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Medieval vegetation dynamics and montane-industrial history of the central Ore Mountains, Czech Republic, as reflected by alluvial geoarchives

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A R T I C L E I N F O

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A B S T R A C T

The methodically complex analysis of alluvial sediments from stream valleys makes it possible to reconstruct the medieval and early modern history of vegetation and land use in low mountain ranges. For this purpose, eight alluvial sections were documented and analysed in the central part of the Ore Mountains at an altitude interval of 700–800 m a.s.l. An interdisciplinary approach was applied using methods from archaeology, micro-artefact analysis, geomorphology, radiocarbon dating, pedology, sedimentology, geochemistry, and archaeobotany. Our results show that the alluvial valley fills are about 1–2 m thick and consist of various sediment types including coarse wood remains. According to radiocarbon dating, these fills represent the last millennium. Before local medieval clearing in the second half of the 13th century CE, the wet valley floors were covered by spruce, supplemented by alder and other woody taxa. The adjacent dry slopes and plateaus were predominantly overgrown by beech and fir. Silver mining of hydrothermal vein deposits, iron smelting, agriculture, and rural settlements were recognised as specific types of medieval and early modern land use in the study area. These different land-use forms occurred contemporarily, but sometimes spatially separated. Over the course of time strong human impact in the area becomes evident, which has led to deforestation, changes in vegetation and relief, soil erosion, siltation of stream valleys, and local geochemical contamination. A special feature, in comparison with other Central European low mountain ranges, is the existence of a mixed mining-agricultural colonisation in the Ore Mountains, as opposed to a mode in which mining and metallurgy clearly precede permanent rural settlement.

1. Introduction

Alluvial deposits are geoarchives, that reflect the past environment of their source catchments (e.g. Werther et al., 2021). Floodplain sediments can record changes in precipitation, local hydrological regimes and increasing anthropogenic forcing caused by deforestation, industrial activities and/or agriculture (Mäckel et al., 2003; Klimek et al., 2006; Gębica et al., 2016; Dreibrodt et al., 2023; Hrubý et al., 2024). Transitions in the human-landscape interaction are captured by an increase in the amount and rate of the overbank deposit formation (Kapustová et al., 2018). However, small river catchments are more susceptible to local land use changes than large river systems and are therefore more suitable for reconstructing human-induced local landscape dynamics (Dotterweich, 2008). Carefully selected stream sites have several

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research advantages. Compared to on-site analyses, the accumulation of sediments, artefacts, botanical macro-remains, subfossil wood and pollen from the entire catchment can also provide evidence of weak, ultra-local or very short-term human activity. In contrast to peat bogs, where the analysed charcoals and metal elements are transported by air (often over unknown distances), the findings in alluvial deposits (e.g. macro-charcoal or artefacts) are clearly associated with local to non-local human impact. An obvious disadvantage of alluvial geoarchives is the often non-linear sedimentation process, which can result in chronological gaps and, on the other hand, in periods of rapid sedimentation. Specific problems are the potential redeposition of older layers with related dating problems and the different conditions for preserving organic matter in different layers of a profile. Multidisciplinary studies of densely sampled profiles can partially compensate for these problems.

The Ore Mountains (Czech: Krušné hory, German: Erzgebirge) in Bohemia (Czech Republic) and Saxony (Germany) is a particularly promising region for this kind of research due to its dramatic and varied land use history over the last millennium (Fig. 1). The Ore Mountains are an example of a relatively late but rapid medieval colonisation (starting in the 12th century CE in the Saxon part) of a previously widely uninhabited mountain area (Billig and Geupel, 1992; Blažek et al., 1993; Thieme, 2008; Kenzler, 2012; Derner, 2018). This region was heavily affected by metal mining (mainly silver, tin and iron) and metallurgy in the 12th-18th centuries AD. This led to an almost complete deforestation, which is unique amongst the low mountain ranges in Central Europe (Thomasius, 1994; Hempel, 2009; Kaiser et al., 2023). More recently, the forced expulsion of the original German population after 1945 was a turning point towards the abandonment of settlements and agricultural land in the Czech part of the mountains, leading to a large-scale reforestation of the region (Balej et al., 2008; Glassheim, 2016). The most recent change in land use of this part is the almost complete conversion of arable land into EU-subsidised meadows and pastures in the period after 1989.

The early modern period of human-nature interaction in the study area is well known from written sources as well as from architectural and artistic features (Nožička, 1957; Ministr, 1967; Wagenbreth and Wächtler, 1990; Claire, 2022; Hrubá et al., 2024). However, the intensity, environmental consequences and spatial distribution of human impact in the Middle Ages (and probably also in prehistory) are still largely hypothetical or at most very locally studied (e.g. Tolksdorf et al., 2015, 2019; Tolksdorf, 2018; Houfková et al., 2019; Kaiser et al., 2021). An advantage for studies on local alluvial deposits is the moderate georelief of the mountain plateau with a dense network of small stream valleys, showing no or only weak imprint of modern infrastructure and other changes.

An intensification of the thematic research resulted from the Saxon/Czech EU archaeological project “ArchaeoMontan” in 2012–2018 (Hemker, 2018; Tolksdorf, 2018). In the Czech part, the surroundings of the abandoned town of Přísečnice/Preßnitz were chosen for new field studies, comprising a geo-archaeological approach (Derner, 2018; Supplement 1). First palaeo-environmental analyses of alluvial sections were performed in 2016 (Kočár et al., 2018), which were continued in 2019–2020 with the discovery of subfossil tree trunks in the Černá voda stream at the village of Černý Potok and resampling of all previously investigated sections (Table 1).

The aims of our research are: (1) to investigate alluvial stream geoarchives for their suitability for reconstructing local medieval and modern vegetation dynamics and montane-industrial history, (2) to reconstruct the natural forest vegetation prior to medieval colonisation, and (3) to reconstruct mining and smelting activities as well as agricultural practices in the study area, i.e. the central part of the Ore Mountains.

2. Regional settings

The study area is located on the plateau of the central Ore Mountains, which is dissected by shallowly deepened stream valleys at an altitude of about 700–900 m a.s.l. (Fig. 2A). The climate is typically montane with an average annual temperature of 5 °C, rainfall of over 800 mm and a short growing season with 110 days. The area is also influenced by a long-lasting snow cover (Plíva and Žlábek, 1986).

The study area belongs to the geotectonic crystalline unit Krušné hory Mts./Erzgebirge – Přísečnice group formed by mesozonally metamorphosed rocks (Škvor, 1975; Sebastian, 2013). The original rocks were a sedimentary complex of mica schists, mica-schist gneisses, quartzites, wacke gneisses and metaconglomerates (Fig. 2B). Prominent mountain peaks are formed by amphibolites, basalts and skarns. Metal-bearing structures are skarns and ore-veins (see chapter 4.4.1; Supplement 2).

With a view to effects on soil formation and vegetation, the varied permeability of the substrates (permeable coarse-grained gneisses to poorly permeable phyllites) is of particular importance. On the plateau, high rainfall and low permeability of the substrates lead to waterlogging and even peat formation. At better drained sites, acidic Cambisols predominate. Other soils include Podzols, Gleysols and Histosols. The current forest vegetation is dominated by spruce monocultures. A few beech

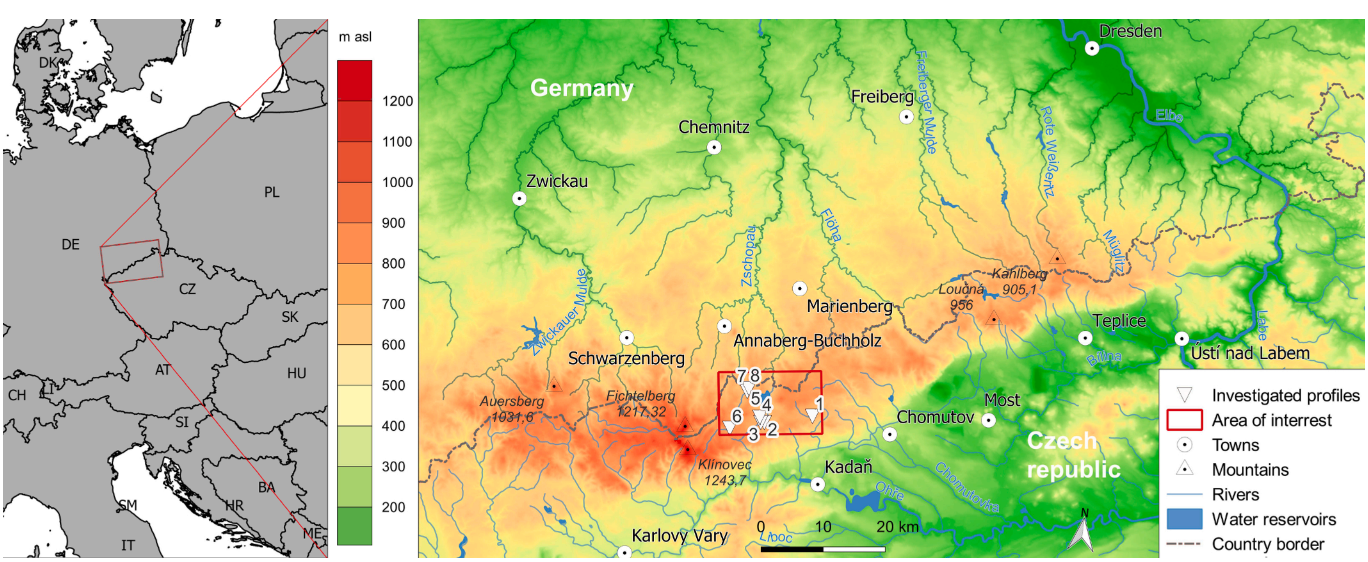

Fig. 1. Study area in the central part of the Ore Mountains. Left: Location of the study area in Central Europe. Right: 1–8: investigated alluvial profiles.

Table 1
Overview on the investigated profiles including site attributes and available data.

Section ID	Profile	Northing	Easting	Altitude (m a.s.l.)	Dating	Soil data	Botanical data	Artefacts
1	Výsluní	50,47120789	13,23558377	754	^{14}C, artefacts	grain size, geochemistry	pollen, macroremains, charcoals	microslags, wood, ceramics
2	Dolina 1	50,45179564	13,12981821	740	^{14}C	grain size, geochemistry	pollen, macroremains, charcoals	microslags
3	Dolina 2	50,45117827	13,12195056	745	^{14}C, artefacts	grain size, geochemistry	pollen, macroremains, charcoals	microslags, ceramics
4	Přísečnice, profile 2016	50,45830904	13,11787677	752	^{14}C	grain size, geochemistry	pollen, macroremains, charcoals	microslags
5	Černý Potok, profile 2016	50,49252081	13,08078351	738	^{14}C	grain size, geochemistry	pollen, macroremains, charcoals	microslags
6	Kovářská	50,43571522	13,05474193	810	^{14}C	geochemistry	pollen, macroremains, charcoals	
7	Černý Potok, profile 1/2019	50,49699596	13,08377761	704	^{14}C, artefacts	grain size, geochemistry	pollen, macroremains, charcoals	microslags, wood, ceramics
8	Černý Potok, profile 2/2019	50,4968646	13,0836475	704	^{14}C, artefacts	grain size, geochemistry	pollen, macroremains, charcoals	microslags, wood, ceramics

stands and single occurrences of other tree species indicate a former natural forest composition in this area consisting mainly of beech, fir and spruce, supplemented by other deciduous trees such as maple, elm and mountain ash (Hempel, 2009; Chytrý, 2012; Kaiser et al., 2023).

