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Cut and covered: Subfossil trees in buried soils reflect medieval forest composition and exploitation of the central European uplands

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Abstract

Knowledge on historic changes in vegetation, relief and soil is key in understanding how the uplands in central Europe have changed during the last millennium, being an essential requirement for measures on forest conversion and nature conservation in that area. Evidence of forest-clearing horizons from the medieval period could be systematically documented at four low- to mid-altitudinal sites (360-640 m a.s.l.) in the Harz (Harz Mountains), Erzgebirge

(Ore Mountains) and Českomoravská vrchovina (Bohemian-Moravian Highlands). Subfossil trees with traces of human cutmarks and burning were recovered from buried wet-organic soils (paleosols) within a context of mining and settlement archaeology, applying a multiproxy-approach by using data from archaeology, palaeobotany, geochronology, dendrochronology, and pedology. Tree stumps and trunks as well as small-scale wood remains represent an *in situ* record of local conifer stands (spruce, fir, pine). Some deciduous tree taxa also occur. Dating of the tree remains yielded ages from the 10th/11th to the 13th/14th centuries A.D. After deforestation, the tree remains were buried by technogenic and alluvial-colluvial deposits. The reconstructed conifer-dominated woodlands on wet soils mirror the local vegetation structure immediately prior to medieval deforestation. As such wet sites are common in the uplands, conifers were significantly present in the natural vegetation even at mid and lower altitudes.

Keywords: forest-clearing horizon, subfossil wood, paleosol, mining and settlement archaeology, late Holocene

1 INTRODUCTION

The dense forest cover of the central European uplands (*ca.* 500-1500 m a.s.l.; Fig. 1) conceals evidence of a cultural landscape with extensive industrial facilities including mines, ore processing plants, smelting furnaces, and water infrastructures. This environmental change began with rural colonization and forest clearance in the early to high medieval period (10th to 13th centuries A.D.) and increased from the early modern period (15th/16th centuries A.D.) forward, drastically changing with ore mining and metallurgy the mountain landscapes. Even though local human influence on the mountain environment was already detected for some prehistoric periods (Valde-Nowak, 2013; Kozáková et al., 2015), a widespread "wilderness" or "uncultivated landscape" (Schreg, 2014) evidently covered most of the uplands before the medieval period. However, due to an already established integration of peripheral low mountain ranges into regional and supra-regional economic systems (e.g. by pasture, logging, seasonal resource exploitation, transit corridors), the changes in land-use often labelled with the term “colonization” during the medieval period may have been more gradual and diverse than often perceived.

Practically the whole and nowadays largely re-forested land surface has been affected by intentional human activities, with the exception of some unusable areas, such as screes, inaccessible sub-alpine mountain peaks and isolated mires. The almost ubiquitous spatial character of past human impact is indicated for terrestrial sites by the regular occurrence of macro- and micro-charcoals in surface soils and kilns, mostly originating from the *in situ* burning of former woodlands (Schmidt & Noack, 2000; Ludemann et al., 2004). Furthermore, common evidence on long-term environmental change is provided by local telmatic, alluvial and colluvial geo-archives and by dendrochronology as well as anthracology (Zolitschka et al., 2003; Tolksdorf et al., 2015). On the other hand, large upland areas are characterized by both past and recent soil erosion, often reducing the thickness and the recording (memory) capacity of the surface sediments and soils (Boardman & Poesen, 2007; Monger & Rachal, 2013). Corresponding to the forests, whose present-day tree composition and stand structure differ substantially from the natural state (Szabó et al., 2017), the surface soils have likewise changed (Hejcman et al., 2013).

Whilst the local vegetation of the past can be reliably reconstructed by means of pollen and macro-remains including charcoals (Nelle et al., 2010), characterization of the pristine soil is best enabled by analysis of buried soils (syn. fossil soils, paleosols, paleo-surfaces; Muhs et al., 2013). In general, knowledge on both historic vegetation and soil helps to understand in detail how a specific mountain landscape has changed during the last millennium and which future trajectories can be assumed with a higher probability. This is of particular interest for the establishment of reference frames on site-adapted natural tree vegetation which can be applied for forest conversion and nature conservation in the uplands (Spiecker, 2003; Milad et al., 2011; Szabó et al., 2017).

Although the medieval and post-medieval environmental history of the central European uplands is a long and a highly developed field of research (e.g., Segers-Glocke & Witthöft, 2000; Stolz & Grunert, 2006; Knapp et al., 2013; Glina et al., 2017; Migoń & Latocha, 2018), a systematic search for and analysis of synchronous buried soils is lacking to date. Such well-preserved buried land surfaces indicating human occupation and exploitation might provide novel information on the pre-anthropogenic environment and the first human impact on mountainous areas. As the medieval settlement and mining activities throughout central Europe must have had an extraordinary impact on vegetation, soil and relief, land surfaces particularly in the uplands must have quite often been buried following strong local erosional events (i.e. on-site soil erosion leading to off-site sediment accumulation) or industrial measures (i.e. intentional deposition / piling). Such corresponding records were acquired recently through research on mining and settlement archaeology in some of the central European uplands such as Harz, Erzgebirge and Českomoravská vrchovina (e.g. Alper, 2003; Hrubý et al., 2012; Tolksdorf, 2018).

This study aims (1) to detect buried soils with *in situ* preserved subfossil wood, (2) describe the pedological, botanical and archaeological properties of these land surfaces as well as the dendrological and chronological details of the wood, and (3) contextualise the records in terms of local landscape dynamics which, according to the archaeological evidence, are largely influenced and driven by past human activities. Furthermore, the study investigates whether the records presented could generally form a new proxy category reconstructing local forest structure and human activities, interrogating comparable records which exist in central Europe and beyond.

Although we present a case study on a specific stratigraphic and topographic setting, the implications of our study broadly contribute to the general questions of exploitation and environmental change of former peripheral, i.e. rather cold mountainous or northern areas (e.g., Bindler et al., 2011; Pini et al., 2017; Tolksdorf, 2018). Particularly the record of subfossil *in situ* wood amidst terrestrial occupation layers connects our study with those dealing with wood found at semi-terrestrial and aquatic sites, i.e. with wetland/alluvial archaeology and palaeoecology of mires, rivers and lakes as well as sea shores (e.g., Howard et al., 2003; Edvardsson et al., 2016; Daniel et al., 2018).

2 STUDY SITES

2.1 General description

All study sites (Fig. 1), located at an altitudinal range of *ca.* 350 to 650 m a.s.l., belong to the central European province of the Variscan mountain belt. The maximal altitudes of these mountain areas reach 1141 m a.s.l. (Harz, Engl. "Harz Mountains"), 1244 m a.s.l. (Erzgebirge, Engl. "Ore Mountains") and 837 m a.s.l. (Českomoravská vrchovina, Engl. "Bohemian-Moravian Highlands"), which represent the high montane altitudinal zone (800-1500 m a.s.l.; Leuschner & Ellenberg, 2017). A common property of these areas is their rather late integration into the ecumene in terms of permanent settlement and agriculture/silviculture or other land use, such as mining, metallurgy and water management. Up to the late Holocene dense forests covered most of the central European uplands. These forests were mentioned by writers of antiquity as, summarized, the "Hercynian Forest" (Latin *Hercynia silva*; Krebs, 2006), representing the high altitude (barbaric) opposite of the (Roman) civilization living at lower altitudes. Large parts of this area were still forests in the 12th/13th centuries A.D., which separated political territories such as the Duchy/Kingdom of Bohemia and the Margraviate of Meissen (later Duchy and Electorate of Saxony), forming in the Erzgebirge and its foothills the *Miriquidi silva* (Engl. “Dark Forest”; Thomasius, 1994).

2.2 Johanneser Kurhaus site

The Johanneser Kurhaus site (51.827611°N, 10.288243°E) is located at an altitude of 565-575 m a.s.l. on the western declivity of the upper Harz plateau next to the mining town of Clausthal within the Spiegelbach Zulauf stream valley, a tributary of the Innerste river (Figs. 1, 2A and 2B). The site consists of weathered greywacke and clayey schist, covered by plantations of *Picea abies* (Norway spruce). Present day mean annual temperature and mean annual precipitation at Clausthal-Zellerfeld weather station is 6 °C and 1330 mm, respectively. From 1987 to 1991 archaeological excavations were conducted, investigating an abandoned and multi-phase medieval mining and settlement site (8th/10th-13th centuries A.D.) within an area of 340 m^2 (Klappauf & Linke, 1989; Alper, 2003). Immediately south of the site a lode exists (German “Zellerfelder Hauptzug”), whose silver content, extractable from galena minerals, was the primary object of local mining activities.

2.3 Warnsdorf site

The Warnsdorf site (50.962348°N, 13.536060°E) is located on the northern foothills of the Erzgebirge in the Tharandt Forest (Figs. 1, 2C and 2D). It represents an abandoned medieval settlement (12th to 14th centuries A.D.), stretching along a west-faced slope dip at 350-370 m a.s.l. The substrate consists of Cretaceous sandstone covered by sandy and peaty soils. The current planted forest is dominated by *Pinus sylvestris* (Scots pine), supplemented by *Fagus sylvatica* (European beech) and *Picea*. The local climate at Grillenburg weather station (384 m a.s.l.) is characterised by a mean annual temperature of 7 °C and a mean annual precipitation of 870 mm (LfULG, 2010). Archaeological excavations from 1982/1983, prove the existence of several artificial (house) platforms and two timbered water wells (Spehr, 2002). The excavations reported preservation of a buried “forest-clearing horizon” with tree stumps and trunks, charcoal and wooden chips. In 2017, one of the excavation profiles (trench E-F) was resampled for this study.

2.4 Cvilínek site

The Cvilínek site (49.348932°N, 15.316345°E) is located near to Černov village in the Českomoravská vrchovina at the headwaters of the Kamenička stream (Figs. 1, 2E and 2F). Lying in the stream valley at an altitude of 640-645 m a.s.l., the substrate consists of granite covered by loams and peat (Cháb et al., 2007). The present-day land cover is meadow and arable land; the forests of the immediate surroundings consist of plantations of *Picea*. The nearest weather station at a comparable altitude (Jihlava) records a mean annual temperature of 7 °C and a mean annual precipitation of 660 mm (Tolasz et al., 2007). Archaeological excavations were performed 2009/2010, proving by uncovering an area of 12,900 m^2 the existence of a medieval ore processing facility operated for the extraction of silver (13th century A.D.; Hrubý et al., 2012). Respective ore occurrences with historic mine facilities were detected a few hundred metres away from this site.

2.5 Ústrašín site

The Ústrašín site (49.3738367°N, 15.1651125°E) is located in the Českomoravská vrchovina at a spring niche attached to the Hejlovka stream and its floodplain (Figs. 1, 2E and 2G). The area investigated has an altitude of 560-565 m, comprising gneiss at the bottom, covered by alluvial and colluvial deposits. The site is used by agriculture and forestry dominated by plantations of *Picea*. The nearest weather station at a comparable altitude (Nová Cerekev) records a mean annual temperature of 7 °C and a mean annual precipitation of 675 mm

(Tolasz et al., 2007). In 2015 archaeological excavations revealed a cut medieval forest (Hrubý & Těsnohlídek, 2016).

3 METHODS AND MATERIAL

3.1 Archaeology and fieldwork

The data presented were acquired during the course of archaeological excavations and subsequent re-sampling campaigns at the four sites presented above. The local studies with their background in mining and settlement archaeology were performed within the period 1987 to 2017. Detailed data on specific archaeological aspects, comprising information on archaeological methods, structures, artifacts, and site formation/interpretation, can be obtained from the references noted above. The stratigraphic investigations as well as sampling of sediments/soils and woods were performed on open vertical sections (profiles) and horizontal trenches (plana) in the period given above.

3.2 Paleobotany

This study uses data from three pollen diagrams comprising 34 samples, two macro-remain diagrams and 19 single samples, and 10 charcoal spectra. Pollen samples were prepared using the standard acetolysis method (Berglund & Ralska-Jasiewiczowa, 1986). Counting occurred at a magnification of 400x with a minimum count of 500 terrestrial pollen grains per sample. Pollen identification and nomenclature mainly follow Beug (2004). Botanical macro-remains were extracted from the bulk samples by flotation and wet sieving. The taxa were determined at 6-40x magnification according to the literature (e.g., Cappers et al., 2012). Attribution of the taxa to ecological units follows Oberdorfer (2001). The microscopic examination of charcoal and subfossil wood samples was carried out on freshly broken surfaces and microsections, respectively, on the three fundamental planes (transverse, longitudinal-radial, longitudinal-tangential) at 40-120x magnification. Identification was performed by means of comparison with preparations from living material or from photographs of recent wood species (Hillebrecht, 1989; Schweingruber, 1990). Generally, the tree taxa mentioned in the Results and Discussion sections are designated by genus, with the common name given the first time it appears in the text.

3.3 Radiocarbon dating and dendrochronology

Radiocarbon (^{14}C) dates are available from a total of 16 samples and their ages are calibrated using OxCal 4.3 (https://c14.arch.ox.ac.uk/oxcal.html; Bronk Ramsey, 2009) applying the IntCal13 data set (Reimer, 2013) with a range of 1σ and 2σ standard deviation for analysis (Table I). The calibrated ^{14}C ages given in the text and figures represent 2σ ranges. The dendrochronological ages are derived from 11 *Abies alba* (silver fir) samples (Table II). The new site chronologies are compared with regional tree chronologies covering the last millennium (e.g., Büntgen et al., 2013).

3.4 Pedology

Soil analyses were performed on 11 samples from Warnsdorf site on the matrix <2 mm in order to assist the designation of sedimentary facies and diagnostic soil horizons. A laser diffraction test (Beckman-Coulter particle analyzer) was used to determine the sand-dominated grain-size distribution. Content of organic matter was estimated by combustion at 550 °C (loss-on-ignition/LOI). Pedological terminology for soil horizons and types follows World Reference Base for Soil Resources (WRB, 2015).

4 RESULTS

4.1 Johanneser Kurhaus site

Sections 2 and 3 show the basic stratigraphy of the Johanneser Kurhaus site (Fig. 3A). The sections run parallel to an abandoned stream course that could, according to a synopsis of all excavation results, be dated for the early medieval period (Supplemental Fig. 1). A *ca.* 70 to 100 cm thick layer of coarse-grained mine spoil, consisting of fragmented rock (gravels, pebbles) in a sandy-silty matrix, overlies a dark brown to black and humic-gleyic buried soil horizon (Ahb) with abundant wood fragments (Figs. 3B-3E) and artifacts (e.g., slags, ore fragments, burnt loam, textiles). The buried soil can be classified as (Fluvic) Gleysol. This wood-bearing horizon occurs extensively in the excavation area, showing the highest density of preserved wood at the southern bank of the abandoned stream. Sedimentary and archaeological evidence in this *ca.* 30 cm-thick horizon partly reflects an aggrading setting, comprising a lower sub-layer possibly from the 8th-9th centuries A.D. (Carolingian era) and an upper sub-layer from the 10th-11th centuries A.D. (Ottonian era). The younger chronological attribution is confirmed in section 3 by a radiocarbon age on *Picea* wood of A.D. 777-977 (Fig. 3A, Table I). According to archaeological finds and stratigraphic considerations, the mine spoil is dated to the end of the 11th/beginning of the 12th century A.D.

The buried soil bears large quantities of wooden remains, including tree trunks with a maximum diameter of 50 cm (Fig. 3E), branches and roots (Fig. 3D). The roots and the existence of fragile plant features, such as the preservation of branches still attached to tree trunks (Fig. 3E), prove an *in situ* record, i.e. autochthonous tree remains including forest soil. Furthermore, abundant small-scale tree remains from *Picea*, such as cones (Fig. 3C), seeds, needles, and buds occur. An analysis of the macro-remains content of two soil samples indicates a prevalence of *Picea* (35%) supplemented by small amounts of *Fagus* (0.2%), *Betula* (birch, 0.2%) and some taller shrubs (4%; Supplemental Table II). Even worked wood, comprising parts of beams and planks as well as chips are preserved. Some wood pieces feature distinct traces of axes and saws. Botanical determination of a further handpicked sample of large wood remains (n = 41) again attests a prevalence of *Picea* (78%), complemented by *Alnus* (alder, 10%), *Fagus* (8%), *Salix* (willow, 2%), and *Acer* (maple, 2%).

Further information on local anthropogenic activities and forest composition in the medieval period are made available by anthracological analyses of charcoal kilns (pit structures) from the "Winterhalbe" sub-site, which is a west-facing slope *ca.* 300 m away to the northwest of sections 2 and 3. The five dated charcoal samples reveal, in a striking contrast to the on-site wood proportions, a prevalence of *Fagus* (58-98%) followed by *Acer* (7-35%), dating in a total age range A.D. 590-1170 (Table I, Supplemental Table III). *Picea* is only slightly represented (1-8%).

With respect to local land use and settlement the Johanneser Kurhaus site can be subdivided into four activity periods, comprising (1) charcoal production in the 8th/9th centuries A.D., (2) melting of galena and silver extraction in the 10th/11th centuries A.D. with accompanying deforestation of the site and deposition of worked wood in the (subsequently) buried soil, (3) mining at the end of the 11th century A.D. or at the beginning of the 12th century A.D. covering the buried soil and its wood remains by mine spoil, and finally (4) settlement together with mining and metallurgy in the first half of the 13th century A.D. (Hillebrecht, 1989; Alper, 2003; Andrae, 2003).

4.2 Warnsdorf site

Section TRD-4 is located at the margin of an anthropogenic platform, representing a substructure with walls (Fig. 4A, Supplemental Fig. 2). The upper part of the stratigraphy consists of sandy material with some cobbles and boulders divided by a buried topsoil horizon (Ob-Eb sequence; Figs. 4B and 4C, Supplemental Fig. 3). Below this a sequence of dark brown peaty soil horizons (Hb) prevails, forming a 30 cm-thick buried soil (Histosol). Its subhorizons differ with respect to the content of plant macro-remains; the LOI values are consistently high (75-85%). The peat consists mainly of moss (*Sphagnum*/peat moss), and radicels from sedges and wood remains (*Pinus*, *Picea*) embedded in an amorphous organic matrix. From the upper part of the peat two radiocarbon ages are available. The section in between 78-84 cm dates at A.D. 1297-1402, whereas the section in between 84-87 cm (bearing a considerable amount of microscopic charcoal) dates at A.D. 1210-1275 (Figs. 4B and 4C, Table I).

In the buried soil a large root from *Pinus* occurs *in situ*. Its outermost (latest) tree rings date at A.D. 997-1155 (Figs. 4B and 4C, Table I). Dendrochronological dating of the root failed, despite the existence of 124 tree rings (MAD-1773). Both this radiocarbon age and a thin layer of covering peat might indicate natural dying or cutting of the tree before the onset of local peat accumulation.

The pollen and macro-plants in the peat together with the sedimentological data (Supplemental Fig. 3) allows for insights into the local vegetation and land-use history during the high medieval period (presented from below/older to above/younger). While signs of human impact are absent from the lowermost peat layer below 95 cm, the first occurrence of *Pteridium aquilinum* (bracken fern) and *Calluna vulgaris* (heather) pollen together with a rising charcoal content appear at 94 cm. Numerous fruits of *Rubus idaeus* (raspberry) together with the rising input of coarse sand and charcoal mark this layer as the onset of local human activity well-before A.D. 1210-1275. *Pteridium aquilinum* and charcoal indicate local burning; the sandy input likely indicates nearby soil erosion. *Rubus idaeus* and *Calluna vulgaris*, indicating open sites, could point to forest-clearing. At 87 cm *Pinus* pollen increases; needle fragments from *Pinus* prove a local growth of this tree. The presence, albeit at low abundances, of *Plantago lanceolata* (ribwort plantain) und *Urtica* (nettle) suggest the establishment of ruderal communities. More direct evidence for agriculture only appears at 83.5 cm in the form of low concentrations of *Cerealia*-type (cereals) and *Centaurea cyanus* (cornflower) pollen. Although these taxa do not necessarily prove on-site cultivation activities, the rising charcoal content may indicate ongoing human impact in this area, fitting well to the pollen spectrum at 80 cm. Here the high content of *Corylus* (hazel) mirrors re-forestation that is also visible in the AP/NAP ratio and low inputs of charcoal and *Cerealia*-type pollen. The recovering forest is indicated by *Picea* pollen, expanding at the cost of *Pinus*. Furthermore, *Abies*, which had previously completely vanished from the forest vegetation, returns. Evidence for an increased land use in the region is reflected by the uppermost pollen sample at 72 cm, where the share of NAP increases and high proportions of *Ceralia*-type pollen and *Plantago lanceolata* occur. The botanical remains in the fossil topsoil of the section (Ob-Eb-sequence) at 30-33 cm exclusively represent needle fragments of *Picea*, showing the prevalence of this species during a later, most probably very modern stage of local forest development.

