

**PEAT BOG AND ALLUVIAL DEPOSITS REVEAL LAND DEGRADATION DURING 16TH AND 17TH CENTURY COLONISATION OF THE WESTERN CARPATHIANS (CZECH REPUBLIC)**

**Short title: DEPOSITIONAL RECORD OF HISTORICAL LAND DEGRADATION IN THE CARPATHIANS**

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## ABSTRACT

Wallachian (shepherd) colonisation of the upper parts of Carpathians, the second largest mountain range in Europe, provides a unique opportunity to study human-induced ecological changes and subsequent sediment mobilisation within slope and fluvial systems. The Wallachians came to the nearly pristine landscape in the Czech part of the Western Carpathians during the 16–17th Century bringing large scale deforestation and grazing to the upper parts of its ridges. Despite the importance of this event, there is a lack of high-resolution multi-proxy reconstructions to help to decipher the relative influence of anthropogenic and climate factors on this landscape. Here we provide a ca. 2.1 kyr record obtained from a peat bog where, using chronological, sedimentological and pollen analyses, we were able to differentiate between environmental conditions before, during and after colonisation. Prior to colonisation, climate deterioration following the onset of Little Ice Age caused changes in forest composition and erosion events (causing a ~AD 0–1500 gap in the record). Abrupt human-induced deforestation detected in the pollen record, together with the abundant fine-grained minerogenic content of peat deposits between AD ~1640 and AD 1870, correspond to increased runoff and sheet erosion on slopes; enhanced by Little Ice Age climate deterioration. The sedimentary record in alluvial deposits downstream indicates that the colonisation of the mountain slopes in this region not only had a local effect on soil

degradation, but it also increased the net aggradation of overbank deposits within valley floors. After reforestation, net aggradation was replaced by river incision into alluvia.

**KEYWORDS:** human impact; environmental change; mountain environment; catchment linkages; palaeoenvironmental proxies

## 1. INTRODUCTION

The colonisation of pristine and virtually untouched landscapes, often connected to deforestation, burning and the spread of agriculture, is a very important anthropogenic activity leading to intensified erosion and the subsequent aggradation of material in colluvial zones and valley floors. Such major palaeoenvironmental effects, from a number of phases of historical colonisation from the Late Quaternary to recent times, have been demonstrated in various settings around the world (e.g. Knox, 2006; Beach & Luzzadder-Beach, 2008; McIntosh *et al.*, 2009).

One of the last European colonisations that affected a nearly intact landscape was the Wallachian colonisation of the mountainous parts of the Carpathians by shepherds during the 13th to 17th Century. This colonisation started in the 12–13th Century in the Southern Carpathians (contemporary Romania) and reached the territory of the Western Carpathians in present day Czech Republic during the 16th to 17th Century (Štika, 2007; Wistuba *et al.*, 2018). The number of shepherds in the mountains of the easternmost region of Czech Republic increased significantly from <20 at the end of the 15th Century to >700 in the first half of the 19th Century and the area was markedly deforested (Pitronová, 1965). Although the geomorphic and ecological impacts of this upland colonisation have been hypothesised in

other studies (e.g. Klimek, 1987), direct radiometric, pollen and sedimentological evidence of the impact of this period is still relatively scarce (Jankovská, 1995; Kukulak, 2000, 2003; Wistuba *et al.* 2018). Recent studies from floodplains situated at the piedmont of the Carpathian Mountains have revealed the significant influence of human-induced land use changes on episodes of fluvial aggradation during the last millennium (Starkel, 2001; Chiriloaei *et al.*, 2012; Geþica *et al.*, 2013). However, the resolution of these floodplain archives is not usually adequate enough to distinguish between the effects of intensive human activity during the Medieval Period, affecting mainly lower lying regions, and the colonisation of higher elevation areas (in case of Wallachian colonisation particularly mountain ridges) which took place several centuries later. Although dating resolution can be much better in peat bog and lacustrine records (e.g. Chambers & Charman, 2004; Geantă *et al.*, 2014, Florescu *et al.*, 2017), in the Carpathians, suitable deposits recording the last several centuries are often limited in their thickness (Feurdean *et al.*, 2009; Tanþau *et al.*, 2011).

In this study we report on the environmental effects of land use changes related to climate fluctuation and human activity over the last two millennia in the mountainous area of the easternmost part of Czech Republic (Olza River catchment; Figure 1). We use sedimentological and pollen analyses, and radiometric dating of landslide-nested peat bog deposits to verify the direct impacts of the terminal phase of Wallachian colonisation in the Western Carpathians (16th to 17th Century) (Jankovská, 1995; Wistuba *et al.*, 2018). High-resolution multi-proxy analysis of deposits in one of the few peat bogs in this region provides a unique opportunity to study the relationship between human-induced land use changes and their effect on the erosion–accumulation regime of mountain slopes. To support our peat bog data, and to evaluate how these geomorphic changes affected the sedimentary flux of the

major river in the catchment, we also performed sedimentological analysis and absolute dating of two floodplain sections lying downstream on the Olza River.

## 2. STUDY SITES

Our study sites: Girová peat bog and the two floodplain outcrops (undercut banks Olza1 and Olza2) are situated in the catchment of the Olza River in eastern Czech Republic, close to the border with Poland and Slovakia (Figure 1, Table 1).

They lie in the Outer Western Carpathians; a fold-and-thrust mountain belt consisting mostly of Mesozoic and Tertiary flysch (Picha *et al.*, 2006). The floodplain outcrops are situated 13 km (Olza1) and 45 km (Olza2) downstream from the peat bog (Figure 1b).

The mountainous part of the region is today forested mainly by *Picea abies* (L.) H. Karst monocultures, introduced to the region in the second half of the 19th Century (mostly after 1870) (Jančík, 1958). Forests occupy ~70 % of the area. From the 16th to 19th Century, the area of forest cover was significantly smaller (39%, Figure 2) due to the related effects of both 'pastoral' and Wallachian colonisation. So-called 'pastoral' colonisation began in the 12th Century and was associated with the rapid development of pre-existing settlements followed by the spread of arable land and pastures; initially in the surroundings of villages, but along valley bottoms and footslopes. In contrast, Wallachian colonisation began in the 16th Century and was characterised by scattered settlement on the upper mountain slopes and ridges, accompanied by the establishment of pastures for sheep grazing (Štika, 2007).

### 3. METHODS

#### 3.1. Coring, documentation and sampling

The deepest part of the peat bog (Figure 1c) was sampled using an Eijkelkamp Russian corer (60 mm diameter). A 130 cm long core was extracted for radiocarbon,  $^{137}\text{Cs}$ , sedimentological and pollen analyses. The core sections were described, the core sectioned at 2.5 cm intervals and stored at 4 °C.

Samples from both ~200 cm long sedimentary sections in floodplain outcrops were described, extracted and stored in the same manner in 5 cm intervals for grain size analysis. In addition, samples from the Olza2 section were subjected to magnetic susceptibility, geochemical and  $^{137}\text{Cs}$  analysis.

#### 3.2. Chronology

A total of five samples from Girová peat bog and four samples from the floodplain outcrops were selected for radiocarbon dating. For laboratory affiliations, sample material and dating methods see Table 2. The age of the uppermost section of the Girová peat bog core was constrained on the principle of event chronostratigraphy (Gale, 2009). We used the abrupt increase in the *Picea abies* pollen curve as a marker for the year AD 1870 ( $\pm 10$  years) reflecting the widespread introduction of a *Picea abies* monoculture. This decade also coincides with a significant increase in specific industrial production locally (Třinec steel works ~20 km north) (Figure 1b) providing an additional independent chronological marker via the heavy metals profile.

