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ORIGINAL ARTICLE

Late-Holocene land use changes caused by exploitation in the mining region of Kitzbühel (Tyrol, Austria)

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Abstract This multi proxy-study attempts to illuminate land use changes resulting from ore exploitation. The rationale is to use different types of proxy data to evaluate interactions between human activities and the environment in order to gain deeper insight into the environmental impact of prehistoric mining activities. This is approached through palynological and supplementary geochemical analyses of a peat core from a mire, situated in the immediate vicinity of a former ore exploitation area in the Kitzbühel (Tyrol, Austria) mining district, together with radiocarbon dating, stratigraphic analysis and loss on ignition. The results indicate the first clear human interference in the natural vegetation at approximately 2000 cal BC. During the Late Bronze Age (c. 1400–950 cal BC), palynologically proven changes of the vegetation were found, including two time periods with forest clearing where values of anthropogenic pollen indicators increased synchronously with rising heavy metal values. Through geochemical analysis a connection to mining activities could be made. Subsequently this period is synchronous with dated mining activities. During the Late Bronze Age and the Iron Age (c. 950–50 cal BC), humans are still present in the region but to a lesser degree. An intense anthropogenic phase follows during the Late Iron Age and Roman Times (c. 50 cal BC–cal AD 200) and is indicated by pasture and tillage. In the following period anthropogenic impact decreases, then enhanced human activities are visible through rising pasture, settlement and cultural indicators from the second half of the Early Middle Ages (since c. cal AD 900). From this point on, eight more clearing episodes up to the 19th century could be detected palynologically. Geochemical analyses and historical sources document a second mining phase during Early Modern Times (15th–16th centuries). This study shows that the combination of palynological, geochemical and archaeological data enables a better understanding of the impact of mining on the environment in the Kitzbühel mining district and is thus applicable to other comparable mining districts.

Keywords Prehistory · Vegetation history · Pollen analysis · Geochemical analysis · Eastern Alps · Bronze age

Introduction

The onset and spread of metallurgy in prehistoric Europe resulted in significant social, cultural and ecological changes. Land use changes such as increased woodland use and mixed farming to support the prehistoric miners impacted the natural vegetation considerably. Moreover, mining activities require energy. In prehistoric times wood and charcoal were the main energy sources for several metallurgical activities, e.g. fire-setting, smelting and casting (Stöllner 2003). In the vicinity of the mines, the trees from the surrounding woodlands were used for timbering and construction of settlements as well as the production of tools for tillage and livestock farming. Over time, the extensive lumbering resulted in the devastation of the natural vegetation cover.

Furthermore, environmental pollution through contamination by heavy metals began with the onset of metallurgy. During the course of ore extraction, dressing and smelting, volatile heavy metals are emitted into the

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atmosphere and subsequently settle through gravity and rain on peat surfaces; they are then archived in the peat deposits. This heavy metal pollution is still measurable today (Livett 1988; Shotyk et al. 1998) and is essential to a better understanding of vegetation and land use changes resulting from mining activities. Moreover, combining these paleo-environmental data with archaeological data enables conclusions about the temporal and spatial development of a mining district. Given that more heavy metals are released in the environment during intensive phases of mining than regression phases, heavy-metal depth gradients in peat deposits may serve as stratigraphic (time)-markers (Matschullat et al. 1997).

In this paper, we present a multi proxy study of a former Alpine mining area that combines pollen and micro-charcoal analyses with heavy metal analyses to reveal the transformation of a natural landscape into a mining landscape. Geochemical analyses conducted during recent decades have revealed that peat and lake deposits archive historic heavy metal pollution (Bränvall et al. 1997; Martínez-Cortizas et al. 1997; Renberg et al. 2001; Shotyk et al. 2002; De Vleeschouwer et al. 2007, 2010). Studies of the impact of mining on the heavy metals deposited at regional and local scales have been done by Bränvall et al. (1999), Mighall et al. (2002, 2009), Le Roux et al. (2004) and Cloy et al. (2005). Other, similar geochemical studies have also been successfully conducted in different mining districts (Monna et al. 2004; Baron et al. 2005; Jouffroy-Bapicot et al. 2007; Breitenlechner et al. 2010). The main objective of this study is to reconstruct the former vegetation and the changes it has undergone since prehistory and to evaluate the observed land use changes in terms of the different human actions related to mining, particularly ore exploitation. The results should reveal the patterns of settlement of the area and clarify whether the colonisation of the region was triggered by mining activities, or whether an agricultural population was resident with which the miners were integrated.

Study area

The Kitzbühel mining district is located in eastern North Tyrol between the mining areas of Schwaz and Mitterberg in Salzburg. The prominent copper and silver ore deposits stretch from St. Johann to the Pass Thurn in the Eastern Alps (Fig. 1) and have been exploited since the Bronze Age. The mining district is organised into several activity centres according to the different mining processes: ore exploitation, processing and smelting. At the end of the Middle Bronze Age and the beginning of the Late Bronze Age, as well as from the middle of the 18th century AD until 1908 (Preuschen and Pittioni 1937), one important ore extraction area was the Kelchalm. Here, the strike length of the prehistoric ore processing heaps extends approximately 450 m and approximately 1,300 m for the historic mining activities. More than 50 ore processing heaps have been documented at the Kelchalm mining site (Preuschen and Pittioni 1937).

