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Legacy of early anthropogenic effects on recent lake eutrophication (Lake Bénit, northern French Alps)

Manon Bajard[a,b,*], David Etienne[c], Sébastien Quinsac[c], Etienne Dambrine[c], Pierre Sabatier[b], Victor Frossard[c], Jérémie Gaillard[c], Anne-Lise Develle[b], Jérôme Poulenard[b], Fabien Arnaud[b], Jean-Marcel Dorioz[c]

[a] E.A. 6293 GeHCO, University of Tours, 37000 Tours, France
[b] Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, EDYTEM, 73000 Chambéry, France
[c] UMR INRA 42 CARRTEL, Université Savoie Mont Blanc, 73376 Le Bourget-du-Lac, France

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ABSTRACT

Mountain lakes are integrated sentinels of changes in the terrestrial environment, where these changes threaten the quality of the ecosystem services these lakes provide, including high biodiversity, economic and leisure activities. Few evidentiary records exist of the long-term relationships between human pressure and observed impacts. Multiproxy analyses of the Lake Bénit sediment sequence, including dating, grain-size, geochemistry, pollen, non-pollen palynomorphs and chironomid assemblage reconstructions, allowed reconstruction of past environmental evolution and lake trophic changes. Combined with soil analyses of the catchment, these data provide a record of the relationships between human activities and the lake-catchment ecosystem, and show the effect of inundation of the shore previously used as pasture. From 2100 to 1100 yrs cal. BP, the catchment was forested. During the Middle Ages, grazing deforested the catchment, triggering an increase in erosion and a change in sediment sources. The lake remained oligotrophic over most of the last millennia. The trophic state changed abruptly in the 20th century with intensification and multiplication of tourist activities in the catchment, *i.e.*, fishing, hiking, while pastoral activities decreased. The sudden eutrophication coincides with an artificial increase of the lake water level in AD 1964 to improve fishing activities. A release of phosphorus (P) from the flooded soils was observed, which may be responsible for the current eutrophication. One thousand years of grazing practices would have led to the observed P concentrations in the soils of the lake shore, transferred by the cattle to this area. Our study highlights the combined effects of past and recent activities on the current eutrophication process, and the legacy of both soils and early anthropogenic activities.

1. Introduction

Understanding the effects of past activities on both the current status/structure of an ecosystem and its functioning is challenging but necessary to ensure the sustainability of the “Earth critical zone” and restore damaged ecosystems (Reed-Andersen et al., 2000; Costanza et al., 2007; Arnaud et al., 2016; Dubois et al., 2018). Ecosystems of the critical zone (*i.e.*, where human societies develop at the interface between the atmosphere, hydrosphere, biosphere and geosphere), such as mountain lake environments, provide services for life (*e.g.*, food supply, climate regulation and the quality of water and recreation areas). The intense use of these services may disrupt their functioning and harm life.

Lacustrine ecosystems are very sensitive to environmental changes, especially in mountains and boreal areas where human activities and climate change appear to be key factors in the disruption of these ecosystems (Rogora et al., 2003; Brisset et al., 2013; Bajard et al., 2017a). Lakes are considered to be integrated sentinels of local and global environmental changes, as they accumulate both the direct effects of environmental forcing factors on the lake itself and those on its watershed (Carpenter et al., 2007; Williamson et al., 2008; Adrian et al., 2009; Schindler, 2009). The morphometric attributes (*e.g.*, shape, depth) of lakes, which determine their oxygenation, especially in benthic areas, are very sensitive to energy inputs (thermal regimes and runoff), and the inputs from the catchment are regulated by the same hydrodynamic processes. They control trophic states of lakes, especially

* Corresponding author at: E.A. 6293 GeHCO, University of Tours, 37000 Tours, France.
E-mail address: manon.bajard@univ-smb.fr (M. Bajard).

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through nutrients inputs. In this context, the littoral zone appears to be a key factor in the relationship between the effects on the catchment and those on the trophic web. The sensitivity of lakes to disruption is also the consequence of the hydrological characteristics of aquatic ecosystems, such as rapid overturn, mixing and resistance, as well as the adaptation of aquatic communities to modifications of their environment.

Eutrophication is one of the most important threat to freshwater ecosystems due to the degradation of water quality, and thus the quality of the entire ecosystem, due to the potential loss of habitats and biodiversity and other associated ecosystem services (Dudgeon et al., 2006; Davidson and Jeppesen, 2013). Eutrophication can be a natural process describing an increase in primary production as a result of an increase in nutrient inputs. This process occurs naturally with the gradual filling of lakes, ponds and other water reservoirs, or in the case of drying and lake level decrease, in response to climate change. Eutrophication can also result from excessive anthropic inputs of nutrients such as nitrogen (N) and phosphorus (P) which increase the primary production (Carpenter et al., 1995; Correll, 1998; Bennett et al., 2001; Jenny et al., 2013; Pinay et al., 2017) and so-called “human induced-eutrophication” or “cultural eutrophication” (Schindler, 2012). In lakes, eutrophication is almost always induced by an excess of phosphorous that is generally provided by an external load from the watershed (Schindler et al., 1995; Schindler, 2012) and often increases suddenly (*i.e.*, within a few years).

External loads causing eutrophication often result from human activities that modify the natural biogeochemical cycling of nutrients within lake watersheds and tend to increase the transfer from the watershed to the lake (*e.g.*, Vitousek, 1997; Smith et al., 1999). Agriculture, and even less extensive pastoral activities, are mainly associated with the redistribution of nutrients in soils. Grazing can produce strong heterogeneities in soil nutrients, concentrating N and P through droppings in small areas such as flat resting places, near water, or in milking places within a few centuries (Bennett et al., 2001; Jewell et al., 2007; Williams and Haynes, 1990). This change in the spatial pattern of soil nutrients can contribute to an increase in the fluxes transferred to surface waters if these enriched source areas are connected to surface waters. Pastoralism has been present for millennia in the Alps, from lowlands to subalpine areas, exerting long-term effects on ecosystems, such as changes in vegetation and soil (Giguet-Covex et al., 2014; Pini et al., 2017; Bajard et al., 2017b). Soils have a memory, *i.e.*, they recorded information of their evolution and land-use evolution, and can retain the impacts of past and present human activities which can be chronologically recorded in lake sediment archives through erosion (Mourier et al., 2010; Sabatier et al., 2014; Poulenard et al., 2015; Bajard et al., 2016). Erosion and, more generally, all modifications of external inputs to freshwater reservoirs, can result in changes in limnology. However, the interactions between past and recent environmental modifications (whether or not of anthropic origin) are more difficult to assess but necessary to understand the functioning of current environments. It is necessary to better understand the relationships between different pressures on lakeshores and ecosystem responses (Coops et al., 2003; Ostendorp et al., 2004; Dubois et al., 2018). In this context, we focus on the human impact on both lakeshore soils and lake trophic status; we especially focus on the link between human pressures that can last for several millennia (*e.g.*, agriculture) and have intensified over the 20th century (Vitousek, 1997; Steffen et al., 2015) and the development of eutrophication. To consider previous modifications of the environment, our approach required to study lake-catchment systems together on long time scales from a paleoenvironmental perspective.

Paleoenvironmental studies based on lake sediment archives allow us to reconstruct the evolutions of past landscapes and human activities and their consequences for soil erosion related to forest clearing and cattle or sheep grazing since the early Neolithic period in the French Alps (*e.g.*, Giguet-Covex et al., 2011, 2014, Arnaud et al., 2012, 2016; Brisset et al., 2012; Simonneau et al., 2013). Lake sediments allow us to reconstruct changes in the lake trophic status. The analysis of the geochemical P contents, of diatoms or chironomid assemblages from lake sediments is used as tracers of nutrient inputs and oxygenation.

We focused on Lake Bénit (1450 m a.s.l.), which is located in the subalpine belt in the western French pre-Alps and has been identified by a local limnological survey as a “lake to protect” (Druart et al., 1999) due to its eutrophication processes. The lake catchment includes both rocky slopes and pastures that are currently partly recolonized by trees (mainly spruce) and shrubs (*Rosa* sp.) The spot is highly frequented by hikers and anglers in summer. Therefore, a summer bar was established in CE 1952, and the water lake level was intentionally increased in CE 1964. These recent changes in anthropic pressures applied on the lake-catchment system have made this area an ideal location for our study to (i) reconstruct the past landscape evolution associated with human activities over the last millennia, (ii) identify the sources of sediments and erosion dynamics and (iii) understand the links between past and present human activities and the trophic state of the lake.

2. Material and methods

2.1. Study site

Lake Bénit (1450 m a.s.l.) is located in the western Alps in the Bargy massif and is part of Marnaz and Mont-Saxonnex villages. It is located between Annecy and Geneva on the left side of the Arve Valley (Fig. 1-A). The lake, which is of glacial origin, is delimited by a limestone cliff of Cretaceous age in the south that rises up to 2230 m a.s.l. and by a Würm moraine ridge in the west that rises up to 1570 m a.s.l. (Fig. 1-B). The surface area of the lake is 0.04 km^2, and its maximum depth reaches 8.7 m (Sesiano, 1993). The lake is fed by four springs flowing through the moraine and the base of the scree. It drains a catchment area of 0.9 km^2 (Druart et al., 1999). A flysch area composed of schists, sandstones and limestones of Nummulitic age crops out between the Cretaceous limestone cliff and the moraine ridge as gullies (Sesiano and Muller, 1986). The flysch area is a flat herbaceous zone that is accentuated and gullied upstream (Fig. 1-B–D). The lake is covered in ice every winter and protected from the sun by the cliff. The mean annual temperature of the village of Mont-Saxonnex is 7.6 °C and the annual precipitations is 1110 mm (climate-data.org). Snow covers the area during winter, and avalanches regularly go down the active scree. The east side of the catchment is forested, while the moraine ridge is partially forested and pastured (Fig. 1-C,D). A small bar was built next to the lake in 1952 and the lake level was increased by 2 m in 1964 to facilitate fishing activities (Fig. 2).

The temperatures of the lake range from 15 to 18 °C at the surface to 8–10 °C at the bottom in August (measured in 2013 and 2016) and from 0 °C at the surface to 4 °C at the bottom in spring (measured in March 2014 and April 2017). Lake mixing occurs when the water column overturns in the autumn when the surface cools, thus oxygenating the bottom (8 $mgO_2.L^{-1}$). The lake exhibits anoxia during most of the year (0 $mgO_2.L^{-1}$ in spring and summer at the bottom), and the oxycline can reach depths of 2 to 5 m (data from August 2013 and March 2014). The PO_4 concentrations range from 5 to 80 $\mu g.L^{-1}$, and a Secchi disk disappeared at a water depth of approximately 3 m, indicating that the bottom water exists in a mesotrophic to eutrophic state (Nürnberg, 1996; Wetzel, 2001).