To support this chronological marker, the  $^{137}\text{Cs}$  activity of the uppermost 30 cm of the core was analysed at 2.5 cm intervals by gamma assay (Department of Geology, Palacký University in Olomouc, Czech Republic).  $^{137}\text{Cs}$  analysis of the upper 160 cm of the Olza2 floodplain outcrop was performed in the same way.

Radiocarbon and chronostratigraphic dating enabled the creation of an age–depth model of the peat bog using the IntCal13 calibration curve (Reimer *et al.*, 2013) and linear interpolation in ‘clam’ package (Blaauw & Goring, 2014) in R software (R Core Team, 2016). To approximate the surface age we used the present date (AD 2011±5). We also included the pollen-inferred hiatus (90 cm) and two events of abrupt deposition (47–40 cm, 77–70 cm) into the age–depth model. Depositional rates in the model were estimated from the weighted average of the calendar ages for every depth.

### 3.3. Magnetic properties, geochemical analysis, LOI and particle size analysis

To enable the sediment sequence correlation, magnetic susceptibility ( $\chi_{\text{LF}}$ ) was determined for the entire Girová peat bog core and the Olza2 section using a Bartington Instruments Ltd MS3 meter and MS2B sensor. In order to investigate the increased  $\chi_{\text{LF}}$  in the upper part of both sequences, we conducted geochemical (XRF) analysis using a Niton XL3t 900 analyser for the uppermost 30 cm of peat bog profile and 160 cm of the Olza2 section. LOI at 500 °C was measured in order to identify allochthonous inputs in the peat bog (Heiri *et al.*, 2001). Particle-size distribution analysis of the fine grain proportion was performed to detect erosion inputs and determined by laser diffraction (Malvern Mastersizer 2000E with Mastersizer 2000 v.5.40 software).

### 3.4. Pollen, spores and stomata

For the upper 120 cm of the peat bog core, pollen analysis was performed using standard procedures. Minerogenic matter was separated with the use of heavy liquid ( $ZnCl_2$ ) (Berglund & Ralska-Jasiewiczowa, 1986). The results are presented as a percentage pollen diagram reconstructed in the program Tilia and Tilia\*Graph (Grimm, 1991). The pollen percentages were calculated on the basis of arboreal and non-arboreal pollen sum (AP + NAP). The percentages of the spores (ferns and mosses) were calculated on the basis of AP + NAP + sum of spores = 100%. Total counts of pollen are represented in a 2 ml sample prepared with glycerine. In addition, Pinaceae stomata, diatom algae, fungi spores, testate amoebae (Rhizopoda) and intestine parasite *Trichuris trichiura* were fixed in samples. For evidence of active erosive processes, spores of *Glomus* have been isolated among the fungal palynomorphs. The diagram was divided visually to local pollen assemblage zones (LPAZ) based on the abundance of ecologically important taxa.

## 4. RESULTS

### 4.1. Girová peat bog

#### 4.1.1. Chronology and depositional rates

Radiocarbon dating indicates that peat deposition started in 180–50 BC (121 cm, Figure 3, Table 2). Assuming a linear sedimentation rate, deposition was rather high immediately after the formation of the depression ( $\sim 7.2 \text{ mm.a}^{-1}$ ) and continued through 170 BC–AD 0 up to a hiatus at 90 cm. The next dated level (AD 1500–1660) at 77.5 cm suggests that at least 1500 years in the peat bog record are missing. After  $\sim$ AD 1500 up to AD 1870, slow ( $\sim 1.7 \text{ mm.a}^{-1}$ )



deposition took place, alternating with two rapid accumulation events ( $\sim 25 \text{ mm.a}^{-1}$ , 77–70 cm, 47–40 cm, Figure 3) inferred from the pollen record. The bottom of second event was dated to AD 1520–1650 (Table 2), which caused reversals in the age models and thus was excluded. In the modern times (AD 1870–2011, 15–0 cm) deposition slowed to  $\sim 1.1 \text{ mm.a}^{-1}$ .

The onset of  $^{137}\text{Cs}$  activity was determined at a depth of 20 cm with a peak probably related to the AD 1986 Chernobyl disaster at 5 cm (Figure 4b). Its position is at odds with the pollen/XRF-based chronology and we excluded the  $^{137}\text{Cs}$  results from the age–depth model.

#### *4.1.2. Lithostratigraphy, particle size distribution, LOI, mineral magnetic properties and geochemical analysis*

The lowermost part of the core (130–120 cm) comprises coarse grained colluvial diamict with minimal organic content (LOI 6 %) (Figure 3, 4a).

The deposits at 120–67.5 cm depth comprise very dark brown to brown sandy silt and decomposed peat formed predominantly by plant macroremains. The upper half of the section has an increasing sand content, reaching values of 20–30% (Figure 3, 4a). The organic content fluctuates within the section; minimum at 90–80 cm (LOI <25%) with a pronounced peak at 70–67.5 cm (LOI 68%) (Figure 4a).

The core from 67.5–15 cm is represented by light yellowish brown silt with some light grey intercalations (Figure 3). The grain-size composition (clayey-sandy silt) is homogenous with a raised sand content (ca. 20%) in the interval 55–60 cm (Figure 4a). LOI reveals two maxima with an organic content >50% at 67.5–60 cm and  $\sim 22.5$  cm, and one minimum at a depth of 40–45 cm (LOI <30 %; Figure 4a).

The uppermost section from 15–0 cm comprises dark brown to very dark grey peat with a clayey-sandy silt fraction (Figure 3) and increase in LOI, which reaches a core maximum 76 % at the surface (Figure 4a).

Values of magnetic susceptibility ( $\chi_{LF}$ ) are very low through almost the whole core (Figure 4a). From 130–15 cm  $\chi_{LF}$  values are fluctuating between 2–11  $\cdot 10^{-8} \text{ m}^3 \cdot \text{kg}^{-1}$  and reflecting the siliciclastic character of the deposit, especially the amount of organics (in negative direction) and partly the grain size (in positive direction).

In the top 15 cm (AD 1870–present), magnetic susceptibility reveals an exponential increase, reaching a maximum value  $\chi_{LF} 93 \cdot 10^{-8} \text{ m}^3 \cdot \text{kg}^{-1}$  at the surface. Correspondingly, there is an abrupt increase in XRF-determined Pb, As, Zn and partly Cu concentrations (Figure 4b). A significant peak in the Fe/Mn ratio was recorded in 15 cm depth.

#### 4.1.3. Biotic proxies: pollen, stomata

The core was subdivided into four different local pollen assemblage zones (G-1–4) (Figure 5). Detailed description of the site vegetation history and interpretation is presented in Table S1.

LPAZ G-1 (120–90 cm, 180 BC–AD 0) is dominated by arboreal species (>85 %), mainly *Abies alba* Mill. and *Fagus sylvatica* L. pollen with small admixture of deciduous trees (Figure 5). The herbs are represented by the pollen of Apiaceae, spores of fern (*Filicales monoletae*) and minor occurrence of secondary anthropogenic indicators connected with pasturing (e.g. *Ranunculus*, *Urtica*, *Plantago major* L., *Rumex acetosella/acetosa*, *Artemisia*). Intestine parasite *Trichuris trichiura* was detected in the record.

LPAZ G-2 (90–67.5 cm, AD 1500–1640). In the pollen spectra coniferous trees (*Abies-Pinus*) dominate. The pollen curve of *Abies* (59 %) culminates at the top of the unit (Figure

5). *Fagus* pollen almost disappears. Microfossils such as *Glomus*, hydrophilic amoebae fauna (*Centropyxis aculeate* Ehrenberg, *Arcella catinus* Penard) and damaged pollen are more abundant. Herbs pollen levels are low (>4.5 %). A minor increase in primary anthropogenic indicator *Cerealia* at the top of this unit can be traced.

