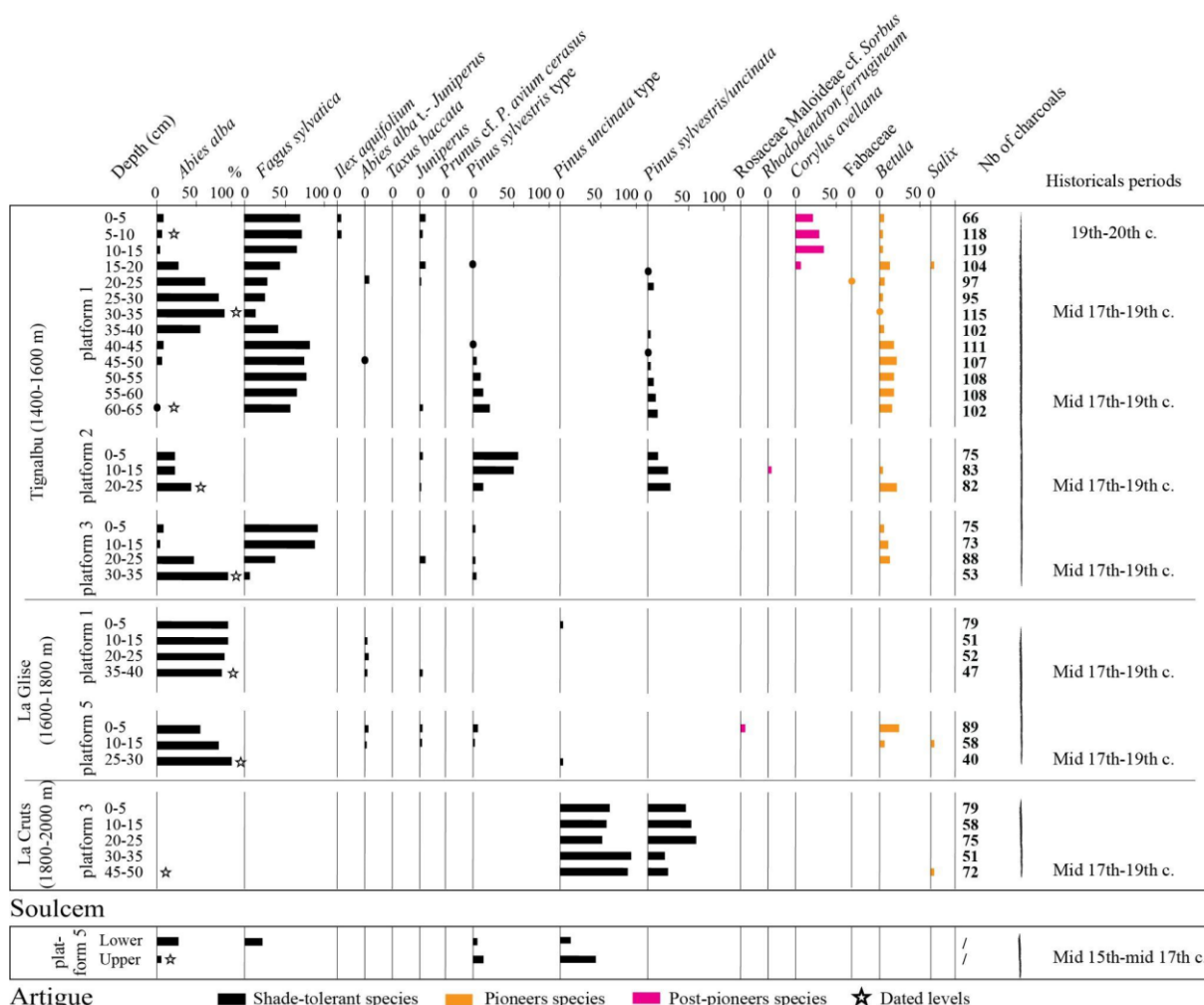
374 In the focus area, soil charcoal analysis (Fig. 1D) highlighted the introduction of woodland grazing systems,  
375 inducing changes in forest species composition: decrease of fir and yew in favor of beech between the Gallo-  
376 Roman and the Carolingian periods (Saulnier et al., 2020). Charcoal analysis also suggested a preferential use of  
377 beech, probably related to a selective management strategy (Fig. 9A). Post-pioneer taxa confirms forest clearings  
378 suitable for grazing. These canopy openings imply the existence of open coppice-type sylvo-facies and/or the  
379 absence of large trees suggested by wood diameters (Fig. 9B) (Fouédjeu et al., 2021b). Beech, which is able to  
380 resprout from stumps, was promoted to improve fuel and fodder production (Petit and Watkins, 2004). These  
381 indications suggest a multi-use management of woodland where the impact of charcoal production was low.

