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Quaternary Science Reviews 227 (2020) 106043

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

6600 years of human and climate impacts on lake-catchment and vegetation in the Julian Alps (Lake Bohinj, Slovenia)

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A R T I C L E I N F O

Article history:
Received 28 June 2019
Received in revised form
28 October 2019
Accepted 30 October 2019
Available online 19 November 2019

Keywords:
Holocene
Paleolimnology
Europe
Vegetation dynamics
Human impact
Pollen
Soil erosion
Sedimentology
Stable isotopes
Inorganic geochemistry

A B S T R A C T

Mountain grazing and ore processing had a significant impact on the Alpine environment in the last 5000 years, but few studies have so far focused on environmental changes of the south eastern Alps. This study investigates the vegetation history and sedimentary processes in the catchment of Lake Bohinj (Julian Alps, Slovenia), where a 12-m-long core was collected in the central part of the lake. Sediment in the early Holocene section of the core was partially reworked due to a major seismic event dated to 6711–6523 yr cal BP (Rapuc et al. 2018), therefore a detailed palaeoenvironmental reconstruction was performed only for the top 4.4 m of the core. Here the results of mineralogical, sedimentological, geochemical, stable isotope ($\delta^{13}C$ and $\delta^{15}N$), and pollen analysis are presented in order to better understand the impact of people (agriculture, grazing, mining) on the environment, and climate-human interactions over the last 6600 years.

The results of palynological research suggest that at ca. 6000 yr cal BP Lake Bohinj was surrounded by mixed forest composed of *Picea*, *Abies*, deciduous *Quercus*, with *Fagus* becoming dominant after ca. 3300 yr cal BP. In the Bronze and especially the Iron Age (3500–2500 yr cal BP), when the region was, according to archaeological data, densely populated, clearing of forests due to agriculture, livestock production and metallurgical activities was detected through Cerealia type pollen, *Plantago lanceolata*, and the decline of *Abies*. These activities probably triggered soil erosion recorded as increased sedimentation rates. In the subsequent centuries human impact on the environment continued (increased), but it seems that the watershed was not destabilised again. Several periods of high terrigenous input were recorded at 6100–6000, 5700–5550, 5000–4600, 3900, 3700–3550, 2300–2200 yr cal BP and could be associated with a mobilisation of river inflow from the eastern flysch bearing catchment, due to river migration during periods of wetter climate. These flood patterns match with periods of enhanced flood activity in the wider Alpine region.

1. Introduction

Grazing and ore processing were among the first activities of people living in the Alps (e.g. Gobet et al., 2003; Walsh et al., 2014; Carrer et al., 2016; Reitmaier, 2017; Reitmaier et al., 2018; Hafner and Schwörer, 2018; Moe and Fedele, 2019; Breitenlechner et al., 2013). More than 5000 years natural resource exploitation has had a significant impact on the delicate Alpine environment. Alpine ecosystems (e.g. alpine meadows and mountain forests), which are limited by low temperatures and short growing season, are sensitive to environmental changes (Leuschner and Ellenberg, 2017, 125). People have altered the vegetation (e.g. decline of *Abies* due to grazing and forest clearance/burning, shift of treeline to lower

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https://doi.org/10.1016/j.quascirev.2019.106043

altitudes, Tinner et al., 1999; Colombaroli et al., 2010; Schwörer et al., 2014), chemical composition of the soil (Röpke et al., 2011) and have had a substantial influence on alpine lake ecosystems.

Among all the geological records, lake sediments are long-term and continuous archives that allow investigation of environmental changes occurring in the catchment, associated with local or regional climatic fluctuations and human impact (Last et al., 2001; Last and Smol, 2001; Arnaud et al., 2016). In the last decades several studies have focused on sedimentological and geochemical record, as well as plant and animal micro and macroremains in lake sediments to reconstruct Holocene climatic fluctuations, flood and earthquake chronicles, vegetation changes, fire regimes, soil erosion and human impact on the environment (e.g. Pini, 2002; Heiri et al., 2003; Gobet et al., 2003; Valsecchi et al., 2008; Magny et al., 2012; Vanniere et al., 2013; Czymzik et al., 2013; Joannin et al., 2014; Morales-Molino et al., 2015; Arnaud et al., 2016; Bajard et al., 2016, 2017a, 2017b; Sabatier et al., 2017). However, studies combining high resolution and multi-proxy analyses (e.g. linking high resolution pollen analysis with sedimentological and geochemical research) are still scarce, especially in the eastern Alps. Lake Bohinj, which is located on the south eastern edge of the Alps (Julian Alps, Triglav National Park), is very sensitive to soil erosion and floods, due to the steep topography and hydrology of its watershed (Fig. 1). The area was settled since at least the Bronze Age (Gabrovec, 1974, 1987; Ogrin, 2006; Horvat, 2006), with a tradition of transhumance grazing and ironworking (Mohorič, 1969; Cundrič, 2002). Therefore, intensive human impact on the environment in the Middle/Late Holocene is expected. This makes the lake and its catchment ideal to study the vegetation, the erosion, and human activities over the Holocene. However, Lake Bohinj has received virtually no scientific attention and the only palaeoecological research of lake sediment can be found in Molnar et al. (1978) where mineralogical, geochemical and pollen composition of eight grab samples and one shallow core (45 cm) were analysed.

In 2012 a new 12-m-long core was collected in the central part of the Lake Bohinj basin. Rapuc et al. (2018) identified 29 earthquake events in the last 6600 years, including a major seismic event at 6617 ± 94 yr cal BP that partially reworked previously deposited sediment. This study also showed that between 3500 and 2000 cal. BP the watershed was destabilised due to human activity leading to an increase in erosion and sedimentation rate. Here we focus on vegetation and erosion history of the catchment using pollen, sedimentological and geochemical record, in combination with published archaeological evidence to assess how the environment was shaped by climatic fluctuations and human activities during the last 6600 years.

2. Study area

Lake Bohinj (526 m a.s.l., Fig. 1) is the largest and deepest permanent natural freshwater lake in Slovenia that covers 3.18 km^2, with a maximum depth of 45 m and a catchment area of more than 100 km^2. It is hydrologically an open lake, with water retention time of ca. 3–5 months (Remec-Rekar and Bat, 2003). The current main water inflows are the Savica River with 5 m^3/s and several underwater karst springs with 3.3 m^3/s from the western and northern part of the watershed respectively, whereas water outflow is located in the eastern part (Fig. 1c, Jezernica - Sava Bohinjka, 8.3 m^3/s, Remec-Rekar and Bat, 2003; Zorn, 2010). The lake hydrology is controlled by rain and retention of precipitation as snow (Remec-Rekar and Bat, 2003; ARSO web page, 2018). The lake is oligotrophic, with phosphorus and nitrogen concentrations of 3–7 μg P/l and 464–528 μg N/l respectively (Remec-Rekar and Bat, 2003).

Lake Bohinj is located in an Alpine area with a temperate climate (average of the coldest month is between 0 and -3 °C, and the warmest month between 15 and 20 °C) and a sub-Mediterranean precipitation regime: 3300 mm annual precipitation with a maximum in the autumn (Ogrin, 1996). Spring and autumn mixing of lake water (homothermia) occurs due to strong winds, whereas a layer of warm surface water (1–3 m deep) forms only in the summer. Between 1951 and 2000 the lowest monthly average temperature of the lake surface water was measured in February (1.5 °C) and the highest in August (17.9 °C) (Remec-Rekar and Bat, 2003).

Lake Bohinj is a lake of tectonic-glacial origin (Buser, 1986; Bavec et al., 2004) and it structurally belongs to the easternmost Southern Alps (Placer, 1999; Vrabec and Fodor, 2006). The catchment area of the lake is composed mainly of Upper Triassic massive and bedded limestones and dolomites (Fig. 1d), with few outcrops of Jurassic to Cretaceous limestones (Buser, 1987; Buser et al., 1986; Jurkovšek, 1987a; 1987b; Šmuc, 2005; Šmuc and Rožič, 2009). During the Quaternary period the glaciers covered the upper part of the mountains and filled the upper reaches of the incised valleys (Buser, 1986, 1987; Bavec et al., 2004). In the immediate vicinity of the lake, primarily along the southern and eastern lake margin, tills of the last glaciation are overlying proglacial lake sediments, which are present up to 50 m above the current lake level (Grimšičar, 1961). The main delta formed by the Savica River, located in the western part of the lake is rich in carbonate sand and gravels, with very little fine material, and presents a smooth subaerial slope.

Forests dominated by a mixture of beech (*Fagus sylvatica*), fir (*Abies alba*) and spruce (*Picea abies*) grow at 200–1600 m a.s.l. (*Homogyno sylvestris–Fagetum* plant association, Marinček and Čarni, 2007; Marinček, 1987, Fig. 1e). Larch (*Larix decidua*) occurs mostly in the alpine vegetation belt above ca. 1200–1500 m a.s.l., forming a treeline at ca. 1800 m, with mountain pine (*Pinus mugo*) and dwarf alpenrose (*Rhodothamnus chamaecistus*), in *Rhodothamno-Laricetum* plant association (Dakskobler et al., 2010). Hop hornbeam (*Ostrya carpinifolia*) and flowering ash (*Fraxinus ornus*) stands (*Ostryo-Fraxinetum orni* Aichinger 1933 and *Cytisantho-Ostryetum* M. Wraber, 1961) are characteristic for steep slopes above the lake (Wraber, 1961; Dakskobler, 2015). They occur on inaccessible rock walls and rockfall areas as pioneer taxa, but can grow also on potential beech sites as a result of long-term forest degradation due to goat grazing (Dakskobler, 2015). Gravel beds along the Savica and Sava Bohinjka Rivers are covered by individual willow shrubs (*Salix eleagnos* and *Salix purpurea*) and stands of gray willow (*Salix eleagnos*) and gray alder (*Alnus incana*). Mixed deciduous stands (European ash (*Fraxinus excelsior*), spruce (*Picea abies*) and beech (*Fagus sylvatica*)) grow on slightly elevated terraces (Dakskobler and Rozman, 2013).