As the available archaeological, stratigraphical and chronological data from Warnsdorf site show, local human activity started at the latest in the form of construction work for a timbered water well at A.D. 1162/1163 (feature “Brunnen 1” being a timber frame made from *Abies* and *Picea* wood; Spehr, 2002; Table II, Supplemental Fig. 2). In the 11th century A.D. or at the beginning of the 12th century A.D., prior to well construction, a rather old *Pinus* tree naturally died or was cut at section TRD-04. Although traces of human felling was not observed on the excavated part of this tree, further large-scale tree remains (trunks) with axe traces, and abundant quantities of small-scale tree remains with toolmarks (i.e. wooden chips of *Abies*) from adjacent excavation trenches (Spehr, 2002; Fig. 4D), clearly indicate human processing of the wood found in the buried peaty soil. According to the youngest radiocarbon age in section TRD-04 human activity could have continued until the 13th/14th centuries A.D., ending with coverage by sandy material of the platform.

4.3 Cvilínek site

In the northern part of the ore processing facility, in a place used for ore washing (Fig. 5C, Supplemental Fig. 4), some dozens of tree stumps and a few tree trunks were excavated *in situ* (Fig. 5F). They are covered by ore processing waste, consisting of gravels and cobbles within a loamy matrix. This sediment cover attains a maximum thickness of *ca.* 100 cm (Figs. 5A and 5B). The tree remains derive from a buried dark brown peaty soil horizon (Histosol; Fig. 5B). Furthermore, large quantities of small-scale tree remains occur (needles, branches, seeds, charcoals, cones; Fig. 5E).

From the total of 35 stumps, 25 (71%) represent *Picea*, 5 (14%) *Alnus*, 3 (9%) *Populus* (aspen)/*Salix* and 1 *Betula* and 1 *Juniperus* (juniper) (3%). Some stumps display a diameter of 40 to 50 cm; but most stumps have smaller diameters between 15 and 30 cm (Fig. 5D). Some modified stumps show traces of fire (n = 13; 37%) and human processing by integration (i.e. cutting of a gutter) into an artificial water channel (n = 4; 11%, Fig. 5G) as well as felling traces (n = 3; 9%).

Dating of the tree remains is provided by their association with archaeological features. As a fundamental prerequisite before establishing the ore processing facility, clearing of the preceding forest was required. The base, i.e. the uppermost root level of the trees, is always integrated into the occupation horizon, which is the level of the medieval ore processing activities. According to the eight dendrochronological ages obtained from construction timbers (*Abies*), they consistently date to the interval A.D. 1266-1269 (Table II). The same age can be assigned to the cut tree stumps and trunks.

Further information on local vegetation composition during the high medieval period is available from sections 1 and 3, located *ca.* 25 m to the northeast and *ca.* 140 m to the southeast from the area of cut stumps and trunks, respectively (Supplemental Fig. 4). Section 1 derives from a 20 cm-thick organic sediment layer, immediately preceding local mining activities (Supplemental Fig. 5). Both uncharred wood remains and charcoal of *Fagus*, *Abies* and *Picea* demonstrate that these trees dominated before the onset of strong human impact. But also a certain proportion of heliophytic woody taxa occurred, such as *Betula*, *Juniperus* and *Populus*/*Salix*. These taxa could represent the impact of some grazing and wood exploitation in a secondary forest with openings and clearings, becoming overgrown with woody pioneer taxa.

In contrast, section 3, representing a 35 cm-thick organic fill of a wooden container in an ore washing facility (Fig. 5C), particularly reflects wood utilization and, to a certain extent, forest composition during the operation phase of the ore processing facility. As suggested by sedimentary and botanical properties, this fill represents rapid sedimentation comprising a few years only. The spectra of uncharred wood and macro-remains are dominated by *Picea*, *Abies* and *Populus*/*Salix* (Supplemental Fig. 6). This reflects a selection particularly of coniferous wood for construction purposes. The assemblage of charcoal, in contrast, contains a higher proportion of *Betula* and *Fagus*, pointing to the preferred use of these wood taxa as fuel. The pollen spectra are dominated by *Picea* (*ca.* 50%), *Pinus*, *Fagus*, and *Abies* (Supplemental Fig. 7). Other woody taxa have a proportion of less than 5%, such as *Betula*, *Alnus* and *Quercus* (oak). Considering the edaphic site characteristics, the pollen data indicate a pattern of an on-site wet forest consisting of *Picea*, *Abies* and *Alnus*, and of drier off-site forests consisting, on the one hand, of *Quercus*, *Fagus*, *Pinus,* and *Carpinus* (hornbeam; i.e. acidophilous mixed forest), and, on the other hand, of *Fraxinus* (ash), *Ulmus* (elm) and *Tilia* (lime; i.e. deciduous scree forest). Additionally, secondary forests with *Betula* and shrubs including *Corylus* are indicated.

In terms of anthropogenic activities Cvilínek represents a complex site where mining (nearby), ore processing including washing, silver metallurgy, and settlement occurred simultaneously (Hrubý et al., 2012). This site operated during the last third of the 13th century A.D. After clearing of a wet forest dominated by *Picea*, its remains were both partly integrated into the industrial constructions and, later, covered by ore processing waste.

4.4 Ústrašín site

Whereas sections 2 and 3 as well as trenches 2 and 3 are located in a spring niche attached to the Hejlovka stream, section 1 is located in its floodplain (Supplemental Fig. 8). At all sub-sites alluvial and/or colluvial sediments cover a dark brown peaty soil horizon (Histosol) with abundant wood remains (Figs. 6A, 6B, 6C, and 6G).

In the spring niche large tree remains representing tree bases with roots of *Picea* were excavated (Figs. 6D and 6E). Toolmarks from axes and fragmented trees attest to the anthropogenic felling and processing of the wood. Larger wood remains prevail on the topographically higher and drier buried land surface, while small wood remains, comprising branches, cones, needles, and charcoal, dominate the topographically lower and wetter sub-site (Fig. 6F). Three radiocarbon dates from the wood range in an age interval from A.D. 1157 to 1442 (Table I).

Macro-remain analyses from the 120 cm-thick section 2 indicate a high charcoal content in the upper part of the buried soil horizon (90-95 cm; Supplemental Fig. 9), pointing, according to the radiocarbon age of A.D. 1322-1442 (Table I, Figs. 6A and 7), to high to late medieval forest-clearing. This observation is also marked by the pollen analysis, when *Picea*, *Abies*, *Alnus*, and *Fagus* decrease, and Poaceae as well as Cyperaceae (grasses) strongly increase. Slightly later the continuous presence of Cerealia (comprising *Secale cereale*, rye) and charcoal begins (Fig. 7). Immediately before clearing, the local forest composition was dominated by *Picea* supplemented by *Abies* and *Alnus*. The same development shows the macro-remain and pollen content of section 3 (Supplemental Figs. 10 and 11), which is much thinner. A piece of *Picea* wood dates the buried peaty soil horizon of section 3 at A.D. 1157-1264 (Table I, Fig. 6G).

In contrast to the other sites presented above, at Ústrašín no further archaeological evidence (such as settlement and mining traces) could be detected except for clear signs of anthropogenic tree felling, fragmentation of stems and branches as well as burning (Hrubý & Těsnohlídek, 2016). The record as a whole is interpreted as a high medieval forest-clearing covered by sediments from subsequent soil erosion.

5 DISCUSSION

5.1 Forest-clearing horizons: a new geoarchaeological feature for the uplands

Although the local landscape development differs somewhat with respect to depositional processes, vegetation change, kind of human impact, and its precise (although generally medieval) dating, the occurrence of a fossil land surface, i.e. buried soil with tree remains reflecting human activities, is a consistent stratigraphical feature of all sites investigated (Table III). These soil horizons are covered, on the one hand, by technogenic deposits (Peloggia et al., 2014) in the form of ore processing waste matter and mining spoil at Johanneser Kurhaus and Cvilínek or sandy material for a substructure at Warnsdorf. On the other hand, it is highly probable that human-induced soil erosion related to local and regional forest-clearing (Břízová et al., 2012; Hrubý, 2012; Hrubý et al., 2014; Szabó et al., 2017; Vejrostová et al., 2017) led to the covering of the medieval land surface at Ústrašín by alluvial-colluvial material. Both types of medieval cover sediments are generally widespread in the uplands although rarely mapped and dated thus far. Waste matter and mining spoil including hollows of former shafts are easily detectable by airborne laser scanning (Falke, 2013; Cembrzyński & Legut-Pintal, 2014; Swieder, 2017). Alluvial sediments from the medieval and post-medieval periods occur in nearly all stream and river valleys, being regionally well investigated (Hoffmann et al., 2008). Colluvial sediments occurring upon slopes (Dreibrodt et al, 2010), are seemingly distributed sparsely at altitudes higher than 500 m a.s.l. However, this impression can be the effect of an apparent lack of knowledge rather than a real scarcity of colluvial deposits in mountain areas (Tolksdorf et al., 2015, 2018a, 2019).

Most of our sites reflect by verification of cutting marks the anthropogenic felling of trees of considerable size, leaving behind well-preserved stumps and trunks. Although the large *Pinus* root in the Warnsdorf excavations exposed no clear cutting marks, wooden chips from *Abies* in the same horizon indicate intentional tree cutting (Fig. 4D).

Pedologically, three of the buried soils detected represent Histosols, one is a (Fluvic) Gleysol (WRB, 2015). These soil types correspond to the local wet-site landforms occupied by people, being primarily small stream valleys with shallow groundwater and, in one case, an interfluve plateau slope poorly drained by nearly impermeable rock. This wet-site setting enabled in each case the long-term preservation of large tree remains and organic artifacts. At Warnsdorf local peat formation in the form of human-induced paludification could be related to the felling or thinning out of the highly water-consuming tree vegetation, as demonstrated in similar contexts in the Sudetes, Massif Central (France) and beyond (e.g., Cubizolle et al., 2003; Treml et al., 2008; Woodward et al., 2014; Glina et al., 2017).

All buried soils investigated bear considerable amounts of charcoal, whereas the artifacts differ. At Cvilínek some tree stumps are integrated into the industrial facilities of the ore processing facility. Furthermore, a multitude of artifacts, such as ceramic sherds, slags and ore pieces, have been found. At Johanneser Kurhaus, in addition to large tree trunks and varied non-wooden artifacts, an extensive assemblage of smaller worked wood occurs, comprising parts of beams and planks as well as chips. By contrast, at Warnsdorf and Ústrašín non-wooden artifacts are completely absent in the buried soils.

Even with partly absence of traditional artifacts, the buried soils represent occupation layers (Holliday, 1992), documenting the clearing of the local mountain forest during the course of mining/metallurgy and settlement activities. More specifically, these buried soil horizons can be referred to as "forest-clearing horizons", conceptually combining vegetation, human impact and soil. Such horizons, marking the human exploitation including burning of formerly forested landscapes, have a worldwide occurrence. But they are, surprisingly, a rarely documented phenomenon both in prehistory and history (e.g., Herrmann et al., 1997; Williams, 2000; Kaiser et al., 2009; Innes et al., 2010; Certini & Scalenghe, 2011; Kaal et al., 2011; Portenga et al., 2016; Alexandrovskiy et al., 2018; Beach et al., 2018; Bishop et al., 2018; Ponomarenko et al., 2018). For the first time such horizons with *in situ* trees dating into the early to high medieval period could be demonstrated by means of our records for the central European uplands. These forest-clearing horizons substantially broaden the findings derived from wood and charcoal debris layers found in alluvial sequences in that area and also ascribed to past deforestation (e.g., Latocha, 2009; Klimek, 2010; Břízová et al., 2012; Kukulak, 2014; Wistuba et al., 2018).

5.2 Implications on vegetation reconstruction

The large *in situ* trees detected represent an incomplete piece of the local forest vegetation at stand-/pedon-scale, which are synchronous to deforestation. Compared to pollen records that normally reflect a supra-local (off-site) to regional scale, and botanical macro-remains and charcoal assemblages which potentially mirror a broad spatial range (e.g., Nelle et al., 2010), the *in situ* trees provide data with a very high spatial and chronological resolution. But only an integration of all available and differing spatially sensitive palaeobotanical data, including large *in situ* trees, macro-remains, charcoals, and pollen, allows for a reconstruction of the on-site forest vegetation. For each site investigated a conifer-dominated woodland on wet soils, primarily with a strong share of *Picea,* becomes apparent (Table III). Further tree taxa are *Abies* (except for Johanneser Kurhaus) and *Pinus* (only Warnsdorf) complemented by different proportions of deciduous wood taxa, such as *Fagus*, *Alnus* and *Betula*.

For Johanneser Kurhaus and Cvilínek information both on the synchronous on-site and off-site vegetation are available. In both cases, a marked contrast of the vegetation composition becomes apparent. At Johanneser Kurhaus an on-site dominance of *Picea* is contrasted by an off-site dominance of *Fagus* supplemented by *Acer*. At Cvilínek, *Picea* prevailing on-site is replaced by *Fagus*, *Quercus*, *Pinus*, and *Carpinus* off-site.

These observations on a site-specific pattern of the early to high medieval forest vegetation, depending on the highly localized edaphic conditions (i.e. relief, water and soil), complement pollen-based vegetation reconstructions for the lower and mid-altitudes in the Hercynian realm. They outline a zonal dominance of deciduous trees (particularly *Fagus*), complemented by conifers (particularly *Abies* and *Picea*; e.g., Beug et al., 1999; Rösch, 2000; Willerding, 2000; Jankovská et al., 2007; Weichardt-Kulessa, 2011; Glina et al., 2017; Bobek et al., 2018). By contrast, local charcoal records from kiln sites at higher elevations at Harz (>700 m a.s.l.) point to *Picea* woodlands with interlocking of *Fagus* and *Acer* on a local scale (Knapp et al., 2015). *Picea*-dominated stands were reported even for areas close to the current timberline (*ca.* 1200-1500 m a.s.l.) in the Šumava/Bohemian Forest and in the eastern Sudetes, indicated by palynology (Kral, 1979) and soil anthracology (Novák et al., 2010), respectively. At a regional scale, charcoal analyses from parts of south-western Germany also prove high frequencies of conifers (*Picea, Abies, Pinus*) for higher altitudes >~800 m a.s.l., showing that the natural site conditions there are generally more suitable for coniferous than for deciduous tree species (Ludemann, 2010). However, a dominance of conifers is also reconstructed for the lower and mid-altitudes of Českomoravská vrchovina (*ca.* 300-600 m a.s.l.) during the medieval and early modern periods, indicated by modelling of palynological and historical data (Szabó et al., 2017). Our record at Cvilínek, lying in the same landscape, contrasts this finding with deciduous trees dominating off-site. Similar records were also obtained from adjacent mountains (Vočadlová et al., 2015; Glina et al., 2017; Kuneš & Abraham, 2017; Dudová et al., 2018).

For Johanneser Kurhaus and Cvilínek the reconstruction of the diachronic vegetation and land-use dynamics is feasible to a certain extent. Additional anthracological data obtained from archaeological features at Johanneser Kurhaus (Knapp et al., 2015) show that the share of *Fagus* decreased from the 10th century A.D. (*ca.* 50%) to the 13th century A.D. (*ca.* 15%), accompanied by a rising share of pioneer trees (*ca.* 5% and 55%, respectively), which include, for instance, *Betula*, *Corylus* and *Sorbus* (rowan). Both *Picea* and *Acer* also decrease, comprising changes from *ca.* 30% to 5% and *ca.* 15% to 10%, respectively. Although in the high medieval period the "Medieval Warm Period/Climatic Anomaly" ended (Büntgen et al., 2011) and, therefore, climatically induced vegetation changes can generally be expected in the mountains, the increase of the pioneer trees reflects a more human rather than climatic impact.

Moreover, for Cvilínek the varied paleobotanical and archaeological record can be used to outline the medieval and post-medieval development of an upland site at mid-altitude under human influence. In the early 12th century A.D. the primeval vegetation of the site was a wet forest consisting of *Picea*, *Abies*, *Alnus*, and some *Fagus* (Phase 1; Fig. 8). Immediately prior to deforestation at *ca.* A.D. 1266/69, the forest stand is dominated by *Picea* and supplemented by both hydrophytic (*Alnus, Salix*) and heliophytic (pioneer) tree taxa (*Betula, Juniperus, Populus*). The pioneer taxa represent the impact of some human-induced grazing and wood exploitation in a secondary forest (Phase 2; Fig. 8). This local finding of an already existing but rather weak human impact *before* heavy intensification in the course of the main occupation/exploitation phase (here by mining/metallurgy) can be corroborated by further records on early to high medieval landscape and vegetation changes in central Europe (e.g., Brather, 2008; Novák et al., 2010; Dudová et al., 2014; Schreg, 2014; Wacnik et al., 2016). It is likely that hardly any forest site, at least at low to mid-altitudes in the central European uplands, remained primeval until the high medieval period. Furthermore, after forest-clearing and the construction as well as operation of an ore processing facility including settlement (Phase 3; Fig. 8), the site was probably abandoned at the beginning of the 14th century A.D., presumably then transforming into an extensive pasture with scattered trees (Phase 4; Fig. 8). Extensive agriculture was established and maintained by the nearby village of Černov, which was founded well before A.D. 1590. Today the site is flooded by water, following dam-lake construction in A.D. 2010, and surrounded by grassland. The off-site vegetation consists of arable land and intensively managed *Picea* forests (Phase 5; Fig. 8).

We are well aware that our findings on conifer-dominated tree stands on wet soils mirror specific site conditions occurring at local scale. However, as stream and river valleys in addition to poorly drained further relief areas (e.g., interfluve plateaus, spring niches and rivulets) are rather common in the uplands and may have served as natural trajectories for human colonization, they spatially represent more than simply marginal sites. Although the natural occurrence of *Picea* at azonal lower sites was already presumed for the Hercynian realm both for today and for the past (Leuschner & Ellenberg, 2017), their undoubted record as natural trees at mid-altitudes in the medieval period helps reconstruct the natural forest pattern in the uplands with more certainty. A further record from the foothills of Erzgebirge (Freiberg, *ca.* 380 m a.s.l.; Tolksdorf et al., 2018b) underlines that a medieval dominance of conifers (in that case of *Abies* and *Picea*) at low-lying wet sites is considerably more common than previously suspected.

5.3 Overview on late Holocene *in situ* tree records in central Europe

Generally, well-documented records of buried *in situ* trees in central Europe are rare, dating into both the late Pleistocene and Holocene (e.g., Friedrich et al., 2001; Dzieduszyńska et al, 2014; Achterberg et al., 2018; Daniel et al., 2018; Kaiser et al., 2018; Reinig et al., 2018; Šamonil et al., 2018). Their scarcity can be explained by typically incidental discovery in the course of construction, raw material extraction and archaeological excavations. Although appropriate sites should be widespread, occurring both in the uplands and lowlands, their targeted detection was lacking in the past. The study presented here represents the best-documented records of subfossil *in situ* trees from the medieval period in the central European uplands within an anthropogenic context. They represent a new and significant “geo-bio-archive” and geoarchaeological feature in this mountain region.