The studied region around the abandoned town of Přísečnice is one of the highest permanently settled areas in medieval Bohemia. In the second half of the 13th century CE, Přísečnice and the surrounding villages were founded on the long-distance road from Bohemia to Saxony (Černá, 2014; Crkal and Volf, 2014; Horák and Klír, 2017; Houfková et al., 2019). Relics of silver and iron ore mining date back to the 1370 s AD (Derner, 2018). A mining crisis in the second half of the 14th and the 15th centuries AD (Schwabenicky, 2009) is reflected by the disappearance of all archaeologically proven mining settlements and smelting sites, and according to written sources, by reforestation (Derner, 2018). In the 16th century CE, the revival and massive expansion of mining in the study area led to the establishment of new mining towns such as Vejprty (Weypert), Výsluní (Sonnenberg) and Jöhstadt (Urban, 2015). In the 17th century CE, new blast furnaces in Sorgental and Kovářská (Schmiedeberg) led to a huge local consumption of wood (Kloub, 2014, 2016). The end of the local mining activities dates back to the first half of the 19th century CE. Centuries of mining and metallurgy have left considerable contamination of surface soils and sediments in the study area (Hošek et al., 2024).

The anthropogenic settings of the presented profiles cover three different areas of land-use: the mining sub-region southwest of Přísečnice along the Střelnický potok (Schießbach) and upper Přísečnice streams (Hammerbach), the iron-smelting area along the Černá voda stream (Schwarzwasser), and the agricultural landscape around Výsluní consisting of medieval field strips (Fig. 2C).

3. Methods

3.1. Fieldwork

All profiles were recorded from outcrops along the stream banks (Supplements 3, 4). After cleaning and documentation, steel boxes with a size of 50 × 10 × 7 cm were used for sampling. Subsampling for analyses on pollen, macro-remains including charcoals, and geochemistry, was performed in the laboratory. The most extensive profiles at the Černý Potok site were documented photogrammetrically using the software Meshroom for the 3D reconstruction and a Harrix matrix for depicting the stratigraphy (Harris, 1989). Micro-artefact, sediment and geochemical samples were taken from different sedimentological units of the profiles in the field.

3.2. Geomorphology

The geomorphometric analysis was based on a 1 × 1 m resolution DTM. Modelling was performed using Wetness Index as modified by SAGA (SAGA TWI) (Beven and Kirkby, 1979; Boehner et al., 2002), Stream Power Index (SPI) (Fried et al., 2000), and Multiresolution Valley Bottom Flatness (MRVBF) (Gallant and Dowling, 2003; Gallant and Hutchinson, 2008; Wang and Laffan, 2009).

For this study cadastre maps from the year 1842 were used (ÚAZK, Císařské povinné otisky, sign. B2/a/6C). We focused on two sites in the valleys of the Černá voda and Přísečnice streams, where we identified changes in the river course. The present-day course of the riverbed was compared with the cartographic image.

In the Černá voda valley, at the section in the village of Černý Potok, the spatial variation of fluvial sediments on the terrace surface was geophysically imaged. The electromagnetic induction method (EMI) was used, applying an electromagnetic conductivity meter CMD-Explorer (GF Instruments, Brno). This instrument allows the measurement of apparent conductivity (Doolittle and Brevik, 2014; Balkov et al., 2017).

3.3. Dating

Plant macrofossils and charcoal were used to obtain 21 AMS radiocarbon dates, measured by the Debrecen and Mannheim radiocarbon laboratories. OxCal 4.2 and 4.2.4 software (Bronk Ramsey, 2013, 2020) and the IntCal 13 atmospheric curve (Reimer et al., 2013) were used to calibrate the radiocarbon dates.

A total of 19 large wood samples were taken from several profiles (Černý Potok/2016, Černý Potok 1/2019 and 2/2019, Přísečnice, Dolina 2, Výsluní) and examined in the Mannheim and Brno dendrolabs.

Dating of ceramic fragments is based on the regional typochronology (Derner, 2018; Geupel and Hoffmann, 2018).

3.4. Sedimentology and pedology

The profiles presented were recorded and sampled in the field with respect to their geological-sedimentological and pedological properties, using both an international (FAO, 2006) and a German soil science standard (Ad-hoc-AG Boden, 2005). Terminology for soil types follows the World Reference Base for Soil Resources (IUSS Working Group WRB, 2015). Layers and horizons are determined according to specific characteristics, which include texture, organic content, colour, stratification, and other aspects (e.g. botanical remains and artefacts). Soil analyses were performed on a total of 39 samples on the matrix matter < 2 mm to assist in the designation of sedimentary facies and diagnostic soil horizons. Laser diffraction (Beckman-Coulter particle analyser) was used to

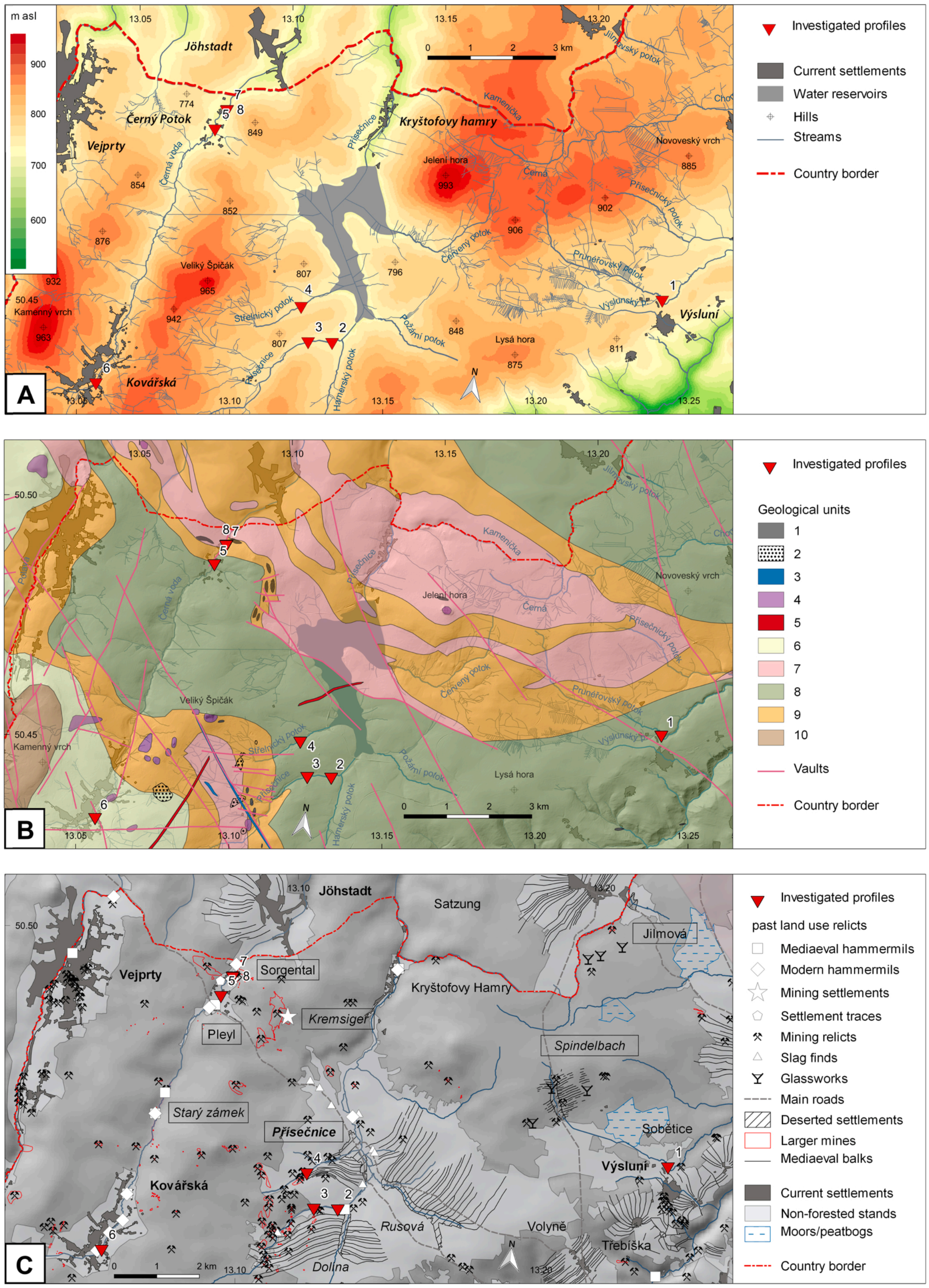

Fig. 2. Regional settings (the map section corresponds to the highlighted small map frame in Fig. 1). A: topography of the region (based on ZABAGED data of ČÚZK and EU DEM from GMES RDA Project). B: geology – 1: outcrop of skarn bodies; 2: hidden skarn bodies; 3: kersanite; 4: tertiary basalts; 5: variscan migmatites (veins); 6: paraseries (Niederschlag group); 7: ortogneisses; 8: paraseries (Pressnitz group – Reichsdorf formation) 9: paraseries (Pressnitz group – Kupferberg strata); 10: metamorphites of St. Joachimstal group (Hoth et al., 1995, Bohdálek et al., 2018). C: Medieval and early modern land use in the study area (Derner, 2018). The digitalisation of medieval to early modern fields, meadows and non-forested area is based on cadastre map from 1842 and Messtischblatt Sachsen 1908. The framed names indicate archaeologically investigated sites.

determine grain-size distribution. Organic matter content was estimated by combustion at 550 °C (loss-on-ignition, LOI; Heiri et al., 2001). Soil pH was analysed potentiometrically in 0.01 M $CaCl_2$ (soil: solution ratio = 1:2.5).

3.5. Geochemistry

A total of eight profiles were sampled in the study area. The trace element content in the < 0.1 mm fraction was analysed. The metal element content was measured in the laboratory of the Czech Geological Survey in Prague after drying and homogenisation using a stable-mounted pXRF device. The so-called pollution factor (EF) was calculated to identify the potential additions of elements compared to the natural concentration in the surface layer (Wu et al., 2014; Muzerengi, 2017) using the following equation:

EF = [Xsample/Ysample] / [Xn/Yreg] where X is the element concentration in the sample. Xn is the element concentration in the local background (the values were taken from Kořistka, 1991). Y is the concentration of the standard element. In our study, aluminium was chosen as a conservative element and a major constituent of clay minerals (for more details see Derner et al., 2022).

3.6. Micro-artefact analysis

Per sample, 0.5–3 l of fresh sediment was collected from the profiles. Particles were separated into 0.5–4 mm, 4–8 mm and above 8 mm fractions by wet sieving followed by dry sieving. The magnetic fraction was extracted using a magnet with a breakaway force of 160 kg. The slags were counted using an optical microscope under reflected light at a magnification of 1 × 20 in a volume of 5 ml. The number of slags was then converted to a standard volume of 1 l of the original wet sediment (cf. Houbrechts et al., 2020).

3.7. Palynology and plant macro-remain analysis

Samples for pollen analysis were prepared using a standard method comprising acetolysis, including the use of hydrofluoric acid (Moore et al., 1991). Pollen atlases (Moore et al.,1991; Reille, 1992, 1995, 1998; Beug 2004) were used for pollen grain identification. The programme POLPAL (Nalepka and Walanusz, 1999; Nalepka and Walanusz, 2003) was used to plot pollen diagrams. Alder (*Alnus*) and wetland species were excluded from the pollen sum.

Samples for plant macro-remains analysis were wet sieved through a set of sieves with a mesh size of 0.25 mm and larger. A stereomicroscope was used to sort plant macro-remains. The fraction above 2 mm was observed for charcoal and non-charred wood fragments. The macro-remains were dried and examined under a stereomicroscope at a magnification of 12 × and larger. Plant species were identified using atlases (Cappers et al., 2006; Velichkevich and Zastawniak, 2006, 2008).

3.8. Meta analysis of geochronological data from the Ore Mountains

Radiocarbon and OSL dates were extracted from published alluvial profiles and analysed using probability density functions (e.g. Hoffmann et al., 2008; Jones et al., 2015) The procedure is described in Kaiser et al., 2021. The border between the colline (hilly region level) and submontane ecologic-altitudinal zone (lowermost upland level) at 300 m a.s.l. (Leuschner and Ellenberg, 2017) was used to delineate, i.e. to exclude and to include alluvial records for this regional compilation.