Mesolithic archaeological sites in the Bohinj area are extremely rare (Fig. 1a). There is more evidence for settlement since the Middle Bronze Age (ca. 3500 yr cal BP), with sites at higher altitudes (ca. 1600 m a.s.l.) and from the beginning of the Early Iron Age (ca. 2700 yr cal BP), when continuous human presence both in the valleys and in the highlands has been documented (Gabrovec, 1966, 1974; 1987; Horvat, 2006; Mohorič, 1969; Cundrič, 2002). Due to the lack of recent archaeological excavations, chemical and metallographic analysis of slag, and archaeobotanical and archaeozoological research, little is known about the former economy. For example, we do not know when the pasture, alpine dairying and mining in the highlands appeared for the first time and what the impact of these activities on the environment was. Between 1580 and 1880 AD, the region, which is rich in bog ore ('bobovec') and limonite, was well known for ironworks and charcoal production (Mohorič, 1969; Cundrič, 2002, Fig. 1a), but the impact of these activities on the environment was not studied. Previous

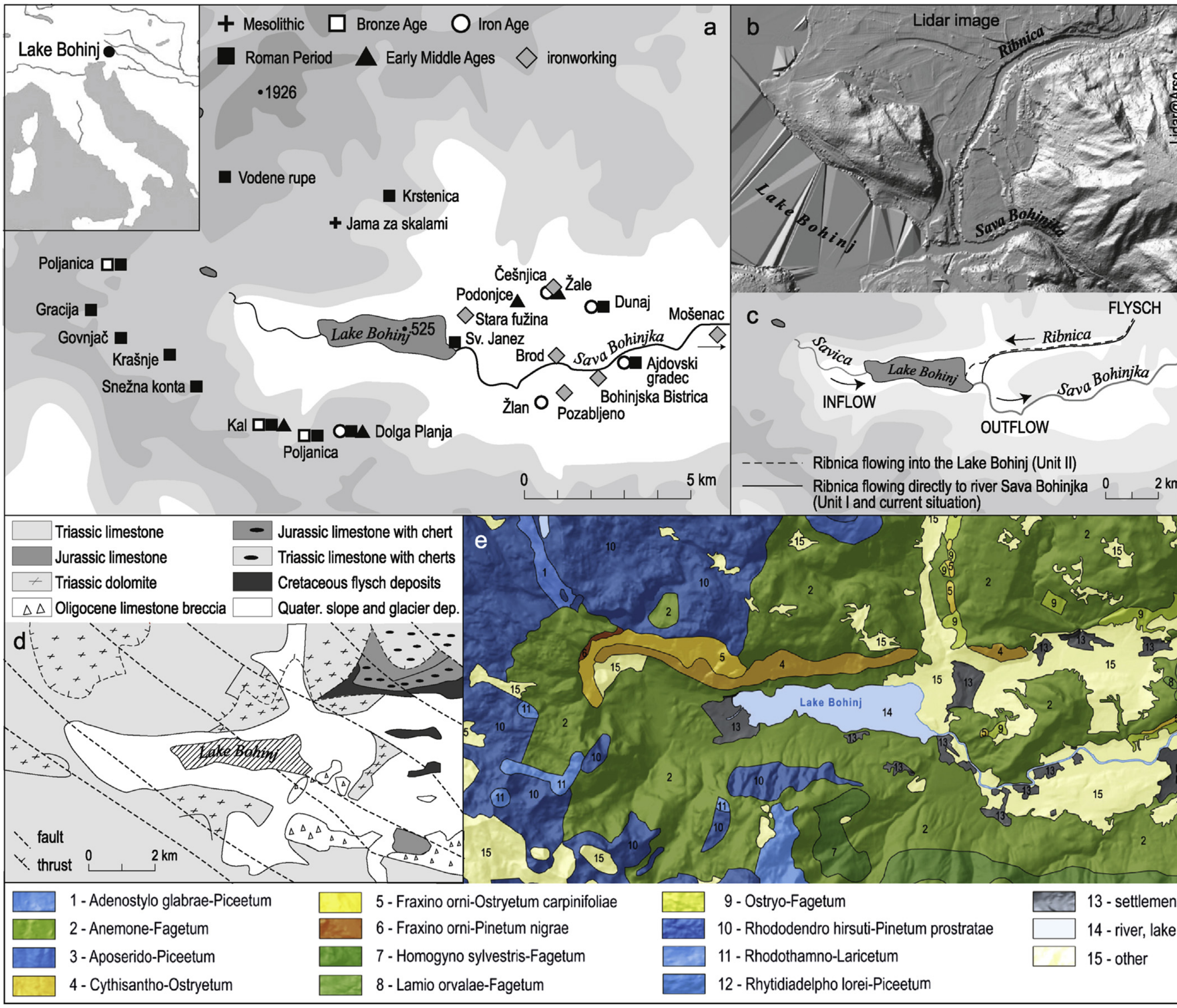

Fig. 1. Lake Bohinj study area. a) archaeological sites (after Ogrin, 2006, 2010) and medieval ironworking (see Table 3), b) LIDAR photo of the area (http://gis.arso.gov.si/atlasokolja/profile.aspx?id=Atlas_Okolja_AXL@Arso), c) map of suggested Lake Bohinj outflows: sedimentation of Unit I (also present-day situation) with the Ribnica River bypassing Lake Bohinj (filled line) and sedimentation of Unit II with inflow of the Ribnica to the lake directly from the east (dotted line). Etnographic legends mention that Vrtovin hill with adjacent 'Sv. Janez' site was an island (A. Pleterski, pres. comm. 2018) d) geological map, e) modern vegetation (courtesy I. Sajko, U. Šilc).

palynological research in the Julian Alps focused on the general development of the Holocene vegetation with low sampling resolution and poor chronological control (Šercelj, 1961, 1965, 1971), while newer detailed and well-dated palynological sequences cover only shorter periods (Culiberg, 2002; Andrič et al., 2009, 2010, 2011).

3. Methods

3.1. Coring

In May 2012 a sedimentary core was collected in the deep basin of Lake Bohinj at 44 m of water depth (46°17′ 6.8″ N, 13°51′ 82.6 ″ E) using a 90-mm diameter piston corer on UWITEC coring platform. A composite profile was constructed from two series of consecutive 2-m-long sections taken from two sites within 5 m of each other laterally, using clearly identifiable stratigraphic marker layers from the overlapping sections of both series, providing a 12.36-m-long continuous sediment profile (BO12). A more detailed methodology is described in Rapuc et al. (2018). In this paper only the results for the upper 443 cm of the core (i.e. the last 6600 years) are presented since part of the early and middle Holocene sequence between 998 and 443 cm (10,320–6600 yr cal. BP) was reworked by a seismic event (Rapuc et al., 2018).

3.2. Age model

The age model of core BO12 (Fig. 2) is described in detail in Rapuc et al. (2018). Before generating the age-depth model with the calibrated ^{14}C ages (Table 1) and the short-lived radionuclide data (Pb-210, Cs-137 and Am-241), the BO12 sequence sediment depth was corrected by subtracting all of the deposits (>3 mm) considered that were instantaneous to build an event-free depth (Rapuc et al., 2018). The first 12 m of the Lake Bohinj sedimentary record

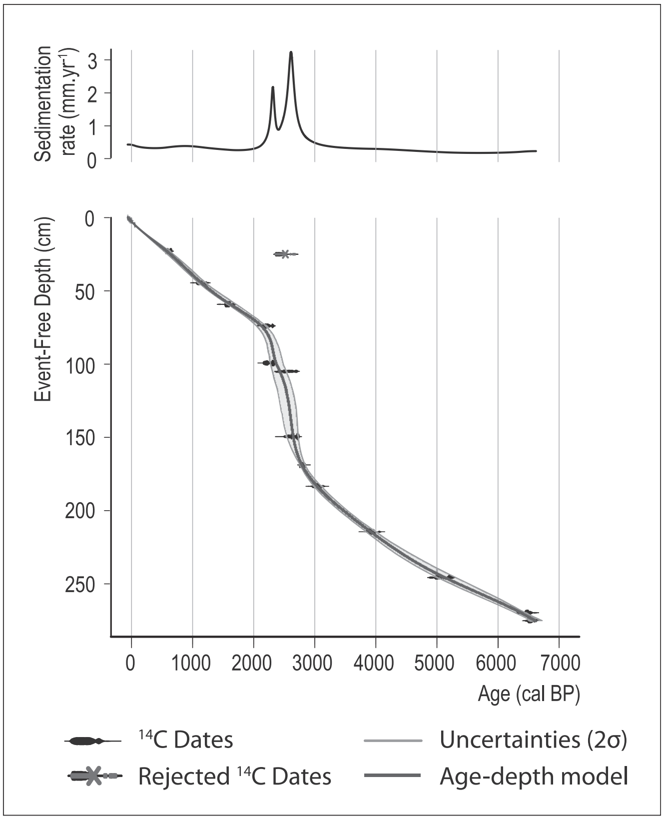

Fig. 2. Lake Bohinj. age-depth model from Rapuc et al. (2018), Fig. 7B.

covers at least 11,560 years, with erosional unconformity at the base of Unit IV (i.e. mixed sediment between 998 and 443 cm, 10,320–6600 yr cal BP). Over the upper 443 cm (last 6600 yr cal BP), the sedimentation is without hiatuses, but contains instantaneous deposits related to earthquake events.

3.3. Sedimentology

Based on visual description, grain size analyses and loss of ignition (LOI) data, the investigated Lake Bohinj sedimentary record can be subdivided into three different sedimentary units (I–III) intercalated with two types of sedimentary layers interpreted as instantaneous deposits triggered by earthquake events (for more detail see Rapuc et al., 2018).

3.4. Mineralogy

From each sedimentological unit 2–4 samples were taken for mineralogical analysis (Table 2). Mineralogical composition of the samples was identified via X-ray diffractometry (Philips, PW 1820) carried out on unoriented powder mounts. Qualitative and semi-quantitative estimations were based on peak intensity measurement of X-ray patterns (Cu Kα/Ni 40 kV, 30 mA) using the X'Pert HighScore software program.

3.5. Geochemistry

Geochemical analyses were carried out at high resolution by X-Ray fluorescence (XRF) on the EDYTEM laboratory's AVAATECH Core Scanner using a rhodium anode. We used a 5 mm sampling step over the whole sequence. The settings used for this analysis were a run at 10 kV and 0.75 mA for 15s to detect the lightweight elements as Al, Si, K, Ti, Mn, Fe and a second run at 30 kV and 0.5 mA for 45s to detect Br, Rb, Sr, Zr and Pb.

Table 2
Lake Bohinj. XRD mineralogical data (%). MCD = Master core depth.

MCD (cm)	Unit	Calcite	Dolomite	Quartz	Illite	Chlorite	Kaolinite
12	U1	18.7	38	12	29.9	0	1.5
73	U1	8.6	48.5	13	27.4	1.1	1.3
123	U2	4.2	0.7	57.7	33.5	3.3	0.6
135	U2	12.3	1	52.1	30.7	3.6	0.2
176.5	U3	18.4	66.6	7.7	7.1	0.1	0
180	U3	21.2	65.1	7.5	6.1	0.1	0
204	U3	29.9	12.8	40.1	16.8	0.4	0
262.5	U3	34.4	28.2	27.1	10.3	0	0
343	U2	10.7	0.8	51.2	32.3	4.5	0.5
386.5	U2	26.3	5.9	40.4	24.3	2.9	0.3
391.5	U2	5.2	3	53.2	33.3	5.4	0
401.5	U1	11.7	46.6	12	26.4	0	3.3

Table 1
Lake Bohinj radiocarbon dates (Rapuc et al., 2018), dates in bold were excluded from the age-depth model. – unidentified plant material.

