



**HAL**  
open science

## A Holocene history of forest vegetation on the northern slopes of a Mediterranean mountain: the Mont Ventoux, Southeast France

Emma Gamba, Sébastien Aurelle, Clémentine Vergnaud, Brigitte Talon

### ► To cite this version:

Emma Gamba, Sébastien Aurelle, Clémentine Vergnaud, Brigitte Talon. A Holocene history of forest vegetation on the northern slopes of a Mediterranean mountain: the Mont Ventoux, Southeast France. *Ecologia mediterranea*, 2022, 48 (2), pp.53-68. hal-03992088

**HAL Id: hal-03992088**

**<https://amu.hal.science/hal-03992088v1>**

Submitted on 16 Feb 2023

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# A Holocene history of forest vegetation on the northern slopes of a Mediterranean mountain: the Mont Ventoux, Southeast France

*Histoire holocène de la végétation forestière du versant nord d'une montagne méditerranéenne : le mont Ventoux (Vaucluse, France)*

Emma GAMBA<sup>1</sup>, Sébastien AURELLE<sup>2</sup>, Clémentine VERGNAUD<sup>3</sup>, Brigitte TALON<sup>1\*</sup>

1. Institut méditerranéen de biodiversité et d'écologie (IMBE), Aix Marseille Université, Avignon Université, CNRS, IRD, Aix-en-Provence, France

2. Aix Marseille Université,

3. Université de Bordeaux

\* Corresponding author: brigitte.talon@imbe.fr

Received: 7 Nov., 2022; First decision: 28 Nov., 2022; Revised: 16 Dec., 2022; Accepted: 20 Dec., 2022

## Résumé

Cette étude vise à reconstituer la composition de la végétation ligneuse passée du versant nord du mont Ventoux en fonction du gradient altitudinal ainsi que l'altitude maximale atteinte par les arbres avant la déforestation des versants, qui fut intense à partir du XII<sup>e</sup> siècle, en lien avec des perturbations passées telles que le surpâturage et les feux de gestion sylvo-pastorale. Profitant de la mise en place d'un transect du suivi écologique ORCHAMP en 2019, six fosses pédologiques réparties depuis 925 m (hêtraie sapinière) jusqu'à 1860 m d'altitude (pins à crochets prostrés) ont fait l'objet de prélèvements pédoanthracologiques (identification et datation des charbons de bois du sol). Toutes les fosses contenaient des charbons de bois. La richesse taxonomique diminue significativement à mesure que l'on s'élève le long du gradient altitudinal. Certains taxons ont été trouvés à des altitudes auxquelles ils sont

aujourd'hui absents, comme le sapin (*Abies alba*) qui s'élevait jusqu'au sommet et formait avec les pins la limite supérieure des arbres. Le hêtre (*Fagus sylvatica*) est bien représenté à basse altitude mais aucun charbon de cette essence n'a pu être trouvé au-delà de 1340 m, alors que l'espèce atteint aujourd'hui 1700 m d'altitude. Les datations montrent que les sols du versant nord du mont Ventoux ont conservé, malgré l'érosion des versants, plus de 4000 ans d'histoire. La période couverte par les 6 datations <sup>14</sup>C AMS obtenues s'étend de l'âge du bronze (3576-3729 cal BP) à la période moderne (346-460 cal BP), soit avant les reboisements de 1860 (RTM, restauration des terrains en montagne). Cette première étude pédoanthracologique se révèle novatrice et parfaitement complémentaire des études paléoenvironnementales préexistantes mais encore insuffisante pour reconstruire l'histoire de la végétation passée du mont Ventoux et anticiper son avenir.

**Mots-clés:** paléoécologie, limite supérieure des arbres, charbons de bois dans les sols, gradient altitudinal, *Abies alba*, *Fagus sylvatica*.

**Keywords:** palaeoecology, treeline, soil charcoal, altitudinal gradient, *Abies alba*, *Fagus sylvatica*, radiocarbon dating.

## Abstract

This study aims at reconstructing the late Holocene vegetation dynamics and the maximum altitudinal limit of forest trees on northern slopes of Mont Ventoux before the intense deforestation of the 12th century, in relation to natural environmental changes and anthropogenic disturbances including fire history and silvo-pastoral practices. Six soil pits were studied out along an altitudinal transect from 925m to 1,860m a.s.l. This transect crosses the beech-fir forests in the lower elevations to open woodlands containing the prostrate hooked pine (*Pinus uncinata*) near the summit. The study was performed within the framework of the ecological monitoring program ORCHAMP. Pedaanthracological data (identified charcoals and their  $^{14}\text{C}$  ages) were further explored by numerical analyses. Charcoal was found in all pits with concentrations significantly decreasing with altitude, as does the proportion of charcoal of deciduous trees over conifers. Some woody species were found at altitudes where they are absent today, notably fir (*Abies alba*) at high elevations, (up to 1,860m). In contrast to fir, the beech (*Fagus sylvatica*) charcoals were not found beyond 1,340m, although the species currently reaches elevations as high as 1,700m a.s.l. Radiocarbon dating results suggest that the soils on northern slopes of Mont Ventoux have not been significantly eroded since at least 4,000 years ago. The period covered by the six obtained AMS  $^{14}\text{C}$  dates extends from the Bronze Age (oldest  $^{14}\text{C}$  age: 3576-3729 cal BP / 1779-1626 BCE) to the Modern Era (youngest  $^{14}\text{C}$  age: 346-460 cal BP / 1490-1604 CE), all pre-dating the 1860's reforestation projects (RTM, Restoration of Mountain Land). This preliminary pedoanthracological study proved to be promising and complementary to other palaeoecological approaches but is still insufficient to provide a complete picture of the past vegetation history of Mont Ventoux.

## Introduction

During the last 10,000 years, climatic changes and human activities have deeply impacted and shaped the mountain landscapes on most of the Earth's surface. The long co-evolution of human societies and these landscapes can partly explain their current diversity and fragmentation (Swenson & Franklin 2000) and particularly the altitudinal and taxonomic variations of the treeline, one of the most important ecotones in mountain environments (Tremblay *et al.* 2016). From a given elevation upward, bioclimatic conditions and particularly the regional temperatures become too constraining for the optimal growth and establishment of tree populations (Holtmeier 1994; Körner 1999; Holtmeier & Broll 2005). However, it has been shown that the treeline was higher

and displayed more tree diversity in most of the European mountain systems (e.g. Pyrenees and the Alps) but lowered almost everywhere due to the agro-sylvo-pastoral pressure (Cunill *et al.* 2013; Finsinger *et al.* 2021; Carnelli *et al.* 2004; Talon 2010). This has particularly been demonstrated by soil charcoal analysis (pedoanthracology) in a number of sites (Carcaillet & Thion 1996; Di Pasquale *et al.* 2008; Talon 2010). Recently, the agro-pastoral abandonment and global warming have been inducing the upward movement of numerous woody taxa, which were restricted to lower elevations. Lenoir *et al.* (2010) have shown that in the case of French mountains, the altitudinal optimum of several forest trees, such as the common hornbeam (*Carpinus betulus* L.), or the common hazelnut (*Corylus avellana* L.) have elevated by approximately 30m per decade since 1980s. In the Spanish Pyrenees, the beech forest upper limit has moved 70m to higher elevations in only 50 years (Labonne *et al.* 2019).

A better understanding of this ecological phenomenon necessitates investigating the long-term dynamics (centennial to millennial) of the upper tree limit in response to climatic variations and human activities. The research presented here belongs to the ORCHAMP monitoring program ([www.orchamp.osug.fr](http://www.orchamp.osug.fr)). This pluri-disciplinary research project is aimed at studying the links between climate change, land-use and biodiversity along altitudinal gradients in the Alpine territory. ORCHAMP sites are characterized by regularly monitored quadrats located at 200m altitudinal intervals and along an approximately 1,000m-long transect. Monitoring efforts are focused on the fauna (soil DNA), vegetation (flora, forest cover, decaying wood), climate (temperature and relative humidity), and soil (<https://orchamp.osug.fr>).

The imprints of past human activities on the structure and dynamics of current vegetation of mountain forest ecosystems will be particularly investigated. More than 30 transects have already been established along N-S altitudinal gradients over Mont Blanc, Maritime Alps, and the Mediterranean massif of Mont Ventoux with alpine characters. The present study takes advantage of the ecological transect of ORCHAMP established by Institut méditerranéen de biodiversité et d'écologie in 2019 on the northern slopes of Mont Ventoux. In the absence of wetlands and lakes for pollen-based vegetation reconstructions, we explored the soil archives of

the experimental pedological pits and apply pedoanthracology to investigate the history of vegetation in relation to human activities.

The main objectives of this study are to reconstruct (i) the composition of woody taxa in forest vegetation of Mont Ventoux and (ii) the altitudinal position of the upper limit of forest (treeline) on the northern slopes in relation to past human disturbances, such as deliberate landscape burning and tree cutting for silvo-pastoral management purposes. We will specifically focus on two forest species, European silver fir (*Abies alba* Mill.) and beech (*Fagus sylvatica* L.), which are characteristic of montane forest belts and form well-established populations on the Mont Ventoux northern slopes as well as the Lure Mountain. Together, they form the southernmost mixed beech-fir populations of Provence region in Southern France. In the face of ongoing global warming, the future of these forests at their southernmost distribution area remains uncertain (Tinner *et al.* 2013; Hendrik *et al.* 2020; Morales-Molino *et al.* 2021). Investigating their history is thus necessary to better predict their current and future ecological trajectories. This study aims at testing two working hypotheses: 1) the floristic composition of the upper forest limit was different in the past from today, 2) the treeline was located in higher altitudes, and 3) both fir and beech forests occupied more extended altitudinal extensions.