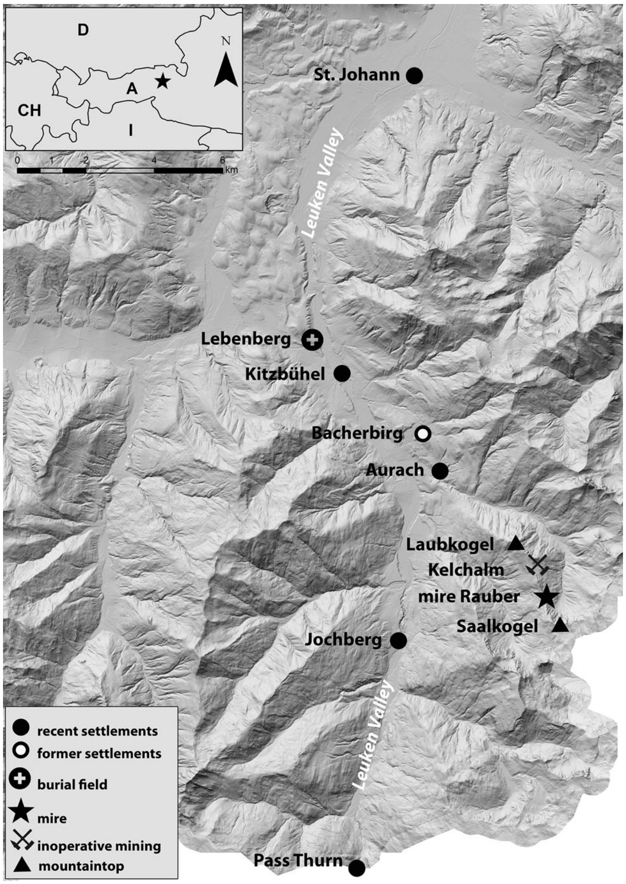


Fig. 1 The area of investigation is located between the townships of Kitzbühel and Jochberg. Near Kitzbühel, the Bronze Age burial ground Lebenberg was excavated. The archaeological site "Bacherbirg" was frequented during the Late Bronze and Early Iron Age. Since the Bronze Age the Kelchalm has served as one of the largest ore exploitation areas in this region. Nearby, the Rauber mire is where the sediment core was taken (basic map: LiDAR Land Tirol 2009)

The Kelchalm mining district belongs to the township of Aurach and is the area of investigation of this study. The site is located on a 3 km long ridge between Laubkogel (1,760 m a.s.l.) and Saalkogel (2,006 m a.s.l.) in the Kitzbühel Alps. Approximately 1 km south of the Kelchalm, in the immediate vicinity of the mine, a 1 ha "saddle mire" (Scheuchzerio-Caricetea fuscae) called "Rauber" is located at 1,762 m a.s.l. (47°23′6.26″N, 12°28′34.19″E; Fig. 1). From its centre a 1.6 m deep peat core was extracted for the pollen and heavy metal analyses.

The potential vegetation on the Kelchalm is high-mountain and subalpine spruce forest (Piceetum) but the forest cover is currently low due to human impact. Alpine pastures and meadows (Poo alpinae-Trisetetalia) intermixed with dwarf shrub heathland (Rhododendro-Vaccinetalia) dominate the landscape. There are extensive pastures that are neither fertilised nor watered (Meisel et al. 1984). Climatically the study area is temperate with cool temperatures in the mountains and a distinct cold season with large amounts of snow. The average annual temperature is low (6.8 °C). Between 1,200 and 1,500 m a.s.l. the average temperature is only 4 °C (meteorological station of Kitzbühel, 763 m a.s.l.). Annual precipitation is over 1,000 mm with the highest amounts falling during the warmest months of the main growing season (Institut für Geographie, Universität Innsbruck 2011). Geologically the study area is part of the northern greywacke zone, which, in Tyrol, is only fully developed in the Kitzbühel Alps (Ampferer 1936; Geologische Bundesanstalt 2003; von Klebelsberg 1942). The ore of the Kelchalm mainly consists of chalcopyrite, and the gangue minerals are quartz, dolomite and ankerite. The chalcopyrite deposits of the east alpine greywacke zone are characterised by comparatively low amounts of trace elements (Lutz et al. 2009).

Archaeological and historical background

In addition to Schwaz the Kitzbühel area was the second most important mining region in Tyrol with more than 50 identified ore processing heaps. The next prominent mining district is located on the Mitterberg (Salzburg, Austria). Nevertheless the Kitzbühel district constitutes a missing link in archaeological research, especially regarding the temporal placement of the mining activities and the duration of the initiation, intensification and regression phases, which remain undetermined and where palaeoecological and geochemical results can provide evidence.

Since the middle of the 19th century AD the prehistoric copper mining in the Kitzbühel region has been studied by archaeologists (Much 1878, 1879; Posepny 1880). From 1930 to 1960, Preuschen and Pittioni (1937) conducted archaeological surveys and excavations on the Kelchalm. These studies document numerous, above-ground Bronze Age mining relicts, which illustrate the importance of this ore deposit during the Bronze Age. More recently Goldenberg (2004), Klaunzer (2008), Stöllner (2009) and Koch Waldner (2013) examined the mining district of Kitzbühel to gain a better understanding of its spatial structure and insight into the production and the technologies used. However, findings of prehistoric settlements are rare in the local valley bottoms and have been insufficiently explored in the investigation area. The Late Bronze Age/Early Iron Age settlement of "Bacherbirg", which is next to Jochberg (Fig. 1) is the only one that has been discovered to date (Krauß 1997, 1998, 1999, 2001, 2002, 2003, 2004, 2005, 2006). Some archaeological surveys of this site have produced initial results but have not enabled a precise assessment of whether this was a fortification or a place of sacrifice. Recently Scheiber (2011) revaluated the excavation findings and features of the Urnfield burial ground "Lebenberg" (Fig. 1), which was discovered in the 1960s (Eibner et al. 1966). The more recent history of the Kitzbühel mining district has been investigated since the early 19th century, and aside from Schwaz, Kitzbühel was the most important mining centre in North Tyrol during the 15th and 16th centuries (Mutschlechner 1967, 1968).

Methods

Field methods and coring

Prospecting for mires that were adequate for study was conducted with an avalanche probe to determine the thickness of the undisturbed bedding of the peat deposit. The mire was selected because of the immediate vicinity to the exploitation site Kelchalm and because this c. 1 ha sized mire collects a local and extra-local pollen signal (Delcourt and Delcourt 1987). The 1.6-m deep sediment core was extracted as a monolith from the deepest point of the mire with a PVC tube (12 cm diameter) in the summer of 2009. The core was stored in a cold room at a constant temperature of 6 °C until subsampling. For analysis the core was divided into 1 cm slices and frozen until the chemical treatment for pollen analyses was conducted in the laboratory.

Sedimentology and loss on ignition (LOI)

The identification and classification of the deposits follow Troels-Smith (1955). The determination of the percentage by weight of organic and minerogenic matter (silicate, carbonate) in the peat core is based on standard LOI analyses specified in Heiri et al. (2001). The samples were first dried at 105 °C for 24 h, heated for 4 h at 550 °C (which provided the organic content) and subsequently heated again for 2 h at 950 °C (which provided the carbonate content). The residual was the silicate content.