Sample name	Core	MCD (cm)	Composite depth (cm)	Radiocarbon age	Age cal yr BP 2 σ range	Sample type
Poz-73377	BO12_01A	34	22.9	630 ± 30	552–662	–
SacA41394	**BO12_01A**	**53**	**25**	**2410 ± 30**	**2351–2684**	**wood**
SacA36003	BO12_01A	78.5	44.5	1210 ± 30	1059–1255	twig
Poz-73378	BO12_01A	95	56.2	1665 ± 30	1446–1691	–
SacA41395	BO12_02A	116	73.9	2230 ± 30	2153–2332	wood
SacA41396	BO12_02A	154.3	99.2	2245 ± 30	2156–2340	twig
SacA41397	BO12_02A	165.8	104.9	2485 ± 30	2439–2724	–
SacA36004	BO12_02A	248	149.5	2545 ± 35	2494–2751	leaf
SacA41398	BO12_02A	277.8	168.8	2675 ± 30	2750–2844	twig
SacA41399	BO12_01B	303.8	183.4	2900 ± 30	2953–3155	twig
SacA41400	BO12_02B	355	214.5	3625 ± 30	3849–4069	twig
SacA36005	BO12_02B	395.5	245.7	4430 ± 35	4874–5276	leaf
SacA41401	BO12_01C	435.3	269.7	5705 ± 30	6408–6600	moss
SacA36006	**BO12_01C**	**444.5**	**275.1**	**6770 ± 40**	**7576–7674**	**wood**
SacA36007	**BO12_03C**	**605**	**275.1**	**5740 ± 30**	**6454–6634**	**wood**
SacA36008	**BO12_01D**	**759**	**275.1**	**8675 ± 40**	**9542–9732**	**wood**
SacA36009	**BO12_03D**	**843.5**	**275.1**	**6300 ± 30**	**7166–7274**	**wood**
SacA36010	**BO12_01E**	**864**	**275.1**	**7105 ± 50**	**7841–8011**	**wood**
SacA36011	BO12_01E	1014.5	282.6	9205 ± 45	10249–10495	wood
SacA36014	**BO12_01E**	**1037.5**	**294.8**	**9815 ± 30**	**11198–11252**	**wood**
SacA36012	BO12_01F	1169.5	411.4	9740 ± 45	10907–11243	wood

3.6. Stable isotopes

Samples for stable isotope analysis were taken at a 2–8 cm resolution throughout most of the core. Total organic carbon content (OC), total nitrogen concentration (TN), and their stable isotope compositions ($\delta^{13}C_{OC}$, $\delta^{15}N_{TN}$) were determined by continuous flow isotope ratio mass spectrometer (IRMS) IsoPrime100 - Vario PYRO Cube (OH/CNS Pyrolyser/Elemental Analyser). Before the analysis, samples for $\delta^{13}C_{OC}$ were treated with 1 M HCl to remove carbonate minerals. An aliquot of dry sample was wrapped into a tin capsule and analysed after combustion in an O_2 atmosphere in a quartz reactor at 1020 °C. All stable isotope values are given conventionally in δ-notation in per mil deviation (‰) relative to the Vienna Pee Dee Belemnite standard (VPDB) for carbon and air-N_2 for nitrogen. The calibration and assessment of the reproducibility and accuracy of the isotopic analysis were based on replicate analyses of laboratory standard materials and international reference materials: IAEA-CH-6 and IAEA-CH-7 for $\delta^{13}C_{OC}$ analysis and IAEA-N-1 and IAEA-N-2 for $\delta^{15}N_{TN}$. The reproducibility was better than 0.2‰ for both carbon and nitrogen.

3.7. Pollen analysis

For pollen analysis, 1 cm^3 of sediment was subsampled with a 2–8 cm resolution throughout most of the core. A standard laboratory procedure was used (HCl, NaOH, HF, acetolysis, staining with safranine, mounting in silicone oil, Bennett and Willis, 2002) and pollen concentration was determined by adding *Lycopodium* spores (Stockmarr, 1971). Pollen was identified using Nikon Eclipse E400 light microscope at 400× magnification, the pollen reference collection at the Institute of Archaeology ZRC SAZU in Ljubljana, and pollen keys (Reille, 1992, 1995; Moore et al., 1991). A minimum of 500 pollen grains of terrestrial vascular plant taxa and fern spores (=pollen sum) was counted in each sample, with the exception of layers with very low pollen concentration (e.g. at 124–224 cm), where pollen sum was <500. Microscopic charcoal concentrations and influxes were estimated in the pollen slide as for pollen (i.e. using exotic *Lycopodium* spores). The pollen data were analysed and plotted using PSIMPOLL 4.26 program software (Bennett, 1998, PSIMPOLL Website, 2006). Pollen diagrams were divided into statistically significant zones (B1–B6) using a broken-stick model (binary splitting by sum of squares, Bennett, 1996). Values lower than 0.5 are marked with a solid dot.

4. Results

4.1. Sedimentology

Over the upper 6600 yr cal BP, three sedimentary Units and two types of instantaneous deposits associated with earthquake events were defined (Rapuc et al., 2018, Fig. 4). Briefly, Unit I (after 2000 yr cal. BP and 3300–6600 yr cal. BP) is mainly composed of very dark gray clay interrupted by a few white clayey laminae and graded beds. Unit II is a dark gray to bluish gray clayey deposit and is present in different parts of the sediment core. Unit III (3300–2200 yr cal. BP) is characterised by clayey to silty gray graded layers. Through the rest of the manuscript, as instantaneous deposits are related to earthquake event and not to climate (flood) or environmental changes we remove all these deposits from the sedimentary sequence and present analyses only on the continuous sedimentation.

The sedimentation rate over the last 6600 yr cal BP derived from event-free age depth modelling allow to identify three different periods (Fig. 4): (i) a period of low sedimentation rate with a gradual increase from 6600 to 2900 yr cal BP (0.3–0.5 $mm.yr^{-1}$), ii) a sudden increase of the rate between 2800 and 2100 yr cal BP, reaching two maxima of 3.2 $mm.yr^{-1}$ at approximately 2600 yr cal BP and 2.2 $mm.yr^{-1}$ at 2300 yr cal BP associated with a decrease to 0.9 $mm.yr^{-1}$ at approximately 2400 yr cal BP and finally (iii) a period of low sedimentation rate (0.5 $mm.yr^{-1}$) over the last 2100 yr cal BP.

4.2. Mineralogy

Sediments are composed of dolomite, calcite, quartz, illite, chlorite and kaolinite in different ratios (Table 2, Fig. 3). After applying principal component analysis (PCA) on the mineralogical data we identified different mineralogical end members.

Unit I is composed predominately of dolomite (38–48%) and illite (26–29%), mixed with other minerals, including calcite (8–18%), quartz (12–13%), and kaolinite (1–3%) (Table 2 and Fig. 3). Unit II is characterised by a high percentage of quartz (40–57%) and illite (24–33%); other minerals occur rarely and include calcite (4–26%), chlorite (3–5%), dolomite (1–6%), and kaolinite (0–0.6%). Unit III is composed predominately of quartz (27–40%), calcite (30–34%), dolomite (12–28%), and illite (10–16%); this unit contains more quartz and less illite than Unit I.

4.3. Geochemical composition of the sediment

We applied a PCA on geochemical data (Sabatier et al., 2010) and identified three different chemical end-members (Rapuc et al., 2018): (i) terrigeneous input (Si, Al, K, Ti, Rb, Zr and Fe), (ii) carbonate component (Ca and at lesser extend Sr) and (iii) organic matter component as Br intensity is correlated to LOI550 (r^2 of 0.79 and $p < 0.001$). The mapping of the units in the PCA reveals that Units II and III are positively correlated to the detrital end-member, with very low carbonate content for Unit II (Rapuc et al., 2018, Fig. 3). Unit I is closer to the organic matter and carbonate end-members. In the Unit III, the Sr/Ca ratio is somewhat higher than the mean ratio along the core. As Br intensity is correlated to

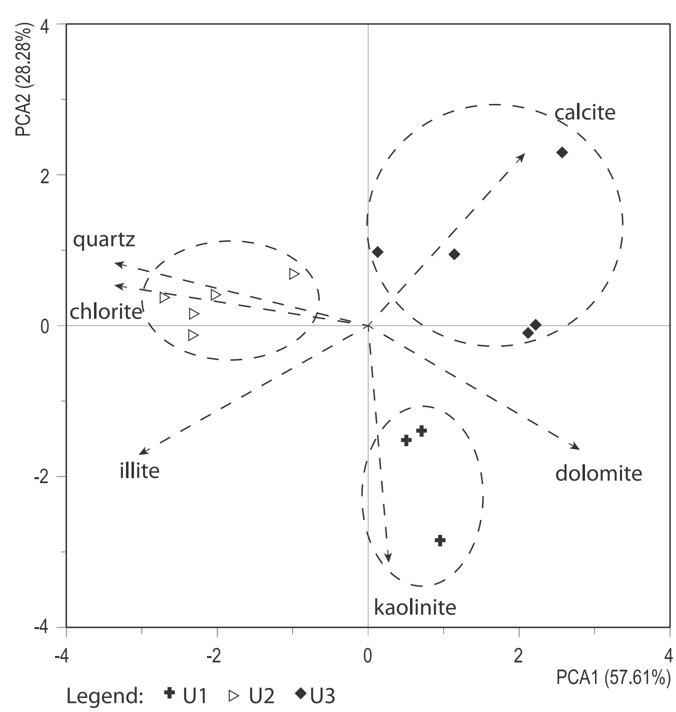

Fig. 3. Lake Bohinj, PCA of mineralogical data.

