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Multi-proxy reconstruction of the Holocene vegetation and land use dynamics in the Julian Alps, north-west Slovenia

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ABSTRACT: Small mountain lakes are natural archives for understanding long-term natural and anthropogenic impact on the environment. This study focused on long-term (last ca. 13 000 years) vegetation changes and sedimentary processes in the catchment area of Lake Planina pri jezeru (1430 m a.s.l.) by using mineralogical, geochemical and palynological methods. Palynological results suggest that regional vegetation between 12 900 and 11 700 cal a BP was a herbaceous–forest tundra (*Pinus*, *Artemisia*, **Poaceae**). Climate warming at the beginning of the Holocene (ca. 11 700 cal a BP) caused the transition from a wetland (Cyperaceae) to an eutrophic lake with alternating anoxic (pyrite) and oxic conditions (gypsum). In addition, the surrounding area became forested (*Picea*, *Larix*, *Ulmus*). *Fagus* expanded at 10 200 cal a BP and *Abies* at 8200 cal a BP. Between 7500 and 4300 cal a BP, human impact on the environment was barely noticeable and mostly limited to grazing. During 4300–430 cal a BP human impact became more evident and gradually increased. The greatest influence was observed from 430 cal a BP onwards, when excessive exploitation of the surrounding area (logging and grazing) severely eutrophicated the lake. © 2022 The Authors. *Journal of Quaternary Science* Published by John Wiley & Sons Ltd.

KEYWORDS: alpine environment; geochemistry; human impact; palaeolimnology; vegetation dynamics

Introduction

The development of vegetation cover is mainly influenced by climate variability (Leuschner and Ellenberg, 2017). This is particularly noticeable in alpine areas, where a strong climatic gradient has additional influence on the development and distribution of taxa (Lotter *et al.*, 2006; Schwörer *et al.*, 2014). Due to many topographic constraints (low temperatures, strong ultraviolet radiation and short flowering season), alpine forests and meadows are subjected to numerous climatic and successional parameters (Leuschner and Ellenberg, 2017). One of the most discussed topics among palaeoecologists is the expansion of *Fagus* in the Early Holocene and the potential reasons for its belated dispersal compared with other tree species (Tinner and Lotter, 2006). This delay has been interpreted as migratory lag (Lang, 1994; Gardner and Willis, 1999), human influence (Lang, 1994; Küster, 1997), fire disturbance (Tinner and Lotter, 2006), climate change (Firbas, 1949; Gardner and Willis, 1999; Tinner and Lotter, 2001), or a combination of those factors. However, these studies are limited to specific alpine regions, and the south-eastern Alps have been insufficiently studied, especially in terms of long-term dynamics.

Moreover, there is a clear human impact on the fragile alpine environment, which has shifted over time from

hunter–gatherer to agricultural activities. Pastoralism is often considered as the main economic activity in the highlands (Giguet-Covex *et al.*, 2014; Bajard *et al.*, 2017), but other activities such as metallurgy and dairy processing should not be overlooked (Dietre *et al.*, 2020). Alpine ecosystems have been transformed into an anthropogenic landscape over time, mainly using slash and burn techniques to expand pastures and logging forests for metallurgical activities (Pini *et al.*, 2017; Andrič *et al.*, 2020). However, human impact on the alpine environment has not been continuous and homogeneous throughout the Alps. Therefore, it is crucial to study and combine both palaeoecological and archaeological analyses in different parts of the Alps during historical times (Walsh *et al.*, 2014).

Both natural changes and past land-use practices are recorded in numerous natural archives, such as lake sediments. However, deciphering natural and/or anthropogenic influences on the environment can be problematic. Here, we chose Lake Planina pri jezeru (referred to as 'Lake PNI'), a small mountain lake that is susceptible to climate variability and records both short-term climate events and long-term changes. In 2014, we obtained a core whose sedimentary record extends from ca. 13 000 cal a BP onwards. By using a number of chemical, mineralogical and palynological analyses our aim was to reconstruct long-term ecological and economic changes. This work is the first high-resolution palaeoecological study to cover the entire Holocene in the highlands of the Julian Alps.

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Study area

Lake PNI is a lake of glacial origin located at an altitude of 1430 m a.s.l. in the Julian Alps, north-west Slovenia (Fig. 1a). It is relatively small (1.5 ha), deep (maximum depth is 11 m) and currently heavily eutrophic (Dobravec and Šiško, 2002). The lake has a weak surface inflow, underwater outflow, and only minor water-level fluctuations, not exceeding 1 m. The lake has a small catchment area of 95 ha, characterised by an alpine climate with high annual precipitation (2500–3000 mm), average January temperature between 0 and -3°C and July temperature between 15 and 20°C (Ogrin, 1996; Dobravec and Šiško, 2002). The maximum elevation of the surrounding peaks is 2864 m – Mount Triglav (Banovec, 1986). Lakes in the vicinity are quite common, especially in the Triglav Lakes Valley. Moreover, in the lowlands Lake Bohinj is the largest permanent lake in Slovenia (Remec-Rekar and Bat, 2003).

Structurally, the catchment area of the lake belongs to the southern Alps (Julian Nappe) and consists of Triassic limestone (Fig. 1b), covered in places by thick Quaternary till and

lacustrine deposits, as is the case in the immediate vicinity of the lake (Rman and Brenčič, 2008, see Supplementary Fig. 1). The area is cut by Miocene to recent dextral strike-slip faults, which cause partial dolomitisation of the limestone.

The vegetation around the lake consists of mountain pasture. Rocky boulders above the lake are overgrown with larches (*Larix decidua*) and spruce forest (*Picea abies*) (Culiberg, 2002; Dobravec and Šiško, 2002). The subalpine belt is dominated by alpine beech forests (*Anemone – Fagetum*). In the belt above 1800 m a.s.l., mountain pine with dwarf alpenrose (*Rhododendro hirsuti–Pinetum prostratae*) dominates (Marinček *et al.*, 2002). On steep slopes near the mountain pasture Planina pri jezeru (above Lake Bohinj) there are hop hornbeam and flowering ash stands (*Ostryo-Fraxinetum ornii* and *Cytisantho-Ostryetum*; Fig. 1c; Dakskobler, 2015).

Archaeological finds in the Julian Alps indicate the presence of humans since the Mesolithic period (11 700–7500 cal a BP). The highlands around Lake Bohinj (Fig. 1d) were already inhabited in the Bronze Age (4300–2800 cal a BP), with archaeological sites reaching up to an altitude of about 1900

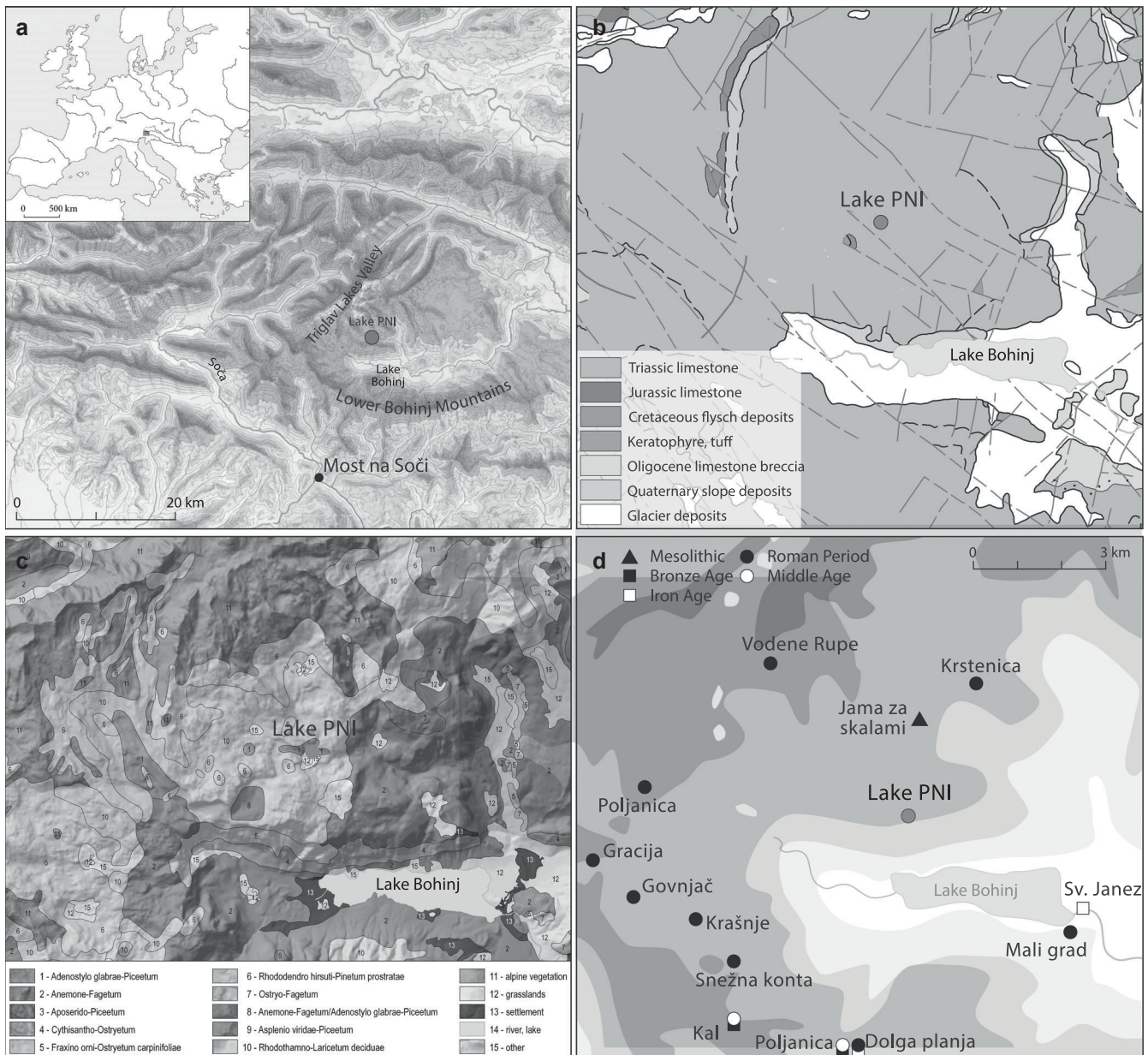


Figure 1. a) Lake PNI study area, b) geological map (after Buser 1986, 1987), c) vegetation map (Šilc U. & Sajko I., ZRC SAZU, Jovan Hadži Institute of Biology) and d) archaeological map (after Ogrin, 2010, 2020).

m (Horvat, 2019). In the Iron Age (2800–2000 cal a BP), the lowlands were more populated, while in the highlands the iron ore ‘bobovec’ was collected and used for iron production (Gabrovec, 1966; Cundrič, 2002; Ogrin, 2010). However, the economy and land use in the highlands are still not well understood. Archaeological finds surrounding the grazing area of Lake PNI are scarce and undated.

