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France)**

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Vegetation history and landscape management from 6500 to 1500 cal. B.P. at Lac d'Antre, Gallo-Roman sanctuary of Villards d'Héria, Jura, France

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Abstract The lake sediment record was used to reconstruct past vegetation dynamics and human impacts from the middle Neolithic (6500 cal. B.P.) to the Middle Ages (1500 cal. B.P.) around Lac d'Antre in the southern Jura mountains of France. This lake was surrounded by the Gallo-Roman sanctuary of Villards d'Héria, which has been widely investigated by archaeologists and enables a comparison between palaeoenvironmental proxies and archaeological data. Pollen and microscopic charcoal analyses were conducted on a 500 cm sediment core with eleven radiocarbon dates providing the chronological control. In a mixed oak woodland context, the successive development of *Taxus*, *Fagus* and *Abies* were mainly caused by climatic variations during the Neolithic, in which there was weak human impact. The first significant signs of human activity were detected during the Bronze Age from 3900 cal. B.P., followed by an increase of human pressure and woodland clearances during the Iron Age, from 2700 cal. B.P. The occupation of the Gallo-Roman sanctuary was continuous with the Iron Age occupation. All the analysed palaeoenvironmental data indicate that the strongest human impact occurred during the Gallo-Roman period, which matches

the occupation of Villards d'Héria previously dated by archaeologists from 2000 to 1700 cal. B.P., 1st to 3rd century A.D. Moreover, there appears to have been a new period of human settlement close to the lake at the beginning of the Middle Ages. The low charcoal accumulation rate (CHAR) recorded during the Bronze and Iron Ages suggests that fire was not the main agent used to clear the dense woods to create new cultivated fields and pastures. High CHAR values recorded during the Roman period may represent fire use for domestic and agro-pastoral activities.

Keywords Human impact · Pollen · Microscopic charcoal · Gallo-Roman period · Holocene · Jura mountains

Introduction

The use of the pollen record to investigate the long-term variability in the human impact on the landscape at the beginning of the Neolithic has been well developed in the Jura region of France (Gauthier 2004; Rachoud-Schneider 1997; Richard 1994; Richard and Gauthier 2007). Some of these studies (Pétrequin 1986; Richard 1997) on lake dwellings have combined archaeological and palaeoenvironmental methodologies. This combination of methodologies has been fruitful because of the richness of archaeological data in these low altitude areas.

Unfortunately, in the highest parts of the Jura mountains up to 500 m a.s.l., wooded areas inhibit archaeological prospection and do not offer the opportunity for archaeologists to fill the gaps in their data. This fact has led to the development of pollen analysis to contribute to our knowledge of the evolution of anthropogenic impacts in the Jura mountains (Gauthier 2002; Richard 2000; Richard and Ruffaldi 1996). Some sites have been subject to detailed

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archaeological studies and excavations and offer perspectives for comparison between archaeological data and palaeoecological proxies; one of these sites is the Gallo-Roman sanctuary of Villards d'Héria that includes a natural lake, Lac d'Antre, located in the middle of the well known archaeological site. This site has been the subject of numerous archaeological investigations since the 18th century (Clerc 1840; Dunod 1709; Lerat 1998; Nouvel et al. 2008; Thévenot 1955), as a result of the quantity and good preservation of Gallo-Roman remains and artefacts. Archaeologists have described this site as a main place of worship of the Sequane people during the Gallo-Roman period.

This palaeoenvironmental study presents a long-term vision of the vegetation history which contributes to the general understanding of ecosystem changes following increasing human impact around Lac d'Antre, and brings new information about the anthropogenic history (type, length and intensity) of earlier parts of the Gallo-Roman period for which archaeologists have no data.

The main objectives of the present study are as follows:

- (1) to detect the potential earlier periods of human impact that have not yet been well described by archaeological excavations and to compare these impacts described by our palaeoenvironmental proxies (pollen, microscopic charcoal and magnetic susceptibility) with the plentiful archaeological data collected for the Gallo-Roman period at the Villards d'Héria site (Lerat 1998; Nouvel et al. 2008) in the context of regional and sub-regional pollen data

- (2) to describe the first fire history from microscopic charcoal of the Jura mountains and compare it with other studies performed in Switzerland, where data on human fire use since the Neolithic (7500 cal. B.P.) has been obtained in high-resolution sequences (Gobet et al. 2003; Tinner et al. 1999, 2005; Valsecchi et al. 2006).
- (3) to analyse the dynamics of *Taxus baccata*, *Abies alba* and *Fagus sylvatica* development between 6350 and 5900 cal. B.P. and the roles of natural and human impacts on these changes.

Environmental settings

Lac d'Antre ($5^{\circ}44'58''E$, $46^{\circ}24'51''N$) is located at 798 m a.s.l. in northeastern France, 25 km west of the border with Switzerland in the southern Jura mountains (Fig. 1a). The climate is semi-continental, characterised by an average annual rainfall of 1,200–1,500 mm and a high temperature range with mild summers with an average July temperature of 15 °C, and harsh and cold winters with an average January temperature of –2 °C.

Lac d'Antre is a natural lake located in an anticlinal valley. It is at a distance of 1 km and located 100 m higher than the village of Villards d'Héria (Fig. 1c). Its catchment area, ca. 550 ha, is surrounded by several mountains that

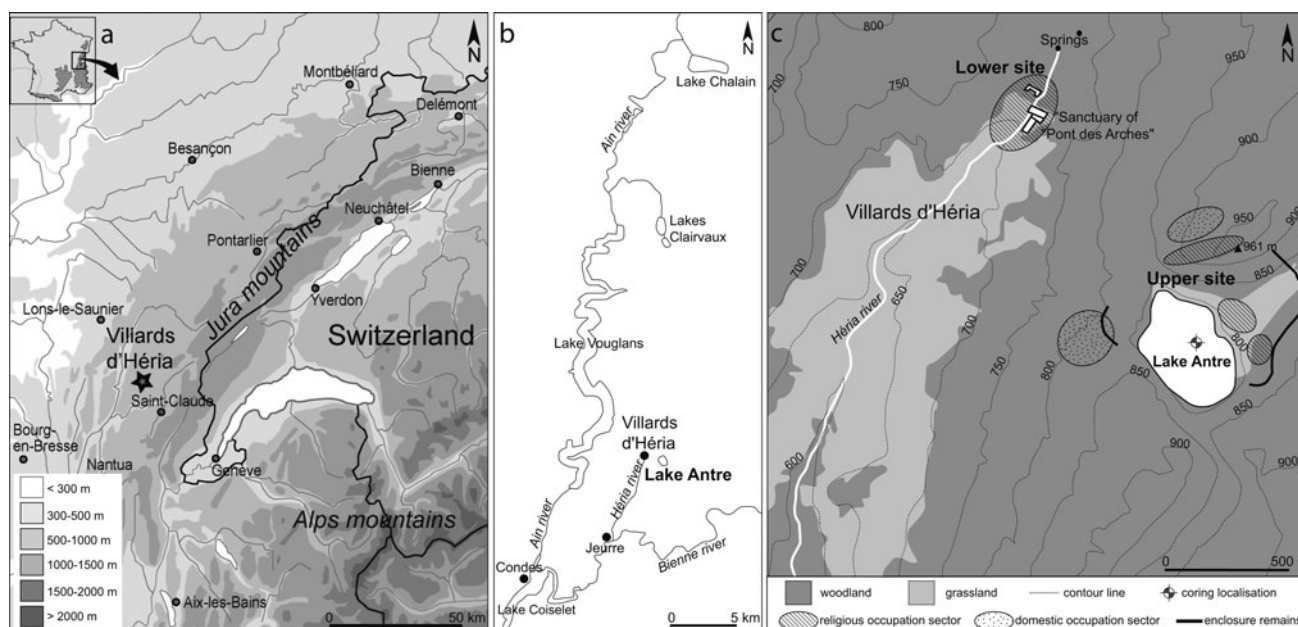


Fig. 1 a The geographical location of Villards d'Héria in the Jura mountains (France). b The regional hydrological context. c The topography, vegetation cover and archaeological context around Lac d'Antre, Villards d'Héria, France