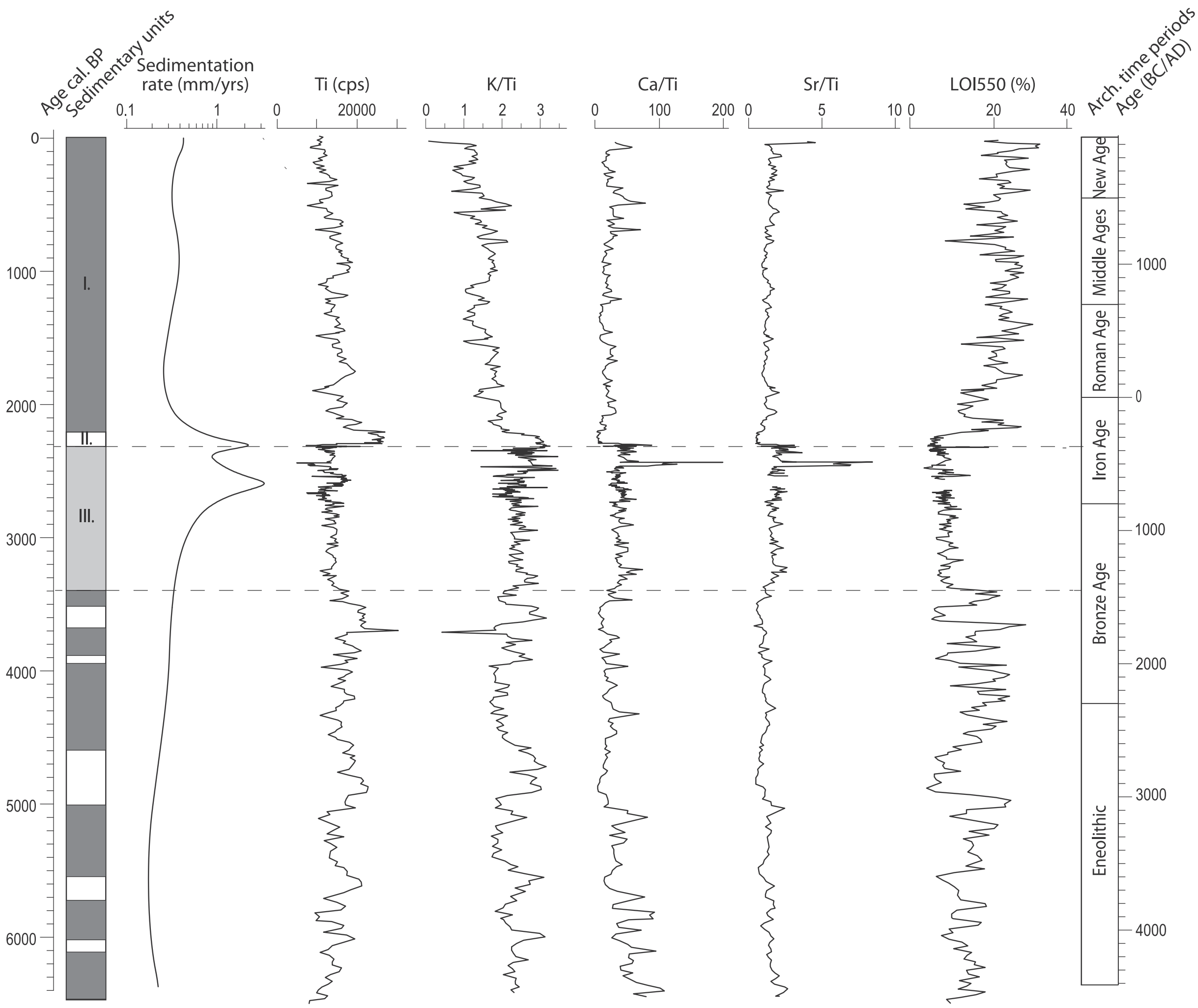

Fig. 4. Lake Bohinj, sedimentation rate and main geochemical results. LOI550 data is calculated form Br vs LOI550 correlation.

LOI550 we transformed Br intensity to high resolution LOI550 content.

4.4. Organic carbon, C/N ratio and stable isotopes of organic matter

OC concentrations of 0.68–8.00 wt % and TN concentrations of 0.08–0.65 wt% were obtained (Fig. 5a). These contents of OC and TN were higher in the upper part of the sediment down to the depth corresponding to the age of 2305 yr cal BP. OC and TN concentrations are correlated (Fig. 5b, $r^2 = 0.86$, $p < 0.01$). An intercept at 0.06 wt % indicates that nitrogen content of samples is not only organic in nature with respect to OC (Stein and Rack, 1995) and thus some influence of inorganic nitrogen on $\delta^{15}N$ values, can be expected. Fig. 5a shows that the lowest concentrations of OC and TN are present in Unit III. The atomic OC/TN ratios ranged from 4.5 to 15.7 with the average of 9.8 ± 2.4. These ranges show different relative contributions of autochthonous/allochthonous organic matter (OM) to sediments: a higher proportion of allochthounous OM corresponds to higher OC/TN ratios. Usually a terrestrial source is characterised by a low $\delta^{13}C_{OC}$ value of −26.6 ± 0.4‰; variable OC/TN ratios 8.3 < OC/TN < 13.7 and variable $\delta^{15}N$ values (1.4–5.2‰). Oligotrophic lakes such as Lake Bohinj might be expected to have relatively high proportions of allochthonous C contribution to sediment OM (Gu et al., 1996). There is no clear pattern on the OC/TN ratio distributions according to sedimentary Units; lower and higher OC/TN ratios are observed in all zones indicating a dynamic system changes occurring in Lake Bohinj. In the sediments, the mean $\delta^{13}C$ value of −27.1 ± 0.8‰ (range: from −28.6 to −24.9‰) and $\delta^{15}N$ value of +0.8 ± 0.8‰ (range: from −0.9 to +1.8‰) were observed. No correlation was observed between OC/TN ratios and $\delta^{13}C$ and/or $\delta^{15}N$ values (Fig. 5c), however, based on $\delta^{15}N$ values, we observed the lowest values in Unit I zone and the highest in Unit III.

4.5. Pollen

The pollen diagram of selected taxa covering the last ca. 6600 yr cal. BP is divided into six pollen zones (Fig. 6a and b). In the lowest zone (B-1, 6600–6400 yr cal BP) pollen of tree taxa prevails, including *Fagus* (25–45%), *Picea* (15–25%), *Abies* (5–15%), *Quercus* deciduous type (10–15%) and *Corylus* (5–10%). The pollen concentration is 10,000–400,000 grains cm^{-3}. The main characteristic of zone B-2 (6400–3750 yr cal BP) is a decline of *Fagus* to <10%, but with individual *Fagus* peaks (20%, 20% and 40%) at 5950, 5600 and 4800 yr cal BP. *Picea* and *Abies* increase to ca. 10–40% and 5–25% respectively. In the pollen zone B-3 (3750–3300 yr cal BP) *Picea* decreases to ca. 10–20%, whereas *Fagus* shortly increases at 3650 yr cal BP, followed by an increased percentage of monolete fern spores (Filicales), degraded pollen and layers with very low pollen concentration (3000–6000 grains cm^{-3}). The highest percentage of *Fagus* pollen (15–50%) was detected in pollen zone B-4

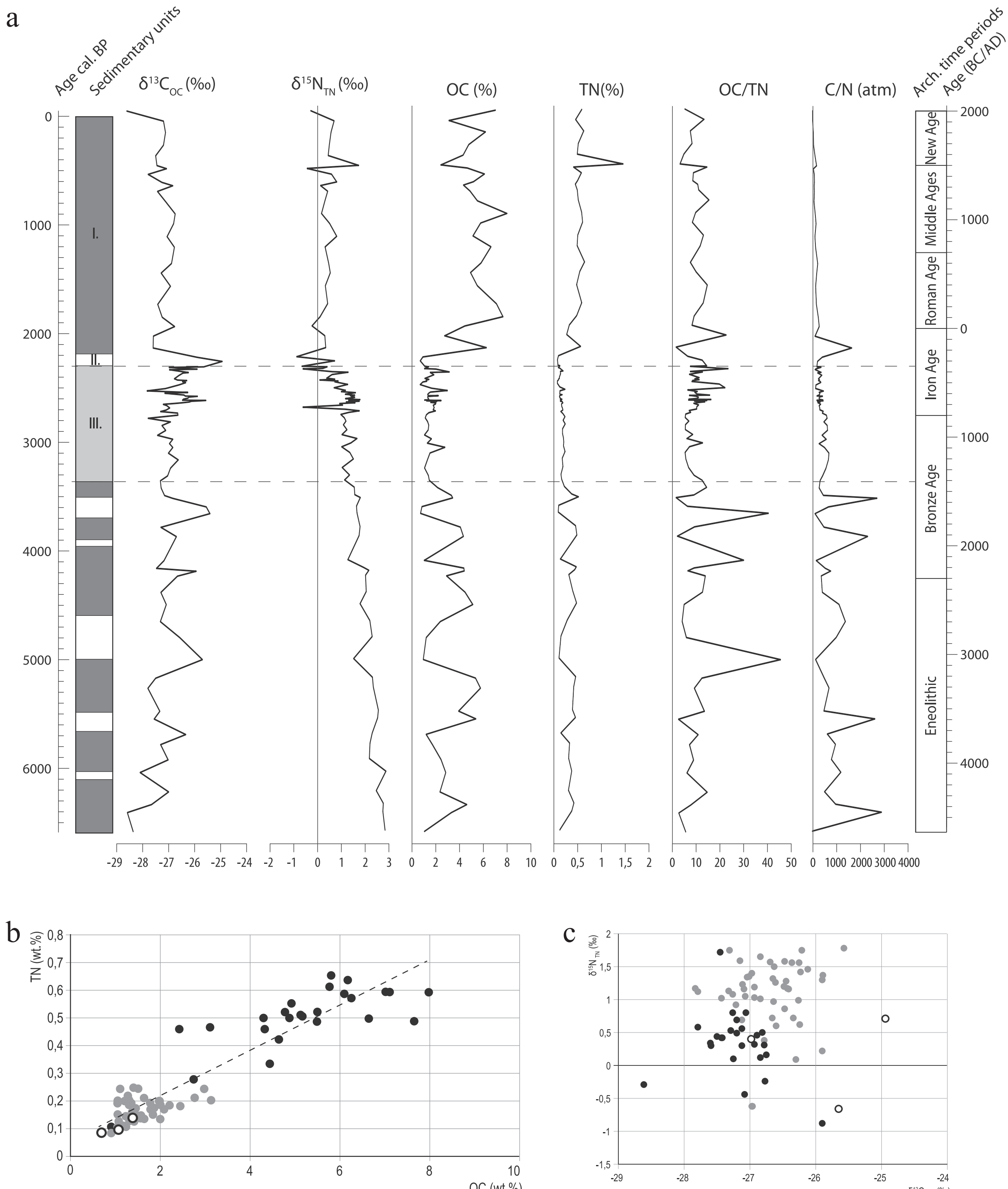

Fig. 5. Lake Bohinj. a) Organic carbon, C/N ratio and stable isotopes of organic matter; b) TN/OC correlation; c) δ^{15}N vs. δ^{13}C values in different Units.

(3350–2650 yr cal BP, lower Unit III), where *Abies* declines to ca. 5–10%. A slight increase of birch (*Betula*), hornbeam and hop hornbeam (*Carpinus betulus* and *Carpinus orientalis/Ostrya* type) was also detected, whereas anthropogenic indicator taxa (e.g. Cereal t., rye (*Secale*), ribwort plantain (*Plantago lanceolata*), goosefoot (Chenopodiaceae)) occur more frequently. A major change of vegetation takes place at the beginning of pollen zone B-5 (2650–2200 yr cal BP), when some tree taxa (e.g. *Abies*, deciduous *Quercus*, but not *Picea*) also decline, whereas herbs (grasses (Poaceae), Chenopodiaceae, mugwort (*Artemisia*), cichories (Cichoriaceae) and Filicales increase. The percentage of degraded pollen increases to 5–10%, whereas pollen concentration in this zone is the lowest of the entire sequence (3000–9000 grains cm^{-3}). Towards the end of zone B-5 the percentage of tree pollen increases again to ca. 90%, however in the subsequent zone B-6 (2200 yr cal BP–AD 2012; Unit I) it remains lower (<80%) and herbs higher (>10%)