4. Results

4.1. Geomorphology

The two studied catchments of the Černá voda and Přísečnice streams have different shapes, which probably leads to different runoff characteristics (Fig. 3). The Černá voda basin is narrow and long, whereas the Přísečnice basin is more compact and morphologically diverse. The steep slopes of the former are divergent (i.e. ridges, see Philip, 1991), and the surface runoff takes place predominantly in narrow, short valleys. The steep slope of the area favours flushing and general erosive tendencies on the land surface. The bottom of the main valley is narrow, except for the section near the village of Černý Potok in the north of the area. It is mainly prone to accumulation processes. In the Přísečnice catchment, well above (south of) the dam reservoir, there is an area of low to moderate gradient of relief. As a result, the TWI model shows a higher proportion of terrain prone to water stagnation. The slopes considered erosive by the SPI model are short and do not form extensive zones. The MRVBF model indicates the presence of many flat areas. However, most of them do not belong to stream valleys but to higher elevated areas.

DTM analysis shows that the study area contains a wide variety of landforms associated with human activity (Fig. 3). These include traces of mining, agriculture, land reclamation, stream regulation, and transport infrastructure.

Comparison of the current pattern of the Černá voda and Přísečnice streams with old maps leads to the conclusion that their curved shapes have significantly changed since 1842 CE as a result of anthropogenic bank regulation (Supplements 5A-D). At the village of Černý Potok, the establishment of water mills led to straightening of the riverbed. In this section of the valley, the geophysical measurements indicate the presence of sediments with properties incompatible with the effects of natural fluvial processes (Supplement 5E), i.e. indicating anthropogenic effects.

4.2. Chronology and radiocarbon dating

From the twenty-one samples dated (Table 2), the oldest age is 420–552 cal AD and the youngest is 1646–1950 cal AD. All the dates prior to the 13th century CE come from uncharred macro-remains. On the contrary, the data obtained from charred macro-remains and charcoals were of late medieval (after 1256 cal AD) or early modern age.

In profiles Černý Potok 1/2019 and 2/2019, two large wood samples were radiocarbon dated. To determine the felling date, wiggle matching (Galimberti et al., 2004), using radiocarbon ages from two maximally distant year rings (see chapter 4.4.2), was applied.

Inverse dates were obtained in three of the eight profiles. Sampling or laboratory errors can be ruled out with high certainty. It can be assumed that in the dynamic fluvial environment the redeposition of older material is responsible for this.

All the dendrochronological examined trees were *Picea*, with one exception (*Abies*). Although the samples had an average of 55 tree rings (total range: 25–170 tree rings), no wood could be dated due to irregular growth patterns and the lack of a regional reference curve for *Picea*.

In some profiles, ceramic fragments provided age estimates for certain layers. With the exception of the medieval finds in the lower section of Přísečnice 1/2019, all further ceramics date into the early modern period.

4.3. Sedimentology and pedology

In terms of the general depositional environment, the profiles represent alluvial sedimentary sequences ranging in thickness from 90 to 230 cm. Common to all profiles is the presence of a significant number of sedimentological sub-facies types, including anthropogenic sediments.

The base of the profiles is mainly formed by coarse fluvial sediments, which predominantly consist of well-rounded gravels/boulders with an axis length in some cases several decimetres long and finer material of pebble and coarse sand (Fig. 4, Supplement 4). These base sediments are free of organic matter (exceptions may be deep roots) and probably date to the late Pleistocene. This is followed by partly stratified fluvial sands

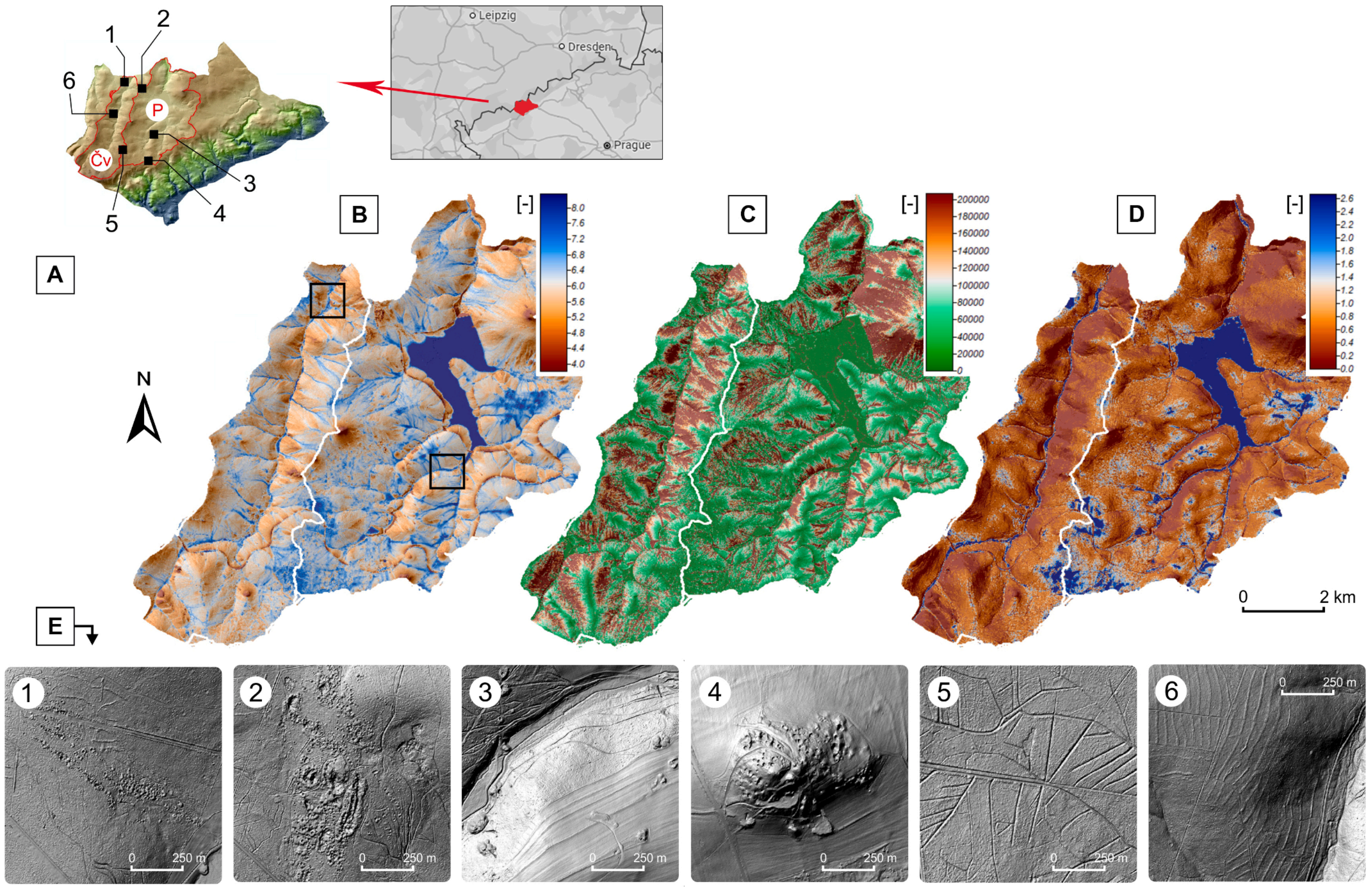

Fig. 3. Topographic conditions for erosion-accumulation processes on the terrain surface in the study area. A: partial catchments of the Černá Voda (Čv) and Přísečnice (P) streams; fields with numbers refer to part E. B: SAGA TWI, high values indicate high surface runoff, black boxes mark study sites shown in Supplement 3. C: SPI, high values indicate areas potentially prone to increased erosion. D: MRVBF, high values show flattening; for stream valleys these are accumulation zones. E: specific anthropogenic landforms determining the intensified supply or modification of hydrological and geomorphological processes – 1: post-mining field; 2: post-mining field; 3: spoil tips at the outlet of adits; agriculture terraces and hammermill / watermill channels; 4: post-mining landforms on a steep slope; 5: ditches; 6: landforms connected with forestry works after the forest dieback (regional environmental catastrophe) in the 1980 s and 1990 s.

Table 2
Radiocarbon dates from the investigated profiles.

Profile	Depth	Lab. nr.	Dated material	Age BP	Age cal AD, 2 δ	Species
ČernýPotok 2016	172–178 cm	DeA-10828 I/1435/5	macrofossils (*Sambucus racemosa*)	635 ± 24	1287–1395	*Sambucus racemosa*
ČernýPotok 2016	196–198 cm	DeA-10829 I/1435/6	macrofossils (Sambucus racemosa)	444 ± 23	1424–1468	*Sambucus racemosa*
ČernýPotok 2016	205 cm	ETH-109511	wood, branch	974 ± 22	1021–1157	?
Černý Potok 1/2019	65–83 cm	ETH-109507	wood 2: 6/7 three ring (*Picea abies*)	1130 ± 22	777–992	(*Picea abies*)
Černý Potok 1/2019	65–83 cm	ETH-109508	wood 2: 167/168 three ring (*Picea abies*)	943 ± 22	1035–1159	*Picea abies*
Černý Potok 2/2019	160–180 cm	ETH-109509	wood 6: 5 three ring (*Picea abies*)	882 ± 22	1050–1222	*Picea abies*
Černý Potok 2/2019	160–180 cm	ETH-109510	wood 6: 81/82 three ring (*Picea abies*)	771 ± 22	1225–1279	*Picea abies*
Dolina 1	79–85 cm	DeA-10824 I/1435/1	macrofossils (*Carex* ssp.)	488 ± 23	1412–1445	*Carex* ssp.
Dolina 1	96–100 cm	DeA-10825 I/1435/2	macrofossils (*Picea abies*)	370 ± 22	1450–1630	*Picea abies*
Dolina 2	68–74 cm	DeA-10826 I/1435/3	macrofossils (*Carex* ssp.)	155 ± 22	1667–1949	*Carex* ssp.
Dolina 2	92–98 cm	DeA-10827 I/1435/4	macrofossils (*Abies alba*)	1567 ± 27	420–552	*Abies alba*
Dolina 2	85–98 cm	Dolina 20_400	wood, cone	1028 ± 19	992–1030	?
Kovářská	89–95 cm	MAMS-29668	macrofossils (*Picea abies*)	742 ± 18	1256–1285	*Picea abies*
Kovářská	131–139 cm	MAMS-29669	macrofossils (*Picea abies, Sambucus* sp.)	224 ± 18	1646–1950	*Picea abies, Sambucus* sp.
Přísečnice	179–185 cm	MAMS-29670	macrofossils (*Picea abies*)	672 ± 19	1279–1385	*Picea abies*
Přísečnice	191–195 cm	MAMS-29671	macrofossils (*Picea abies*)	699 ± 18	1270–1378	*Picea abies*
Výsluní	56–62 cm	MAMS-29672	macrofossils (*Picea abies*)	352 ± 19	1463–1633	*Picea abies*
Výsluní	86–92 cm	MAMS-29673	macrofossils (*Carex* ssp.)	713 ± 19	1266–1293	*Carex* ssp.

and silts, partly silty or sandy gyttjas (lacustrine deposits). In these sediments, the maximum silt content is 70 % and the maximum sand content is 83 %, forming silt loams to loamy sands. With a maximum of 8 %, clay has a subordinate share. In one profile (Dolina 2), peat is also formed near the base, although the definitional limit of organic content for peat is slightly undercut at 28 %. The maximum organic content in the carbonate-free gyttjas is 35 %. The gyttjas were probably formed in abandoned stream meanders (oxbow ponds). In the lower alluvial sediments, there are mostly layers of coarse and fine woody debris consisting of tree trunk segments, root wood, branches, conifer cones, as well as conifer needles and deciduous leaf residues in dense packing. Coarse charcoal fragments are also present. The radiocarbon dates near