are covered by a dense woodland with *Fagus sylvatica* and *Abies alba*, typical of the second plateau of the Jura mountains. Meadows and pastures are located in the bottom of the anticlinal valley. On the eastern and northern banks, an intermittent stream and several springs feed the lake. The 13 ha lake is drained by a karstic hole through the upper Jurassic marly calcareous substratum. In the Héria valley, 100 m lower down, water emerges from several springs, which form the river Héria which is a tributary to the Rhône stream through the rivers Bienne and Ain (Fig. 1b). Today, the water depth of the lake is regulated by a dam to an average depth of 5.65 m.

Archaeological settings

The oldest settlements in this area, dating from the Neolithic and Bronze Age periods, are located between 15 and 30 km to the north towards the Ain valley around Lac de Chalain and Lac de Clairvaux (Fig. 1b; Pétrequin and Pétrequin 1988).

In the vicinity of Villards d'Héria, the first occupation is not well known, but a few archaeological artefacts (two sickles) from the Bronze Age (4250–2750 cal. B.P.) were discovered during archaeological investigations (Rothé 2001). However, no building remains from this period have been discovered.

Villards d'Héria is known by archaeologists as the main place of worship of the Roman period Sequane people (Lerat 1998). The site was continuously settled from the 1st to the 3rd century A.D. (2000–1700 cal. B.P.). This large place of worship was established in a remarkable context in which water was an omnipresent element and was the basis for the organisation of the sanctuary. During the Gallo-Roman period, the hydrological relationship between the lake and the Héria springs was known and used (Nouvel et al. 2008). This fact explains the split establishment of the site, with the two parts separated by 1 km (Fig. 1c): (1) the upper site, organised around the lake, consisting of three religious areas composed of several buildings (mostly temples) included in an enclosure; two areas found outside this enclosure have produced domestic remains, suggesting that they could have been residential places; (2) the lower site, 100 m lower down, consisting mainly of a large building composed of a temple and thermal baths (200 m in length) constructed above the river Heria (Nouvel et al. 2008).

During the Gallo-Roman period, Villards d'Héria was not isolated. The currently open landscape along the Bienne valleys has allowed numerous archaeological discoveries, such as rural settlements at Jeurre and Condes (Fig. 1b; Rothé 2001) and cities along the Ain valley (Nouvel et al. 2008).

Materials and methods

Sampling and dating

Three overlapping cores were taken with a Russian peat sampler (GIK type, 100 cm long and 5 cm in diameter) from the frozen lake surface in the centre of Lac d'Antre. The basal till was reached at 850 cm. In the scope of this paper, we focused on a section of the master core covering the chronological period of interest, between 765 and 258 cm in depth.

Magnetic susceptibility was measured at 5 mm intervals with a Geotek Multi Sensor Core Logger, and high-resolution pictures of sediment were correlated by overlapping the core section and creating a continuous sequence: the master core (Fig. 2). The sedimentary record consisted of light-brown clay silt with laminations (765–700 cm), dark-brown silt with dark laminations (700–650 cm), brown silt with dispersed and millimetre-length laminations (650–500 cm), dark brown silt with laminations (500–360 cm) and dark brown silty clay with millimetre-length light and dark laminations (360–258 cm).

Eleven AMS radiocarbon dates were obtained at the Poznan Radiocarbon Laboratory on terrestrial macroscopic plant remains along the entire sequence (Table 1). Ages were calibrated at 2σ ranges with CALIB 6.0.1., using the IntCal09 calibration curve (Reimer et al. 2009). Therefore to estimate ages along the entire profile, we used a mixed-effect regression model (Heegaard et al. 2005). A linear model would create an exaggerated modification of the sedimentation rate between 632 and 662 cm, while no major change in the stratigraphy of the sediments was observed. Thus, the age-depth model was extrapolated over the undated 93 cm on the basis and the sedimentation rate was estimated on the previous section (662–758 cm) (Fig. 2). This extrapolation is confirmed by the similar date of the *Abies* and *Fagus* expansions in the Lac d'Antre sequence and in other pollen analyses at a regional scale (De Beaulieu et al. 1994).

Pollen and microscopic charcoal analyses

Subsamples of 1 cm³ were taken at 8 cm intervals and prepared for pollen and microscopic charcoal analysis using the standard procedure (Fægri and Iversen 1989). Five *Lycopodium clavatum* tablets were added to each subsample to estimate the microscopic charcoal concentration (Stockmarr 1971). Pollen and microscopic charcoal was identified and counted together on pollen slides at $\times 500$ magnification.

At least 500 pollen grains of terrestrial plants (Total Land Pollen, TLP) were identified and counted in each subsample, using transmitted light. Pollen identification

Fig. 2 An age-depth model (constant variance) with expected ages along the sequence (*bold line*), 95 % confidence intervals (*grey line*), 2σ range probability distribution and estimated sedimentation accumulation rate (cm/year)