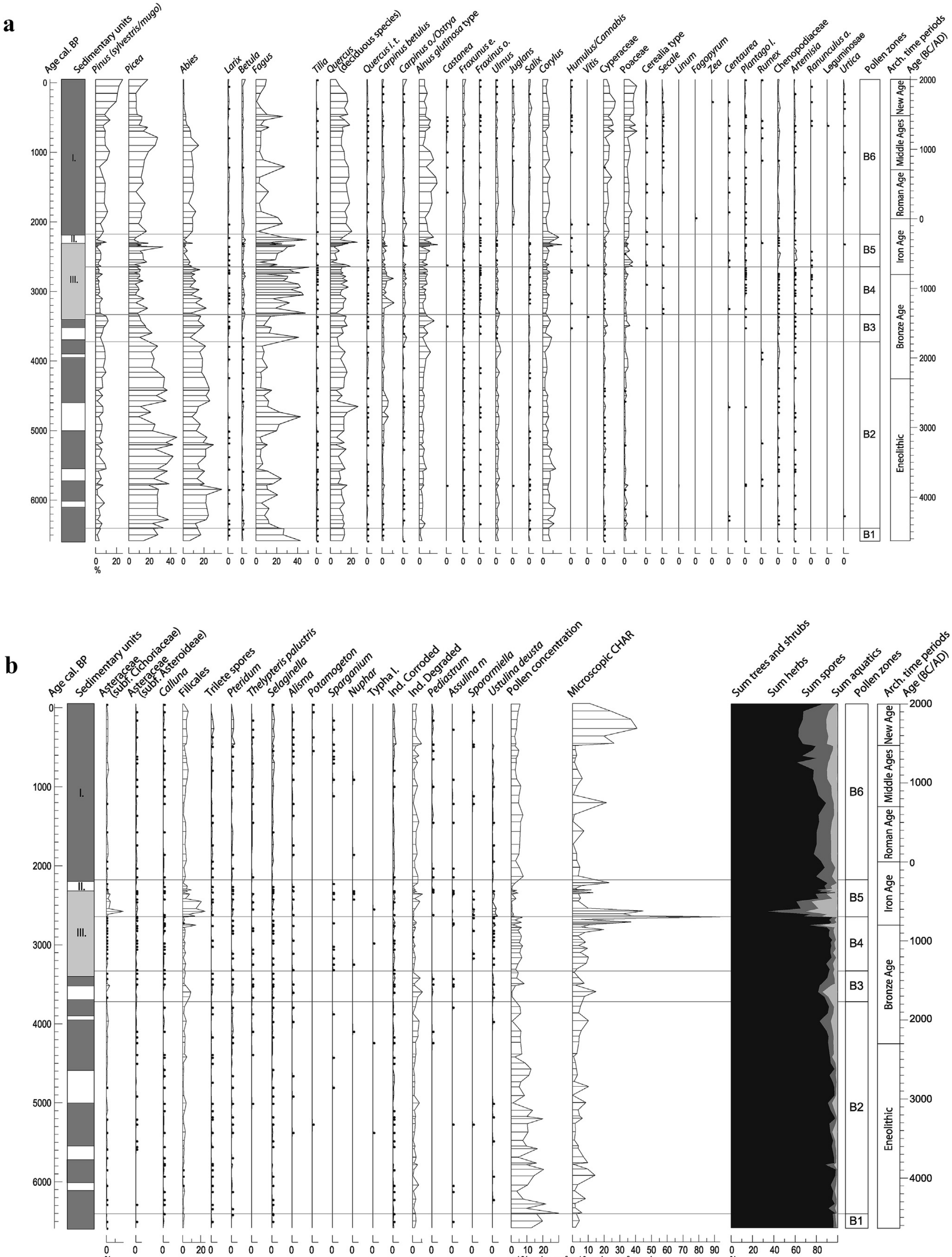

Fig. 6. a, b. Lake Bohinj, pollen diagram of selected taxa. Taxa, present with <0.5% are marked with a solid dot.

than in zones B-1 to B-4. Towards the top of the sequence, after ca. 800 yr cal BP, herbs, including anthropogenic indicator taxa increase to ca. 12–28%, whereas tree taxa (especially *Picea* and *Abies*, partly *Fagus*) decline and start to increase again only in the last century.

5. Discussion

5.1. Sedimentological and hydrological changes in the lake-catchment system

The investigated Lake Bohinj succession is composed of three sedimentological Units that differ from mineralogical, geochemical and sedimentological point of view.

The current sedimentation and most of the Unit I (Table 2, Figs. 3 and 4) is characterised mainly by carbonate terrigenous material (dolomite), with few siliciclastic terrigenous material and relatively high organic matter contents. According to the geology of the lake catchment (see Fig. 1d) this sediment originates from central and western part of the watershed, and is mainly brought by the Savica River feeding a large delta in the western part of the lake.

Unit II is present throughout the succession in six discrete time intervals, lasting from ca. 100 to almost 400 years (6100–6000, 5700–5500, 5000–4600, ca. 3900, 3700–3550 and 2300–2200 yr cal BP, Figs. 4–7). It is composed of clastic terrigenous material (ca. 80% of all minerals, Table 2) dominated by quartz and illite (which explains higher K content, illustrated by higer K/Ti ratio, Fig. 4). Sediment in this unit also has higher $\delta^{13}C_{OC}$ values and contains more *Fagus* and degraded pollen (Figs. 5a, 6 and 7). The only possible large source of this material is located in the eastern part of the lake-catchment where outcrops of Cretaceous siliciclastic flysch deposits are located (Fig. 1d). However, there is no active river inflow from the east (Fig. 1c) in the current setting as the Ribnica River completely bypasses the lake and is flowing directly to the Sava Bohinjka outlet (Fig. 1c). Therefore, direct input of large amount of quartz and illite to the lake from this part of the watershed is currently not possible. Thus, the mobilisation of eastern lake catchment in Unit II marks the onset of an avulsion and direct inflow of the Ribnica River into the lake from the east (Fig. 1c). These events can be related to 'normal' autocyclic process, seismic events (at least for the older occurrence of the Unit II, see Rapuc et al., 2018) or wetter climate and higher lake level/floods (see 5.2 and Fig. 7). Our interpretation is supported by abandoned older Ribnica River channels (Fig. 1b), abrupt changes from Unit I to Unit II and vice versa and mineral composition of lake pelagic sedimentation in Unit II.

The Unit III (3400–2300 cal. BP) is mineralogically quite diverse, however the majority of grains belong to carbonates (Table 2). In this sense it is mineralogically similar to Unit I, however in Unit III quartz predominates over illite. Also here the majority of grains was deposited to the lake from the central and western part of the catchment area.

The upper part of the Unit III (ca. 2470–2450 yr cal BP) is different from the lower part and composed almost exclusively of carbonates while other minerals represent only a minor fraction (15%, Table 2). In this part a higher Ca/Ti and Sr/Ti ratio (Fig. 4), indicates a high amount of terrigenous carbonates. Namely, the Triassic marine carbonates from the catchment area contain a higher amount of Sr in comparison to authigenic lake carbonates. In this upper part of the Unit III we observed the lowest concentrations of OC and TN and the highest atomic OC/TN ratios (proxy for input of allochthonous organic matter such as terrestrial C3 plants; Fig. 5a), while the sedimentation rates are drastically higher than in the entire core (Fig. 4). We interpret this change as an onset of higher (almost an order of magnitude higher) erosion rates and mobilisation of both, fine-grained carbonate fraction from older glacial sediments deposited in the eastern and central part of the lake catchment, and probably soils formed since the Late Glacial period.

The content of K and Ti (K/Ti ratio) is related to different amount of input from flysch vs. carbonate catchments and the intensity of soil weathering (Arnaud et al., 2012; Bajard et al., 2017a). Deep soil horizons, which are close to the parent material, are richer in K, whereas well-weathered horizons closer to the surface are depleted in K (Bajard et al., 2017a). The K/Ti ratio can thus be used as an indicator of weathering (Arnaud et al., 2012) and allows to distinguish whether material deposited in a lake comes from deep or surface soil horizons. K/Ti values are very high in Units III and II (during the mobilisation of eastern flysch catchment), relatively constant in Unit I below 3500 yr cal BP and show a decreasing trend since 2200 yr cal BP, probably reflecting a higher contribution of weathered material to the lake sediment (Fig. 4). During the phase of high erosion, in the second part of Unit III (2470–2300 yr cal BP) the mobilized material is mainly low weathered. During Unit II, the increase in K/Ti could be interpreted as source origin, tracking flysch erosion through the Ribnica River direct inflow.

5.2. Middle Holocene (6600–3500 yr cal BP): vegetation history and lake-catchment system

The pollen record suggests that between 6600 and 3500 yr cal BP Lake Bohinj was surrounded by mixed forest of *Fagus*, *Picea*, *Abies* and deciduous *Quercus* (Fig. 6a and b). This forest composition was not stable and shows short-term variability in the proportion of the main tree species. Fluctuations of *Picea*, *Abies* and *Fagus* abundance can be associated with fire frequency (see microcharcoal influx, Fig. 6b). Palaeoecological research in the Balkans (Serbia, Bulgaria) namely indicated that *Picea abies* (fire return interval: FRI 500 yrs), *Picea omorika* (FRI > 100 yrs) and *Abies alba* (FRI 350 yrs) can tolerate low-intensity/frequency fire regimes (Finsinger et al., 2017; Feurdean et al., 2019). Recent ecological research indicates that in todays warmer and/or drier climate *Abies alba* seems to be growing more and is probably more drought tolerat than beech (Bosela et al., 2018). In the Carpathian Mountains the Holocene establishment of *Fagus sylvatica* was facilitated by fire, but its expansion coincided with major gaps in fire events, whereas severe or large and frequent fires negatively affected *Fagus sylvatica* (Feurdean et al., 2017a,b). A similar pattern of fire and vegetation dynamics can be suggested also for Lake Bohinj, where presumably a wetter climate (Unit II, see discussion above/below) and/or periods with lower fire frequency/intensity (Fig. 6b) presumably led to short-term expansions of *Fagus*, whereas *Fagus* decline is associated with microcharcoal peaks (at ca. 5900, 5700, 4800 and 3600 yr cal. BP). The lack of continuous sampling for micro- and macrocharcoal at Lake Bohinj does not allow us to resolve the impact of fire return interval (FRI) on forest composition and additional research is needed to clarify this topic.

Human impact on the environment was very weak. *Picea* and *Abies* increased between 6400 and 5000 yr cal BP, whereas *Fagus* declined. Individual pollen grains of primary (Cerealia type and *Linum*) and secondary anthropogenic indicator taxa (e.g. *Centaurea*, *Plantago lanceolata*, Chenopodiaceae, *Artemisia*, Poaceae) as well as slightly increased microcharcoal concentration from 6200 to 5800 yr cal BP tentatively suggest small scale forest clearance and the expansion of agricultural fields and grazing areas in the vicinity of Lake Bohinj. However, only individual Eneolithic stone artefacts from uncertain archaeological contexts (Gabrovec, 1974, 1987; Vičič, 1983; Valič, 1987) were discovered in the area. This is in contrast to numerous pile dwelling archaeological sites found at Ljubljansko barje in central Slovenia ca. 60 km southeast of our site