## Study Site

### Physical setting

Mont Ventoux (44.172912° N, 5.278177° E) culminates at an elevation of 1,910m. It is 25km long (east-west axis) and 15km wide (north-south axis) and is at the confluence of the Alpine and Mediterranean phytogeographical zones (Rouveyrol & Leroy 2021). The northern slopes, steeper than the southern slopes, are subjected to very harsh ecological conditions. The average annual precipitation (from 1994 to 2007) is 1,270mm at the Mont-Serein meteorological station (1,445m altitude). Characteristic of the Mediterranean-type of climate, the annual precipitation is irregularly distributed along a year and mainly falls in autumn-winter-spring with presence of summer droughts (Cailleret 2007). The average annual temperature is 6.6°C (Ladier 2004).

## Forest vegetation of Mont Ventoux: past and present

Today, a mosaic of forest composed of different coniferous and deciduous species occupies the two slopes of Mont Ventoux, showing a vertical zonation mainly controlled by the altitudinal temperature gradient. The history of the vegetation of Mont Ventoux is very well documented for the Modern and Contemporary Era thanks to available historical archives, notably those of the forestry services. Before the 13th century, forest exploitation was practiced on the northern slopes while the southern flanks were cultivated and grazed. The Great Plague (1347-1348 CE) and the Hundred Years' War (1337-1453 CE) caused demographic decline and agro-pastoral abandonment that favored forest recolonization. Forest clearing was resumed from the 16th century with the increase in population and the growing need for wood (timber, firewood, charcoal) and agro-pastoral lands (Martin-Gousset *et al.* 2019). The deforestation of the mountain continued until the 19th century. The consequences of the ancient deforestation, dating to as early as the Bronze Age, on the current distribution of forest vegetation on the northern slope of Mont Ventoux have been described by L. Martin-Gousset *et al.* (2019) for the Mont Ventoux Biological Reserve (Réserve biologique intégrale du mont Ventoux - RBI-MV) officially created in 2010 by the French National Forestry Office (ONF) (Terracol *et al.* 2017). The RBI-MV (906ha), situated slightly northeast, covers an altitudinal gradient of 1200 m, from supra-Mediterranean to subalpine bioclimatic belts (680-1880 m). The current forest stands are largely the result of the mountain land reforestation program termed RTM (Restauration des Terrains de Montagne) in the 19th to early 20th centuries. Indeed, in the 1860s, the RTM service undertook the reforestation of Mont Ventoux with various coniferous and deciduous species to fight against soil erosion (Ningre 2007).

Thanks to a vertical vegetation zonation scheme within the RBI-MV located to the east of our transect and elegantly drawn and described by C.F. Martins (Martins 1838, in Martin-Gousset *et al.* 2019), it is possible to get an idea about the state of the forest vegetation of the northern slope before the RTM reforestations. On this sketch, while the supra-Mediterranean zone seems to be occupied by lavender and thyme heaths

instead of deciduous oak forests, the montane zone still presents in its lower part (1,000-1,250m) stands of wild maple (*Acer opalus* Miller) and beech, and in the upper part (up to 1,800m), fir, hooked pine (*Pinus mugo* Turra subsp. *uncinata* (Ramond ex DC.) Domin) and common juniper (*Juniperus communis* L. subsp. *nana* (Hook.) Syme). The upper treeline is depicted at 1,650m. From this sketch, the forest above 1,400m is very open. The distinctive silhouette of some of the fir and beech trees in the sketch, which are today considered as relict stands, confirms this graphic representation by C.F. Martins. Their candelabra-like aspect and well-developed low branches indicate conditions of growth without inter-individual competition and thus a certain degree of openness. The oldest stands of the RBI-MV, left to evolve naturally for more than a century, owe their survival to their hardly accessible position above the steep rock cliffs. Indeed, it is in these relict stands that the oldest known trees in Vaucluse are found (> 400-year old firs and 300-year old beech trees) (Terracol *et al.* 2017).

Although the vegetation of the mountain slope corresponding to our transect is not as well documented prior to the 19th century RTM plantations, it is clear that the absence of steep slopes and rock cliffs allowed an easier access to forest stands compared to the RBI-MV. This fact facilitated the deforestation that was much greater there as is evident in the photographs taken at the late 19th century by the agents of the Eaux et Forêts (Collective 2004). In the northern slope of Mont Ventoux, there are numerous caves and cavities in the rock cliffs containing the accumulations of biological remains, which have been used by prehistorians for palaeoenvironmental reconstructions (Crégut-Bonnoure *et al.* 2005). For instance, the charcoal assemblages collected in the

infilling of the René Jean cave (1,650m), in particular, also rich in bear bones dated from the Neolithic to the Middle Ages, has made it possible to recognize three species: fir, Scots pine (*Pinus sylvestris* L.) or hooked pine and birch leaf maple (*Acer opalus*) (Thinon 2007). They indicate wildfires that occurred between 1,650m and the summit, which is equivalent to the topmost part of our transect located one to two kilometers to the west. Only hooked pine is still thriving in this altitudinal belt today. Finally, the last data likely to provide precise spatial information on the forest species that colonized the summit of Mont Ventoux come from an exploratory pedoanthracological study carried out by M. Thinon (1978) on the southern slope. A pit dug in a summit lithosol at 1,810m altitude, on the crest, yielded a beech charcoal, which has not been dated (Thinon 2007). All these works indicate that since at least the Middle Neolithic (Crégut-Bonnoure *et al.* 2005), Mont Ventoux, even at its summit, has been covered by forest species such as fir, beech and Scots/hooked pine, which later disappeared mostly as a result of fires at least partly linked to pastoral management. Our study aims to complete this information, both spatially and temporally.

The current forest vegetation covering the northern slopes of Mont Ventoux in which our study transect was set up is the result of both RTM reforestation and spontaneous regeneration of the original species over the last few decades, thanks to the forest cover provided by these reforestations. The species used in plantations are the Austrian black pine (*Pinus nigra* J.F. Arnold subsp. *nigra*), Scots pine (*P. sylvestris*) and downy oak (*Quercus pubescens* Willd.) in the supra-mediterranean and lower montane, Scots pine, loblolly pine (*Pinus mugo* subsp. *uncinata*), and larch

**Table 1 – Main tree species observed on the current plots. The star\* indicates species remained from RTM plantations.**

**Tableau 1 – Principales essences arborescentes présentes sur les placettes actuelles. L'étoile\* indique les essences issues de plantations RTM.**

VTN1 925m	VTN2 1,130m	VTN3 1,340m	VTN4 1,510m	VTN5 1,675m	VTN6 1,860m
<i>Abies alba</i> * <i>Pinus sylvestris</i> * <i>Juniperus communis</i>	<i>A. alba</i> * <i>P. sylvestris</i> *	<i>A. alba</i> *	<i>A. alba</i> * <i>Pinus mugo</i> subsp. <i>uncinata</i> *	<i>P. mugo</i> subsp. <i>uncinata</i> *	<i>P. mugo</i> subsp. <i>uncinata</i>
<i>Quercus ilex</i> <i>Q. pubescens</i> <i>Buxus sempervirens</i> <i>Acer opalus</i> <i>Sorbus aria</i> <i>Viburnum lantana</i>	<i>Fagus sylvatica</i> <i>B. sempervirens</i> <i>A. opalus</i> <i>S. aria</i> <i>V. lantana</i>	<i>F. sylvatica</i> <i>S. aria</i>	<i>F. sylvatica</i>		

(*Larix decidua* Mill.) in the middle montane, and finally loblolly pine in the upper montane (Martin-Gousset *et al.* 2019).

The main trees and shrub species currently present on our plots are summarized in Table 1.

## Materials and methods

### Sampling sites

In 2019, an altitudinal transect containing six permanent plots (VTN1 to VTN6) was established on the northern slopes of Mont Ventoux, from 925 to 1,860m elevation (Figure 1). Within each plot, a 900m<sup>2</sup> (30m × 30m) quadrat was delimited for applying different monitoring protocols of the ORCHAMP project (<https://orchamp.osug.fr/Protocoles>). A pedological pit was dug outside each permanent plot but at the immediate proximity of one of its four corners in order to describe the physico-chemical properties of soil profile. Once the pedological properties of the six soil profiles were described, we sampled them for our soil charcoal analysis to reconstruct the fire history and woody vegetation dynamics.

Wood charcoals are organic materials with high resistance to biological degradation and once buried in the soil, are preserved for very long periods of time (Thinon 1992, Talon *et al.* 2005; Marguerie *et al.* 2010). After carbonization, wood anatomy is well-preserved making its taxonomic identification possible (Chabal 1997). Despite this, many charcoals are difficult to identify whether because they are covered by different deposits (clays, sands, crystals) or show a vitrified aspect (McParland *et al.* 2010) i.e. the wood structure can be distinguished but the anatomic elements are fused together preventing the identification (Marguerie *et al.* 2010).

The study of charcoals coupled with their AMS radiocarbon dating allows reconstructing the dynamics and composition of vegetation with high spatial precision and on the millennial time scale (Carcaillet & Thinon, 1996; Touflan *et al.* 2010; Robin *et al.* 2013).