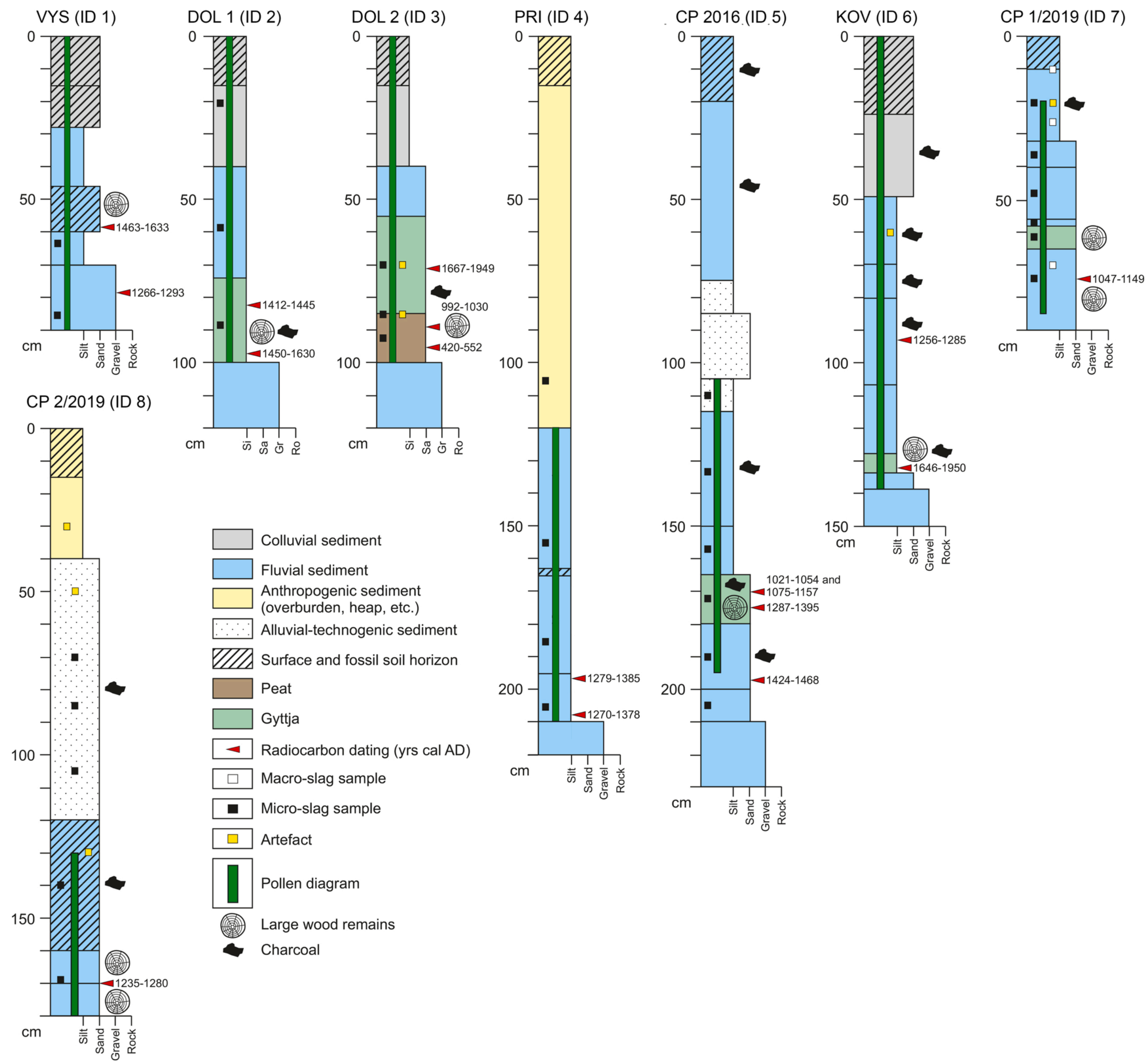

Fig. 4. Lithological logs showing the investigated profiles with sedimentological-pedological information and radiocarbon data as well as sampling positions for palaeobotanical, macro-/microslag and archaeological analyses. Further details, e.g. on pedological horizontation, are given in Supplement 4.

the base mostly point to a medieval age of the coarse wood layers. There is, thus, a distinctive hiatus between the late Pleistocene gravel base and these fluvial sands and gyttjas from the late Holocene. The upper part of the profiles is characterised by fluvial silts and sands, alluvial-technogenic sediments (i.e. fluvially transported material from ore preparation and metallurgic activities upstream), anthropogenic sediments (overburden, heap), and colluvial silts and sands. Charcoal is common in all sediment types. Ceramic artefacts indicate an early modern to modern age (16th to 19th centuries AD).

The topsoils of the alluvial profiles are humic and gleyic due to the nearby groundwater level (Fig. 4, Supplement 4). In terms of soil typology, they represent Fluvisols, Technosols and Anthrosols, all with gleyic properties. Two profiles (Výsluní, Dolina 2) have buried (fossil) horizons forming palaeosols (Fig. 4). They represent Ahb and Heb horizons, respectively. Further pedological differentiation, such as illuviation of sesquioxides and clay or brunification, could not be observed in the surface and buried soils except gleying. The pH analyses available for three profiles (Dolina 2, Černý Potok 2016, Černý Potok 2/2019) show a strongly to weakly acidic status with values between 4.2 and 5.4.

Profile descriptions and soil analytical data are documented in Supplement 6.

4.4. Human impact reflected by archaeobotany, micro-artefact analysis and geochemistry

According to the past land use, the region can be divided into three sub-regions: the main silver-mining area along the Přísečnice stream and its left-hand tributaries, the iron smelting area in the valley of the Černá voda stream, and the rest of the area with agricultural use (Fig. 2C). Different human impact is reflected by archaeobotany, micro-artefact analysis and geochemistry (Figs. 5–9, Supplement 7–11).

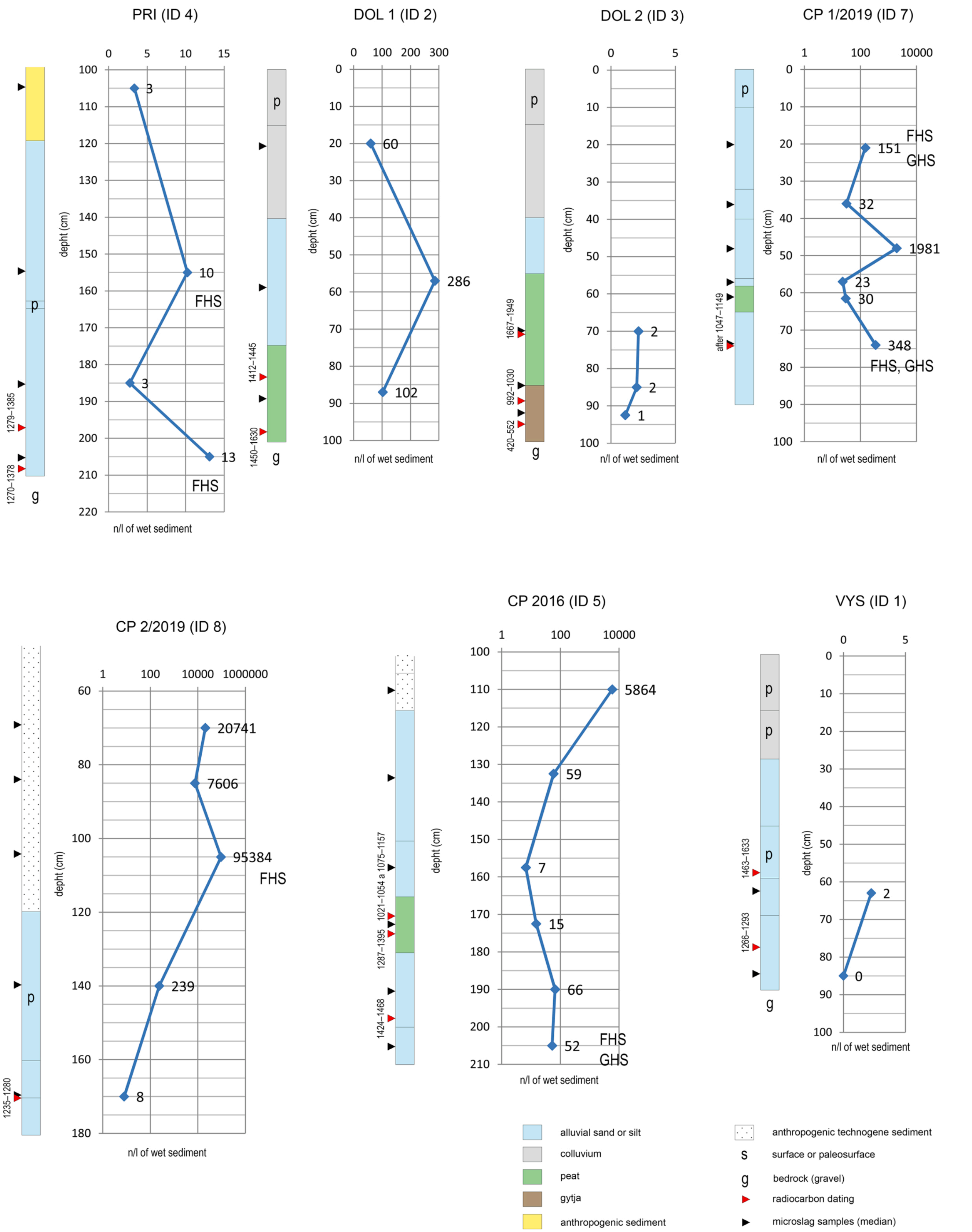

Fig. 5. Count of microslags (0.5–30 mm) per litre of wet sediment from the alluvial profiles recorded in the Přísečnice area. FHS: flake hammerscales; GHS: globular hammer-scales.

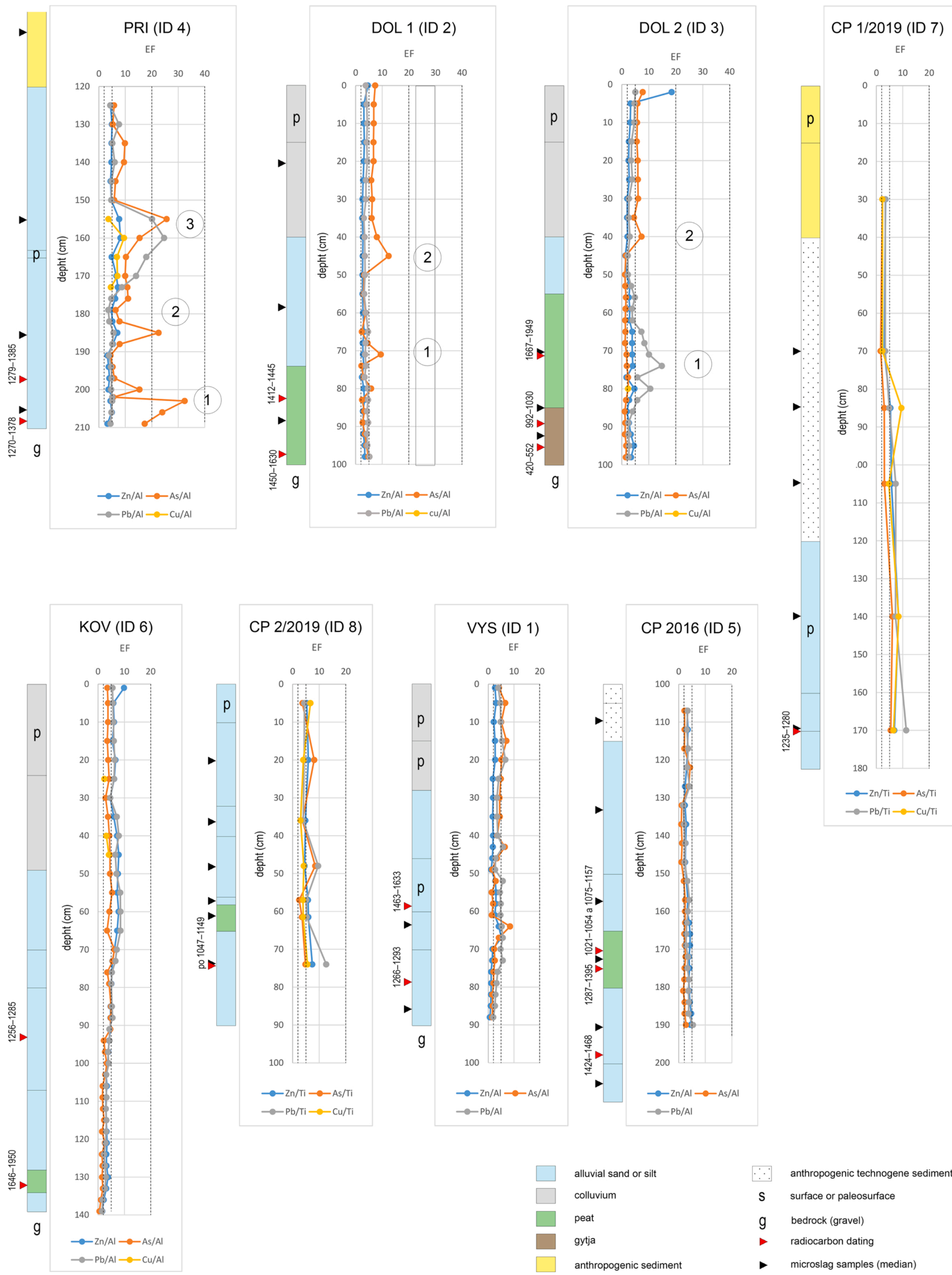

Fig. 6. Geochemical enrichment factor (EF) of selected elements of the investigated profiles.