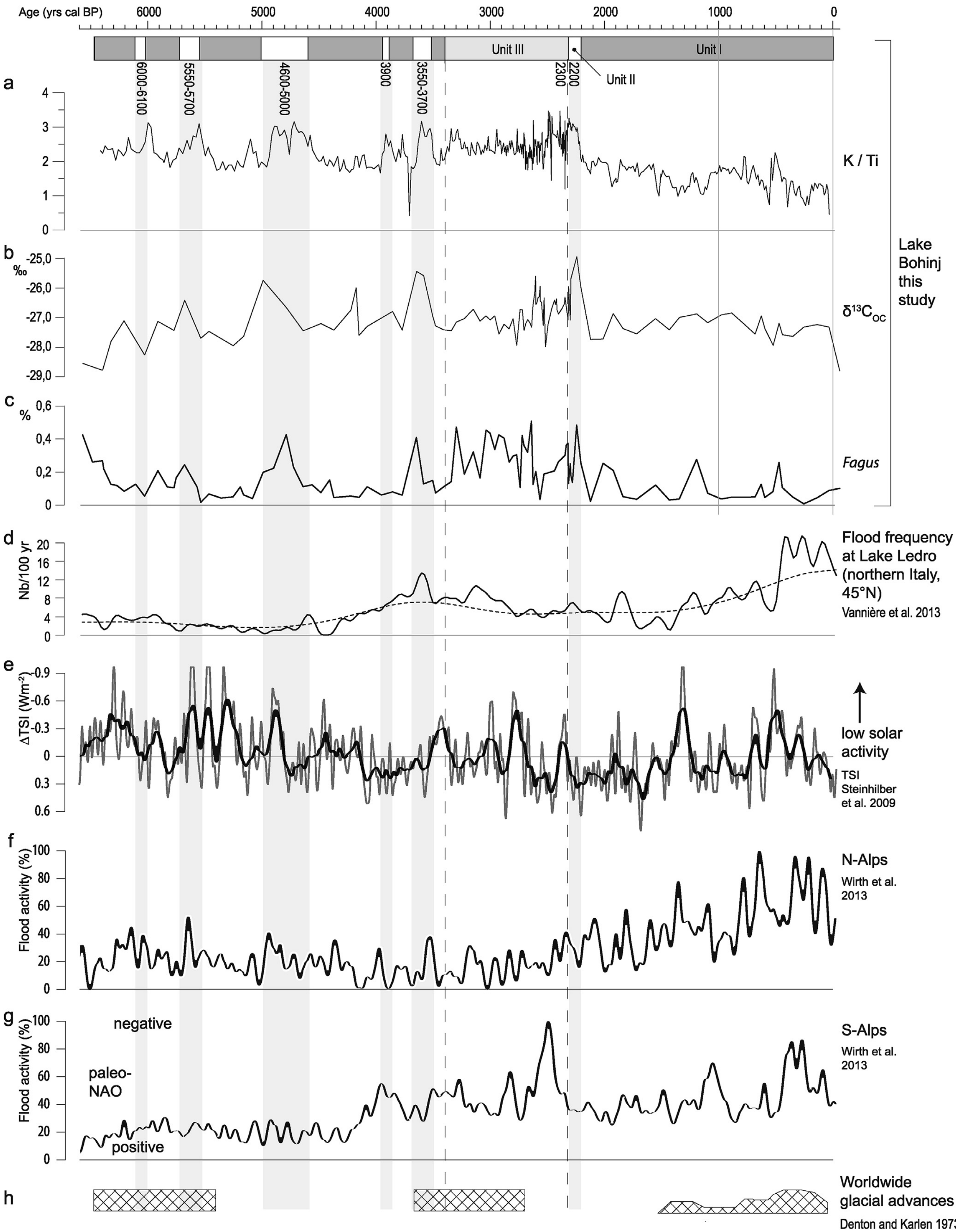

Fig. 7. Comparison of Lake Bohinj results with other palaeoenvironmental archives. a–c) Lake Bohinj (this paper), d) flood frequency at Lake Ledro (Vanniere et al., 2013), e) variations in TSI (Steinhilber et al., 2009), f) flood activity in the N-Alps and S-Alps (g), Wirth et al. (2013), h) worldwide glacial advances (Denton and Karlén, 1973). Gray shaded areas mark Unit II events at Lake Bohinj.

(Velušček, 2006; Tolar, 2018). The lack of archaeological sites and weak anthropogenic pollen signal in Bohinj indicates that the surrounding area was only sparsely settled. There is no evidence of soil erosion or changes in OC and TN content, OC/TN ratios; $\delta^{13}C$ and $\delta^{15}N$ values indicate still high presence of autochthonous OM in sediments.

After 5800 yr cal BP human impact on the environment is less visible, but *Fagus* stays low (5–15%), with the exception of several *Fagus* peaks at 5950, 5600, 4800 and 3700 yr cal BP. These peaks correspond with sedimentary unit change (Unit II) with high sliliciclastic content of terrigenous input (high K/Ti ratio, see chapter 5.1). In these samples pollen concentration is very low, with increased percentage of degraded pollen and microcharcoal concentration in some samples. Sporadic change to Unit II sedimentation is related to mobilisation of inflow from the eastern, flysch bearing catchment (see chapter 5.1) in periods of more humid climate, due to different possible reasons (e.g. higher lake levels or channel migration of the Ribnica river, see previous chapter; Fig. 1c). The spread of *Fagus*, which is sensitive to summer drought and low temperatures (Ellenberg, 1988; Maxime and Hendrik, 2011; Cheddadi et al., 2016), was presumably promoted by wetter climate (and consequently gaps in fire events). Another possibility is that *Fagus* pollen peaks can be associated with taphonomic reasons. Namely, because of altered hydrological conditions, the pollen source area also changed: more *Fagus* was presumably growing in the lowlands, along the Ribnica river, which brought more soil organic matter (including *Fagus* pollen) to the lake.

5.3. Bronze and Iron Age (3500–2000 yr cal BP): intensive human impact on the vegetation, destabilisation of the catchment and soil erosion

The anthropogenic indicator pollen taxa indicate that human impact on the environment started to increase again at 3500 yr cal BP. The sporadic occurrence of cereal pollen (Cerealia type and *Secale*), ruderal taxa (e.g. Chenopodiaceae) and grazing indicators (*Plantago lanceolata* and *Sporomiella* spores of coprophilous fungi) suggest an intensification of farming activities in the Bronze Age. Forest clearances are also suggested by a higher percentage of Poaceae, *Betula* and *Corylus*. Also a decline of *Pinus* can be associated with human activities at treeline. Palaeoecological research in central and Northern Iberia suggested that, although highland pines (*Pinus nigra, Pinus sylvestris, Pinus unicata*) are resilient to natural fire regimes of frequent small-moderate fires and rare high intensity fires, frequent human-caused crown fires and the onset of intensive farming can lead to their demise over an extensive area (Rubiales et al., 2012; Morales-Molino et al., 2017). Anthropogenic disturbance, e.g. fire and browsing could have affected *Abies*, a taxon sensitive to grazing (Tinner et al., 1999). The abundance of *Abies* pollen declined below ca. 15% and in the last 3000 years never recovered to pre-Bronze Age values again. A similar demise of *Abies* in the late Holocene, associated with human impact which significantly reduced its potential spatial range was detected also on other study sites in Mediterranean and central Europe (Tinner et al., 2013; Büntgen et al., 2014). The results of archaeological research confirm human presence in the area. In the immediate vicinity of the Lake Bohinj only individual bronze objects were found, however, Eneolithic or Bronze Age and younger archaeological sites were discovered higher in the mountains (1500 and 1640 m a.s.l., after ca. 2300 yr cal BC, i.e. 4250 yr cal BP; Gabrovec, 1974, 1987; Ogrin, 2006, 2010; Horvat, 2006, Fig. 1a) and it is possible that alpine grazing areas were already in use (Klek, Pokljuka plateau, Andrič et al., 2011), similarly as in the Swiss and Austrian Alps (Gobet et al., 2003; Drescher-Schneider, 2010; Von Scheffer et al., 2019).

At 3300 yr cal BP the forest composition changed: *Fagus* dominated forests spread, whereas *Picea* and *Abies* started to decline. The main reasons for this vegetation change are presumably linked to wetter climate and human impact. It was demonstrated that in Europe *Fagus* and *Abies* advanced in periods of wetter conditions (Huntley, 1988; Tinner and Lotter, 2006), but small-scale disturbance by fire and human impact can also promote the spread of *Fagus* (Bradshaw and Lindbladh, 2005; Tinner and Lotter, 2006; Bradley et al., 2013; Feurdean et al., 2017a,b). Due to lack of palaeoclimatological studies in the Bohinj region it is difficult to estimate the impact of climate on the vegetation. *Fagus* increase can be associated with globally wetter (and probably colder) climate (see Table 4). Lake Ledro (Magny et al., 2012, 2013) and other lakes south of the Alps experienced high lake levels and higher flood frequency between 4200 and 2400 yr cal BP (Vanniere et al., 2013; Wirth et al., 2013; Sabatier et al., 2017; Rapuc et al., 2019), which coincides with minima in solar activity (Wirth et al., 2013; Sabatier et al., 2017, Fig. 7). The Lake Bohinj geochemical data from this period still indicates autochthonous OM and higher bioproductivity of the lake, but OM content decreases in relation to increased sedimentation rate (dilution). Grazing which became increasingly important (Poaceae, *Plantago lanceolata* and *Sporormiella*) also affected forest composition. Due to clearance and/or grazing of *Fagus* forest more *Carpinus betulus* and *Carpinus orientalis/Ostrya* types were growing in the area. The erosion rate increased at that time with an input of terrigenous material (silicate and carbonate), as observed in Lake Iseo (Italia, Rapuc et al., 2019). During this period higher values for K/Ti ratio can be interpreted as low weathered material input, lower soil horizon or more probably parent material linked to low soil thickness in this area. Unit III in the lower part (3400–2600 yr cal BP) still contains roughly the same ratio of carbonate vs. non carbonate minerals (Table 2), suggesting both east and west origins of the sediment.

At 2600 yr cal BP the pollen record significantly changed in a relatively short (ca. 50–100 years) time period. Tree taxa (*Fagus*, *Abies* and *Quercus;* both, pollen percentage and influx data) declined, whereas *Corylus*, Poaceae and other herb taxa (e.g. Chenopodiaceae, *Artemisia*, Cichoriaceae, Filicales) increased due to human impact (forest cutting/burning) and taphonomic processes (herb pollen from degraded, grazed areas was presumably flushed into the lake). At this time, we record a huge erosion increase to reach its maximum value. A high percentage of degraded pollen and low pollen concentration agree with this very high terrigenous input with stable K/Ti ratio and the mineral composition changes to almost pure carbonate at 2300 yr cal BP, which was presumably derived mainly from eastern and southern parts of the catchment (see chapter 5.1). During this period, a higher amount of allochthonous OM was observed (higher OC/TN ratio) and also, low OC and TN content. The dissolution of exposed fine-grained detrital carbonate was the principal source of dissolved inorganic carbon at that time, contributing isotopically-enriched runoff to the lake, which in turn would generate OM with relatively high $\delta^{13}C$ values (cf. Diefendorf et al., 2008; Janbu et al., 2011). Spores of the genus *Sporormiella* fungi, indicators of dung produced by increased population densities of domestic herbivores (van Geel, 2001; Etienne et al., 2013), and *Ustulina deusta* acospores, which causes soft-rot on wood of several tree species (including *Abies, Fagus* and *Quercus*, van Geel, 2001; Bobek et al., 2018) were also recorded.