### Pedoanthracological sampling and laboratory preparation

Soil samples were taken continuously from the bottom to the top of the profile at 10cm-thick levels (Saulnier *et al.* 2015). In total,

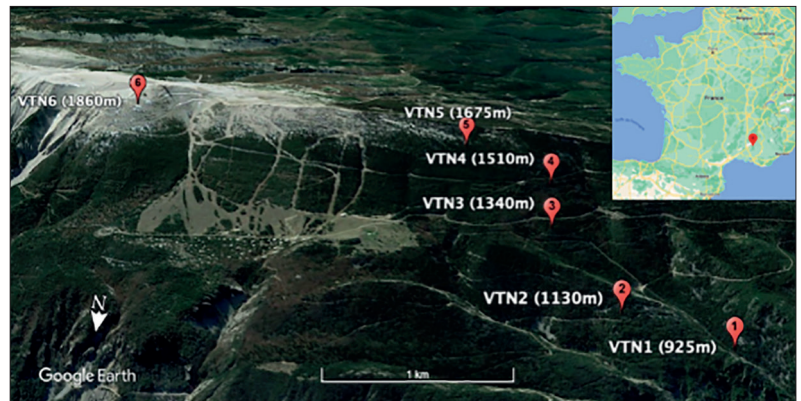


Figure 1 – Map showing the location of the study site and the sample plots located on the ubac of Mont Ventoux (Google Maps and Google Earth).

Figure 1 – Carte de localisation du site d'étude et des placettes d'échantillonnage situées à l'ubac du mont Ventoux (Google Maps et Google Earth).

81 samples weighing about 135kg were taken from the six soil pits and transferred in 34 bags to the laboratory. The sieving protocol is described in a number of papers (e.g. Carcaillet & Thinon 1996, Saulnier *et al.* 2015). The soil samples are dried and then weighed to obtain the dry weight in kg. Each sample is then stirred in water with the addition of a small amount of deflocculant (sodium hexametaphosphate) to facilitate the suspension of organic elements. The supernatant (including plant debris and charcoal) and then the mineral elements are poured onto a column of 4 sieves (1cm, 1.25mm, 800µm, and 400µm), rinsed, and dried in oven (40°C). Coarse material > 1cm is weighed and its weight subtracted from the total soil weight for the calculation of specific anthracomass (SA). In this study, the mineral fractions and the organic fraction between 400 and 800µm were not studied.

Charcoals were picked one by one using flexible forceps under a stereomicroscope and put into micro-tubes labeled by level, fraction (organic or mineral) and size class (e.g. VTN2 20-30 Root > 800µm). For each depth, given the limited time available for this study, 20 charcoals were randomly picked from the largest size class (> 1.25mm). If the considered size class had fewer than 20 charcoals or nothing, the rest of charcoals were picked from the smaller size class (> 800µm). Charcoals were identified using an episcopic microscope (Olympus model BX41) with dark field and magnification range of x100 to x500. Identifications were based on observation of transverse, radial longitudinal, and tangential longitudinal sections and using the available

literature on wood and charcoal anatomy (Jacquiot 1955; Schweingruber 1990; Vernet *et al.* 2001) as well as the charcoal reference collection of pedoanthracology of the Institut méditerranéen de biodiversité et d'écologie.

The identification of charcoal can be more or less easy because it depends on the state of conservation of the extracted fragments. The worst case is that of indeterminable “vitrified” charcoal. To this should be added the problem of differential identification; some genera or species are more difficult to identify than others, especially on small charcoals, because they are anatomically very close, such as Scots pine and hooked pine or, in the case of juvenile structures, fir and juniper. In such cases, they are named *Pinus sylvestris/uncinata* or *Abies/Juniperus*. In some cases, it may not be possible to go beyond the genus (e.g. *Acer*), family (e.g. Rosaceae) level and even to distinguish the deciduous from coniferous trees.

### Radiocarbon dating

The selection of the charcoal pieces to achieve <sup>14</sup>C dating was performed according to their significance to the overall charcoal taxonomic spectrum. Six single charcoal fragments weighing at least 2mg were selected for radiocarbon dating from the set of taxonomically identified charcoals and shipped to Poznan Radiocarbon Laboratory, Poland. The radiocarbon ages were calibrated and the probability distribution curves were graphically created in R package “clam” run in RStudio version 4.1.0 (Blaauw 2010; R Core Team 2021) using the IntCal20 calibration curve (Reimer *et al.* 2020). The results are reported in Appendix 2.

### Calculation of specific anthracomasses

All the sorted charcoals are weighed in order to calculate the specific anthracomass (SA) and to make the quantities of charcoals comparable from one pit to another. In our study, the specific anthracomass corresponds to the ratio between the mass in mg of extracted coals (fraction > 800µm) and the total mass in kg of dry soil (fraction < 1cm), expressed in mg.kg<sup>-1</sup> or in parts per million (ppm). Three types of specific anthracomass were calculated:

The Specific Anthracomass per Profile (SAP) which corresponds to the mass of all charcoals (identified and unidentified) in a pit (in mg), related to the total mass of soil (in kg).

The Specific Anthracomass per Level (SAL), which corresponds to the mass of all the coals contained in a level (in mg), compared to the total mass of soil in that same level (in kg).

The Taxonomic Specific Anthracomass (TSA), which corresponds to the mass of all the charcoal of a given taxon contained in a level or pit (in mg), related to the total mass of soil of this level or pit (in kg).

### Statistical tools

The results of the identifications, expressed as TSA, were processed graphically using C2 data analysis software, version 1.7.7, developed by Steve Juggins, in order to present them as anthracological diagrams. A logarithmic scale was applied to the SA values in order to compare them more easily. The dataset resulting from this study is partly based on qualitative data of the “Presence/Absence” type for charcoal identifications as well as for the current vegetation surveys (carried out as part of the ORCHAMP protocol in 2019) on all plots. Two Correspondence Analysis (CA) were conducted to compare the diversity of woody species currently present on the plots with the taxonomic composition of the anthracological results. The data are expressed in “Presence/Absence”. Beforehand, as regard charcoal data, taxa encountered several times on all the plots and so-called “rare” taxa, i.e. those identified only in one plot, must be distinguished. These rare taxa are included in the analyses as additional qualitative variables. The CA function of the “FactoMineR” package (Le *et al.* 2008) was used to perform these analyses. The package was run in RStudio version 4.1.0 (R Core team 2021).

Diversity measures on the surveys are summarized as measures of taxonomic richness. Specific diversity was assessed on the anthracological data. Indeed, the sum of taxa present as charcoal for each soil level in each pit was calculated. In order to test the variation of the number of taxa with altitude, a one-factor ANOVA followed by a Bonferroni test. The objective was to compare two-to-two plots and to demonstrate a significant difference or not in the number of taxa against the altitude.

## Results

### Anthracological diagrams

A total of 458 charcoals were identified and attributed to 15 woody taxa (Appendix 1, Figure 7): *Abies*, *Abies/Juniperus* sp., *Juniperus* sp., *Pinus sylvestris/uncinata*, *Pinus* sp., *Taxus baccata*, *Fagus sylvatica*, *Acer* sp., *Prunus* sp., *Amelanchier* sp., *Sorbus* sp., Rosaceae, *Quercus* sp., *Betula* sp., *Fraxinus* sp. Analysis of the soil charcoals revealed great diversity in the anthracological record between pits, both quantitatively and qualitatively. Charcoal was found in all pits and in all levels, with a clear decrease in taxonomic diversity towards higher elevations. Conifers were identified along the entire transect. Fir is the most represented and frequent conifer in terms of quantity: it is found in all pits. At 1,860m (VTN6), it is even the only taxon identified. Yew (*Taxus baccata* L.) was identified twice, in the deepest level of VTN1 (90-110cm) at 925m, and at the middle of VTN4 profile (30-40cm) located at 1,510m. No hardwood was identified above 1,340m elevation (VTN3). In terms of quantitative values, beech remains the most represented hardwood, particularly in VTN1 where it is found throughout the profile.

### Statistical analysis of qualitative data

The correspondence analysis (CA) of the soil anthracological results (Figure 2) differentiates the pits according to the taxa identified. The CA axes 1 and 2 explain 72.45% of the variability of the data set (48.88% for axis 1 and 23.57% for axis 2). The CA scatter plot spatially separates pits located below 1,510m (VTN1, VTN2 and VTN3) from those higher than 1,510m (VTN4, VTN5 and VTN6). Above 1,510m of altitude (VTN4), the taxa found are mostly conifers such as fir, pine, yew and juniper. Below this altitude, charcoal from deciduous trees such as beech, oak (*Quercus* sp.), maple (*Acer* sp.), ash (*Fraxinus* sp.), birch (*Betula* sp.) and Rosaceae (*Rosoideae Prunoideae* and *Maloideae*) are more abundant. In a more specific way, we were able to identify taxa such as *Taxus* at 925m and *Pinus* up to 1,340m as well as *Juniperus*, and *Pinus sylvestris/uncinata* up to 1,510m. Note also the significant proportion of vitrified charcoals present in all pits. Small in size and mostly cylindrical in shape, these charcoals