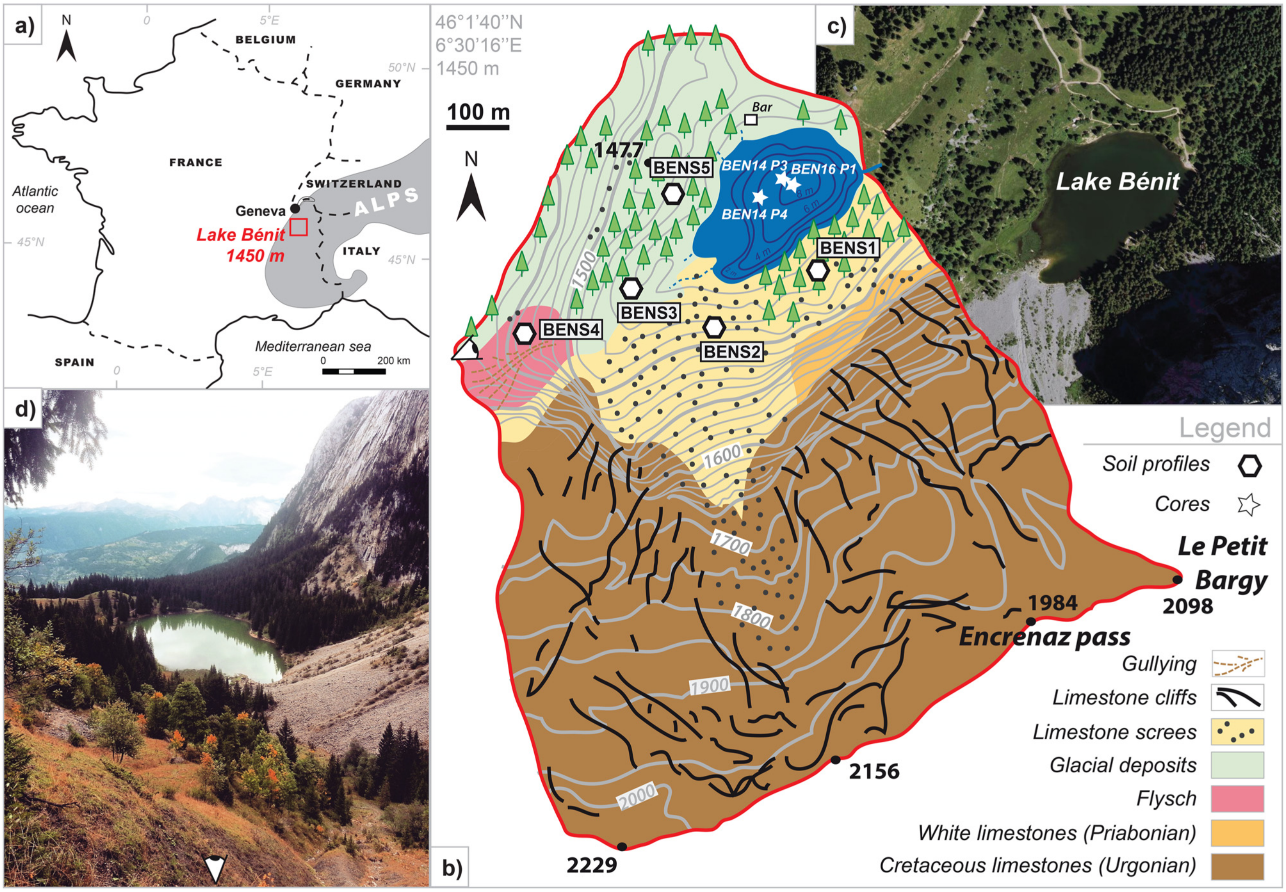

Fig. 1. Location of Lake Benit in the Western Alps a), simplified geological map of the catchment b), aerial photograph c) and view from the west side of the lake d). The bathymetry of the lake is adapted from Sesiano (1993).

2.2. Soil sampling

Four soil profiles (BENS1, BENS3, BENS4 and BENS5) were described and sampled based on their horizons (Figs. 1-B and 2). The latest fine flow of the limestone scree was also sampled (BENS2), as were the coarse elements of the flysch (BENS4-R). The FAO (Food and Agriculture Organization) soil classification (WRB - FAO, 2014) and the Guidelines for soil description (FAO, 2006) were used for horizon and soil denominations. Four transects, located perpendicular to the lake moraine shore (*i.e.*, glacial deposit in Fig. 1), were auger-sampled every 15 cm to 45 cm when possible, with three positions: out of the lake (A), in the current littoral zone (B) and in the lake (C, < 50 cm of water), corresponding to soils flooded by changes in water level (Fig. 3). The samples collected from soil profiles and transects were dried and sieved to a size of 2 mm for further laboratory analyses. The coarse elements from the flysch and the scree were crushed for geochemical analysis.

2.3. Sediment sequence and chronology

2.3.1. Coring

The first coring campaign performed in September 2014 allowed extracting four short gravity cores from the lake at depths of eight meters depth (BEN14-P1 – *IGSN no: IEFRA05HO*; BEN14-P2 - *IGSN no:* IEFRA05HP; BEN14-P3 - *IGSN no:* IEFRA05HQ) and 6 m (BEN14-P4 - *IGSN no:* IEFRA05HR - *IGSN codes refer to an open international database*, www.geosamples.org). The cores from the deepest part of the lake were 65 to 78 cm long, while the core at a depth of 6 m was 98 cm long. Thus, most of the analyses were performed on the longest core BEN14-P4, which was collected at a depth of 6 m. This core is considered to be the reference master core. A second coring campaign from the ice-covered surface in winter 2016 allowed us to retrieve one core, that was 165 cm long, at a depth of 8 m (BEN16-P1 - *IGSN in progress*). All cores were split lengthwise into two halves. Each half-section was described in detail, and pictures were taken with a resolution of 20 pixel. mm^{-1}. The lithological description of the cores allowed the identification of different sedimentary units. Correlations between cores BEN14-P4, BEN14-P3 and BEN16-P1 were performed using visual and XRF core scanner analyses (See SI-I).

2.3.2. Grain-size distribution

The grain-size distribution of the sediment was determined every centimeter using a Malvern Mastersizer 2000 G laser particle sizer after its organic matter (OM) was burned by hydrogen peroxide during a three-day period. Ultrasounds were used to dissociate mineral particles and to avoid their flocculation. Every 10 cm, several drops of a 0.5 N-HCl solution were added to assess the effect of decarbonatation on the grain-size. The results of the grain-size distribution were processed using MATLAB software and presented in a contour plot with a color scale based on the abundance of particles (in percentage) in each grain-size class (Fig. 4).

2.3.3. Analysis of pollen and non-pollen palynomorphs

A total of 26 subsamples of approximately 1 cm^3 were collected from the BEN14 P4 core for the analysis of pollen and Non-Pollen Palynomorphs (NPPs). After adding tablets of exotic spores (*Lycopodium clavatum*) (Stockmarr, 1971) to calculate concentrations of NPPs, subsamples were prepared chemically (HCl, NaOH,

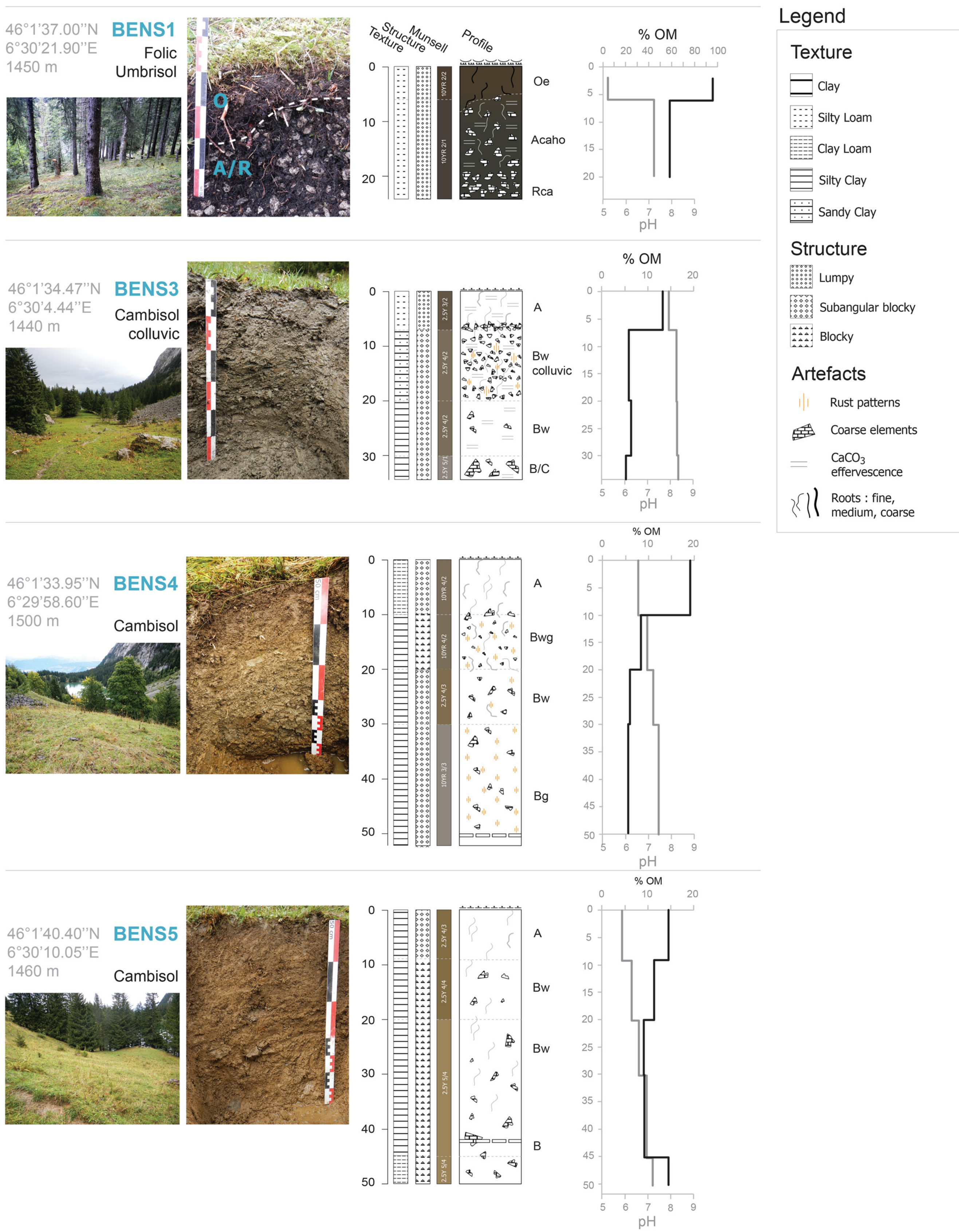

Fig. 2. Pedologic description of the soil profiles (texture, structure, color), including OM content (Loss On Ignition at 550 °C) and measured pH values. Horizons were defined using the WRB (FAO, 2014) and the Guidelines for soil description (FAO, 2006).