Radiocarbon dating

AMS-radiocarbon dating (accelerator mass spectrometry-radiocarbon dating) is needed to create a detailed chronology of the pollen and geochemical sequences.

After an exploratory pollen analysis at every 10 cm, ten 2–5 g fresh weight substrate samples (Table 3; Fig. 2) were taken. The bio- and lithostratigraphy of the core was assessed to avoid sampling disturbed strata, and the samples were subsequently lyophilised for 24 h. The AMS-

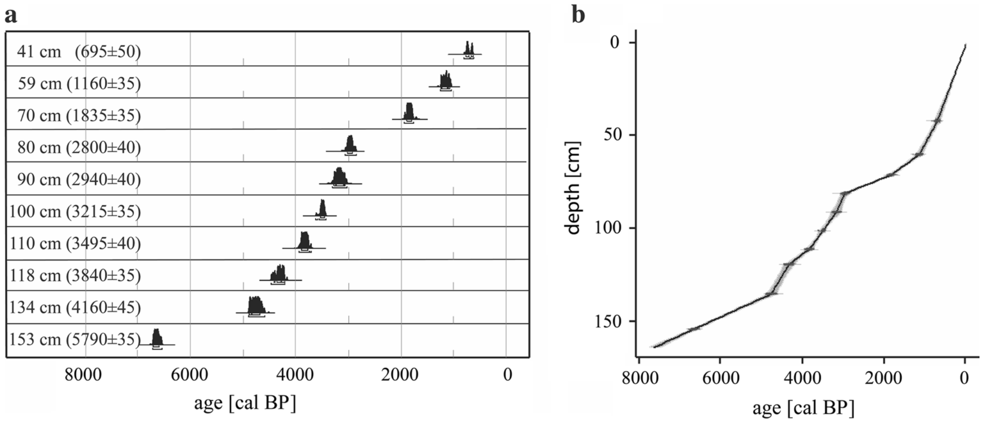


Fig. 2 **a** Multi-plot of the probability distribution for the ten calibrated radiocarbon dates of the Rauber site. Samples are displayed in stratigraphic order (graph from OxCAL). **b** Age-depth model of the sediment column (0–163 cm) extracted from the Rauber mire

dating was conducted at the VERA-Laboratory of Isotope Research of the Faculty of Physics, University of Vienna.

The calendar year time-scale was generated by R i386 2.15.2 (R Development Core Team 2012) by means of the “clam” package (Blaauw 2010) using the IntCal09 calibration curve (Reimer et al. 2009). The calculations were conducted at a 95 % confidence level with 1,000 iterations. The calendar age point estimates for depths were based on weighted averages of all age-depth curves with linear interpolation between the dated levels. The depths below the lowermost radiocarbon date were linearly extrapolated by “clam” referring to the two lowermost dated depths. The calendar scale was cal BP at a resolution of 1 year, and the ages were calculated every 1 cm from 0 to 163 cm. For better visibility a Bayesian analysis multi-plot was made with the OxCal v3.10 calibration program (Bronk Ramsey 1995; Fig. 2). The calibrated age values correspond to a 2σ-confidence interval. This chronology was used for drawing linear time pollen diagrams and for all temporal indicators (converted to cal BC/AD) presented in the text.

Chemical digestion and analysis of pollen, spores, NPPs and micro-charcoal

Changes in the vegetation and land use over time are reconstructed by pollen analyses. Prehistoric human settlement activities and related land use changes are recorded by so-called “Landnam-phases” (Iversen 1941, 1956) that are reflected in changes in the arboreal pollen (AP) values and the occurrence of anthropogenic indicator species (Behre 1981).

For a preliminary exploratory analysis, standardised subsamples with a constant volume of 1 cm^3 were taken at a distance of 10 cm. To achieve greater time resolution, the core was then sampled in more detail (sample size 1 cm^3): in the section starting from the surface to 50 cm in depth and from 90 to 112 cm, every 2 cm was investigated, in the 50–90 cm section and from 112 to 133 cm, every 1 cm, and between 113 and 163 cm every 3 cm. The chemical digestion of the samples for the palynological analyses follows the standardised method (Erdtman 1960; Seiwald 1980) using chlorination, acetolysis and if necessary, hydrofluoric acid (HF) treatment. For calculations of pollen concentrations, tablets with a defined amount of exotic pollen (*Lycopodium clavatum*) were added before the chemical treatment (Stockmarr 1971). Permanent mounts were stained with fuchsine and embedded in glycerine. The identification and quantification of pollen and other palynomorphs was then conducted under a light microscope at 400 × magnification (and also at 1,000× magnification supported by phase-contrast in critical cases). To generate a robust dataset, 1,000 AP grains were counted for every sample. The pollen and spore types were determined using standard identification keys for the central European pollen flora (Punt et al. 1976–1988; Moore et al. 1991; Reille 1992, 1995; Fægri and Iversen 1993; Beug 2004) and the reference collection at the Botanical Institute of the University of Innsbruck. In addition to pollen and spores, non-pollen palynomorphs (NPPs), such as spores of coprophilous fungi and zoological micro-fossils as well as micro-charcoals (*particulae carbonae* of size classes < 50 µm > 50 µm > 100 µm), were identified and counted.

The pollen diagrams were computed with the Fagus program (Gelmini 1997), which was developed at the Botanical Institute of the University of Innsbruck. The pollen counts are represented graphically by curve-silhouette diagrams (Fig. 3), the black display area corresponds to percentage values obtained for a defined aggregation of pollen, and the grey display area is a 10× exaggeration. This pollen aggregation is composed of AP and non-arboreal pollen (NAP), excluding the Cyperaceae. The micro charcoals are represented as percentage values of the pollen sum defined above.

The zonation of the pollen diagram into "local pollen assemblage zones (LPAZ)" follows Cushing (1967). Such bio-zones are defined by the dominant pollen and spores without reference to climate, vegetation or sediment (Hedberg 1972a, b). The zonation is calculated as a combination of (i) the broken-stick-model from PSIMPOLL (Bennett 2009), (ii) the broken-stick-model in R i386 2.15.2 (R Development Core Team 2012) with the "rioja" package through CONISS (Grimm 1987) using the Euclidean distance for clustering and (iii) fine visual adjustment.