An assumption that major environmental change through the large erosion increase at 2600 yr cal BP was triggered by human impact (forest cutting for metallurgy and grazing) is supported also by archaeological data. Numerous early Iron Age sites, settlements and cemeteries dated to the 6th and 5th century BC (i.e. 2550–2350 yr cal BP), were discovered in the area suggesting that people from the Soča valley (in the richest phase of 'Sv. Lucija' cultural group) settled Bohinj in their quest for new sources of (iron) ore (Gabrovec, 1974, 1987). Two lowland hilltop Iron Age archaeological settlements (Ajdovski gradec and Dunaj pri Jereki), where numerous iron ore (bobovec) and slag remains were found (Morlot, 1850; Gabrovec, 1966; Mohorič, 1969; Cundrič, 2002) are located east of Lake Bohinj (Fig. 1a). In cremated graves of near-by cemeteries pottery and bronze, iron, glass and amber objects (jewellery and tools) were discovered (Gabrovec, 1974) indicating various metallurgical and handcraft activities and widespread trade routes. However, due to the lack of modern archaeological excavations of Iron Age settlements (including archaeobotanical and archaeozoological research), past economy and agricultural activities in the region are not very well investigated. It is interesting that only a few mountain Iron Age sites were discovered, which is in contrast to the Bronze Age situation (numerous high altitude and only few lowland sites/artefacts). Also archaeological and palaeoecological research of Swiss and Austrian sites suggests that human impact on mountain ecotones was strongest in the Bronze Age, Roman and Medieval periods (Gobet et al., 2003; Drescher-Schneider, 2010), when phases of intensified land-use, coincident with periods of warm climate were detected in Swiss lakes north and south of the Alps (Tinner et al., 2003). In the Iron Age mountain archaeological sites are less numerous (south eastern Alps: Horvat, 2019; Mandl, 1996; southern western Alps: Walsh et al., 2014), but with quite intensive human activities in the lower altitudes (valley floors and abutting mountain slopes, Walsh et al., 2014). It is possible that the Iron Age archaeological settlement pattern and economy were affected by climatic fluctuations, e.g. colder climate between ca. 2800–2300 yr cal BP (Bond et al., 1997; Haas et al., 1998; Magny, 2004; Wanner et al., 2011; Rach et al., 2017). At Lake Ledro (N Italy), e.g., a major lake level highstand is dated to 2600 yr cal BP (Magny et al., 2012). Therefore, we propose that the Iron Age soil and rock erosion in Lake Bohinj was triggered by human impact and presumably further strengthened by a wet climate.

5.4. Forest recovery and environmental changes in the last 2000 years

Forest shortly recovered in the Late Iron Age at ca. 2250 yr cal BP, but never reached pre-Bronze Age extent again. According to pollen data agriculture and grazing continued also after 2200 yr cal BP, when the presence of allochthonous OM in sediments is still high and decreasing trend of K/Ti values indicates increasing an contribution of well weathered material to the lake sediment (see chapter 5.1). The sedimentation rates and mineral composition suggest stabilisation of the catchment and a change to sedimentation conditions that existed up until today. In the last ca. 2000 years people never triggered an intensive erosion and fast sedimentation rate, comparable with the Iron Age destabilisation of the catchment. Presumably the majority of fine-grained till material was already washed to the lake and the remaining soils stabilised.

A few poorly investigated Late Iron Age (La Tène, 2250–1965 yr cal BP) sites located east of Lake Bohinj (Ajdovski gradec and Dunaj pri Jereki, Fig. 1a) were settled also throughout the entire Roman period (Gabrovec, 1966, 1987). According to the pollen record (Fig. 6) human impact on the environment became more intensive again in the Early Roman Period at ca. 2100 yr cal BP, when Bohinj was presumably part of *Regnum Noricum* and its iron trade routes (Gabrovec, 1987, ŠašelKos, 1998). *Fagus* forest declined and *Juglans* (walnut tree), which was popular with the Romans (Tinner et al., 1999; Gobet et al., 2000; Conedera et al., 2004, Kaltenrieder et al., 2010), started to occur regularly in pollen samples. Roman Age settlements (Fig. 1a) were located east of Lake Bohinj and on its eastern shore (Josipovič et al., 2012), as well as in the mountain areas (Horvat, 2002, 2013).

During the Late Antiquity crisis at ca. 450 AD (1500 yr cal BP) when lowland settlements (in other regions of Slovenia) were mostly abandoned (Ciglenečki, 1999), new fortified hilltop settlements (400–1050 m a.s.l.) were constructed at the foothills of the Alps; Ajdovski gradec was presumably fortified (Gabrovec, 1987). The number of the Alpine high altitude sites (1400–1900 m a.s.l.) significantly increased (Horvat, 2013).

Fortified hilltop settlements were abandoned in the 6th and the 7th century AD (i.e. 1450–1250 yr cal BP, Ciglenečki, 1999). Decline of population and subsequent (mostly *Fagus*) forest regrowth at the Roman/Early Medieval transition (1300–1200 yr cal BP) is reflected also in the pollen diagram (Fig. 6). At the beginning of the 7th century AD Slavic populations settled Bled (ca. 20 km north east of Bohinj; Pleterski, 2010, 2013) and presumably also the Bohinj area, and their impact is visible in the pollen diagram after ca. 1200 yr cal BP (i.e. AD 750), when the landscape became less forested again. Due to the lack of modern archaeological research in Bohinj, the Slavic settlement pattern and economy are poorly investigated. Both cemeteries, Podonce and Žale east of Lake Bohinj, are dated after the end of 8th century AD (Šmid, 1908; Vičič, 1983; Valič, 1987). A few pieces of early medieval pottery were discovered on the mountain sites Kal and Dolga Planja, which were presumably settled between the Late Antiquity and Medieval period (ca. 400–1100 AD, Ogrin, 2006, 2010; Horvat, 2002, J. Horvat and L. Lavrenčič pers. comm. 2018, Fig. 1a).

Between 1100 and 700 yr cal BP (AD 850–1250) forest clearance intensified again (decline of *Fagus, Quercus, Carpinus b.*, but increase of *Abies* and *Picea* at 800–900 yr cal BP, i.e. AD 1050–1150) and Cerealia production (Crealia type and *Secale*) advanced to support an increasing population. Over this period, the erosion rate seems to slightly increase but stays relatively low, as well as the K/Ti ratio, probably in relation to little material available in the watershed. Historical sources from the 11th century AD already mention most of the present-day villages in the region (Knific, 1984; Pleterski, 1984, 1986, 2013, Cundrič, 2002). However, not much is known about medieval ironworking. Simple furnaces for melting ore, dated to the 11th century AD, were presumably located at Mošenac near Sava Bohinjka ca. 6 km east of Lake Bohinj (Cundrič, 2002). Historical sources mention numerous ironworks, which were located east of Lake Bohinj and dated to the 12th–14th centuries AD (see Table 3). The impact of these activities on the vegetation is visible in the pollen diagram (decline of *Fagus*, which was presumably used as fuel in ironworks, Fig. 6). The late medieval decline of *Abies* (AD 1150 and especially after AD 1350) is presumably associated with more intensive dairy-based mountain grazing (Pleterski, 1986). At ca. 500 yr cal BP the increase of *Fagus* (AD 1450) suggests short-lived forest recovery, probably due to a less intensive forest clearance. Considering age uncertainties (±42 years), this event could be linked to an epidemy of plague in the 14th century AD and AD 1510 (Gestrin, 1984).

5.5. The period of most intensive ironwork (1580–1880 AD)

In the 16th century AD blacksmiths from northern Italy (Brescia) settled in Bohinj and built 2–3 m tall smelting-furnaces (AD 1581: Bohinjska Bistrica, AD 1582: Stara Fužina; Mohorič, 1969; Cundrič, 2002). At the end of the 16th century AD 94 t/yr of iron was produced in Bohinj (Cundrič, 2002) and widespread forest devastation related to *Fagus* charcoal production, grazing and production of shingle roofs (*Larix, Picea, Abies*) and wooden objects (mostly *Picea* and *Abies*) was reported (Zois report 1776, after Veber, 1987). Decline of these tree taxa is visible in the pollen record (Fig. 6). In the second half of the 18th century AD, when the Zois family monopolized iron ore production, a new smelting furnace for better

Table 3
Medieval ironworking in Bohinj area, all ironworks were located east of Lake Bohinj (see Fig. 1a; after Mohorič, 1969 and Cundrič, 2002).

Age	Ironworks
11th century AD	simple furnaces for melting ore: Mošenac near Sava Bohinjka
12th century AD	Češnjica
14th century AD	Staro Klad'vo (later renamed to Stara Fužina) along the Mostnica river, Brod
16th century AD	Bohinjska Bistrica (1540), Pozabljeno (1562), 'brescian' furnaces in Bohinjska Bistrica (1581) and Stara Fužina (1582)
17th and 18th centuries AD	new smelting furnace in Bohinjska Bistrica (1791)
19th century AD	ironworks in Bohinj started to decline, 1890: furnaces in Bohinjska Bistrica were burnt down

Table 4
Periods of (globally) wetter and presumably colder Middle/Late Bronze Age climate.

Global palaeoclimate archives		
3100–2400 yr cal BP	GISP 2 Greenland Ice Core	O'Brien et al. (1995)
3500–2500 yr cal BP	glacier fluctuation, ice core and marine records	Mayewski et al. (2004)
3300–2400 yr cal BP	global glacier advances	Denton and Karlén (1973)
4700 and 2700 cal. BP	global temperature and precipitation reconstructions	Wanner et al. (2011)
after 3200 yr cal BP	Fennoscandia, pollen-climate modelling	Seppä and Birks (2001)
Central Europe and the Alps		
after 3300 yr cal BP	glacier advances in the Alps	Ivy-Ochs et al. (2009); Le Roy et al. (2015)
3800–3300 yr cal BP	central European cold period (CE 7), vegetation at timberline	Haas et al. (1998)
3500–3100 yr cal BP	mid-European lake-level record	Magny (2004)
4200 yr cal BP and after 3500 yr cal BP; warm peak at 3700 yr cal BP	speleothem record from the Austrian Alps and Romania	Fohlmeister et al. (2012); Onac et al. (2002)
4500–3800 yr cal BP	northern Italian speleothem and lake level data	Heiri et al. (2003); Zanchetta et al. (2016)
4200–2400 yr cal BP	lakes south of the Alps, lake level and flood frequency record	Magny et al. (2012), 2013; Wirth et al. (2013); Vanniere et al. (2013); Sabatier et al. (2017); Rapuc et al. (2019)

exploitation of ore and charcoal was built in Bohinjska Bistrica in AD 1791. In the next ten years this furnace produced 213 t of crude iron and used 5200 t of iron ore and 9500 t of charcoal per year (Cundrič, 2002). This could explain the extremely low percentages of *Fagus* pollen (0.7%) and an increase in microcharcoal concentration (Fig. 6).

The period of most intensive ironwork (AD 1580–1880) is clearly seen in the pollen diagram (Fig. 6). Due to intensive charcoal production the percentage of *Fagus* pollen significantly declined, whereas microcharcoal concentration increased. Workers in ironworks needed more food, thus agricultural activities were intensified (pollen of Cerealia type, *Secale, Plantago lanceolata*). Also *Humulus/Cannabis* (hop/hemp type) pollen, which is (similarly as elsewhere in Europe, Long et al., 2017) present with individual pollen grains since ca. 3500 yr cal BP, increased. Due to the limited natural carrying capacity of Bohinj environment, some food was also imported (Mohorič, 1969). In the 19th century AD forests were damaged due to heavy ironwork exploitation and grazing. Historical records from AD 1852 testified that due to the lack of *Fagus* wood, charcoal was produced from *Picea,* which is much less suitable for smelting furnaces; the suitability of *Sphagnum* peat for fuel was also tested (Cundrič, 2002). Conflicts between miners (charcoal production) and farmers (forest grazing of goats) were commonplace (Smolej, 1984). Large clear-cuts of forests in AD 1848–1849 were still exposed to soil erosion 30 years after cutting, and therefore young trees (predominantly *Picea*) were planted between AD 1888–1907 (Smolej, 1984).