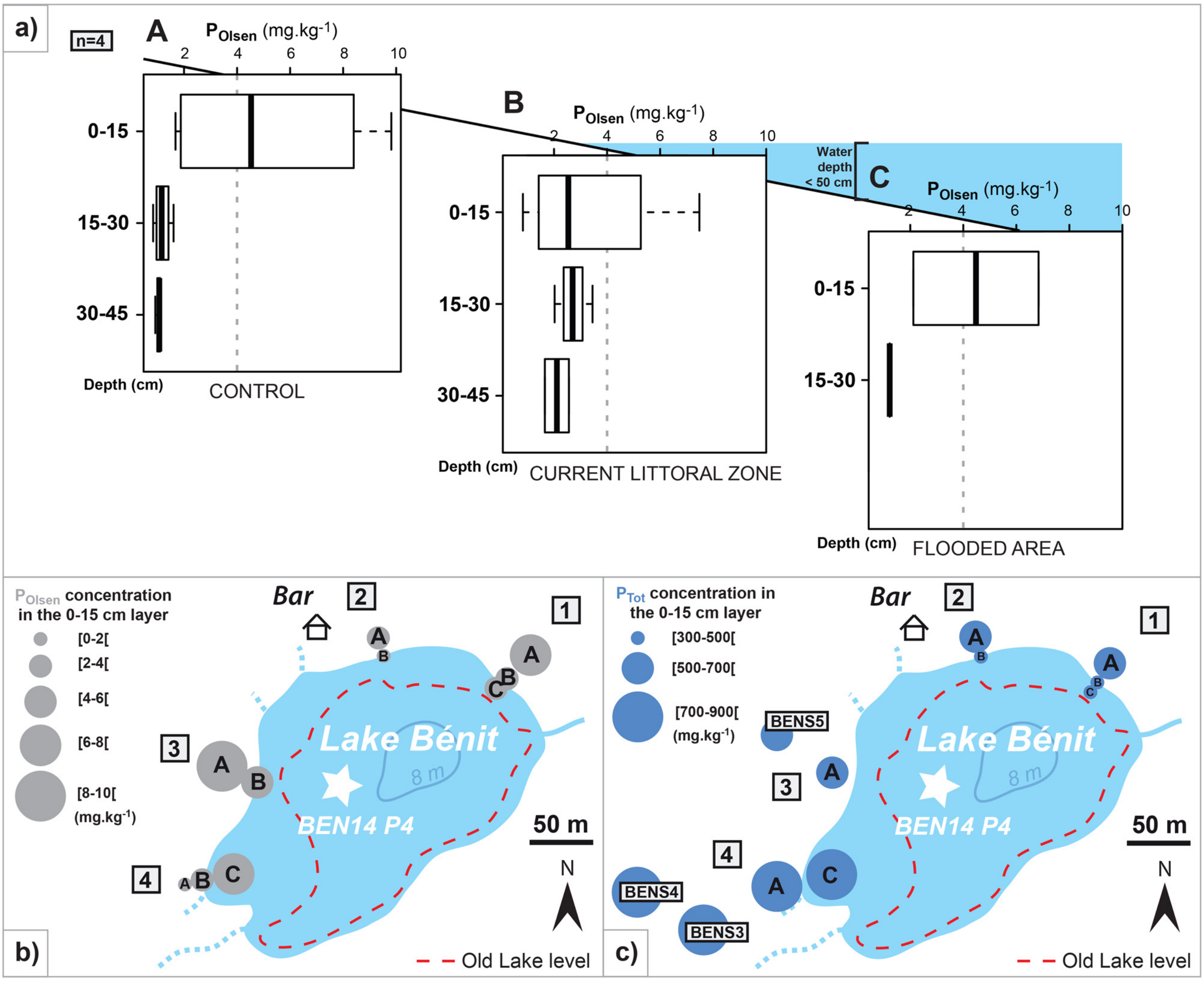

Fig. 3. a) Boxplot of available phosphorus (POlsen) distribution along the four transects on the Lake Bénit shore, out of the lake (A), in the current littoral zone (B), in the lake (C, < 50 cm of water) and according to depth. b) Distribution of POlsen concentrations around the lake in the surface samples (0–15 cm). c) Distribution of total phosphorus (PTot) concentrations around the lake in the surface samples (0–15 cm) and in the surface samples of BENS3, BENS4 and BENS5 soils.

HF, HCl and acetolysis) and physically (any material greater to 100 μm was removed by sieving) following the standard procedure of Faegri and Iversen (1989). At least 500 pollen grains of terrestrial plants (Total Land Pollen, TLP) were identified and counted in each sub-sample. Pollen identification was based on an identification key (Beug, 2004) and photograph book (Reille, 1992). Grass pollen grains greater than 40 lm in annulus diameter were classified as Cerealia-type to exclude wild grass species (Beug, 2004). Arboreal (AP) and Non-Arboreal Pollen (NAP) were expressed as percentages of the total land pollen sum (TLP) to reconstruct the vegetation dynamic in the catchment.

NPPs were counted in pollen slides following the procedure described by Etienne and Jouffroy-Bapicot (2014) and expressed in terms of concentration (spores. cm^{-3}) and accumulation rates (spores. cm^{-2}. $year^{-1}$). Among all of the NPPs identified, the strict coprophilous fungal ascospores *Sporormiella* sp. (HdV-113) and *Podospora* sp. (HdV-368) (Van Geel, 2002) were summed and used as an indicator of local variations in grazing pressure (Etienne et al., 2013; Doyen and Etienne, 2017).

2.3.4. Chironomid analysis

A total of 74 one-centimeter-thick samples were continuously sampled along the BEN14-P3 sediment core for chironomid analysis to identify ecological changes within the lake. Specifically, chironomid reconstruction allowed us to infer hypolimnetic oxygen conditions (Brodersen and Quinlan, 2006) as well as habitat availability (*e.g.*, Langdon et al., 2010). The samples were exposed for successive 2 h periods in HCl (10%) and KOH (10%) solutions at room temperature to dissolve carbonates and deflocculate OM, respectively. The residues were sieved through a non-standard 150-μm-mesh-size filter. Chironomid head capsules (HC) were handpicked from the sieving residue under a stereomicroscope at a 40 × magnification. The HC were then mounted on slides using Aquatex© (Merck, Darmstadt, Germany) mounting medium, and identification was performed under a compound microscope at 200–1000 × magnification. Identification was based on the guides of Brooks et al. (2007). Due to the use of a non-standard mesh size (150 μm instead of more commonly used - 100 μm), some bias might be present in our analysis and results were therefore interpreted accordingly.

2.3.5. Chronology

The chronology of the Lake Bénit sediment sequence is based on seven ^{14}C measurements performed on terrestrial plant macroremains, as well as short-lived radionuclide measurements (^{210}Pb and ^{137}Cs). AMS Radiocarbon dates were performed using an

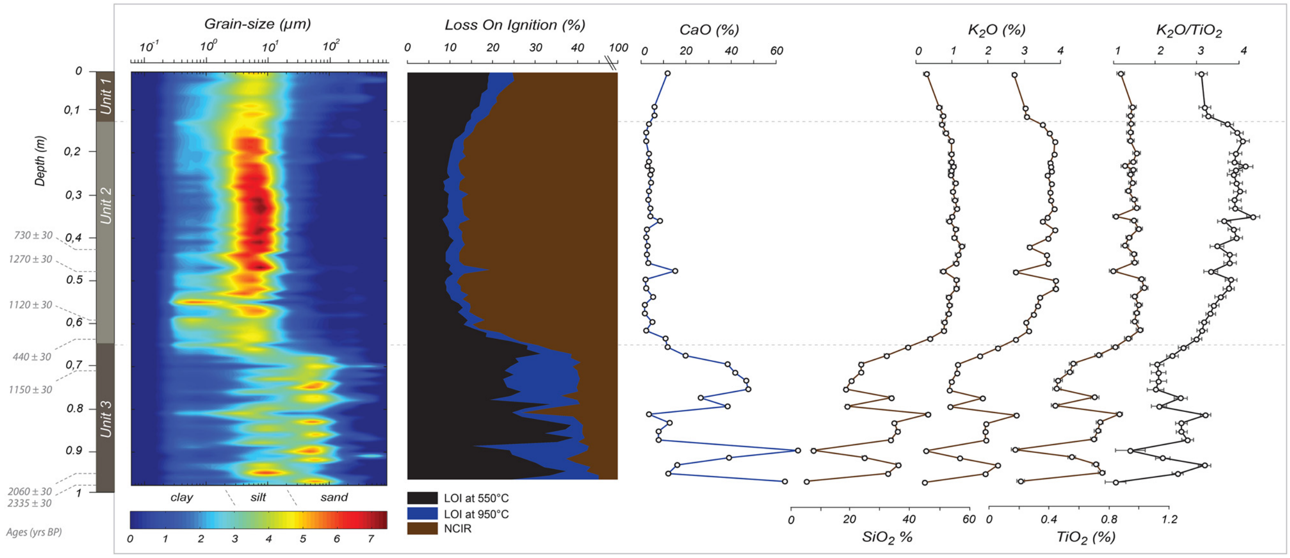

Fig. 4. Comparison of the downcore sediment grain-size data of Lake Bénit with loss on ignition at 550 °C and 950 °C, its NCIR (Non-Carbonate Ignition Residue) and the XRF geochemistry of major elements (CaO, SiO_2, K_2O, TiO_2 and K_2O/TiO_2). The color scale of the grain-size contour plot refers to the abundance (in percentage) of each grain-size class, with the less abundant in blue and the most abundant in red (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

accelerator mass spectrometer (AMS) at the Poznan Radiocarbon Laboratory and at the Beta Analytic Radiocarbon Dating Laboratory in London (Table 1). The ^{14}C ages were converted to 'calendar' years using the calibration curve IntCal13 (Reimer et al., 2013). Short-lived radionuclide measurements were performed at the Modane Underground Laboratory (LSM) on the uppermost sediments (Reyss et al., 1995) using a 2-cm sampling step. The age–depth model was then generated using R software and the R-code package 'Clam' version 2.2 (Blaauw, 2010).

2.4. Soil and sediment analysis

2.4.1. Loss on ignition

Loss on ignition (LOI) analyses were performed on all samples from soil transects and profiles, according to depth, to estimate the organic matter (OM) and carbonate contents following heating at 550 °C for 4 h and 950 °C for 2 h, respectively (Heiri et al., 2001). LOI analyses were also performed on sediment samples obtained using a continuous 1-cm sampling step along the entire sediment sequence, with the same heating parameters.