Previous palynological analyses in the highlands of Julian Alps (Šercelj, 1961, 1963, 1965, 1971) had a low sampling resolution, cores were rarely dated and are therefore difficult to compare. Modern analyses have either focused on lowland sites (Andrič *et al.*, 2009, 2020) or cover shorter time periods (Andrič *et al.*, 2010, 2011). Previous palynological studies around Lake PNI focused on the vegetation changes over the last 250 years (Culiberg, 2002). Culiberg (2002) suggested that grazing was important around the Lake PNI, as pollen of many anthropogenic indicators occur (*Urtica*, *Plantago lanceolata* and *Rumex*). *Fagus* was extensively logged for metallurgy or cut down in order to clear the area for pastures. Nevertheless, the proportion of trees has been fluctuating, indicating that grazing and logging were not equally intensive.

Methods

Coring

In 2014 sediments of Lake PNI were cored using a Uwitec gravity corer with hammer (N46.31116000 W13.82719000, WGS84) in the deepest part of the basin at 11 m water depth. The 237 cm long core was retrieved and then cut into two sections (section PNI14–01A 127 cm, section PNI14–01B 110 cm), which were split longitudinally into two halves at the EDYTEM laboratory. Each half-section was described in detail and photographed. A lithological description of the sequence, for which we used the Munsell colour chart, allowed the identification of different sedimentary facies.

Radiocarbon dating

The age–depth model is based on 15 ^{14}C samples of the organic terrestrial remains (tree leaves, twigs or needles, not all of them were identified), which were measured in the Poznan Radiocarbon Laboratory and the Laboratoire de Mesure 14 C (LMC14) ARTEMIS at the CEA (Atomic Energy Commission) Institute at Saclay.

Mineralogy

Mineralogical composition of the samples ($n=42$) was identified via X-ray diffractometry. A Philips PW3710 X-ray diffractometer was used with Cu-K α 1.54060 Å radiation generated at 40 kV and 30 mA. The samples were scanned at a rate of 3° per minute, over the range of 2–70° (2 θ). The diffraction patterns were identified with the data from X’Pert HighScore Plus software using the data from the PAN-ICSD database, version 2.3 and Rietveld polynomial for quantitative determination of the phases. The amorphous compound was determined using an external standard phase (NIST-676a) to determine an instrument intensity constant (K-factor) (O’Connor and Raven, 1988).

Geochemistry

X-Ray fluorescence (XRF) analysis was performed on the surface of the split sediment cores, which was covered with 4 μm thick Ultralene, at 2 mm intervals using an Avaatech core scanner (EDYTEM). The geochemical data were obtained with

two tube settings: 10 kV at 0.175 mA for 10 s for Al, Si, S, K, Ca and Ti, and 30 kV at 0.2 mA for 15 s for Cu, Zn, Br, Rb, Sr, Zr, Mn, Fe and Pb (Richter *et al.*, 2006). Three replicates were measured every 10 cm to estimate the standard deviation. Each individual power spectrum was deconvoluted into relative components (intensities), expressed in counts per second. Principal component analysis (PCA) was performed on the geochemical results using R software (R Core Team, 2018) to find element correlations between, and hence to identify principal sediment end-members, which were used to better constrain each sedimentological facies (e.g. Sabatier *et al.*, 2010).

Element relative abundances were expressed as centred log-ratio (CLR) to avoid dilution effects due to water (e.g. Weltje *et al.*, 2015). The following elements ($n=15$) were used to calculate the geometric mean: Al, Si, S, K, Ca, Ti, Mn, Fe, Cu, Zn, Br, Rb, Sr, Zr and Pb. For the same potential matrix effects, element ratios were expressed as logarithms (ln) of XRF counts ratios that are linearly related to the log ratios of corresponding absolute concentrations (Weltje and Tjallingii, 2008).

Stable isotope analyses

Samples for total organic carbon (TOC), total nitrogen content (TN) and stable carbon isotope analysis ($\delta^{13}\text{C}_{\text{OC}}$) were taken at a 2 cm resolution throughout most of the core. TOC, TN and $\delta^{13}\text{C}_{\text{OC}}$ were determined by elemental analyser isotope ratio mass spectrometer (EA/IRMS) IsoPrime100 – Vario PYRO Cube (OH/CNS Pyrolyser/Elemental Analyser). Before the analysis, samples for TOC content and $\delta^{13}\text{C}_{\text{OC}}$ were treated with 2 M HCl to remove carbonate minerals, while TN content was determined on the bulk samples without acidification. An aliquot of dry sample was wrapped in a tin capsule and analysed after combustion in an O $_2$ atmosphere in a quartz reactor at 1020°C. The $\delta^{13}\text{C}_{\text{OC}}$ values were reported relative to the V-PDB (Vienna-Pee Dee Belemnite) standard. The results were normalised against the following reference material: IAEA-CH-6, USGS40. To ensure the accuracy of the results other reference material, IAEA-CH-3, was analysed through the sequence and used as control material. The analytical precision of measurement for $\delta^{13}\text{C}_{\text{OC}}$ was $\pm 0.2\%$, while for TOC and TN content was $\pm 3\%$.

Palynological analysis

Samples were extracted from the core (using a metallic volumetric subsampler) every 1–2 cm (with the exception of the reworked sediment, i.e. event layer deposits; see *Results*, Units C and A) in order to obtain ca. 50–100 years’ resolution throughout the core. A total of 160 samples with a volume of 1 cm 3 were prepared following the standard method by adding *Lycopodium* spores, HCl, NaOH, HF, acetolysis, safranin dye and silicone oil (Bennett and Willis, 2002). The minimum sum of 500 pollen grains was counted in each sample using a light microscope Nikon Eclipse E400. For the identification of pollen identification keys, atlases (Moore *et al.*, 1991; Reille, 1992, 1995; Beug, 2004; Faegri and Iversen, 1989) and the reference collection of the Institute of Archaeology, ZRC SAZU were used. Non-palynological palynomorphs (*Sporormiella*; Van Geel, 2002; Gelorini *et al.*, 2011), stomata of conifers (Hu *et al.*, 2016) and charcoal particles were noted. The pollen diagram was made using Psimpoll program 4.261, where zonation was determined with binary splitting by sum-of-squares (Bennett, 2005).

Results

Sedimentary units

The sediment core of Lake PNI can be divided into four different sedimentary units (Fig. 2).

Unit D

The oldest unit is Unit D (237–221 cm) characterised by dark grey (2.5Y 4/1) silt to clay with some lighter grey (2.5Y 7/2) lamina (Fig. 2). Mineralogically it is characterised by a relatively low content of amorphous matter, ranging from 38% at the bottom of the unit to 22% at the top of the unit (Fig. 3). Mineral components in the lower part are predominantly clay minerals (36–45%) and quartz (11%) while carbonates are rare (calcite 0–15%, dolomite 3–13%). Albite is also present (1–4%). TOC (5.2%) is the lowest, in parallel with low $\delta^{13}\text{C}_{\text{OC}}$ (-30.3‰) (Fig. 4). The atomic C/N ratio ranges from 12.8 to 24.4. Ti values are the highest in the entire sequence, whereas Br values are very low.

Unit C

Unit C (221–127 cm), consists of black (2.5Y 2.5/1) clay, rich in organic matter with some light carbonate-rich lamina. At 185 cm, we observed a 1 cm large carbonate rock. Between 177.2 and 181.8 cm an event layer deposit is present. It is characterised by a normal gradation from silty sand to clay cap, with the base rich in macro-organic remains. Fine lamination is observed between 165 and 175 cm. Mineralogically this unit is similar to the previous Unit D. Clay minerals reach 22–33% of all mineralogical

content. Other minerals that are present are calcite (1–25%), dolomite (1–15%) and quartz (3–12%). The exception is the lower part of Unit C, where we observe a few 'exotic' layers. One noticeable difference is the occurrence of rather large gypsum content at depth 201–200 cm (4.2% of all minerals) and at 208–209 cm with 4.9%. This second layer is characterised by the only occurrence of amphibole in the entire PNI succession. Amphibole accounts for 5.2% of the total mineral fraction, accompanied by clay minerals (21.9%), gypsum (4.9%), quartz (2.8%) and almost no carbonates (only 0.3% calcite and 1% dolomite). The geochemical record shows high amplitude variation of TOC (11.3–35.9%), $\delta^{13}\text{C}_{\text{OC}}$ (-37.9 to -27.8‰) and Ca. The C/N ratio ranges from 14.3 to 40.1. Ti values are lower and Br values higher than in Zone D.

Unit B

Unit B (127–78 cm) consists of a homogeneous olive brown (2.5Y 4/4) silt to clay with 5 mm thick dark lamina. Mineralogically it is relatively homogeneous, with siliciclastic minerals (clays 22–32%, quartz 5–7%) that predominate over carbonates (calcite 5–27%, dolomite 1–9%). Other minerals are present only in small quantities. The only difference is in the upper part of the unit at 80 cm depth, where carbonates can reach about 30% of all minerals. Geochemically this unit records relatively uniform geochemical content of Ti, Br, TOC (21.1–34.4%), $\delta^{13}\text{C}_{\text{OC}}$ (-35.8 to -30.8‰). The C/N ratio ranges from 15 to 24.5. Ca values are lower than in the previous unit. Pb values peak towards the top of the unit.

