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Vegetation history, human impact and climate change during the last 700 years recorded in annually laminated sediments of Lac Pavin, France

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Abstract

This paper presents a 1.80-m-long varved sediment record documenting the vegetation history by pollen and diatom analysis recovered from Lake Pavin, a volcanic crater lake in the Auvergne (French Massif Central). High-resolution sampling and a varve-based age model allowed the reconstruction of ecosystem responses to both regional climate change and human impact. According to the present varve chronology, the Lake Pavin sequence covers the last 700 years, thus representing the late Subatlantic period (i.e. from the Late Medieval onwards). The pollen record largely reflects intensive human influence (clearing, cultivation and grazing) on the lake surrounding area. The arboreal pollen spectrum of the entire sequence is co-dominated by *Fagus* and *Quercus*, except during the 20th century. However, whilst the *Quercus* record is relative stable, several major fluctuations are discernable in the *Fagus* curve. An increase in *Pinus* and *Picea* shortly before of the turn the 20th Century, indicates afforestation by conifers. The varve counting indicates that the most prominent signal in the *Fagus* curve occurs during the period between about 1540 and 1670 AD. During this interval, the initial drop in the *Fagus* curve is estimated to have taken 5–10 years, with the subsequent recovery occurring over a similar period. Since there is no clear evidence of tree population replacement, such rapid signals imply that the fluctuations in the *Fagus* curve reflect variations in pollen production, being influenced by the cooler temperatures experienced during a cold spell of the Little Ice Age.

Keywords: vegetation history; *Fagus*; varved sediments; Little Ice Age; French Massif Central

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1. Introduction and background information

1.1. Preface

Previous investigations on the vegetational history of the French Massif Central have produced a number of particularly significant pollen diagrams, reflecting vegetational development during the last five major climatic cycles, including the Holocene (De Beaulieu et al., 1982; Guenet and Reille, 1991; De Beaulieu and Reille, 1992; Reille et al., 1992; De Beaulieu and Reille, 1995; Reille and de Beaulieu, 1995; Juvigné et al., 1996; Reille et al., 2000; De Beaulieu et al., 2001; Rioual et al., 2001; Guiter et al., 2003). According to palynological studies by several authors (Lang and Trautmann, 1961; Guenet and Reille, 1991; Reille, 1991), pollen spectra from the higher parts of the Auvergne are dominated by beech during the Subatlantic period. Records indicate that this was a time of widespread forest clearance, even at higher elevations, which led to the almost complete destruction of woodland. The results presented here from Lake Pavin provide a palaeobotanical record, covering the interval from the end of the Medieval period to the present day (1999). The present study considers the vegetational and climatic changes that have occurred during historical times in more detail than has been previously possible.

1.2. Introduction

Large and rapid climatic shifts, such as those observed during the Weichselian Lateglacial, are particularly clear in palynological records. Climate change in lowland Europe during the Holocene does not result in short-term deforestation and reforestation of large areas, but rather causes alterations in the productivity and competition of existing plant populations, according to the ecological and physiological tolerances of the particular plant species and communities involved. Nevertheless, it seems likely that human activity, rather than the climatic variability, dominates patterns of vegetational change from at least the Neolithic onwards. As a consequence, palynological evidence of natural climatic changes, which are generally less pronounced than anthropogenically induced events, only seems to be preserved in regions sensitive to vegetational and climate change (e.g. sensitive altitudes or ecotones) (Ammann et al., 1998; Liu et al., 1999; Peteet, 2000; Van der Knaap et al., 2000). Nevertheless, if sampled at an appropriate resolution, pollen sequences can reflect short-term changes in vegetation dynamics associated with human activities and fire, in addition to the response of pollen production to weather patterns.

Within the Project "Natural climate variations from 10,000 years BP to the present day" (KIHZ; Negendank et al., 2001), high-resolution palaeobotanical studies are being conducted on a short core from Lake Pavin, French Massif Central. The primary focus of this project was to establish whether Holocene climatic fluctuations (i.e. cold spells during the Little Ice Age) are recorded in the pollen data.

1.3. Lake Pavin

Lake Pavin (45°55′ N; 2°54′ E) is a maar lake, located at 1197 m a.s.l. in a remote area of the volcanic Puy de Dome region, a part of the Mont-Dore mountain range of the French Massif Central. The almost circular lake has a diameter of about 750 m, a surface area of 44 ha and a maximum water depth of about 97 m (Fig. 1). Nowadays, the crater wall rises, for the most part, 50 m above the level of the current lake, its slopes covered by a mixture of deciduous and coniferous trees that limit erosion.

1.4. Recent climate and vegetation

The region is characterised by an oceanic-montane climate. A mean annual temperature (between 1946 and 1974) of 6.5 °C was observed at Besse-en-Chandesse, the closest meteorological station to the lake, located at an elevation of 1050 m a.s.l. The annual thermal amplitude ranges between −5 and 20 °C (Rioual, 2000). Annual precipitation in the catchment averages between 1600 and 1700 mm (Meybeck et al., 1975; Bouchet, 1987). The climate diagram from this station (Fig. 2) indicates precipitation maxima in May and also between the period November and January (Rioual, 2000). The lake surface usually freezes during the winter months (Schmid, 1997).

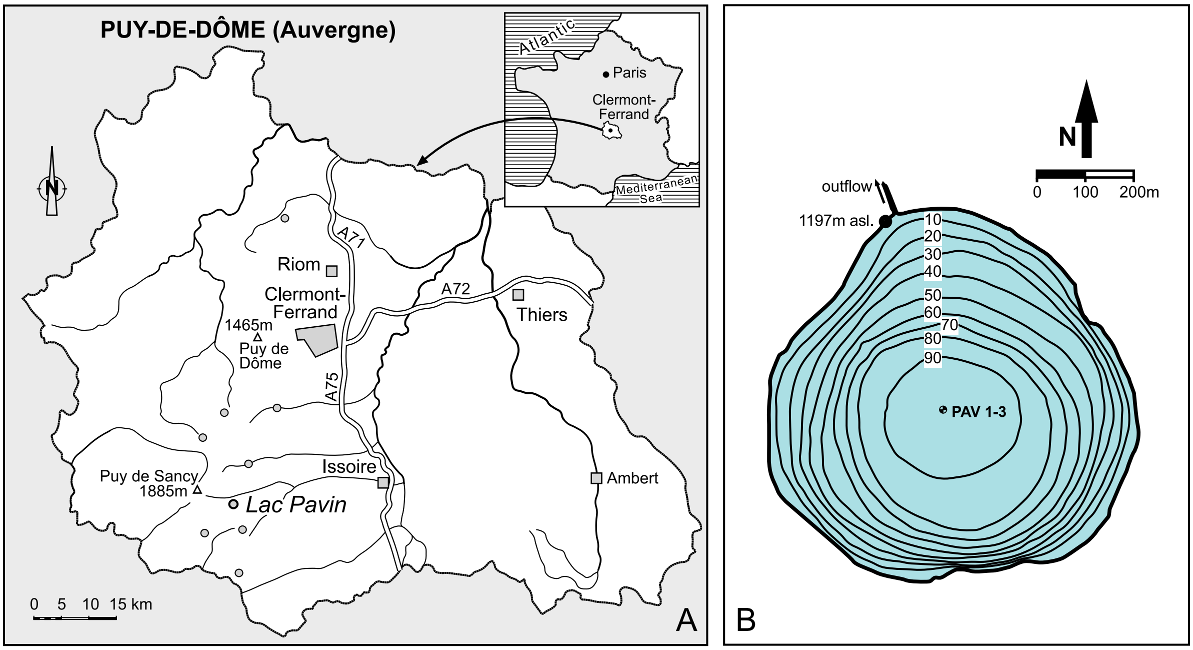

Fig. 1. Lake Pavin. (A) Location of the lake in the Auvergne, French Massif Central, (B) bathymetric map with coring point (redrawn after Delebecque, 1898).