A compilation of *in situ* tree records for the late Holocene (i.e. younger than *ca.* B.C. 2500) for the central European uplands and beyond (Fig. 1; Supplemental Table 1) reveals, that only 17 from a total of 43 sites show traces of human processing. These traces normally comprise cut marks of axes and wooden chips. One third of the central European record is from the uplands, whereas two thirds spread into the lowlands including sea coasts. With respect to their geomorphic setting most sites represent peatlands, including raised bogs and fen mires (n = 17) as well as stream and river valleys (n = 16), whereas the rest (n = 10) spread over coasts, slopes and lakes. The trees were buried by sediments mostly of telmatic and fluvial origin, supplemented by eolian, colluvial, marine, and technogenic deposits as well as water (subaquatic setting). The taxa comprise a broad range of tree species with dominating *Quercus* and *Pinus*. Further species are *Fraxinus*, *Alnus*, *Salix*, *Picea*, and *Abies*.

Dating of these records is provided by geochronology, dendrochronology, archaeology, and written sources. A total of 93 radiocarbon ages shows some age clusters centered around B.C. 1800, B.C. 1300, B.C. 800, A.D. 200, and A.D. 1300 using probability density functions (Bronk Ramsey, 2017; Fig. 9). This age data distribution is dominated by tree records derived from peatlands, accounting to approximately 75% of the total trees dated. This age data distribution only reflects the status of the available dates, thus illustrating the current state of research. There are further sites with *in situ* occurrences mainly of *Pinus* and *Quercus* from several peatlands in northwestern Germany and The Netherlands which are dated by dendrochronology primarily into the mid- to late Holocene periods (Leuschner et al., 2002; Bauerochse et al., 2008; Achterberg et al., 2016). But, as these trees normally show no anthropogenic traces, are mostly older and represent a specific research matter of the lowlands, they will not be discussed further within the scope of our study.

6 CONCLUSIONS

Knowledge on historic changes in vegetation, relief and soil is key in understanding how the uplands in central Europe have changed during the last millennium. Moreover, reconstructing native site conditions based on field records allows for reasoning of local reference frames, being an essential requirement for measures on forest conversion and nature conservation in the mountains.

For the first time, evidence of forest-clearing horizons with *in situ* preserved trees are systematically documented at four low to mid-altitudinal sites in the central European uplands. This constitutes a new and promising geoarchaeological feature for this area, documenting the clearing of mountain forests by human exploitation. Applying a multiproxy-approach by using data from archaeology, palaeobotany, geochronology, dendrochronology, and pedology, we were able to draw the following conclusions:

- The *in situ* trees with traces of human felling and partly of burning were recovered from buried wet-organic soils (Histosols, Gleysols) within a context of mining/metallurgy and settlement archaeology.
- The *in situ* trees represent remnants of the local forest vegetation at stand-/pedon-scale, which are synchronous to deforestation. Botanical determination revealed the trees to be dominantly conifers (*Picea*, *Abies*, *Pinus*). Some deciduous tree taxa also occur (*Alnus*, *Fagus*).
- The trees can be dated from the 10th/11th to the 13th/14th centuries A.D. After deforestation the tree remains and forest soils were buried by technogenic and alluvial-colluvial deposits.
- These findings on conifer-dominated tree stands on wet soils mirror specific site conditions at local scale. As such sites are rather common in the uplands, they spatially represent more than simply marginal sites.
- Future regional research on buried forest-clearing horizons should strengthen the chronological resolution. Multi-method palaeobotany as well as applications in organic and isotope geochemistry of these buried soils (e.g.,) will fully exploit their archive potential.

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AUTHOR CONTRIBUTIONS

All authors listed have participated in the research presented in this manuscript. KK, PH, JFT, and GA have made a substantial, direct and intellectual contribution to the work, while KK led the writing of this article, with PH, JFT, and GA co-writing sections of the paper. CH, PK and LP performed analyses and interpreted data, and LS helped carry out the conceptual visualization. IH contributed to the interpretation of the results. All authors discussed the results and commented on the manuscript. All authors have approved the final manuscript.

CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Tables

Table I: Radiocarbon data from the sites investigated. Data calibration was performed with program OxCal 4.3 (https://c14.arch.ox.ac.uk/oxcal.html; Bronk Ramsey, 2009) using the IntCal13 data set (Reimer, 2013) with ranges of 1σ and of 2σ standard deviation for analysis.

Table II: Dendrochronological data from the sites investigated.

Table III: Topographical, stratigraphical, chronological, and paleoecological characteristics of the buried soils and subfossil *in situ* trees investigated.

Figures

Fig. 1: (A) Elevation map of central Europe showing the sites investigated (1 Johanneser Kurhaus, 2 Warnsdorf, 3 Cvilínek, 4 Ústrašín) and further sites with late Holocene *in situ* tree occurrences (for decoding and referencing of IDs 5-43 see Supplemental Table 1). (B) Scene

from the medieval law book “Sachsenspiegel” (Engl. “Saxon Mirror”; Eike von Repgow, original version 13th century A.D.), showing, from left to right, the legal transfer of ownership (foundation charter), forest-clearing and construction measures (Heidelberger Sachsenspiegel, central Germany, 14th century A.D., http://digi.ub.uni-heidelberg.de/diglit/cpg164, CC BY-SA 3.0 DE).

Fig. 2: Photographs of the sites investigated and of surrounding landscapes. (A) View over the high plateau of Harz, Germany, from Achtermannshöhe top (925 m a.s.l.) northwards to Brocken summit (1141 m a.s.l.; photograph: S. Lachmann, 2018). (B) Johanneser Kurhaus site, Harz, located at a stream valley (570 m a.s.l.) and covered by a spruce stand during excavations locally starting in 1988 (photograph: F.-A. Linke). (C) Mountain crest area of eastern Erzgebirge, Germany, showing the mining collapse structure at Altenberg (diameter: 400 m, depth: 130 m, area: 12 hectare) with view south-westwards to Kahleberg top (905 m a.s.l.; photograph: N. Kaiser, 2008, CC BY-SA 2.5). (D) Resampling campaign in 2017 at Warnsdorf site, foothills of Erzgebirge, located upon slope (360 m a.s.l., photograph: K. Kaiser). (E) View from Křemešník top (767 m a.s.l.), Českomoravská vrchovina, Czech Republic, southwards to the Javořice range (837 m a.s.l.; photograph: P. Hrubý, 2010). (F) Excavation in 2009 at Cvilínek site, Českomoravská vrchovina, located at a stream valley (640 m a.s.l.; photograph: ARCHAIA Brno). (G) Excavation in 2015 at Ústrašín site, Českomoravská vrchovina, located at a stream valley (560 m a.s.l.; photograph: ARCHAIA Brno).

Fig. 3: Johanneser Kurhaus site, Harz, Germany. (A) Drawing of sections 2 and 3 with wood-bearing soil horizon at the bottom (features 580 and 896), radiometrically dating at A.D. 777-977. (B) Photograph of section 14 (front view) with wood-bearing soil horizon at the bottom which is indicated by index 3. (C) Photographs of cones from *Picea* found in the wood-

bearing soil horizon (black and white photograph). (D) Photograph of section 2 (plan view) with the prepared wood remains in the soil horizon at the bottom (feature 580). (E) Photograph of section 12 (plan view) with a *ca.* 3 m long segment of a tree trunk of *Picea* found in the wood-bearing soil horizon at the bottom (feature 580).

Fig. 4: Warnsdorf site, foothills of Erzgebirge, Germany. (A) Trench E-F according to Spehr (2002, modified). (B) Section TRD-4 with large tree root of *Pinus* projected against the profile wall and peaty soil horizon at the bottom. (C) Photograph (front view) of section TRD-4 (total scale of the ruler on the right is *ca.* 80 cm). (D) Photograph of wooden chips from *Abies* collected from the peaty soil horizon at the bottom (black and white photograph: Spehr, 2002).

Fig. 5: Cvilínek, Českomoravská vrchovina, Czech Republic. (A) Drawing of section 2 with large conifer tree fragment and peaty soil horizon at the bottom (features 6404 and 1180). (B) Photograph (front view) with the bottom detail of section 2 (total scale of the ruler on the left is *ca.* 80 cm). (C) Photograph (plan view) of well-preserved wooden construction details (containers, chute, piles) of an ore washing facility during excavation, dendrochronologically dating at A.D. 1266-1268 (length of the container to the left is *ca.* 1.8 m). Immediately on the right of this container the heavily decomposed remains of a cut conifer tree stump occurs (white arrow). (D) Photograph of the excavation area showing several large and small tree stumps (white arrows); for scaling see the person in the foreground. (E) Photographs of cones from *Picea* associated with tree stumps. (F) Photograph of large conifer wood remains (trunks, stumps; white arrows) during excavation; length of the trunk in the foreground is *ca.* 4.5 m. (G) Large *Picea* stump (diameter *ca.* 35 cm) with roots showing signs of anthropogenic processing.

Fig. 6: Ústrašín site, Českomoravská vrchovina, Czech Republic. (A) Drawing of section 2 with abundant wood fragments and peaty soil horizon at the bottom (features 0187-0191), radiometrically dating at A.D. 1322-1442. (B) Photograph (front view) of section 2. (C) Photograph (front view) of section 1. (D) Photograph of trench 2 (plan view) showing well-preserved tree remains of *Picea*, which are separated by a linear boulder structure being part of a modern drainage trench. (E) Detail photograph of trench 2 (plan view) showing some tree bases of *Picea* with roots. (F) Photograph of trench 3 (plan view) showing abundant small-scale tree remains of *Picea* (roots, branches, cones). (G) Photograph (front view) of section 3 with a peaty soil horizon with abundant wood fragments and charcoal in the middle, radiometrically dating at A.D. 1157-1264.

Fig. 7: Stratigraphy, geochronology and palynology of section 2 at Ústrašín site. Selected taxa from pollen analysis are displayed. The calculating sum is based on total terrestrial pollen.

Fig. 8: Conceptual model showing the medieval and modern landscape development in the uplands of central Europe outlined by the Cvilínek record (unscaled image). Phase 1: Primary forest; beginning 12th century A.D. Phase 2: Secondary forest with some man-made clearings and grazing; first half of 13th century A.D. Phase 3: Forest-clearing with establishment of ore mining, ore processing facility and settlement; second half of 13th century A.D. Phase 4: Establishment of an extensive pasture with scattered trees; 14th-15th centuries A.D. Phase 5: Current landscape with dam-lake surrounded by intensive farmland and managed forest.

Fig. 9: Temporal distribution of radiocarbon ages from late Holocene *in situ* tree remains in central Europe using the OxCal programme (https://c14.arch.ox.ac.uk/oxcal.html; Bronk Ramsey, 2009, 2017). The respective data and further information are given in Supplemental Table 1.

Supplemental Material

Supplemental Table I: Sites with late Holocene *in situ* tree remains in central Europe with respective references.

Supplemental Table II: Johanneser Kurhaus site. Determination of botanical macro-remains from two samples of the wood-bearing soil horizon at the bottom (feature 580; Andrae, 2003, adapted).

Supplemental Table III: Johanneser Kurhaus site. Botanical analysis and radiocarbon ages of charcoal spectra from charcoal kilns of the “Winterhalbe” sub-site (Hillebrecht, 1989; Alper, 2003, adapted).

Supplemental Fig. 1: Johanneser Kurhaus site. Map of the excavation features (Alper, 2003, adapted).

Supplemental Fig. 2: Warnsdorf site. Map of the excavation features (Spehr, 2002, adapted).

Supplemental Fig. 3: Warnsdorf site. Stratigraphy, analytical results and zonation/phases of section TRD-04.

Supplemental Fig. 4: Cvilínek site. Map of the excavation features (Hrubý et al. 2012, adapted).

Supplemental Fig. 5: Cvilínek site. Analysis of uncharred wood and charcoal from an organic layer of section 1.

Supplemental Fig. 6: Cvilínek site. Analysis of uncharred wood, macro-remains and charcoal from an organic sediment layer of section 3 (Hrubý et al., 2014, adapted).

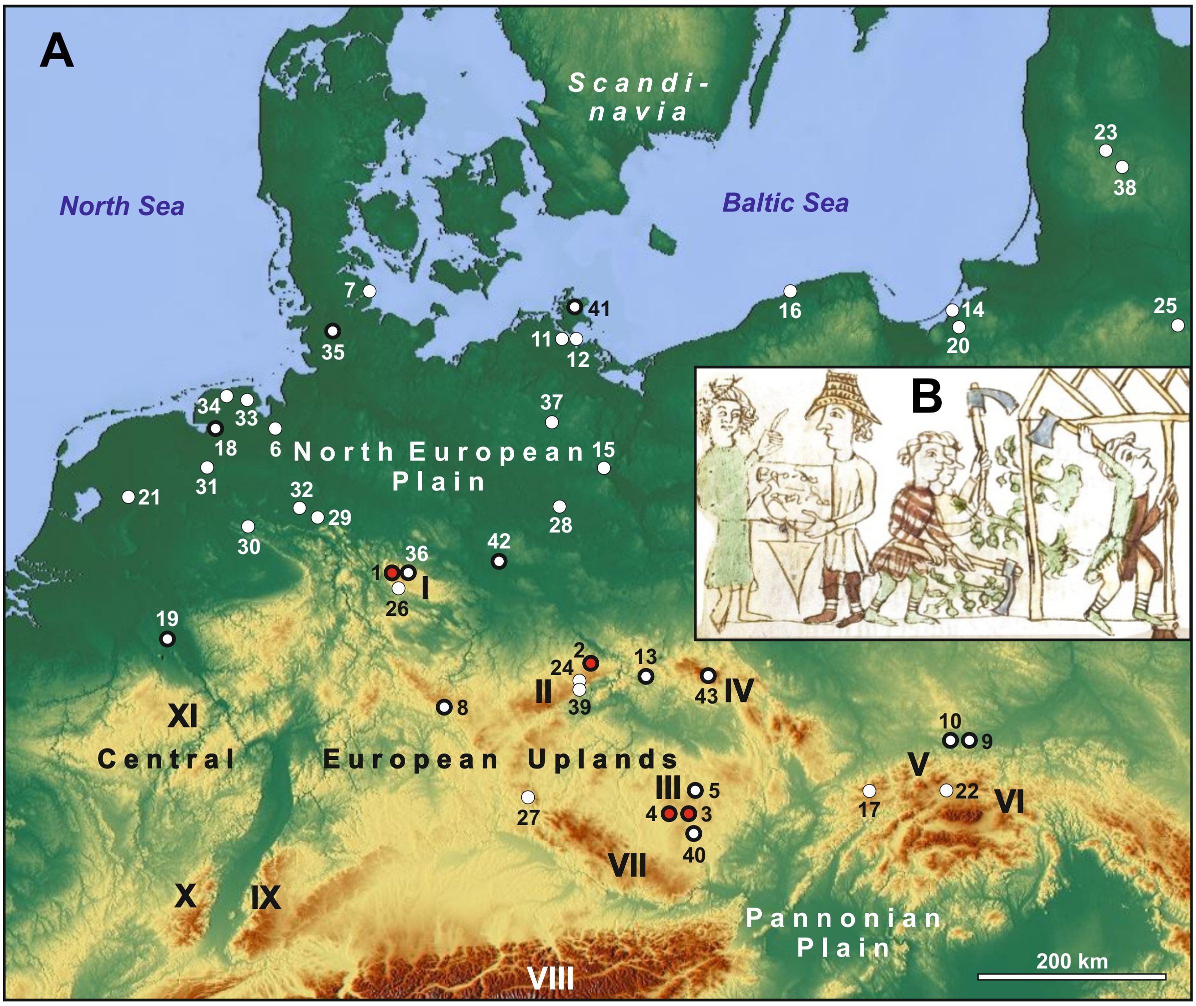
Supplemental Fig. 7: Cvilínek site. Pollen analysis from an organic sediment layer of section 3 (Hrubý et al., 2012, adapted).

Supplemental Fig. 8: Ústrašín site. Map of the excavation features (Hrubý & Těsnohlídek, 2016).

Supplemental Fig. 9: Ústrašín site. Analysis of macro-remains and charcoal (unspecified) of section 2 (units of the ordinates are numbers). Whereas woody taxa given with species names (e.g., *Abies alba*) refer to seeds of specific taxa, counts in the "Wood" column on the right refer to pieces of unspecified wood including trees and shrubs.

Supplemental Fig. 10: Ústrašín site. Analysis of uncharred wood (unspecified), macro-remains and charcoal (unspecified) of section 3.

Supplemental Fig. 11: Ústrašín site. Pollen analysis of section 3.



● Site investigated (IDs 1-4)

○ Further site with late Holocene *in situ* tree remains; with anthropogenic context

○ Further site with late Holocene *in situ* tree remains; without anthropogenic context

Selected upland areas:

I	Harz	VII	Bayerischer Wald-Šumava
II	Erzgebirge-Krušné hory	VIII	Alps
III	Českomoravská vrchovina	IX	Schwarzwald
IV	Sudetes	X	Vosges
V	Beskids	XI	Rhenish Massif
VI	Carpates		

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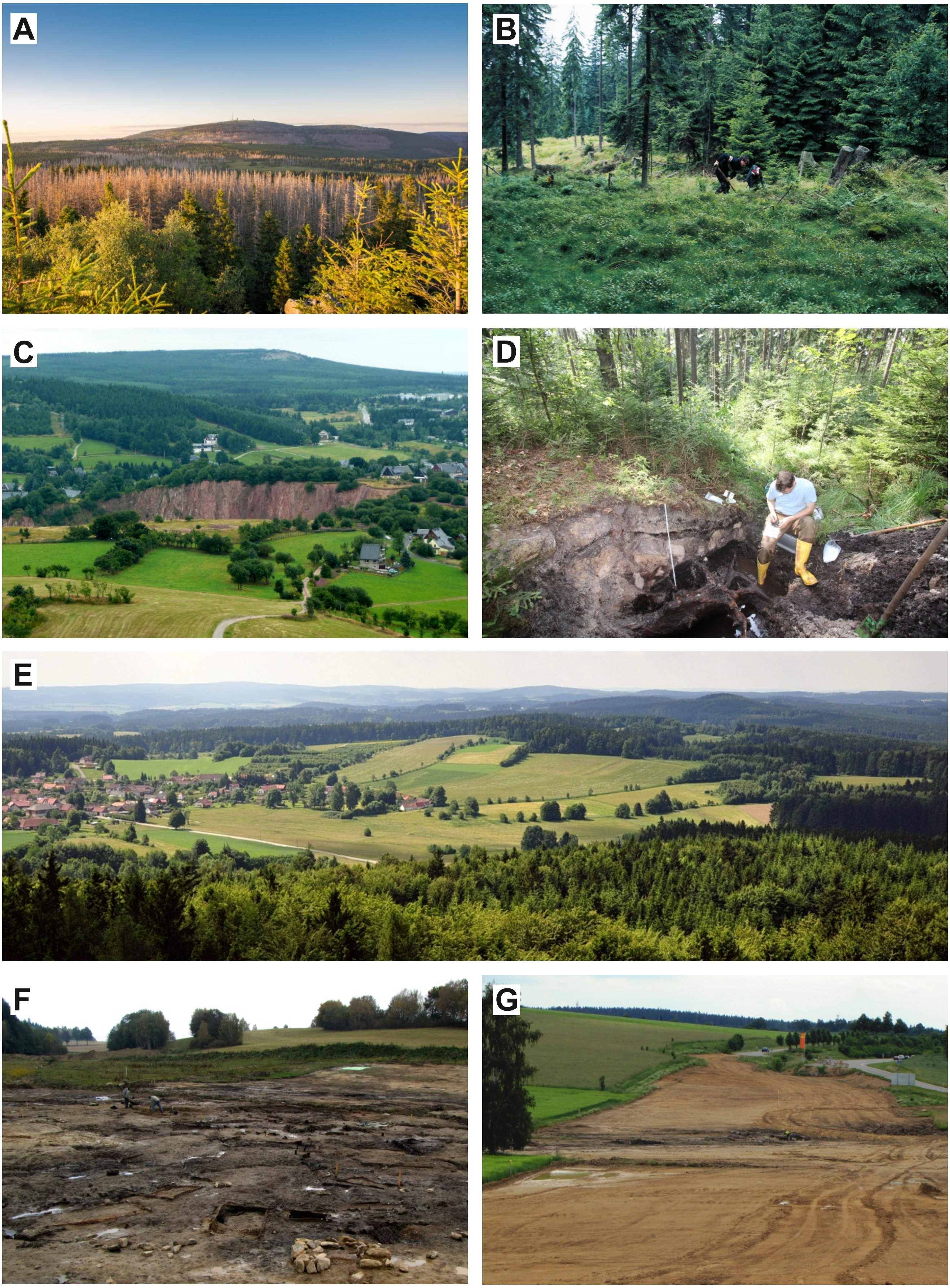


Fig. 2: Photographs of the sites investigated and of surrounding landscapes. (A) View over the high plateau of Harz, Germany, from Achtermannshöhe top (925 m a.s.l.) northwards to Brocken summit (1141 m a.s.l.; photograph: S. Lachmann, 2018). (B) Johanneser Kurhaus site, Harz, located at a stream valley (570 m a.s.l.) and covered by a spruce stand during excavations starting in 1988 (photograph: F.-A. Linke). (C) Mountain crest area of eastern Erzgebirge, Germany, showing the mining collapse structure at Altenberg (diameter: 400 m, depth: 130 m, area: 12 hectare) with view towards Kahleberg top (905 m a.s.l.; photograph: N. Kaiser, 2008, CC BY-SA 2.5). (D) Resampling campaign in 2017 at Warnsdorf site, foothills of Erzgebirge, Germany, located upon slope (360 m a.s.l., photograph: K. Kaiser). (E) View from Křemešník top (767 m a.s.l.), Českomoravská vrchovina, Czech Republic, southwards to the Javořice range (837 m a.s.l.; photograph: P. Hrubý, 2010). (F) Excavation in 2009 at Cvilínek site, Českomoravská vrchovina, located at a stream valley (640 m a.s.l.; photograph: ARCHAIA Brno). (G): Excavation in 2015 at Ústrašín site, Českomoravská vrchovina, located at a stream valley (560 m a.s.l.; photograph: ARCHAIA Brno).