Indicator species for anthropogenic impacts, such as pasture, tillage or settlement, are defined in Table 1 and compiled from Behre and Kučan (1986), Bortenschlager (1991, 2000), Breitenlechner et al. (2010) and Festi et al. (2013).

The AP/NAP index is an estimate of the openness of the vegetation (Aario 1940; Favre et al. 2008), and in combination with the indicator species described above, it is also an indicator of anthropogenic influence. An index of between 3 and 4 corresponds to approximately 75–80 % of the local climax tree pollen, and 20–25 % of the terrestrial non-arboreal pollen. This coincides with today's treeless vegetation that surrounds the mire. If this value is also found at other depths, similar vegetation and land cover is assumed in accordance with the concept of uniformitarianism (Simpson 1970; Birks and Birks 1980).

For the investigation area it was defined and specified that the following changes in the percentage values and/or concentration values reflect an anthropogenic clearing phase: The values of *Picea* (spruce) and *Abies* (fir) are decreasing, Poaceae (true grasses) are increasing. In addition the cumulative curves pasture and settlement indicators as well as cultural indicators and micro-charcoals (>50/>100 μm) are increasing. In this case the rising micro-charcoal values are caused by intentional fires and human activities (e.g. slash and burn). The micro-charcoals were added to the pattern of clearing because fire has a major impact on the vegetation (Tinner et al. 2000) and because is also linked with several workflows in mining (e.g. ore roasting, fire setting for exploitation).

Heavy metal analyses

In this study, 30 samples with a dry weight of 0.2–1 g each, were taken every 2–5 cm from the peat core and geochemically analysed. The elements Cu, As, Sc and Sb were analysed by neutron activation analyses (NAA) (Perlman and Asaro 1969; Kuleff and Djingova 1990). The samples were measured with Ortec high purity germanium detectors. Pb, Ti and, for a second dataset, Sc were analysed by a Quadrupole Inductively Coupled Plasma-Mass Spectrometer (Thermo Scientific XS 2, ICP-MS) (Houk et al. 1980; Shotyk et al. 1997, 1998) at the Curt Engelhorn Centre for Archaeometry in Mannheim, Germany.

The Cu, As and Sb values were normalised by the conservative element Sc (from the NAA-measurement) as the natural variation in the abundance of mineral matter has a crucial effect on the elements measured in peat samples (Shotyk 1996; Weiss et al. 1997, 1999; Shotyk et al. 2001, 2002). The normalisation of Cu, As and Sb enables an estimation of the anthropogenic contribution to natural metal(loid) deposition. Pb was normalised according to Shotyk et al. (2001):

$$[\mathrm{Pb}]_{\mathrm{lithogenic}} = [\mathrm{Sc}]_{\mathrm{sample}} \times (\mathrm{Pb/Sc})_{\mathrm{atmosphericsoildust}}$$

To calculate the Pb/Sc ratio for the atmospheric soil dust, according to Shotyk et al. (1998), the lowest values of Pb (0.28 μg/g) and Sc (0.07 μg/g) deposited in the basic minerogenic layers between 8,030 and 5,320 cal BP were used. When the lithogenic component of Pb is calculated, anthropogenic Pb can be estimated as follows:

$$[\mathrm{Pb}]_{\mathrm{anthropogenic}} = [\mathrm{Pb}]_{\mathrm{total}} - [\mathrm{Pb}]_{\mathrm{lithogenic}}$$