2.4.2. P-XRF mineral geochemistry

A portative ED-XRF (P-XRF) spectrometer (S1 TITAN Bruker) was used to measure the major element contents, which were expressed as relative percentages of oxides. The analyses of gently crushed soil samples (according to horizons), soil transect samples (every 15 cm according to depth), and sediment samples (every 2 cm) were performed through a 4-μm-thick Ultralene film in a 32-mm-diameter plastic cup. The samples were triplicated and analyzed over 60 s by using the internal calibration mode of the GeoChem Standard instrument (Shand and Wendler, 2014). The OM content that was deduced from the LOI at 550 °C was added to the sum of the major elements. Consequently, the elemental results were brought to 100% to overcome the closed sum effects that are linked to variations in OM (Baize, 2000). The standard deviations of the replicates were lower than the errors introduced by the instrument, which were thus used as conservative measurement uncertainties.

2.4.3. CNP analysis

The total organic carbon (C_{org}) and nitrogen contents of lake sediments were determined through combustion with an elemental CHN analyzer every 2 cm until reaching a depth of 22 cm and then every 3 cm below, on samples previously decarbonated with an acid solution. Then, the C/N ratio was calculated to determine the origin of OM. The total phosphorus concentration (P_{tot}) was measured in the surface horizons of the BENS3, BENS4 and BENS5 soils, in the 0-15-cm samples of shore-lake transects and in the sediment sequence after undergoing hot sodium hydroxide digestion. A labile fraction of total P (P_{olsen}) was extracted from soil transects, every 15 cm according to depth, and sediments according to the method of Olsen (1954) by mixing 1 g of sediment (or soil) with 20 ml of a 0.5 N-NaHCO3 solution, following the same sampling for sediment samples as used for C_{org} and N analyses. This

Table 1
Radiocarbon ages for the Lake Bénit sediment sequence.

Core name	Lab. Code	Depth (cm)	Sample type	Age (yrs BP)	Cal. Min (cal. BP)	Cal. Max (cal., BP)	Prob.
BEN14-P4	Poz-69616	42,0	Plant macroremains	730 ± 30	653	709	91,5
BEN14-P4	**Beta**-46357	**48,0**	**Plant macroremains**	**1270 ± 30**	**1173**	**1286**	**92.3**
BEN14-P4	Beta-462835	59,5	Wood, herbs	1120 ± 30	956	1086	91,8
BEN16-P1	**Poz**-81886	**63,5***	**Seed**	**440 ± 30**	**462**	**532**	**94,1**
BEN14-P4	Poz-69617	71,5	Bark	1150 ± 30	980	1150	86,8
BEN16-P1	Poz-81887	96,7*	Twigs, wood	2060 ± 30	1948	2116	95
BEN14-P4	**Poz**-69615	**98,0**	**Wood**	**2335 ± 30**	**2312**	**2436**	**95**

Bold samples correspond to dates excluded from age-depth modeling.
* XRF-correlated depth.

fraction can be considered to be representative of the bioavailable fraction of P, both in soils and sediments (Jordan-Meille et al., 1998). The spectrophotometric determination of P-PO4 in all extracts was carried out using the molybdenum blue method (Murphy and Riley, 1962) at 882 nm on a Cary® 50 UV–vis spectrometer (Agilent).

Photosynthetic pigments were extracted overnight using a solution of acetone and water (90:10) (76 samples collected at 1 to 2-cm sampling steps from the BEN14 P4 core). The resulting extracts were used to quantify the total carotenoids via a spectrophotometer following the recommendations of Guilizzoni et al. (2011). The carotenoid concentrations were expressed in mg per gram of sediment per year (TC in mg. g^{-1}.an^{-1}) as an indicator of the variation in the lacustrine primary production and then normalized by the organic matter content (mg. g^{-1} of OM) to reconstruct the past phosphorus concentration in the water column (TP_w in μg.L^{-1}) following the formula published by Guilizzoni et al. (2011).

2.5. Statistical analysis

Principal component analysis (PCA) was performed with the results of the geochemical analyses of the lake sediments and soil, soil transect and rock samples of the catchment, including the TiO_2, SiO_2, K_2O, Al_2O_3, CaO, Fe_2O_3 contents, K_2O/TiO_2, Al_2O_3/TiO_2 ratios and OM content. PCA was used to determine the origin of the sediment in the catchment (Sabatier et al., 2010). These analyses were performed using R 2.13.1 (R Development Core Team, 2011).

3. Results

3.1. Soil characterization

Two main soil types were identified in the Lake Bénit catchment based on their main evolutionary processes (*e.g.,* humification, decarbonatation and acidification), pH values and parent material. Folic Umbrisols develop on stabilized limestone screes on the right shore of the lake (BENS1), while Cambisols develop on flysch (BENS3 and BENS4) and on the moraine ridge (BENS5). BENS1 is characterized by a shallow depth (< 25 cm), a very high OM content (> 50%) and pH values ranging from 5 at the surface to 7 at the bottom (Fig. 2). Cambisols are deeper and mainly comprise silty clay and OM contents of less than 20% (Fig. 2). The pH of BENS3 is 8 and ranges with depth from 6.5 to 7.5 for BENS4 and from 6 to 7 for BENS5. The texture of BENS3 is coarser than those of the other Cambisols because it developed in the alluvial zone before the lake, downstream of the flysch gullies. BENS3 and BENS4 present some rust patterns (Fig. 2). The total phosphorus contents in the surface horizons of BENS, BENS4 and BENS5 are 895, 815 mg.kg^{-1} and 647 mg.kg^{-1}, respectively.

3.2. Distribution of phosphorus along the soil transects

In the soils around the lake, the P_{Olsen} concentrations range from 1.7 to 10 mg.kg^{-1} (5.1 mg.kg^{-1} on average) in the first 15 cm and remain lower than 2 mg.kg^{-1} below this depth (Fig. 3-aA). In the littoral zone, P_{Olsen} ranges from approximately 0.8 to 7.5 mg.kg^{-1} (3.4 mg.kg^{-1} on average) in the surface, from 2 to 3 mg.kg^{-1} between 15 and 30 cm and less than 3 mg.kg^{-1} below this depth (Fig. 3-aB). The P_{Olsen} concentrations range from 2 to 6.8 mg.kg^{-1} (4.5 mg.kg^{-1} on average) in the surface and remain very low until 30 cm in the flooded soils (Fig. 3-aC). The distribution of the bioavailable P concentration in the 0–15 cm layer decreases from the shore (A) to the lake (C), except in transect 4 (Fig. 3-b).

The concentrations of total phosphorus (P_{tot}) on the surface (0–15 cm) of the soil transects range from 360 to 808 mg.kg^{-1} (Fig. 3-c). The P_{tot} concentrations are higher in the soils that developed on the flysch area (> 700 mg.kg^{-1}) in the southwest region of the lake than those on the moraine ridge soils (< 700 mg.kg^{-1}), and they are much lower in the moraine flooded soils (< 500 mg.kg^{-1}).

3.3. Lithology and sediment analyses

Based on lithological descriptions and grain-size and LOI data, three sediment units were identified in BEN14-P4 (Fig. 4). Unit 3, which occurs between 98 and 65 cm, is very dark gray and presents an important sedimentary fraction between 20 and 100 μm, with limestone gravels that have been identified as dropstones. The sediment of Unit 2 (65 to 13 cm) is greenish-gray, with millimetric laminae. Unit 1 (top 13 cm) is very dark gray with a darker level appearing between 13 and 11 cm and very homogenous sediment in the first six centimeters. The grain sizes in Units 2 and 1 mainly range between 2 and 10 μm but are more dispersed in Unit 1 (Fig. 4). The LOI at 550 °C range from 15 to 35%, 8 to 15%, and 14 to 19% in Units 3, 2 and 1, respectively (Fig. 4). The LOI at 950 °C range from 2 to 21% in Unit 3 and remains less than 6% in Units 1 and 2. The CaO content shows the same trend as the LOI 950 °C, with higher variability in Unit 3 and very low contents in Units 2 and 1. The contents of SiO_2, K_2O and TiO_2, as well as K_2O/TiO_2 ratio present the same variations as the NCIR of LOI, with lower contents and higher variability in Unit 3 and higher but less variable contents in Units 2 and 1 (Fig. 4).

3.4. Age-depth model

The measurement of short-lived radionuclides allowed the dating of the upper 19 cm of the core (Appleby and Oldfield, 1978). A logarithmic plot of ^{210}Pbex activities (Fig. 5-a) according to mass-depth shows stable values for the upper 8 cm followed by a linear decrease (Fig. 5-a). According to the 'constant flux, constant sedimentation rate' (CFCS) model (Goldberg, 1963; Krishnaswamy et al., 1971), the $^{210}Pb_{ex}$ activities indicate a mean accumulation rate of 2 mg.cm^{-3}.yr^{-1} between 19 and 6 cm and very fast sediment deposition for the first 6 cm with almost constant $^{210}Pb_{ex}$ activities. If we use this accumulation rate (70 mg.cm^{-3}.yr^{-1}), the first 6 cm represent 2 years. The ^{137}Cs activity profile (Fig. 5-a) shows a first peak at a depth of 13 ± 1 cm and another one at 9 ± 1 cm; these peaks are interpreted to reflect the maximum atmospheric production of ^{137}Cs in 1963 (nuclear tests) and the Chernobyl accident in 1986 (Appleby et al., 1991), respectively. The beginning of the first ^{137}Cs activity peak could correspond to the first fallout of ^{137}Cs related to nuclear weapons tests dated to CE 1955 in the Northern Hemisphere. Considering the ^{137}Cs peaks in 1986 and 1963, the sedimentation rate determined from the extrapolation of $^{210}Pb_{ex}$ activity to the top of the core does not agree with the coring year (2014). Both visual observations and the ^{137}Cs and $^{210}Pb_{ex}$ activities of the first six centimeters of sediment indicate the strong homogeneity of the sediment that could be an artefact out of the continuous sedimentation. This hypothesis is supported by the comparison with the other cores, where these 6 cm are not recorded (Fig. 5-b). A problem during the coring could have occurred, if the tube had touched the bottom of the lake and bounced before the real coring started. Slumps are also common in lake sedimentary deposits, especially on the shores of lakes. Erosion of the shores could also have bring punctual clods of soil and sediments. Thus, the first 6 cm of BEN14-P4 were not considered in the subsequent analyses. Following this correction, the artificial radionuclide peaks and ages derived from the 210Pbex-CFCS model show good agreement and provide an accurate and continuous age–depth relationship over this part of the sediment sequence. These data were then incorporated into Clam to generate an age–depth model of the entire core (Fig. 5-b).