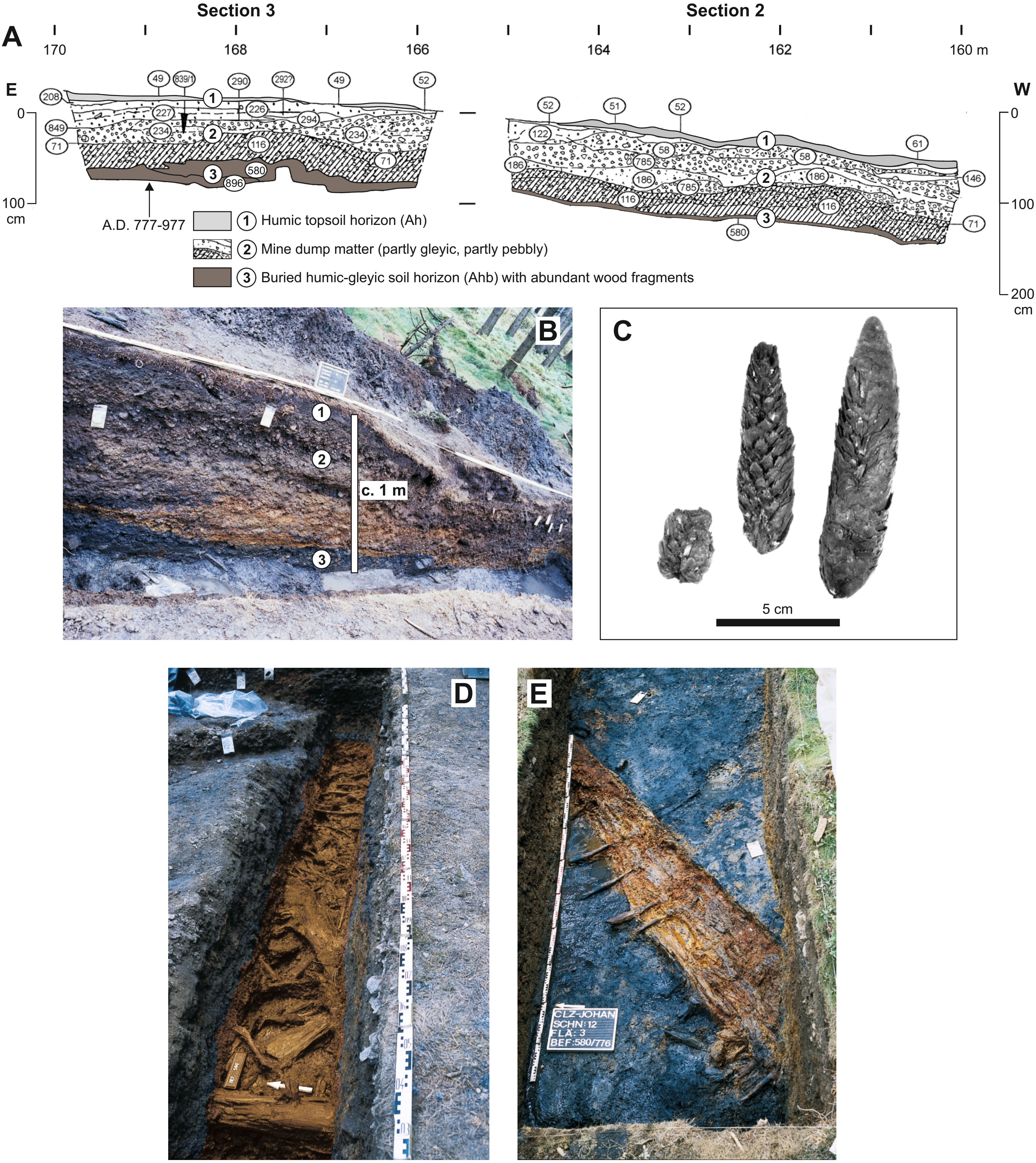


Fig. 3: Johanneser Kurhaus site, Harz, Germany. (A) Drawing of sections 2 and 3 with wood-bearing soil horizon at the bottom (features 580 and 896), radiometrically dating at A.D. 777-977. (B) Photograph of section 14 (front view) with wood-bearing soil horizon at the bottom which is indicated by index 3. (C) Photographs of cones from *Picea* found in the wood-bearing soil horizon (black and white photograph). (D) Photograph of section 2 (plan view) with the prepared wood remains in the soil horizon at the bottom (feature 580). (E) Photograph of section 12 (plan view) with a *ca.* 3 m long segment of a tree trunk of *Picea* found in the wood-bearing soil horizon at the bottom (feature 580).

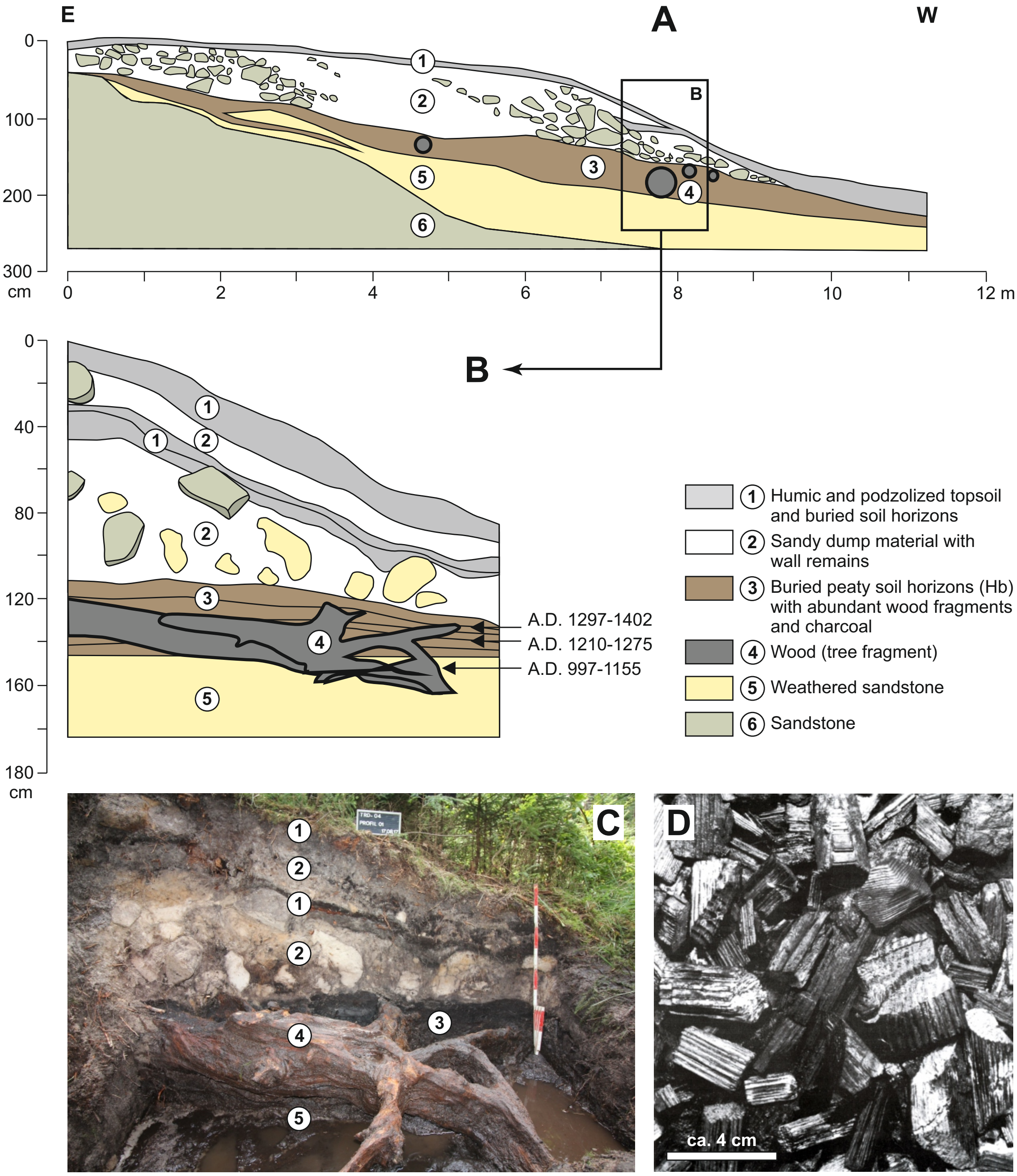


Fig. 4: Warnsdorf site, foothills of Erzgebirge, Germany. (A) Trench E-F according to Spehr (2002, modified). (B) Section TRD-4 with large tree root of *Pinus* projected against the profile wall and peaty soil horizon at the bottom. (C) Photograph (front view) of section TRD-4 (total scale of the ruler on the right is *ca.* 80 cm). (D) Photograph of wooden chips from *Abies* collected from the peaty soil horizon at the bottom (black and white photograph: Spehr, 2002).

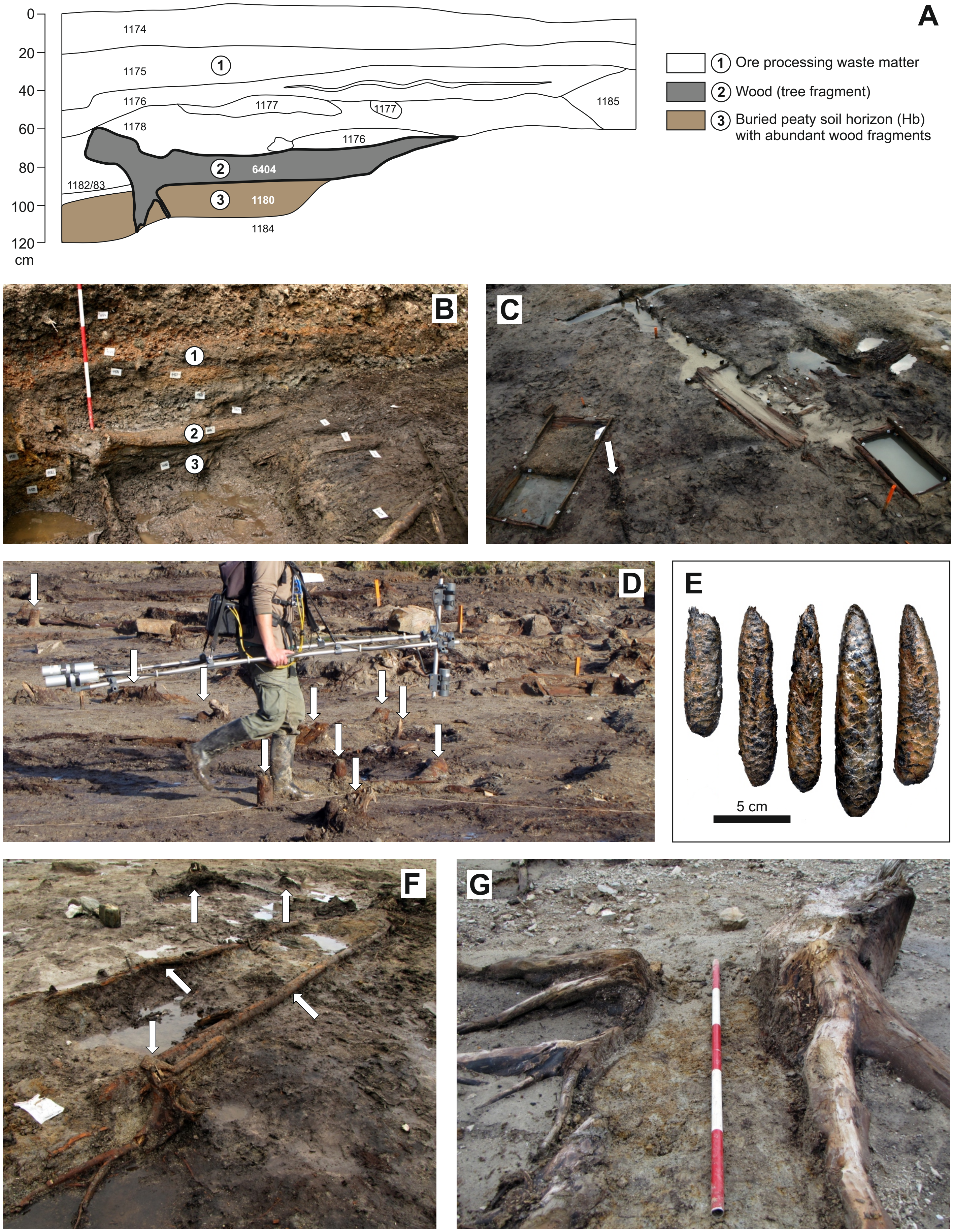


Fig. 5: Cvilínek, Českomoravská vrchovina, Czech Republic. (A) Drawing of section 2 with large conifer tree fragment and peaty soil horizon at the bottom (features 6404 and 1180). (B) Photograph (front view) with the bottom detail of section 2 (total scale of the ruler on the left is ca. 80 cm). (C) Photograph (plan view) of well-preserved wooden construction details (containers, chute, piles) of an ore washing facility during excavation, dendrochronologically dating at A.D. 1266-1268 (length of the container to the left is ca. 1.8 m). Immediately on the right of this container the heavily decomposed remains of a cut conifer tree stump occurs (white arrow). (D) Photograph of the excavation area showing several large and small tree stumps (white arrows); for scaling see the person in the foreground. (E) Photographs of cones from Picea associated with tree stumps. (F) Photograph of large conifer wood remains (trunks, stumps; white arrows) during excavation; length of the trunk in the foreground is ca. 4.5 m. (G) Large Picea stump (diameter ca. 35 cm) with roots showing signs of anthropogenic processing.

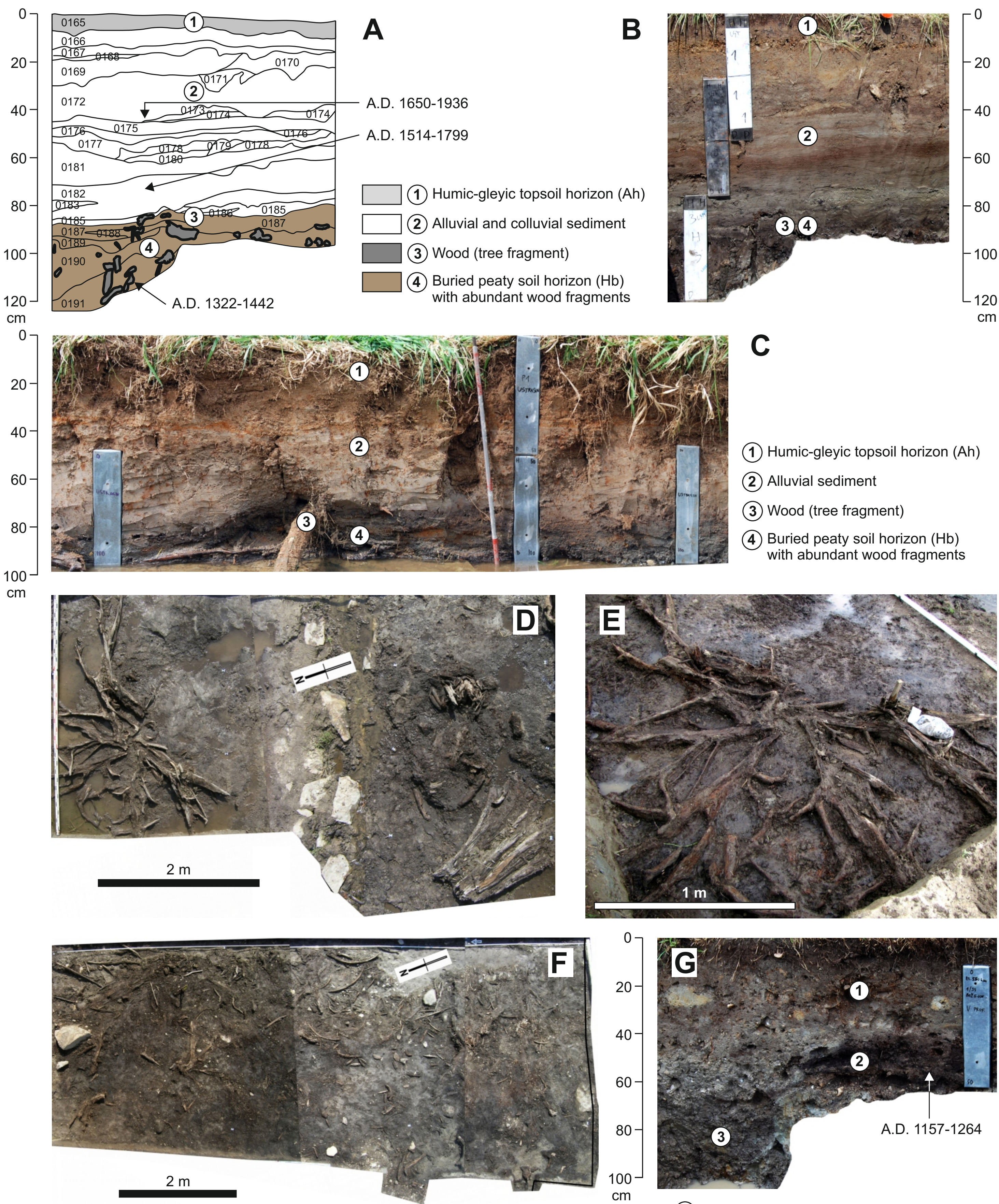


Fig. 6: Ústrašín site, Českomoravská vrchovina, Czech Republic. (A) Drawing of section 2 with abundant wood fragments and peaty soil horizon at the bottom (features 0187-0191), radiometrically dating at A.D. 1322-1442. (B) Photograph (front view) of section 2. (C) Photograph (front view) of section 1. (D) Photograph of trench 2 (plan view) showing well-preserved tree remains of Picea, which are separated by a linear boulder structure being part of a modern drainage trench. (E) Detail photograph of trench 2 (plan view) showing some tree bases of Picea with roots. (F) Photograph of trench 3 (plan view) showing abundant small-scale tree remains of Picea (roots, branches, cones). (G) Photograph (front view) of section 3 with a peaty soil horizon with abundant wood fragments and charcoal in the middle, radiometrically dating at A.D. 1157-1264.