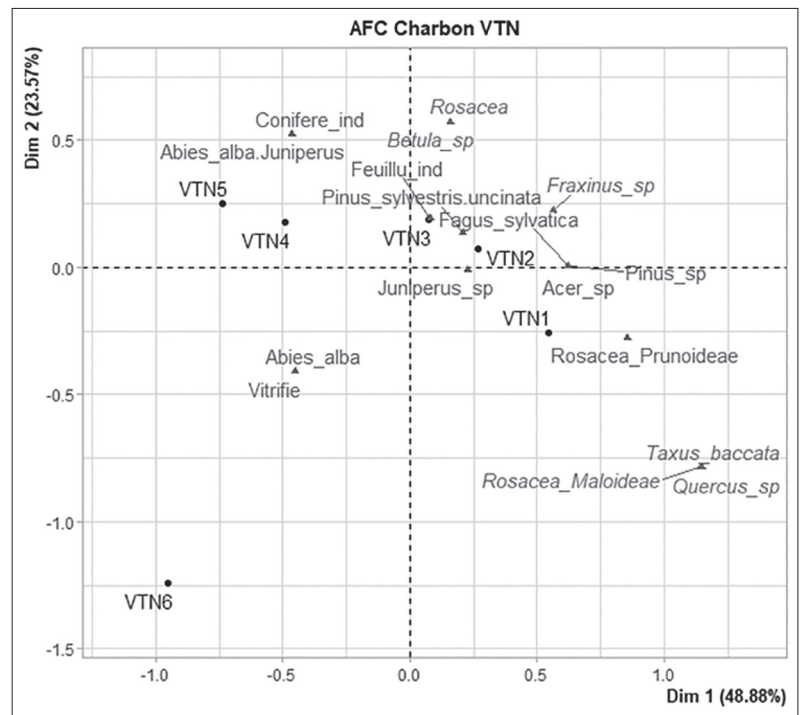


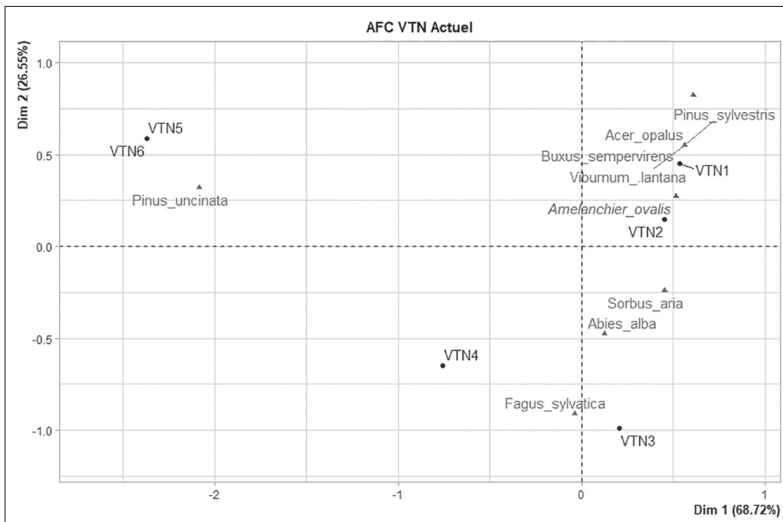
Figure 2 – Scatter plot of the Correspondence Analysis (CA) performed on identified charcoals data per pit (presence/absence per pit). The pits are shown in black, the identified charcoals in grey and the “rare” taxa in italic. VTN = Ventoux Nord. Inertia percentages: 48.88% (axis 1) and 23.57% (axis 2).

Figure 2 – Diagramme de dispersion de l'Analyse factorielle de correspondance (AFC) réalisée à partir des données d'identification de charbons par fosse (présence/absence par fosse). En noir sont représentées les placettes; en gris, les charbons de bois identifiés; en italique les taxons « rares ». VTN = Ventoux Nord. Pourcentages d'inertie: 48,88% (axe 1) et 23,57% (axe 2).

seem to result from the carbonization of very small diameter twigs, perhaps from microchamaephytes (5-15cm).

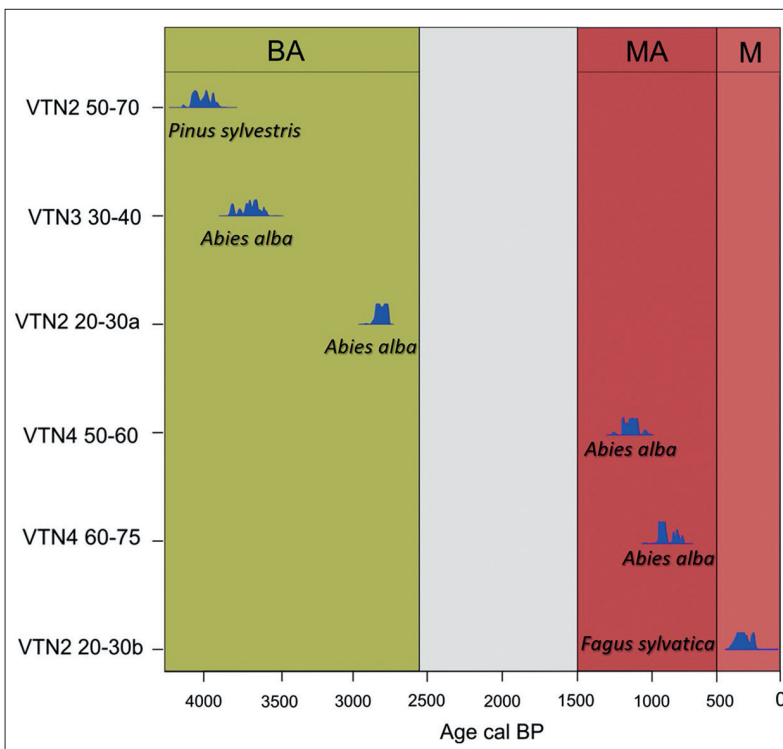
The second CA applied to modern vegetation data also helps to distinguish between plots (Figure 3). The two CA axes account for 95.27% of the variability in the dataset (68.72% for axis 1 and 26.55% for axis 2). The three lower altitude plots are spatially separated from the three higher altitude plots. Nevertheless, plots VTN3 and VTN4 are relatively close. This proximity is due to the presence of beech and fir in both plots. According to these surveys, deciduous trees are mainly present at lower elevations and become less abundant from 1,510m upward. Species not shown on the scatter plot are those present only in plot VTN1 i.e. common juniper (*Juniperus communis*), false cherry (*Prunus mahaleb* L.), holm oak (*Quercus ilex* L.), downy oak (*Quercus pubescens*), glossy buckthorn (*Rhamnus alaternus* L.), alpine buckthorn (*Rhamnus alpina* L.), sessile-leaved laburnum (*Cytisophyllum sessilifolium* (L.)





**Figure 3 – AFC performed on modern floristic data per plot (presence/absence per plot). The plots are shown in black, the species in grey and the 'rare' taxa in italic. VTN = Ventoux Nord. Inertia percentages explained by two axes are 48.88% for Axis 1 and 23.57% for Axis 2.**

**Figure 3 – AFC réalisée à partir des données d'identification de végétation actuelle par placette (présence/absence par placette). En noir sont représentées les placettes; en gris, les espèces identifiées; en italique les taxons « rares ». VTN = Ventoux Nord. Pourcentages d'inertie: 68,72 % (axe 1) et 26,55 % (axe 2).**



**Figure 4 – Temporal distribution of the probability distribution curves of the six identified and dated charcoals against the main historical periods. (AB) Bronze Age (4200-2750 BP); (MA) Middle Age (1500-500 BP); (M) Modern Era (450-150 BP). The historical periods are based on the chronology adopted by INRAP ([www.inrap.fr](http://www.inrap.fr)).**

**Figure 4 – Distribution temporelle des courbes de distribution de probabilité des six charbons identifiés et datés par rapport aux principales périodes historiques. (AB) Âge du bronze (4200-2750 BP); (MA) Moyen-Âge (1500-500 BP); (M) Période moderne (450-150 BP). Voir l'INRAP pour la chronologie ([www.inrap.fr](http://www.inrap.fr)).**

O. Lang), daphne laurel (*Daphne laureola* L.), and hedge honeysuckle (*Lonicera xylosteum* L.) up to 1,130m (VTN2) and birch leaf maple (*Acer opalus*), boxwood (*Buxus sempervirens* L.), wayfarer (*Viburnum lantana* L.), oval-leaved serviceberry (*Amelanchier ovalis* Medik.), and Scots pine were recorded. Whitebeam (*Sorbus aria* L.) is present up to 1,340m (VTN3). Conifers were present on all plots, such as common juniper (VTN1), Scots pine (VTN1 and VTN2) and fir (VTN1 to VTN4). Plots VTN5 and VTN6 are very different from the others in terms of factors. They are distinguished by the fact that they are occupied only by hooked pine. It is possible to interpret axis 2 as a gradient of closure of the environment. It distinguishes closed environments (VTN3, VTN4) from more open environments (VTN1, VTN2, VTN5, VTN6).

## Radiocarbon dates

The soils of the northern slope of Mont Ventoux have recorded nearly 4,000 years of vegetation history (Appendix 2). The earliest radiocarbon dates back to the Bronze Age (VTN2, 3903-4088 cal BP / 1953-2138 BCE) and the latest one to the Modern Era (VTN2, 346-460 cal BP / 1604-1490 CE). Fir charcoal was dated to the Bronze Age (VTN2 and VTN3) and the Middle Ages (VTN4), pine to the Bronze Age (VTN2), and beech to the Modern Era (VTN2). The time distribution of the ages is illustrated in Figure 4 as the probability distribution curves which represent the calibrated ages with 2-sigma errors. The total absence of radiocarbon ages dating to the Iron Age and Classical and Late Antiquity is also noted.