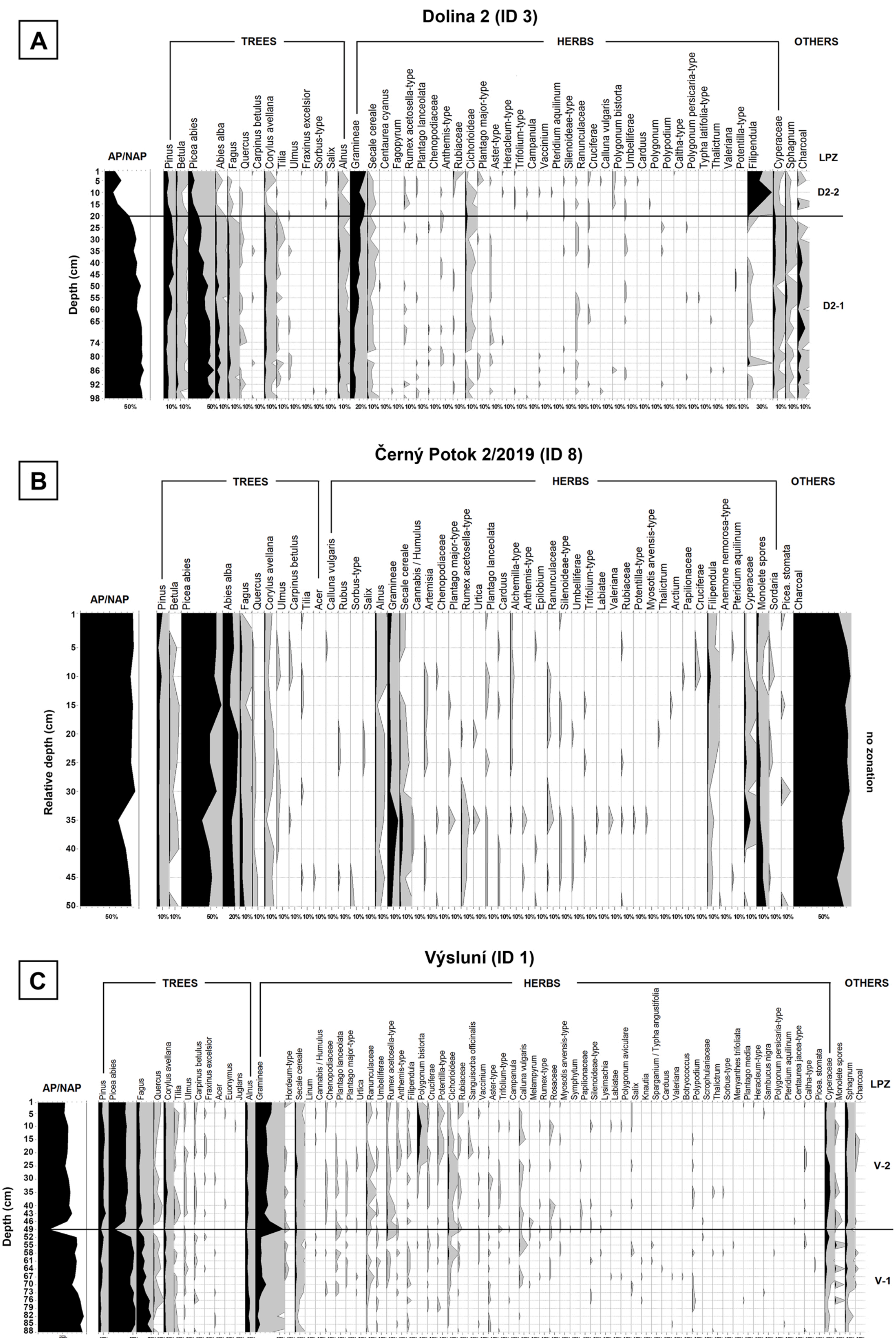

Fig. 7. Pollen diagrams from three local land use areas. A: Dolina 2 (minining area). B: Černý potok 2/2019 (smelting area). C: Výsluní (agricultural area). The relative depth corresponds to the sampled column (see Fig. 7).

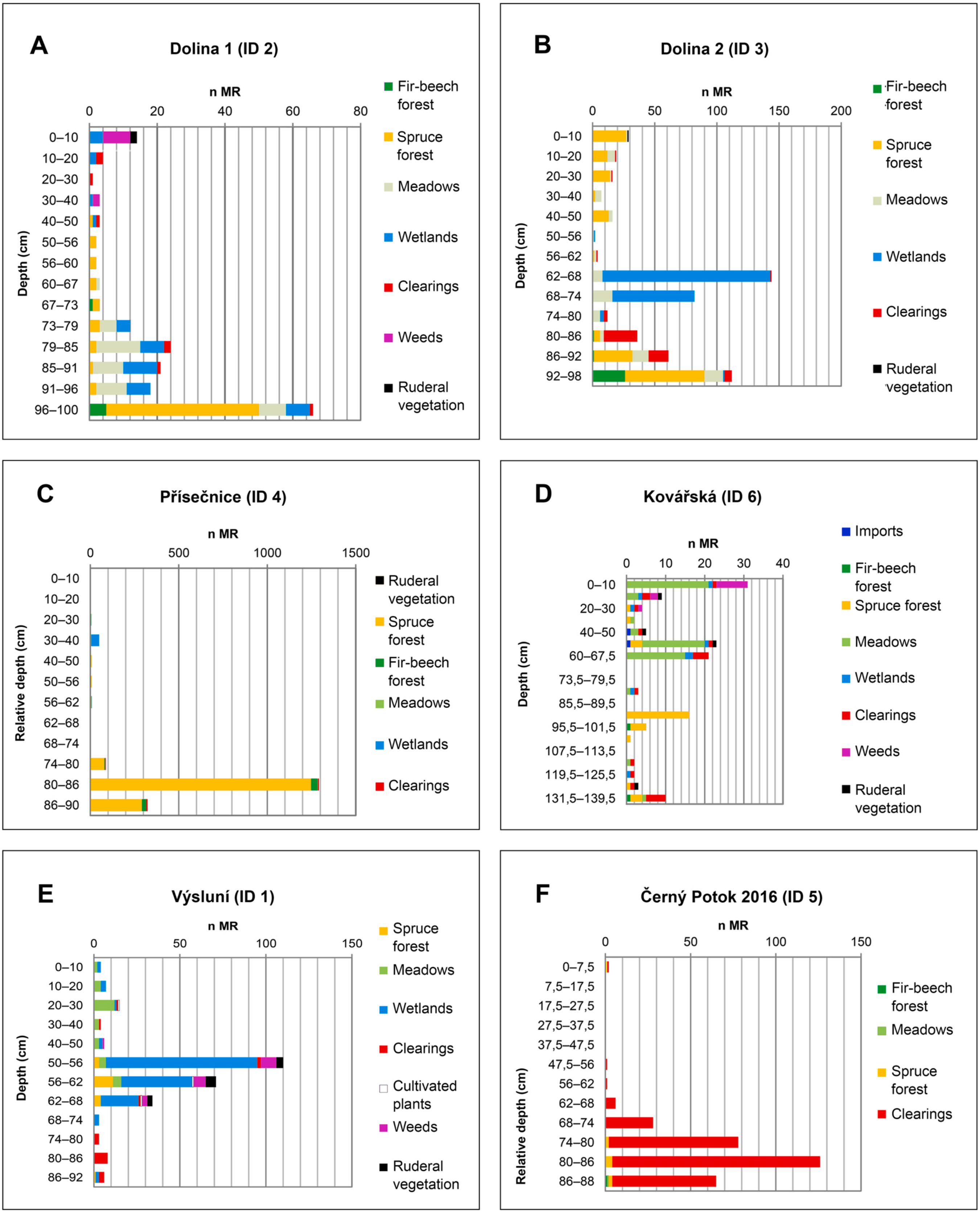

Fig. 8. Plant macro-remain analyses of the investigated profiles. The relative depth corresponds to the sampled column (see Fig. 7). A: Dolina 1. B: Dolina 2. C: Přísečnice. D: Kovářská. E: Výsluní. F: Černý Potok 2016.

Fig. 9. Archaeological finds. A: Finds in the profiles Černý Potok 1/2019 and 2/2019: 1–3: hammerscales; 4: microslags; 5–7: slags; 8–9: medieval pottery; 10–11: early modern pottery; w 2–4; 6: wood; w 12: worked wood; w 13: burned wood. B-E: position of woods in profile (B, C: profile 1/2019; D, E: profile 2/2019).

4.4.1. Mining sites (profiles Dolina 1, Dolina 2 and Přísečnice)

These profiles are located on the margins of medieval plough-land and forest. They are downstream from silver mines on hydrothermal veins, and more distant from iron mines in skarns (Derner et al., 2023). The Přísečnice profile starts in the 13th century CE, whereas Dolina 1 starts in the 15th–17th centuries AD. Uncharred macro-remains from the basal peat layer of Dolina 2 date to 420–552 cal BP. Nevertheless, the first evidence of human activity, indicated by charcoal and early modern pottery from the overlying gyttja layer, is early modern (17th century CE and later).

Micro-slags are present in quantities ranging from one to several dozen (Fig. 5). In the lower two layers of the Přísečnice profile, flake hammerscales were present. The most probable explanation is the operation of forges by medieval and early modern mines.

Přísečnice is the only one of our investigated profiles reflecting significant metal enrichment. The EF values of arsenic form three distinct local maxima with EF values higher than 20 labelled with 1, 2 and 3 (Fig. 6). Only maxima 2 and 3 are accompanied by elevated EF values of lead. Only maximum 3 has a significantly elevated lead value (>20). The EF maxima of zinc are not very pronounced (EF in the range of 5–10) and occur only with the arsenic maxima 2 and 3. Elevated copper EF values (max EF 10) were also found around the third maximum. Otherwise, the copper content was below the detection limit in other parts of the profile. The EF values in the Dolina 1 and 2 profiles are lower than in the Přísečnice profile. They form local maxima of the detected elements, especially arsenic, occurring at locations parallel to the two younger maxima in the Přísečnice profile.

Since the local geochemical background itself is characterised by low trace element contents, the significant enrichment suggests that the primary source of contamination in the stream sediments is mining of hydrothermal veins of the so-called “five element formation” (As-Ag-Bi-Co-Ni) or magnetite skarn bodies with only weakly pronounced Zn and Cu contents. Access to the deposits by mining and ore processing (crushing, washing and roasting) has resulted in the release of the geochemical aureole of elements (As, Zn, Pb) from the weathering zone to the alluvial deposits. The maxima of Pb might be considered as a consequence of mining the polymetallic ore veins (Lowag, 1903) or of silver ore smelting.

The peaks of the EF record correspond well with the two assumed main phases of mining and ore processing in the catchment area of this profile in the 13th-14th centuries AD and in the 16th-18th centuries AD (with the highest EF values).