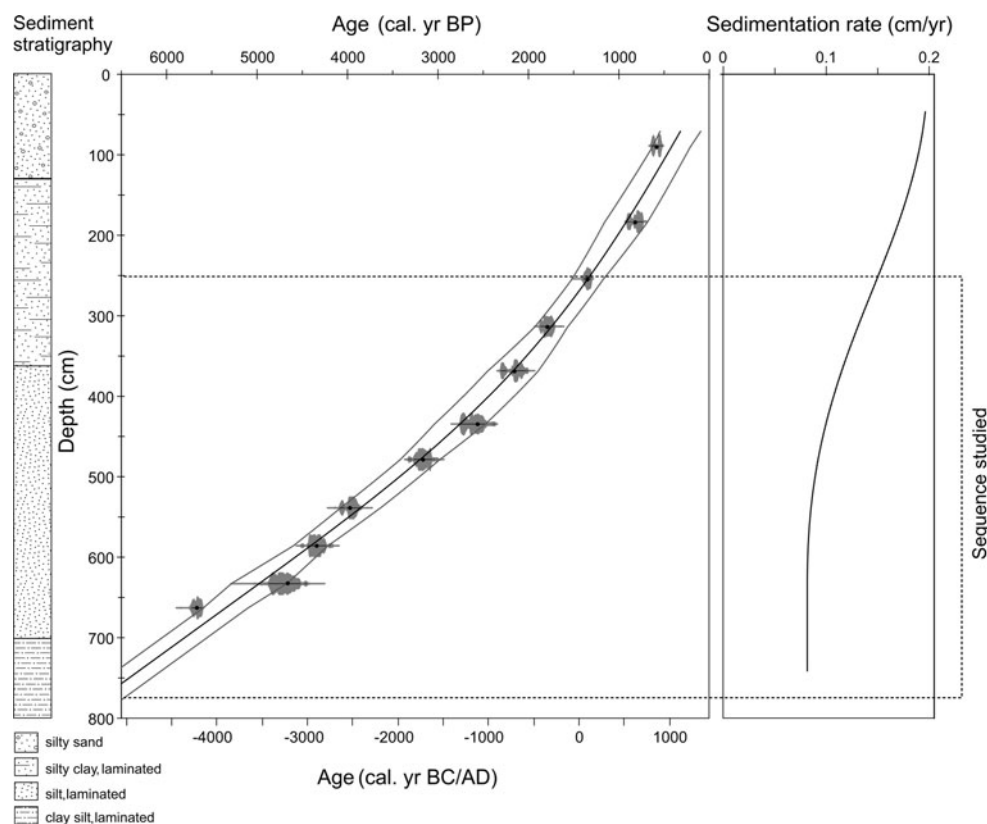


Table 1 AMS radiocarbon dates from Lac d'Antre, calibrated with the CALIB 6.0.1 program using the Intcal09 calibration curve

Lab. code	Depth (cm)	AMS ^{14}C (years B.P.)	Calib. Age (years B.P., 2σ -range)	Mean age (cal. years B.P.)
Poz-24685	90–91	560 ± 30	522–642	582
Poz-31635	183.5–184.5	885 ± 30	732–908	820
Poz-20748	254–256	1455 ± 30	1301–1392	1346.5
Poz-24686	313–315	1850 ± 30	1715–1865	1790
Poz-24687	368–370	2145 ± 35	2003–2305	2154
Poz-31636	434.5–435	2530 ± 50	2368–2752	2560
Poz-24688	478–480	2980 ± 35	3007–3322	3164.5
Poz-20751	536–542	3640 ± 35	3860–4083	3971.5
Poz-24690	585–587	3910 ± 40	4183–4498	4340.5
Poz-13490	632–633	4190 ± 80	4445–4875	4660
Poz-24691	662–664	4940 ± 30	5603–5726	5664.5

was based on determination keys (Beug 2004), photograph books (Reille 1992, 1998) and a reference collection of modern pollen types. Grass pollen grains over 40 μm in diameter were classified as Cerealia-type to exclude a large part of the wild grass pollen (Andersen 1979; Beug 2004). Pollen counts were expressed as percentages of TLP excluding spores and aquatic plants from the total pollen sum. Seven local pollen assemblage zones (LPAZ ANT1 to ANT7) were delineated using CONISS software (Grimm 1992). Human impact was detected using anthropogenic pollen indicators (API) such as *Plantago lanceolata*, *P. major/media*, *Rumex acetosa/acetosella*, *Artemisia*,

Chenopodiaceae, *Urticaceae* and *Papaver* (Behre 1981, 1988). These pollen indicators are presented together in a summary curve.

Microscopic charcoal counting was carried out following the method described by Finsinger and Tinner (2005). Microscopic charcoal was identified under transmitted light as black and opaque particles with angular contours (Clark 1988). The identification was checked using reflective light (using oil immersion) to distinguish microscopic charcoal from uncharred organic matter, which is black and opaque, but does not reflect light. Charcoal measurements (length, width and area) were taken using picture analysis software

(Visilogxpert 6.4). Only particles between 86 and 2,000 μm^2 area were included in the fire history reconstruction (Patterson 1987; Tinner et al. 1998, 1999; Whitlock and Larsen 2001). Particles larger than 2,000 μm^2 were not used in this paper because they were very scarce in our samples. Past regional fire activity is presented as the charcoal accumulation rate per area (CHAR is expressed in $\text{mm}^2/\text{cm}^2/\text{year}$).

Results

Chronology

The record covers 5,000 years from the Neolithic (6500 cal. B.P. at 765 cm) to the beginning of the early Middle Ages (1400 cal. B.P. at 258 cm) (Fig. 2). The sediment accumulation rate was constant from 765 to 425 cm (6800 cal. B.P. to 2900 cal. B.P.) with an estimated rate of 0.09 cm/year and increases to an average of 0.13 cm/year from 425 cm (2900 cal. B.P.) until the end of the record (1500 cal. B.P.).

Therefore, the sampling resolution of the pollen and charcoal analyses at 8 cm intervals (Fig. 3) represents the mean value of every 88 years (ANT1–ANT4) or 60 years (ANT5–ANT7).

Pollen analyses

The pollen record is separated into seven local pollen assemblage zones (LPAZ) (Fig. 3).

The pollen record begins in ANT1 (6600–6350 cal. B.P.) with high percentages of arboreal pollen (AP/T ca. 95 %). The vegetation cover was dominated by a mixed oak woodland composed of *Quercus* (oak), *Ulmus* (elm), *Tilia* (lime), *Fraxinus* (ash) and *Acer* (maple). *Corylus* (hazel), which was the main taxon during the occupation of the site by boreal woodland, maintained high pollen percentages. From 6500 cal. B.P., the first appearance of *Abies* (fir) is recorded, followed by that of *Fagus* (beech) from 6350 cal. B.P.

In ANT2 (6350–5850 cal. B.P.), the most important change was the appearance and strong expansion of *Taxus* (yew) (30 %). This yew increase was concomitant with the first development of *Fagus* and *Abies*. Simultaneously, the mixed oak woodland and *Corylus* slowly declined.

During ANT3 (5850–4300 cal. B.P.), mixed oak woodland and *Corylus* continued to decrease, and *Taxus* percentages fell in favour of a sharp expansion of the beech-fir woods indicated by the increase from 5 to 20 % of *Abies* and by the increase from 5 to 30 % of *Fagus*. Continuous occurrences of *Picea* (spruce) pollen appeared around 5750 cal. B.P. The increase of *Betula* (birch), *Alnus* (alder) and *Salix* (willow) may suggest the development of a

wetland area around the lake. The first signs of human activity are suggested by the increases in Poaceae and API (*Plantago lanceolata*, *Rumex acetosa/acetosella*).

The beech-fir woodland still dominated in ANT4 (4300–2700 cal. B.P.) (AP/T ca. 90 %), and the first occurrences of *Carpinus* appeared at 3500 cal. B.P. At 3900 cal. B.P., the small increases in Poaceae and API (*Plantago lanceolata*, *Rumex acetosa/acetosella*, *Urticaceae*) were in contrast to slight decreases in *Fagus*. The first Cerealia appeared around 3400 cal. B.P., and became continuous ca. 3200 cal. B.P. onwards.

In ANT5 (2700–2250 cal. B.P.), the beginning of the zone was characterised by the collapse of *Fagus* (of 20 %), the decline of *Abies* and *Alnus* and an increase in *Corylus*. Poaceae and API values (*Plantago lanceolata*, *Rumex acetosa/acetosella* and *Artemisia*) increased at the same time, and Cerealia percentages were low but continuous. After a short collapse, *Fagus* percentages returned rapidly to 40 % but decreased again in favour of *Abies* and *Quercus* at the end of this period.