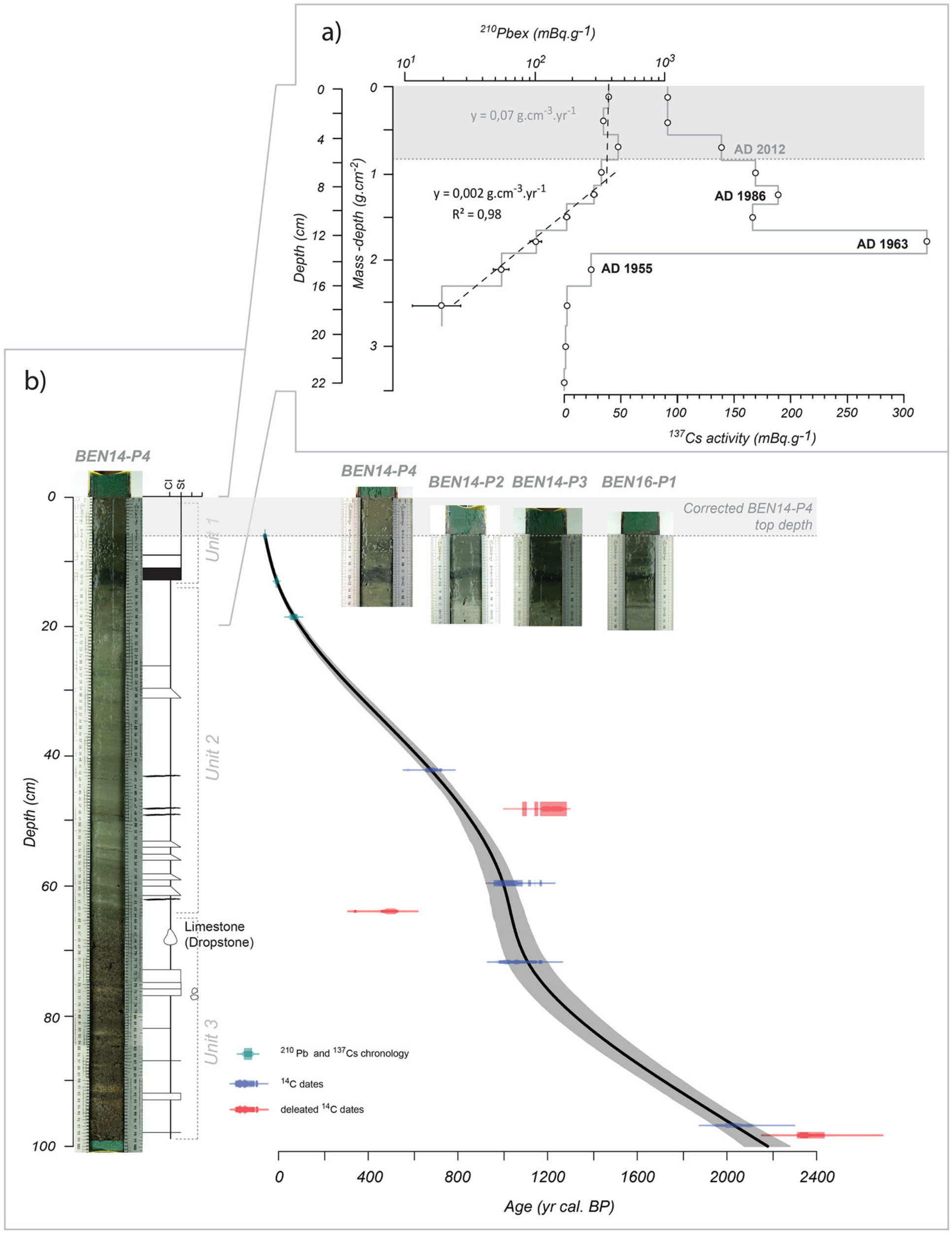

Fig. 5. Age-depth model of the Lake Benit sedimentary sequence including 210Pb/137Cs chronology (a) and 14C ages (b). Uncertainties are included in the 137Cs activity dots. The top core of BEN14-P4 was corrected for its first 6 cm to fit with the 210Pb/137Cs chronology.

A total of 7 radiocarbon ages were obtained from the selected macroremains collected from the BEN14-P4 and BEN16-P1 cores (Table 1). Three radiocarbon dates were excluded from the age–depth model (bold in Table 1). The Poz-69615 and Poz-81887 samples were too close to each other in terms of both depth and age. Thus, the older sample (Poz-69615) was removed from the age-depth modeling. The Poz-81886 sample, which was dated at 440 yrs BP appears too young compared to the other dates below (1150 yrs BP) and above (1120 yrs BP) it. Thus, it was also removed. The sample Beta-463577, which was dated to 1270 yrs BP, is slightly older than the Beta-462835 and Poz-69617 samples that overlie it. Beta-463577 was probably reworked and has also been removed from the age–depth model. The model was computed with Clam using a smooth relationship (Blaauw, 2010).

The age–depth model shows two major increase in the sedimentation rate, namely, one in the Middle Ages and one in the last century (Fig. 5-b). Unit 3 spans the period of 2100-1000 yrs cal. BP, with a mean sedimentation rate of 0.25 mm.yr^{-1} until 1200 cal. BP. Unit 2 covers the period between 1000 and 100 yrs cal. BP. Unit 2 exhibits a change in the sedimentation rate at its base, where it increases to 1.5 mm.yr^{-1}. Then, it decreases from 1.5 to 0.35 mm.yr^{-1} and finally increases again after 400 yrs cal. BP, mainly over Unit 1, until reaching its present day value of 1.6 mm.yr^{-1}.

3.5. Quantification of pollens and NPPs

The pollen percentages are dominated by arboreal pollens (AP) between 2100 and 1000 yrs cal. BP, with an average value of 80% of AP (Fig. 6-g). The percentages of non-arboreal pollens (NAP) increase from 1070 to 970 yrs cal. BP to reach an average value of 50% between 970 yrs cal. BP and CE 1970. The NAP percentage reached a maximum of 65% at 200 yrs cal. BP and slightly decreased during the last century (Fig. 6-g).

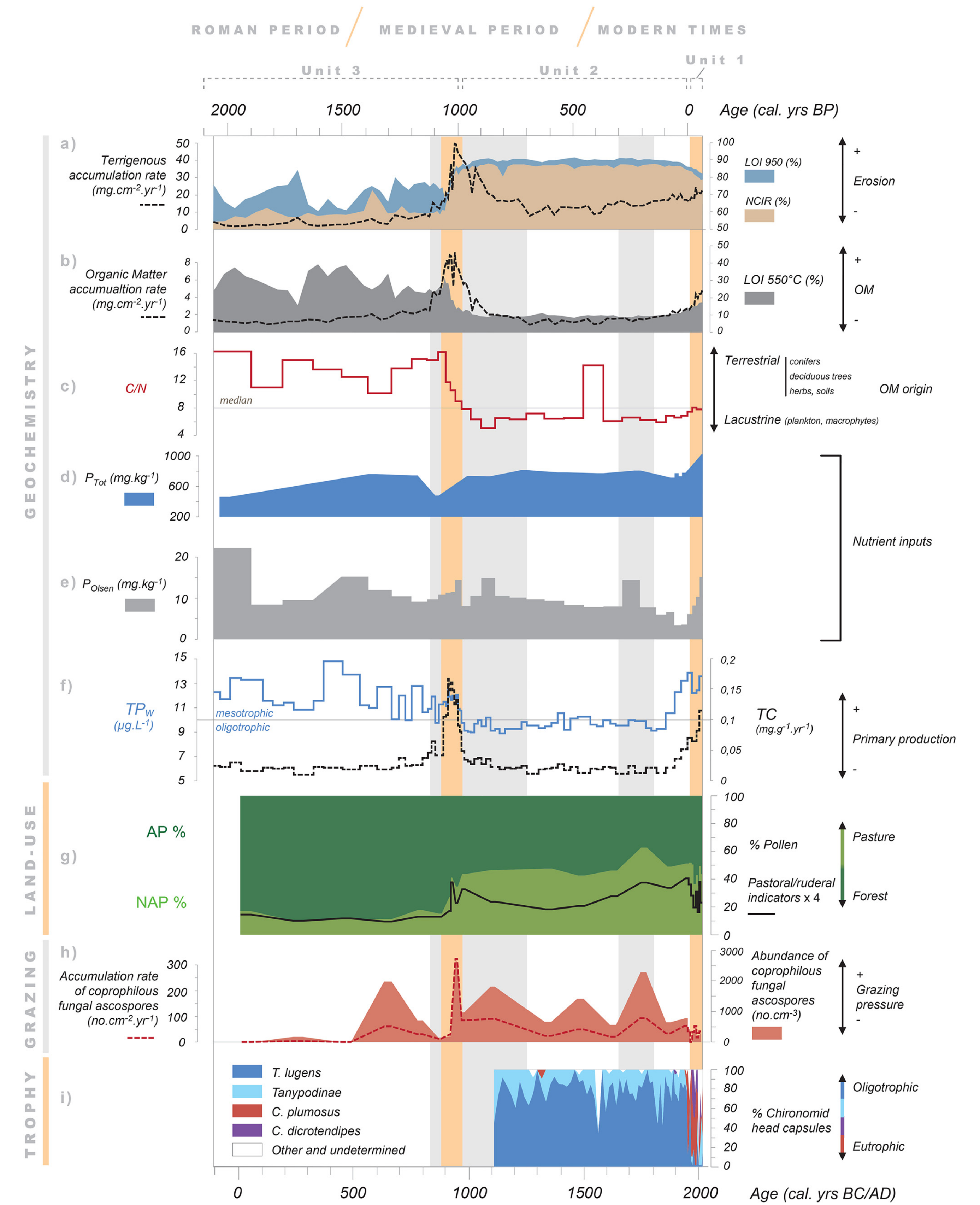

Fig. 6. Comparison of the geochemistry - LOI **a)**, **b)** and C/N ratio **c)**, total and available P analysis **d)**, **e)** - of Lake Benit sediment core with total P in water (TPw) infered from total carotenoids (TC) **f)**, land-use evolution (pollen analysis **g)**), grazing activity (NPPs analysis **h)**) and the trophy of the lake (chironomid analysis **i)**). NAP = non-arboreal pollen, AP = arboreal pollen. The pastoral/ruderal indicator curve includes *Plantago lanceolata*, *P. major/media*, *P. alpina*, Plantago sp., *Urticaceae*, *Rumex acetosa/acetosella*, *Artemisia*, *Chenopodiaceae*, *Centaurea cyanus*, *Papaver* and is exaggerated x4. Dotted lines represent accumulation rates.