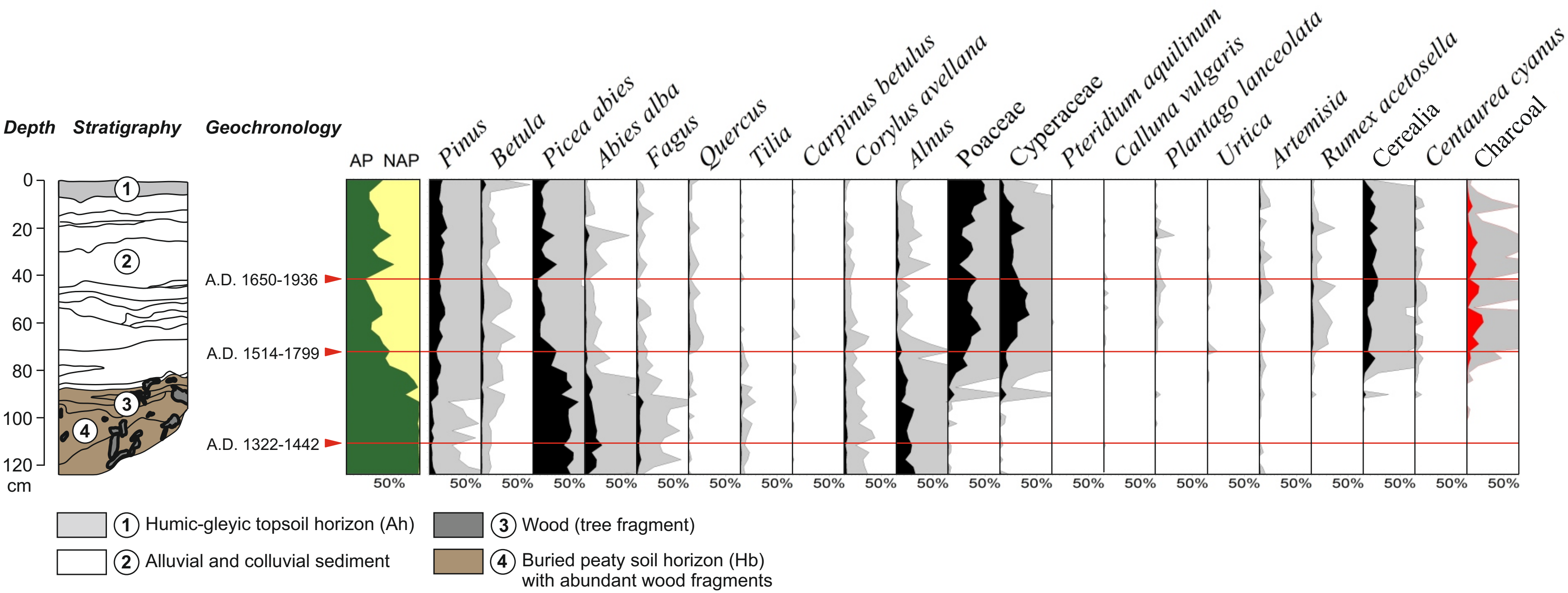


Fig. 7: Stratigraphy, geochronology and palynology of section 2 at Ústrašín site. Selected taxa from pollen analysis are displayed. The calculating sum is based on total terrestrial pollen.

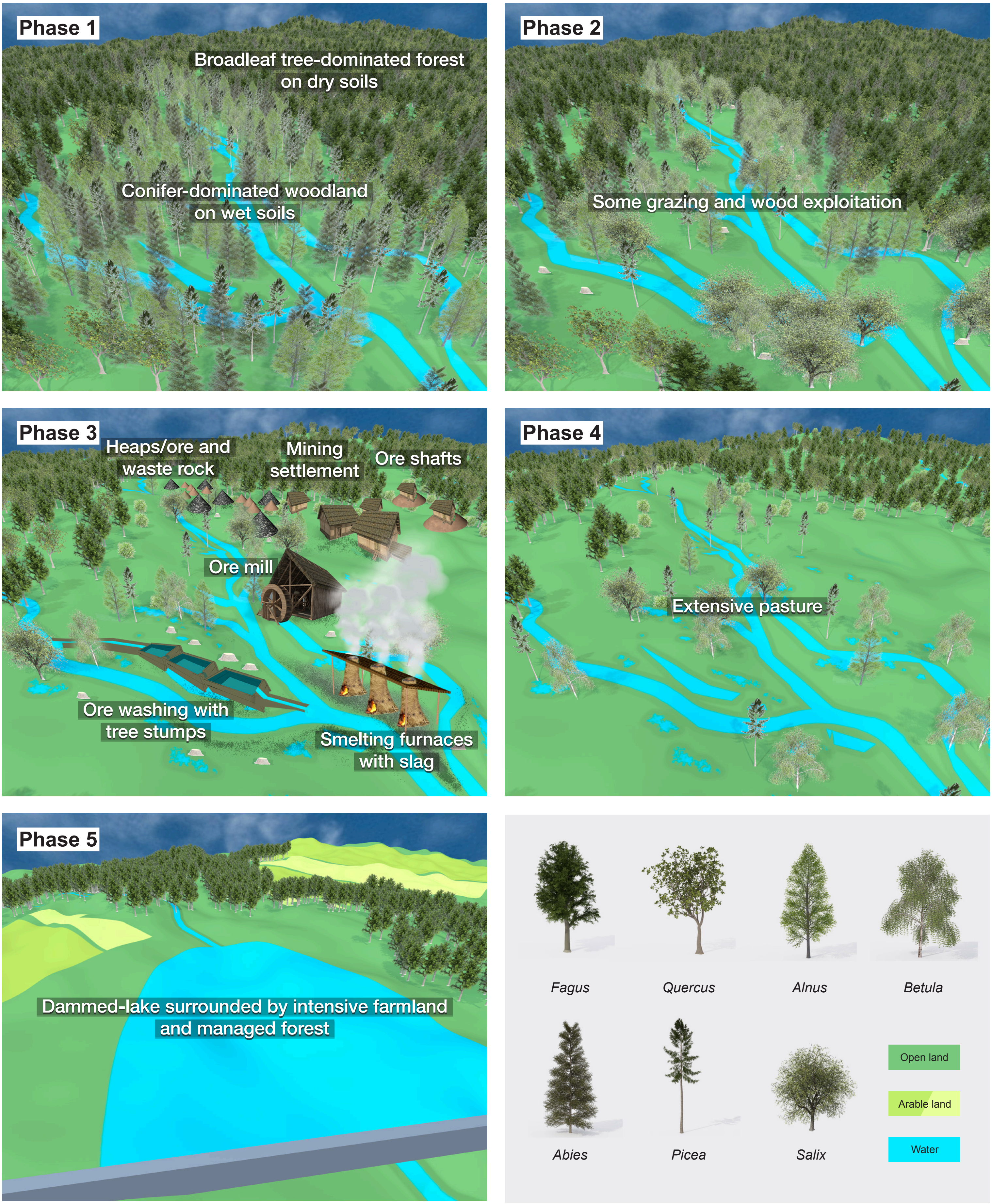


Fig. 8: Conceptual model showing the medieval and modern landscape development in the uplands of central Europe outlined by the Cvilínek record (unscaled image). Phase 1: Primary forest; beginning 12th century A.D. Phase 2: Secondary forest with some man-made clearings and grazing; first half of 13th century A.D. Phase 3: Forest-clearing with establishment of ore mining, ore processing facility and settlement; second half of 13th century A.D. Phase 4: Establishment of an extensive pasture with scattered trees; 14th-15th centuries A.D. Phase 5: Current landscape with dam-lake surrounded by intensive farmland and managed forest.

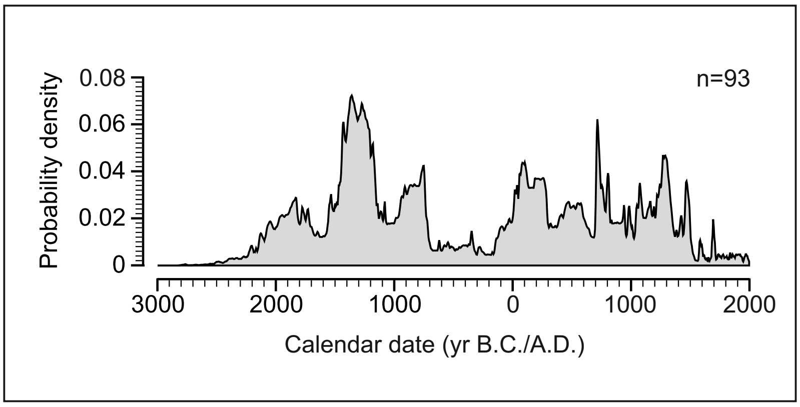


Fig. 9: Temporal distribution of radiocarbon ages from late Holocene *in situ* tree remains in central Europe using the OxCal programme (https://c14.arch.ox.ac.uk/oxcal.html; Bronk Ramsey, 2009, 2017). The respective data and further information are given in Supplemental Table 1.

Table I: Radiocarbon data from the sites investigated. Data calibration was performed with program OxCal 4.3 (https://c14.arch.ox.ac.uk/oxcal.html; Bronk Ramsey, 2009) using the IntCal13 data set (Reimer, 2013) with ranges of 1σ and of 2σ standard deviation for analysis.

Site	**Sample ID**	**Lab ID**	**Dating method**	**Depth below surface**	**Material**	**Age**	**Age range calibrated IntCal 13, 1σ**	**Age range calibrated IntCal 13, 2σ**
			[AMS, conv.]	[cm]		[^{14}C yr B.P.]	[A.D.]	[A.D.]
Johanneser Kurhaus	FNr. 4312 - Befund 896	KI-4695	conv.	105 cm	Wood (*Picea*)	1140 ± 20	885-963	777-977
Johanneser Kurhaus	Winterhalbe - Grube 14	Hv-15752	conv.	40 cm	Charcoal (*Fagus*)	1170 ± 115	721-981	646-1147
Johanneser Kurhaus	Winterhalbe - Grube 15	Hv-15753	conv.	40 cm	Charcoal (*Fagus, Acer*)	1290 ± 95	652-865	591-969
Johanneser Kurhaus	Winterhalbe - Grube 17/1	Hv-15749	conv.	40 cm	Charcoal (*Fagus, Acer*)	1125 ± 65	778-991	723-1024
Johanneser Kurhaus	Winterhalbe - Grube 17/2	Hv-15750	conv.	40 cm	Charcoal (*Fagus, Acer*)	1065 ± 65	894-1024	776-1151
Johanneser Kurhaus	Winterhalbe - Grube 19	Hv-15751	conv.	40 cm	Charcoal (*Fagus, Acer, Picea*)	1110 ± 130	727-1029	660-1166
Warnsdorf	TRD-04	MAMS-33871	AMS	78-84	Peat	610 ± 24	1303-1395	1297-1402
Warnsdorf	TRD-04	MAMS-33872	AMS	84-87	Charcoal	793 ± 24	1224-1261	1210-1275
Warnsdorf	TRD-04-01	Poz-98724	AMS	105	Wood (*Pinus* root)	975 ± 35	1018-1150	997-1155
Warnsdorf	Hausstelle II	Bln-2984	conv.	-	Charcoal	680 ± 50	1274-1387	1257-1400
Warnsdorf	Brunnen 2	Bln-2985	conv.	c. 250	Wood (conifer)	1230 ± 50	695-874	669-938
Úštrašín	Úštrašín 40-45, section 2	Poz-78413	AMS	40-45	Seeds/organic macro-remains	185 ± 30	1665-1936	1650-1936
Úštrašín	Úštrašín 70-75, section 2	Poz-78415	AMS	70-75	Wood (conifer)	270 ± 30	1525-1664	1514-1799
Úštrašín	Úštrašín P2 4, section 2	Poz-74607	AMS	110	Wood (*Picea* tree fragment unspecified)	525 ± 30	1400-1435	1322-1442
Úštrašín	Úštrašín S4 2, trench 2	Poz-74606	AMS	30-35	Wood (*Picea* branches)	815 ± 30	1210-1260	1168-1266
Úštrašín	Úštrašín P1 3, section 3	Poz-74445	AMS	45-50	Wood (*Picea* branches)	835 ± 30	1169-1245	1157-1264

Table II: Dendrochronological data from the sites investigated.

Site	Sample ID	Lab ID	Tree species	Archaeological context	Felling date [A.D.]	Reference
Warnsdorf	Brunnen 1D	C-2393	*Abies alba*	Water well	1163	Spehr, 2002
Warnsdorf	Brunnen 1C	C-2392	*Abies alba*	Water well	1162	Spehr, 2002
Warnsdorf	Brunnen 1B	C-2394	*Abies alba*	Water well	1162	Spehr, 2002
Cvilínek	5406	-	*Abies alba*	Ore washing equipment	1266/1267	M. Rybníček, pers. comm.
Cvilínek	4405	-	*Abies alba*	Ore washing equipment	1267/1268	M. Rybníček, pers. comm.
Cvilínek	5405	-	*Abies alba*	Ore washing equipment	1267/1268	M. Rybníček, pers. comm.
Cvilínek	0427	U6245	*Abies alba*	Ore washing equipment	1267/1268	T. Kyncl, pers. comm.
Cvilínek	0425	U6241	*Abies alba*	Ore washing equipment	1268/1269	T. Kyncl, pers. comm.
Cvilínek	0428	U6243	*Abies alba*	Ore washing equipment	1268/1269	T. Kyncl, pers. comm.
Cvilínek	1497	U6242	*Abies alba*	Ore washing equipment	1268/1269	T. Kyncl, pers. comm.
Cvilínek	1415	U6244	*Abies alba*	Ore washing equipment	1269	T. Kyncl, pers. comm.

Table III: Topographical, stratigraphical, chronological, and paleoecological characteristics of the buried soils and subfossil *in situ* trees investigated.

Property	**Johanneser Kurhaus**	**Warnsdorf**	**Cvilínek**	**Ústrašín**
Altitude [m a.s.l.]	570	360	640	560
Covering sediment	Gravelly mine spoil	Sandy dump matter (substructure)	Gravelly ore processing waste matter	Alluvial and colluvial sediment
Buried soil type [WRB, 2015]	(Fluvic) Gleysol	Histosol	Histosol	Histosol
Large subfossil tree taxa detected *in situ* with dating	*Picea*; 9th/10th century A.D.	*Pinus*; 11th/12th century A.D.	*Picea, Alnus, Populus/Salix, Betula, Juniperus*; 13th century A.D.	*Picea*; 12th-15th centuries A.D.
Further tree taxa determined using macro remains	*Fagus, Betula, Alnus, Salix, Acer*	*Picea, Abies*	*Abies, Fagus*	*Abies, Alnus*
On-site forest vegetation reconstructed	*Picea*-dominated woodland on wet soils with some deciduous wood taxa	Mixed conifer-dominated woodland on wet soils with varying shares of *Pinus, Picea* and *Abies*	*Picea*-dominated woodland on wet soils with some deciduous wood taxa	*Picea*-dominated woodland on wet soils with some deciduous wood taxa
Context of human activity with dating	Deforestation and melting of silver; 10th/11th century A.D.	Deforestation and extraction of raw material (sandstone) and/or settlement; (11th-) 12th-14th centuries A.D.	Deforestation and ore processing including washing, silver metallurgy and domestic settlement; 13th century A.D.	Deforestation; 13th century A.D.

Supplemental Table I: Sites with late Holocene in situ tree remains in central Europe with respective references.