In ANT6 (2250–1700 cal. B.P.), AP/T percentages reduced from 90 to 80 %, mainly as a result of a strong decrease in *Abies* (15 %). *Fagus* and *Alnus* percentages remained constant along with successive increases of *Betula* and *Corylus* followed by *Ulmus*, *Tilia* and *Fraxinus*. NAP percentages reached 20 % because of increases of Poaceae, API, Cerealia and other herbs (Caryophyllaceae and Anthemideae). Among the crops, *Secale*-type pollen appeared.

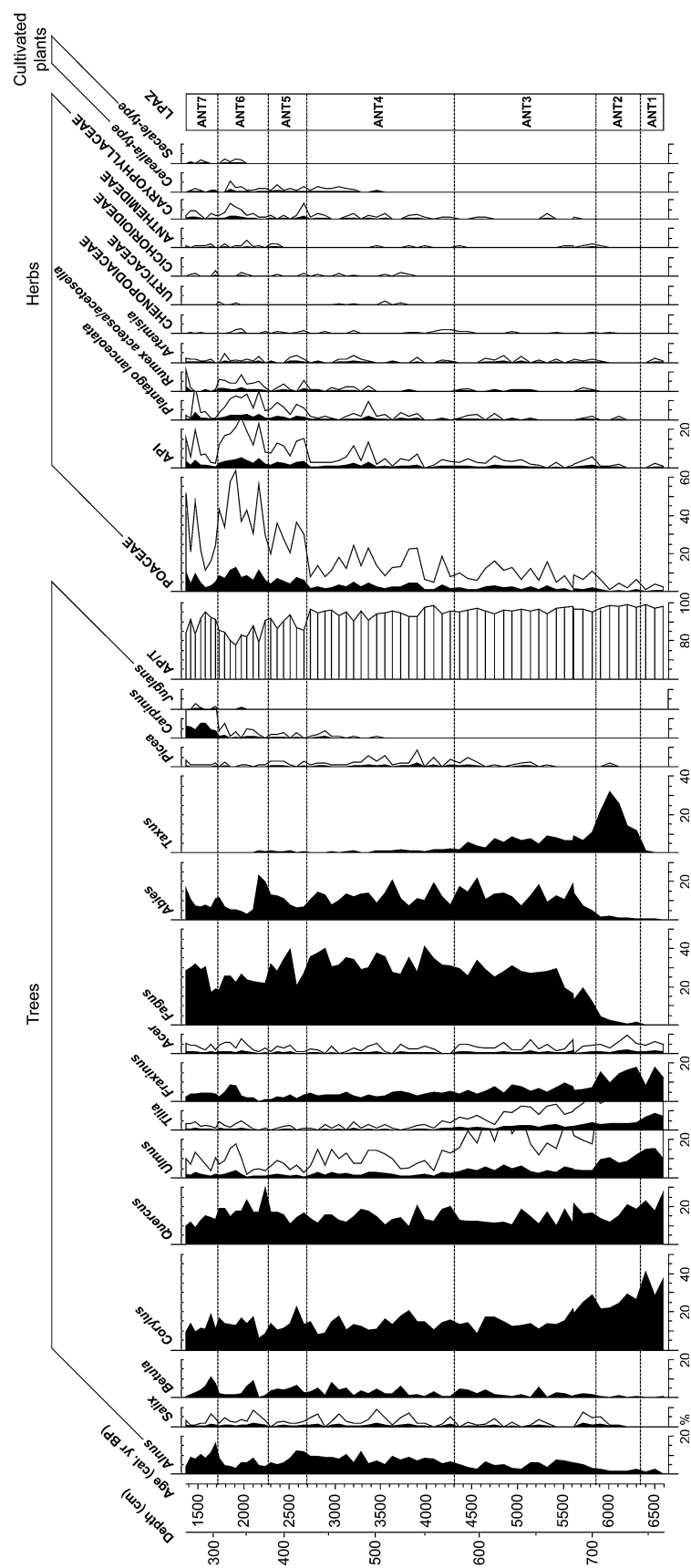
The last zone, ANT7 (1700–1400 cal. B.P.), was characterised by decreases in Poaceae, API and Cerealia and an expansion of woodland (AP/T ca. 85 %). Increased woodland was led by *Abies* and *Carpinus* before an expansion of *Fagus*. The concomitant increase in *Alnus* and *Betula* suggests a wetland expansion around the lake.

Finally (ca. 1500 cal. B.P.), Poaceae and API increased again, particularly as a result of *Plantago lanceolata*, before the expansion of *Rumex acetosa/acetosella*.

Microscopic charcoal analyses

The CHAR record is presented in Fig. 4. Throughout Zones ANT1 to ANT3, the CHAR remained low (mean 0.2 $\text{mm}^2/\text{cm}^2/\text{year}$), with no significant variations. Zones ANT4 and ANT5 were characterised by a general rise in CHAR values (mean 0.35 $\text{mm}^2/\text{cm}^2/\text{year}$) with several low-amplitude peaks (<1 $\text{mm}^2/\text{cm}^2/\text{year}$). The strongest increase in CHAR values occurred in ANT6, with two consecutive peaks with high amplitude between 2000 cal. B.P. and 1700 cal. B.P. The highest peak reached 11 $\text{mm}^2/\text{cm}^2/\text{year}$, and the second reached 3 $\text{mm}^2/\text{cm}^2/\text{year}$. CHAR values subsequently decreased and fluctuated under 0.7 $\text{mm}^2/\text{cm}^2/\text{year}$ until the end of the record in ANT7.

Fig. 3 A diagram of selected pollen taxa from Lac d'Antre. API: *Plantago lanceolata*, *Plantago major/media*, *Rumex acetosa/acetosella*, *Artemisia*, *Chenopodiaceae*, *Urticaceae* and *Papaver*. The exaggerated curves are $\times 5$ for pollen (*solid line*)



Magnetic susceptibility measurements

Magnetic susceptibility (MS) values (Fig. 4) increased during ANT1 followed by a progressive decline throughout ANT2. MS values reached their minimum at the beginning of ANT3. Subsequent values were relatively stable until a sharp increase at the end of the zone. In ANT4, MS values fluctuated with successive peaks at low amplitude around the same mean value. ANT5 and ANT6 were characterised by an upward trend composed of three peaks (2700–2550; 2150–2000 and 1900–1700 cal. B.P.). After this trend, the MS values decreased rapidly in ANT7 and remained constant throughout this period.

Discussion

5,000 years of vegetation dynamics and human impacts (Figs. 3, 4)

The Neolithic-early Bronze Age; 6500–3900 cal. B.P. (4450–1950 cal. B.C.)

Around the middle Neolithic (5850 cal. B.P.), decreases in *Ulmus* and *Fraxinus* and an increase in *Corylus* are correlated with an increase in Poaceae and simultaneous occurrences of *Plantago lanceolata* and *Rumex acetosa/acetosella*. The same kind of pollen variation and API occurrences were previously identified in other sites and were interpreted as small anthropogenic clearings (Richard 1994, 1997; Richard and Ruffaldi 1996). This finding can be interpreted as the development of temporary pastoral activity around Lac d'Antre. However, it cannot be excluded that a natural woodland transition or local disturbances such as windthrow or aging woodland stands may have caused this type of effect on the pollen spectra (Richard 2000).