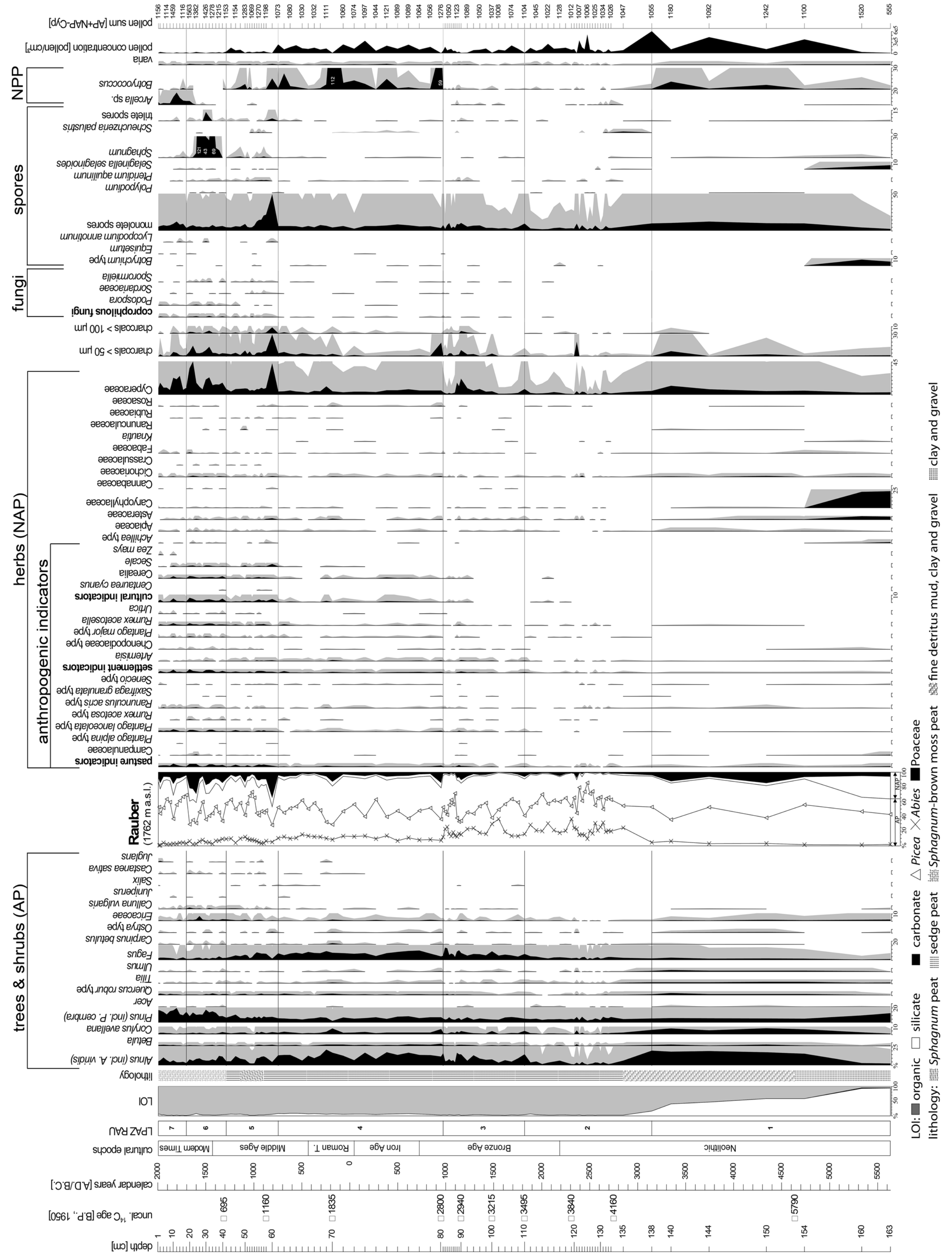
Results

Sedimentology

The monolith taken from the Rauber saddle mire has a thickness of 1.63 m and consists mainly of peat (Table 2). The lowest 10 cm (163–153 cm) of the core are composed of clay and gravel (*Argilla steatodes* with clay particles < 0.002 mm and *Grana glareosa minora* with 6.0-2.0 mm mineral particles) with a low concentration of pollen (~40,000 grains/cm^3) compared to the overlaying organic material (~190,000 grains/cm^3). These layers (153–135 cm) consist of 18 cm of clayish fine detritus mud with gravel (*Limus detritosus* with fragments of plants and animals <c. 0.1 mm, *Argilla steatodes* and *Grana glareosa minora*). This fine detritus mud gradually transforms into a 77 cm-thick (135–58 cm) sedge peat (*Turfa herbacea*), with *Sphagnum* and brown mosses at 58–48 cm in depth (*Turfa sphagni, T. herbacea, T. bryophytica*). At 42 cm the Cyperaceae peat (*Turfa herbacea*) merges into a *Sphagnum* peat (*Turfa sphagni*; *Turfa herbacea*) that constitutes the uppermost layers (48–0 cm). The degree of humosity of the peat is low and fluctuates between 1 and 2 through a depth of 0–135 cm.

Loss on ignition (LOI)

The minerogenic parts in the sediment correspond to carbonate and silicate and are represented as their own graph


Rauber (1762 m a.s.l.)
trees & shrubs (AP)
Alnus (incl. A. viridis)
Betula
Corylus avellana
Pinus (incl. P. cembra)
Acer
Quercus robur type
Tilia
Ulmus
Fagus
Carpinus betulus
Ostrya type
Ericaceae
Calluna vulgaris
Juniperus
Salix
Castanea sativa
Juglans
herbs (NAP)
anthropogenic indicators
pasture indicators
Campanulaceae
Plantago alpina type
Plantago lanceolata type
Rumex acetosa type
Ranunculus acris type
Saxifraga granulata type
Senecio type
settlement indicators
Artemisia
Chenopodiaceae type
Plantago major type
Rumex acetosella
Urtica
cultural indicators
Centaurea cyanus
Cerealia
Secale
Zea mays
Achillea type
Apiaceae
Asteraceae
Caryophyllaceae
Cannabaceae
Cichoriaceae
Crassulaceae
Fabaceae
Knautia
Ranunculaceae
Rubiaceae
Rosaceae
Cyperaceae
charcoals > 50 µm
charcoals > 100 µm
fungi
coprophilous fungi
Podospora
Sordariaceae
Sporormiella
spores
Botrychium type
Equisetum
Lycopodium annotinum
monolete spores
Polypodium
Pteridium aquilinum
Selaginella selaginoides
Sphagnum
Scheuchzeria palustris
trilete spores
NPP
Arcella sp.
Botryococcus
varia
pollen concentration [pollen/cm³]
pollen sum [AP+NAP-Cyp]
lithology
LOI
LPAZ RAU
1 2 3 4 5 6 7
cultural epochs
Neolithic
Bronze Age
Iron Age
Roman T.
Middle Ages
Modern Times
calendar years [A.D./B.C.]
uncal. 14C age [B.P., 1950]
695 1160 1835 2800 2940 3215 3495 3840 4160 5790
depth [cm]
LOI: ■ organic □ silicate ■ carbonate △ Picea × Abies ■ Poaceae
lithology: Sphagnum peat sedge peat Sphagnum-brown moss peat fine detritus mud, clay and gravel clay and gravel

◀**Fig. 3** Relative pollen diagram (selected species) of the Rauber mire, near the Kelchalm. Silhouette curves with *black backgrounds* correspond to percentage values (%) based on a pollen sum of AP + NAP − Cyperaceae, and the *solid line* with the *grey background* is a 10× exaggeration (‰). *Scale* each *pitch line* represents 5 %, *symbols* in the main diagram: *times symbol* = *Abies*, *triangle Picea*, *filled circle Pinus*, *solid line* border of the AP and NAP fraction, *black area* values of Poaceae. The charcoals are indicated as percentages of the pollen sum

in the pollen diagram (Fig. 3). The carbonate values are low and reach an average of 0.2 % for the whole deposit due to the geological background.

The basal clay and gravel layers (160–163 cm) contain the highest values of silicate (93.5 %). In the basal layers from 154 to 160 cm the silicate values decrease and the organic values increase (41 %), but the deposit is still limnic. Until 140 cm the organic compounds are constant at approximately 40–50 %. Between 140 and 135 cm the deposited peat corresponds to c. 3,100 cal BC and the organic material adds up to 80 % or more. In the following layers the components do not change noticeably and the organic material fluctuates around an average of 96.4 %. No major disturbances, e.g. erosion, accumulation or entries from the outside through time, are observable in the peat sequence.