LPAZ G-3 (67.5–15 cm, AD 1640–1870) reveals a major change in pollen spectra with an abrupt, upward trending increase in herbs. NAP culminates at 50.4 % below the unit top (Figure 4a, 5). Substantial part of NAP is represented by primary and secondary anthropogenic indicators (e.g. *Plantago major/media*, *Rumex*, *Ranunculus*, *Taraxacum*-t., *Avena*, *Polygonum aviculare*, *Artemisia*, Poaceae, *Cerealia*, *Secale*, *Triticum*, *Fagopyrum*, *Centaurea cyanus*, *Sedum* and *Euphorbia*). At the top of the unit, NAP decreases suddenly to 25 %. At the beginning and the end of the zone a short-term increase in *Betula* pollen is identified.

LPAZ G-4 (15–0 cm, AD 1870–present) is dominated by *Picea abies* pollen with an abrupt increase in the percentage of arboreal taxa (nearly 100% at the top of the section) and a corresponding decrease in NAP to 2.5% (Figure 4, 5). *Algae* vanish in this unit. Primary anthropogenic indicators disappear towards the top of the core.

## 4.2. *Olza1* floodplain outcrop

### 4.2.1. Chronology and lithostratigraphy

The *Olza1* section reveals a 200 cm thick sequence of massive overbank deposits overlying the sediments of a palaeochannel and the lowermost channel facies of imbricated gravels (Figure 6). Organic palaeochannel deposits (200–145 cm) are incised into underlying gravels and consist of very dark brown to brown silts. The basal part (organic detritus) of the

palaeochannel infill shows an age 730–110 BC. The overlying deposits (145–0 cm) show slight upwardly coarsening, brownish grey silty sands which have accumulated since AD 1440–1800 (Figure 6).

### *4.3. Olza2 floodplain outcrop*

#### *4.3.1. Chronology, lithostratigraphy, mineral magnetic properties, geochemical analysis*

The Olza2 outcrop is represented by a 210 cm thick sequence of overbank deposits with occasional gravely inclusions overlying basal channel gravels (Figure 6). Overbank deposits consist of several units differing in grain size and overall texture. The basal sequence (210–180 cm; probably facie of a lateral levee) consists of light yellow sands. This unit is overlaid by alterations of silty and sandy, light to brownish grey layers of overbank sediments. The base of overbank sedimentation (170 cm) yields an age AD 1490–1650. Another radiocarbon age (AD 1520–1800) obtained at 85 cm overlaps with this sample in uncertainty margins and shows that 85 cm of overbank deposits accumulated with a minimum sedimentation rate  $>10 \text{ mm.a}^{-1}$ . The uppermost ~50 cm has accumulated since the beginning of the 19th Century, i.e. the time interval when extensive black coal mining and smelting works started in the surrounding area. This is evidenced by the common occurrence of anthracite within the deposits and the exponential increase in  $\chi_{\text{LF}}$  as well as Zn and Pb concentrations. The onset of  $^{137}\text{Cs}$  activity is detected at 50 cm with a peak probably related to the AD 1986 Chernobyl disaster at 20 cm below the floodplain surface (Figure 6).

## 5. DISCUSSION

The Girová peat core covers (although not continuously) ca. 2.1 kyr and contains traces of human activity, making it possible to discuss the effects of both anthropogenic and climate factors on vegetation cover and geomorphic processes. Furthermore, alongside this upland mire site, the Olza River floodplain deposits highlight the links between the considerable land use changes caused by Wallachian colonisation in the mountains and the sedimentary flux downstream.

### *5.1. Climate and anthropogenic impact within the Girová peat bog slope system*

#### *5.1.1. Before Wallachian colonisation (180 BC – ~AD 1640)*

The biotic proxies and physical properties of the deposits suggest that during this period, the evolution of the study site and its surroundings was influenced mainly by climate factors. The minor influence of humans at the onset of Roman Period is indicated by the occurrence of plants associated with pastures and meadows (Table S1), as well as the intestinal parasite *Trichuris trichiura* (first stage of human activity in Figure 5). Although human occupation of the mountainous sections of the nearby Polish part of the Western Carpathians since ca. BC 4000 has been reported, these sparse settlements were of little significance for the ecology of the mountains and were restricted to a small number of locations (Margielewski, 2006; Margielewski *et al.*, 2010).

The accumulation of colluvial deposits at the bottom (130–120 cm) of the depression may be attributed to locally enhanced erosion from a fresh landslide surface (Margielewski, 2006). The onset of the peat bog (180–50 BC) thus provides a minimum age for this large rotational landslide (Figure 1c). This event correlates well with a relatively humid phase (ca. 400 BC–

AD 0, Roman Period) recorded nearby as demonstrated by an increased frequency of landslides (Margielewski, 2006) and large floods in the Polish Vistula River catchment (Starkel *et al.*, 2006). During 180 BC–AD ~0 (Roman Period) dense *Abies-Fagus* forest dominated the site's surroundings. A similar vegetation composition was revealed at the bottom sections of peat bogs ~20 km west of our site by Jankovská (1995). Rapid deposition ( $\sim 7.2 \text{ mm.a}^{-1}$ ) can be associated with the early successional stages of peat bog formation (Charman *et al.*, 2015) and with a minerogenic input from the landslide-disturbed slopes (Figure 4a).

The peat bog record is interrupted by a depositional hiatus, indicated by radiocarbon dating, the shift in arboreal pollen to *Abies-Pinus* forests and disappearance of deciduous trees at 90 cm depth. The age–depth model suggests a gap from ~AD 0–1500 (Figure 3) and dates the overlying core section to the Little Ice Age (LIA). In the greater Tatra Mts. region (Western Carpathians, ~70 km east of our site), the LIA was associated with a series of pronounced cold periods between ~AD 1300 and 1850 (Büntgen *et al.*, 2013; Figure 7b). The core section dated to ~AD 1500–1640 (G-2 unit, 90–65 cm) overlaps with one of these periods, corresponding to the Spörer solar minimum (AD 1500–1550; Usoskin, 2017; Figure 7b) and subsequent warming. The vegetation composition, slope erosion indicators (spores of *Glomus*, frequent inputs of coarse material), evidence of very rapid accumulation (i.e., the abundance of damaged pollen, reduced pollen concentrations) and temporary flooding of the depression (indicated by hydrophilic amoebae) suggest climate deterioration and the intensification of slope processes.