During the late Neolithic (5200–4300 cal. B.P.), occurrences of *P. lanceolata* and *R. acetosa/acetosella* may suggest a new and temporary grazing activity. The intensity of this settlement certainly remained low because these pollen occurrences are difficult to correlate with systematic and synchronous decreases in tree pollen.

During the Neolithic, people seem to have settled at the lowest altitudes around Lac de Clairvaux and Lac de Chalain (Fig. 1b; Pétrequin 1986; Pétrequin et al. 2000). Recent pollen and sedimentological analyses at Lac de St-Point which is 850 m a.s.l. and 60 km north of Lac d'Antre (Leroux et al. 2008; Leroux 2010) suggest regular settlement of the area beginning at 6000 cal. B.P. However, the highest altitude was usually only crossed by small groups using a shifting cultivation system. This system generated local and temporary impacts that have been revealed by

pollen studies in the Jura mountains (Gauthier and Richard 2007; Richard 1994) and in other mountainous areas such as the northern Alps (De Beaulieu and Goeury 2004; Vorren et al. 1993) and the Pyrenees (Galop 2006).

The Bronze Age; 3900–2750 cal. B.P. (1950–800 cal. B.C.)

From 3900 cal. B.P. onwards, several increases of NAP percentages such as Poaceae and API, CHAR and MS values are correlated and reveal a fluctuating human influence around the lake. Accordingly, the successive decreases in *Fagus* may represent repeated clearances. From 3200 cal. B.P. onwards, late Bronze Age, the continuous curve of Cerealia indicates a permanent agricultural presence near the site.

The intensification of evidence of human activity around the lake was suspected from the discovery of artefacts during archaeological prospection (Nouvel et al. 2008). At a regional scale, the archaeological data suggest an increase in human occupation during the early Bronze Age (Martineau et al. 2007). Pollen analyses in the Jura mountains revealed human occupation throughout this period (Gauthier 2004; Richard and Gauthier 2007). The human impact was weak and discontinuous and was characterised by small clearances and minor pastoral and agricultural activities such as those detected at Lac d'Antre.

The Iron Age, 2750–2000 cal. B.P. (800–50 cal. B.C.)

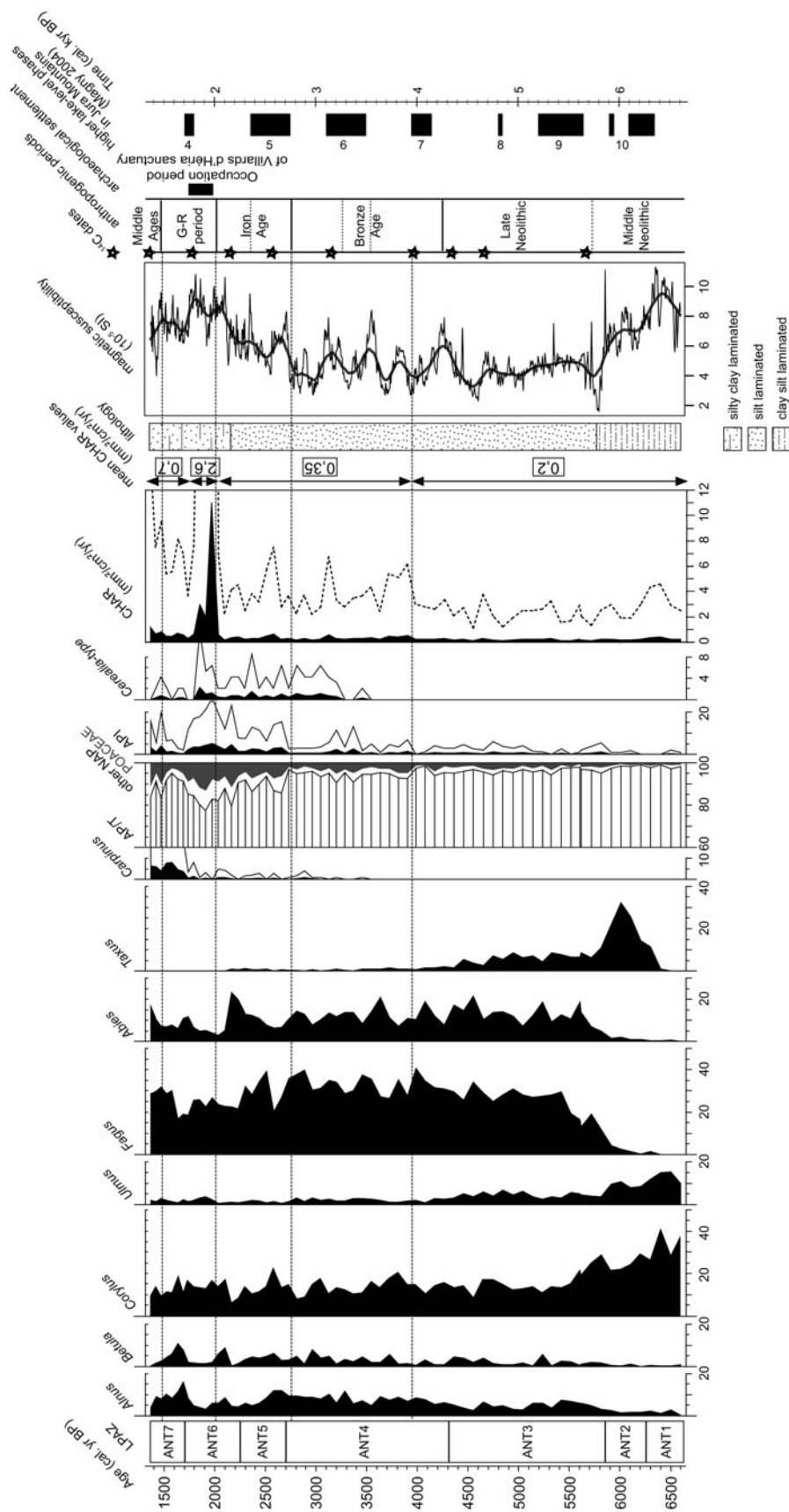
The decreases in woodland trees (*Fagus* and *Abies*) and lake shore trees (*Alnus*) beginning in the first Iron Age period (“Hallstatt”, ca. 2700 cal. B.P.) suggest woodland clearances and an increase in human activity around the lake. Simultaneously these practices caused soil erosion, indicated by increased MS values. *Corylus* benefited from woodland modifications as a pioneer and woodland edge tree (Bégeot 1998).

Between ca 2500 and 2200 cal. B.P., a regrowth of woodland, firstly of *Fagus* and secondly of *Abies*, is contemporary with a sharp decreasing trend of the API and with a stability of the magnetic susceptibility. All these changes are consistent with a temporary decrease in human pressure.

Successive clearances of *Fagus* followed by *Abies* during the second Iron Age (“La Tène”, at 2350 cal. B.P.) coincided with an increase in grazing pressure (API and Poaceae), soil erosion (MS) and an increased woodland edge area (*Betula*, *Corylus*). There was no extension of cultivated land during the Iron Age, as Cerealia percentages are consistent with those of the Bronze Age.