## Discussion

The anthracological analysis of the ORCHAMP transect plots on the northern slopes of Mont Ventoux revealed the presence of charcoal in all pits from 925m (VTN1) to 1,860m (VTN6) and at all depth levels. Our interpretation is that the erosion following the historical deforestation of the slopes of Mont Ventoux could not wash away the entire soil cover. In fact, the dates obtained in this study all predate the RTM plantations of the late 19th and early 20th centuries. The scree deposits clearly visible on RTM photographs from the

beginning of the 20th century (Collectif 2004) have protected the relatively deep, charcoal-rich soils. Woody species (phanerophytes to chamaephytes) have thus reached as high as the 1,860m elevation corresponding to the top of our transect but slightly lower than the summit (1,910m). Numerous similar studies have demonstrated the presence of charcoal up to very high altitudes, in currently open montane steppes and grasslands mostly under grazing (e.g. Carcaillet & Thinin 1996; Tinner & Theurillat 2003; Ali *et al.* 2005; Talon 2010, Cunil *et al.* 2012). These results help to illustrate the important role of fire, both natural and anthropogenic in the establishment of current ecosystems and the current position of the altitudinal tree line (Theurillat & Guisan 2001).

To clarify the elevation at which the upper forest limit was located on this slope of Mont Ventoux prior to its deforestation, we compared the total charcoal richness of different pits, and more specifically, the decrease in general specific anthracomass (GSA) with increasing elevation (Talon 2010; Cunil *et al.* 2012). The comparison of GSAs shows a significant decrease from 1,675m (VTN5) upwards. Combining qualitative (taxonomic composition) and quantitative (SA) data allows us to suggest that the upper forest limit on the north slope of Mont Ventoux was around 1,510m (VTN4) and that the tree limit reached 1,860m (VTN6). While the upper limit of the forest is higher today, largely due to RTM plantations, the upper limit of the trees is essentially the same.

Comparing the specific SA values of conifers and hardwoods, the latter becomes less abundant from 1,130m and the maximum SA value of conifers is encountered at 1,510m (VTN4). These results are consistent with the current ecological distribution pattern of hardwoods and softwoods along an altitudinal gradient. Indeed, as temperature decreases with altitude (about 0.55°C every 100m), it directly affects the physiology and biology of mountain woody species (Ozenda 1985). With regard to the modern vegetation of Mont Ventoux, the pedoanthracological results accurately reflect the current distribution between deciduous and coniferous trees according to altitude. Indeed, from 1,675m (VTN5) upward, the number of taxa decreases significantly: averagely, four taxa are reduced to one in the topmost pits located in the summit. This decrease corresponds to the transition from the montane zone (1,100 to 1,600m) to

the subalpine zone (1,600 to 1,800m) on the northern slopes of Mont Ventoux (according to Gobert & Pautou 1968). The data also shed light on the role played by beech and fir.

Comparison of the current surveys (woody vegetation only) (Table 1) of the VTN1 and VTN2 plots with the corresponding anthracological assemblages reveals a good agreement between taxonomic diversity, despite the fact that the anthracological identifications (Appendix 1) often stop at lower taxonomic levels (genus or family e.g. Rosaceae). For plots VTN1 and VTN2, *Buxus* and *Viburnum* are the only taxa not identified at all in the charcoal assemblages. On the contrary, plot VTN3 appears to have had higher taxonomic richness in the past than present. In this plot we found *Acer* and *Betula*, which are absent from the modern vegetation. These preliminary results suggest that some species have had different altitudinal ranges than today.

Beech is currently present in the vegetation of plots VTN1 to VTN4, up to 1,510m elevation (Table 1). However, it was not found in the anthracological assemblages of VTN4, but only in those of plots VTN1 to VTN3. Considering that a larger sampling effort (> 20 charcoals) might have revealed it in VTN4, before publishing this work, we randomly picked up another 20 charcoals (> 1.25mm). But we did not find any beech. However, we did find yew. Since beech is currently present in plot VTN4, represented by a few old individuals scattered throughout the stand and formerly exploited in coppicing mode, we can assume that there has been no fire for several centuries (indeed, the dates obtained for this pit do not go back beyond the Middle Ages) or that the fire, if there was any, did not affect the beech trees. The last hypothesis is that there were no beech trees on this plot at the time of the last fire events. Only conifers provided charcoal. The absence of beech charcoal does not mean that beech was absent on the plot. In pedoanthracology, as in all paleoecological disciplines, the absence of a taxon may not mean a true absence of the taxon in the landscape and must always be interpreted with great caution (Birks & Tinner 2016)

The presence of yew charcoal is more surprising. This gymnosperm, a component of the beech-fir forest, is present today occasionally in association with beech in the communal forest of Beaumont-du-Ventoux, west of the Grand Vallat (Martin-Gousset *et al.* 2019), i.e.,

in our study area, but not at this altitude. It is also found further east, in the cliffs of the RBI as well as on the southern slopes. Yew (*Taxus baccata*) must therefore have played a more important role in vegetation in the past than today. Palynological and archaeoanthracological data show that yew expanded rapidly in Provence around 5500-5000 BC, when the agro-pastoral economy of the Neolithic period was being established but rapidly after, it started declining perhaps because of human intervention to cut it for its toxicity (Martin & Thiébaud 2010). Unfortunately, the few charcoals found in Mont Ventoux do not allow us to go further than confirming its presence on the slope in the past.

These first results indicate that, in the past, beech and yew, along with fir, occupied an altitudinal range between 900 and 1,300m altitude on the northern slopes of Mont Ventoux. The absence of old radiocarbon dates makes it difficult to propose the exact timing of the establishment of this “beech-fir forest” on Mont Ventoux. On the basis of palynological data, beech was present in Provence in low- and mid-altitude areas as early as the Atlantic period with a strong expansion in the Subboreal period, as early as 4,700 years BP (Andrieu-Ponel *et al.* 2000; Azuara *et al.* 2018). However, the location of these beech forests in Provence could never be accurately specified by palynologists due to the regional character of pollen data and good pollen dispersal of beech. At 1,130m elevation (VTN2), we identified a beech charcoal dated to the Modern Era (346-460 cal BP / 1490-1604 CE). This date, although recent, confirms the presence of beech on Mont Ventoux before the 1860s reforestation activities. It is thus supposed that the species was truly present in Mont Ventoux as suggested by Andrieu-Ponel *et al.* (2000). However, in the absence of more radiocarbon-dated beech charcoals, it is not still possible to confirm its presence on Mont Ventoux since the Atlantic period.

Fir tree has been found at all altitudes, from 925m to 1,860m. It represents about 35% of the identifications. Its presence up to 1,860m (VTN6) indicates that its upper limit was higher than today which does not exceed 1,510m (VTN4). The four dates obtained on fir fragments reveal that it was present on the northern slope of Mont Ventoux between 3,729 cal BP (Bronze Age) and 900 cal BP (Middle Ages), at an altitudinal range of 1,130m to 1,340m. The fragments found in VTN6 are too small to be dated. Therefore,

it is not known when fir tree occupied the highest elevation of the transect (1,860m). It is also not known whether it occupied this slope well before the Bronze Age although this is quite possible. Indeed, the presence of fir in southern France dates from the end of the last glaciation (Younger Dryas) (Terhürne-Berson *et al.* 2004). One of the charcoals found in the René Jean cave (but not identified), between an upper level dated to the Middle Ages and a base level dated to the Middle Neolithic, has been dated to 3025 ± 40 BP, i.e. the Middle Bronze-Final Bronze transition (Cregut-Bonnoure *et al.* 2005). The fir charcoal found in this same cave infill can therefore be attributed to this period (Thinon 2007). Fir pollen has been recorded in Provence as early as the Atlantic period at low altitude in the Baux marshes (Andrieu-Ponel *et al.* 2000), but the geographical provenance of its pollen has never been elucidated. As *Abies* pollen is very heavy, it seems unlikely that it comes from the fir trees on the north face of the Ventoux, 60km away; it could rather come from the neighbouring Alpilles area. Multiplying the pits supported by additional radiocarbon dates will allow us to complete the phytogeographical history of these two species in Provence.

We have not obtained any date posterior to the reforestation of the 19th century (RTM). The soils have not therefore been totally eroded despite successive deforestations, and still retain a lot of paleoecological information. However, this information is not chronostratified. Three of the six dates come from the same pit (VTN2): the beech and fir extracted from the same sample (20-30cm) however, are of very different ages (Modern Era and Bronze Age, respectively), while the fir and pine, both dated to the Bronze Age, come from two very different depths (20-30cm and 50-70cm, respectively). This observation common in most of pedoanthracological studies (e.g. Brasseur *et al.* 2022), reminds us that the existence of a chronostratigraphy for soil profiles that might spontaneously come into mind is far from obvious (Appendix 1 Figure 7). The pedological analysis carried out within the framework of the ORCHAMP protocol, in particular the granulometric analysis, could contribute to a better understanding of the burial patterns of charcoal in the soils.

## Conclusion

Although being exploratory and preliminary, this study contributed to improve our understanding of the long-term vegetation history on the northern slopes of Mont Ventoux. Despite heavily impacted by intensive deforestation since the 13th century and particularly in Modern Era, most of the soils developed under the former forest vegetation have survived centuries of torrential erosion. Their charcoal content has thus been preserved and can be used to depict the fire history linked to the natural and anthropogenic processes.

Fir trees occupied the entire slope from 925m (VTN1) to the summit (VTN6) at 1,860m. Today, they do not exceed the altitude of 1,600m. The presence of charcoal of this taxon in the highest pit suggests that the summit cap, currently occupied by a few scattered prostrate hooked pines, would have had a more closed canopy than today. It is worth to recall that a beech charcoal was also found on the summit ridge (Thinon 2007). The upper tree line, today composed of only hooked pine, would have thus been more diverse (with fir and beech) and the treeline position was higher than today. Our results also confirm that the forest species such as beech and fir that have been growing spontaneously in the 1860s RTM plantations, particularly in the understory of the VTN4 hooked pine, are those that occupied this altitudinal zone before the deforestation. The upper altitudinal limit of the forests was higher in the past, around 1,510m (VTN4), and consisted of stands of fir and yew (VTN4).