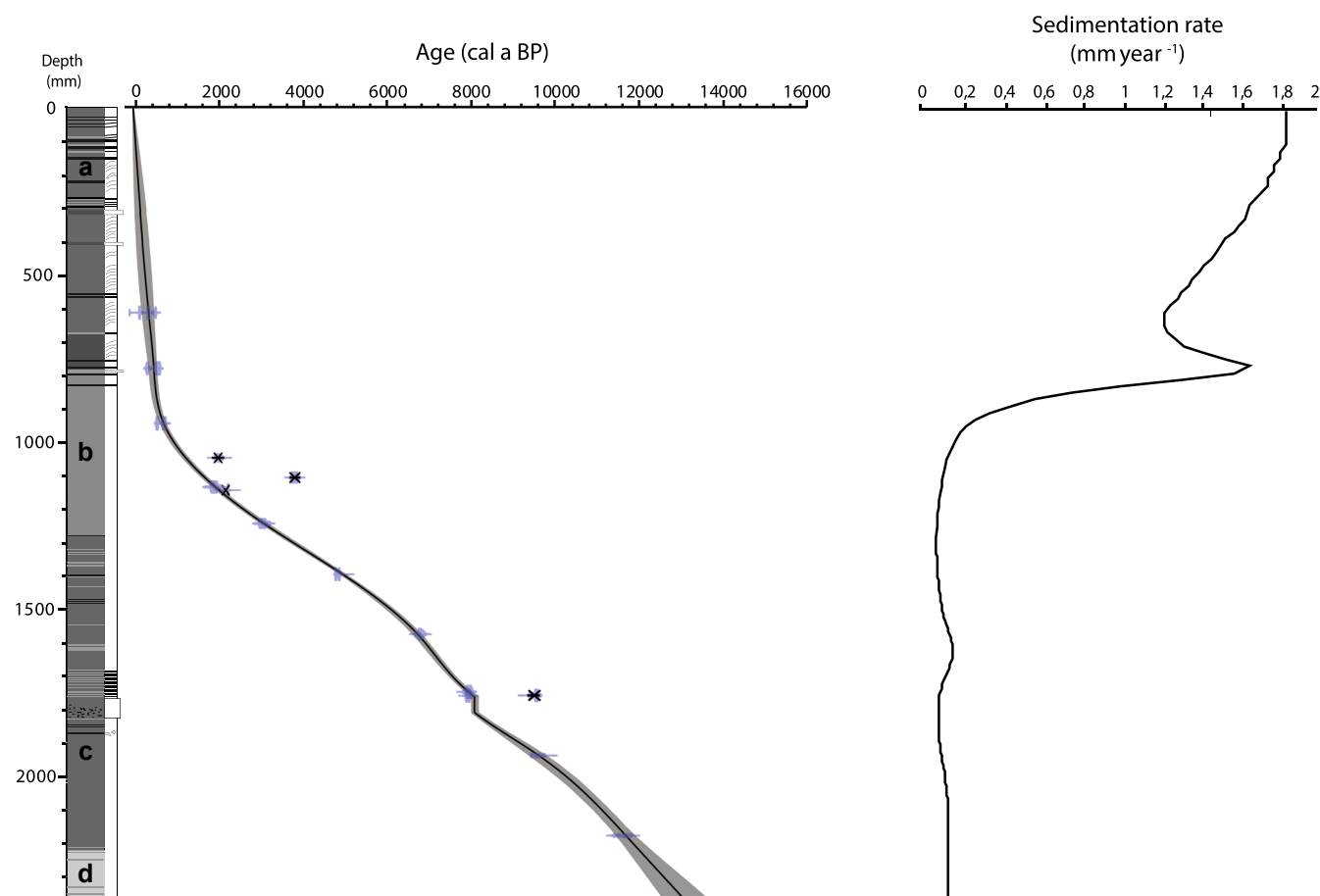


Figure 2. Age–depth model with the sedimentation rate. Time span of each unit: Unit D (13 100–12 000 cal a BP), Unit C (12 000–3500 cal a BP), Unit B (3500–430 cal a BP) and Unit A (after 430 cal a BP). [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/terms-and-conditions)]

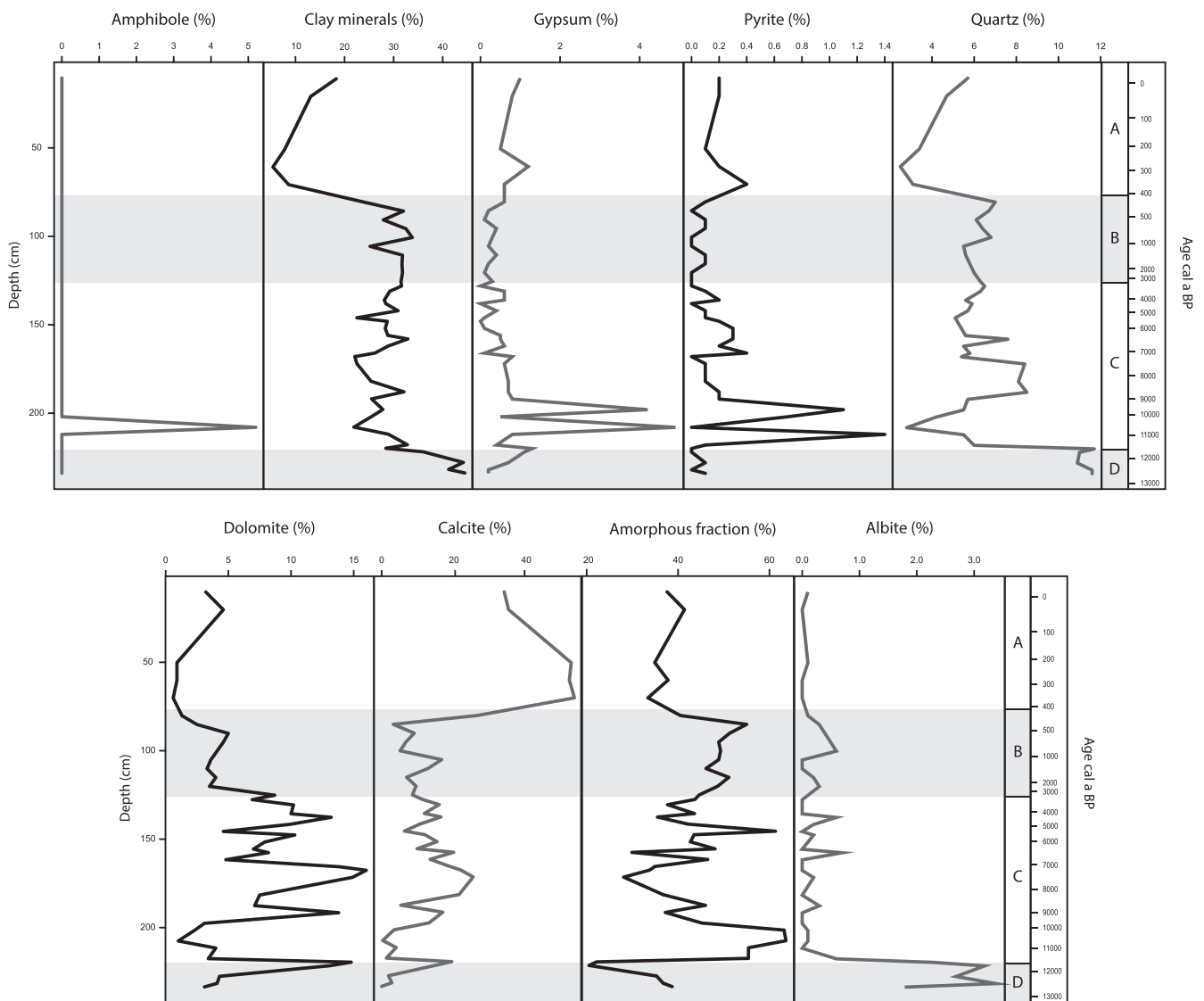


Figure 3. Mineralogical data, each mineral is presented as a relative percentage (%). Illite, kaolinite and chlorite are combined in clay minerals (%). Note that scale is not the same for all axes.

Unit A

The uppermost part of the core is represented by Unit A, which consists of dark grey (10YR 4/1) clay with some black and greyish brown (10YR 5/2) lamina. We noted three event layer deposits (77.6–77 cm, 40.8–40 cm, 31.8–30.8 cm) characterised by brownish yellow (10YR 6/6) silt lamina more enriched in terrigenous material. For dating purposes three instantaneous events in Unit A and one in Unit C were removed before age modelling (Sabatier *et al.*, 2017). In Unit A, carbonates (calcite 33–54%, dolomite 1–5%) predominate over clay minerals (8–19%) and quartz (3–6%), while other minerals are present in traces. Ca values increase, whereas Br declines. It records quite uniform TOC (14.2–24.3% $\delta^{13}\text{C}_{\text{OC}}$ (-36.5 to -28.7‰), while C/N ratio ranges from 13.2 to 27.9.

Principal component analysis

A PCA was conducted on bulk XRF data coupled with TOC, C/N and $\delta^{13}\text{C}_{\text{OC}}$ (see Supplementary Fig. 2) with Dimensions 1, 2 and 3 representing 73.9% of total variability. PCA results show three distinct end-members with: i) high positive loading on Dimension 1 for terrigenous elements (Zr, Ti, Sr, K, Si, Al, Sr); ii) positive loading on Dimension 2 for organic carbon (TOC) and some other

elements such as Pb, Mn and Br; iii) negative loading on Dimension 2 for Ca associated with carbonate content and $\delta^{13}\text{C}_{\text{OC}}$. C/N shows positive loading on Dimension 3 as well as Ca and TOC, while Pb shows negative loading on this dimension (see Supplementary Fig. 2). Unit D is mainly influenced by the terrigenous end-members, while unit A is negatively correlated to the terrigenous end-member and positively correlated with the carbonate. Units C and B have almost the same compositional influence (mixture of terrigenous organic matter end-members and to a lesser extent carbonate for Unit C) on the PCA with higher variability for Unit C (Fig. 4).