However, no archaeological remains were discovered at our site, and archaeological data at these altitudes are

Fig. 4 A synthetic pollen diagram, microscopic charcoal influx ($\text{mm}^2/\text{cm}^2/\text{year}$) and magnetic susceptibility with lowess smoother (50 samples window) from Lac d'Antre. Cultural periods are indicated in the right-hand scale with the period of the Villards d'Héria site occupation and lake level phases described by Magny (2004). The exaggerated curves are $\times 5$ for pollen (solid line) and $\times 10$ for charcoal (dotted line)



scarce at a regional scale (Rothé 2001). In the Jura mountains, palaeoenvironmental studies describe a weak and irregular occupation (Gauthier 2004; Gauthier and Richard 2009; Richard and Gauthier 2007), perhaps resulting from a climatic cooling estimated from a transgressive phase of the lake level during the first Iron Age (Magny 2001; Van Geel and Magny 2000). Nevertheless, some sites located at high altitudes but close to the main road through the Jura mountains (“La Chaux d’Arlier”, for example) have records of a continuous human impact (Gauthier 2002; Gauthier and Richard 2007). At a regional scale, the fluctuations are different in their chronology and characteristics (Röpke et al. 2011; Tinner et al. 2003). This suggests rather local events and shows the difficulty of discerning a general trend at a regional scale. Finally, human impact during the Iron Age seems to have been derived from a complex interaction between human activities, local vegetation history and climatic changes.

The Gallo-Roman period, 2000–1474 cal. B.P. (50 cal. B.C.–cal. A.D. 476)

All of the palaeo-proxies show an increase in human impact from 2000 to 1700 cal. B.P. These modifications fit well with the archaeological evidence and the settlement of the Villards d’Héria sanctuary from the 1st to the 3rd centuries A.D. (2000–1700 cal. B.P.) (Lerat 1998). The building of this sanctuary, described as a major place of worship of the Roman period Sequanie, would certainly have involved an increased local human activity and an expansion of open land, as shown by an increase of Poaceae, Caryophyllaceae and API, such as *Plantago lanceolata*, *Rumex acetosa/acetosella* and *Artemisia*. In parallel, small decreases in tree percentages (*Alnus* and *Fagus*) are recorded and indicate a few supplementary clearances during this period. The soil erosion, recorded by magnetic susceptibility, reaches its maximum with values close to those reached at the end of the Iron Age. Finally, the Gallo-Roman sanctuary construction and settlement continued through the Iron Age occupation and certainly occurred in an already open landscape.

The pollen spectra, with pastoral indicators and low percentages of crop indicators during the Gallo-Roman period, suggest the development of pastoral and small-scale cultivation activities in the catchment area. This finding is confirmed by the presence of a potential domestic area (Fig. 1c), which suggests a permanent human presence and the development of subsistence farming activities in parallel with the religious activities.

Regrowth of woodland (AP/T from 80 to 95 %) and a decrease in open-land taxa (Poaceae and API) coincided with the date of the abandonment of the Gallo-Roman sanctuary at the end of the 3rd century A.D. (ca.

1700–1650 cal. B.P.) that has been demonstrated by archaeological evidence (Lerat 1998). This event may have been a consequence of the instability of political and economic life partly caused by the insecurity arising from the Barbarian invasion between the 4th to 6th centuries A.D. (1650–1450 cal. B.P.) (Rothé 2001). The effects of this abandonment on the plant community included the colonisation of the wet zone on the lake shores by *Alnus* and the colonisation of cleared areas by *Betula*. After colonisation by pioneer trees, the woodland cover spread with the expansion of *Fagus* and *Carpinus* involving a stabilisation of the soil, illustrated by a decrease in MS values. Many pollen studies in the Jura mountains (Gauthier and Richard 2007) and in other areas of western Europe (Richoiz 1998; Rösch 1992; Tinner et al. 2003) have also recorded this agro-pastoral decrease in the 4th or 5th centuries A.D. (1650–1550 cal. B.P.). Moreover, the regrowth of *Carpinus* after the human impact during the Roman period has been described in previous studies in eastern France (Etienne et al. 2011; Gauthier 2004), in southern Germany (Rösch 2000) and in Poland (Ralska-Jasiewiczowa et al. 2003). This pollen was sporadic until the second part of the Gallo-Roman period, when *Carpinus* percentages reached 5 %. Hornbeam seems to have benefited from the decrease in human pressure and played a prominent part in the regrowth of woodland in the area. Compared with other trees such as *Abies*, *Fagus* or *Quercus*, *Carpinus* grows more rapidly, has a high stump sprouting ability and produces a large amount of pollen, which may have facilitated its expansion.

The beginning of the early Middle Ages, 1474–1400 cal. B.P. (cal. A.D. 476–550)

After the short re-growth of woodland with *Carpinus* and *Fagus*, there are signs of site re-occupation. The increase in Poaceae, API and Cerealia pollen highlight the new establishment of pasture, cultivated land and open land around Lac d’Antre. This kind of farming renewal after the end of the Barbarian invasions around the 6th or 7th century A.D. (1450–1350 cal. B.P.) has been described in other pollen studies in Jura (Gauthier 2004) and in southern Germany (Rösch 1992).

The role of fire in vegetation dynamics

Along with the study of the evolution of vegetation dynamics, this study reconstructs the first fire history for the Jura mountains. The climate and vegetation of this area limit natural ignition and fire spread. Therefore, the fire activity detected from CHAR can easily be ascribed to burning by humans. Thus, our study area brings together a palaeoenvironmental archive from Lac d’Antre and an

archaeological site, the sanctuary of Villards d'Héria, which provides the opportunity to investigate the link between fire history and human activities.

The first increase in CHAR values occurs during the early Bronze Age (ca. 3900 cal. B.P.). These values coincide with the first weak signs of human impact characterised by the increase in API percentages, indicators of landscape openness (Poaceae) and a few clearance practices (Fig. 4). At 3200 cal. B.P., another increase of CHAR values is correlated with the decreases of *Fagus* and *Abies* and an increase of Cerealia-type. The fire was certainly used to clear areas for the expansion of the farming around the lake. Indeed, several studies in Switzerland, in the northern and southern Alps, have shown a strong correlation between charcoal and API beginning with the early Bronze Age (4250 cal. B.P.) (Gobet et al. 2003; Tinner et al. 2005; Valsecchi et al. 2006). Thus, fire was intentionally used for the clearance of woodlands and the establishment of pastures and cultivated land.

The Iron Age is characterised by the first phase of woodland reduction which affected local vegetation. A peak in CHAR values at ca. 2600 cal. B.P. coincided with *Fagus* and *Abies* clearances, an increase in pasture pollen indicators (API and Poaceae) and the presence of crop cultivation (Cerealia-type pollen). This increase of CHAR values may be the result of the use of fire to clear new areas and favour the expansion of pasture. Although the human activity became more pronounced, peak amplitudes and trends of CHAR values were of the same order of magnitude as those during the Bronze Age.

The strongest fire phase recorded in the Lac d'Antre sequence occurred during the Gallo-Roman occupation of the sanctuary. The two highest peaks of the sequences, 11 and 3 mm²/cm²/year, were correlated with the increase in API and Cerealia-type pollen and with the lowest AP/T percentages recorded (approximately 80 %). Thus, the general increase in CHAR values during the settlement of the Gallo-Roman sanctuary (2.6 mm²/cm²/year) coincided with an increased landscape openness and the expansion of areas for grazing and other farming activities. Given the proximity between the settlement and the lake, domestic activities such as heating, cooking (Sadori et al. 2004; Sadori and Giardini 2007) or other undetermined activities relating to the life in the sanctuary may have caused an increase in CHAR values. The use of fire as part of farming practices may have been a side benefit from the production of charcoal.