The spatial resolution of pedoanthracology thus appears to be relevant for reconstructing the altitudinal fluctuations of the upper vegetation boundary of Mont Ventoux as well as its floristic composition. Wood charcoal and its dating provide much valuable information about the important role of forest fires in establishing present-day vegetation patterns. Higher spatial resolution of pedoanthracological data is however needed to confirm this: use replicates at similar elevation and sample every 100m of elevation instead of 200m, but this was the grid of the Orchamp protocol.

It remains to study how the woody vegetation of Mont Ventoux, in particular beech and fir, will react to ongoing global warming. Some authors predict a progression of fir towards higher altitudes, but with a more restricted range (Cailleret & Davi 2008). Our work

shows that fir has already colonized the upper part of the slope in the past, so it is natural that it will return there regardless of the climate warming. Beech has probably also colonized the upper part. The analysis of the pit transect on the southern slope (ORCHAMP VTS) will certainly provide answers to these questions. This work has allowed us to take a step back on the potential of the forest species to understand the future. It is necessary to continue this work, particularly with other dating methods (dendrochronology) and obtaining further radiocarbon dates, in order to correctly and more precisely retrace the history of the past vegetation of Mont Ventoux.

## Acknowledgments

The authors wish to thank Maryse Alvitre for her technical assistance in laboratory analyses and Dr. Emmanuel Gandouin for his thoughtful advice in statistical data analysis. They also thank the entire field team that participated in the ORCHAMP soil-anthracology sampling campaign (Lenka Brousset, Brunetto William, Raphaël Gros, Frédéric Guiter, Quentin Lambert and Yoann Pinguet). Thanks to Bruno Fady and Frederic Guibal for their advice in the reflection of this work. This work was supported by a Master thesis student grant awarded by French Government (France 2030 perspective) through “l’Initiative d’Excellence d’Aix-Marseille Université” and in the frame of the research consortium for ecological transition entitled l’Institut méditerranéen pour la transition écologique (ITEM, A\*MIDEX AMX-19-IET-01). Radiocarbon dating was supported by the program “Zone Atelier Alpes” financed by CNRS-INEE.

## References

- Ali, A.A., Carcaillet, C., Talon, B., Roiron, P., & Terral, J.F. (2005). *Pinus cembra* L. (arolla pine), a common tree in the inner French Alps since the early Holocene and above the present treeline: a synthesis based on charcoal data from soils and travertines. *J. Biogeogr.* 32, 1659-1669.
- Andrieu-Ponel, V., Ponel, P., Jull, A. J., de Beaulieu, J. L., Bruneton, H., & Leveau, P. (2000). Towards the reconstruction of the Holocene vegetation history of Lower Provence: two new pollen profiles from Marais des Baux. *Veg. Hist. Archaeobot.* 9, 71-84.

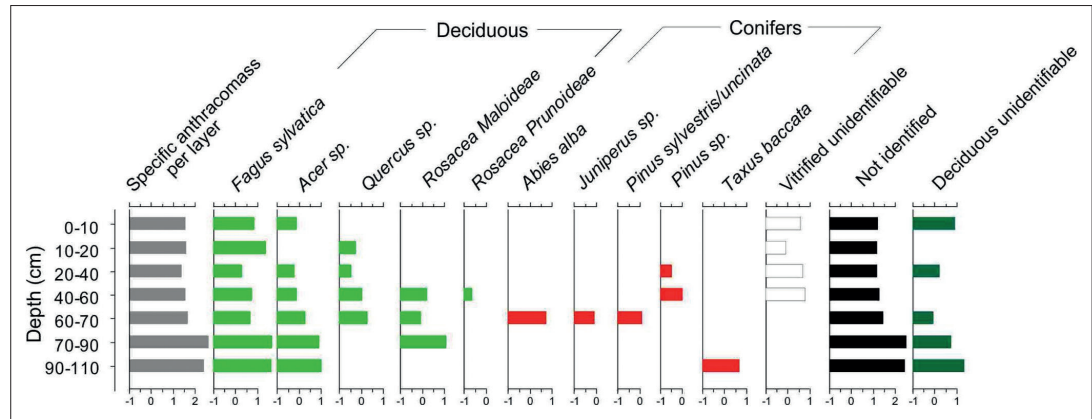
- Azuara, J., Lebreton, V., Peyron, O., Mazier, F. & Combourieu-Nebout, N. (2018). The Holocene history of low altitude Mediterranean *Fagus sylvatica* forests in southern France. *J. Veg. Sci.* 29, 438-449.
- Birks, HJB., & Tinner, W. (2016). Past forests of Europe. In: San-Miguel-Ayanz J, de Rigo D, Caudullo G, Houston Durrant T, Mauri A(eds) European atlas of forest tree species. Publication Office of the European Union, Luxembourg, pp. 36-39.
- Blaauw, M., (2010). Methods and code for "classical" age-modelling of radiocarbon sequences. *Quat. Geochronol.* 5, 512-518.
- Brasseur, B., Ertlen, D., & Robin, V. (2022). Soil Archives: Where Soilscape History Meets Present-day Ecosystems. *Historical Ecology: Learning from the Past to Understand the Present and Forecast the Future of Ecosystems*, 85-97.
- Cailleret, M., (2007). *Dendroécologie comparée du sapin pectiné et du hêtre commun le long d'un gradient altitudinal*. Mémoire de Master 2 Systèmes écologiques : fonctionnement et modélisation des écosystèmes terrestres, 34 p.
- Cailleret, M., & Davi, H. (2008). Impact potentiel du changement climatique sur la croissance et la répartition de deux espèces en co-occurrence sur le mont Ventoux : le sapin pectiné (*Abies alba* Mill.) et le hêtre commun (*Fagus sylvatica* L.). Résumé. In: 9<sup>e</sup> Journées d'écologie fonctionnelle, La Grande Motte, France. 1 p.
- Carcaillet, C. & Thion, M. (1996). Pedoanthracological contribution to the study of the evolution of the upper treeline in the Maurienne Valley (North French Alps): methodology and preliminary data. *Rev. Palaeobot. Palynol.* 91, 399-416.
- Carnelli, A.L., Theurillat, J.P., Thion, M., Vadi, G. & Talon, B. (2004). Past uppermost tree limit in the Central European Alps (Switzerland) based on soil and soil charcoal. *Holocene* 14, 393-405.
- Chabal, L. (1997). Forêts et sociétés en Languedoc (Néolithique final, Antiquité tardive) : L'anthracologie, méthode et paléoécologie. Maison des sciences de l'Homme. Collectif (2004). *Restaurer la montagne, photographies des eaux et forêts du XIX<sup>e</sup> siècle*, Catalogue d'exposition. Musée Arlaten, Somogy, Paris.
- Crégut-Bonnoure, E., Argant, A., Argant, J., Ayache-Donat, B., Billiou, D., Bocherens, H., ... & Thion, M. (2005). Les cavités karstiques du mont Ventoux (Vaucluse, France) : des ours bruns (*Ursus arctos* L.) et des milieux d'altitude à l'Holocène. *Bull. Soc. Hist. Nat. Toulouse* 141, 5-18.
- Cunill, R., Soriano, J. M., Bal, M. C., Pèlachs, A. & Pérez-Obiol, R. (2012). Holocene treeline changes on the south slope of the Pyrenees: a pedoanthracological analysis. *Veg. Hist. Archaeobot* 21, 373-384.
- Cunill, R., Soriano, J.M., Bal, M.C., Pèlachs, A., Rodriguez, J.M., & Pérez-Obiol, R. (2013). Holocene high-altitude vegetation dynamics in the Pyrenees: a pedoanthracology contribution to an interdisciplinary approach. *Quat. Int.* 289, 60-70.
- Di Pasquale, G., Marziano, M., Impagliazzo, S., Lubritto, C., De Natale, A. & Bader, M.Y. (2008). The Holocene treeline in the northern Andes (Ecuador): first evidence from soil charcoal. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 259, 17-34.
- Finsinger, W., Vanel, Q., Ribolini, A., & Tinner, W. (2021). Early to late Holocene vegetation and fire dynamics at the treeline in the Maritime Alps. *Veg. Hist. Archaeobot.* 30, 507-524.
- Gobert, J. & Pautou, G. (1968). Carte de végétation Feuille XXXI-40 - Vaison - In: *Doc. Carte Vég. Alpes*, tome VI.
- Hendrik, D., François, C., Christian, P., William, B., Florence, J., Arnaud, J. & Nicolas, M. (2020). Les effets de la sécheresse et de la sylviculture sur la croissance des sapins, hêtres et cèdres au mont Ventoux. *Rendez-vous techniques de l'ONF* 63, 22-24.
- Holtmeier, F.-K. (1994). Ecological aspects of climatically-caused timberline fluctuations. Review and outlook. In: *Mountain environment in changing climates* (ed by Beniston M.). Routledge, London, pp. 220-233.
- Holtmeier, F.-K., & Broll, G. (2005). Sensitivity and response of northern hemisphere altitudinal and polar treelines to environmental change at landscape and local scales. *Glob. Ecol. Biogeogr.* 14, 395-410.
- Inrap. (2021). *Inrap*. available at <https://www.inrap.fr/>. Last access dated to 14 June 2021.
- Jacquot, C. (1955). *Atlas d'anatomie des bois des conifères*. Centre technique du bois. Paris, 2 t.
- Körner, C. (1999). *Alpine plant life*. Springer Verlag, Berlin, Heidelberg, New York.
- Labonne, S., Cordonnier, T., Kunstler, G. & Fuhr, M. (2019). Forêts de montagne et changement climatique: impacts et adaptations. *Sci. Eaux & Territoires* 28, 38-43.
- Ladier J. (2004). *Les stations forestières des Préalpes sèches, définition, répartition, dynamique, fertilité*. ONF, Direction territoriale Méditerranée, Aix-en-Provence.
- Le, S., Josse, J. & Husson, F. (2008). FactoMineR: An R Package for Multivariate Analysis. *Journal of Statistical Software* 25(1), 1-18.
- Lenoir, J. R. M. H., & Gégout, J. C. (2010). La remontée de la distribution altitudinale des espèces végétales forestières tempérées en lien avec le réchauffement climatique récent. *Revue forestière française* 62(3-4), 465-476.
- Marguerie, D., Bernard, V., Begin, Y., & Terral, J.F. (2010). *Anthracologie et dendrologie. La dendroécologie : principes, méthodes et applications*. Presses de l'Université Laval, Québec.
- Martin-Gousset, L., Terracol, J., & Roux, J.P. (2019). Habitats et dynamiques de végétation en ubac du mont Ventoux – Étude de la Réserve biologique intégrale. *Naturae* 5, 113-164.
- Martin L. & Thiébault S. (2010). L'if (*Taxus baccata* L.): histoire et usage d'un arbre durant la Préhistoire récente. L'exemple du domaine alpin et circum-alpin. *Anthropobotanica* 1(4), 3-20.
- McParland, L.C., Collinson, M.E., Scott, A.C., Campbell, G., Veal, R. (2010). Is vitrification in charcoal a result of high temperature burning of wood? *J. Archaeol. Sci.* 37, 2679-2687.
- Morales-Molino, C., Steffen, M., Samartin, S., van Leeuwen, J. F., Hürlimann, D., Vescovi, E., & Tinner, W. (2021). Long-term responses of Mediterranean mountain forests to climate change, fire and human activities in the Northern Apennines (Italy). *Ecosystems* 24, 1361-1377.
- Ningre, J.M. (2007). Le reboisement du Ventoux au XIX<sup>e</sup> siècle: techniques et travaux. *Forêt méditerranéenne* 28, 319-326.
- ORCHAMP (2021). Available at <https://orchamp.osug.fr/>. Last access dated to 14 June 2021.
- Ozenda, P. (1985). *La végétation de la chaîne alpine dans l'espace montagnard européen*. Masson, Paris.