Age–depth model

The age–depth model was constructed from 11 ^{14}C dates (Table 1) of terrestrial organic remains on the event-free sediment sequences and covers the last ca. 13 100 years. Four ages were excluded because they appear too old, probably due to macroremains stored in the lake catchment, and would result in age inversion (bold in Table 1). For dating purposes three instantaneous events in Unit A and one in Unit C were removed before age modelling (Sabatier *et al.*, 2017, see *Results, Age–depth model*). The calculated age–depth model (Fig. 2) was produced by a smooth spline interpolation using

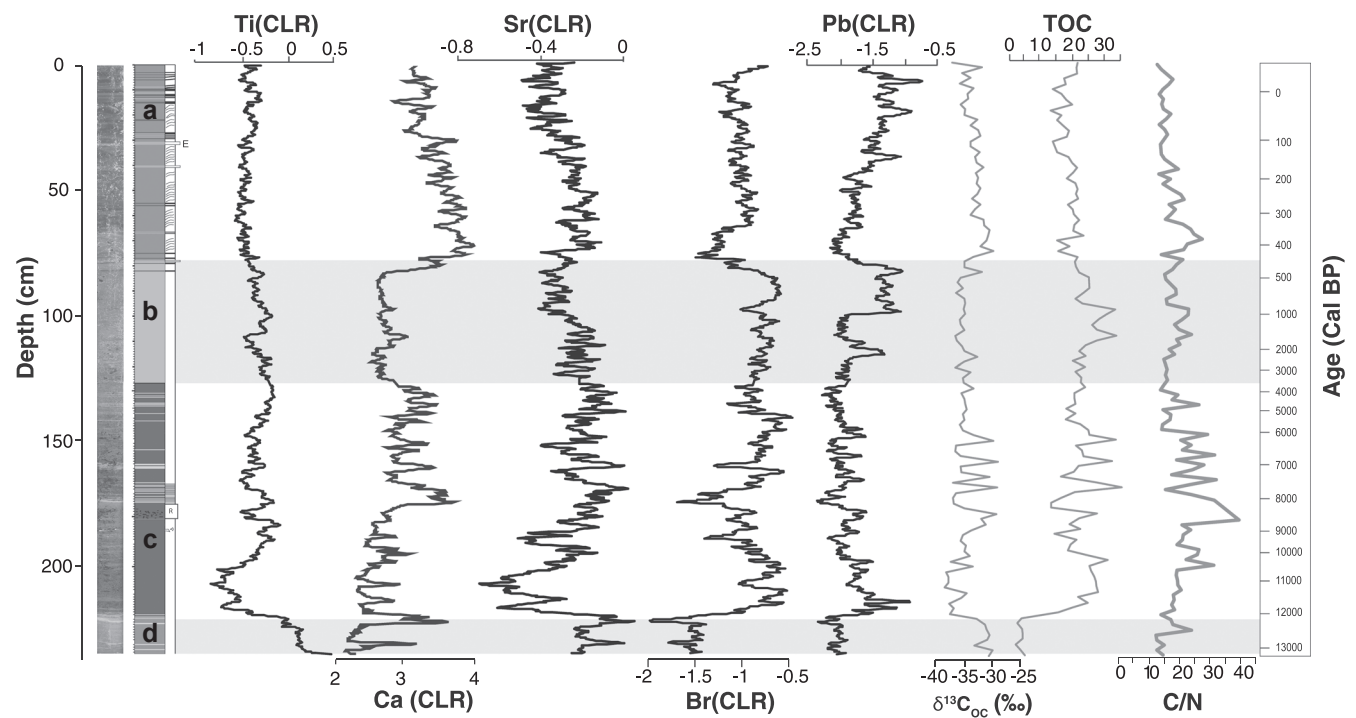


Figure 4. Main geochemical results presented down core.

Table 1. Radiocarbon dates. Dates in bold were excluded from the age–depth model.

PNI		Depth (cm)	Age ^{14}C (BP)	2σ cal a (BP)	Sample type
1A 61 – 62	SacA 41402	61.5	255 ± 30	151–429	Unidentified plant material
1A 78 – 79	SacA 57525	78.5	400 ± 30	326–513	Unidentified plant material
1A 94 – 95	SacA 57526	94.5	700 ± 30	564–688	Unidentified plant material
1A 104 – 105	Poz–120180	104.5	2040 ± 50	1888–2126	<i>Larix decidua</i> needles
1A 110 – 111	Poz–120158	110.5	3520 ± 30	3702–3876	<i>Picea abies</i> needles & seed
1A 113 – 114	SacA 41403	113.5	1955 ± 30	1827–1986	Unidentified plant material
1A 114 – 115	Poz–120159	114.5	2315 ± 30	2185–2361	<i>Picea abies</i> needles
1A 124 – 125	SacA 57527	124.5	2890 ± 30	2928–3143	Unidentified plant material
1B 12 – 13	SacA 57528	139.5	4345 ± 30	4848–5027	Unidentified plant material
1B 30 – 31	SacA 41404	157.5	5950 ± 35	6677–6881	Unidentified plant material
1B 47 – 48	SacA 57529	174.5	7075 ± 40	7827–7976	Unidentified plant material
1B 53 – 54	SacA 39967	180.5	7110 ± 40	7873–8008	Unidentified plant material
1B 53 – 54	SacA 41405	180.5	8395 ± 40	9304–9494	Unidentified plant material
1B 66 – 67	Poz–120160	193.5	8740 ± 50	9556–9901	<i>Picea abies</i> needles & seed, <i>Larix decidua</i> needle
1B 90 – 91	SacA 57530	217.5	10 085 ± 50	11368–11 968	Unidentified plant material

IntCal20 calibration curve (Reimer *et al.*, 2020) and the R package ‘Clam’ version 2.2 (Blaauw, 2010). The time span of sedimentary units is: 13 100–12 000 cal a BP (Unit D), 12 000–3500 cal a BP (Unit C), 3500–430 cal a BP (Unit B) and after 430 cal a BP (Unit A). The calculated sedimentation rate shows two distinct periods. The first period with low sedimentation rate (<0.2 mm yr⁻¹) is in the lower part of the core between 13 100 and 600 cal a BP. After 600 cal a BP the sedimentation rate increased with the first peak (1.6 mm yr⁻¹) at 420 cal a BP. Note that this peak could also be artificially created by age–depth modelling. At 300 cal a BP the sedimentation rate dropped to 1.2 mm yr⁻¹ and gradually increased to 1.8 mm yr⁻¹ until the top of the core.

Palynological results

The pollen diagram (Figs 5, 6) is divided into six pollen zones (PNI P1 – PNI P6). In the lowest zone PNI P1 (13 100–12

000 cal a BP, 236–220 cm), corresponding to Unit D, *Pinus* predominates among tree taxa (up to 50%) and Poaceae (10–15%), *Artemisia* (5–30%) and Chenopodiaceae (up to 10%) among herb taxa.

In zone PNI P2 (12 000–10 200 cal a BP, 220–200 cm, Unit C) the temperate taxa *Picea*, *Larix*, *Quercus* and *Ulmus* expanded around 11 700 cal a BP. Stomata of *Picea* were found at about 11 600 cal a BP. Closed forest (>90% tree taxa) was established around 11 000 cal a BP.

In zone PNI P3 (10 200–8900 cal a BP, 200–188 cm), *Corylus* and *Fagus* reached more than 2% around 10 200 cal a BP and quickly spread (up to 25%). Tree taxa dominated the area, predominantly *Fagus* (10–30%) and *Picea* (20–40%).

In zone PNI P4 (8900–4500 cal a BP, 188–136 cm), *Abies* expanded around 8200 cal a BP. The first anthropogenic indicators (*Plantago lanceolata*, *Sporormiella*) appeared around 7500 cal a BP, but the percentage of Poaceae remained low (0.5–2%).