Table 1 Indicator species for pasture and settlement activities, as well as cultural indicators

Pasture indicators	Settlement indicators
Aconitum-type	*Artemisia*
Campanulaceae	Chenopodiaceae-type
Centaurea	*Plantago major*-type
Gentianaceae	*Polygonum aviculare*
Juniperus	*Rumex acetosella*
Plantago alpina-type	*Urtica*
Plantago lanceolata-type	Cultural indicators
Pteridium aquilinum	*Cannabis sativa*
Ranunculus acris-type	*Castanea sativa*
Rumex acetosa-type	*Centaurea cyanus*
Sanguisorba minor-type	Cerealia
Saxifraga granulata-type	*Juglans*
Scabiosa	*Secale*
Senecio-type	*Zea mays*
Thalictrum	
Trifolium-type	
Coprophilous fungi	
Cercophora	
Podospora/Zopfiella	
Sordariaceae	
Sporormiella	

Coprophilous fungi are complementary indicators of pasture activities

Dating

The results of the AMS-radiocarbon dating are shown in Table 3 and Fig. 2. The 153 cm basal radiocarbon date is 4639 cal BC for the onset of organic deposition.

The age-depth model (Fig. 2b) is based on ten radiocarbon data points and shows the variability in accumulation rates of the Rauber mire. The peat formation begins at c. 2850 cal BC (135 cm) with an accumulation rate of 0.4 mm/year. Subsequently during the Early Bronze Age the accumulation rate decreases to 0.2 mm/year and rises again in the Middle Bronze Age to 0.3 mm/year and in the Late Bronze Age to 0.5 mm/year. During the Iron Age, Roman Times and Early Middle Ages peat accumulation is reduced to 0.1 mm/year. Since c. cal AD 900 (58 cm) the mire grows faster at a rate of 0.4 mm/year and since the Late Middle Ages (c. cal AD 1330, 40 cm) with an accumulation rate of 0.7 mm/year. The chronology of the pollen diagram for Rauber relies on the interpolation between the single radiocarbon dates established by this age-depth model.

Vegetation history

Vegetation development is recorded in the peat deposits of the Rauber mire since the early Neolithic starting with a *Picea*-*Alnus*-Poaceae zone (LPAZ RAU1, 163–138 cm, Table 4). The two lowermost samples reflect a sparse spruce forest (*Picea* 45 %) surrounding the mire with plenty of herbal taxa in the understory, such as Poaceae (20 %), Cyperaceae, Caryophyllaceae (20 %), Campanulaceae, *Achillea* (yarrow), *Artemisia* (mugwort), *Selaginella* (spike moss) and *Botrychium* (common moonwort). *Abies* and *Fagus* (beech) have already immigrated into the study area and have started to spread through the lower altitudes. At low altitudes *Picea*, together with *Abies* and *Fagus* forms the mountain mixed-alpine forest. The proportions of *Fagus* and *Abies* are gradually reduced with increasing altitude so that *Picea* is the predominant forest-forming tree in the surroundings of the mire.

The *Picea*-*Abies* zone (LPAZ RAU2, 138-110 cm) covers the time period from c. 3150–1800 cal BC, which correspond to the end of the Neolithic and the Early Bronze Age. At the onset of peat accumulation approximately 2850 cal BC (135 cm depth), *Abies* expands into higher altitudes and a spruce-fir forest (Piceeto-Abietetum) evolves in the surroundings of the mire and persists until the Middle Ages (c. cal AD 800). At c. 2600 cal BC (Fig. 3) the values of *Picea*, *Abies* and some of the deciduous woody taxa (*Alnus*, *Betula*, *Corylus avellana*) are decreasing; and those of several herb taxa (e.g. Poaceae, Asteraceae <5 %, Cichoriaceae <5 %, Ranunculaceae) are

Table 2 Stratigraphy with indication of depth and sediment description of the Rauber mire following Troels-Smith (1955)

Depth (cm)	Sediment description	Troels-Smith classification
0–42	*Sphagnum* peat	TbS^{1} 3, Th^{1} 1
42–48	Sedge peat	Th^{2} 4
48–58	*Sphagnum*—brown moss—sedge peat	TbS^{2} 2, Th^{2} 1, Tb^{1} 1
58–135	Sedge peat	Th^{2} 4
135–153	Fine detritus mud, clay and gravel	Ld^{1} 2, As 1, Gg (min.) 1
153–163	Clay and gravel	Gg (min.) 3, As 1

Table 3 Radiocarbon dates, calibrated ages as well as the estimated age from the age-depth model of the analysed substrate samples from the Rauber mire

Lab. code	Depth (cm)	Material	^{14}C age (BP) (1σ-range)	cal age (BP) (2σ-range)	Probability (%)	cal age (BP)	Estimated age
VERA-5673HS	41	Peat	695 ± 50	557–606	31.1	639	AD 1311
				625–725	63.8		
VERA-5674HS	59	Peat	1,160 ± 35	980–1,039	27.3	1078	AD 872
				1,044–1,173	67.7		
VERA-5812HS	70	Peat	1,835 ± 35	1,701–1,867	95	1769	AD 181
VERA-5675HS	80	Peat	2,800 ± 40	2,791–2,997	95	2902	952 BC
VERA-5813HS	90	Peat	2,940 ± 40	2,964–3,218	94.4	3110	1160 BC
				3,233–3,237	0.5		
VERA-5814HS	100	Peat	3,215 ± 35	3,365–3,484	91.1	3433	1483 BC
				3,529–3,553	3.8		
VERA-5815HS	110	Peat	3,495 ± 40	3,645–3,660	2.5	3771	1821 BC
				3,686–3,871	92.4		
VERA-5676HS	118	Peat	3,840 ± 35	4,151–4,360	84.5	4260	2310 BC
				4,366–4,407	10.4		
VERA-5677HS	134	Peat	4,160 ± 45	4,539–4,540	0.2	4700	2750 BC
				4,550–4,552	0.4		
				4,569–4,834	94.4		
VERA-5673HS	153	Mud	5,790 ± 35	6,497–6,666	95	6589	4639 BC

increasing, which reflects an opening of the landscape between 2600 and 2300 cal BC. At the end of this RAU2 pollen assemblage zone (c. 2000 cal BC, 114 cm) the percentage and influx values (pollen accumulation rates, PAR) of both *Picea* and *Abies* decrease again for the following 200 years. The percentage values of *Picea* diminish from 70 to 40 % and those of *Abies* from 20 to 15 %. Therefore the values of *Abies* first increase and then decrease with a time delay relative to the *Picea* pollen curve. The reason for this may be that (i) more *Abies* is growing in the wider surroundings, (ii) *Abies* is coming closer to the sedimentation basin, or most likely, (iii) the more open vegetation canopy resulting from less *Picea* reduces the filter effect, so more *Abies* pollen is deposited in the mire. Moreover the micro-charcoals (<50 µm and >50 µm), the Poaceae and the curves for the pasture and settlement indicators (*Plantago lanceolata*-type, *P. major*-type, *Rumex acetosella, R. acetosa*-type) achieve higher values than before and the first occurrence (absolute pollen limit) of Cerealia is recorded (c. 2000 cal BC, 114 cm). This pattern is indicative of clearing, in particular the subsequent secondary succession of *Alnus* (alder) and *Betula* (birch) that takes place on the site. At lower altitudes, *Fagus* and *Corylus* (hazel) are spreading.