ID	Site	Country code	Northing	Easting	Altitude	Site geomorphology	Radiocarbon age	Radiocarbon age calibrated	Dendro age	Written source	Anthropogenic context	Reference short	Reference long
			[Dec. degr.]	[Dec. degr.]	[m a.s.l. / b.s.l.]		[^{14}C yr B.P.]	[B.C. / A.D.]	[B.C. / A.D.]	[A.D.]			
1	Johanneser Kurhaus	DE	51.827611°	10.288243°	570	stream valley	1140 ± 20 (KI-4695, spruce)	-	-	-	x	Alper, 2003; this study	Alper, G. (2003). „Johanneser Kurhaus". Ein mittelalterlicher Blei-/Silbergewinnungsplatz bei Clausthal-Zellerfeld im Oberharz. Materialhefte zur Ur- und Frühgeschichte Niedersachsens 32. Rahden/Westf.: Leidorf.
2	Warnsdorf	DE	50.962348°	13.536060°	350	plateau (interfluve)	975 ± 35 (Poz-98724, pine)	-	-	-	x	Spehr, 2002; this study	Spehr, R. (2002). Die Wüstung Warnsdorf im Tharandter Wald. Mitteilungen des Freiberger Altertumsvereines, 91, 5-62.
3	Cvilínek	CZ	49.348932°	15.316345°	650	stream valley	-	-	in situ tree stumps of spruce indirectly dated by construction wood (1266-1269 A.D., 8x fir)	-	x	Hrubý et al., 2012; this study	Hrubý, P. Hejhal, P., Hoch, A., Kočár, P., Malý, K., Macháňová, L., Petr, L., & Štelcl, J. (2012). Středověký úpravnický a hornický areál Cvilínek u Černova na Pelhřimovsku. Památky archeologické, 103, 339-418.
4	Ústrašín	CZ	49.3738367°	15.1651125°	560	stream valley	815 ± 30 (Poz-74606, spruce), 835 ± 30 (Poz-74445, spruce), 525 ± 30 (Poz-74607, spruce), 270 ± 30 (Poz-78415, conifer)	-	-	-	x	Hrubý & Těsnohlídek, 2016; this study	Hrubý, P., & Těsnohlídek, J. (2016). I/34 Božejov, Ondřejov, Pelhřimov. Zpráva o provedení záchranného archeologického výzkumu. Číslo archeologického výzkumu A 019/2015. Unpublished Report, ARCHAIA Brno, o.p.s.
5	Koječín	CZ	49.537827°	15.491336°	580	stream valley	-	-	in situ tree remains of fir and spruce indirectly dated by construction wood (1254/55 A.D., 3x fir)	-	x	P. Hrubý, pers. comm.	-
6	Rade	DE	53.261333°	8.496887°	1	river valley (Weser)	3115 ± 65 (Hv-12684), 2780 ± 60 (Hv-12686), 2760 ± 55 (Hv-12687, all tree species unknown)	-	-	-	-	Behre, 1985	Behre, K.E. (1985). Die ursprüngliche Vegetation in den deutschen Marschgebieten und deren Veränderung durch prähistorische Besiedlung und Meeresspiegelbewegungen. Verhandlungen der Gesellschaft für Ökologie, 8, 85-96.
7	Schlei	DE	54.671152°	10.034359°	0 to -2	coastal lagoon (Baltic Sea)	3540 ± 30 (KI-5143, alder), 3040 ± 40 (KI-5142, alder), 3010 ± 35 (KI-5144), 2680 ± 60 (KI-5124, alder), 3650 ± 50 (KI-5145, oak)	325–25 B.C. (KI-3206, oak), 1890–1575 B.C. (KI-3204, oak)	-	-	-	Dörfler et al., 2009	Dörfler, W., Jakobsen, O., & Klooß, S. (2009). Indikatoren des nacheiszeitlichen Meeresspiegelanstiegs der Ostsee. Eine methodische Diskussion am Beispiel der Ostseeförde Schlei, Schleswig-Holstein. Universitätsforschungen zur prähistorischen Archäologie, 165, 177-186.
8	Friesen	DE	50.277210°	11.333402°	367	upper slope of a small hill	1830 ± 25 (KI-4876, tree species unknown)	-	-	-	x	Dotterweich, 2003	Dotterweich, M. (2003). Land use change and soil erosion during the past 5000 years – case studies from northern Bavaria. In A. Lang, K. Hennrich, & R. Dikau (Eds.), Long Term Hillslope and Fluvial System Modelling – Rhine River Catchment. Lecture Notes in Earth Sciences, 101. (pp. 195-224). Heidelberg: Springer.
9	Branice-Stryjów (Vistula)	PL	50.043937°	20.132201°	194	river valley (Vistula)	1850 ± 60 (Gd-2081, oak)	-	-	-	x	Kalicki & Krąpiec, 1995	Kalicki, T., & Krąpiec, M. (1995). Problems of dating alluvium using buried subfossil tree trunks: lessons from the 'black oaks' of the Vistula Valley, Central Europe. The Holocene, 5, 243-250.
10	Kujawy (Vistula)	PL	50.044461°	20.099745°	198	river valley (Vistula)	-	-	975-980 A.D., 1310-1320 A.D. (oaks)	-	x	Kalicki & Krąpiec, 1995	Kalicki, T., & Krąpiec, M. (1995). Problems of dating alluvium using buried subfossil tree trunks: lessons from the 'black oaks' of the Vistula Valley, Central Europe. The Holocene, 5, 243-250.
11	Karrendorf	DE	54.167702°	13.387034°	0	coastal plain (Baltic Sea)	-	775-885 A.D. (Hv-24550, oak)	-	-	-	Lampe & Janke, 2004	Lampe, R., & Janke, W. (2004). The Holocene sea-level rise in the Southern Baltic as reflected in coastal peat sequences. Polish Geological Institute Special Papers, 11, 19-30.
12	Koos	DE	54.172067°	13.412179°	0	coastal plain (Baltic Sea)	-	620-660 A.D. (Gds-246, oak)	-	-	-	Lampe & Janke, 2004	Lampe, R., & Janke, W. (2004). The Holocene sea-level rise in the Southern Baltic as reflected in coastal peat sequences. Polish Geological Institute Special Papers, 11, 19-30.
13	Břehyně	CZ	50.578508°	14.703260°	271	dammed stream valley (pond)	-	-	-	1366-1460 A.D. (pine, spruce)	x	Meduna et al., 2010	Meduna, P., Sádlo, J., & Novák, J. (2010). Archeologie (nejen) středověké krajiny, aneb o Bezdězském lese. Živá archeologie, 11, 87-91.
14	Vistula Lagoon	PL	54.403724°	19.715489°	-2	coastal lagoon (Baltic Sea)	3295 ± 35 (Poz-15116, alder)	-	-	-	-	Leczynski et al., 2007	Leczynski, L., Miotk-Szpiganowicz, G., Zachowicz, J., Uscinowicz, S., & Krapiec, M. (2007). Tree stumps from the bottom of the Vistula Lagoon as indicators of water level changes in the Southern Baltic during the Late Holocene. Oceanologia, 49, 245-257.
15	Wesensee	DE	52.908184°	13.978989°	42	lake	-	-	1548 A.D. (C-88027), 1554 A.D. (C-88028), 1547 A.D. (C-88029), (all oak)	-	-	Stöhr, 2017	Stöhr, M. (2017). Aktuelle und historische Wasserstandsschwankungen des Wesensees bei Brodowin im UNESCO-Biosphärenreservat Schorfheide-Chorin. Unpublished bachelor thesis, University of Applied Sciences Eberswalde, Germany.
16	Ustka	PL	54.593935°	16.901683°	5	coastal cliff (Baltic Sea) with aeolian sediments	2610 ± 60 (GdS-1169, willow), 2835 ± 50 (GdC-526, oak)	-	-	-	-	Wróblewski et al., 2013	Wróblewski, R., Fedorowicz, S., & Kamieńska, K. (2013). Holocene sediments of the Ustka Cliff (Northern Poland) in view of radiometric dating. Geochronometria, 40, 187-194.
17	Lučovec Brook/Bílá	CZ	49.431145°	18.382760°	680	stream valley	1630 ± 70 (Ki-12760), 1780 ± 70 (Ki-12756), 1780 ± 70 (Ki-12758, all samples from one conifer trunk!)	-	-	-	-	Pánek et al., 2009	Pánek, T., Smolková, V., Hradecký, J., & Šilhán, K. (2009). Late Holocene evolution of landslides in the frontal part of the Magura Nappe: Hlavatá Ridge, Moravian-Silesian Beskids (Czech Republic). Moravian Geographical Reports, 17, 2-11.
18	Boomborg/Hatzum	DE	53.297657°	7.335694°	0	river valley	2665 ± 90 (Hv-2050, probably alder stump)	-	-	-	x	Behre, 1970	Behre, K.E. (1970). Die Entwicklungsgeschichte der natürlichen Vegetation im Gebiet der unteren Ems und ihre Abhängigkeit von den Bewegungen des Meeresspiegels. Probleme der Küstenforschung im südlichen Nordseegebiet, 9, 13-47.
19	Elsbachtal	DE	51.075847°	6.513744°	67	stream valley	680 ± 50 (UtC-3531, willow)	-	-	-	x	Berthold, 2003; Kalis et al. 2010	Berthold, J. (2003). Das Elsbachtal im Mittelalter und der frühen Neuzeit. Archäologie einer Kulturlandschaft. PhD thesis, University of Bonn, Germany. Kalis, A. J., Meurers-Balke, J., Schamuhn, S., & Tegtmeier, U. (2010). Archäobotanik zur spätmittelalterlichen Wasserwirtschaft im Elsbachtal. Materialien zur Bodendenkmalpflege im Rheinland, 21, 175-179.
20	Rucianka	PL	54.256438°	19.736932°	33	raised bog	2570 ± 60 (Ki-13846, pine), 2660 ± 50 (Ki-13847, pine), 2420 ± 60 (Ki-13848, pine), 2820 ± 50 (Ki-13849, pine), 2790 ± 40 (MKL-1301, pine), 3190 ± 50 (Ki-13850, oak)	-	-	-	-	Barniak et al., 2014	Barniak, J., Krąpiec, M., & Jurys, L. (2014). Sub-fossil wood from the Rucianka raised bog (NE Poland) as an indicator of climatic changes in the first millennium BC. Geochronometria, 41, 104-110.
21	Zwolle-Stadshagen	NL	52.524884°	6.063382°	-1	river valley	-	-	131 B.C. - 567 A.D. (oak, n=59), 58-527 A.D. (ash, n=36)	-	-	Kooistra et al., 2006; Sass-Klaassen & Hanraets, 2006	Kooistra, M. J., Kooistra, L. I., Van Rijn, P., & Sass-Klaassen, U. (2006). Woodlands of the past – The excavation of wetland woods at Zwolle-Stadshagen (the Netherlands): Reconstruction of the wetland wood in its environmental context. Netherlands Journal of Geosciences 85, 37-60. Sass-Klaassen, U., Hanraets, E., 2006. Woodlands of the past – The excavation of wetland woods at Zwolle-Stadshagen (the Netherlands): Growth pattern and population dynamics of oak and ash. Netherlands Journal of Geosciences, 85, 61-71.
22	Puscizna Wielka	PL	49.438038°	19.780150°	670	raised bog		-	1100-610 B.C. (pine, n=125)	-	-	Krąpiec et al., 2016	Krąpiec, M., Margielewski, W., Korzeń, K., Szychowska-Krąpiec, E., Nalepka, D., & Łajczak, A. (2016). Late Holocene palaeoclimate variability: The significance of bog pine dendrochronology related to peat stratigraphy. The Puścizna Wielka raised bog case study (Orawa-Nowy Targ Basin, Polish Inner Carpathians). Quaternary Science Reviews, 148, 192-208.
23	Kegai Mire	LT	55.836898°	22.295163°	166	fen mire	3240 ± 45, 3753 ± 51 (both ash); 3892 ± 120 (oak)	-	-	-	-	Vitas, 2009	Vitas, A. (2010). Dendrochronological analysis of subfossil Fraxinus and Quercus wood excavated from the Kegai Mire in Lithuania. Baltic Forestry, 15, 41-47.
24	Reitzenhain	D	50.574518°	13.224307°	745	raised bog		2130-1930 B.C. (Bln-3852, tree species?), 1940-1770 B.C. (Bln-3853, tree species?),	-	-	-	Christl, 2004	Christl, A. (2004). Verschiebungen der Höhengrenzen der ur- und frühgeschichtlichen Besiedlung am Erzgebirge: Diskussion der Ursachen dargestellt am mittleren Bereich. Alteuropäische Forschungen N.F., 5. Langenweissbach: Beier & Beran.
25	Rieznyčia	LT	54.483333°	24.533333°	137	raised bog	1280 ± 40 (pine), 1330 ± 35 (pine), 1160 ± 35 (pine), 1880 ± 30 (pine), 1820 ± 25 (pine), 1965 ± 30 (pine)		-	-	-	Edvardsson et al., 2018	Edvardsson, J., Stančikaitė, M., Miras, Y., Corona, C., Gryguc, G., Gedminienė, L., Mažeika, J., & Stoffel, M. (2018). Late-Holocene vegetation dynamics in response to a changing climate and anthropogenic influences – Insights from stratigraphic records and subfossil trees from southeast Lithuania. Quaternary Science Reviews, 185, 91-101.
26	Auf dem Acker-Moor/Harz	DE	51.748584°	10.444912°	825	raised bog	-	c. 1500 B.C. (pine), c. 1830-2010 B.C. (spruce)	-	-	-	Willutzki, 1962	Willutzki, H. (1962). Zur Waldgeschichte und Vermoorung sowie über Rekurrenzflächen im Oberharz. Nova Acta Leopoldina N.F., 25, 4-52.
27	Torflohe	DE	49.616563°	12.549182°	495	raised bog	1575 ± 80 (H-421/368, pine), 1630 ± 85 (H-418/365, pine), 1590 ± 80 (H-419/364, pine)		-	-	-	Firbas et al., 1958	Firbas, F., Münnich, K. O., Wittke, W. (1958). C14-Datierungen zur Gliederung der nacheiszeitlichen Waldentwicklung und zum Alter von Rekurrenzflächen im Fichtelgebirge. Flora, 146, 512-520.
28	Havelländisches Luch	DE	52.692381°	12.791940°	26	fen mire	3632 ± 100 (oak), 3617 ± 100 (Bln-734, alder), 3570 ± 130 (oak), 3400 ± 90 (oak)		-	-	-	Mundel, 1995; Mundel, 2002	Mundel, G. (1995). Das Vorkommen von subfossilen Eichenresten im Havelländischen Luch in seiner Beziehung zur Niedermoorgenese. Telma, 25, 85-96. Mundel, G. (2002). Moorgeologisch-moorbodenkundliche Untersuchungen in Brandenburg. Archives of Agronomy and Soil Science, 48, 7-18.
29	Totes Moor	DE	52.511679°	9.387935°	38	raised bog	all pines: 2910 ± 45 (Hv-25844), 2920 ± 45 (Hv-25845), 3010 ± 45 (Hv-25859), 3015 ± 45 (Hv-25841), 3015 ± 45 (Hv-25843), 3040 ± 45 (Hv-25842), 3040 ± 50 (Hv-25850), 3070 ± 45 (Hv-25856), 3075 ± 45 (Hv-25849), 3115 ± 45 (Hv-25851), 3120 ± 45 (Hv-25858), 3120 ± 50 (Hv-25853), 3130 ± 45 (Hv-25847), 3140 ± 45 (Hv-25854), 3175 ± 45 (Hv-25857), 3190 ± 45 (Hv-25855), 3225 ± 45 (Hv-25848)	-	-	-	-	Achterberg et al., 2016	Achterberg, I. E. M., Frechen, M., Bauerochse, A., Eckstein, J., & Leuschner, H. H. (2016). The Göttingen tree-ring chronologies of peat-preserved oaks and pines from Northwest Germany. Zeitschrift der Deutschen Gesellschaft für Geowissenschaften, 168, 9-19.
30	Venner Moor	DE	52.431945°	8.177773°	45	raised bog	-	-	263 pine samples dating in between c. 2420 and 2080 B.C., 53 oak samples dating in between c. 2420 and 2170 B.C., 19 oak samples dating in between 280 and 190 B.C.	-	-	Delorme et al., 1983; Eckstein et al., 2010	Delorme, A., Leuschner, H. H., Tüxen, J., & Höfle, H.-C. (1983). Der subatlantische Torfeichen-Horizont "Sieden", erneut belegt im Toten Moor am Steinhuder Meer. Telma, 13, 33-51.
31	Borsumer Moor	DE	53.036864°	7.256699°	-1	raised bog	2130 ± 55 (Hv-10246), 2340 ± 50 (Hv-10476), 1925 ± 55 (Hv-10478), 1985 ± 60 (Hv-10477) - all oak (Delorme et al., 1981)	-	21 oak samples dating in between 310 and 100 B.C. (Delorme et al., 1983)	-	-	Delorme et al., 1981; Delorme et al., 1983	Delorme, A., Leuschner, H. H., Höfle, H.-C., & Tüxen, J. (1981). Über die Anwendung der Dendrochronologie in der Moorforschung am Beispiel subfossiler Eichenstämme aus niedersächsischen Mooren. Eiszeitalter & Gegenwart, 31, 135-158. Delorme, A., Leuschner, H.-H., Tüxen, J., & Höfle, H.-C. (1983). Der subatlantische Torfeichen-Horizont "Sieden", erneut belegt im Toten Moor am Steinhuder Meer. Telma 13, 33-51.
32	Hochmoor bei Sieden	DE	52.649830°	8.903787°	32	raised bog	-	-	16 oak samples dating in between 450 and 190 B.C. (Delorme et al., 1981)	-	-	Delorme et al., 1981	Delorme, A., Leuschner, H. H., Höfle, H.-C., & Tüxen, J. (1981). Über die Anwendung der Dendrochronologie in der Moorforschung am Beispiel subfossiler Eichenstämme aus niedersächsischen Mooren. Eiszeitalter & Gegenwart, 31, 135-158.
33	Jever	DE	53.558105°	7.898034°	-2	fen mire	-	-	14 oak samples dating in between c. 2500 and 1500 B.C.	-	-	Leuschner et al., 1986	Leuschner, H. H., Delorme, A., Tüxen, J., & Höfle, H.-C. (1986). Über Eichenwaldhorizonte in küstennahen Mooren Ostfrieslands. Telma, 16, 61-82.
34	Esens	DE	53.640594°	7.619343°	1	fen mire	-	-	c. 280 oak samples from 10 subsites dating in between 3300 and 250 B.C.	-	-	Leuschner et al., 1986	Leuschner, H. H., Delorme, A., Tüxen, J., & Höfle, H.-C. (1986). Über Eichenwaldhorizonte in küstennahen Mooren Ostfrieslands. Telma, 16, 61-82.
35	Tieleburg	DE	54.274051°	9.341625°	0	river valley	-	alder (n=1)? Indirect age: 872-691 A.D.	alder (n=1)? Indirect age: 1235-1255 A.D.	-	x	Biermann et al., 2018	Biermann, F., Dannath, Y., Kirleis, W., Magnussen, S., & Posselt, N. (2018). Die erste Tielenburg? Die mittelalterliche Wehranlage an der Tielenau bei Pahlen (Dithmarschen). Burgen und Schlösser, 59, 131-156.
36	Mittlerer Schalker Teich	DE	51.839036°	10.391769°	530	stream valley (former pond)	-	-	-	before 1670 A.D. (spruce)	x	K. Malek/Goslar, pers. comm.	-
37	Dambecker See	DE	53.443969°	12.944291°	63	lake	-	-	-	15th/16th century A.D. (pine)	-	Kaiser & Zimmermann, 1994; Küster & Kaiser, 2010	Kaiser, K., & Zimmermann, A. (1994). Physisch-geographische Untersuchungen an Mooren und Seen im Havelquellgebiet (Müritz-Nationalpark). Teil 1: Allgemeine physisch-geographische Aspekte, Moorstratigraphie, jüngere Landschaftsgeschichte und aktuelle Raumnutzung. Berichte der Akademie für Naturschutz und Landschaftspflege Laufen/Salzach (Bayern), 22, 147-173. Küster, M., & Kaiser, K. (2010). Historische und aktuelle Gewässerentwicklung im Havel-Quellgebiet (Mecklenburg-Vorpommern). In K. Kaiser, J. Libra, B. Merz, O. Bens, & R. F. Hüttl (Eds.), Aktuelle Probleme im Wasserhaushalt von Nordostdeutschland: Trends, Ursachen, Lösungen. Scientific Technical Report, STR10/10. (pp. 116-124). Potsdam: Deutsches GeoForschungsZentrum.
38	Užpelkių Tyrelis	LT	56.082157°	21.832811°	153	raised bog	all pines (n=20): 2080 ± 70, 1980 ± 40, 2050 ± 50, 1950 ± 60, 1764 ± 80, 1680 ± 50, 1610 ± 50, 1540 ± 60, 1210 ± 40, 1295 ± 40, 1450 ± 70, 1040 ± 40, 860 ± 80, 830 ± 80, 995 ± 40, 900 ± 40, 450 ± 40, 760 ± 40, 650 ± 70, 130 ± 40 (no lab numbers available; all data from Estonian Institute of Zoology abd Botany/Tartu)	-	ca. 140 pine samples dating ca. 200 B.C.-2000 A.D.	-	-	Pukienë, 2001	Pukienë, R. (2001). Natural changes in bog vegetation reconstructed by sub-fossil tree remnant analysis. Biologija, 2, 111-113.
39	Hora Svatého Šebestiána	CZ	50.526844°	13.226678°	836	raised bog	several pine and spruce trunks, dated at around 3000 B.P.	-	-	-	-	V. Treml/Prague, pers. comm.	-
40	Velký Pařezitý rybník	CZ	49.228856°	15.375780°	675	dammed stream valley (pond)	-	-	-	before 1565 A.D. (stumps of a yet unspecified tree species)	x	L. Petr/Brno, pers. comm.	-
41	Ralswieck	DE	54.469935°	13.447815°	1	shoreline of coastal lagoon (Baltic Sea)	-	-	-	around 775 A.D. (roots of a yet unspecified tree species)	x	Herrmann, 1997	Herrmann, J. (1997). Ralswiek auf Rügen. Die slawisch-wikingischen Siedlungen und deren Hinterland. Teil I – Die Hauptsiedlung. Beiträge zur Ur- und Frühgeschichte Mecklenburg-Vorpommerns, 32. Lübstorf: Archäologisches Landesmuseum Mecklenburg-Vorpommern.
42	Boner Hauptteich	DE	51.970303°	12.169028°	72	dammed stream valley (pond)	-	-	-	before 1757 A.D. (stumps of a yet unspecified tree species)	x	S. Lachmann/Zerbst, pers. comm.	-

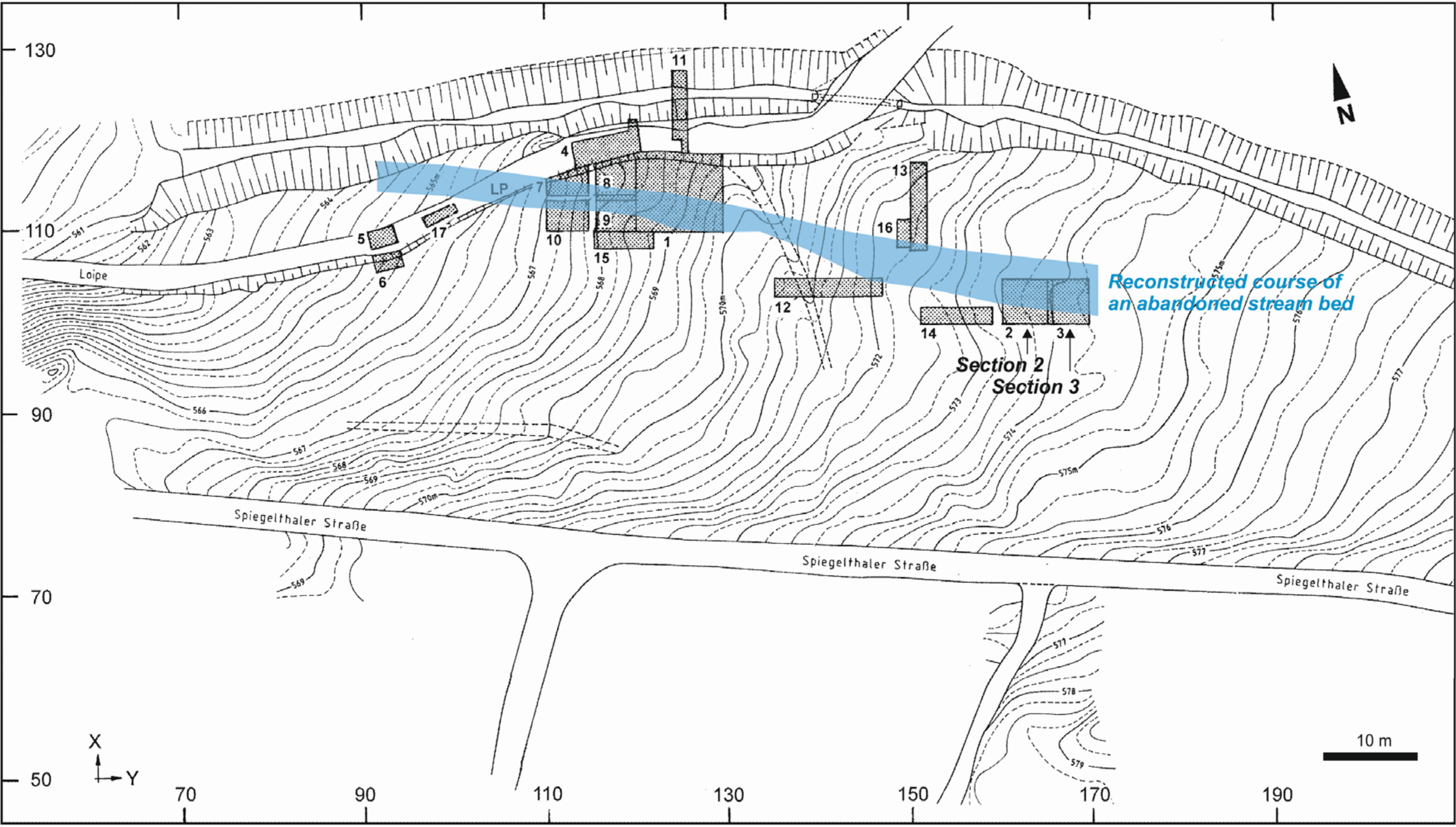
Supplementary Table 2: Johanneser Kurhaus site. Determination of botanical macro-remains from two samples of the wood-bearing soil horizon at the bottom (feature 580; Andrae, 2003, adapted).