### 5.1.2. During Wallachian colonisation (AD ~1640–1870)

A decrease in arboreal pollen, followed by enhanced fine grained input (probably from sheet slope erosion), was dated to the interval AD 1520–1790 and lasted up to AD 1870 (unit G-3; Figure 3, 4a, 5). The abrupt onset of *Rumex*, *Plantago lanceolata*, *Avena*, and *Polygonum aviculare*, and also the presence of *Cerealia* and *Fagopyrum* at the unit bottom clearly shows a land cover change associated with intensive grazing activities and farming in the close vicinity of the peat bog (second stage of human activity in Figure 5). These land use changes can undoubtedly be attributed to the arrival of the Wallachians in this region during the 16th to 17th Century (Jančík, 1958; Jankovská, 1995; Wistuba *et al.*, 2018). The NAP curve culminated in ~AD 1780–1840 with a sudden drop after this period. This corresponds to historical records of peak deforestation in the region in the second half of the 18th Century, when >25,000 sheep and goats grazed in the upper catchment of the Olza River (Pitronová, 1965). The presence of extensive pastures and fields at this time is also shown in historical maps (AD 1836, Figure 2). Subsequently, the appearance of pioneer trees indicates that grazing activities declined in the first decades of the 19th Century (Jančík, 1958). Wallachian colonisation of the study area overlaps with climate deterioration in Central and Eastern Europe around AD 1500–1820, especially in the Maunder minimum (Glaser *et al.*, 2010; Büntgen *et al.*, 2013; Figure 7b). Even though proxy-based palaeoclimatic reconstructions can be sensitive to the potential blurring of climate factors by human activity (Lamentowicz *et al.*, 2011; Geantă *et al.*, 2014), the climate deterioration at the study site is indicated by the decrease in *Abies* sp., increases in humidity indicators (*Cyperaceae* and diatom algae concentration) and the enhanced input of fine grained material from sheet erosion (Table S1, Figure 4a). Similar, but less pronounced records of enhanced soil erosion due to the synergic effect of climate and human-induced deforestation have been observed in other peat bogs and

lakes in Eastern Europe (e.g. Margielewski, 2006; Lamentowicz *et al.*, 2011; Tanțău *et al.*, 2011; Florescu *et al.*, 2017).

### 5.1.3. After Wallachian colonisation (AD 1870–present)

Gradual human-induced afforestation of the mountains by *Picea abies*, detected in the G-4 core unit (third stage of human activity in Figure 5, Table S1), started in the first decades of the 19th Century and culminated in the second half of the 20th Century. Since ~AD 1870 a large portion of the region has been afforested by *Picea abies* plantations producing timber for heavy industry (Jančík, 1958). Amplified effects of climate warming and human-induced afforestation across the region can be considered as a cause of drying of the peat bog, reflected by the decrease in sedimentation rate ( $1.1 \text{ mm.a}^{-1}$ , Figure 3), the disappearance of *Algae* and also by the presence of peak in the Fe/Mn ratio in the profile (Figure 4b, 5).

The exponential growth of the *Picea abies* curve in our pollen diagram correlates well with  $\chi_{\text{LF}}$  values and concentrations of Pb, As and Zn. This most likely reflects the onset of massive emissions of magnetic particles and heavy metals in the second half of the 19th Century reflecting extensive smelting works in Třinec (~20 km north of the sampling site). In comparison with these chronological markers,  $^{137}\text{Cs}$  activity displays a slight discrepancy as its occurrence follows the increase in heavy metals concentrations and also the exponential growth of *Picea abies* curve dated to the end of 19<sup>th</sup> Century. This misalignment may be explained by vertical migration of  $^{137}\text{Cs}$  (Ciszewski *et al.*, 2008; Parry *et al.*, 2013).



## 5.2. Linkages between Wallachian colonisation-induced land use changes and sediment flux in the Olza River

In addition to the peat bog core revealing local anthropogenic effects within the slope system, we can also identify erosion impacts related to the disturbance of these mountain slopes on the floodplains of the rivers downstream (Figure 6). The two outcrops show thick deposits (145–170 cm) of overbank silty sands, the bottom parts of which were dated to AD 1440–1800 and AD 1490–1650, i.e. correlating strongly with the period of human-induced deforestation and following soil cover degradation detected within the peat bog (Table 2, Figure 6). Although the onset of this major change in sediment flux within the slope and fluvial systems overlaps with the LIA, our pollen signals clearly reveal its connection with the colonisation of the mountains in the 16–17th Century. Furthermore, both in the peat bog and alluvial sequences, this sedimentary change took place several centuries after the onset of LIA (~AD 1300; Büntgen *et al.*, 2013). However, it is probable that the deforested and grazed slopes were subsequently more susceptible to erosion by intense rainfalls during the LIA (Glaser *et al.*, 2010). Such amplification of climate factors by human impact has been reported elsewhere e.g., Kadlec *et al.* (2009) and Wistuba *et al.* (2018). The effects of human-induced increases in sediment fluxes in the mountains may be accommodated downstream within the larger rivers. For instance, Kadlec *et al.* (2009) found no increase of deposition rates for the Morava River during the last 500 years. However, in the same catchment, closer to the mountain foothills, Stacke *et al.* (2014) identified a significant increase in the floodplain's vertical accretion following ~AD 1460–1630.

Afforestation of the mountain slopes after ~AD 1870 was probably also reflected in the decreased sediment supply to rivers which responded by accelerated incision into the alluvia and bedrock (Škarpich *et al.*, 2016; Wistuba *et al.*, 2018).

### 5.3. Regional comparison

Several studies throughout the Carpathian Mountains show evidence of landscape changes connected to this colonisation of mountain ridges and slopes. Figure 7 reveals the onset of the last human-induced, abrupt sedimentary changes recorded within peat bogs and alluvia across the Carpathian region. In the Czech part of Carpathians, massive overbank accumulation in two small mountain catchments ~25 km west of Girová peat bog was reliably attributed to deforestation of mountain ridges during Wallachian colonisation (Wistuba *et al.*, 2018). In the Polish Carpathians, there are several cases of charcoal-rich minerogenic horizons dated to the 14–17th Century which are embedded within peat bog sections (Margielewski & Kovalyukh, 2003; Margielewski, 2006). Aggradation of 1–3 m thick overbank deposits connected to forest clearance and farming in the 14th to 15th Century has also been described from the eastern part of the Polish Carpathians (Kukulak, 2000, 2003). Further to the east, in the Ukrainian Carpathians, Geþica *et al.* (2013) described exceptionally thick alluvium (~5m) in the Dniester River valley where the onset of sedimentation was dated to AD 1440–1630. In the Romanian part of Carpathians, there is a little geomorphic and sedimentary evidence of mountain colonisation (Chiriloaei *et al.*, 2012), but other studies provide pollen records of significant land-use changes of mountain slopes during last ca. 500 years (Feurdean *et al.*, 2009; Tanþau *et al.*, 2011, Geantă *et al.*, 2014, Florescu *et al.*, 2017).

Analogies to similar responses in mountain landscapes in the last millennium can also be found in other Central European regions. Many recent studies from this region have emphasised the geomorphic role of various periods of historical colonisation (e.g. Klimek, 2002; Klimek *et al.*, 2006); some of them have even shown that human-induced geomorphic processes during last several centuries were the most effective of the whole Holocene epoch (Latocha & Migoń, 2006).

## 6. CONCLUSIONS

Our multi-proxy study of the Girová peat bog on the upper slopes of the Western Carpathians (Czech Republic) provides evidence of the mountain environment's response to climate changes and human impact. The peat bog started to evolve ca. 180–50 BC (Roman Period) and up to ~AD 1640 its surroundings comprised an almost pristine, naturally forested area. Intensive erosion events on slopes disturbed by the landslide were detected during this period. An increased intensity in erosion events during the LIA caused a pronounced hiatus (~AD 0–1500 gap) in the record. The onset of the major human induced landscape change was dated to AD 1520–1790 and is characterised by an abrupt increase in the percentage of herbs and fine grained minerogenic material within the peat bog deposits. This was attributed to the Wallachian colonisation of the area, the last phase of human-induced deforestation, grazing and farming affecting the mountainous parts of the Carpathians. Amplifying the geomorphological impacts of the climate deterioration of LIA, these land use changes caused increased runoff, accelerated sheet erosion and the delivery of minerogenic deposits to sedimentary sinks such as peat bogs and floodplains. However, its impact was spatially limited to the immediate mountain slopes and the nearest valley floors. Deposition within the peat bog has declined slightly since ~AD 1870, indicating that the sedimentary flux and soil degradation on slopes was effectively eliminated after the introduction of the legal protection of forests in the mid 19th Century. Future investigations could reveal to what extent this major land use change influenced the aggradation of alluvium in the more distant piedmont of the Carpathians. Furthermore, did this colonisation also lead to the development of major erosional landforms such as gullies and landslides?