The overlying LPAZ RAU3 (*Picea*-*Alnus*-*Fagus*-zone, 110–81 cm) is dated to the Early and Late Bronze Age and extends from c. 1800–970 cal BC. At the beginning of this zone, *Picea* is regenerating and achieves values of 65 %. Consequently Poaceae and settlement indicators decline. At approximately 1700 cal BC the values of *Picea* taper off again while those of *Abies* rise. Subsequently the Poaceae and Cyperaceae expand again; the pasture and settlement indicators show no enhanced percentage values. In addition the values for charcoals (>50 µm) increase, which suggests fire activity in the surroundings. In the following zone *Picea* reaches a maximum and then declines again to a

Table 4 Definition of the local pollen assemblage zones (LPAZ) of the Rauber pollen diagram

LPAZ	Name	Depth (cm)	Upper limit	Chronozones	Time span (cal, inter/extrapolation)
RAU7	*Picea*-Cyperaceae-zone	0–18	Upper limit of pollen data	Subatlantic	AD 1700–2009
RAU6	*Picea*-Poaceae-Cyperaceae-zone	18–42	Increase of *Picea*, *Pinus*, decrease of *Alnus*, Poaceae, Cyperaceae	Subatlantic	AD 1290–1700
RAU5	*Picea*-Poaceae-zone	42–61	Increase of Poaceae, Cyperaceae, *Pinus*, decrease of *Abies, Picea*	Subatlantic	AD 750–1290
RAU4	*Picea-Alnus*-zone	61–81	Increase of Poaceae, Cyperaceae, decrease of *Picea*	Subatlantic, Subboreal	970 BC–AD 750
RAU3	*Picea-Alnus-Fagus*-zone	81–110	Increase of *Alnus*, *Fagus*, decrease of *Abies*	Subboreal	1820–970 BC
RAU2	*Picea-Abies*-zone	110–138	Decrease of *Abies*, *Picea*	Subboreal	3150–1820 BC
RAU1	*Picea-Alnus*-Poaceae-zone	138–163	Decrease of *Alnus*, Poaceae, Cyperaceae	Atlantic	5630–3150 BC

The time specification follows the interpolation between the single radiocarbon dates, the undermost estimated date is a result of extrapolation from the radiocarbon date at 153 cm

minimum. Simultaneously the charcoal particles (>100 µm) and Poaceae, as well as the pasture and settlement indicators maintain maximum values, indicating local clearing. At 1200 cal BC the empirical pollen limit of Cerealia starts. At approximately 1000 cal BC the spruce-fir forest regenerates again and the pasture and settlement indicators, as well as the crops, show a minimum.

The LPAZ RAU4 (*Picea-Alnus*-zone, 81-61 cm) covers several epochs and ranges from 970 cal BC to cal AD 750 (Table 4), which corresponds to the end of the Bronze Age, the Iron Age, Roman Times and the Early Middle Ages. The predominant vegetation is still a spruce-fir forest (Piceeto-Abietetum) with a small amount of *Alnus* at the timber line and *Fagus* at lower altitudes. At the beginning of the zone (80 cm) there are noticeable peaks for Poaceae and charcoals (>50 µm) in combination with a minimum of *Picea*. Settlement indicators are recorded at considerably high values. During Roman Times another opening of the forest is visible in the pollen diagram as between c. 50 cal BC and cal AD 180 (72–70 cm) the values of *Picea* and *Abies* are decreasing. The values of *Picea* decrease from 55 to 30 % and micro-charcoals (>50 and >100 µm) concomitantly display increased values. This decline is also visible in the pollen accumulation rates (PAR); which corroborate clearing. The Poaceae, settlement indicators and crops show maximum values (Fig. 3). In contrast, *Alnus* is increasing as is *Corylus avellana* with a time-delay. *Castanea sativa* (chestnut) and *Secale cereale* (rye) occur for the first time (empirical pollen limit). *Juglans* (walnut) is later introduced at c. 250 cal AD (69 cm). Between cal AD 180 and 500 (70–65 cm), corresponding to Late Roman and the first phase of the Early Middle Ages, a regeneration of the spruce-fir forest (Piceeto-Abietetum) is recorded, suggesting a decline in anthropogenic influence. Although reduced to a minimum, settlement indicators are still recorded, which in combination with moderate fire activity, suggests constant human interference.

The following LPAZ RAU5 (*Picea*-Poaceae-zone, 61–42 cm) is characterised by extensive forest clearings and includes the High Middle Ages and the beginning of the Late Middle Ages (c. AD 750–1300). From cal AD 800 onwards, the pollen diagram reflects eight additional clearing phases (Table 6) with increasing intensification in Early Modern Times. At the beginning of the zone a distinct drop in *Picea* and *Abies*, in combination with synchronously higher values of charcoals (>50 and 100 µm) and a spread of Poaceae, reflects the clearing of the local vegetation cover. Afterwards the clearing is used for pasture as indicated by a remarkable record of *Plantago lanceolata*-type and *Ranunculus acris*-type pollen and coprophilous fungi (*Podospora, Cercophora, Sporormiella,* Sordariaceae) as well as settlement indicators. Tillage was also practiced in the vicinity of the mire, which is reflected in the considerable cereal and *Secale* pollen found in combination with *Centaurea cyanus* (cornflower). Additionally non-arboreal, herbal pollen taxa (e.g. Cichoriaceae, *Achillea*-type) are increasing from approximately 10 % to a mean of 30 % (Fig. 3). This pattern suggests slashing and burning.