- R Core Team (2021). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.
- Reimer, P.J., Austin, W., Bard, E., Bayliss, A., Blackwell, P. G., Ramsey, C. B., ... & Talamo, S. (2020). The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0-55 cal kBP). *Radiocarbon* 62, 725-757.
- Robin, V., Knapp, H., Bork, H.R. & Nelle, O. (2013). Complementary use of pedoanthracology and peat macro-charcoal analysis for fire history assessment: illustration from Central Germany. *Quat. Int.* 289, 78-87.
- Rouveyrol, P., Leroy, M. (2021). *L'efficacité du réseau Natura 2000 terrestre en France*, UMS PatriNat (OFB/CNRS/MNHN), Paris.
- Saulnier, M., Talon, B., & Édouard, J.L. (2015). New pedoanthracological data for the long-term history of forest species at mid-high altitudes in the Queyras Valley (Inner Alps). *Quat. Int.* 366, 15-24.
- Schweingruber, F.-H. (1990). *Anatomie europäischer Hölzer. Anatomy of European woods*. Eidgenöss. Forschungsanst für Wald, Schnee und Landschaft, Birmensdorf. Verlag Paul Haupt, Bern.
- Swenson, J.J., & Franklin, J. (2000). The effects of future urban development on habitat fragmentation in the Santa Monica Mountains. *Landsc. Ecol.* 15, 713-730.
- Talon, B. (2010). Reconstruction of Holocene high-altitude vegetation cover in the French southern Alps: evidence from soil charcoal. *Holocene* 20, 35-44.
- Talon, B., Payette, S., Filion, L., & Delwaide, A. (2005). Reconstruction of the long-term fire history of an old-growth deciduous forest in Southern Québec, Canada, from charred wood in mineral soils. *Quat. Res.* 64, 36-43.
- Terhürne-Berson, R., Litt, T., & Cheddadi, R. (2004). The spread of *Abies* throughout Europe since the last glacial period: combined macrofossil and pollen data. *Veg. Hist. Archaeobot.* 13, 257-268.
- Terracol, J., Blanc, G., Micas, L., Diaz, É., Gruhn, G., & Voiry, H. (2017). La Réserve biologique intégrale du mont Ventoux, un espace d'étude des écosystèmes forestiers hors sylviculture. *Naturae* 5, 1-28.
- Theurillat, J. P., & Guisan, A. (2001). Potential impact of climate change on vegetation in the European Alps: a review. *Clim. Chang.* 50, 77-109.
- Thinon, M. (1978). La pédoanthracologie : une nouvelle méthode d'analyse phytochronologique depuis le Néolithique. *Comptes rendus de l'Académie des sciences de Paris*, 287, série D : 1203-1206.
- Thinon M. (1992). *L'analyse pédoanthracologique. Aspects méthodologiques et applications*. Thèse de doctorat ès sciences de l'Université Aix-Marseille III.
- Thinon, M. (2007). La végétation du mont Ventoux au cours des derniers millénaires. *Forêt méditerranéenne* 28, 289-294.
- Tinner, W., & Theurillat, J.P. (2003). Uppermost limit, extent, and fluctuations of the timberline and treeline ecocline in the Swiss Central Alps during the past 11,500 years. *Arct., Antarc., Alp. Res.* 35, 158-169.
- Tinner, W., Colombaroli, D., Heiri, O., Henne, P. D., Steinacher, M., Untenecker, J., ... & Valsecchi, V. (2013). The past ecology of *Abies alba* provides new perspectives on future responses of silver fir forests to global warming. *Ecol. Monogr.* 83, 419-439.
- Touflan, P., Talon, B., & Walsh, K. (2010). Soil charcoal analysis: a reliable tool for spatially precise studies of past forest dynamics: a case study in the French southern Alps. *Holocene* 20, 45-52.
- Treml, V., Šenfeldr, M., Chuman, T., Ponocná, T., Demková, K. (2016). Twentieth century treeline ecotone advance in the Sudetes Mountains (Central Europe) was induced by agricultural land abandonment rather than climate change. *J. Veg. Sci.* 27, 1209-1221.
- Vernet, J.-L. et al. (2001). *Guide d'identification des charbons de bois préhistoriques et récents Sud-ouest de l'Europe: France, Péninsule ibérique et îles Canaries*. CNRS Éditions, Paris.

## Appendix

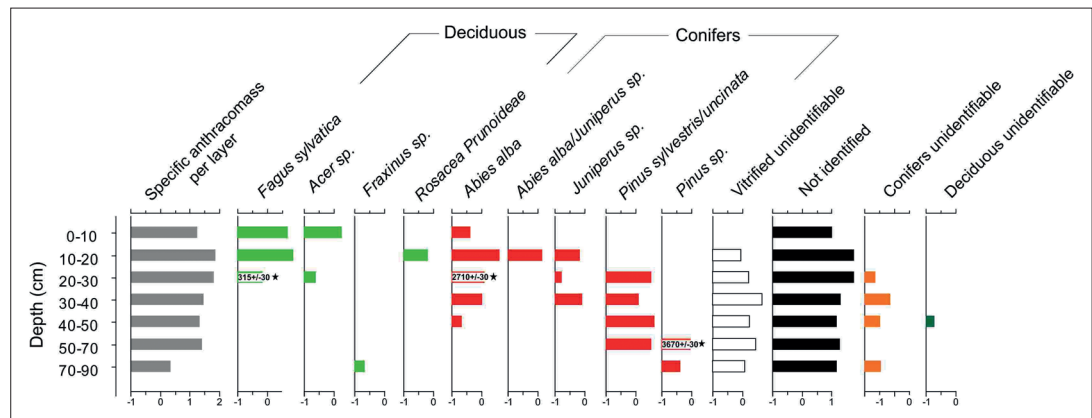
**Appendix 1 – Anthracological diagrams. Figures 1 to 7: depth (m) on the ordinate and specific anthracomass in logarithmic scale on the abscissa. Hardwoods in green and conifers in red. ASN: Specific Anthracomass by Level and ASP: Specific Anthracomass by Profile/Pit.**

**Annexe 1 – Diagrammes anthracologiques. Figures 1 à 7 : profondeur (m) en ordonnée et anthracomasse spécifique en échelle logarithmique en abscisse. Feuillus en vert et conifères en rouge. ASN : Anthracomasse spécifique par niveau et ASP : Anthracomasse spécifique par profil/fosse.**