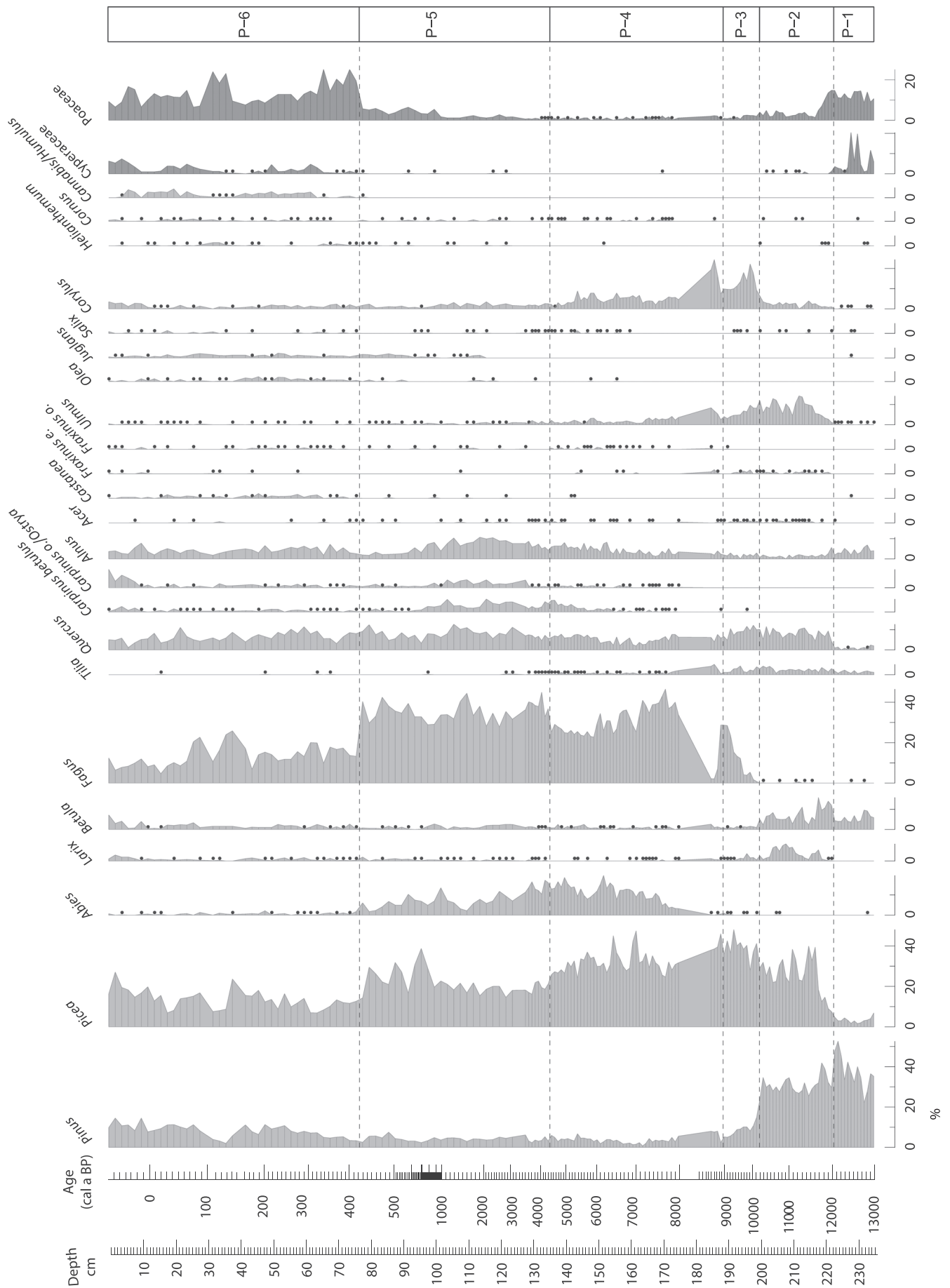


Figure 5. Selected pollen taxa. Samples marked with a solid dot are present with <math><0.5\%</math>.

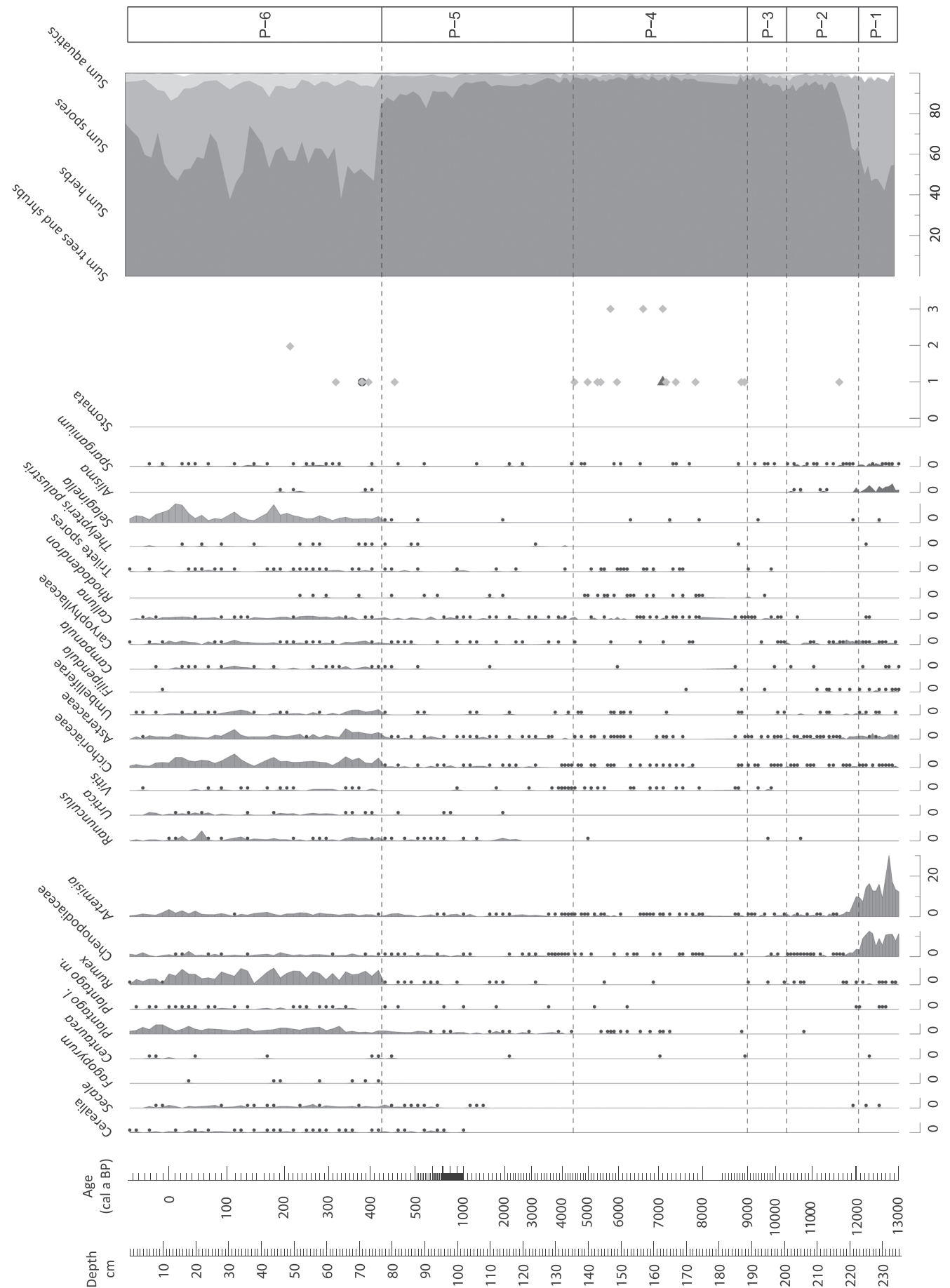


Figure 6. Selected pollen taxa. Samples marked with a solid dot are present with <0.5%. Stomata: triangles *Taxus*, diamonds *Picea*, dots *Abies*.

In the zone PNI P5 (4500–430 cal a BP, 136–77 cm, Unit B), *Fagus* is the most dominant taxon (25–45%), followed by *Picea* (15–40%). There is a slight increase of *Carpinus orientalis/Ostrya*, *Carpinus betulus* and Poaceae (2–5%). Anthropogenic indicators occur throughout the whole zone. *Secale* and Cerealia appear around 1500 cal a BP and 1000 cal a BP, respectively. The percentage of tree taxa slightly decreased to about 80–90% and the percentage of herbs (Poaceae – 10–20%, *Rumex* – up to 7%, *Plantago lanceolata* – up to 5%) and spores (*Selaginella* – up to 10%) increased.

In the upper zone PNI P6 (after 430 cal a BP, 77–0 cm, Unit A), *Fagus* decreased and *Picea* increased, with *Fagus* 5–15% and *Picea* 10–20%. The percentage of tree taxa decreased significantly, ranging from 30–60% throughout the zone. Therefore, a higher increase of herb taxa is observed, with Poaceae 5–25%, *Rumex* up to 5%, Cichoriaceae up to 5% and Asteraceae up to 5%.

Discussion

Climate-induced sedimentological and vegetation changes

In the Younger Dryas (12 900–11 700 cal a BP), Lake PNI was a marsh-like environment (higher values of Cyperaceae, *Alisma*, *Sparganium*) with predominant sedimentation of terrigenous siliciclastic material (clay minerals, quartz, albite) (Fig. 3) and low TOC (Fig. 4), which is further supported by geochemical data that show high content of the terrigenous end-members (e.g. Ti, see Supplementary Fig. 2, Unit D). After the Wurm deglaciation the area was subjected to deposition of aeolian silty material coming mainly from the glacially and wind-eroded metamorphic–igneous rocks, most probably from the central eastern Alps (Skaberne *et al.*, 2009). The mineralogical composition of the aeolian material investigated in soils by Skaberne *et al.* (2009) is quite similar to our samples; namely, it consists of quartz, albite, muscovite, clays and also some heavy minerals like amphiboles, pyroxenes and granates. As in other parts of the Alps (Tinner *et al.*, 1996; Pini, 2002; Ilyashuk *et al.*, 2009; Finsinger *et al.*, 2021), the vegetation around the lake (Fig. 5, 6) was herbaceous–forest tundra with sparse *Pinus* and *Betula* stands and perennial herbs (*Artemisia*, Poaceae).

Between 12 450 and 12 200 cal a BP an increase in sedimentation of carbonates and a decrease in sedimentation of amorphous material is observed (Fig. 4). In addition, the C/N ratio, which indicates the input of terrigenous organic matter (Meyers, 1994), increased, while the Ca/Ti ratio decreased, indicating higher siliciclastic terrigenous input (Kylander *et al.*, 2011). This suggests the possible onset of a more humid and warmer climate (Bajard *et al.*, 2016) in the region, which caused the remobilisation of terrigenous fine-grained carbonate till fraction and the filling of the marsh.

Between 11 700 and 10 200 cal a BP, the mineralogical data show the highest values of amorphous material, while the calcite and dolomite content is extremely low. This is coupled with an additional decrease in Ti and a strong increase in Br, which presents a high affinity to organic matter (Leri and Myneni, 2012; Bajard *et al.*, 2016) possibly related to algal organic matter accumulation (Guevara *et al.*, 2019) and the occurrence of diatoms (Kerfoot *et al.*, 1999). The C/N ratio of around 15 indicates a mixture of lacustrine algal and terrestrial organic matter. Lower values of Ti, associated with higher vegetation cover, are reflected in the rapid decrease in terrigenous input due to soil stabilisation (Bajard *et al.*, 2016).