From 1500 cal. B.P., the decrease in general CHAR values coincided with the abandonment of the sanctuary demonstrated by archaeologists. This decrease in fire events corroborates the decrease in farming and grazing practices and a period of re-growth of woodland around Lac d'Antre. The increase in CHAR values around

1500 cal. B.P. indicates a period of fire use to re-open the surrounding landscape before another expansion of grazing and farming activities.

The reconstitution of the fire history for Lac d'Antre fits well with the successive periods of human impact identified by pollen analysis and archaeological discoveries. However, the use of fire across these different historical periods was not uniform.

First, fire use was absent or very sparse during the Neolithic and was not correlated with the slash-and-burn agriculture described in other studies of this period (Carcaillet 1998; Clark et al. 1989; Martineau et al. 2007; Rius et al. 2009; Tinner et al. 2005). In addition, fire was not the main tool for tree clearance during the Bronze and Iron Ages around Lac d'Antre. Several studies in Switzerland have recorded higher charcoal influxes during the Bronze Age, from 3950 cal. B.P. (Gobet et al. 2003; Valsecchi et al. 2006) or the Iron Age at approximately 2550 cal. B.P. (Tinner et al. 2005) and have related these influxes to clearances of the tree cover by humans. Conversely, fire seems to have played a primary role during the Gallo-Roman period, 2000–1800 cal. B.P. This period is generally characterised by low fire occurrences during which fire was used to maintain meadows and fields in a general pattern of keeping the land open (Rius et al. 2009). This particularity in our fire record is certainly the result of the existence of Lac d'Antre in the middle of an archaeological site in full expansion during the Gallo-Roman period, which involved a concentrated and sharp increase in human pressure and resource requirements.

Natural or human influences on the expansions of *Taxus baccata*, *Fagus sylvatica* and *Abies alba*

The data available permit a discussion of a specific aspect of the vegetation dynamics. The cause of the appearance of *Fagus* and *Abies* has been extensively discussed in the literature (Tinner and Lotter 2006; Valsecchi et al. 2008). However, at Lac d'Antre, a rapid expansion of *Taxus* beginning at ca. 6350 cal. B.P. coincided with the disappearance of the mixed oak woods, and its decline corresponded with the development of the beech-fir woods (Fig. 3). In the literature, few pollen studies have identified such a sharp *Taxus* expansion, and this may be linked to the difficulty in identifying yew pollen and the short period of time when it was present. Most of the pollen analyses that have mentioned the occurrence of *Taxus* (>5 %) during the Atlantic Period (8850–5350 cal. B.P. in western Europe) are located in the Jura mountains and in their southern regions (Fig. 5a). Percentages of *Taxus* of approximately 10 % were recorded in Chalain (Richard 1997) and Arinthod (De Beaulieu and Richard, unpublished), both of which are located close to Lac d'Antre. In the southern part of the Jura mountains, similar percentages were described in

Pluvis (Borel et al. 1990) and higher percentages (30 %) in Cerin (Ruffaldi 1993). From 5 to 20 % were recorded in “Ile Crémieu”, in the southern Jura mountains in Hières-sur-Amby (Clerc 1988) and in Moras (unpublished) and in the sub-alpine foothill areas in St. Julien de Ratz, Grand Ratz and Grand Lemps by Clerc (1988). Anthracological (charcoal) studies have also described, in the same area of southern Jura and pre-Alps and during an identical period with a stronger expansion between 7450 and 6950 cal. B.P., an expansion of yew by charcoal identification in cultural layers (Martin and Thiébault 2010). Finally, this type of sharp *Taxus* expansion has also been detected in other pollen studies in France at Marais du Grand-Chaumet (Vannière 2001) and in Switzerland at Seedorf (Richoz 1998). From a geographical point of view, *Taxus* does not seem to have an altitudinal preference, growing equally well in both hills and mountains <800 m a.s.l.

The phases of the *Taxus* expansion are dated in some of these sites by AMS radiocarbon dates. The possible age of *Taxus* establishment and expansion at Lac d’Antre was taken from the extrapolated part of the age-depth model. These radiocarbon dates were calibrated with CALIB 6.0.1 using the IntCal09 calibration curve. They correspond to different moments in the invasion of *Taxus* (Lang 1992): establishment (Tet), expansion (Tex), stabilisation (Ts) and recession (Tr) (Fig. 5b).

In the present state of the data, the distributions of *Taxus* invasions are not contemporary with the geographical locations of the sites. Thus, migration lag appears to be a factor that influenced *Taxus* development. *Taxus* expansion seems to follow a south-north transect. The first establishments occur in the sub-alpine foothills at sites 1–3, before its colonisation of the southern part of the Jura mountains at sites 4–6. Following this, yew became established northwards to the latitudes of the Jura at Lac d’Antre, site 8 and in western France at site 12.

Additional studies on the migration of *Taxus* in France and other countries will be necessary to confirm the hypothesis of a refuge area for *Taxus* close to sub-alpine mountains, before its migration towards the north.

For all sites previously cited, the establishment of *Taxus* took place between the decrease of the mixed oak woodland and the spread of *Fagus*. *Taxus* appeared at three sites (sites 1–3) during a phase in which *Abies* was well established; so yew establishment does not seem to have been limited by fir. However, for the large majority of the pollen studies, *Taxus* recession is linked with the expansion of *Fagus*, which also follows the direction of its migration from a refuge area in the sub-alpine foothills (De Beaulieu et al. 1994; Magri et al. 2006). Thus, as with its appearance and expansion, the recession of *Taxus* seems to have followed a south-north direction.