Sample ID	2516/1	2516/2
Sample weight (g)	3070	4790
Woods	(n)	(n)
Picea abies , needle	12	10
Picea abies , needle part	96	178
Picea abies , seed	3	-
cf *Fagus sylvatica* , bud	-	1
Betula spec., fruit	-	1
Corylus avellana , fruit	-	2
Sambucus nigra , seed	2	3
Rubus idaeus , seed	12	12
Rubus idaeus , charred seed	1	3
Rubus spec., seed	1	3
Dwarf-shrubs		
Vaccinium myrtillus	5	6
Species of deciduous forests		
Corydalis spec., seed	1	-
Fragaria spec., seed	-	4
Ajuga reptans , fruit	2	1
Carex muricata agg., fruit	1	-
Species of spring-fed swamps and brook sides		
Chrysosplenium spec., seed	2	1
Scirpus sylvaticus , fruit	20	59
Glyceria spec., fruit	1	1
Typha spec., fruit	1	-
Juncus spec., seed	9	18
Carex remota / C. leporina , fruit	2	5
Mentha arvensis / M. aquatica , fruit	-	1
cf. *Lythrum salicaria* , seed	1	1
Perennial ruderal species		
Urtica dioica , fruit	-	5
Rumex obtusifolius , fruit	2	6
Rumex obtusifolius / R. crispus , fruit	4	17
Poa trivialis / P. pratensis , fruit	4	1
Galeopsis tetrahit / G. speciosa , fruit	2	-
cf. *Artemisia vulgaris* , fruit	1	-
Cirsium vulgare / C. oleraceum , fruit	3	-
Cirsium spec., fruit	-	1
Picris hieracioides , fruit	1	2
Cichorium spec., fruit	1	-
Achillea millefolium , fruit	-	1
Step-resistant species		
Plantago major , seed	1	4
Polygonum aviculare , fruit	2	3
Prunella vulgaris , fruit	2	2
Poa annua , fruit	1	7
Ranunculus repens , fruit	-	4
Polygonum hydropiper , fruit	1	-
Field and garden weeds		
Agrostemma githago , seed	-	1
Anthemis arvensis , fruit	2	4
Papaver argemone , seed	3	1
Anagallis arvensis , seed	1	1
Fallopia convolvulus , fruit	2	-
Scleranthus annuus , fruit	-	2
Valeranella dentata , fruit	-	1
Spergula arvensis , seed	-	2
Chenopodium album , fruit	-	1
Stellaria media , seed	2	2
Polygonum lapathifolium , fruit	1	-
Polygonum lapathifolium / P. persicaria , fruit	-	1
Rumex acetosella , fruit	2	-
Other wild species		
Agrostis spec., fruit	57	60
Hypericum tetraptera / H. maculatum, seed	22	25
Stellaria graminea, seed	2	3
Stellaria uliginosa / Cerastium spec., seed	5	5
Carex vulpina / C. muricata agg., fruit	1	1
Hieracium spec., fruit	1	2
Carex spec., fruit	2	-
Rumex spec. / Polygonum spec., fruit	1	2
Rumex spec., perigon	2	1
Luzula spec., seed	-	2
Viola spec., seed	-	1
Umbelliferae, fruit	1	1
Gramineae, fruit	22	37
Compositae, fruit	1	3
Cultivated species		
Secale cereale, fruit	-	1
cf. Linum usitatissimum, seed	-	1
Total number	327	524

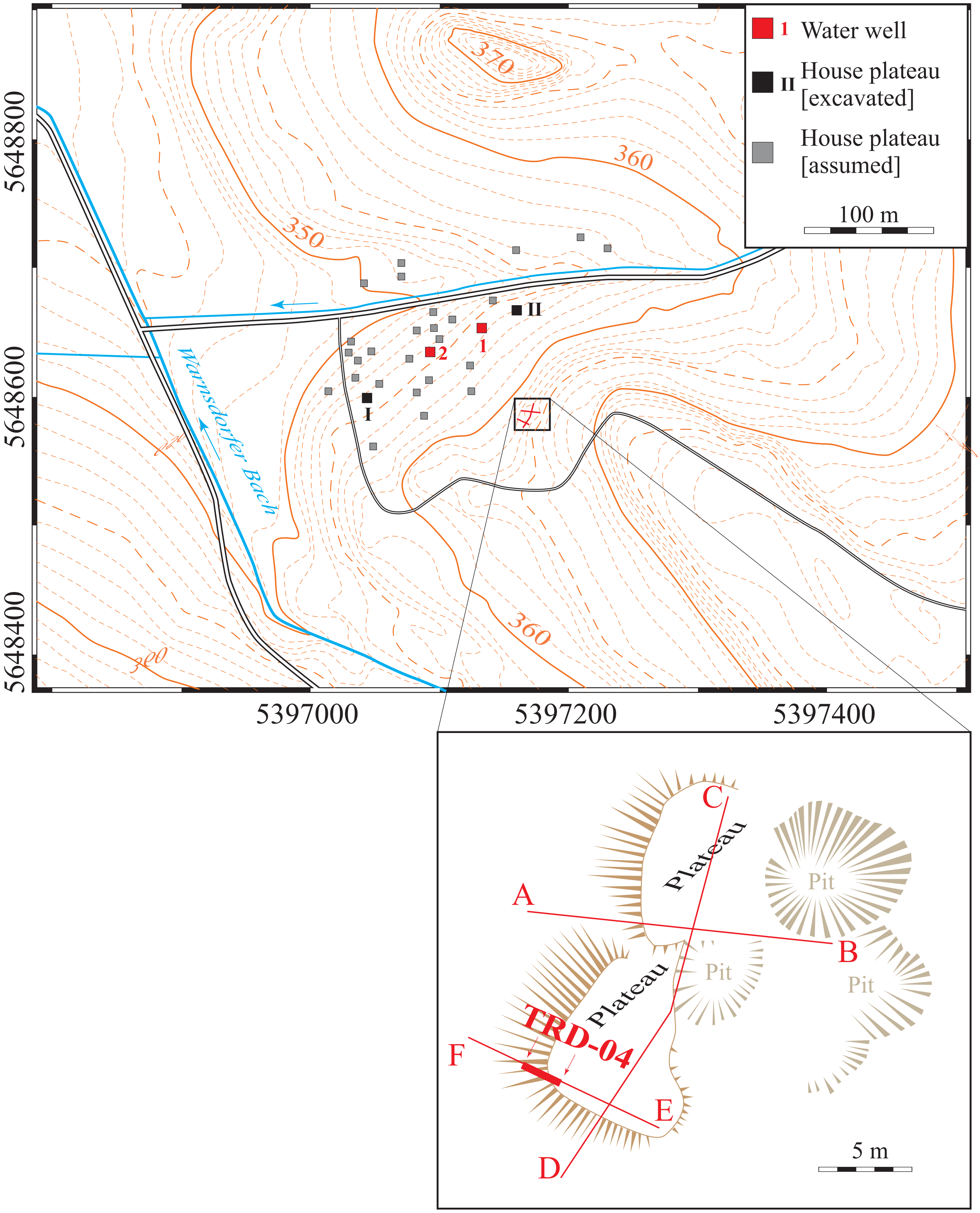
Supplementary Table 3: Johanneser Kurhaus site. Botanical analysis and radiocarbon ages of charcoal spectra from charcoal kilns of the "Winterhalbe" sub-site (Hillebrecht, 1989; Alper, 2003, adapted).

	Number	%
Grube (kiln) 1 (no age available)		
Fagus sylvatica	9	75
Deciduous wood, undifferentiated	3	25
Grube (kiln) 12 (no age available)		
Fagus sylvatica	52	83.4
Acer sp.	5	8.1
Quercus sp.	1	1.6
Betula spec.	1	1.6
Deciduous wood, undifferentiated	3	4.8
Grube (kiln) 13 (no age available)		
Salix sp.	11	23.5
Betula spec.	8	17
Corylus avellana	4	8.5
Alnus spec.	2	4.3
Acer sp.	2	4.3
Fagus sylvatica	1	2.1
Sorbus aucuparia	1	2.1
Betula / Populus / Salix	16	34
Picea abies	1	2.1
Bark, indeterminated	1	2.1
Grube (kiln) 14, A.D. 646-1147 (1170 ± 115 yr B.P.)		
Fagus sylvatica	39	97.5
Betula spec.	1	2.5
Grube (kiln) 15, A.D. 591-969 (1290 ± 95 yr B.P.)		
Fagus sylvatica	28	93
Acer sp.	2	6.7
Grube (kiln) 17/1, A.D. 723-1024 (1125 ± 65 yr B.P.)		
Fagus sylvatica	45	58.4
Acer sp.	27	35.1
Betula spec.	4	5.2
Bark, indeterminated	1	1.3
Grube (kiln) 17/2, A.D. 776-1151 (1065 ± 65 yr B.P.)		
Fagus sylvatica	49	66.2
Acer sp.	19	25.7
Betula spec.	3	4.1
Corylus avellana	1	1.4
Alnus spec.	1	1.4
Picea abies	1	1.4
Grube (kiln) 19, A.D. 660-1166 (1110 ± 130 yr B.P.)		
Fagus sylvatica	15	62.5
Acer sp.	6	25
Picea abies	2	8.3
Populus spec.	1	4.2

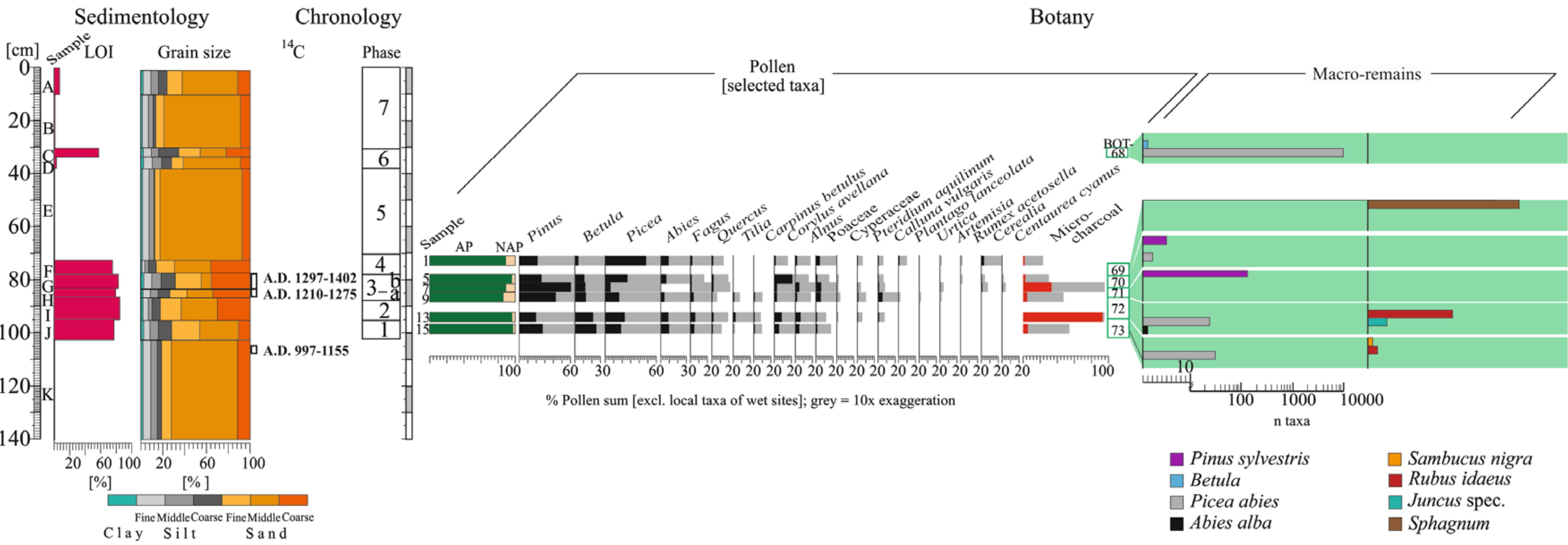
Supplemental Figure 1: Johanneser Kurhaus site. Map of the excavation features (Alper, 2003, adapted).



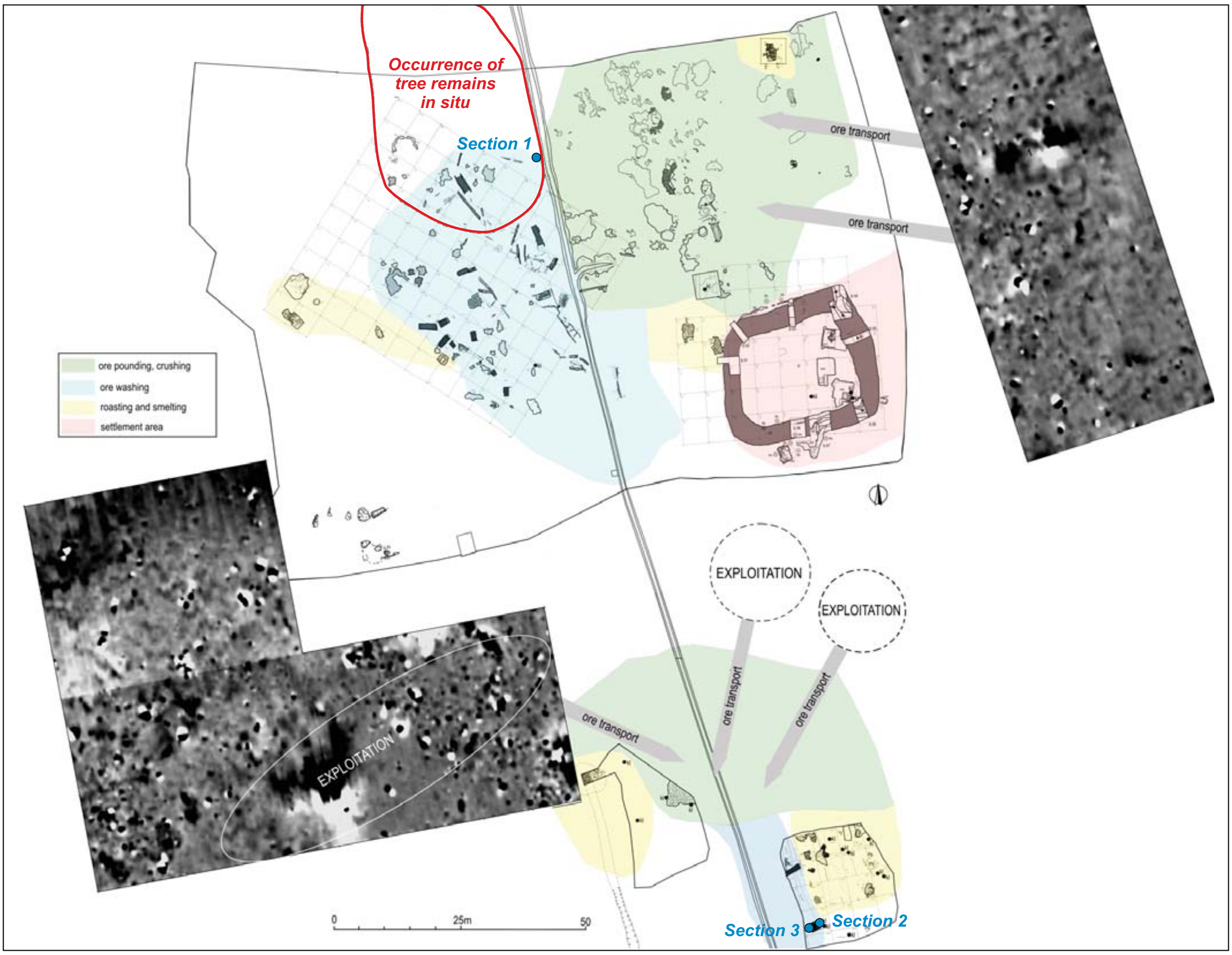
Supplemental Figure 2: Warnsdorf site. Map of the excavation features (Spehr, 2002, adapted).



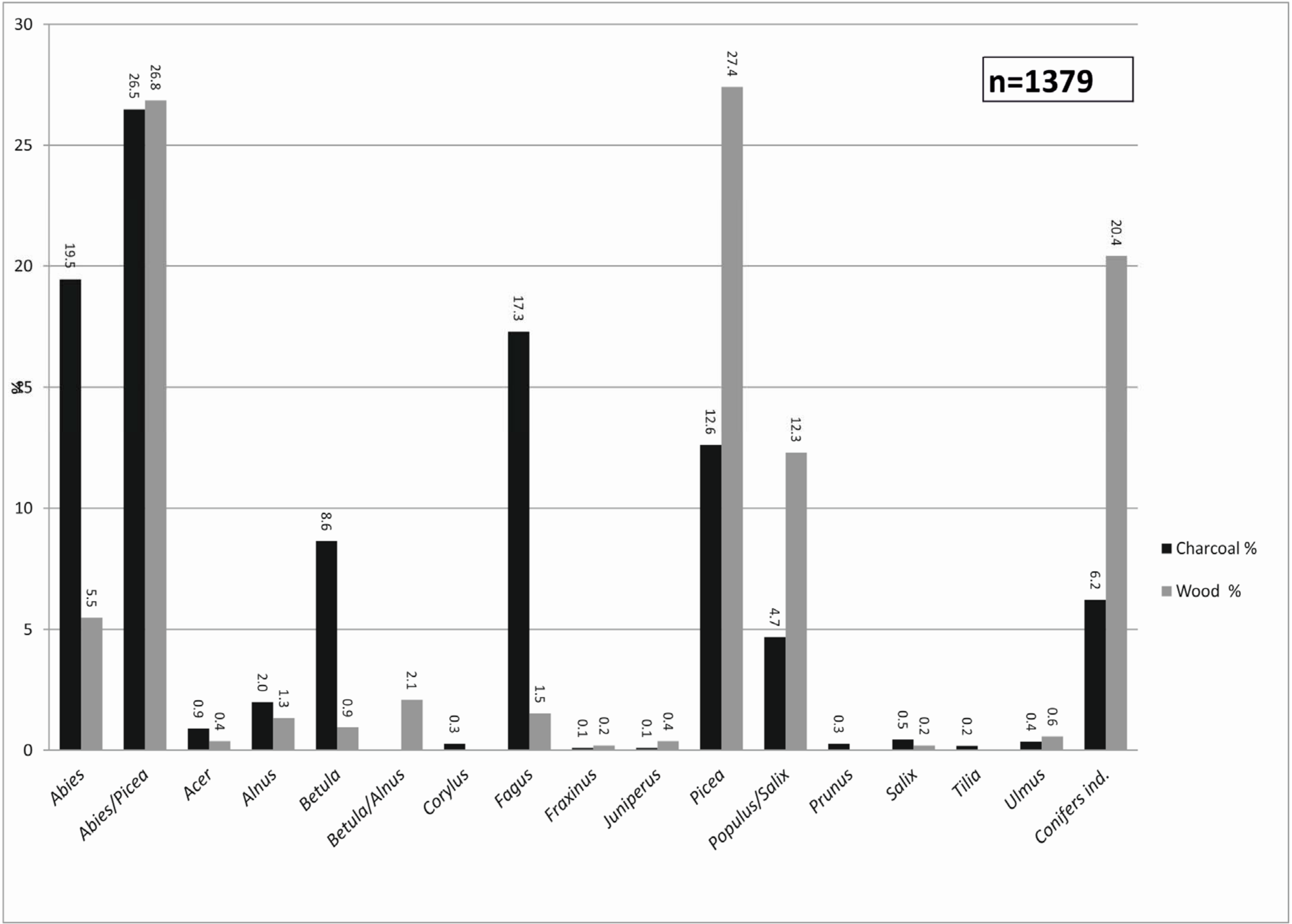
Supplemental Figure 3: Warnsdorf site. Stratigraphy, analytical results and zonation/phases of section TRD-04.