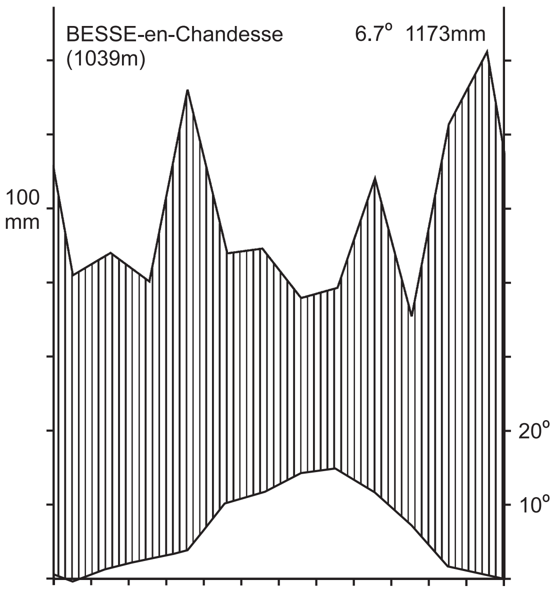

Fig. 2. Climatic diagram of Besse-en-Chandesse (redrawn after Lang and Trautmann, 1961).

The observations of Luqet (1926) and Lemée (1956) (in Lang and Trautmann, 1961), together with those of our own, indicate that the recent vegetation of the Auvergne can be characterised as follows.

The investigated site lies in the montane Fagion belt, which ranges between 750 and 1500 m. In general, these forests are dominated by *Fagus sylvatica* with occasional occurrences of *Abies alba* and *Fraxinus excelsior*. Biotopes associated with marginal zones along rivers are lined with bushes of *Alnus glutinosa* and *Salix*, with an undergrowth rich in tall forbs. The Fagion belt lies between the lower deciduous-forest zone, characterised by Quercion and Carpinion communities, and the upper alpine zone. The upper coniferous zone of *Picea*, normally present between the Fagion zone and the alpine zone, is absent in this case. Instead, a zone of beech-dominated forest occurs, where trees become progressively smaller and the canopy becomes more open. As the canopy continues to thin, *Betula pendula*, *Betula pubescens*, *Sorbus aria* and *Sorbus aucuparia* become increasingly common, especially in clearings and at the forest edge. Above the tree line, tall forb, meadow and dwarf-shrub heath communities dominate. Natural *Pinus* stands occur on slopes in the eastern part of the Auvergne. *Picea* is not an indigenous species.

Today, the Auvergne is a region of widespread agriculture, such that meadows, pastures and dwarf-shrub heaths dominate the landscape. Intensive grazing means that the modern tree-line occurs at about 1200–1400 m, in a rolling landscape often afforested by *Picea*. *Fagus* and *Abies* woods are restricted to slopes and deep valleys. During the last 100 years or more, there has been an expansion of *Abies* to the detriment of *Fagus*. Stands of *Castanea* and *Juglans* derive from post-Roman plantations.

The sampling site is ringed by trees that extend right down to the lakeshore because of the steep crater walls. Characteristic reed and riparian communities are absent. In the narrow-banded littoral zone, *Potamogeton* occurs as small populations. *Fagus* is the dominant tree species on the inner crater slopes surrounding the lake, although *Abies* and *Picea* are also present locally and a few pine trees occur near the outlet stream. *Corylus avellana*, *Sorbus aucuparia*, *Sorbus aria*, *Sambucus racemosa*, *Ribes rubrum* and *Populus* sp. are important components of more open, steep and rocky stands (especially on block fields). The field layer within the crater commonly includes *Athyrium filix-femina*, *Polypodium vulgare*, *Pteridium aquilinum*, *Vaccinium myrtillus*, *Phyteuma spicatum*, *Prenanthes purpurea* and *Rubus idaeus*. The majority of the area around the Puy de Montchal, south of Lake Pavin, has been afforested with *Picea*, but *Salix* and *Juniperus* bushes, together with tall forbs and dwarf shrubs (including *Astrantia major*, *Aconitum napellus*, *Calluna vulgaris*, *V. myrtillus*, *Solidago virgaurea*, *Cicerbita plumieri* and *Gentiana lutea*) cover the northwestern slopes of the mountain.

The modern diatom assemblage from Lake Pavin is dominated by small planktonic taxa, namely *Cyclotella pseudostelligera* and *Stephanodiscus parvus* in spring and *Cyclotella radiosa* in summer and autumn. Furthermore, high proportions of *Aulacoseira subarctica* occur in autumn and winter. *Asterionella formosa* also contributes a significant proportion of the total spring and/or autumn assemblages. This annual pattern appears to have been stable during the past 25 years (Devaux, 1975; Amblard, 1988; Rioual, 2000).

1.5. Historical records

Traditionally, the Auvergne is a region of widespread agriculture. Overpopulation and associated poverty became problems in the Auvergne during the period between the 12th and 17th centuries. However, the Hundred Years War between 1337 and 1453 AD and the Black Death (1348 AD) have caused a strong, temporary decline of population and economic pressure.

Historical aspects relating to the area surrounding Lake Pavin are very sparse (Eusebio, 1925; Trement, personal communication). As a result of the colonisation of the valleys surrounding Lake Pavin since the early Medieval, intensive clearings have taken place (Eusebio, 1925; Lang and Trautmann, 1961).

In middle of the 19th century, tree plantations (*Pinus*, *Picea* and *Larix*) were first established near to the lake (Martin, 1985). Since the later part of that century, the entire Massif Central has suffered from progressive demographic decline and land abandonment, whilst many cereals crops have been replaced by pasture (Reille et al., 1992).

2. Methods

2.1. Coring and sampling

During a coring campaign in 1999, organized by GeoForschungsZentrum Potsdam (GFZ-Potsdam), several short gravity cores were taken at Lake Pavin. A finely laminated sediment succession of a maximum of 182 cm (PAV 1–3) from the centre of the lake was recovered (core loss 70–66 cm). The sediments were subsampled at a resolution of 1 cm for pollen analysis and of 5 cm for diatom analysis.

2.2. Pollen analysis

The sediments were volumetrically subsampled every centimetre, thus providing a temporal resolution of ca. 3–4 years. The preparation of the pollen samples involved treatment with HCl, KOH, HF and hot acetolysis mixture, in accordance with the methods described by Berglund and Ralska-Jasiewiczowa (1986) and Faegri and Iversen (1989). Sample residues were mounted in glycerine and analysed using an Olympus BX 40 microscope at ×400–1000 magnification. More than 800 arboreal pollen grains were counted per sample. The pollen taxa were identified with the assistance of *Northwest European Pollen Flora* parts I to VII (Punt, 1976; Punt and Clark, 1980, 1981, 1984; Punt et al., 1988, 1995; Punt and Blackmore, 1991; Reille, 1995, 1998, 1999; Moore et al., 1991 and the reference collection of the Senckenberg Forschungsstation für Quartärpaläontologie (Research Station for Quaternary Palaeontology) Weimar). The pollen percentage diagram was constructed on the basis of total terrestrial pollen, which excludes aquatic and telmatic plants and pteridophytes. In addition, the amount of charcoal fragments was estimated.