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## SUPPORTING INFORMATION

**Table S1.** Summary of the pollen stratigraphy, chronology, vegetation history and evolution of the Girová peat bog and its surroundings.

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**Table 1.** Study site characteristics.

Study site	Coordinates / Elevation	Temperature <sup>a</sup> / Rainfall <sup>a</sup>	Site description
<b>Girová</b> Peat bog (Figure 1c)	49° 32.08'N 18° 49.36' E / 640 m a.s.l.	*8.1 °C / *976 mm	0.9 ha peat bog occupying a near-scarp depression of a large fossil, rotational landslide on the northern slopes of Girová Mt. Apart from the peat bog itself, which is overgrown by herbs (particularly <i>Equisetum palustre</i> L., <i>Mentha longifolia</i> (L.) Huds., <i>Urtica dioica</i> L.), trees are only present as individuals of <i>Salix caprea</i> L., <i>Picea abies</i> (L.) H. Karst., <i>Fagus sylvatica</i> L., <i>Acer pseudoplatanus</i> L., <i>Corylus avellana</i> L. and <i>Sambucus racemosa</i> L. at the edge of the peat bog. The wider surroundings of the site are densely forested by a <i>Picea abies</i> monoculture.
<b>Olza 1</b> Floodplain outcrop (Figure 1d)	49° 38.00'N 18° 42.70' E / 328 m a.s.l.	**8.9 °C / **931 mm	Olza River floodplain at the foothills of the mountains; 13 km downstream from the Girová peat bog. The surface of Holocene floodplain stands 2–3 m above the river channel. Bedrock is not exposed.
<b>Olza 2</b> Floodplain outcrop (Figure 1e)	49° 52.50'N 18° 29.40' E / 212 m a.s.l.	**8.9 °C / ***751 mm	Olza River floodplain 45 km downstream from the Girová peat bog, close to the town of Karviná within an urbanised and industrialised section of the floodplain standing 3–5 m above the river channel. Bedrock is not exposed.

<sup>a</sup>Mean annual temperature and annual rainfall with respect to AD 1981–2010 measured at \*Jablunkov, \*\*Ropice and \*\*\*Karviná meteorological stations (for locations, see Figure 1b, data source: ČHMÚ).

**Table 2.** Radiocarbon dates obtained in the study.

Depth (cm)	Lab. ID	Material	<sup>14</sup> C age (a BP ± error)	Cal. age (2σ)	Median age (cal a, BC/AD)	*sam ples sent to Cent er for Appl ied Isoto pe Studi es, Univ ersit y of
Peat bog samples:						
121	*UGAMS-9249 <sup>a</sup>	<i>Picea abies</i> needles	2100 ± 20	180-50 BC	120 BC	
97.5	*UGAMS-11043 <sup>a</sup>	<i>Picea abies</i> needles	2070 ± 25	170 BC-AD 0	90 BC	
77.5	*UGAMS-11510 <sup>a</sup>	<i>Picea abies</i> needles	290 ± 25	AD 1500-1660	AD 1560	
65	*UGAMS-9250 <sup>a</sup>	<i>Picea abies</i> needles	270 ± 20	AD 1520-1790	AD 1640	
47 <sup>c</sup>	*UGAMS-11044 <sup>a</sup>	<i>Picea abies</i> needles	290 ± 20	AD 1520-1650	AD 1560	
Floodplain samples:						
195	**Ki-15213 <sup>b</sup>	leaves	2280 ± 80	730-110 BC	330 BC	
145	**Ki-15214 <sup>b</sup>	wood	320 ± 70	AD 1440-1800	AD 1570	
170	***GdA-1792 <sup>a</sup>	charcoal	300 ± 30	AD 1490-1650	AD 1560	
85	***GdA-1793 <sup>a</sup>	charcoal	260 ± 25	AD 1520-1800	AD 1650	

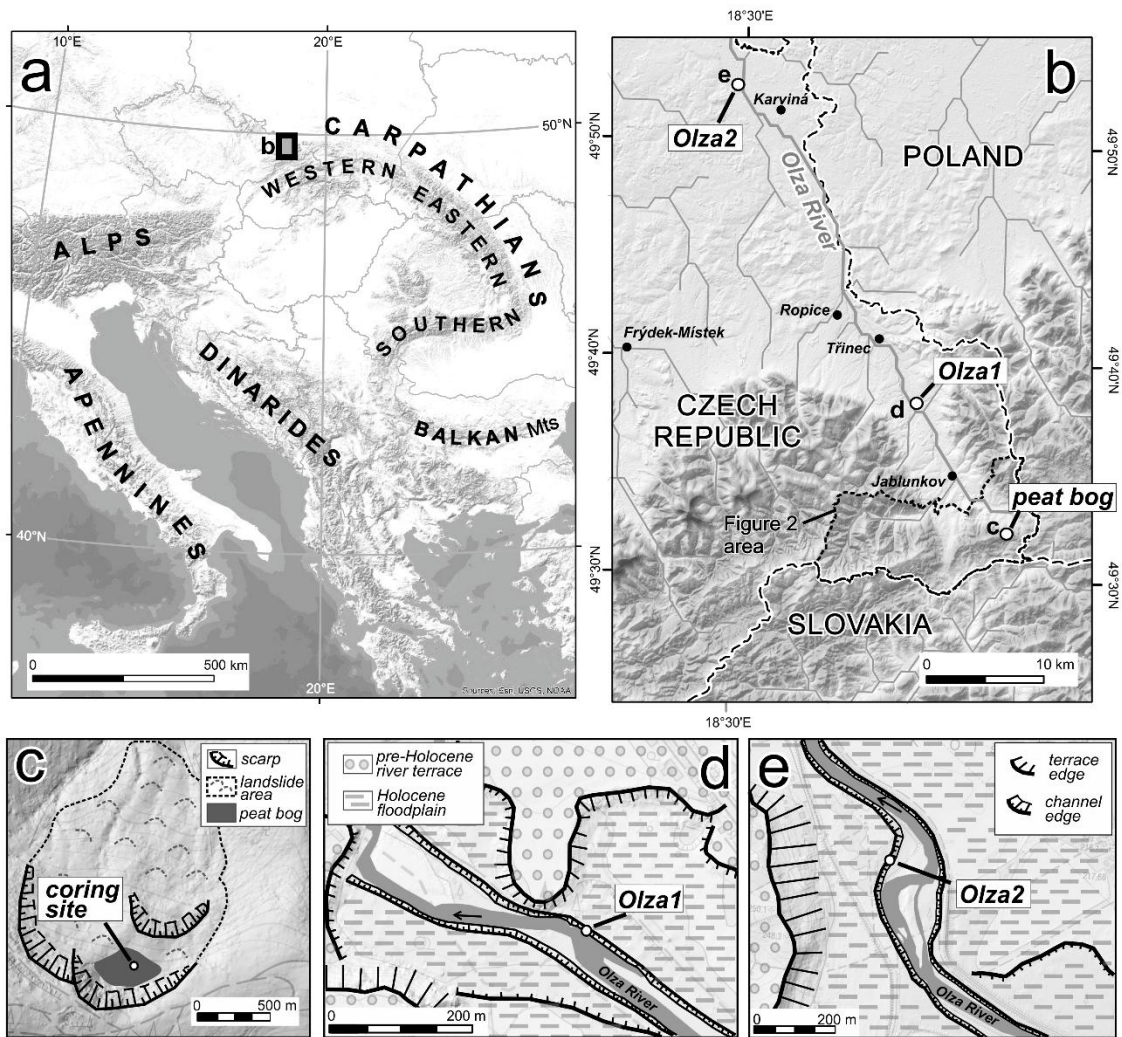
Georgia, USA

\*\* samples sent to Kyiv Radiocarbon Laboratory, Ukraine

\*\*\* samples sent to Gliwice Radiocarbon Laboratory of the Institute of Physics, Silesian University of Technology, Poland