The Dolina 1 and 2 profiles reflect a similar vegetation development (Fig. 7A, 8A-B, *Supplements* 10C-F). The first stage is a Picea-dominated wet forest with surrounding tree stands consisting of Fagus and Abies. Subsequent deforestation becomes visible at a depth of 80–86 cm, when charcoal appears and the Fagus and Abies pollen contents decline. The sites developed into wet meadows. Cereals and other human indicators are also visible in the pollen record. The upper part of the profiles shows a decrease in micro-charcoal and a higher abundance of Filipendula, indicating the diminishing of human influence.

The Přísečnice profile contains a similar pollen record with Picea dominating. Abies, Fagus, Pinus, and Corylus are also common. The local vegetation is a wet meadow consisting of species from forest glades. Cereals and micro-charcoal show low abundances (Fig. 8C, *Supplements* 8B, 10G).

4.4.2. Smelting sites (profiles Černý Potok 2016, Černý Potok 1/2019 and Černý Potok 2/2019)

The profiles from the Černá voda stream are situated 400 m (profile Černý Potok 2016) and 100 m (profiles Černý Potok 1/2019 and Černý Potok 2/2019), respectively, downstream from medieval hammermills/smelters, which were restored and equipped with blast furnaces in the 17th century CE (Fig. 2C) (Kloub, 2014). The only known important mine, Engelsburg, exploited magnetite and hematite in a large skarn body (*Supplement 2*). The spoil heap from its main gallery covered the upper part of the Černý Potok 2/2019 profile. In the lowest alluvial sediments of the profiles Černý Potok 1/2019 and Černý Potok 2/2019 coarse and fine wood remains are present, including tree trunks from spruce. After a sequence of alluvial sandy-silty layers with lots of micro-slags, medieval ceramics and macro-slags (both in profile Černý Potok 1/2019) follows a technogenic layer from the early modern period consisting of coarse slag fragments (in profiles Černý Potok 2/2019 and Černý Potok 2016) (Fig. 9). Profiles Černý Potok 1/2019 and Černý Potok 2/2019 are radiocarbon dated per wiggle matching of tree-rings of woods in the lowest alluvial layers dating to post 1041–1149 cal AD (CP 1/2019, wood without the outer rings) and to 1235–1280 cal AD (CP 2/2019). Profile Černý Potok 2016 is of late medieval age, with inverse radiocarbon dating. The early modern period was documented by ceramic finds in the profile Černý Potok 2/2019 above 120 cm (Derner et al., 2023).

Micro-slags were present in very high concentrations, from tenths to hundred thousand per liter in the technogenic upper layers (Fig. 5). This finding corresponds well to the production of iron smelters and blast furnaces. As observed in other regions, the amount and size of slag depend on the distance from the furnace (Jockenhövel and Willms, 1993). The presence of hammerscales may be linked to the primary forging in hammermills, which were part of the smelters (Pleiner, 2006; Dieudonné-Glad and Conte, 2011). Hammerscales of globular glassy appearance (Fig. 9/2) are believed to originate from a stroke of a hammer on the primary iron, whereas the slag remains are expelled, and their glassy phases are melted. During their flight out of the crude iron, they solidify in the open space to the globular form (Jouttijärvi, 2009; Houbrechts et al., 2020). We assume, they could originate in secondary forging, too, by melting of so-called flux, i.e. an intentional sandy cover inhibiting extensive oxidisation of metal surfaces in the forge (McDonnel, 1991).

Surprisingly, no significant geochemical metal enrichment was documented in any of these profiles (Fig. 6). This finding can be explained by the fact that the iron slags are geochemically very simple, and do not release substantial trace elements by weathering into the clay fraction. Furthermore, the local skarn bodies as sources of the magnetite differ geochemically barely from the background.

The pollen records of these profiles show no significant changes. Sediment accumulation rates were high (Fig. 7B, Supplements 8C, 9C). *Picea* dominates all sections. *Abies* and *Fagus* are less common. Herbs and anthropogenic indicators are rare. Only micro-charcoal indicates human activities.

The detection of charcoal and wood by macro-remain analysis of profile Černý Potok 1/2019 confirms a local dominance of *Picea* and a lesser presence of *Abies* (Supplements 11A, C, E). Profile Černý Potok 2/2019 shows a higher proportion of *Fagus* charcoal, which can be interpreted as a selection of this high-calorific firewood for ore smelting. The analysis of wood detects only *Picea* and *Abies* (Supplement 11F). Indicators of human presence such as *Urtica dioica* and *Persica lapathifolia*, *Rumex acetosella* and *Polygonum arenastrum* are essential. These taxa, together with charred needles and *Hordeum*, could indicate small mining or smelting settlements occurring in the stream valley.

4.4.3. Agricultural land and settlements (profiles Výsluní and Kovářská)

The Výsluní site in the Pruněřovský potok stream is surrounded by medieval field strips of the Sobětice village and a deserted early modern sawmill. No smelting and mining upstream is known. The bottom layer dates back to the 13th century CE. The section above 70 cm is early modern and younger.

The lower section 88–49 cm shows a high abundance of Picea and less Fagus, Abies and Corylus (Fig. 7C). Quercus and Carpinus, however, reflect surrounding slopes at lower altitudes, i.e. far-distance pollen input. Indicators of open forests and further open habitats peak at 56–62 cm. The section between 68–50 cm contains a higher share of aquatic and wetland plants. Weeds from nutrient-poor fields (e.g. Valerianella dentata, Viola arvensis/tricolor, Neslia paniculate) occur here, contrasting with plant records (Chenopodium album, Urtica urens) indicating nutrient-rich conditions, for example through manure concentration or fertilisation activities. The record of Cannabis sativa is a rather unusual find for a mountainous region so far. The section 68–62 cm contains lots of non-charred wood of Picea including axe chips (*Supplements* 10A, B). The layers above 50 cm have high abundances of grasses and a high share of wetland meadow species both in pollen and macro-remains (e. g. Polygonum bistorta, Fragaria vesca, Potentilla erecta). Further, charred grains of Secale cereale have been recorded (Kočár et al., 2018; Fig. 8E).

Only one micro-slag in the early modern layer and no geochemical metal enrichment reflects the site's rural character (Figs. 5, 6).

The Kovářská profile was recorded in the Černá voda stream valley, right in the centre of an early modern iron smelters town. The site is located downhill from an abandoned blast furnace.

Radiocarbon dating yielded inverse ages, with an early modern age at the bottom and a high medieval age (13th century CE) above. The older age may indicate yet unknown pre-modern iron smelting activities in the upper part of the Černá voda stream.

The lower part of the profile (139–97 cm) palynologically records a local forest vegetation dominated by *Picea*. Anthropogenic indicators are almost absent, except *Plantago major*. A sharp change occurs at a depth of 97 cm, indicated by a decline of *Abies*, an increase in grasses and cereals, and a huge abundance of micro-charcoals. Ruderal and

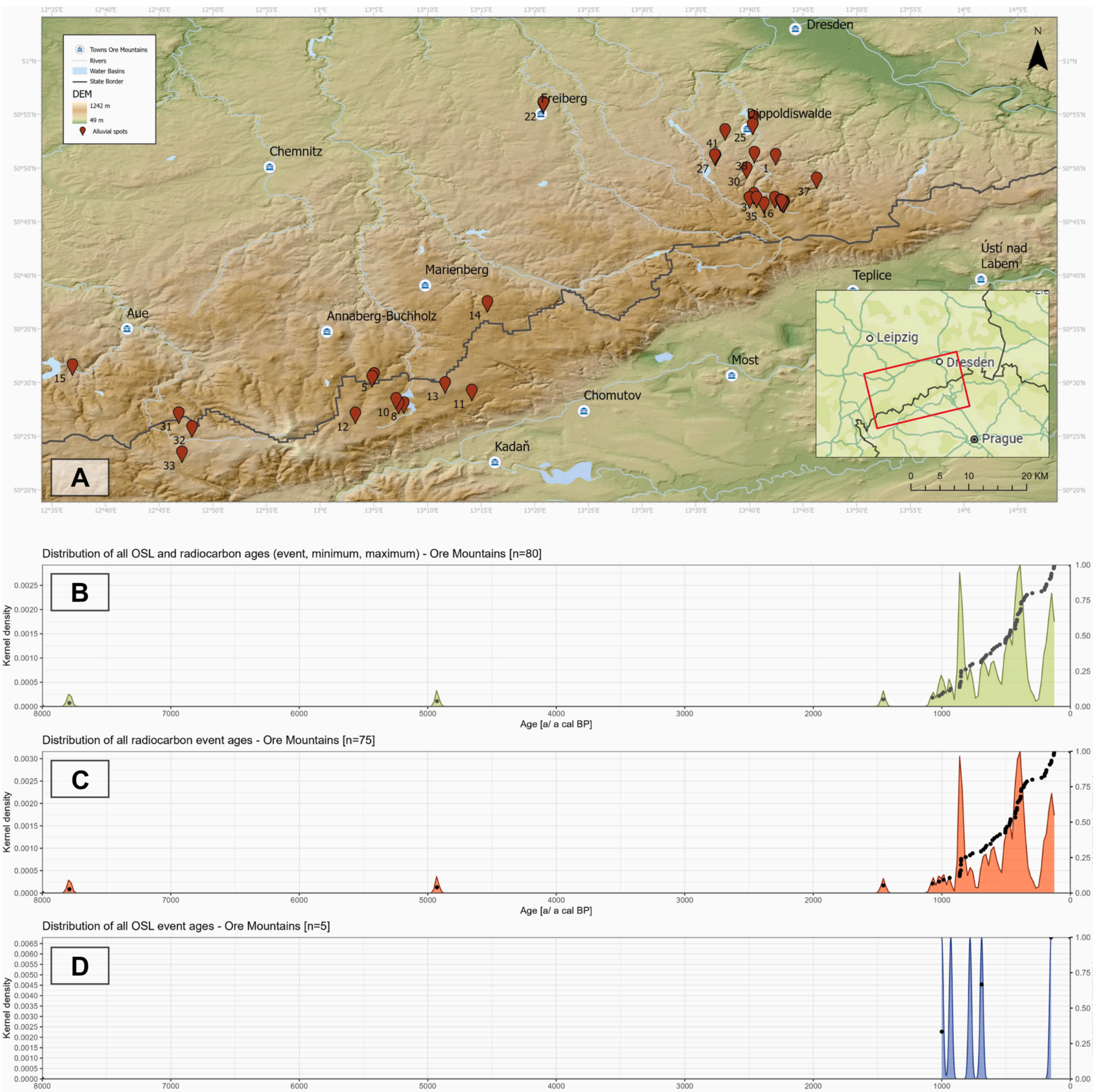

Fig. 10. Geochronological dating of alluvial sequences in the Ore Mountains. A: spatial distribution of sites with dated alluvial sequences (for decoding the site ID and for further details including references see Supplement 10). B: distribution of all radiocarbon and OSL ages (n = 80). C: distribution of the radiocarbon ages (n = 75). D: Distribution of the OSL ages (n = 5).

trampling indicators became common (Supplement 9B). Macro-remains show ruderal species such as *Chenopodium album*, *Urtica dioica*, and species of wet meadows. Particularly remarkable is the record of *Ficus caria* and *Vitis vinifera*, indicating the import of valuable fruits (Fig. 8D; Kočár et al., 2018). The site was used as a dumping ground for settlement waste. The abundance of macro-charcoal is very high. *Picea* dominates the macro-remain record (Supplement 10I). The upper layers contain pieces of black (hard) coal from the modern period.

No geochemical enrichment of metal elements was detected (Fig. 6).