2.3. Diatom analysis

Diatom slides were prepared according to Battarbee (1986) and Renberg (1990). Polystyrene microspheres of known concentration were added to the samples to allow the estimation of absolute diatom abundances (Battarbee and Kneen, 1982). A minimum of 600 diatom valves was counted from each slide (Naphrax mountant, R.I.=1.74) using a microscope (Zeiss Orthoplan, oil immersion, DIC) at ×1000 magnification. Taxonomic designations primarily followed standard floras (e.g., Krammer and Lange-Bertalot, 1991a,b, 1997a,b; Lange-Bertalot and Metzeltin, 1996). To aid the identification of problematic species, selected samples were analysed using a scanning electron microscope (Zeiss DSM). Chrysophyte stomatocysts were also counted and their percentages calculated with respect to the total sum of diatoms and chrysophycean cysts.

The computer programs TILIA 2.0 and TILIA GRAPH (Grimm, 1991) were used to calculate and present the palynological and diatom data. Some percentage curves are also presented with an additional exaggerated scale (×10). Zonation of the pollen assemblage data was established by eye, whereas statistical methods were used to zone the diatom stratigraphy.

2.4. Dating methods

The age of each analysed sample was determined by varve counting at an annual resolution. The investigation and counting of the sediment laminae were undertaken on a continuous series of large-scale thin sections, which provided both chronological and lithological information. Varve counting was performed using a microscope (Axiolab, Zeiss) at a magnification between ×25 and ×630. In those parts of the sequence where laminae preservation was too poor to enable counting, the average thicknesses of the layers above and below the problematic section were used to estimate the period represented.

3. Results

3.1. Chronology

The current varve chronology indicates that the detailed multi-proxy palaeoecological record from Lake Pavin presented here covers the last 700 years. Fig. 3 illustrates the age model for the Pavin sequence.

3.2. Pollen record

According to the present varve chronology, the percentage pollen diagram for the short core from Lake Pavin (Fig. 4) reflects the vegetational history of the study site from about 1300 AD onwards. The diagram is somewhat simplified, showing only the most important arboreal taxa, herbs, ferns and aquatics. Charcoal contents are very low throughout the entire studied sequence and therefore not shown on the diagram.

In the pollen diagram (Fig. 4), the arboreal taxa are grouped according to whether they are considered most indicative of the Fagion belt, the Quercion/Carpinion belt, forest plantations, long-distance transport or other, unspecified, locations. Grouping of the non-arboreal taxa reflects whether they are most strongly associated with arable farming, meadows and pastures, ruderal habitats or other, undefined, biotopes.

In the core studied, all the arboreal pollen spectra, except that from the youngest pollen zone, are co-dominated by *Fagus* and *Quercus*. However, whilst the *Quercus* curve is relative stable, several significant, temporary fluctuations are visible in the *Fagus* curve. Open ground taxa are also relatively well

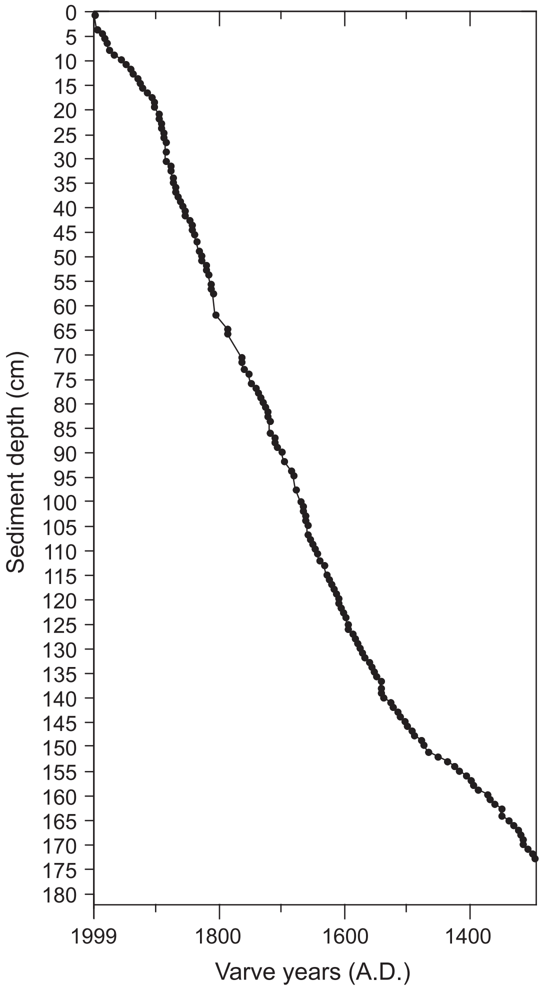

Fig. 3. Age–depth diagram of the Pavin sequence.

represented in the pollen record. The pollen signatures of herbs, including Gramineae, cereals, *Rumex acetosa* type and *Humulus*/*Cannabis* type, clearly indicate a vegetation greatly influenced by continuous anthropogenic activity. The pollen curves of grasses, cereals and *Rumex* all exhibit distinct, if somewhat limited, variability.

Variations in *Fagus* and those taxa indicative of human impact were used to define six local pollen assemblage zones (LPAZ), designated LPAZ 1 to LPAZ 6. A detailed discussion of changes in the terrestrial vegetation in terms of human impact and climatic influences follows in Section 4.1.

3.3. Diatom record

More than 100 diatom species representing 24 genera were identified in the sequence and the percentages of selected diatom taxa are represented in Fig. 5. Three major diatom zones (DZ) were recognized on the basis of the dominance of planktonic diatom taxa.

3.3.1. DZ 1 (182–112.5 cm, end of the 13th century—1634 AD)

The lowermost diatom zone is characterised by the dominance of *Stephanodiscus parvus* and *Asterionella formosa*, which together comprise between 33 and 99% of the total diatom assemblage. The occurrence of *Cyclotella pseudostelligera* and *Aulacoseira granulata* is restricted to the oldest sediment samples. Common periphytic taxa are *Fragilaria brevistriata* and *Navicula* cf. *minima*.

3.3.2. DZ 2 (112.5–22.5 cm, 1634–1894 AD)

This zone is characterised by the appearance of *Aulacoseira subarctica* (accounting for 22%, on average) and slightly lower percentages of *Stephanodiscus parvus*. *Asterionella formosa* continues to occur, at frequencies ranging from 2% to 34%. *Cyclotella pseudostelligera, Stephanodiscus oregonicus* and *Nitzschia paleacea* are present in low numbers from 100 cm (~1675 AD) upwards.

3.3.3. DZ 3 (22.5–0 cm, 1894–1999 AD)

In terms of overall species assemblage composition, this zone exhibits only subtle differences from the preceding one. It is mainly characterised by an increase in *Cyclotella pseudostelligera* percentages. The frequency of *Nitzschia paleacea* also increases slightly, accounting for up to 20% of the total diatom assemblage, whereas *Stephanodiscus oregonicus* nearly disappears.