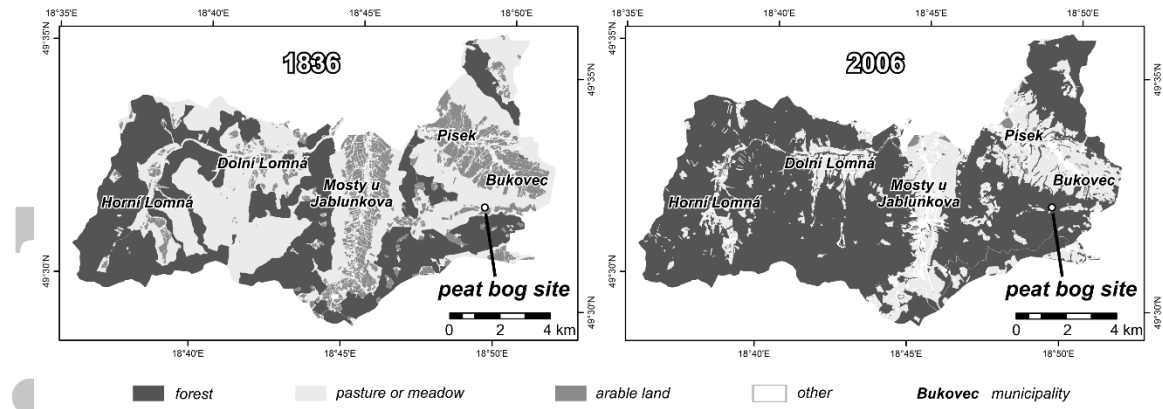
<sup>a</sup> Accelerator Mass Spectrometry method<sup>b</sup> Liquid Scintillation Counting method<sup>c</sup> Re-deposited older material, excluded from the age–depth model

FIGURE CAPTIONS



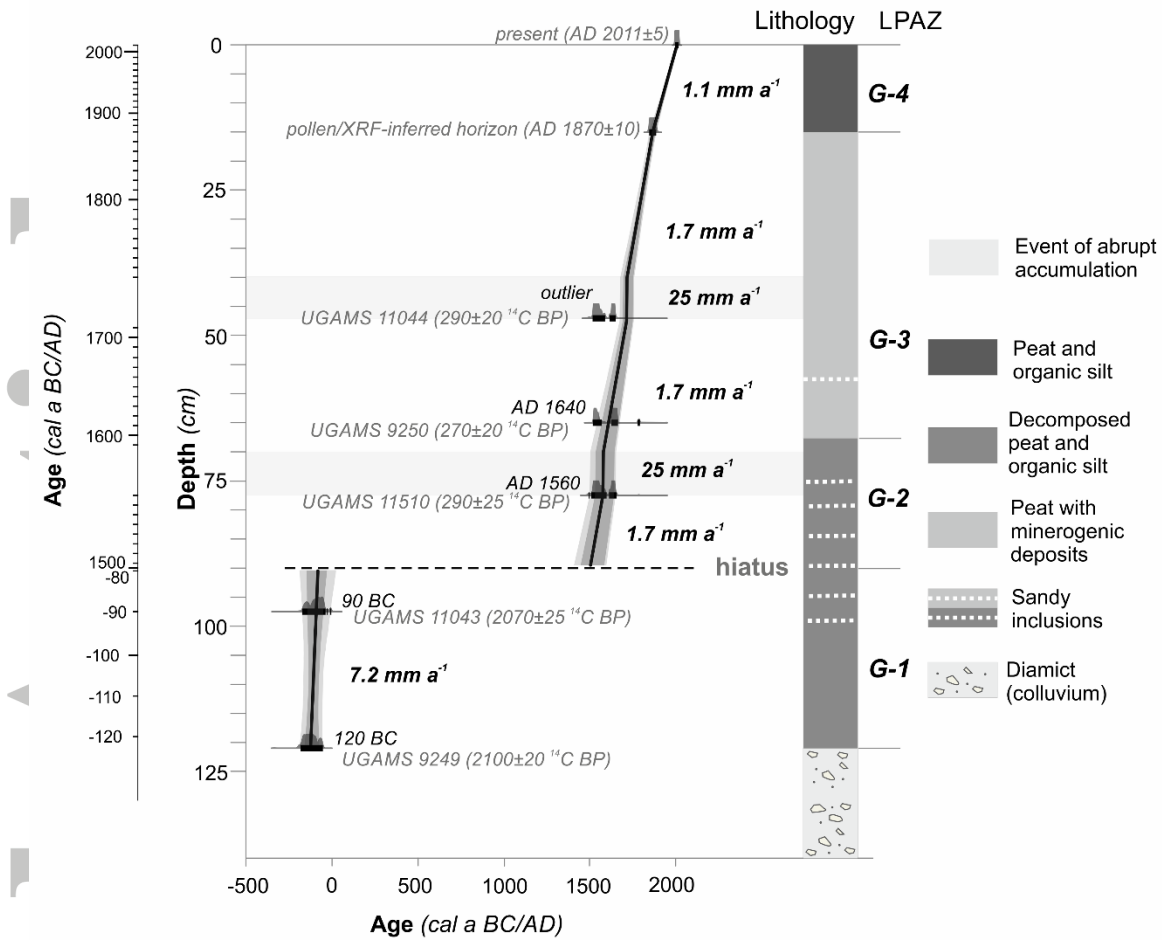
**Figure 1.** Location of study sites in a – Carpathian Mountains, b – Olza River catchment (source of background data: Esri, USGS, NOAA); Simplified geomorphic sketches of study sites: c – Girová peat bog; d – Olza1 floodplain outcrop; e – Olza2 floodplain outcrop (source of topographic background: DMR5G and ZM10, provided by ČÚZK).