5. Discussion

5.1. Stratigraphy and geochronology of alluvial sites in the Ore Mountains

Our eight alluvial sections analysed in the stream valleys around Přísečnice show evident common characteristics. The thickness of the alluvial sediments ranges from a minimum of around 100 cm to a maximum of about 200 cm. The alluvial sediments, i.e. all the sediments deposited locally in the floodplains of the streams over time, are very heterogeneous and include fluvial sands and silts, peats, gyttjas from oxbow ponds as well as various anthropogenic-technogenic sediments (Fig. 4). These gravelly-sandy to mostly silty minerogenic and organic sediments lie on a base of gravel, some of which contains stones and boulders. Very characteristic are layers with larger wood remains, usually found at the base of the sections (Fig. 9B-E). The alluvial sediments regularly contain charcoal and, in some cases, pottery sherds. The pollen stratigraphy of the profiles and the radiocarbon dates show that the alluvial sediments mostly originate from the High Middle Ages. The gravelly profile base is very probably dated back to the late Pleistocene, as other studies on rivers and streams in the Ore Mountains and its surroundings suggest (Barsch, 1964; Pommerenke, 1975; Wolf and Seifert, 1991; Elznicová et al., 2021; von Suchodoletz et al., 2024).

Therefore, the stream valley infills around Přísečnice are generally not older than 1000 years. Between the gravel base and these alluvial sediments, a hiatus spans almost the entire Holocene, i.e. over 10.000 years. To check whether this is a local peculiarity or a regional phenomenon, the dated alluvial sections available from the entire Ore Mountains were compiled, their radiocarbon and OSL dates extracted and analysed using probability density functions (Fig. 10A, B).

We have compiled 75 radiocarbon dates from 38 sites for the Ore Mountains. In addition, there are five Optically Stimulated Luminescence (OSL) dates from three sites (Fig. 10A, Supplement 12). The vast majority of geochronological data concerns samples that directly originate from fluvial sediments (alluvial silts and sands). The clear majority of the radiocarbon OSL dates, date to the last millennium (Fig. 10B-D). This means that from the perspective of the alluvial sequences dated so far in the Ore Mountains, a dominant late Holocene age is visible, which includes our findings around Přísečnice. Where the few OSL dates do not allow for further conclusions (Fig. 10D), the radiocarbon dates may already reveal certain temporal density centres. This mainly concerns a peak around 850 cal BP and another one around 400 cal BP (Fig. 10C), which corresponds to about 1100 CE and 1550 CE, respectively.

This alluvial chronology, which is, of course, somewhat imprecise for statistical reasons, can be linked to the phased history of land use and, thus, to the history of erosion in the Ore Mountains in the Middle Ages and modern times. After its general beginning in the middle of the 12th century CE, the colonisation and mining history of this region shows several phases of a flourishing and declining economy, including agriculture and forest use (Derner and Lissek, 2018; Hemker, 2018; Tolksdorf, 2018; Cappenberg et al., 2019; Kaiser et al., 2021; Hemker and Cappenberg, 2022). Each boom phase was associated with increased forest use in terms of deforestation, timber exploitation and thus an increase in open land (Kaiser et al., 2023). Particularly formative phases, and the late 15th and 16th centuries AD (Wagenbreth and Wächtler, 1990).

With respect to the spatial density of records and the specific results on the late Holocene alluvial dynamics, our investigations around Přísečnice show particularly close parallels to those around Dippoldiswalde in the eastern Saxon Ore Mountains, about 50 km to the northeast (Fig. 10A). Multiple records of alluvial sections have been investigated as part of systematic geoarchaeological investigations (Bertuch and Cappenberg, 2018; Bertuch and Herbig, 2018; Bertuch and Konetzke, 2018; Tolksdorf and Bertuch, 2018). Most of the artefact-bearing (ceramic sherds, slag, charcoal) fluvial sands, silts and loams lie directly on the late Pleistocene gravel beds or even on the weathered bedrock without older Holocene sediments. The Holocene sediment range in thicknesses from a few decimetres to about one metre. Radiocarbon dates show two peaks, which indicate a forced formation of the alluvial sediments during the late medieval and early modern period, synchronous with the second mining boom and, to a lesser extent, also during the high medieval colonisation phase, including the first mining boom.

This dominance of late Holocene alluvial sediments, or better still, the onset of Holocene alluvial sedimentation only in the last millennium, is a general feature of many Central European low mountain ranges (e.g. Raab et al., 2005; Dotterweich, 2008; Latocha, 2009; Fuchs et al., 2011; Hrubý et al., 2014; Wistuba et al., 2018). During the early Holocene, most floodplains were relatively stable with limited floodplain aggradation. After this initial period of relative stability, sedimentation rates increased during the mid- and late Holocene, with the most important deposition phase often occurring during the last 1000 to 2000 years. The sedimentation history of most floodplains can be linked to the local land-use history. In contrast, the influence of climatic variations on floodplain aggradation is often reported to be of minor importance (Notebaert and Verstraeten, 2010). This can now also be confirmed for the Ore Mountains based on our and other data.

A final aspect of the discussion of our findings around Přísečnice concerns the multiple evidence of coarse woody debris (mostly from *Picea*), including trunk segments, near the base of the profiles (Figs. 12B-E). The wood has often been fluvially transported for at least a short distance, as evidenced by the apparent fragmentation, rounding features and the general absence of tree bark. These woods are, therefore, not in-situ forest remains in the sense of a fossil (buried) land surface, but allochthonous material from the immediate vicinity of the profile sites.

Radiocarbon dating and pollen analyses show that the wood layers are mostly medieval in age. Their formation is very probably linked to the clearing of the surrounding forests. In some respects, they can also be described as “forest clearing horizons”, as they have already been frequently detected for this period in both alluvial and terrestrial settings in the low mountain ranges in Central Europe (Kukulak et al., 2002; Wistuba et al., 2018; Kaiser et al., 2020; Hrubý et al., 2024). In addition, it can be assumed that wood as transported and sedimented dead wood generally played a significant role in the densely forested stream and river floodplains of the region before clearing and modern watercourse maintenance measures (e.g. Kaczka, 1999; Hering et al., 2000; Brierley et al., 2005; Wohl, 2013).

5.2. Local medieval vegetation history obtained by palaeobotanical data

A comparison of the analysed profiles shows that the main differences depend on the chronostratigraphy, i.e. whether the record belongs to the period before colonisation (lower part of the Kovářská profile) (Fig. 8D; Supplements 9B, 11G), to the period of medieval human activity as Černý Potok 2016 (Fig. 8F; Supplements 8C, 10*H*), Černý Potok 1 and 2/2019 (Fig. 7B; Supplements 9, 11A-F) or reflects continuous sedimentation up to the present as Dolina 2 (Fig. 7A, 8B; Supplement 8F). The chronological position is, therefore, the key factor in determining the local pollen record.

The pre-colonisation period is represented only by non-charred macro-remains, comprising mainly *Picea*, which dominates in the pollen record as well.

A similar pattern is also found in the arboreal pollen spectrum of all profiles associated with the medieval and early modern period of intensive human impact. This includes changes in the AP/NAP ratio (arboreal/non-arboreal pollen), thus in the forest area, not in the tree species composition. The dominance of *Picea* in all pollen records is due to its local presence together with other tree taxa (such as *Alnus*) in the investigated stream valleys (Fig. 7; Supplements 8, 9). This close association of *Picea* in the low mountain ranges of Central Europe with the floodplains of streams and rivers has been proven many times both by palaeobotanical findings for the late Subatlantic (e.g. Kajukało et al., 2016; Hájková et al., 2019; Kaiser et al., 2020; Hrubý et al., 2024) and by recent ecological observations (e.g. Caudullo et al., 2016; Leuschner and Ellenberg, 2017; Daněk et al., 2019). Overall, *Picea* dominance is expected zonally above ca. 800–1000 m a.s.l. (i.e. varying depending on the geographical location of the low mountain range) and azonally in the moist valleys. The charcoal analysis gives a more differentiated picture (Supplements 10, 11). *Abies* and *Fagus* dominated the charcoal, which is probably due to the preferred local use of these tree species. In the smelting area (Černý Potok 2016 and 2/2019), *Fagus* charcoal dominates because this wood was favoured as fuel for smelting processes (Supplements 8H, 9B). In contrast to *Picea*, which had dominantly grown the wet stream sites, *Fagus* and *Abies* together generally dominated the surrounding slopes and dry plateaus prior to the colonisation phase. However, a certain proportion of *Picea* can also be expected on relatively dry sites as further evidence from the Ore Mountains suggests (Kaiser et al., 2023).

The frequency of cereal pollen, ruderal species and pasture indicators depends on agricultural activities, not on mining or smelting. These pollen indicators reflect well the settlement structure (medieval in Výsluní, postmedieval in Kovářská) and the neighbouring fields (Fig. 8C; Supplement 9B), not only the deforestation (Černý potok)..

A particularly remarkable feature of the Kovářská profile is the record of macro-remains from figs (*Ficus carica*) and grapes (*Vitis vinifera*) from the settlement period in the 17th century CE and later (Kočár et al., 2018). Although a generally rare finding to date, these comparatively luxurious goods indicate a remarkably good food supply for the mining communities, even at relatively high altitudes in the mountains. Comparable findings with a slightly older, i.e. medieval evidence of figs, rice (*Oryza sativa*) and pepper (*Piper nigrum*) are available from the mining town of Freiberg in neighbouring Saxony (Schubert and Herbig, 2017). There is also evidence of figs from the 13th century CE from a mining site in the Bohemian-Moravian Highlands (Hrubý et al., 2024).

The subsequent post-mining period is characterised by the progressive erosion and filling of the valleys in the agricultural areas (Výsluní profile). The mining and smelting areas (Černý Potok and Dolina profiles) developed differently. After initial clearing, they were covered by meadows or secondary forests, which prevented further accumulation of alluvial sediments.

For a comparison of our new palaeobotanical records from the stream valleys around Přísečnice with already existing findings, the pollen diagram in the deserted Spindelbach village (ca. 3 km northwest of the alluvial profile Výsluní; Houfková et al, 2019; Marešová, 2022) and the pollen diagram "Kovářská peat bog" (ca. 2 km east of the Kovářská alluvial profile; Bohdálková et al., 2018) are available (Supplement 1).

The 82 cm-thick alluvial-colluvial Spindelbach profile (ca. 850 m a.s.l.) shows an almost balanced distribution of the three main tree species *Fagus*, *Abies* and *Picea* at the beginning of the 14th century CE, predating the subsequent local colonisation. The area was cleared around 1350 CE to establish an agrarian settlement. The village declined and was finally abandoned in the period about 1450–1480 CE. After abandonment, forest regeneration started, which is reflected in a renewed increase of *Picea,* forming a secondary forest together with *Betula.* *Fagus* and *Abies* never reached their former abundance level (Houfková et al., 2019).

The 300 cm-thick pollen diagram of the Kovářská Bog / peat core KV1 (870 m a.s.l.) records a mixed forest of *Fagus*, *Abies* and *Picea* around 1200 CE. A specific anthropogenic influence is reflected in the presence of pasture and settlement indicators such as *Juniperus*, *Calluna vulgaris*, *Plantago lanceolata* and *Artemisia*. The expansion of agricultural activities in the vicinity is reflected by cereals and *Centaurea cyanus*. Around 1500 CE, the character of the forest composition had changed considerably. *Abies* and *Fagus* decreased significantly, while *Picea* and *Pinus* increased. The diversity of herbaceous species also notably increased, and at the end of this period, NAP started to prevail over AP (Bohdálková et al., 2018).

In comparison with the entire Ore Mountains, i.e. both the Bohemian and the Saxon side, our palaeobotanical findings in the stream valleys around Přísečnice represent a particularly high spatial and chronological coverage of the Middle Ages and the Early Modern period. They fit into the general knowledge of the zonal forest composition before the beginning of the high medieval deforestation in the Ore Mountains without contradiction: At that time, dense forests were present from the submontane (ca. 300–500 m a.s.l.) to the montane zone (ca. 500–900 m a.s.l.), in which *Fagus* and *Abies* predominated, and to a lesser degree also *Picea* occurred. Other tree species (e.g. *Acer, Ulmus, Pinus, Fraxinus, Alnus*) also grew in smaller proportions, but with potentially greater local participation. The high-montane zone (ca. 900–1200 m a.s.l.), i.e. the uppermost crest area, was dominated by *Picea* (Kaiser et al., 2023). However, details of the forest clearing, subsequent land use and, in some cases, later secondary forest development could be illustrated by our findings with a resolution not previously possible in the region (see Chapter 4.4; Figs. 7, 8; Supplements 8–11).