Periphytic taxa occur at comparatively low frequencies (5–20%) throughout the sequence, gradually decreasing in abundance from the beginning of DZ 2 onwards. Diatom concentrations range from 2.3×10^8 to 3.5×10^9 valves g^{-1} dwt, achieving their highest values during DZ 1. This mainly reflects the relative abundance of small planktonic species, such as *Stephanodiscus parvus* and *Cyclotella pseudostelligera*. Chrysophycean

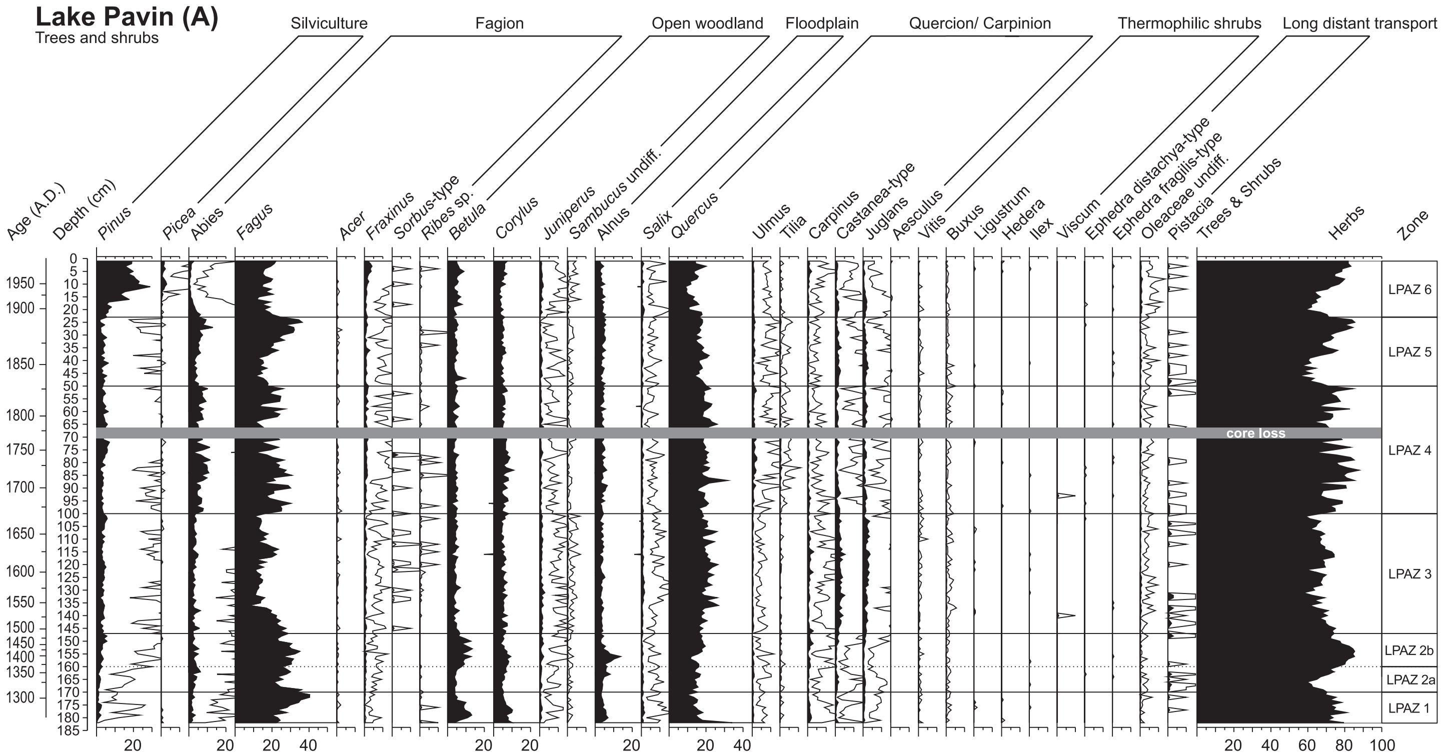

Fig. 4. Simplified pollen diagram of relative frequencies. (A) Woody taxa, (B) herbaceous taxa.

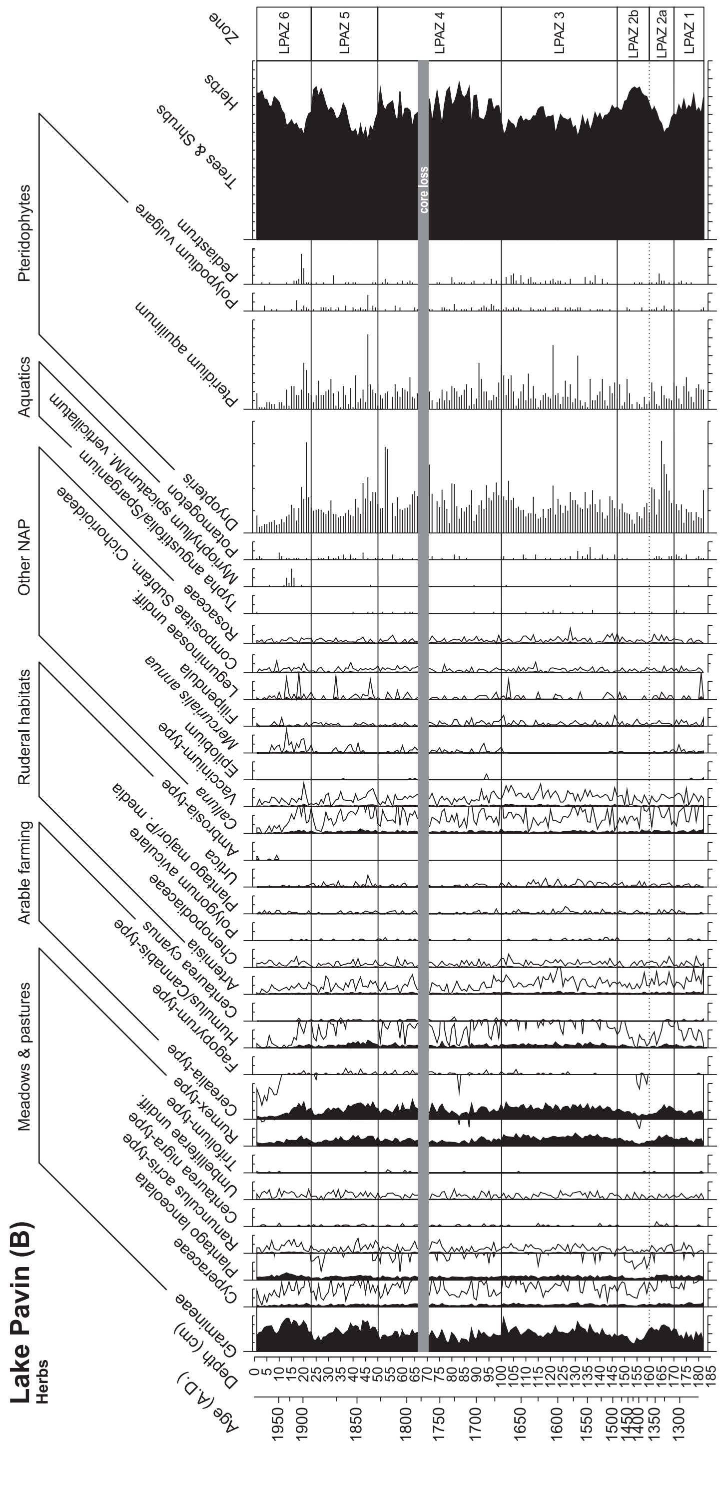

Fig. 4 (*continued*).