The concentration of strict coprophilous fungal ascospores is low (under 12 spores. g^{-1}) from 2100 to 1040 yrs cal. BP (Fig. 6-h). It increases at 1070 yrs cal. BP and reaches a maximum during the Middle Ages (66 spores. g^{-1}). This concentration remains high (40 spores. g^{-1} on average) from 1070 to 200 yrs cal. BP, decreases after 200 yrs cal. BP and has remained below 20 during the last 50 years. The accumulation rates of fecal fungal spores are high during the Middle Ages (327 spores. $cm^{-2}.yr^{-1}$) and ranged otherwise from 0 to 94 spores. $cm^{-2}.yr^{-1}$, reaching maximum values at 1300, 900 and 200 yrs cal. BP (Fig. 6-h).

3.6. Chironomid identification

Among the 15 chironomid taxa identified in the sediment samples, four of them represented more than 95% of the total counts, namely, *Tanytarsus lugens, Chironomus plumosus, Dicrotendipes* sp. and Tanypodinae. *T. lugens* dominated the chironomid assemblages in association with Tanypodinae over most of the studied time period with rather stable relative abundances (Fig. 6-i). A drastic change occurred ca CE 1950, when the relative abundances of *T. lugens* and Tanypodinae decreased; these were replaced by *C. plumosus* and *Dicrotendipes*, with *C. plumosus* representing the new dominant taxa (Fig. 6-i).

3.7. Mineral and organic geochemistry

The C/N ratio ranges from 10 to 16.5 from 2100 to 1070 yrs cal. BP and decreases until 900 yrs cal. BP (Fig. 6-c). It remains below 8 after 970 yrs cal. BP, except at 400 yrs cal. BP (14.4). The total P concentration tends to slightly increase throughout the last 2100 years, with average values of 613 $mg.kg^{-1}$ before 1000 yrs cal. BP and 766 $mg.kg^{-1}$ from 1000 yrs cal. BP to CE 1950, and it reaches 1020 $mg.kg^{-1}$ at the top of the core (Fig. 6-d). The P_{Olsen} concentration ranges from 3.7 to 22.5 mg. kg^{-1} over the last 2000 yrs (Fig. 6-e). The average concentration from 2000 to 900 yrs cal. BP is 12 $mg.kg^{-1}$. It decreases after 900 yrs cal. BP until reaching 3.7 $mg.kg^{-1}$, except at 250 yrs cal. BP (14.7 $mg.kg^{-1}$). Then, the P_{Olsen} concentration increases from CE 1961 yrs to the present (15.4 $mg.kg^{-1}$). The accumulation rate of total carotenoids (TC) is constant from 2100 to 1200 yrs cal. BP exhibits a mean value of 0.02 $mg.g^{-1}.yr^{-1}$ (Fig. 6-f). TC increases from 1200 yrs cal. BP, with a significant peak between 1063 to 984 yrs cal. BP reaching up to 0.17 mg. $g^{-1}.yr^{-1}$. The accumulation rate then decreases and stabilizes in the same order of magnitude as was observed before 1200 yrs cal. BP with an average value of 0.02 $mg.g^{-1}.yr^{-1}$. After 95 yrs cal. BP, it increases again and reaches a new maximum in the last decade of 0.12 $mg.g^{-1}.yr^{-1}$. The inferred total P in water (TP_w) displays the highest concentrations (10 to 15 $\mu g.L^{-1}$) and exhibits high variability between 2100 and 984 yrs cal. BP (Fig. 6-f). From 984 to 95 yrs cal. BP, the TP_w concentration remains stable, with an average value of 9.5 $\mu g.L^{-1}$, and it increases over the last 150 yrs up to 14 $\mu g.L^{-1}$.

3.8. Geochemical endmembers

The first two dimensions of the PCA (Dim 1 and Dim 2) explain 86% of the variability in the geochemical data of the sampled soils, rocks and sediments (Fig. 7). The PCA correlation circle shows three main endmembers (Fig. 7-a). The first one is positively correlated to the first component and yields high positive loadings for SiO_2, TiO_2, Fe_2O_3, Al_2O_3, Al_2O_3/TiO_2 and K_2O, thus representing terrigenous materials. This endmember can be divided into two parts: one is K_2O positive on dimension 2, and the other is SiO_2 and TiO_2 negative on Dim 2. The other two endmembers, yielded by CaO and OM, respectively, present negative loadings on Dim 1. CaO is positively correlated to dimension 2, and OM is negatively correlated to dimension 2. The sample map was colored based on the age of sediment and the origins of the soil and rock samples (Fig. 7-b). The soil profiles are well individualized. BENS1 is related to the organic pool, BENS5 is related to TiO_2 and SiO_2, and BENS3 and BENS4 are more closely related to the potassium-enriched part of the terrigenous endmembers. The rocks from the limestone scree are related to CaO, and the rocks from the flysch are closer to the potassium-enriched part of the terrigenous endmembers, between BENS3 and BENS4. The chemical signature of the soil transect sample on the shore of the lake (A position) is the same as that of BENS5 (Fig. 7-b). B position samples are more dispersed throughout the terrigenous endmembers. C position samples are close to the most recent sediment samples, which are correlated to Dim 1. Sediments between 2000 and 1000 yrs cal. BP are distributed between the CaO endmembers and the siliceous part of the terrigenous endmembers (Fig. 7-b). Sediments between 1000 and 0 yrs cal. BP in age are mainly attached to the potassium part of the terrigenous endmembers.

4. Discussion

4.1. Origins of the sediments

4.1.1. Mineral fraction

The coarse carbonated fraction (from fine sand to centimeter-scale dropstones) of the sediment suggests that snow avalanches from the limestone scree go down to the frozen lake in winter, carrying carbonated materials (Fig. 4 and SI-II). The ice begins to melt from the lake shores at the end of spring, creating ice patches moving on the lake surface that then melt and deposit the material at the bottom of the lake. The PCA highlights the two main sources of sediment which correspond to the limestone scree (from which the coarse carbonated fraction originates) and to the flysch area (Fig. 7-b). The composition of the moraine ridge is heterogenous, mixing allochthone glacial deposits and autochthonous materials from the limestone and the flysch (Sesiano and Muller, 1986). Therefore, the corresponding parent material was not included in the sampling strategy. However, this glacial formation is well characterized by its soils (*i.e.*, BENS5, and shore transects 1,2 and 3), as shown in the PCA (Fig. 7-b) and by the total P concentrations of surface soils, higher in the flysch area than they are in the moraine ridge (Fig. 3-c). The sediments from 2000 to 1000 yrs cal. BP appear to have originated from the input of both limestone scree and soils that developed on the moraine ridge, while sediments of the last millennia appear to be mainly derived from the flysch area. Compared to the flysch area, the soils of the moraine ridge seem to participate minorly in the mineral lake inputs, while its surface in the catchment is higher and highlights the more important erodibility of soils that formed on the flysch, over the last millennia, as reflected by the current gullies upstream. The most important erodibility of the flysch material also explains the glacial over-deepening that formed the lake in this region (Sesiano and Muller, 1986). The contribution of the flysch to the sediments from 2000 to 1000 yrs cal. BP is not visible, perhaps due to the degree of weathering of soils before 1000 yrs cal. BP. Soils may have evolved since the glacial retreat, *i.e.*, approximately upper Dryas (11.8 ka cal. BP) and Preboreal (12.7 ka cal. BP) ages (Sesiano and Muller, 1986). It is thus possible that the long-term evolution of soils on the flysch material led to soil with geochemical signatures close to those of the moraine ridge. Then, they were disrupted and rejuvenated by deforestation and agropastoral activities in the Middle-Ages, increasing their potassium contents (Bajard et al., 2017a). The difference between BENS3 and BENS4 tends to confirm this hypothesis. BENS4, which is located upstream of BENS3, is more weathered and depleted in exchangeable bases (*i.e.*, K^+ and Ca^{2+}), as reflected by its position in the PCA, where it is closer to BENS5 and SiO_2 than K_2O and CaO as BENS3 is (Fig. 7-a). Furthermore, we can note the completely distinct geochemistry of the Umbrisol (BENS1) that developed on the stabilized limestone scree in the southern region of the catchment (Figs. 2 and 7). Because of their highly