In the 19th century AD the ironwork industry in Bohinj started to decline due to various socioeconomic reasons (e.g. wars and economic depression, Mohorič, 1969; Cundrič, 2002) and ended in 1890 when furnaces in Bohinjska Bistrica burnt down and many workers moved to Jesenice. Towards the end of the 19th century AD needs for construction wood increased: the Bohinj railway leading to the Soča valley and Trieste, was built in 1906 (Smolej, 1984). Agrarian overpopulation at ca. 1900 AD (Petek, 2004, 2005) was followed by farming decline after the second world war and forest regrowth (forest grazing was forbidden in 1958), which is already seen on the top of the pollen diagram, where tree taxa (*Fagus, Picea*) start to increase again.

5.6. Human impact vs. climate change and inter-regional comparisons

Vegetation changes in the catchment of Lake Bohinj were significantly shaped by both human activities and climatic fluctuations. The first traces of small-scale Neolithic agriculture and grazing at ca. 6200–5800 yr cal BP in the Bohinj area coincide with the earliest agro-pastoral activities in the foothill up to alpine zones elsewhere in the Alps (e.g. Pini, 2002; Rey et al., 2013; Pini et al., 2017; Moe and Fedele, 2019; Walsh et al., 2014), but did not lead to major changes of the vegetation, forest composition or soil erosion. The first seasonal exploitation of high-elevation alpine pastures in the western and central Alps, which triggered a change in forest composition (decline of *Abies alba* and *Pinus cembra*), is dated to ca. 5600–5500 yr cal BP (Schwörer et al., 2015; Pini et al., 2017; Moe and Fedele, 2019).

In the Bronze Age (after ca. 4200 yr cal BP) when agriculture and (mountain) grazing affected forest composition (decline of *Abies*) in Bohinj, increasing anthropogenic activity was detected throughout the Alps, from lowlands to high altitude areas. The vegetation response to forest clearance/burning and grazing varied between regions due to various climate, altitude, bedrock and vegetation composition/history: e.g. clearance of mixed broadleaved deciduous forests with *Pinus sylvestris* on the southern Swiss Alps (Morales-Molino et al., 2015), decline and local extinction of *Abies* in lowlands of southern Alps (Tinner et al., 1998, 1999) and in montane belt of Bernese Alps (Rey et al., 2013; Schwörer et al., 2015), clearing of *Picea* forest in the montane and subalpine zone of St. Antoin valley (Röpke et al., 2011), expansion of *Larix decidua* (and *Alnus viridis*) in the subalpine zone of Engadine and Ötztal Alps (Gobet et al., 2003; Festi et al., 2014), decline of *Pinus cembra* in the subalpine/alpine zone of western Italian Alps (Pini et al., 2017), and deforestation of *Abies* forest and lowering of forest line (removal of *Pinus cembra* and expansion of *Larix*) in southern French Alps (Walsh et al., 2014). In addition to intensified human pressure, the vegetation was affected also by a complex pattern of Bronze Age dry/wet climatic oscillation (e.g. Holzhauser et al., 2005; Magny et al., 2009), phases of land-use expansion/contraction (Tinner et al., 2003), and treeline and glacier variations (Nicolussi et al., 2005; Badino et al., 2018; Le Roy et al., 2015). Also in the Bohinj area several Middle/Late Bronze Age (ca. 3420–2750 yr cal BP; 1500–1950 m a.s.l.; Horvat, 2019) archaeological sites were discovered in the subalpine vegetation belt, yet further research is needed to reconstruct changes in the archaeological settlement pattern, climate, vegetation, and the economy in order to estimate whether land-use of high-altitude ecotones expanded in periods of more favourable climate.

In the Iron Age (ca. 2600 yr cal BP) grazing and forest clearance, in conjunction with a wetter climate, triggered soil erosion in the Bohinj area. A similar increase of human pressure on lowland vegetation was also detected in the southwestern Alps (Lago Piccolo di Avigliana; 700–500 and 300–100 yr cal BC; Finsinger and Tinner, 2006), where it was assumed that a change in economy (the use of iron ploughs and scythes) led to higher erosion rates. A change in the archaeological settlement pattern and the economy was also detected at higher altitudes: forest clearance below treeline presumably marks the beginning of traditional dairy-based summer farming in the Italian central Alps (Moe and Fedele, 2019), whereas the first permanent buildings (dry stone huts) and dairy lipids on ceramics in the montane zone of eastern Switzerland indicate the beginning of milk processing at the Late-Bronze Age/Iron Age transition (Carrer et al., 2016; Reitmaier et al., 2018). However, the intensity of human impact on the high-altitude vs. lowland environment is not clear. For example, in the Southern French Alps archaeological and palynological evidence indicates intensive human activity in the lowlands (agriculture and pastoralism), whereas the archaeological record for high altitude activity is very rare, but palynological evidence suggests the continuation of mountain grazing (Walsh et al., 2014). Similarly, a decline of Iron Age high altitude sites was also detected in the central and western Alps (Hafner and Schwörer, 2018; Reitmaier, 2017; Reitmaier et al., 2018). High altitude Iron Age sites are also very rare in the Julian Alps (Horvat, 2019), whereas the Lake Bohinj record indicates very intensive (lowland) pressure on the environment. Therefore, a detailed analysis of high-altitude vegetation and economy is needed in the future to address the question of lowland vs. high altitude vegetation, climate, human impact, and socioeconomic reasons for these changes.

Iron Age destabilisation of the Bohinj watershed was unique in the last 6600 years. In the subsequent centuries human pressure on the vegetation intensified, but soil erosion was not intensive any more, suggesting that the stability of the catchment depends also on the erosion history (i.e. the availability of material in the catchment to be eroded). In the last 2000 years several phases of stronger (i.e. more open landscape: La Tène and Early Roman and Early Medieval Periods, AD 1580–1880) and weaker human impact (i.e. more forested landscape: Late Iron Age, Late Roman/Early Medieval transition, 14th/15th centuries AD), seems to depend on the population density as testified by archaeological data and historical sources. These phases show some similarities with other Alpine regions, e.g. intensive medieval forest clearance (pastoralism and mining) was detected throughout the Alps (Walsh et al., 2014). Millennia-long land use reduced forest cover (decline of all three keystone species: *Abies, Fagus* and *Picea*) and changed forest composition in the region. Due to athropogenic disturbance, *Abies* declined throughout central and Mediterranean Europe, although palaeoecological (Tinner et al., 2013) and ecological studies suggest that it can survive in relatively warm conditions (Bosela et al., 2018; Büntgen et al., 2014).

Changes in precipitation affected vegetation composition and sedimentological processes. Several periods of high terrigenous input to Lake Bohinj during periods of wetter climate match with periods of enhanced flood activity in wider, Alpine realm (Wirth et al., 2013, Fig. 7). It is interesting that the first three humid phases with Ribnica inflow into Lake Bohinj (6100–6000, 5700–5550, 5000–4600 cal. BP) coincide with periods of increased flood activity in the Northern Alps (Wirth et al., 2013), whereas subsequent sedimentation changes (3900, 3700–3550, 2300–2200 cal. BP and Unit III) and an increase of *Fagus* can be associated with increased flood activity in the Southern Alps (4200–2400 cal. BP), including Lake Ledro (Vanniere et al., 2013; Wirth et al., 2013, Fig. 7). After the major erosive crisis, Ribnica inflow into the lake was no longer recorded, while the more humid phase of the Little Ice Age (LIA) has increased the flood frequency (Vanniere et al., 2013; Wirth et al., 2013; Sabatier et al., 2017) and intensity (Sabatier et al., 2017) at a regional scale. This apparent paradox could be explained by human occupation dynamics and limitation of sediment input from the Ribnica River, as observed in Lake Iseo (Rapuc et al., 2019).

6. Conclusions

In the last 6600 years Lake Bohinj went through 3 phases of environmental changes.

In phase 1 (6600–3400 yr cal BP) most of the sediment was derived from western and central catchments. The landscape was predominantly forested, the fluctuations of pollen abundance of *Picea, Abies* and *Fagus* were presumably associated with climate fluctuations and fire regimes. Only small areas were covered by agricultural fields and pastures, and human impact on the environment was not significant. This phase was interrupted by five periods of completely altered sedimentation, associated with a mobilisation of inflow from the eastern, flysch-bearing catchment in periods of more humid climate (6100–6000, 5700–5550, 5000–4600, 3900, 3700–3550, 2300–2200 yr cal BP).

Phase 2 (3400–2200 yr cal BP) corresponds to a long period of more intensive human impact and a wetter climate, with an influx of sediment of western and eastern origin and higher sedimentation rate. An increase and subsequent decline of *Fagus* was presumably triggered by a wetter climate and human impact (pastoralism and decline of *Abies*, metallurgical activities) on the environment. At its peak, human activity in the Iron Age (2600 yr cal BP) triggered massive soil erosion.

In Phase 3 (after 2200 yr cal BP) 'Phase 1 type' of sedimentation returned, but without any mobilisation of the eastern flysch catchment. Human impact on the environment increased, with phases of weaker (more tree pollen, especially *Fagus*) and stronger human activities (e.g. metallurgical activities and decline of *Fagus* AD 1580–1880), the landscape stabilised, and soil erosion was less intense as in the Iron Age.

This research demonstrated the significance of detailed multi proxy sedimentological and palynological research to better understand the impact of human activities and vegetation change on sedimentation processes in the lake catchment area. Detailed sedimentological studies of lake sediments are essential to understand the taphonomy of the pollen record. Flood layers contain terrestrial material and pollen, including taxa from overgrazed areas, which are overrepresented in phases of soil erosion.

Acknowledgements

This research was funded by the Slovenian Research Agency, programmes: P6-0064 (Archaeological research), P1-0143 (Cycling of substances in the environment, mass balances, modelling of environmental processes and risk assessment), P1-0195 (Geoenvironment and geomaterials), project J7-6857 (Vegetation and hydrology of Ljubljansko barje in the past, present and future – a consequence of succession, human impact or climatic fluctuations?). The permission for coring (No. 678 35620-1078/2012-6) was issued by ARSO (Slovenian Environmental Agency). We thank the MISTRAL/PALEOMEX via Hotmed project for funding. We are grateful to E. Régnier, B. Wilhelm, S. von Grafenstein, R. Jensterle, D. Valoh and J. Dirjec for help with coring. Figures were prepared by T. Korošec. We would like to thank to M. Ogrin and J. Horvat for help with Fig. 1a and S. Žigon to perform stable isotope analysis. I. Sajko and U. Šilc prepared vegetation map (Fig. 1e). Comments on the first draft of the paper by A. Feurdean, N. Caf, T. Nagel and archaeologists from ZRC SAZU (A. Pleterski, M. Šašel Kos, S. Tecco Hvala, Z. Modrijan, L. Lavrenčič) are gratefully acknowledged. We are very grateful to two anonymous reviewers for constructive comments and corrections.

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