During the period 11 800–11 600 cal a BP, the expansion of *Picea*, *Larix*, *Quercus* and *Ulmus* indicates a warmer and more

humid environment. At ca. 11 600 cal a BP, the area around Lake PNI was already covered with forest (90% of the tree taxa), which is furthermore proven by the occurrence of stoma of *Picea*, implying local presence. This indicates that the treeline shifted to higher elevations in the 100–200 years following the Pleistocene–Holocene boundary (11 700 cal a BP). A rapid expansion of tree taxa has already been observed in the central Swiss Alps (Tinner and Kaltenrieder, 2005), Venetian pre-Alps (Vescovi *et al.*, 2007) and further illustrates a rapid response of vegetation to Holocene climate warming.

Higher Pb values from 11 800 to 11 600 cal a BP could be due to aeolian transport of dusty particles from the Sahara (Shotyk *et al.*, 1998, 2002) as the catchment consists solely of carbonate rocks (Rman and Brenčič, 2008). Presumably, Pb was partially washed into the catchment area by remobilisation of 'old' dust material with melting glaciers where Saharan dust was deposited during colder periods, and atmospheric inflow from the Sahara (Jiménez-Espejo *et al.*, 2014).

Pyrite was detected at 11 400 cal a BP and 10 600–10 200 cal a BP, suggesting occasional anaerobic conditions in the lake. The average C/N ratio of 20 indicates the presence of terrestrial organic carbon, probably from soil. The anoxic conditions can be further supported by very low $\delta^{13}\text{C}_{\text{oc}}$ ranging from -37.9‰ to -36.1‰ . A possible process that can lead to such low $\delta^{13}\text{C}_{\text{oc}}$ is that oxidation of ^{13}C -depleted biogenic methane released from the sediments to the water column contributed to ^{13}C -depleted dissolved CO_2 to the dissolved inorganic carbon (DIC) reservoir. This means that the assimilation of this DIC would result in the synthesis of ^{13}C -depleted biomass. Alternatively, ^{13}C -depleted biogenic methane formed in the sediment could enable the expansion of methanotrophic organisms that produced ^{13}C -depleted biomass (Hollander and Smith, 2001 and references therein). Higher values of gypsum (11 100–10 100 cal a BP) represent a diagenetic feature and are the result of oxidation of pyrite by calcium-rich oxidising water (Bain, 1990).

Between 10 200 and 4500 cal a BP the percentage of tree taxa remains high (>90%), indicating that the area around the lake was heavily forested. Mineralogically, however, this unit is quite diverse, with higher values of calcite and dolomite, indicating carbonate supply from the watershed and lower values of organic matter. Higher values of $\delta^{13}\text{C}_{\text{oc}}$ and C/N reaching up to 40 indicate a terrigenous input of organic matter, supported by lower Br content during the short-term increase in C/N values. The highest C/N ratios in the sediment (28–40) are supported with the highest TOC content (25.1–34.5 wt%). Nevertheless, the high amount of dolomite combined with the short-term variation of Ca content indicates terrigenous carbonate input, possibly due to shorter periods of increased precipitation, which is still influenced by the terrigenous end-members (see Supplementary Fig. 2). Moreover, continuous erosion, despite heavily forested surroundings can be implied by relatively high values of Ti. The relative contributions of allochthonous (terrestrial) and autochthonous carbon to sediment TOC was assessed using an isotope mass balance (Ogrinc *et al.*, 2005), where it was estimated that the terrigenous fraction can account for up to 75% of TOC. This is further proven by values of Sr (see Fig. 4) that indicate carbonate input from the watershed through erosion (Kylander *et al.*, 2011) that coincide with Ca values.

The relatively late expansion of *Corylus* (around 10 200 cal a BP) corresponds to other pollen records in the southern Alps (Lago Piccolo di Avigliana, Finsinger *et al.*, 2006; Lago di Origgio, Tinner *et al.*, 1999), where *Quercus* and *Ulmus* preceded the hazel expansion. Several studies concluded that the subsequent expansion of hazel was due to lower moisture availability in the Early Holocene (Tinner and Lotter, 2001;

Finsinger *et al.*, 2006). Chironomid-based temperature reconstructions in the central eastern Alps showed greater seasonal contrasts with hot, dry summers and cold winters between ca. 10 000 and 8600 cal a BP, with a thermal maximum of up to 4.5°C higher temperatures than present (Ilyashuk *et al.*, 2011). Additionally, Feurdean *et al.* (2008) found that in north-western Romania two centennial-scale events occurred at ca. 10 350–10 100 and 8350–8000 cal a BP with lower winter temperatures, decreased precipitation and increased summer temperatures. This roughly coincides with our pollen record, which shows two peaks of *Corylus* (ca. 20%) between 10 000–9900 and 8400–8300 cal a BP. Theuerkauf *et al.* (2014) suggested that hazel spread from warmer south-facing slopes during the drier climate in northern central Europe, which could be attributed to our site. Finsinger *et al.* (2006) and Tinner *et al.* (2005) suggested that the spread of *Corylus* was promoted by forest fires, but our data do not confirm that since the charcoal influx does not significantly increase before or during *Corylus* peaks. Thus, we assume that the predominant factors for the expansion of *Corylus* were climatic, with higher seasonal contrast (colder winters, hot summers) and a generally drier climate. That caused drought stress to a majority of the other tree taxa, especially during the vegetation period and consequently allowed the spread of *Corylus*, as it is more adapted to longer periods of drought (Finsinger *et al.*, 2006).

However, between the two *Corylus* peaks (9900–8400 cal a BP), the proportion of *Fagus* increased and reached up to 25%, indicating further upward shift of the timberline with *Fagus* at a lower elevation and *Picea* forests at a higher elevation. Previous studies in different parts of Slovenia have shown relatively high values of *Fagus* in the Early Holocene (Šercelj, 1963; Culiberg *et al.*, 1981; Andrič *et al.*, 2008). In conjunction with genetic analyses, researchers have suggested that *Fagus* refugia were located in Slovenia and northern Croatia (Magri *et al.*, 2006; Brus, 2010).

Together with *Abies*, *Fagus* is one of the most shade-tolerant and water-dependent taxa (Leuschner and Ellenberg, 2017). A comparison of the ecophysiological responses of modern populations of *Abies* and *Fagus* in the Dinarides has shown that *Abies* is more susceptible to drought and overall dry conditions, whereas *Fagus* is able to regenerate more quickly (Čater and Levanič, 2019). Therefore, we propose that the environment in the south-eastern Alps was still influenced by a high seasonal contrast with frequent summer droughts, but climatic conditions were still favourable enough for *Fagus* establishment. Magri *et al.* (2006) suggested that *Fagus* was able to expand over the hilly and mountainous areas with sufficient humid conditions, avoiding dry plains such as the Pannonian plain and Po plain. Nowadays, the Julian Alps are influenced by the highest alpine precipitation (ARSO, 2021) with average annual precipitation between 2500 and 3000 mm (Ogrin, 1996). This is affected by the humid south-westerly winds blowing perpendicular to the Dinaric–Alpine orographic barrier (ARSO, 2021).

Lambeck *et al.* (2004) noted that at ca. 14 500 cal. a BP the sea-level of the Adriatic Sea was lower by ca. 85–90 m. A relatively slow subsidence rate of about 1 mm per year enabled sea-level change in the Early Holocene by flooding the North Adriatic Sea. The base of the transgression is proven by a number of very high-resolution seismic profiles and facies analyses on sedimentary cores that show peat layers dated to the Younger Dryas (Correggiari, Roveri & Trincardi *et al.* 1996).

Ravazzi *et al.* (2006) argued that those terrestrial conditions caused more continental climate in the late Pleistocene, proven by the absence of broad-leaved thermophilous trees coupled with the shrubs and herbs adapted to dry sites in the

Apennines. Additionally, at the onset of the Holocene, expansion of taxa like *Abies* was prevented or delayed, which is related to lower moisture. That coincides with the sea ingression over the Northern Adriatic depression.

Despite the more continental conditions, it is possible that there was still more precipitation in the Early Holocene than in the other parts of the Alps. This, therefore, allowed the development of *Fagus* populations in the area. However, due to the limited palaeoclimatic reconstructions in the south-eastern Alps, it is not possible to explain why the (micro) climate was so favourable for *Fagus* populations compared with the other regions of the Alps.

As in other parts of the Alps, a cold 8200 cal a BP event caused a decrease in mean temperature of 1.5–2°C (Tinner and Lotter, 2001). With a decrease in summer temperatures and consequent decreased drought stress, *Abies* expanded at about 8200 cal a BP and a coupled increase in *Abies* and *Fagus* outcompeted *Corylus*, which declined. Recent research focusing on modern *Abies* populations has found that one of the main reasons for the reduced *Abies* proportions in southern Europe are the drought-induced periods of water stress associated with a drier and warmer climate (Hernández *et al.*, 2019).

Sporadic pollen of *Plantago lanceolata* and spores of the genus *Sporormiella* were noted at 7500 cal a BP (Fig. 6). Behre (2007) suggested that *Plantago* is indigenous to central Europe, since it occasionally appeared in pollen diagrams prior to anthropogenic activities. However, other authors suggested that *Plantago lanceolata* is an archaeophyte, i.e. not native to central Europe (Leuschner and Ellenberg, 2017). In addition, finds of *Sporormiella* could be due to the grazing of wild animals in the area (Davis and Shafer, 2006; Ejarque *et al.*, 2011). However, with the co-occurrence of *Plantago lanceolata* and *Sporormiella* we can assume that there was a low anthropogenic pressure on the environment around the grazing area of Lake PNI. No spores of *Sporormiella* were found before the Neolithic and pollen of *Plantago lanceolata* was detected in two samples. Pini *et al.* (2017) suggested that Neolithic people were probably only seasonally present in the highlands of the Alps and did not drastically interfere with the environment. Moreover, with the increase in Ca/Ti and charcoal influx (Fig. 7) and no sign of deforestation (Fig. 6) pastoralism was probably restricted to localised small-scale pastures that caused erosion and in-lake production due to more organic matter being washed into the lake. In other parts of the Alps, human impact on the environment has been recognised since the beginning of the Neolithic in the alpine valleys (e.g. Colombaroli *et al.*, 2013) and Middle to Late Neolithic in the highlands (Schwörer *et al.*, 2014; Pini *et al.*, 2017; Gilck and Poschlod, 2021).