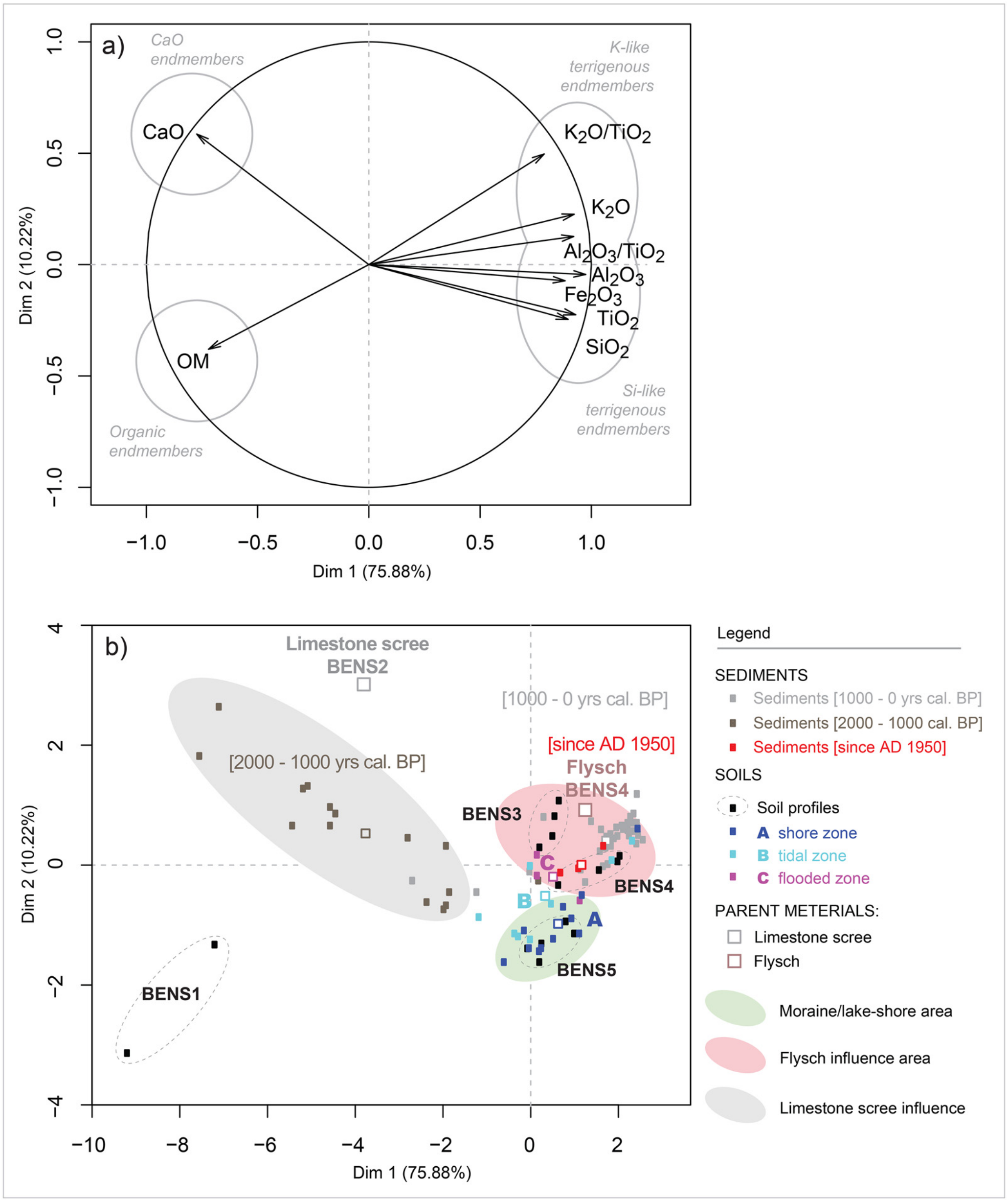

Fig. 7. Identification of sediment sources to Lake Benit with PCA analysis including geochemistry of sediment core samples, soil samples (BENS soil profiles and A-B-C shore transects) and rocks sampled in the limestone scree and in the flysch. PCA allows the identification of the sediment sources to Lake Bénit. a) Correlation circle. b) map of individual samples colored by ages for sediment and origin of soil samples and rocks.

organic nature, these thick soils are rarely enhanced for agricultural purposes and their contribution to erosion is low (Bajard et al., 2017a).

4.1.2. Organic matter

The variations in the C/N ratio are used to determine changes in the origin of OM and reflect local erosion processes and lacustrine productivity (Kaushal and Binford, 1999; Lerman et al., 1995). The algal organic matter produced in lakes has lower C/N ratios (< 10) than vascular plants (> 20) because vascular plants contain cellulose and lignin (Meyers, 1994; Lerman et al., 1995; Tyson, 2012). Among vascular plants, arboreal woody plants that have more lignin than herbs also have higher C/N ratios (*e.g.*, 40–45 for beech leaf, 65 for conifers). However, their degradation leads to lower C/N ratios (*e.g.*, litter), which is also true for aquatic plants (Tyson, 2012). Thus, the C/N ratios in soils range from 8 in the most active layer (*e.g.*, in meadows or active forest litters) to 40 in the lowest active layers, *e.g.*, under coniferous forest (Duchaufour, 1970). The interpretation of changes in the C/N ratio must be considered based on their different sources, *i.e.*, terrestrial and aquatic, as well as other proxies (*e.g.*, erosion and land-use) because of possibly contrasting processes leading to these C/N values (Enters et al., 2006). In the Lake Bénit sediments, the low OM accumulation rate associated with the to high C/N ratio is interpreted to reflect an aquatic OM source, while a low C/N ratio represents the input of terrestrial OM (Fig. 6-b-c).

4.2. Evolution of the landscape and human activities of Lake Bénit over the last 2100 yrs

4.2.1. From 2100 to 1100 yrs cal. BP (150 BCE to CE 850): an undisturbed forested system

From 2100 to 1100 yrs cal. BP, erosion was low and the proportion of tree pollens (Fig. 6-a-g), mainly spruce, alder and beech, was high, thus indicating a forested area. The high C/N ratio indicates inputs of arboreal organic matter and confirms that a forested landscape existed around the lake (Figs. 6-c and 8 -a). Although terrigenous inputs to the lake came from the limestone scree during avalanches and from the runoff on the slopes around the lake, they mainly came from the moraine area that covers the main part of the lakeshore (Fig. 7). The very low abundances of coprophilous fungal spores and pastoral pollen indicators indicate the lack of or low grazing activity in the catchment, which is unusual for a subalpine area in this region and during this period. The main deforestation activities for livestock grazing began during the Neolithic (ca. 7500-4500 BP) and increased during the Bronze Age (ca. 4500-3000 BP) and the Roman period (ca. 2500-1500 BP) (Giguet-Covex et al., 2014; Valese et al., 2014; Bajard et al., 2016; Pini et al., 2017). The geographic impossibility of moving cattle up to pastures higher than 1600 m to follow the grass growth may not have increased interest in this pasture area during the Roman period, while other surrounding mountains offered the possibility for pasture due to their longer exposure to sun. During this period, the concentration of total P in water inferred from the total carotenoid concentrations suggests the lake was in a mesotrophic state.

4.2.2. From 1100 to 0 yrs cal. BP (CE 850–1950): opening of the environment and development of grazing activities

Between 1100 and 1000 yrs cal. BP, erosion increased from 10 to 50 mg.cm^{-2}.yr^{-1} and reached its maximum throughout the last 2000 years (Fig. 6-a). During the 9th century, the proportion of AP percentages decreased sharply to the benefit of ruderal plants, suggesting a quick change in the composition of local vegetation, which is supported by the decrease in the C/N ratio. The catchment was deforested and used as a pasture area with the development of grazing activities, as suggested by both the strict coprophilous fungal ascospore concentrations and accumulation rates (Figs. 6-h and 8 -b). The late development of human activities in the Lake Benit catchment may be due to the increase in demography in the Middle Ages in the French Alps. This increase would have trigger higher needs in pasture and wood to sustain the development of societies.

As indicated by the PCA (Fig. 7), the mineral inputs changed, with the disappearance of the coarse carbonated fraction from the limestone scree and the destabilization of the flysch area due to grazing. The causes of the lower carbonate inputs are not completely understood. It first suggests a decrease (or a stop) of the avalanche episodes that cannot be explained by climate variability since the Middle Ages. There is no variability in the carbonate content corresponding to a warmer climate in the medieval period and to a colder climate in the following Little Ice Age. Moreover, the deforestation of the catchment would have led to an increase in avalanches, unless the deforestation led to other avalanche conditions, such as smaller but much more regular avalanches that brought fewer coarse materials into the frozen lake. The stabilization of the scree is also possible, but its synchronization with the change in landscape remains obscure. The more important contribution of the flysch area after 1000 yrs cal. BP is explained by the increased erodibility of this formation to runoff compared to the moraine ridge, which was emphasized by grazing and easily formed gullies on the deepest slopes. Furthermore, the position of the flysch formation on a flat area represents an ideal place for cattle grazing and could have accentuated erosion.

Erosion decreases after 1000 yrs cal. BP during the Middle Ages and stabilizes after 700 yrs cal. BP during the late Middle Ages to a higher level than was observed before 1100 yrs cal. BP (Fig. 6-a). The nature of the inputs is also stabilized until CE 1900, as shown by the constant concentrations of most of the geochemical proxies (*i.e.*, LOI, C/N ratio, total and available P). However, the accumulation rates of the coprophilous fungal ascospores decrease, which could reflect a decrease in the local pastoral pressure, as is also suggested by the decrease in the proportion of ruderal pollen during the late Middle Ages. The consistent nature of inputs whit decreasing grazing activities highlights the deep modifications of the catchment. There is no resilience, and this new steady state could result from the progressive stabilization of the pastoral area following the erosive crisis triggered by the deforestation.

From 300 to 150 yrs cal. BP (CE 1650–1800), the available data concerning P concentrations, NAP and ruderal pollens percentages, and strict coprophilous fungal spores indicate that pastoral activities increase again during the Little Ice Age (Fig. 6-D-e-g-h).

Over the entire period between 900 yrs cal. BP and CE 1950, the dominant abundances of chironomid *T. lugens* and Tanypodinae remained relatively steady (Fig. 6-i). *T. lugens* and Tanypodinae are mainly associated with well oxygenated waters (Saether, 1979; Hirabayashi et al., 2004; Brooks et al., 2007; Millet et al., 2010) and could indicate that the lake existed in an oligotrophic state until the 1950's. But due to the use of a non-standard mesh size, these results could be biaised. These observations are nonetheless consistent with both the concentration of total P in water inferred from TC, which also indicates the oligotrophic state of the lake (Nürnberg, 1996; Wetzel, 2001) between 1000 and 200 yrs cal. BP (Fig. 6-f) and with the constant concentration of total P in the sediment and the slight decrease of available P, except during the period of 300 - 150 yrs cal. BP (Fig. 6-d-e). However, the total P in water inferred from TC increases gradually from CE 1900 while no substantial change in the chironomid community were recorded before CE 1950 with our non-standard method.

4.2.3. Consequences of human-induced modifications in the 20th century

After the 1950's, all of the proxies indicate a major environmental change (Fig. 6). Both the concentrations and accumulation rates of organic matter increase (Fig. 6-a-b). The C/N ratio increases slightly to 8, indicating inputs from the watershed (Fig. 6-c). The percentages of NAP, including those of ruderal pollen, and coprophilous fungal ascospores, decrease, indicating the reduction of local pastoral activities (Fig. 6-g-h), as confirmed by the recovery of spruce. The concentrations of both total and available P in the sediment also increase. The concentration of total P in the water reaches a maximum, and the chironomid assemblages drastically change (Fig. 6-i). The dominance of C. plumosus is indicative of oxygen depletion conditions at the bottom of the lake. Eutrophication may be a primary driver of the change in oxygen conditions as suggested by other proxies. Changes in ice coverage duration can also foster hypoxic conditions and influence chironomid assemblages (Granados and Toro, 2000). Nonetheless, the relative increase in annual air temperature over the recent decades does not support a major implication of the duration of ice coverage duration in driving oxygen dynamic. *Dicrotendipes* is associated with littoral zones and with macrophytes (Engels and Cwynar, 2011). Changes in the chironomid assemblage could therefore result from the eutrophication of the lake. The evolution of the lake trophic status could be associated with the high concentrations of P in the water reached in the 1950's, which are reflected in the sediment by both the total and available P concentrations. This excess nutrient reflected by P concentrations could have triggered both the eutrophication and the increase in the OM concentration of the sediment.

4.3. Recent eutrophication associated with past nutrient storage and recent lake-level increase

4.3.1. Development of new activities and eutrophication process dynamics

Following the reduction of pastoral activities, new leisure activities developed around the lake, such as hiking and fishing.

Fish introductions were reported from at least the end of the 19th century (Druart et al., 1999) and could explain the rise in the concentration of P in water that occurred at that time, prior to the chironomid community changes. With the rise of hiking and fishing, a summer bar was built on the shore of the lake in CE 1952 and the lake level was raised in CE 1964 to flood the macrophyte (*Equisetum* sp.) belt surrounding the lake to allow easier access for anglers. The raising of the lake outlet in CE 1964 triggered a lake level rise of 2 m and doubled the lake area. The lake level fluctuated for several years before stabilizing, triggering bank undercutting and floating mottles.