382 In the early 14th c., the increased regulation of charcoal production has been interpreted as the result of a “first  
383 forest crisis” (Bonhôte et al., 2000; 2002; Davasse, 2006). Despite the incontestable extension of clearings (Galop  
384 et al., 2013), charcoal analysis has shown that woodland was managed and conserved in mountain and subalpine  
385 areas (Davasse, 2000; Py-Saragaglia et al., 2017). They were privileged places for domestic and industrial uses,  
386 causing episodic and local over-exploitation (Verna, 2001, p. 95) and motivating improved regulation and the  
387 creation of forest reserves (e.g. for mine timber<sup>58</sup>).

388 In the focus area, three platforms ran between 1295-1442 cal AD, but probably not simultaneously (Fig. 9A, Table  
389 1). While charcoal from these platforms suggest that fuel wood was probably harvested in beech woodland, soil  
390 charcoal has revealed the existence of mixed fir-beech stands (Saulnier et al., 2020). Consequently, we assume  
391 that fir was excluded from charcoal supply and reserved for other purposes, involving a specific management  
392 system with beech treated as coppice and fir as standard (Fouédjeu et al., 2021b).

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<sup>58</sup> Supplementary file 1, doc n°14.



394 Artigue ■ Shade-tolerant species ■ Pioneers species ■ Post-pioneers species ★ Dated levels

395 Fig. 11 Anthracological diagram of Artigue and Soulcem showing the relative frequencies of taxa. Points represent  
 396 taxa with relative frequencies of lower than 1% (Davasse, 1989; 2000).

397 Two field surveys performed in the Auzat valley (1563-64) reported the existence of an old-growth forest  
 398 composed of a significant proportion of senescent trees<sup>59</sup>. Charcoal burning was presented as the only way to  
 399 enhance these woodlands that could not be exploited for timbering due to poor accessibility. Although this account  
 400 may overstate bloomeries installation, it suggests that large forest areas still covered these valleys.

401 Six platforms from the focus area and six others located in Arbu (4) and Artigue (2) ran between the mid-15th c.  
 402 to mid-17th c.(Figs. 8, 9A, Table 1) (Davasse, 2000, pp. 163–164). Charcoal analysis reflects the use of more  
 403 diversified species (beech and fir, with weak proportion of other species) (Fig. 9A). It still suggests that a mixed  
 404 fir-beech woodland was maintained, with wide structural diversity, as observed at Artiès (Fig. 11) (Dubois, 1995).

<sup>59</sup> Supplementary file 1, doc n°64-65; 67.

405 A shift in charcoal burning practices would have occurred following an increase in the use of fir and a decrease in  
406 wood caliber (Fouédjeu et al., 2021b; Fig. 9B), probably between the 16th c., when Ferraziel bloomery was built,  
407 and the early 17th c., when the iron industry was booming. In Artigue, the almost exclusive use of fir assumes a  
408 high fir-dominated forest (Métailié and Jalut, 1991; Davasse, 2000, pp. 163–164).

409 In 1669, forest Reformation reports described “degraded” woodland, insufficiently stocked to ensure industrial  
410 demand<sup>60</sup>. This perception was probably inherited from fears of lacking high forests suitable for timber (Poublanc,  
411 2019; 2020). Far from the high forest ideal, beech coppice-dominated woodlands were composed of 60% beech,  
412 34% mixed beech-fir stands and 6% fir (Davasse, 2000, pp. 90–97; 237–238; Poublanc, 2019, pp. 55–56). The  
413 stands where dominated most were located in the valleys downstream and in the upper part of slopes, and were  
414 mainly composed of 25-50 to 100 year-old trees. Information about 18th c. woodland composition and structure  
415 is scarce and dispersed (Davasse, 2000, pp. 111–113). Beech was omnipresent, sometimes associated with hazel  
416 and oak. The harvesting of beech seeds for replanting is also attested<sup>61</sup>. Fir was still present in several valleys,  
417 where it was mixed with oak.

418 In the focus area and Soulcem (Figs. 9A, 11), some platforms could date to after the 1740 prohibition. Charcoal  
419 analysis showed the preferred use of beech with the occasional admixture of fir. In addition to poor fir regeneration  
420 induced by canopy removal leading to scattered trees, the beech coppice-dominated system did not favor large  
421 high forest trees. Canopy removal was most likely unfavorable to both young fir and beech, which are shade  
422 species in the juvenile stage (Unrau et al., 2018). In the absence of an upper-story, people solved this problem  
423 using a coppice selection system (Salvador, 1930; Nicolescu et al., 2018). Conversely, the predominant use of fir  
424 with beech, pine and a greater diversity of broadleaved trees at Soulcem reveals the persistence of a fir-beech forest  
425 with clearings (Davasse, 2000).