Between 5900 and 4500 cal a BP, *Fagus* declined and *Abies* and *Picea* became more widespread, with the regular appearances of *Picea* stomata. In addition, *Plantago lanceolata* was absent between 5400 and 4400 cal a BP. The area around the lake was probably heavily forested (>90% taxa), which could mean that *Picea* and *Abies* were more locally present and *Fagus* was at lower elevations. Palaeoclimatic reconstructions show cooling at this time (5300–4900 cal a BP and 4600–4400 cal a BP, Haas *et al.*, 1998; 5600–5000 cal a BP, Magny and Haas, 2004), which could be the reason for the expansion of *Abies* and *Picea*.

Subtle human impact on the vegetation

Between 4500 and 430 cal a BP *Fagus* was the dominant taxon in the area. Together with the increase of *Alnus*, which requires high soil moisture (Dakschobler *et al.*, 2013), it can be

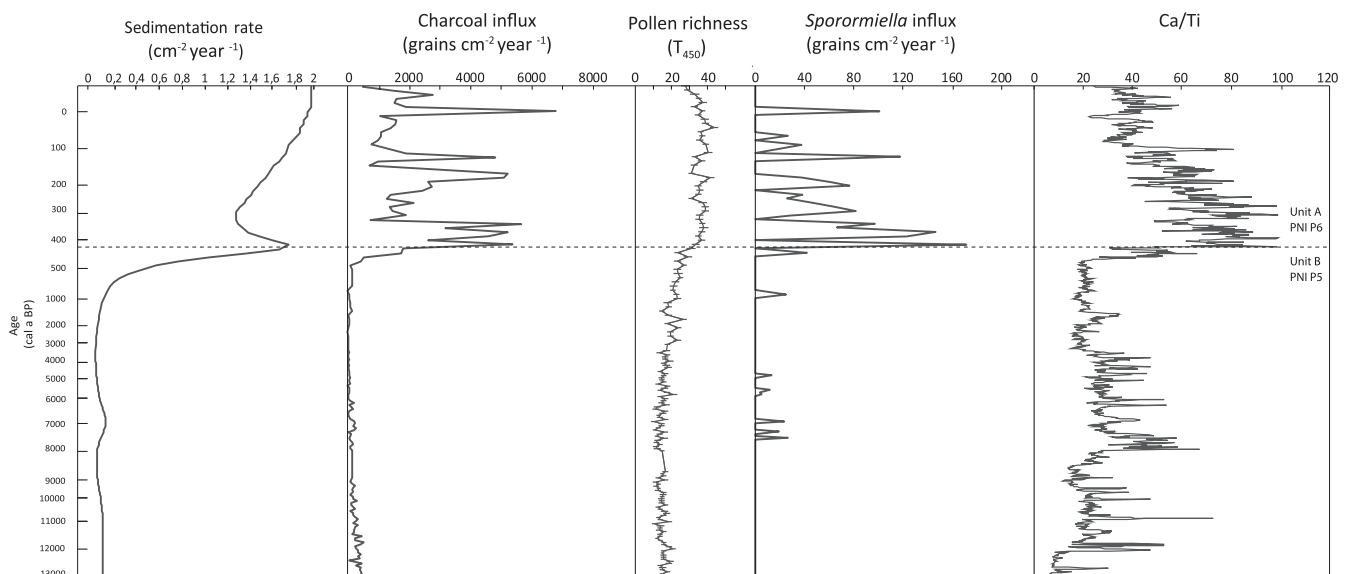


Figure 7. Comparison of sedimentation rate (mm year^{-1}), charcoal influx ($\text{grains cm}^{-2} \text{ year}^{-1}$), pollen richness (min. 450 pollen grains), *Sporormiella* influx ($\text{grains cm}^{-2} \text{ year}^{-1}$) and Ca/Ti ratio (CLR). See increase at ca. 430 cal a BP that was induced by increased human impact. Mainly, with increased charcoal and pollen richness, more open landscape was created, presumably due to development of pastures, which is indicated by higher *Sporormiella* influx. That led to increased erosion (Ca/Ti ratio) and eutrophication of the lake (see Fig. 4, $\delta^{13}\text{C}_{\text{oc}}$, C/N ratio), which is indirectly reflected in increased sedimentation rate.

attributed to the wetter conditions. The absence of *Picea* stomata and higher values of *Fagus* may indicate that subalpine *Fagus* forest was present locally, with *Picea* forest growing at higher altitudes. *Carpinus betulus* and *Carpinus orientalis/Ostrya* were more abundant, probably due to the clearing of *Fagus* forests (Dakskobler, 2015) for grazing.

Forest composition and the type of litter affect the chemical composition and pH of the soil, which can be eroded and transported into the lake (Bajard *et al.*, 2016). At Lake PNI, Ca peaks are characteristic for the period before *Fagus* became the dominant taxon in the region (i.e. 8200–4500 cal a BP), presumably due to the acidifying effects of *Picea* needles on soils (Berger *et al.*, 2004). That increased the acidification of the soils and consequently concentrations of Ca in soluble form were higher. Eventually, as *Picea* forests were being replaced by *Fagus* forests, there was a decrease in terrigenous carbonate that was washed into the lake (Fig. 4). Additionally, a possible local establishment of *Fagus* forest could be the cause of low terrigenous carbonate during that time (between 3500 and 500 cal a BP, Unit B), since broad-leaved trees regulate the amount of rainfall that reaches the ground during severe rainfall events (Altieri *et al.*, 2018), resulting in limited soil erosion and therefore a stabilised catchment area. However, the C/N ratio varies between 15 and 25, indicating mixed autochthonous and allochthonous input of organic matter into the lake (Enters *et al.*, 2006).

From the Bronze Age (4300 cal a BP) onwards, human impact is more pronounced, with a lower proportion of tree taxa, especially *Abies* (maximum 5%) indicating forest grazing (Tinner *et al.*, 1999). Anthropogenic indicators (mainly *Plantago lanceolata*) were continuously present throughout the whole zone. However, the gradual decline of the tree taxa could indicate that anthropogenic pressure on the grazing area around Lake PNI was not as substantial as in the lowlands, especially in the Iron Age at ca. 2600 cal a BP (Andrič *et al.*, 2020). Most of the archaeological evidence in the area was found above 1500 m a.s.l. (Fig. 1d), presumably in the grassy areas that did not require prior clearing (Ogrin, 2010). Herders most likely kept their cattle at higher elevations where meadows were naturally present. At Vodene Rupe (1600 m

a.s.l.), a bronze cowbell dated to the Roman Period (1900–1700 cal BP) was found (Ogrin, 2010), which also proves pastoralism at higher altitudes. In addition, lower percentages of charcoal suggest that there were no anthropogenic fires during this period.

In other parts of the Alps, vertical seasonal transhumance has been developed since 7000 BP (Hafner and Schwörer, 2018), and dairy processing since the Late Bronze/Early Iron Age (Carré *et al.*, 2016), resulting in the construction of more permanent buildings with stone foundations (Dietre *et al.*, 2020). Since the Iron Age, this was also the case in the Julian Alps, where stone constructions were found mainly in the Lower Bohinj Mountains. The main reason for this was that people from the Sv. Lucija cultural group (area of present-day Most na Soči) were crossing the Lower Bohinj Mountains (Fig. 1a; Ogrin 2010) to look for ore in the area of Bohinj (Gabrovec, 1974). The majority of archaeological finds (especially in the Lower Bohinj Mountains) have been dated to the Roman Period. The greater area of Bohinj was presumably part of Regnum Noricum (Gabrovec, 1987), which was famous for its crafted metal products, praised by the Romans and exported to Aquileia (Gulf of Trieste). This was possible due to the rich ore deposits in the area, probably collected in the highlands with the ore found next to the stone buildings (Dolga Planja na Voglu; Ogrin, 2020). Higher Pb values in the Roman Period (2000–1800 cal a BP; Fig. 4) indicate metallurgical activity. From 1950 cal a BP *Juglans* appears constantly in the pollen diagram, suggesting that walnut could be spread in the area with the arrival of the Romans (Mercuri *et al.*, 2013).

The migration of Germanic, Hunnic and Slavic tribes in the Late Antiquity/Early Middle Age (1500–1000 cal a BP) forced the locals to seek refuge in settlements at higher altitudes (Ogrin, 2010). These settlements were mostly located in the Lower Bohinj Mountains (Poljanica za Zadnjim Voglom) and some in the same localities that were already used in the Iron Age/Roman times (Kal za Zadnjim Voglom, Dolga Planja na Voglu; Ogrin, 2010, 2020). However, the decrease in Pb values indicates a decline of the metallurgical activities, which is reflected in a slight increase in arboreal taxa. Since 1500 cal

a BP, pollen of *Secale* and since 1000 cal a BP, Cerealia-type pollen, appear frequently. However, historical sources are sparse when it comes to arable farming in the highlands of the Julian Alps. In addition, cereals are self-pollinating and thus spread poorly (Bottema, 1992; Tinner *et al.*, 2007) and are therefore insufficiently represented in the pollen assemblages (Soepboer *et al.*, 2007). Nevertheless, long-distance dispersion or transfer of pollen in the fur or the faeces of the livestock cannot be completely excluded (Dietre *et al.*, 2020).