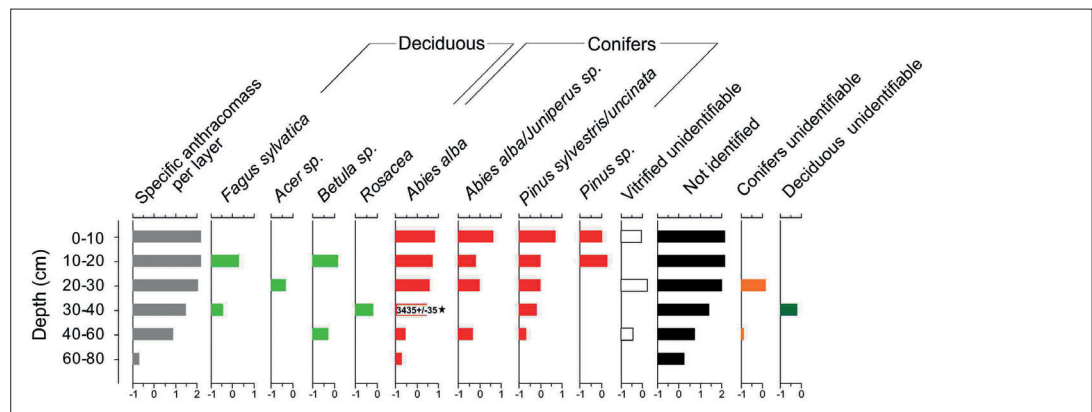
**Figure 1 – Pedoanthracological diagram of the soil pit VTN1 (925m). The number of identified charcoals represents 25% of total charcoals.**

**Figure 1 – Diagramme anthracologique de VTN1 (925m) (25 % de charbons identifiés).**



**Figure 2 – Pedoanthracological diagram of the soil pit VTN2 (1,130m). The number of identified charcoals represents 22% of total charcoals.**

**Figure 2 – Diagramme anthracologique de VTN2 (1 130m) (22 % de charbons identifiés).**



**Figure 3 – Pedoanthracological diagram of the soil pit VTN3 (1,340m). The number of identified charcoals represents 10% of total charcoals.**

**Figure 3 – Diagramme anthracologique de VTN3 (1 340m) (10 % de charbons identifiés).**

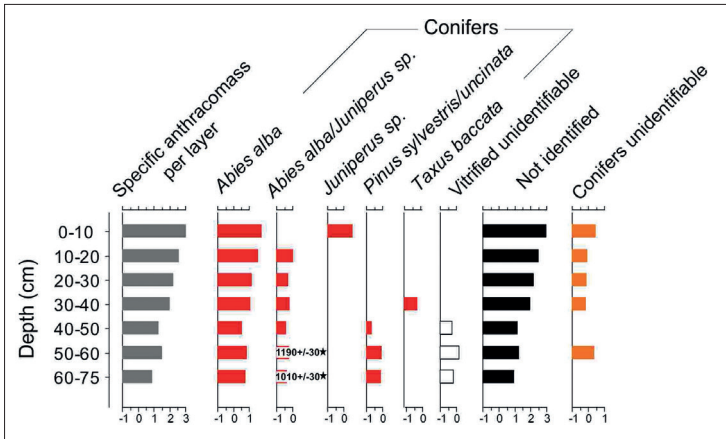


Figure 4 – Pedoanthracological diagram of the soil pit VTN4 (1,510m). The number of identified charcoals represents 9% of total charcoals.

Figure 4 – Diagramme anthracologique de VTN4 (1 510m) (9 % de charbons identifiés).

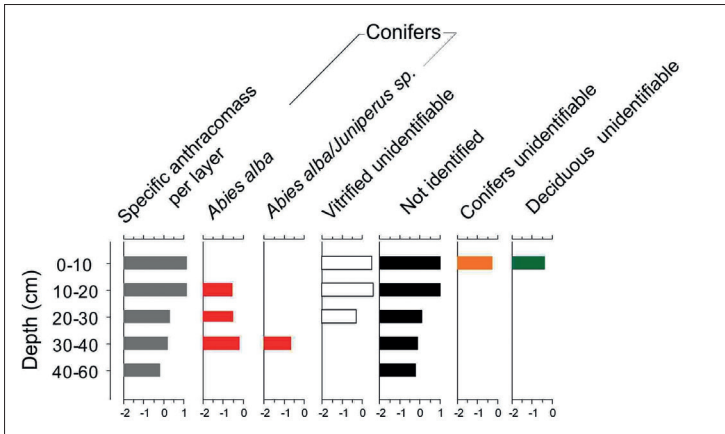


Figure 5 – Pedoanthracological diagram of the soil pit VTN5 (1,675m). The number of identified charcoals represents 27% of total charcoals.

Figure 5 – Diagramme anthracologique de VTN5 (1 675m) (27 % de charbons identifiés).

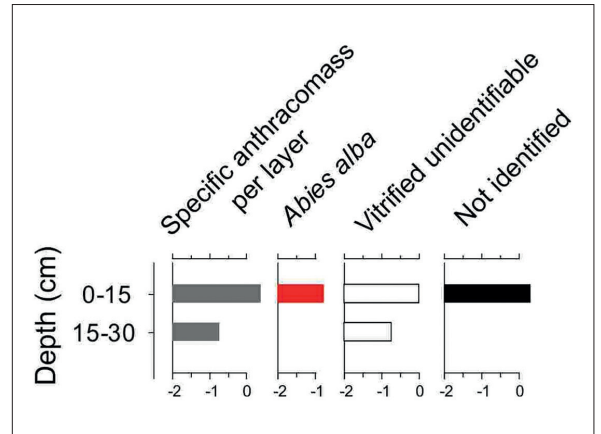


Figure 6 – Pedoanthracological diagram of the soil pit VTN6 (1,860m). All extracted charcoals of the profile are identified and presented in the diagram.

Figure 6 – Diagramme anthracologique de VTN6 (1 860m) (100 % de charbons identifiés).

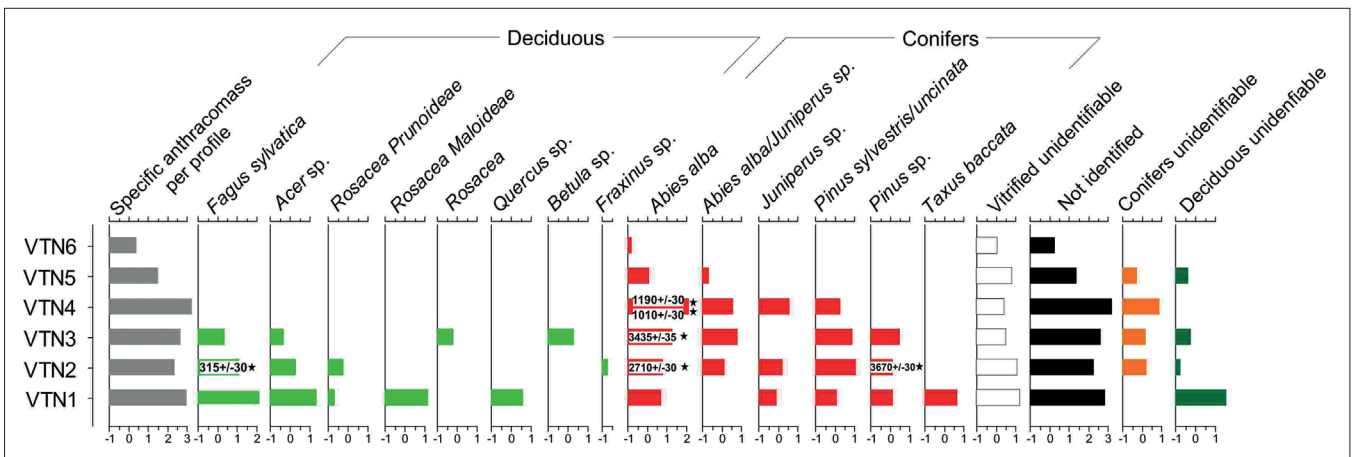


Figure 7 – Pedoanthracological diagram of all the soil pits. The pits are arranged in order of increasing altitude.

Figure 7 – Diagramme anthracologique toutes fosses confondues. Les placettes sont rangées par altitude croissante.



**Appendix 2 – Radiocarbon dates (Poznan Radiocarbon Laboratory). Calibrated in calendar years using the “clam” package of the R software. BP = before present = before 1950 ; BC = before christ = before our era ; AD = Anno Domini = 1950-BP (inrap.fr).**

**Annexe 2 – Datations radiocarbone (Poznan Radiocarbon Laboratory). Calibrées en années calendaires à l'aide du package « clam » du logiciel R. BP = before present = before 1950 ; BC = before christ = avant notre ère ; AD = Anno Domini = 1950-BP (inrap.fr).**

Pit	Depth (cm)	mg	Taxa	Lab. no.	Age <sup>14</sup> C	Calib BCE/CE	Calib BP	Time period
VTN 2	20-30	3,7	<i>Abies alba</i>	Poz-136796	2710 ± 30 BP	908-808 cal BCE	2757-2857 cal BP	Bronze Age
VTN 2	20-30	1,7	<i>Fagus sylvatica</i>	Poz-136797	315 ± 30 BP	1489-1604 cal CE	346-460 cal BP	Modern period
VTN 2	50-70	2	<i>Pinus sp.</i>	Poz-136798	3670 ± 30 BP	2139-1954 cal BCE	3903-4088 cal BP	Bronze Age
VTN 3	30-40	2	<i>Abies alba</i>	Poz-136800	3435 ± 35 BP	1780-1627 cal BCE	3576-3729 cal BP	Bronze Age
VTN 4	50-60	5,8	<i>Abies alba</i>	Poz-136158	1190 ± 30 BP	774-895 cal CE	1055-1176 cal BP	Middle Age
VTN 4	60-75	4,7	<i>Abies alba</i>	Poz-136801	1010 ± 30 BP	992-1048 cal CE	902-958 cal BP	Middle Age