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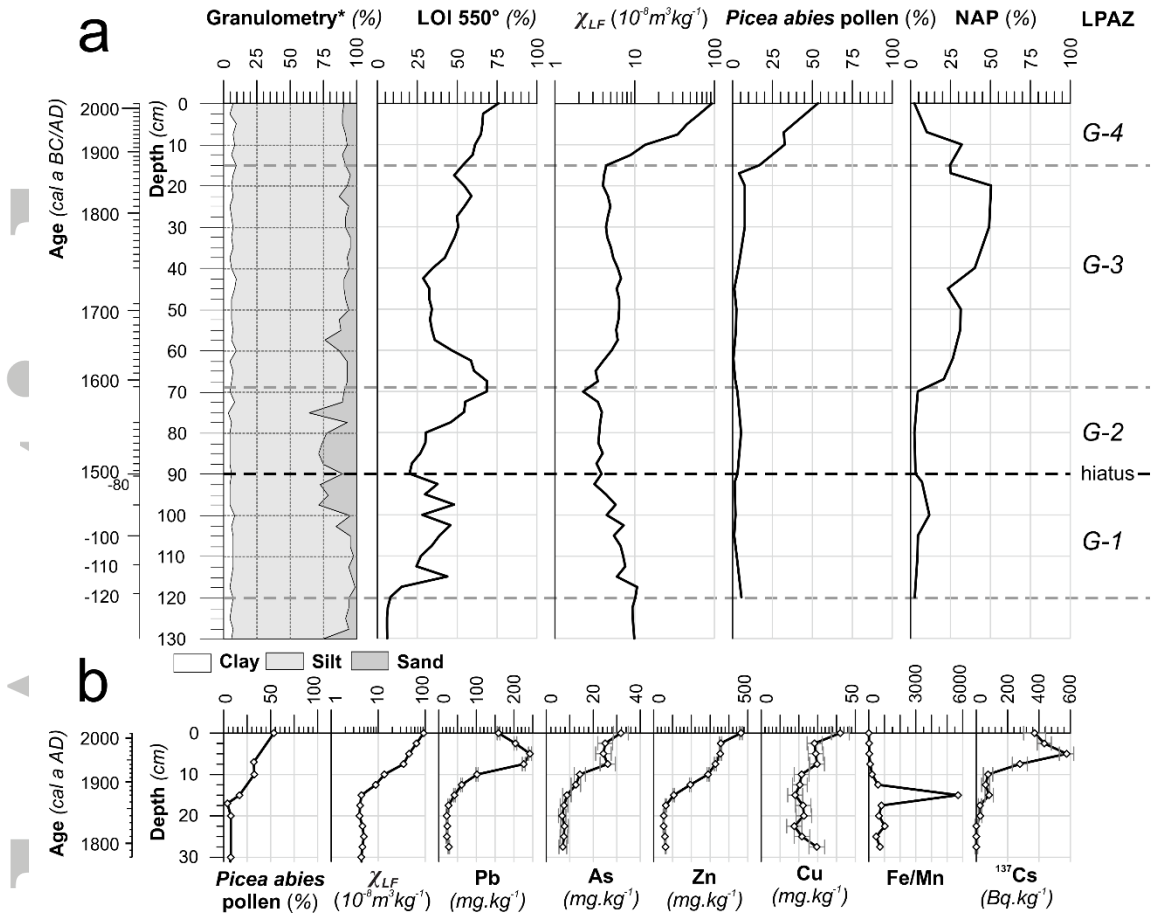
**Figure 2.** Comparison of land use patterns in the mountainous part of the Olza River catchment in the Czech Republic in AD 1836 and 2006 (source: Imperial Imprints of the Stable Cadastre and Orthophoto, provided by ČÚZK).

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**Figure 3.** Age–depth model, lithology and LPAZ units of the Girová peat bog sequence. Light shaded envelope represents two-sigma error, while the dark shaded envelope represents one-sigma error of the modelled chronology. Black text are medians for radiocarbon ages used in the model and bold text are sedimentation rates.

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**Figure 4.** Physical, sedimentological, pollen and geochemical properties of the Girová peat bog sequence: a – whole sequence; b – upper 30 cm. \* Granulometry was determined as a percentage from grains <2 mm.