Flooded soils currently contain less total and available P compared to the non-flooded soils surrounding the lake, especially those on the moraine ridge shore, suggesting a release of P from flooded soils with the lake-level increase (Fig. 3). However, the distribution of available P on the flysch area (transect 4, Fig. 3-b) presents the opposite trend, with more important contents observed in the flooded soil (position C) than on the shore (position A). This effect can be explained by the higher erodibility of the flysch: the available P is mainly contained in surface soil (Fig. 3-a-A) and accumulates downstream with erosion. The same process can also explain the consistent concentrations of total P in the flysch area (Fig. 3-b, *i.e.,* transect 4, BENS3 and BENS4). The steady erosion in this area appears to homogenize the total P in the surface soil. Thus, the increases in total and available P, which could be responsible for the lake eutrophication, are likely due to the release of soil from the moraine ridge following the lake-level increase. Hikers and the settlement of the summer bar could not have triggered such an abrupt effect on the nutrient supply, while grazing had already lasted for several centuries without causing a noticeable evolution in the chironomid community. Moreover, several studies have observed eutrophication following lake-level fluctuations associated with P excess (Hambright et al., 2004; Punning et al., 2008; Moos et al., 2009), which supports this hypothesis.

4.3.2. Modification of P cycling with human activities

The higher P values in the surface soil of the shore than downward could have a natural and/or anthropic origin. Phosphorus is naturally enriched in top soil, as it is recycled by vegetation, and higher P concentrations are often reported in pastured and grassland areas compared to forested areas (Ross et al., 1999; Jobbágy and Jackson, 2001; Wang et al., 2009). Between 2000 and 1000 yrs cal. BP, the mean total P concentration in the sediments was lower (613 $mg.kg^{-1}$) but slowly increased, relative to that observed after deforestation under grassland (between 1000 yrs cal. BP and CE 1950; 766 $mg.kg^{-1}$). After the rise in lake level, the concentration reached 1020 $mg.kg^{-1}$. The exports of total P from the watershed tend to be higher under grassland than under forest and depend on the geological substrate (Dillon and Kirchner, 1975; Dorioz and Trevisan, 2013). An increase in the total P concentration of sediment from the Middle Ages could have resulted from both the modifications in land use and associated changes in the sediment sources within the watershed. However, the available P source is more important on the moraine ridge shore (Fig. 3-b) and will thus contribute more actively to eutrophication, while it only slightly affects to particulate inputs.

Herbivores play a major role in nutrient cycling (*e.g.,* Williams and Haynes, 1990; Sitters et al., 2017). Higher P concentration in mountain pastured surface soils can result in two processes, namely, anthropic inputs, such as the spreading of organic fertilization, and the natural distribution of animal feces, which is concentrated in the remaining and ruminate areas. In the extensive pasture context of the Lake Bénit catchment, spreading is not practiced. However, the redistribution and concentration of animal excrement close to the lake is strongly conceivable, as cattle mainly grazed on the lower flatter parts of the pasture (Jewell et al., 2007), *i.e.*, on the shore of the lake, close to the water. Animals would have concentrated their dungs, and thus accumulated nutrients, especially P, in these areas where they would likely have rested and ruminated (Fig. 8-c). It is even possible that these main flat areas may have been flooded in CE 1964. Moreover, the trampling on the shores induced by the concentration of cattle in these patches could have strengthened their destabilization after flooding and increased the release of P (Marlow and Pogacnik, 1985; Bennett et al., 2001).

The modification and concentration of nutrients such as P in soils can last long after their input (Reed-Andersen et al., 2000; Dupouey et al., 2002; Bennett et al., 2001). The effect of grazing, since the Middle Ages could have resulted in the P enrichment of the soil on the shores of Lake Bénit. Therefore, we suggest that the combined effects of historical grazing and the recent lake-level increase for fisheries is responsible for recent eutrophication of the lake (Fig. 8-d).

4.3.3. Aftereffect of the diachronous signals of anthropogenic effects

The recent eutrophication of Lake Bénit highlights the combination of anthropogenic effects at different time scales. Medieval grazing practices have had direct effects on the environment, such as the modifications of landscape and erosion, thereby triggering after-effects of the long soil storage of nutrients, such as the recent lake eutrophication, which behaves partly as a "palaeo-anthropocene" effect. The recent release of soil P with lake-level increase derived from long-standing practices first underlines the strong ability of soils to buffer the anthropic impacts on freshwater ecosystems and their ability to become sources when environmental conditions change. A similar feedback process was shown by Sabatier et al. (2014) in a vineyard with the release of banned remnant pesticide (DDT) in a lake after recent herbicide-induced erosion. The remobilization of P also underlines the diachronous onset of the "Anthropocene". Past human activities are not necessary immediately visible but can appear and last long afterwards (Aubert, 1960; Edgeworth et al., 2015), as a result of new practices and new planning, thus intensifying their impacts. This result strongly suggests considering old human practices when establishing management policies of territories in order to carefully adapt to new needs. Furthermore, the after-effects, *i.e.*, P release, are recycled and emphasized by the action of introduced fishes. Fishes can continuously suspend phosphorus that is fixed in surface lake sediments, *i.e.*, particulate P, or that in undecomposed organic matter (Elizabeth et al., 1992; Huser et al., 2016), and also by increasing human touristic pressure (*e.g.*, Druart et al., 1999; Hadwen et al., 2003; Ostendorp et al., 2004; Dokulil, 2014). The multiplication and superposition of human activities are a chain of events working as a cascade effect. They accentuated the human imprint on the environment in the last century and both participate and sustain the idea of the "great acceleration" (Steffen et al., 2015).

5. Conclusion

The combined analyses of geochemistry (including major elements, C, N and P), pollen, coprophilous fungal ascospores and chironomids of the Lake Bénit sediment sequence allowed us to reconstruct past dynamics of the catchment and changes in the trophic lake status. Performing a comparison with soil geochemistry allowed us to determine the origin of sediment in the catchment and to understand the relationship between practices (*e.g.,* agriculture, leisure) and observed processes (*e.g.,* erosion, eutrophication). The Lake Bénit sediment sequence spans the last 2100 years. The catchment was forested until the Middle Ages, without extensive human activities. Sediments came from

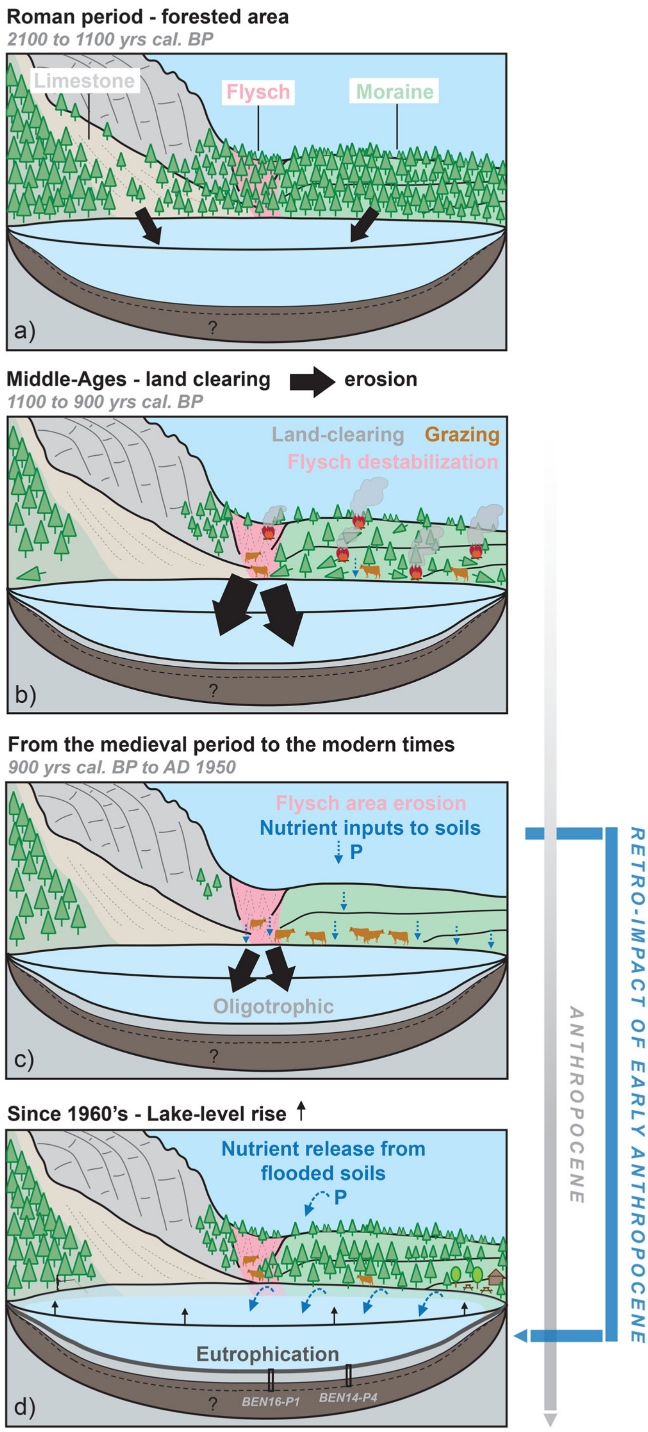

Fig. 8. Evolution of the Lake Benit catchment and heritage of early anthropic activities on the current functionning of the lake-catchment system with eutrophication triggered by P release from soils after 1960's lake level rise.

avalanches of limestone scree and runoff of the moraine ridge with very low inputs. After 1100 yrs cal. BP, the catchment was deforested for cattle grazing. Erosion increased and mainly from the flysch area that was destabilized and gullied. Chironomid assemblages indicate that the lake was oligotrophic. The changes in assemblages in the second half of the 20th century underline the still-visible eutrophication of the lake. Eutrophication is associated with the change in activities in the catchment, *i.e.*, fishing and hiking, leading to a lake-level increase in CE 1964, while pastoral activity decreased. The available and total phosphorus contents in the soils on the shore of the lake, which were analyzed along four transects from the flooded area to the out of-water area, suggest that a release of P from the flooded soils was responsible for the eutrophication. Grazing animals play a major role in nutrient cycling and the long-grazing practices of the last millennia would have led to the high P concentration on the shores of the lake. Our study highlights the combined effects of past and recent activities on the current eutrophication process, as well as the legacy of early anthropogenic effects through soil destabilization that must be more taken into account for the future management of social ecosystems.

Data References

Sedimentological and geochemical data (*i.e.,* XRF, LOI, Grain-size, CNP and total P analyses) will be available on https://www.pangaea.de/.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ancene.2018.11.005.

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