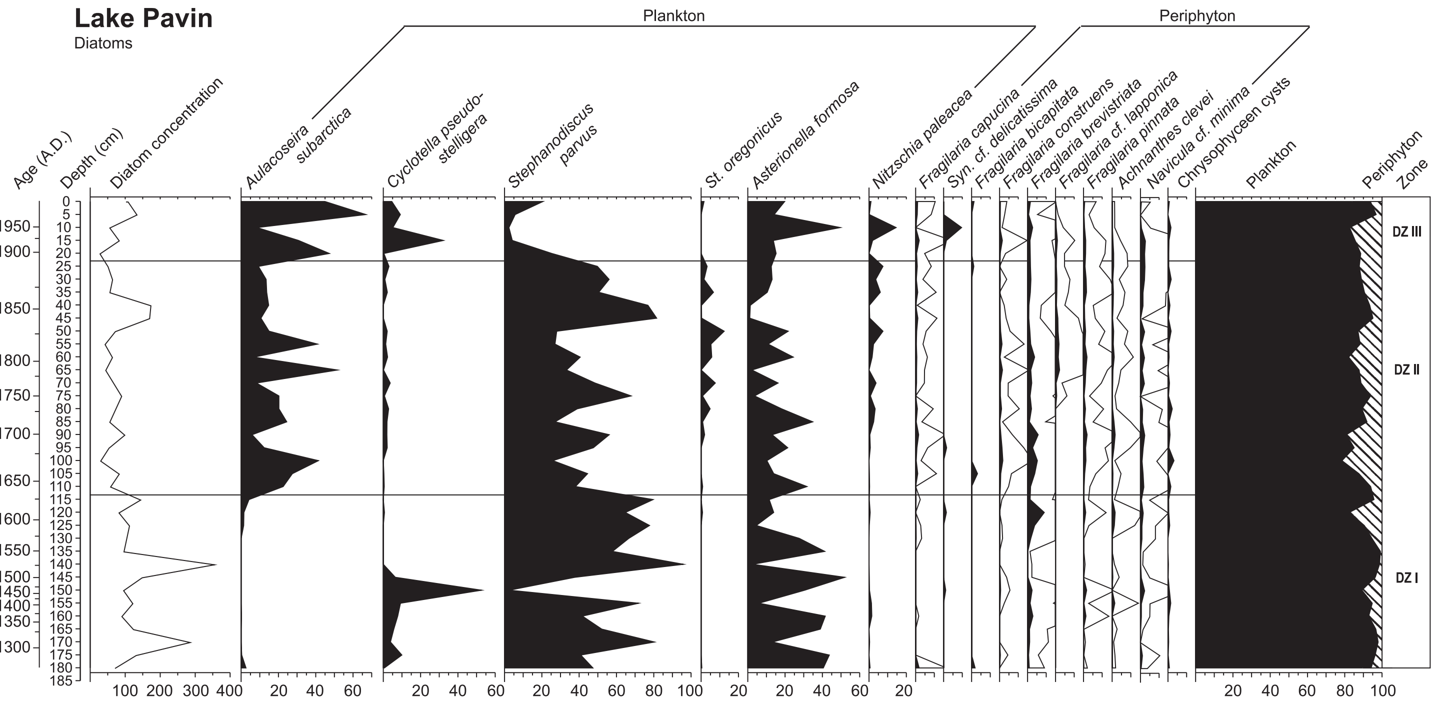

Fig. 5. Diatom concentration and relative frequencies of the most common diatom taxa (DZ=diatom zone).

cysts are absent or were recorded in relatively low percentages.

4. Discussion

4.1. Pollen stratigraphy and vegetational development

4.1.1. LPAZ 1 (182–170 cm, end of the 13th century—1315 AD)

The lowermost local pollen zone is characterised by rapidly increasing *Fagus* values, which peak at about 40%, suggesting that beech-dominated forest was common in the surrounding area (Huntley and Birks, 1983). *Abies* values of 2–5% suggest the local presence of fir (Huntley and Birks, 1983). *Quercus*, originating from the Quercion/Carpinion belt, comprises a substantial proportion of the total pollen spectrum (10–15%). *Carpinus*, *Castanea*-type and *Juglans*, which represent this same vegetation belt, consistently contribute about 1–2% of the total flora. The relative high *Betula*, *Corylus* and NAP values (5–12%, 5–10% and 25–40%, respectively), the last of which includes anthropogenic indicators, suggest that agriculture may have occurred in cleared areas. Cereal values of over 2% suggest the presence of fields close to the site (Reille, 1991). The proportions of Poaceae, cereals and *Rumex acetosa*-type increase slightly in the upper part of this zone, whilst the actual end of LPAZ 1 is marked by a rapid decline in *Fagus* (from 40% at 171 cm to 21% at 166 cm).

4.1.2. LPAZ 2 (170–147 cm, 1315–1495 AD)

This zone is characterised by a gradual change in the degree of human impact. An initial phase, in which anthropogenic influences increase, is followed by a regeneration phase, indicated by the establishment of pioneer woodland. Consequently, two subzones (a and b) have been defined.

4.1.3. Subzone 2a (170–160 cm, 1315–1375 AD)

The above-mentioned beech decline is short lived and as it begins to recover, *Corylus* and *Alnus* also start to expand. A contemporaneous increase in the main human impact indicators suggests that former woodland areas were converted into farmland. The specific indicator taxa present imply that the clearings were probably used for both pastoral and arable purposes (see Fig. 4B). However, the postulated phase of intensified cultural impact lasted only for about 25 years (between approximately 1315 and 1340 AD). Thereafter, in rapid succession, the relative abundances of taxa indicative of arable farming (especially cereals), then pastures and meadows (*Plantago lanceolata* and wild grass pollen), and finally ruderal habitats (especially *Artemisia*) each undergo significant declines.

4.1.4. Subzone 2b (160–147 cm, 1375–1495 AD)

The initial part of this subzone corresponds to a slight expansion in *Fagus*. It is possible that this was a consequence of increased beech pollen production, resulting from the improved light availability in the now more open stands (Aaby, 1986). The peaks exhibited in the *Alnus*, *Betula* and *Corylus* curves, presumably indicate the abandonment of the cleared areas and the subsequent expansion of pioneer woodland. The overall frequency of human impact indicators, as a percentage of the total flora, reaches its minimum value at this time. However, these taxa begin to increase once more above 150 cm in response to declines in *Alnus* and *Corylus*. The described pattern may nevertheless indicate a significant, if temporary, reduction in anthropogenic pressure on the forest environment, which lasted approximately 125 years (1350–1475 AD). This corresponds to the period of general demographic decline and land abandonment that affected the whole Massif Central during the Hundred Years War and after the Black Death of 1348.

4.1.5. LPAZ 3 (147–100 cm, 1495–1670 AD)

The beginning of this zone is characterised by a steady decline in *Fagus* combined with a notable increase in herb pollen, the latter being closely related to human activity. This suggests that increasing anthropogenic influences prevented successful woodland regeneration. Beech values reach a minimum (mostly 10–15%) between 136 and 100 cm, such that although the proportion of *Quercus* increases only slightly during this interval, it nevertheless becomes the dominant taxon (20–25%). In contrast, this significant feature of the *Fagus* pollen curve does not substantial affect those of other taxa, indicating a consistent human influence. A short-lived *Fagus* maximum occurs between 1625 and 1635 AD (117–113 cm).