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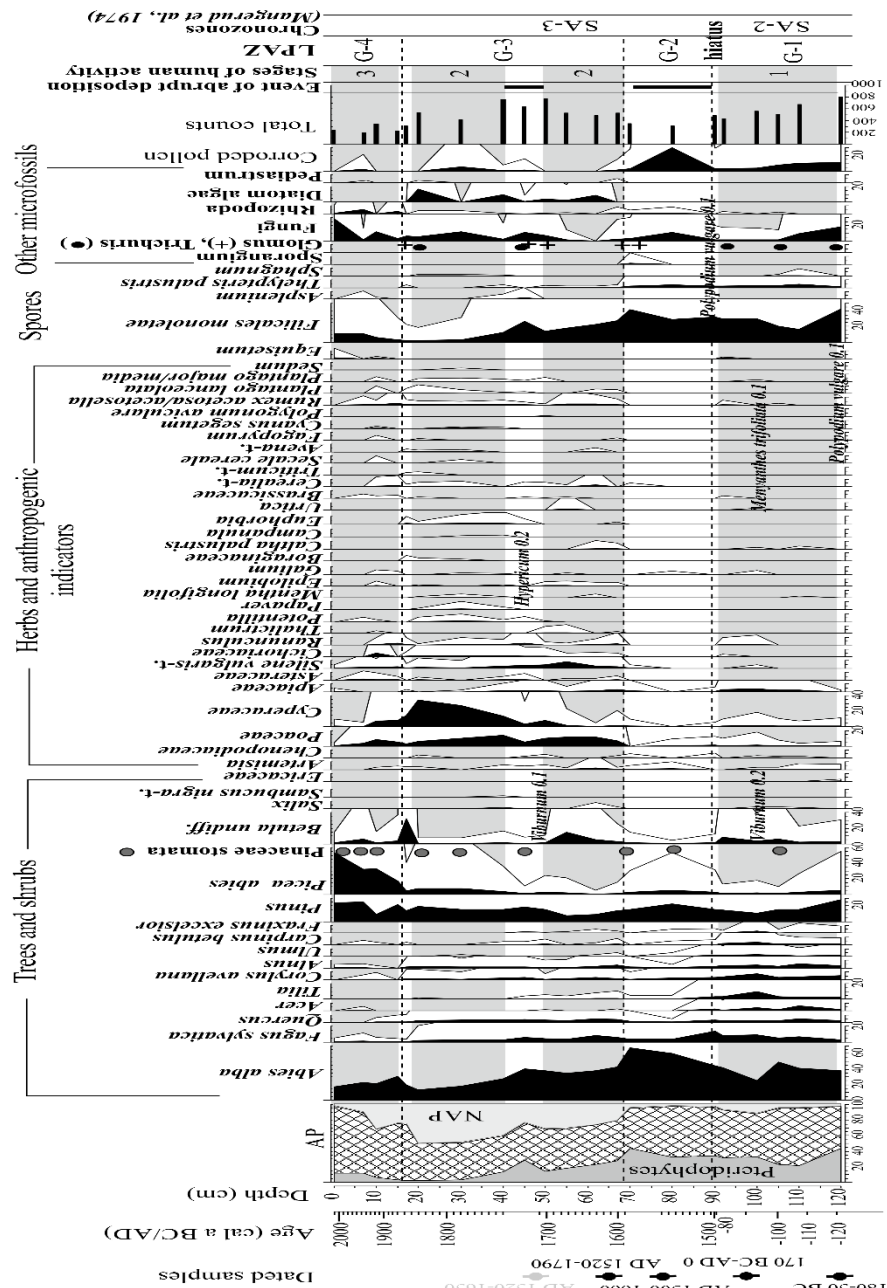
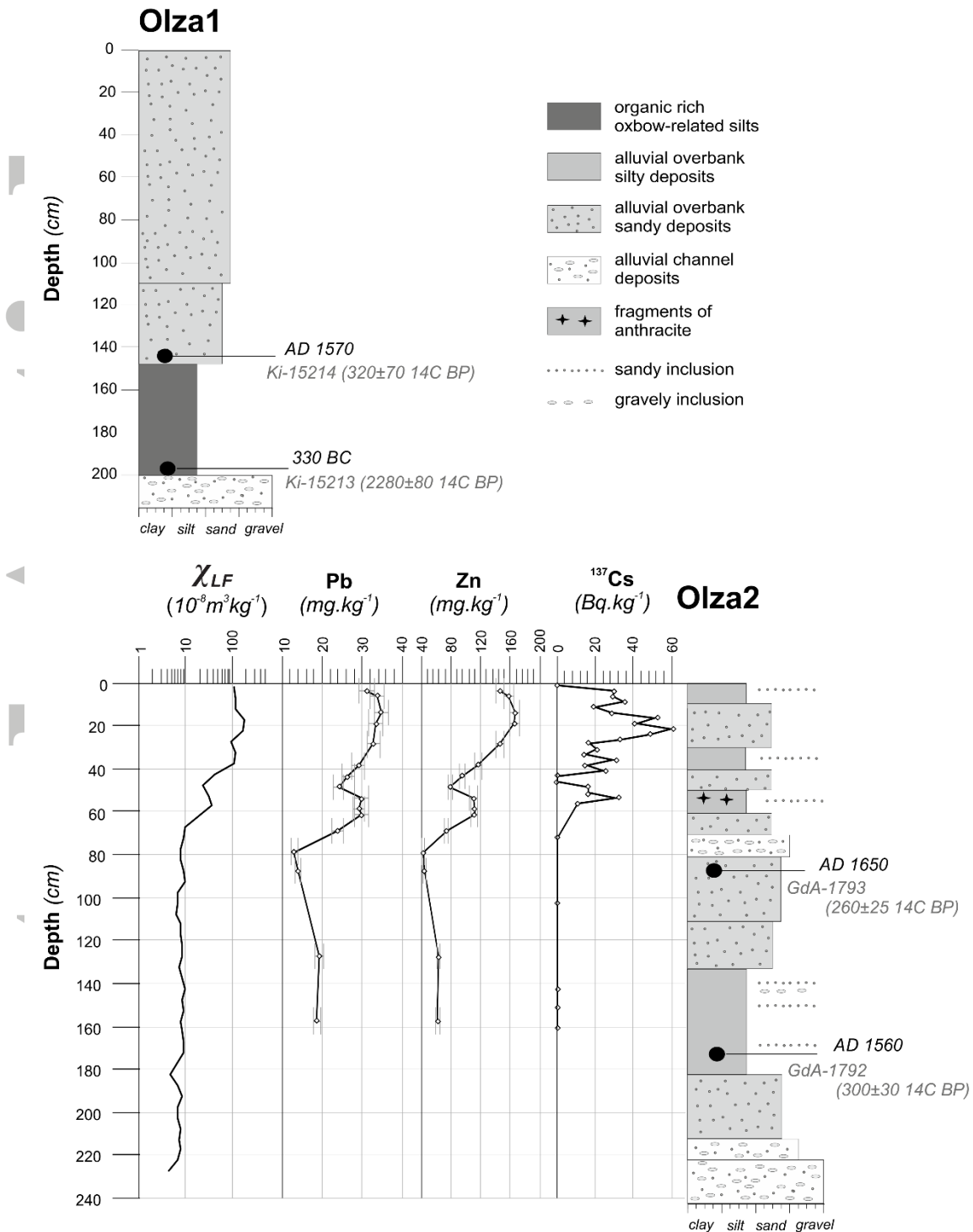
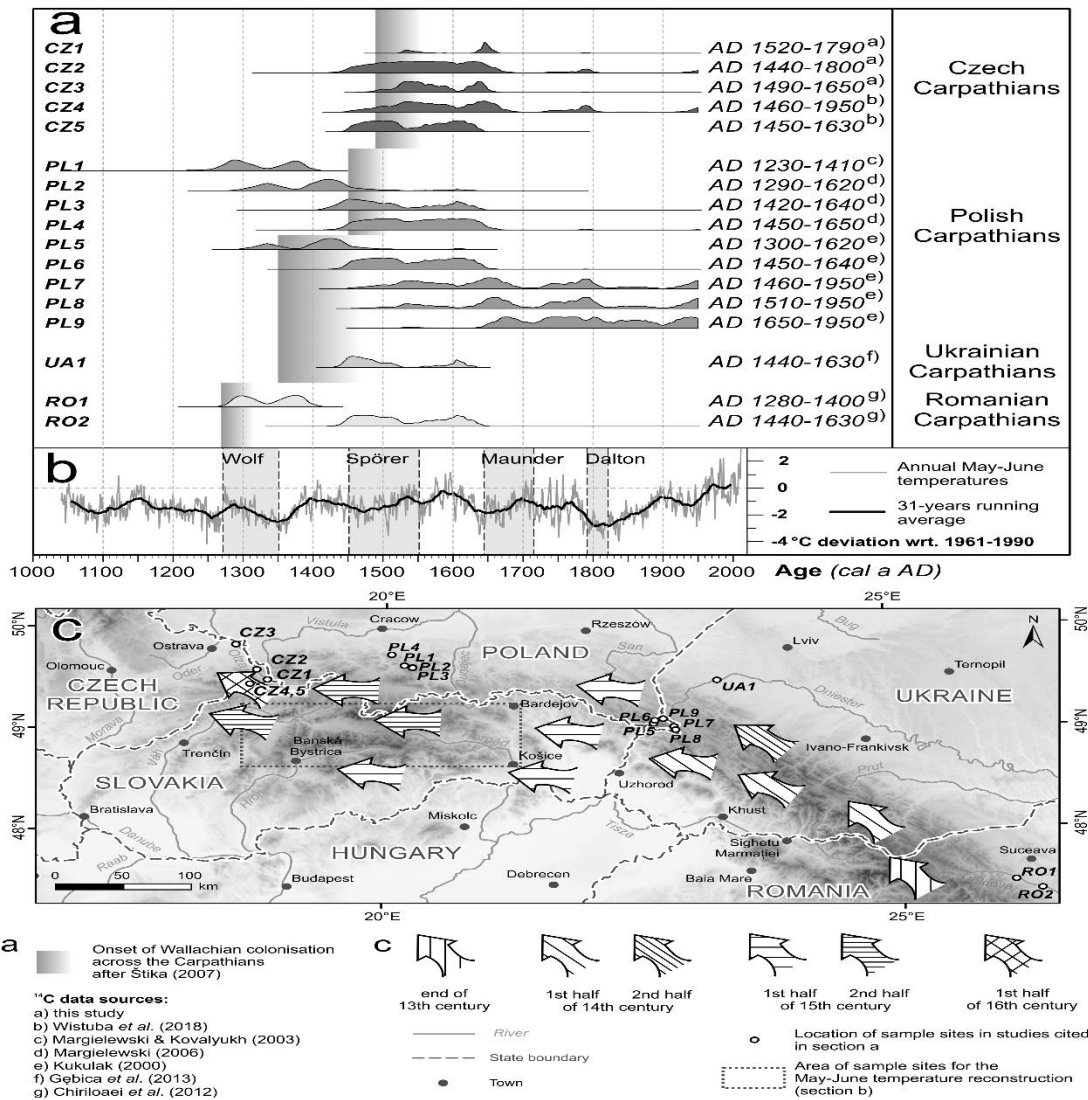


Figure 5. Percentage pollen and microfossil diagram of the Girová peat bog sequence.



**Figure 6.** Lithology and chronology of the floodplain outcrops of the Olza River and the physical and geochemical properties of the Olza2 sedimentary sequence. Black dates are medians for calibrated ages.





**Figure 7.** a – Radiocarbon dating of last human-induced abrupt sedimentary change recorded within peat bogs and alluvial plains in various parts of the Carpathians; b – West Carpathian May–June temperature anomalies wrt. AD 1961–1990 (Büntgen *et al.*, 2013) and solar activity minima (Usoskin, 2017); c – Timing of the Wallachian colonisation in Carpathian regions (after Štika, 2007, source of topographic background: SRTM3, provided by USGS; Natural Earth vector data).