5.3. *Local medieval land-use history obtained by archaeological, geomorphological, historical and geochemical data*

The first written sources about settlement and mining in the study area date back to the 14th century CE (Balášová and Burghardt, 2014). Thus, older human history can only be traced using archaeological and natural scientific methods, including, for instance, anthropology, archaeobotany and various geosciences.

The question of already pre-medieval human activities, such as mining/metallurgy, livestock grazing or the use of mountain-crossing trade routes (see Kozáková et al., 2020; Tolksdorf et al., 2020; Kaiser et al., 2023), cannot be answered by our study. Most of the alluvial profiles recorded here start their sedimentation during the transition from the high to late Middle Ages (Fig. 4, Table. 2). All the older radiocarbon data are based on uncharred macro-remains. Among the profiles, only the basal peat layer of Dolina 2 could be considered as a potential geoarchive of this period, but with only little chronological resolution. To answer such specific pre-medieval research questions, peat bogs are more suitable, as is illustrated in pollen and geochemical records from other sites in the Ore Mountains (Veron et al., 2014, Bohdálková et al., 2018; Houfková et al., 2019; Kaiser et al., 2023). However, the lack of recognisable anthropogenic deposits means that the potential human impact during this period could be very limited.

The charcoal and charred macro-remains of our profiles are dated to the second half of the 13th century CE and later. This dating is consistent with the current state of local archaeological research (Crkal and Volf, 2014; Volf, 2014; Derner, 2018; Houfková et al., 2019). In terms of medieval landscape use, the study area can be divided into three subareas: 1) silver mining of hydrothermal vein deposits, well documented by peaks of the contamination factor EF of arsenic, zinc and lead and only slightly increased concentrations of micro-slag, possibly originating from the mine smithies; 2) iron smelting area in the Černý potok stream valley with no geochemical indications by EF but with significantly increased amounts of micro-slag; 3) agricultural land and settlements with no geochemical enrichment of metallic elements or notable occurrence of micro-slag.

In some profiles (e.g. Přísečnice), medieval silver mining was geochemically detected without complementary archaeological or historical evidence (Fig. 6). Thus, geochemistry can in a sense serve as a prospection tool for mining archaeology (Matschullat et al., 1997;

Thorndycraft et al., 2004; Raab et al., 2005).

The presence of macro- and micro-slags and geochemical indications already in the lowest layers, together with cereal pollen, indicate the contemporaneity of agricultural (rural) and mining colonisation of the Ore Mountains, despite differences at individual sites. For example, the Černá voda stream valley remained largely uninhabited until the 17th century CE. Further corroboration of this hypothesis is the approximate synchronicity of all three types of medieval landscape uses in our study area. The mixed mining-agricultural colonisation with already developed settlement structures (villages, towns, castles, mining settlements) and laws is typical for the Ore Mountains and enabled their surprisingly rapid colonisation after ca. 1150 CE (Thieme, 2002, 2008; Kenzler, 2012). This is in contrast to other European low mountain ranges, where mining/smelting significantly predates the permanent settlement, as in the Harz or Black Forest (Steuer, 1992). The later, i.e. early modern peaks of geochemical metal records and excessive micro-slags concentrations, correspond well with the peak of silver-mining in the 16th-17th centuries AD and to the construction of the first blast furnaces in that region. Nevertheless, EF fluctuation might partially result from natural conditions, i.e., fluvial dynamics caused by climatic impact.

The environmental impact of the various land uses took different forms and had different consequences. It is assumed that the consumption of wood by charcoal burners operating in favour of ore smelting was enormous. This is very well documented in various European medieval and early modern smelting regions (e.g. Schenk, 1996; Groenewoudt, 2007; Ludemann, 2010; Deforce et al., 2021).

As the charcoal sites are predominantly located on steep slopes of the Černá voda valley, the runoff after deforestation is likely to be rapid and massive at first, which led to a relatively large thickness of the local alluvial layers (for charcoal site research in the region see Kočár et al., 2018). Mining itself utilised only a limited amount of coniferous wood for mine construction (Tolksdorf et al., 2015). However, its side effects such as the spread of heaps, ore processing plants and the construction of mining settlements also led to a certain degree of deforestation and erosion on slopes as well as sediment accumulation in floodplains, as observed, for example, at the Kaječín and Cvilínek sites in the Bohemian-Moravian Highlands (Kaiser et al., 2020; Hrubý et al., 2024). The fluctuating intensity of mining probably facilitated the recovery of the forest in phases. This is indicated by the fact that the decline of the originally high arboreal-pollen ratio (AP/NAP) and the first changes in forest composition in the mining and metallurgical areas occur first in the uppermost parts of the profiles. This phase most likely corresponds to the well-studied local wood scarcity in the mid-18th century, after the limits of forest recovery had been exceeded after about two centuries of intensive iron smelting and timber exploitation (Ministr, 1967). Although only moderate sedimentation was observed in the relatively flat agricultural areas, deforestation was stronger and more permanent here, as evidenced by the low AP/NAP ratio as early as the Middle Ages. More than 700 years of local mining/smelting, deforestation and step-by-step development of settlement and agriculture resulted in various anthropogenic relief forms. Extensive mining fields with numerous heaps are particularly important for valley sediment formation, which were the source of fine material flushed towards the river channels. On the other hand, sediment transport is limited by the terracing of slopes. Terrace systems related to stripped field systems are also well developed in the study area (Horák and Klír, 2017) and beyond (Poledník Mohammadi et al., 2024). In general, the area must be considered to have been subjected to strong human influence in the past.

6. Conclusions

Alluvial sediments deposited in stream valleys enable the reconstruction of the local vegetation and land-use history (Fig. 11). By analysing several sediment sequences from neighbouring stream valleys, the understanding can be extended to supra-local dynamics and even weak, ultra-local or very short-term human activities can be detected. An ideal test site for such studies is the area near the crest of the central Ore Mountains, which, on the one hand, has a favourable flat relief and a large number of small stream valleys. On the other hand, the Ore Mountains generally show a dramatic and varied land use history since the Middle Ages, which led to a strong imprint on contemporary alluvial archives. Applying an interdisciplinary approach to characterise the

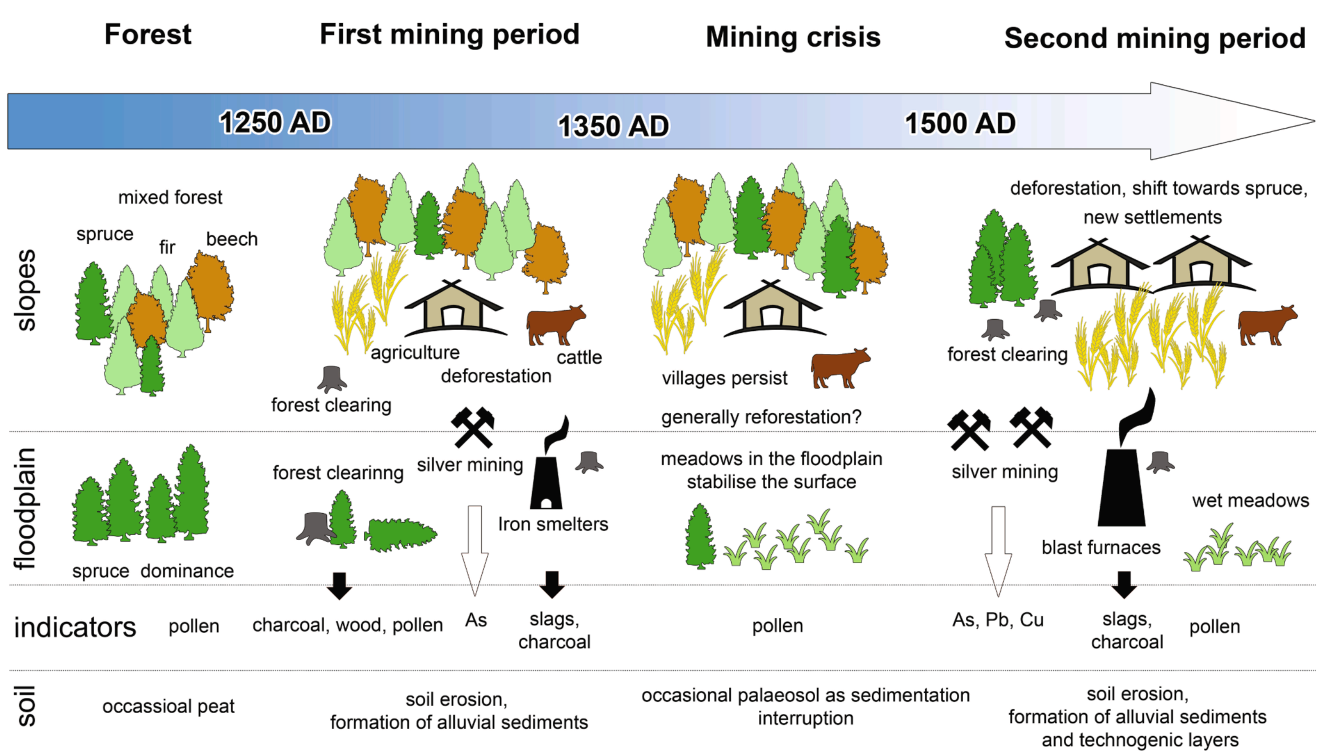

Fig. 11. Schematic representation of the development of vegetation and land use in the periods under study.

properties of local alluvial sediments and their potential to reconstruct historical environmental changes in that area, we were able to draw the following conclusions:

- The thickness of the investigated profiles is between one and two metres. The alluvial facies are very heterogeneous and include fluvial sands and silts, peats, and gyttjas from oxbow ponds, as well as various anthropogenic-technogenic sediments. Coarse woody debris consisting of *Picea* remains was regularly found at the base of the profiles. It represents a “forest clearing horizon” created in the course of medieval deforestation. The stream valley infills are mostly not older than about 1000 years. Their formation is mainly linked to the input of minerogenic matter from soil erosion of the surrounding slopes and the remains of mining and metallurgical activities along the streams.
- Based on palaeobotanical analyses, the investigated profiles show a dominance of wet *Picea* woodlands directly in the stream valleys before the medieval colonisation, supplemented by some other tree species, especially *Alnus*. *Fagus* and *Abies* together dominate the surrounding slopes and plateaus. However, also at relatively dry positions a certain proportion of *Picea* occurs. Other tree species (e.g. *Acer*, *Ulmus*, *Pinus*, *Fraxinus*) also grew in smaller proportions on average on both wet and dry sites but with potentially greater local participation.
- First anthropogenic activities in the study area are detectable on the basis of the alluvial profiles for the second half of the 13th century CE. This corresponds well with the archaeological record. Different forms of local land use can be identified from the High Middle Ages onwards, largely synchronised in different phases but partly spatially separated: silver mining from hydrothermal vein deposits, iron smelting and agriculture, and rural settlement. Deforestation and changes in vegetation, large-scale soil erosion and anthropogenic relief changes, sedimentary filling of stream valleys and local geochemical contamination are the characteristics of a strong human impact and, thus, of a severe environmental change in the Middle Ages and early modern period. Notably, the mixed mining-agricultural colonisation is typical for the region, in contrast to some other Central European low mountain ranges, where mining and smelting preceded permanent rural settlement.

CRediT authorship contribution statement

Kryštof Derner: Writing – review & editing, Writing – original draft, Visualization, Project administration, Investigation, Funding acquisition, Conceptualization. **Knut Kaiser:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Libor Petr:** Writing – original draft, Visualization, Investigation, Conceptualization. **Petr Kočár:** Writing – original draft, Visualization, Investigation. **Romana Kočárová:** Writing – original draft, Visualization, Investigation. **Anna-Maartje de Boer:** Writing – original draft, Visualization, Investigation. **Marek Kasprzak:** Writing – original draft, Visualization, Investigation. **Michał Łopuch:** Visualization, Investigation. **Petr Bohdálek:** Writing – original draft, Visualization, Investigation. **Jiří Crkal:** Investigation. **Petr Lissek:** Writing – original draft, Visualization, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2024.108520.

Data availability

Data will be made available on request.

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