4.1.6. LPAZ 4 (100–50 cm, 1670–1830 AD)

The base of this LPAZ is defined by a sudden increase in *Fagus* values, from about 10% to 25%. In fact, this zone as a whole is characterised by notable fluctuations in the relative abundance of this species (in the order of 10–30%). The amount of *Abies* increases from less than 5% in previous zones to about 5–10% in LPAZ 4, indicating that fir had become a significant component of the surrounding forest at this time (Huntley and Birks, 1983). *Ulmus*, *Tilia* and *Fraxinus* became slightly more common, whereas *Carpinus*, *Castanea* and *Juglans* appear less frequently than in the preceding period. Gramineae, Cerealia and *Rumex acetosa*-type also seem less abundant, probably because of the higher proportions of *Fagus* and *Abies*.

4.1.7. LPAZ 5 (50–23 cm, 1830–1895 AD)

The transition to LPAZ 5 is indicated by declines in *Fagus* and *Abies*, coupled with an increase in NAP, particularly in indicators of human impact. This suggests another temporary decrease in the density of the canopy (between 1835 and 1870 AD), caused by intensified clearance and agricultural activities. The majority of this zone is, however, characterised by a distinct resurgence of *Fagus* and *Abies* and an associated fall in NAP. This feature corresponds to the general demographic decline and land abandonment experienced in the French Massif Central since the later part of the 19th century (Reille et al., 1992). Nevertheless, the end of LPAZ 5 is marked by another pronounced decline in *Fagus* and *Abies*.

4.1.8. LPAZ 6 (23–0 cm, 1895–1999 AD)

The uppermost pollen zone, which continues up to 1999, is characterised by a steep rise in *Pinus* and, somewhat later, a slight increase in *Picea*, reflecting reafforestation. Following declines in both *Fagus* and *Abies*, there is a corresponding increase in Poaceae, Cerealia, *Plantago lanceolata* and *Rumex acetosa*-type, suggesting another increase in the importance of arable and pastoral farming. However, correlation with the varve chronology indicates that the cultivation of Cannabaceae virtually ceases following the Second World War. Furthermore, the contemporaneous decrease in Cerealia pollen and disappearance of *Centaurea cyanus* suggest that grain cultivation also discontinued in the vicinity of Lake Pavin at this time. Meadows and pastures, on the other hand, remained an important feature in the landscape. During the second half of the 20th century, *Fraxinus* assumed a more important role (especially along the roads) achieving a maximum value of 4%. In about 1950, the first pollen grains of the synanthropic *Ambrosia*-type appear.

4.2. Pollen source area

The composition of, and variation in, pollen spectra depends on the complex interaction of a variety of factors, including the geographic setting of the lake, its sedimentary processes, the character of the various pollen source areas and their spatial relation to the site being investigated, in addition to the production and dispersal characteristics of the pollen grains themselves. In order to interpret reliably the patterns of floral change preserved in high-resolution fossil pollen records, it is essential to take into account the nature of the relationship between each vegetation source and its corresponding fossil pollen assemblage.

Both empirical studies (for example, Janssen, 1973; Jackson, 1990) and model simulations (Prentice, 1985, 1988; Sugita, 1993; Koff et al., 2000) have indicated that the size of a sedimentary basin strongly influences the way in which pollen records reflect vegetational cover. In essence, the influence of extra-local and regional components of the pollen assemblage will become more pronounced as the surface area of the sedimentary basin increases.

For a basin of any given size, the relevant pollen source area is defined as the area beyond which the correlation between pollen loading and distance-weighted plant abundance does not improve (Sugita, 1994; Sugita et al., 1999). In other words, beyond this zone vegetational variations have little influence on the character of the pollen assemblage accumulating in the lake. However, each individual taxon will have its own unique pollen source area, which is governed by its relative abundance (Sugita, 1994) and the production and dispersal characteristics of its pollen (Sugita, 1993; Koff et al., 2000). According to several authors (for example, Sugita, 1994; Van der Knaap and van Leeuwen, 1998; Koff et al., 2000), the predominant local pollen source is the vegetation within a few hundred metres of the lakeshore. The regional component, on the other hand, originates from plants growing between several hundred and several thousand metres from the study site.

The theoretical calculations of Sugita (1993, 1994) imply that a relatively large proportion of any pollen accumulating in a sedimentary basin the size of Lake Pavin (about 44 ha) will probably originate from distant sources. Pollen assemblages recovered from Lake Pavin, therefore, probably represent the integration of material from a large source area, corresponding to a variety of habitats and including pollen from taxa such as *Quercus*, *Carpinus*, *Ulmus*, *Tilia*, *Castanea*, *Juglans*, *Aesculus*, *Buxus* and *Vitis*. The presence in the studied core of *Ephedra*, *Olea* and *Pistacia* pollen, all of which must have originated from fully Mediterranean habitats, provides clear evidence of long-distance transport of pollen (see Drescher-Schneider, 1993).

Observations of modern vegetational communities suggest that *Fagus*, *Abies*, *Picea*, *Acer*, *Sambucus*, *Sorbus, Ribes, Calluna* and *Vaccinium* mainly contribute to the local fraction of the Lake Pavin pollen spectra. This derives predominantly from the closed forest belt that surrounds the lake (aerial dispersed and washed in from the steep slopes around the lake), which is characterised by taxa that produce relative heavy pollen grains (e.g. *Fagus*, *Abies* and *Picea*) and which must have a significant influence on the preserved pollen spectra. Taxa such as *Salix*, *Corylus*, *Fraxinus*, *Betula*, Gramineae, Cyperaceae, *Plantago lanceolata*, *Rumex* type, *Drypteris* type and *Pteridium aquilinum* contribute to both the local and regional components, whilst cereal pollen appears to change from being a rather local element to a regional one. In recent times, small numbers of pine trees, which are very good pollen producers that spread pollen over large distances, have become established close to the lake, such that *Pinus* is over-represented in the pollen diagram and contributes to the local and regional components.

4.3. Rapid Fagus fluctuations—human impact and/or climate variability?

The Lake Pavin pollen record clearly demonstrates the variable influence of human activities on landscape development during the last seven centuries. Comparison of this sequence with similar high-resolution pollen records from Switzerland (Van der Knaap et al., 2000) reveals a number of consistent features in the main pollen curves. In particular, it appears that the two regions have experienced similar land-use changes during the last two centuries. However, the gradual decline in *Fagus* and *Abies* preserved in the Swiss deposits is not evident in the Pavin record. In fact, the pollen sequence from Lake Pavin is characterised by several rapid fluctuations in these taxa, particularly in the case of *Fagus*. Questions therefore arise regarding the cause of such rapid fluctuations and why *Fagus* was repeatedly able to recover so promptly? In this context, since climatic variations and human activities leave similar signatures in pollen records, it is essential to discriminate between natural impacts, both on the landscape and on the terrestrial and aquatic vegetation, and those superimposed by anthropogenic activity.