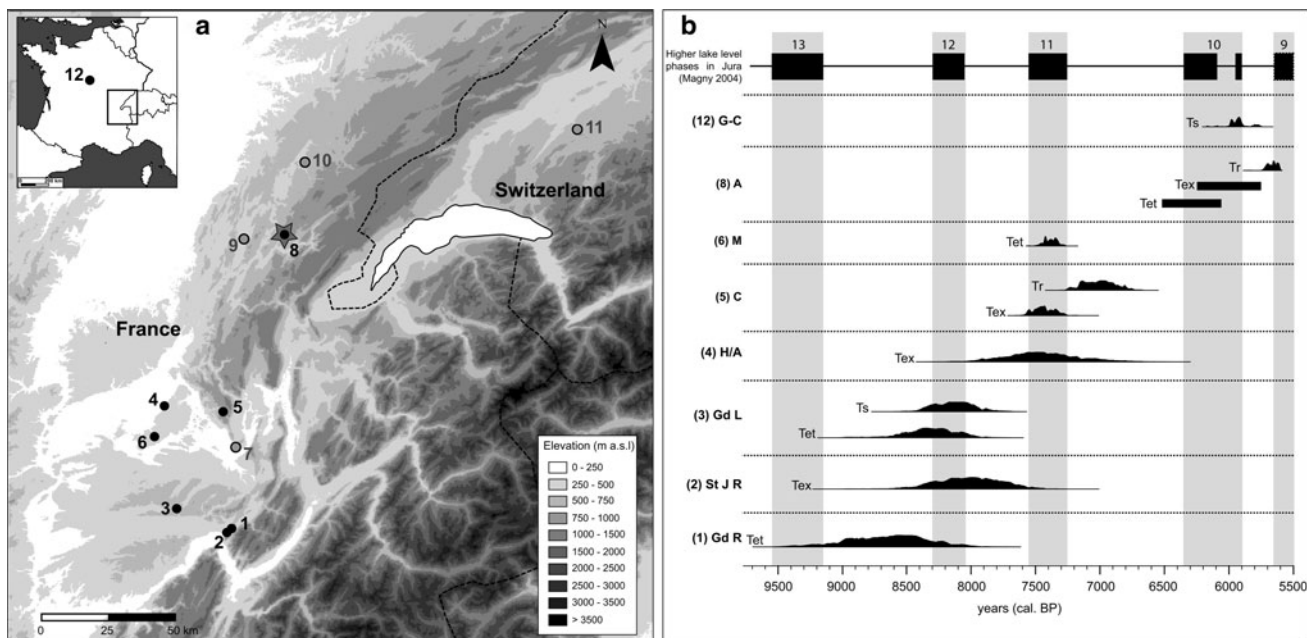


Fig. 5 **a** The geographical location of sites with a percentage of *Taxus* >5 % during the Atlantic Period: 1 St Julien de Ratz, St J R (650 m); 2 Grand Ratz, Gd R (650 m); 3 Grand Lemps, Gd L (456 m); 4 Hières sur Amby, H/A (212 m); 5 Cerin, C (764 m); 6 Moras, M (304 m); 7 Pluvis (215 m); 8 Antre, A (798 m); 9 Arinthod (450 m); 10 Chalain (484 m); 11 Seedorf (609 m); 12 Marais du

Grand-Chaumet, G-C (145 m). **b** The distribution of the dates (2σ range) for the *Taxus* episode record for the round black sites: Tet, *Taxus* establishment; Tex, *Taxus* expansion; Ts, *Taxus* stabilisation; Tr, *Taxus* recession correlated with the higher lake level phases in Jura (Magny 2004). The black squares for the Lac d’Antre sequence correspond to radiocarbon date estimates using the age-depth model

Just as global climate change, local parameters such as geographical location, altitude, micro-climate, inter-specific competition, soils (Haas et al. 1998; Tinner and Lotter 2006) and human activities (Richoz 1998; Valsecchi et al. 2008) all may have played roles in the appearance and expansion of *Fagus* and *Abies*, these factors also probably influenced the establishment of *Taxus*.

At all of the sites studied, *Taxus* appeared during the Holocene climatic optimum (9000–5500 cal. B.P.) but only after its maximum, when a progressive climatic degradation to wetter and colder conditions caused the decline of the mixed oak woodland and the transition to a beech-fir woods (De Beaulieu et al. 2006). For the majority of the sites (sites 4–10 and 12), *Taxus* seems to have benefited from this global climatic context to grow and become an established population during the transition between these two woodland associations. At sites 1–3, *Taxus* expansion also coincides with the decline of the mixed oak woodland. However, the concomitant presence of *Taxus* and *Abies* is probably the result of the early expansion of *Abies* in this area linked with the proximity of the Würm refuge area (Clerc 1988).

During the Pleistocene, in the previous interglacial periods (during Oxygen Isotope Stages 5e, 9e and 11c), similar significant increases of yew are recorded in several sites in France (De Beaulieu et al. 2006; Pons et al. 1992; Reille et al. 1998). The climatic context and vegetation dynamics that existed when *Taxus* appeared and developed were very similar to those of the Holocene. This highlights the important role played by the global climatic conditions in the dynamics of *Taxus*.

Regional climatic conditions seem also to have played a role in *Taxus* development. Indeed, the yew expansion at Lac d'Antre (and sites 11 and 12) was correlated with the higher lake-level called “10—Grand Maclu” (6350–5900 cal. B.P.) described by Magny in the Jura mountains, corresponding to a cooling and humid phase (Fig. 5b; Magny 1995, 2004). In two other sites (sites 4 and 5), the *Taxus* expansion occurred earlier, but it was also correlated with a high lake-level phase “11—Cerin”. This might be linked to the ecological preferences of *Taxus* for high atmospheric humidity without extreme low temperatures (Verrière-Cuvillier 2001).

No human impact was recorded during the beginning of the mixed oak woodland decline and the expansion of *Taxus* and the regression of Lac d'Antre. However, the potentially weak human impact described previously is synchronous with the expansions of *Fagus* and *Abies*. This small disturbance of the woodland cover may have facilitated the spread of these two trees at a local scale. However, human influence appears to have been too weak to exceed the natural disturbances and certainly cannot solely account for the spread of *Fagus* and *Abies* at the regional or

European scale (Giesecke et al. 2007; Huntley 1996; Richoz 1998; Tinner and Lotter 2006).

Conclusion

The main results of this multi-proxy study of the Lac d'Antre sequence are as follows:

- (1) This study provides new data on the regional human history and corroborates or completes the available but scarce archaeological data. Indeed, the palaeoenvironmental results reveal earlier and later human settlement apart from the Gallo-Roman establishment at Villards d'Héria. The first weak signs of human settlement are detectable in the early middle Neolithic (ca. 5850 cal. B.P.) and in the Bronze Age (ca. 3900 cal. B.P.). However, a more extensive and intensive human pressure began during the Iron Age (2700 cal. B.P.), when woodlands and lakeshores were both affected by clearances. Further archaeological investigations are needed to confirm that these settlements existed before the well-known Gallo-Roman sanctuary was founded. The establishment of the Sequane sanctuary took place at the same time as an Iron Age occupation at the site. There was an increase of open landscape for the development of the sanctuary that coincided with farming activities in a generally wooded landscape. There is also a close chronological correlation between our different proxies and the date of Gallo-Roman occupation (1st century A.D.) and abandonment (4th century A.D.) of the site demonstrated by numerous archaeological data. A previously unknown human impact phase was recorded during the Middle Ages, but archaeological discoveries have not yet confirmed these results.
- (2) The periods of increased fire activity detected were all attributable to burning by humans. During the Bronze and Iron Ages, the increase from the low CHAR values recorded during the clearance phases reflect a limited use of fire as a means of managing the landscape in the Jura mountains. The main phase of fire use was recorded during the first part of the Gallo-Roman period and was correlated with the higher population pressure revealed by pollen analyses and archaeological studies. During this period, fire was probably mainly used for domestic activities relating to the life in the sanctuary and may also have been used as part of the farming practices in the catchment area.
- (3) The establishment of *Taxus baccata*, *Fagus sylvatica* and *Abies alba* seems mainly to have been influenced by climatic variations during the middle Neolithic

(6400–5500 cal. B.P.). The end of the maximum climatic optimum and the development at a regional scale of a cold and wet climatic phase was favourable to the establishment of *Taxus* (6350–5900 cal. B.P.). Climatic and human factors may have played a role in this period of change in the woodlands. However, the human impact detected around Lac d'Antre was too weak to exceed the climatic impact. Finally, the establishment of *Taxus*, *Fagus* and *Abies* near our site seems to have been mainly driven by climatic variations.

Further analyses on the upper part of the sequence, from the Middle Ages to the present day, will complete our knowledge of the history of human settlement and activities around this site.

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