426 The 1807 forest inventory depicted woodland as still covering large but fragmented areas, shaped by the extension  
427 of mid-altitude agro-pastoral settlements (Davasse, 2000, pp. 242–244). Woodland was mainly composed of young  
428 beech coppice (10-20 year-old), sometimes mixed with fir hardwood species. However, adult beech woodlands  
429 (100-200 year-old) were maintained in some areas. Fir-dominated forest, with 80 to 100 year-old high trees, still  
430 existed in five districts, but some of them were “badly managed” or “exhausted”(e.g. at Sem). The upper part of  
431 the Suc forest was composed of a beech-fir forest and the lower part by degraded beech coppice.

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<sup>60</sup> Supplementary file 1, doc n°249, fol. 136 (1669); 231, fol. 418 (1667).

<sup>61</sup> Supplementary file 1, doc n°576.

432 Forest cover dropped sharply between 1807 and 1860, reaching its historical minimum (Davasse, 2000, pp. 124;  
433 130–132), which coincides with the population and agro-pastoral economy maximum (Dengerma, 1934; Davasse,  
434 2006; Gibert et al., 2012). In Suc, the beech-fir forest was almost entirely converted into a beech coppice in 1860,  
435 with isolated firs (Davasse, 2000, pp. 124–130). Charcoal analysis confirms the near disappearance of fir around  
436 the 19th-20th c. in the focus area (Fig. 9A). In the same way, in Soulcem, results suggest the harvesting of relict  
437 fir trees (Fig. 11). In 1892, the focus area was managed in a coppice selection system, with 20-50 year-old beech  
438 trees, and was then gradually converted into high forest (Fouédjeu et al., 2021a).

### 439 **Conclusion**

440 The results presented allow us to answer the research questions posed. First, our reappraisal of the iron industry  
441 chronology highlighted significant fluctuations over time. As such, and contrary to widespread ideas, continuity  
442 of iron production from late Antiquity to the central medieval period cannot be demonstrated as of yet. Moreover,  
443 the emergence and spread of the water-powered bloomery in the 14th c. did not result in the stabilization or  
444 significant growth of local iron smelting. Late medieval industrial development was short-lived and had already  
445 slowed in the mid-15th c. Despite the entrepreneurial boom initiated in the mid-16th c. in the upper valleys, the  
446 real catalyst for the iron industry came only in the early 17th c. in the lower valleys. In the mid-17th c., the Catalan  
447 technology gave new impetus to charcoal iron smelting, which reached its greatest intensity. The industrial fabric  
448 then remained more or less the same until the charcoal iron industry ended in the late 19th c.

449 Second, local management policies tried to ensure the sustainability of charcoal supply, and consequently, of forest  
450 resources, to support industrial development efforts through woodland use restrictions and the outsourcing of a  
451 part of charcoal supply. Although some authors have noted a first forest crisis as soon as the 14th c., caused by  
452 increased charcoal consumption by water-powered bloomeries, in-depth analysis of platforms shows industrial  
453 pressure on mountain forest resources remained relatively weak. Likewise, instead of the residual “shreds”  
454 previously proposed for the 16th c., charcoal making still occurred in a well-stocked mountain woodland that was  
455 conservatively managed. But the conversion of certain forest areas into beech-dominated coppice led to changes  
456 both in forest structure and biodiversity features, with the declining regeneration of fir and the increase of light-  
457 demanding species.

458 Third, significant forest cover decline began most likely during the 17th c. and accelerated in the 18th c., after  
459 charcoal manufacturing prohibition, mostly because of increased domestic, pastoral and agricultural needs, due to

460 the 18th c. demographic explosion. Consequently, our results do not support the historical decline of the Pyrenean  
461 mountain forest cover induced by the growth of the iron charcoal industry. The intensification of agro-pastoralism  
462 was apparently the real cause of the mid-19th c. minimum forest cover, but deeper investigation of intensive  
463 livestock breeding and extensive mountain agriculture is required.

464 To conclude, this integrated study rejects the common premise that the charcoal-based iron industry in European  
465 mountains necessarily led to forest depletion. Conversely, it supports the hypothesis of the sustainable management  
466 of woodland (practices and policies), allowing the perpetuation of fuel resources and the support of industrial  
467 growth. Such interdisciplinary research should be applied in other places in order to unveil interactions between  
468 forest and pre-industrial societies.

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