Not including the period of variable *Fagus* values between 100 and 50 cm, in no less than five separate instances, the beech pollen curve exhibits an abrupt drop of at least 10%, in just 5–20 years, with no immediate corresponding recovery of the same magnitude (Fig. 6A, D, F, H and J). A similar, although more gradual, decrease in *Fagus* occurs over 120 years between 154 and 138 cm (Fig. 6C). Subsequently to declines A, H and J, there are clear peaks in the relative frequencies of taxa normally associated with anthropogenic activities. *Fagus* decline C is likewise accompanied by an increase in human impact indicators (Fig. 4B), whereas there appears to be no such anthropogenic signal following declines D and F. According to Sugita et al. (1997), such readily detectable changes in pollen percentages are probably the result of a disturbance patch significantly larger in area than the studied lake (at least eight times greater) located at, or near, the lake shore and produced by, for example, fire, wind falls or clear-felling. However, the limited amount of charcoal recovered from the Lake Pavin sequence, coupled with a lack of distinct *Pteridium aquilinum* spore peaks, provides no palaeobotanical indication for natural fires or slash-and-burn activities adjacent to the study site since the Late Medieval period. Extensive clear-felling or wind falls on the steep inner crater slopes also seem unlikely, since the

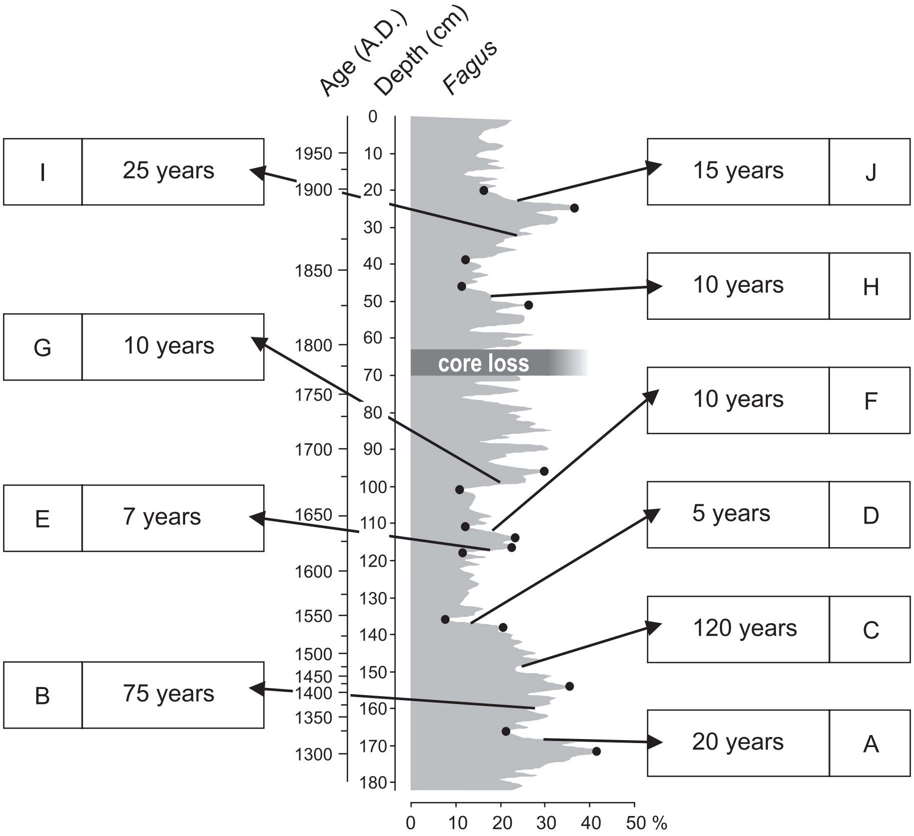

Fig. 6. Chronological characteristics of the *Fagus*-curve (see text).

geochemical record (publication of geochemical data in preparation) lacks any indication of erosional events that would undoubtedly follow such occurrences. The low frequency of pollen types indicative of felling activities (such as *Epilobium*, *Digitalis*, *Urtica*, *Calluna*, *Vaccinium* and *Juniperus*), combined with a lack of significant peaks in these taxa, further supports this interpretation. In conclusion, if the described declines in *Fagus* do indeed reflect anthropogenic interference, the above-described observations imply that such vegetational disturbance must have occurred outside the inner slopes of the crater.

Rapid increases in *Fagus*, comparable in duration and magnitude to the decreases described above, occur at several points in the Lake Pavin record (Fig. 6B, E, G and I). *Fagus* rise B lasts 75 years, during which time human impact indicators become gradually less important, being replaced by pioneer tree taxa (*Alnus*, *Betula*, *Corylus*). This succession clearly indicates the abandonment of farmland and the subsequent initial stages of woodland regeneration. However, the other *Fagus* rises (Fig. 6E, G and I) occur over much shorter periods (between 7 and 25 years) and lack an associated increase in pioneer trees and shrubs, suggesting that the expansion of *Fagus* was so rapid that it prohibited the development of such a succession. Consequently, since there is no clear evidence of tree population replacement, it seems likely that these rapid changes in the *Fagus* curve actually indicate variations in pollen production. This, in turn, implies that the relative abundance of beech pollen in the fossil record is directly influenced by climatic parameters.

According to Huntley et al. (1989), mean January and July temperatures of −1 and 18 °C, respectively, represent the optimum pollen production conditions for European *Fagus silvatica*. Pollen abundance values fall significantly with decreasing January temperatures (Huntley et al., 1989) and *F. silvatica* does not occur where the mean temperature of the coldest month is below −3 °C. Van der Knaap and van Leeuwen (2003) also conclude that mild winters favour the production of pollen in *Fagus*. Furthermore, Andersen (1980) uses recent studies to infer a correlation between the flowering intensity of *Fagus* and the average summer temperature of the preceding year.

Since the surface of Lake Pavin has usually frozen during the winter months in recent years (Schmid, 1997) and as the average January temperature only falls below −2° in higher areas of the Auvergne (Lang and Trautmann, 1961), average air temperatures during the coldest month at the elevation of the study site are between 0 and −2 °C. This implies that, in this area, unusually cold conditions will have an adverse affect on *Fagus* pollen production. Furthermore, the average temperature of the warmest month above 1000 m is between 10 and 15 °C (Lang and Trautmann, 1961), which is below the optimum summer temperature for pollen production in *Fagus*. Nevertheless, average temperatures do not tell the whole story. Growth and reproduction rates in trees are both primarily influenced by short-term variations in temperature, including extreme weather events (Jochimsen, 1986; Holtmeier, 1995; Litschauer, 2000). As demonstrated by recent studies, pollen production rates for an individual plant can vary enormously from year to year (e.g. Andersen, 1980; Jochimsen, 1986; Litschauer, 2000). Van der Knaap et al. (2001) have demonstrated that the type of weather a tree experiences in 1 year greatly influences the quantity of pollen it releases in the ensuing year. The higher the temporal resolution at which a fossil sequence is sampled, the less these annual fluctuations in pollen production will be smoothed out by the amalgamation of pollen produced over several years. Therefore, the period between 1670 and 1830 AD, which is characterised by variable *Fagus* values, seems to have been affected by unsettled climatic conditions.

The period of low frequencies as well as short-term fluctuations of *Fagus* covering more than 250 years from the middle of the 16th century to the middle of the 19th century represents what is commonly considered to be the main phase of the Little Ice Age, including its coldest episodes (e.g. Jones et al., 1998; Free and Robock, 1999; Pfister, 1999).

The youngest decrease of *Fagus*, at the beginning of the 20th century, also corresponds to a period that is generally characterised by colder climatic conditions, sun spot minima, and a lower total solar irradiance (Lean et al., 1995; Overpeck et al., 1997; National Geophysical Data Centre (NGDC)). This supports the hypothesis that the pollen production of *Fagus* at Lake Pavin is climatically controlled. However, during the last 170 years the influence of climate becomes less clear, probably because of strong human inference and the overrepresentation of *Pinus* pollen.