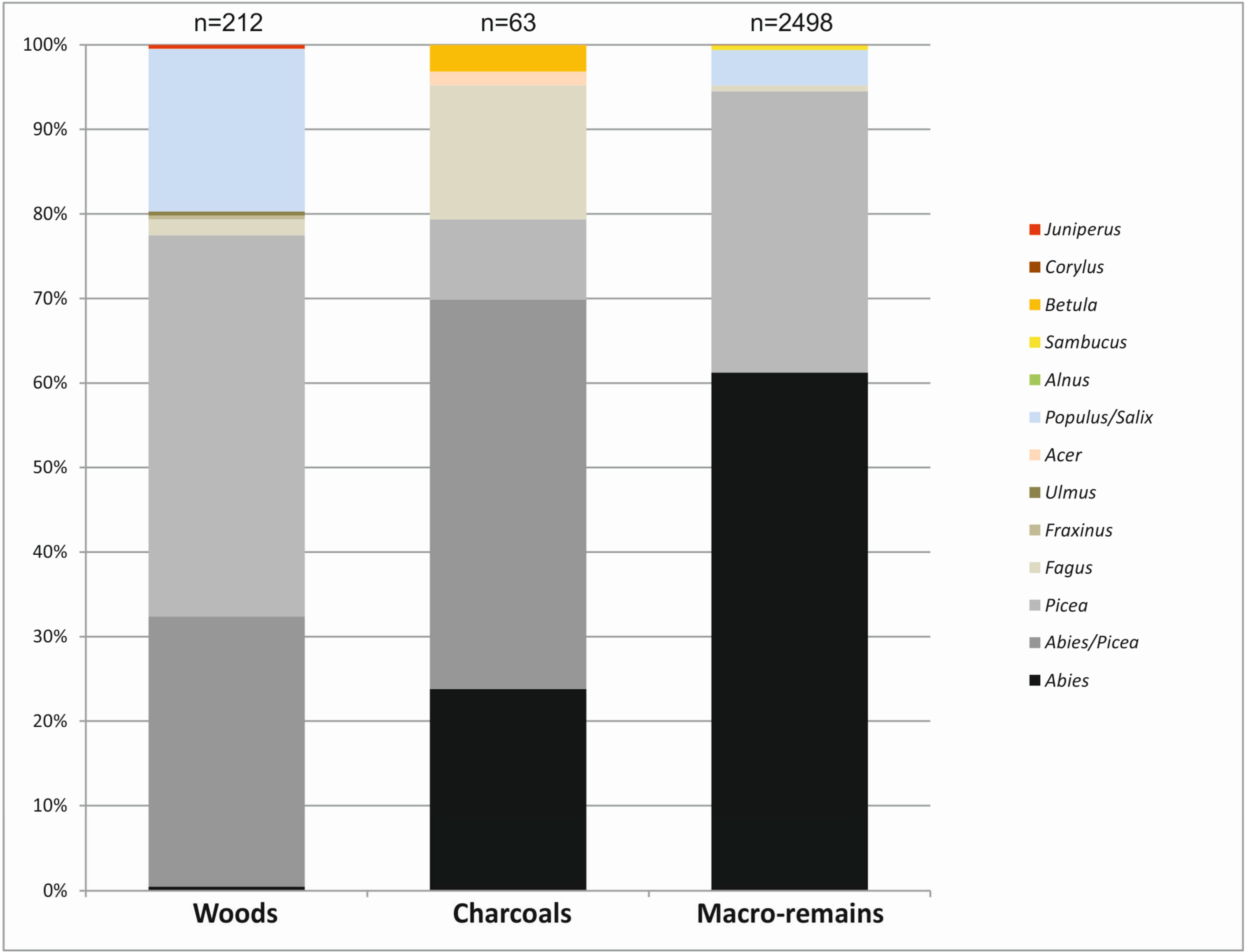
Supplemental Figure 4: Cvilínek site. Map of the excavation features (Hrubý et al. 2012, adapted).



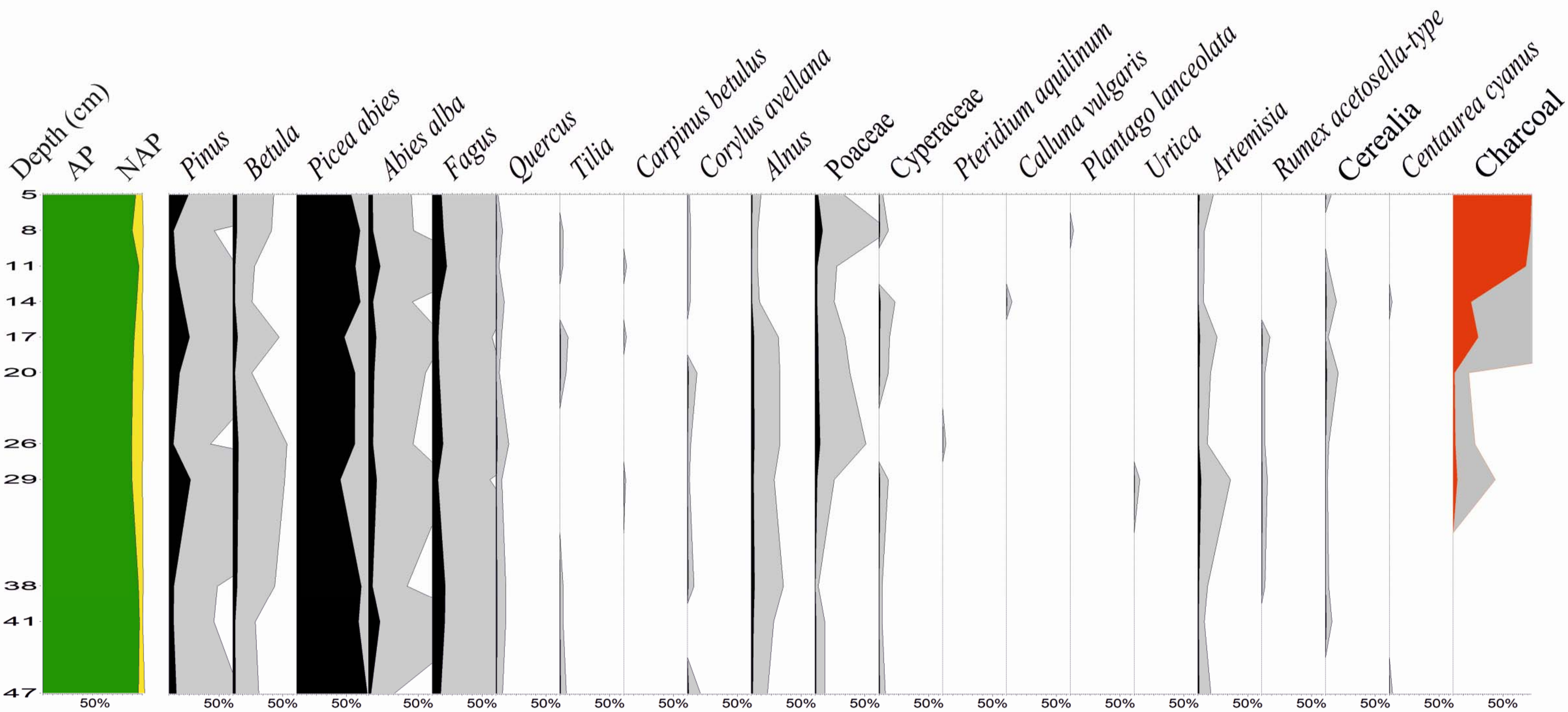
Supplemental Figure 5: Cvilínek site. Analysis of uncharred wood and charcoal from an organic layer of section 1.



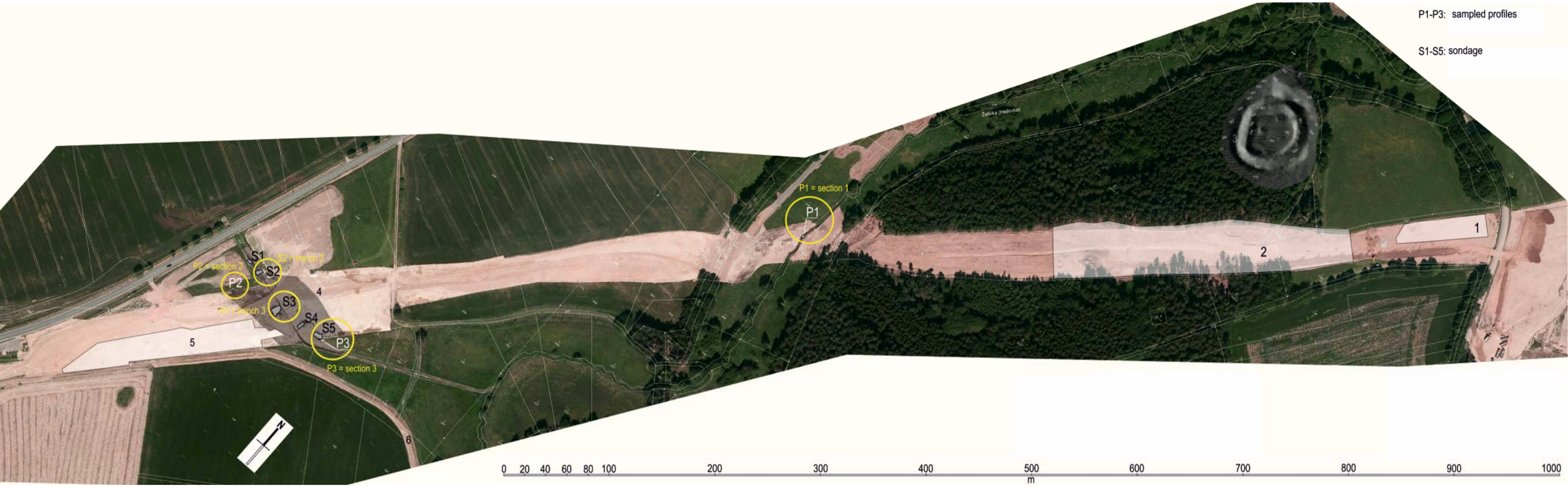
Supplemental Figure 6: Cvilínek site. Analysis of uncharred wood, macro-remains and charcoal from an organic sediment layer of section 3 (Hrubý et al., 2014, adapted).



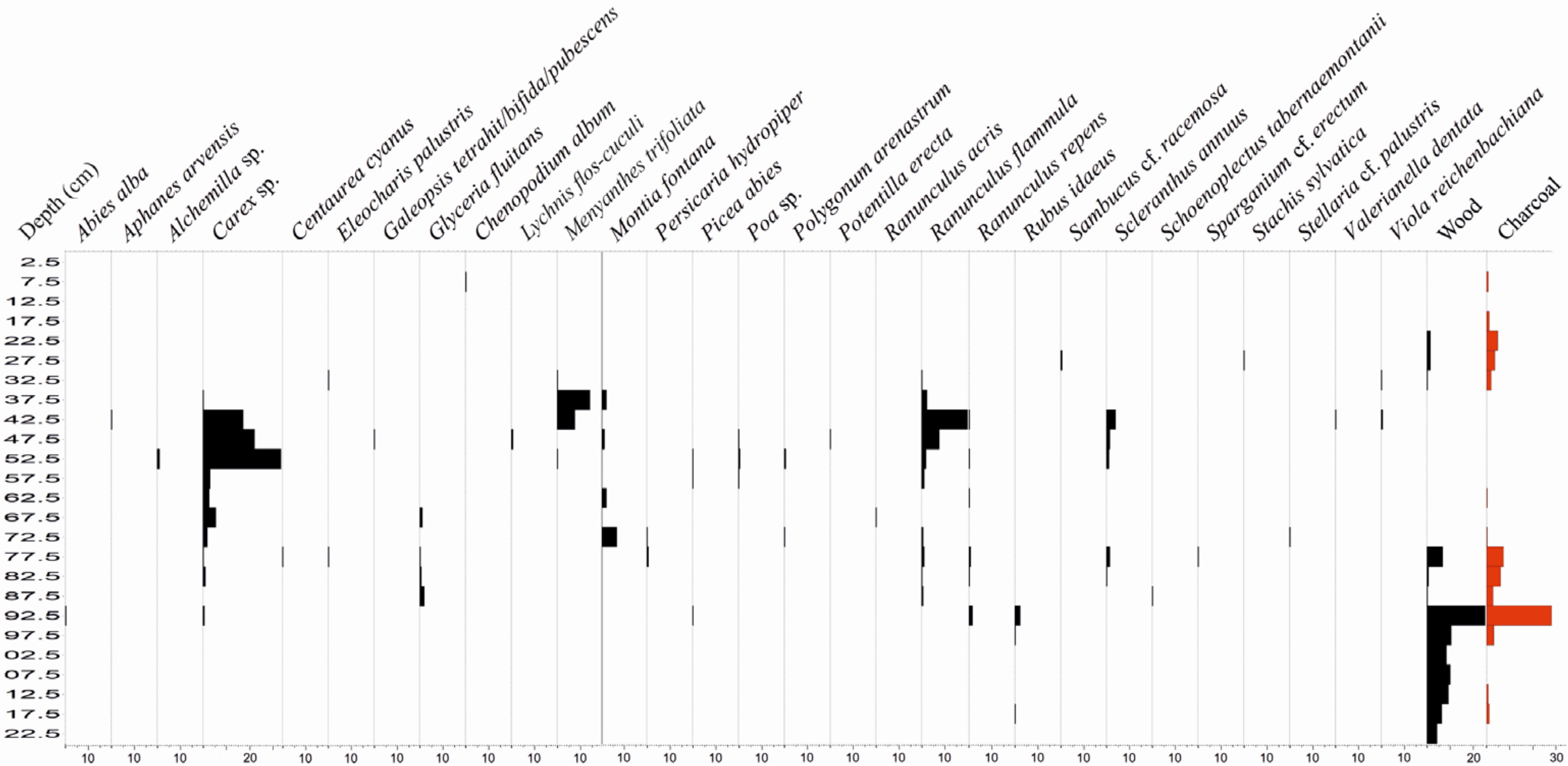
Supplemental Figure 7: Cvilínek site. Pollen analysis from an organic sediment layer of section 3 (Hrubý et al., 2012, adapted).



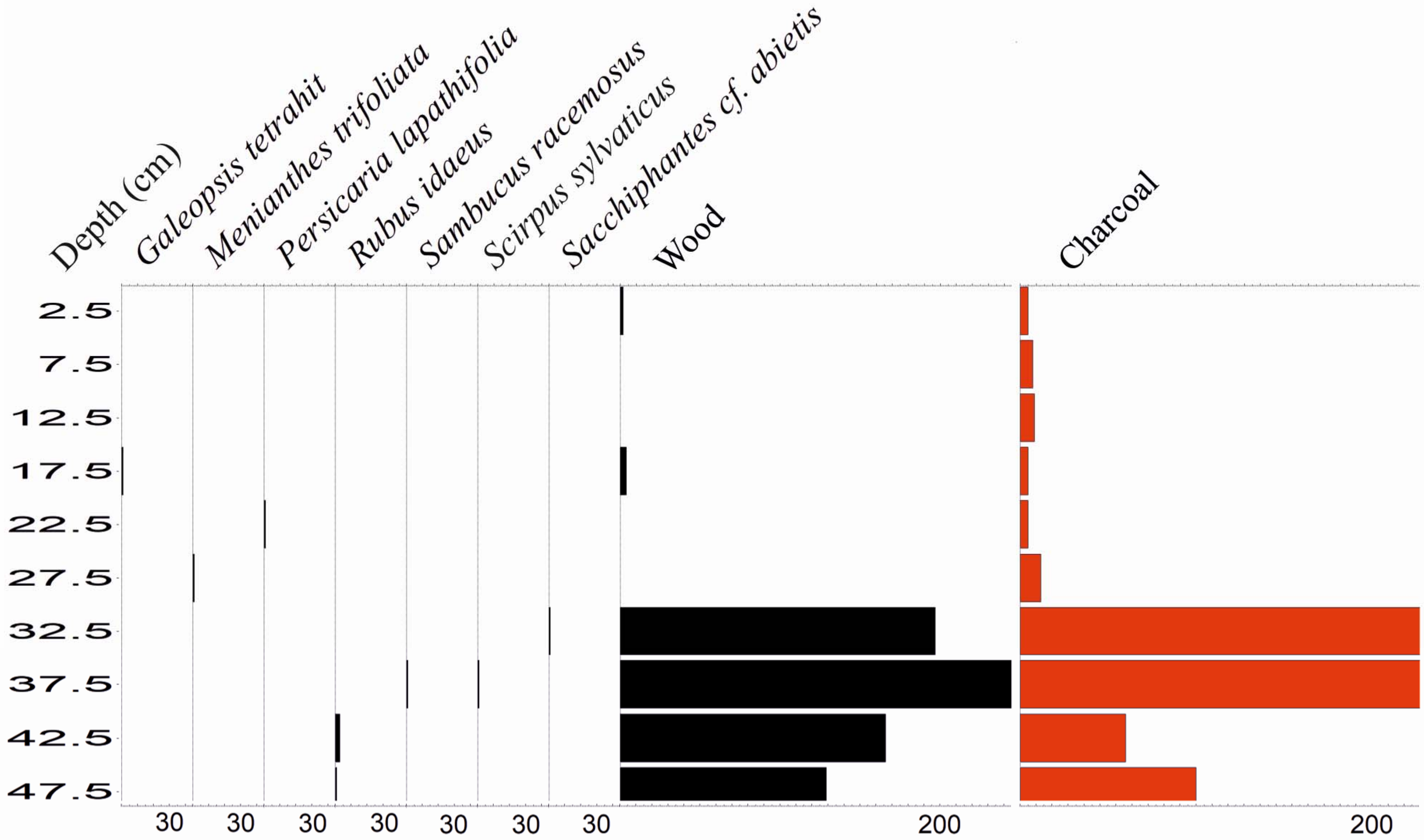
Supplemental Figure 8: Ústrašín site. Map of the excavation features (Hrubý & Těsnohlídek, 2016).



Supplemental Figure 9: Ústrašín site. Analysis of macro-remains and charcoal (unspecified) of section 2 (units of the ordinates are numbers). Whereas woody taxa given with species names (e.g., *Abies alba*) refer to seeds of specific taxa, counts in the "Wood" column on the right refer to pieces of unspecified wood including trees and shrubs.



Supplemental Figure 10: Ústrašín site. Analysis of uncharred wood (unspecified), macro-remains and charcoal (unspecified) of section 3.



Supplemental Fig. 11: Ústrašín site. Pollen analysis of section 3.