Between the 11th and the middle of the 16th century (900–450 cal a BP), Pb levels rise again, indicating the return of metallurgical activity. In the lowlands, simple furnaces were built in Mošenac in the 11th century, in Češnjica in the 12th century and in Staro Klad'vo (east of Lake Bohinj) in the 14th century (Cundrič, 2002). However, in contrast to Lake Bohinj (Andrič *et al.*, 2020), the proportion of *Fagus* did not decrease, which could mean that logging was mainly restricted to the lowlands. The sedimentation rate increased during this period, due to the opening up of the landscape, which coincides with the slight decrease in the proportion of tree taxa (mainly *Abies*).

Elevated Pb values in the Roman and High to Late Middle Ages may be regional in nature and transferred from larger metallurgical centres. Most probably they were transferred from the Balkans (Longman *et al.*, 2018); however, centres in Spain cannot be completely excluded (Elbaz-Poulichet *et al.*, 2020). Nevertheless, a number of archaeological finds were found in the highlands and valleys of the Julian Alps, indicating slag in the vicinity of archaeological localities and iron-smelting facilities (Mohorič, 1969), implying that the signal is at least partly local. However, additional analysis would be required to separate local from regional signals of lead.

Intensive human impact with pastoralism and ironworking

In Modern times (after 430 cal a BP), human impact on the environment (forest clearance) was considerable. In this unit, calcite is the predominant mineral accompanied by high and constant input of amorphous material. On the other hand, terrigenous minerals such as dolomite, clay and quartz occur only in smaller percentages, but as the sedimentation rate drastically increases (Unit A), the terrigenous flux was probably relatively high. That indicates an input of regional allochthonous detrital material coming from the catchment, but with relatively low detrital carbonates as those were probably previously dissolved in soils. Higher $\delta^{13}\text{C}_{\text{oc}}$ and relatively low C/N, associated with a very high calcite content of autochthonous origin, indicate eutrophic conditions in the lake. During high eutrophication nitrification is usually so intense that the ^{13}C -enriched biomass overwhelms all other biological sources leading to a more positive $\delta^{13}\text{C}_{\text{oc}}$ (Hollander and Smith, 2001). The C/N ratio varies between 10 and 25, reflecting the important terrigenous organic input combined with autochthonous (algal) source of organic content (Enters *et al.*, 2006). The sedimentation rate and pollen richness index increased, probably as a consequence of further opening up of the landscape (Matthias *et al.*, 2015) coupled with the increased in-lake production of organic matter.

Due to the increased occurrence of the spore *Selaginella selaginoides* (spikemoss), which is typical for subalpine and alpine meadows (Lauber *et al.*, 2012), it can be assumed that open meadows were common in the highlands of the Julian Alps. In addition, charcoal particles increased significantly due to intensive and repeated burning of the area around Lake PNI, to clear and open the land to pastures. The influx of

Sporormiella spores increased drastically and, along with *Rumex*, *Urtica* (requires high nutrient conditions), *Plantago lanceolata* and Asteraceae appear regularly in the samples, suggesting high grazing activity. Percentages of *Abies* are negligible, probably due to the continuous influence of pastoralism on the environment (Tinner *et al.*, 1999). The general trend of decreasing C/N ratios in the core may be due to more severe human impact with higher nutrient inputs, as pastoralism is the main economic activity in the area of Lake PNI. With less arboreal vegetation around the lake and thus a more open landscape in the last 430 years, autochthonous input was more pronounced. Throughout the period, the percentage of *Cannabis/Humulus* fluctuated (maximum of 5%), but the historical records do not mention the use or cultivation of either plant in the area. The process of the hemp retting, which was used prior to rope-making to extract the fibre, could be the reason for higher percentages of hemp that had been previously soaked in water, causing high amounts of pollen to be washed into the lake (Lavrieux *et al.*, 2013).

Pb content in Early Modern times never reached the values from the Middle Ages, due to new and indirect methods of ore smelting that were introduced to the area by blacksmiths from Bergamo. At the beginning of the 16th century they were building the Brescia furnaces, which were more efficient and had higher utilisation of iron (Mohorič, 1969; Cundrič, 2002). Low percentages of *Fagus* were due to the logging in the Bohinj area for metallurgy. In the mid-19th century (100 cal a BP) *Picea* also declined, which is consistent with historical sources stating that beech felling was so strong that only spruce remained (Cundrič, 2002). Palynological data from Lake Bohinj show a similar decline in *Fagus* and *Picea* (Andrič *et al.*, 2020), which could indicate more regional deforestation for metallurgical purposes. In the late 20th century, tree taxa start to increase (up to 70%) due to the abandonment of agricultural practices and reforestation of the area. Since 1981, the greater area of the Julian Alps has been protected as Triglav National Park, with most economic activity limited to tourism and to a lesser extent logging and pastoralism (Zorn *et al.*, 2015).

Regional comparison – human impact

A comparison of the pollen diagram from Lake PNI (1430 m a.s.l.) with Lake Bohinj (Andrič *et al.*, 2020), located in the lowlands of the Julian Alps (526 m a.s.l.), shows that human impact on the environment was lower in prehistory, especially in the Iron Age (ca. 2600 cal a BP). However, at Lake PNI *Plantago lanceolata* has been continuously present since at least about 7500 cal a BP (with a break between 5400 and 4500 cal a BP). In the lowlands around Lake Bohinj, the continuous occurrence of *Plantago lanceolata* started at around 3000 cal a BP, suggesting that pastoralism was established earlier in the highlands than in the lowlands. On the contrary, the appearance of cereals in the lowlands is earlier (Lake Bohinj, ca. 3300 cal a BP) than in the montane zone (Lake PNI, ca. 1500 cal a BP). With many archaeological artefacts found at higher altitudes (>1500 m a.s.l.) (Horvat, 2019; Ogrin, 2010, 2020), the question arises whether different altitudinal belts were used for different purposes and whether this is the same scenario in different parts of the Alps.

In the South Tyrol, agrarian practices in the lowlands were first observed at around 8000–7000 cal a BP and more prominent human impact in the Bronze Age (Putzer *et al.*, 2016). Festi *et al.* (2014) found that in the Ötztal mountains arable farming preceded the pastoralism and argued that the main reason for pastoralism in the highlands was met with the demographic increase and substantial

enhancement in food production in the Middle Bronze Age. On the contrary, Kutschera *et al.* (2014) and the references therein have found evidence for pastoralism from at least ca. 6500 cal a BP in the highlands of the the Ötztal mountains. Schwörer *et al.* (2015) found that anthropogenic indicators in the northern Swiss Alps occurred earlier at higher elevations (2765 m a.s.l., ca. 7000 cal a BP) than at the lower elevations (1382 m a.s.l., ca. 5800 cal a BP). This was mainly by compartmentalising economic activities, with pastoralism at the higher altitudes and arable farming at the lower altitudes (Hafner and Schwörer, 2018). Curdy (2007) suggested that human impact was barely perceptible in the Neolithic with Neolithic people having summer pastures in the subalpine belt and permanent settlements in the valleys. From the Bronze Age onwards, with the increase in the number of people and the consequent greater need to exploit natural resources, people also began to use the middle, montane belt.

These contradictory results should be investigated further, mainly by trying to understand why economic activities varied in different alpine regions. In particular, whether trends in the use of different altitudinal belts were general, or the effects were simply different in particular regions and/or archaeological periods.

Conclusions

Lake sediments hide many interesting secrets that are of interest to various researchers in the evolution of, for example, aquatic systems, anthropogenic impacts or climate change. With high-resolution analyses and the combination of sedimentological, geochemical and palynological data, we found that forest development in the south-eastern Alps quickly followed climate warming that occurred at the transition from the Pleistocene to the Holocene. In addition, a warmer and/or wetter environment caused the shift from wetland to the formation of a eutrophic lake, with alternating anoxic (appearance of pyrite) to oxic (appearance of gypsum) conditions. Higher values of *Corylus* and the absence of *Abies* in the Early Holocene indicate periods of relatively dry climate that lasted until about 8200 cal a BP, when *Abies* became more common. Furthermore, a rapid increase in *Fagus* confirms the early establishment of this tree taxon in the south-eastern Alps at around 10 200 cal a BP. The earliest human impact was noted at the beginning of the Neolithic with the first occurrence of anthropogenic indicators indicating pastoralism, which resulted in slightly increased erosion and in-lake production. From ca. 4500 cal a BP onwards, vegetation and human impact have had a greater impact on the lake geochemistry, with direct climatic influence being hard to detect. The establishment of *Fagus* forests around the lake stabilised the catchment area, causing less erosion. Nevertheless, human impact started to increase gradually towards the late Middle Ages, mainly due to strengthened pastoralism, but also due to the introduction of agrarian practices in Late Antiquity. In the Modern Period (since 430 cal a BP) significant anthropogenic pressure disrupted the stable period in the lake catchment, mostly with deforestation of the area for charcoal production and opening up the landscape for pastoralism, which caused the eutrophication of the lake.

In summary, this work also demonstrates the importance of interdisciplinary research by combining numerous methods to reconstruct environmental changes. Moreover, by understanding the factors that influence environmental changes in the past we can predict the future development of alpine habitats. Short-term climatic models for the Julian Alps show more precipitation in winter months, less in summer months and

overall higher temperatures (Bergant, 2007); coupled with the continued human impact, this may have a big impact on the vegetation and lake stability. With more extreme events, erosion might potentially destabilise the lake catchment area even further and drier summers might limit the regeneration of alpine forests and/or change the composition of the forest, mainly by promoting more thermophilous taxa.

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Supporting information

Additional supporting information can be found in the online version of this article.

Supplementary Figure 1. Simplified geological map of the area around Lake PNI, redrawn from Rman & Brenčič (2002).

Supplementary Figure 2. Principal component analysis of combined geochemical and isotope (total organic carbon, $\delta^{13}\text{C}_{\text{OC}}$ and C/N) results presented downcore.

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