Van der Knaap and van Leeuwen (2003) propose that the relation between local pollen abundance and climate is relative simple, as it mainly concerns the pollen produced by a single stand. It is notable, therefore, that in contrast to the climate-induced variability apparent in the *Fagus* record, which represents the most prominent tree around Lake Pavin, none of the other pollen curves from the sequence exhibit such characteristics. Conversely, the regional component of the pollen record integrates a large area that includes a variety of habitats, each of which may respond differently (in terms of pollen production) to climatic perturbations than the biotopes adjacent to the study site.

4.4. Lake ecosystem responses to human and climatic interference

Whereas the interpretation of fossil pollen and spores enables the terrestrial vegetation at the time of deposition to be reconstructed, the diatom content of a sediment reflects the ecological changes that occurred in the aquatic environment itself. Many of environmental constraints that determine the composition of an algal assemblage are directly or indirectly related to climate. For example, the extent of snow and ice cover on a lake may have a profound influence on diatom habitat availability (i.e. Smol, 1983, 1988). Climatic changes can also affect lake circulation patterns and, therefore, influence nutrient recycling and their availability to diatoms. However, in lake ecosystems subjected to anthropogenic modification, such climate related signals may be obscured. Nevertheless, diatom assemblages preserve considerable palaeoecological information that can be used to support other palaeoenvironmental techniques, in order to differentiate between climatic- and anthropogenic-induced perturbations.

The sequence was sampled at a lower resolution for diatoms than for pollen. However, episodes in the pollen record characterised by the presence of human impact indicators coincide well with maximum diatom concentrations and the dominance of *Stephanodiscus parvus* [around 170 (1315 AD) and 140 cm (1540 AD); 50–23 cm (1830–1895 AD)]. As this species has an ecological preference for nutrient-rich waters (Bennion, 1994; Wunsam and Schmidt, 1995), anthropogenic deforestation and enhanced nutrient fluxes from enlarged pastures would improve its growing conditions.

In contrast, decreased diatom concentrations and high frequencies of *Cyclotella pseudostelligera*, which prefers low levels of nitrate, phosphate and silica (Rioual, 2000), suggest a period of reduced nutrient availability during LPAZ 2b (160–147 cm, 1375–1495 AD).

In high Arctic lake sediments, the ratio of planktonic to periphytic diatoms is indicative of the length of ice cover (Smol, 1988; Douglas et al., 1994; Douglas and Smol, 1999). The longer the ice cover, the shorter the growing season for the planktonic diatoms and the greater the relative abundance of littoral species. This relationship has also been proven in Siberian (Flower et al., 1998) and Alpine lakes (Lotter and Bigler, 2000), where lower concentrations of planktonic diatoms and higher frequencies of small periphytic *Fragilaria* species are recorded during the colder episodes of the Little Ice Age. At Lake Pavin, however, changes in the length of ice cover may produce only weak signals in the planktonic/periphytic ratio. The geomorphological characteristics of maar lakes restrict the extent of the littoral habitat and thus limit the development of distinct littoral diatom communities. Consequently, the slight increase in periphytic taxa (especially *Fragilaria brevistriata*) above 140 cm may be only tentatively interpreted as indicating an extended ice-cover duration.

The increasing importance of *Aulacoseira subarctica* from ca. 110 cm (1650 AD) onwards, a species that prefers low water temperatures (Stoermer and Ladewski, 1976; Rioual, 2000), may also be interpreted as indicative of relatively cold conditions. This species grows in late winter and early spring during overturn (Kilham et al., 1996) and is a strong competitor in low light conditions. It has been observed growing deep in the water column and persisting in the metalimnion during the summer (Interlandi et al., 1999). Kilham et al. (1986) hypothesised that the heavily silicified *Aulacoseira subarctica* may also indicate conditions of deep circulation and abundant silicon fluxes. Wind-induced water turbulence and the length of time that the lake surface is free of ice are probably the most important factors controlling *A. subarctica* growth.

5. Synthesis and conclusions

The current varve chronology indicates that the detailed palaeoecological record from Lake Pavin presented here covers the last 700 years. For the most part, the sequence reflects intensive human influence of the natural landscape close to the lake. However, climate may also have played an important role, as indicated by rapid fluctuations in the *Fagus* curve. The main conclusions are as follows:

(1) In the late 13th century, a succession of pioneer trees (*Betula*, *Alnus* and *Corylus*), combined with the presence of the climax tree species *Fagus*, suggests a local rearrangement of forest patches close to the lake.

(2) An abrupt drop in *Fagus* during the early 14th century suggests a clearance phase and/or a climatic deterioration. A contemporaneous increase in the main human impact indicators suggests that previously woodland areas were converted into farmland. However, the postulated phase of intensified cultural impact only lasted for about 25 years (between approximately 1315 and 1340 AD). This short-term event is also reflected by a temporary peak in diatom concentration values, which are dominated by the eutrophic taxon *Stephanodiscus parvus*.

(3) During the period between approximately 1350 and 1475 AD, the overall frequency of human impact indicators, as a percentage of the total pollen assemblage, reaches its minimum value. Simultaneously, increases in *Fagus*, *Betula*, *Alnus* and *Corylus* indicate that once cultivated

land reverted back to woodland, as human pressures were reduced. This feature corresponds to a general demographic decline and land abandonment phase that affected the whole Massif Central during the Hundred Years War and after the Black Death of 1348. The diatom flora also clearly reflects these changing environmental conditions, since decreasing diatom concentrations and a recurrence of the oligotrophic *Cyclotella pseudostelligera*, indicate reduced nutrient loadings in Lake Pavin.

(4) Rises in the main anthropogenic indicators (wild grasses, cereals, *Plantago lanceolata* and *Rumex*) between 1475 and 1540 AD indicate increased human impact, which prevented successful woodland regeneration. Since this period, no expansion of pioneer woodland can be recognised. Once again, this change in land-use affected the water quality of Lake Pavin, resulting in another peak in *Stephanodiscus parvus* and an overall increase in diatom concentrations.

(5) Whilst the anthropogenic indicators remain at about their previous levels between 1540 and 1670 AD, *Fagus* values fall to a minimum. During this interval, the initial drop in *Fagus* is estimated to have taken 15–20 years, with the subsequent increase having a similar duration. These rapid signals suggest that *Fagus* minima may represent differences in pollen production (possibly affected by colder winter temperatures) during the traditional maximum of the Little Ice Age. Colder or longer winters may also be indicated by the appearance of *Aulacoseira subartica.*

(6) The period between 1670 and 1830 AD is characterised by variable *Fagus* values, possibly affected by unsettled climatic conditions. However, Gramineae, Cerealia and *Rumex acetosa*-type seem less abundant, probably because of the higher proportions of *Fagus* and *Abies* pollen.

(7) Increases in cultural activity at around 1830 AD are observed both in the diatom and pollen records. Conversely, the lower abundances of anthropogenic indicators and the recovery of *Fagus* during the later part of the 19th century probably reflect the progressive demographic decline and land abandonment that occurred at this time. Increases in *Pinus* and *Picea* during the 20th century indicate the establishment of forestry plantations.

However, during the last 170 years the influence of climate becomes less clear, probably because of strong human inference and the overrepresentation of *Pinus*.

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