At approximately cal AD 1000, fire activity is reduced for about a 100 years (*particulae carbonae* > 100 µm) and *Picea* expands again. At approximately cal AD 1240 another clearing episode is recorded, albeit on a smaller scale than the previous one (LPAZ RAU5). The Poaceae (up to 5 %) as well as the Cyperaceae achieve higher values. Simultaneously the values of *Picea* are decreasing whereas the indicator taxa for pasture (1 %, e.g. *Artemisia,* Campanulaceae, *Pteridium aquilinum, Senecio*-type), settlement

(1 %, e.g. *Rumex acetosella, Plantago lanceolata*-type, *Urtica*) and cultivation (1.7 %, e.g. Cerealia, *Secale, Castanea, Juglans*) are increasing. In this zone, herbal diversity is multiplied and all common families, such as Asteraceae, Cichoriaceae, Fabaceae, Apiaceae, Caryophyllaceae, Rosaceae, Plantaginaceae and Campanulaceae are represented. The dwarf shrubs also show enhanced pollen values, the Ericaceae reach almost 1 % and *Calluna vulgaris* (common heather) obtains values of 0.8 %. Basically during the Middle Ages and Modern Times (LPAZ RAU5-RAU7), the values for settlement indicators (e.g. *Rumex acetosella, Plantago lanceolata*-type, *Urtica*) as well as crop plants are increasing and reflect an intensification of settlement activities. In addition higher values for pasture indicators and coprophilous fungi indicate increasing pasture activities. During the High Middle Ages (c. cal AD 1050–1290, 52–42 cm), the pollen diagram shows a slight reduction in human impact, which increases again in Early Modern Times (c. cal AD 1290–1530, 42–28 cm) and persists until recent times. It is striking that the phases of increasing *Picea* values, which correspond to the regeneration phases are shorter than in prehistory. This suggests intensification of anthropogenic influences on the vegetation in recent times since c. cal AD 750.

With the onset of LPAZ RAU6 (*Picea*-Poaceae-Cyperaceae zone, 42–18 cm), land reclamation continues and reaches its largest extent. This LPAZ encompasses the Late Middle Ages and Early Modern Times (c. AD 1300–1700). In this zone the NAP values culminate at 30 %. The Poaceae add up to 15 % and the Cyperaceae to 20 %. Additionally the settlement indicators (4 %) and crops (3 %) achieve their highest values. Simultaneously the pasture indicators, e.g. *Plantago lanceolata*-type, *Ranunculus acris*-type, *Rumex acetosa*-type, and Campanulaceae, are increasing to 2.4 % and indicate an intensification of grazing activities. At the lower limit of LPAZ RAU6 (c. cal AD 1430, 34 cm) decreasing *Abies* values occur. This may be due to the selective removal of the species or be a reaction to fire (Tinner et al. 2000), which is supported by increasing charcoal values. An additional piece of evidence of the open landscape is the increasing values of dwarf shrubs up to 1.7 %.

The LPAZ RAU7 (*Picea*-Cyperaceae-zone, 18–0 cm) reflects a regeneration of the *Picea* forest. The arboreal percentage values again reach 80 % while *Picea* adds up to 56 %, and *Abies* increases to 3 %. Consequently within the NAP the Poaceae (8 %) and Cyperaceae (13 %) show decreasing values, but the herbal spectra are unchanged (except for *Sanguisorba minor*). The accumulation curves of the pasture and settlement indicator species and the crops continue to show considerably high values. Beginning in cal AD 1840, *Secale* is replaced by neophyte *Zea mays* (sweet corn).

The openness of the landscape and the periodic "thinning out" of the forest since the Bronze Age is substantiated by the AP/NAP-index, an indicator of vegetation cover. Therefore an aggregation of local, terrestrial AP and NAP pollen was formed. The AP aggregate is comprised of *Abies, Alnus viridis, Betula, Picea, Pinus cembra* and *Pinus*. The NAP composite includes shrubs (*Calluna vulgaris,* Ericaceae, *Juniperus, Salix*) and all terrestrial herbaceous taxa except species from the valley bottom (Cannabaceae, *Cannabis sativa*, *Zea mays,* varia) and distinct species growing on the mire (Cyperaceae, *Drosera, Scheuchzeria palustris*). For the last 1,100 years (from 0 to 58 cm), the total of the local AP results in a mean of 74.27 %, and the mean is 18.37 % for the NAP. This results in a local AP/NAP index of 4.0. An index value of less than four (1.6 at 163 cm, 1.7 at 160 cm) is found for the two lowermost samples from the sediment column and at 150 cm (Fig. 5). Furthermore a ratio of 4/1 or less is very frequently reached by the samples at 80, 70 cm and from 60 cm on. An index of three, or a ratio of 3/1 AP/NAP is found for 140, 90 cm and from 59 cm on for four more depths (Fig. 5).

Heavy-metal analyses

The chalcopyrite ore of the Kelchalm includes few trace elements (Lutz et al. 2009). The Ti values vary between 46 and 398 ppm (ICP-MS), and those for Sc vary between 0.347 and 2.16 and 0.38 and 1.61 ppm for NAA and ICP-MS, respectively. The values for both elements are positively correlated with the silicate values from the LOI analyses, which highlight the fact that the two elements are natural soil components that are not volatile but are added to the deposit through erosion (pers. comm. Michael Prange, DBM, 26.11.2012). Furthermore Sc is a conservative lithogenic element. The Sc values of the two measurements, NAA and ICP-MS, are virtually indistinguishable from each other and from the Ti values. However the NAA Sc values were used to normalise the volatile metal Cu and the metalloids As and Sb (Shotyk et al. 1998, 2001). The values measured for Cu with NAA range between 15 and 50 ppm, those of As range between 0.6 and 34.6 ppm, and the Sb values fall between 0.09 and 93 ppm. Pb was estimated with ICP-MS; and the values range from 1.09 up to 278 ppm.

The Cu/Sc ratio shows relatively high values during the Neolithic and decreases during the Early Bronze Age (Fig. 4). At approximately 1160 cal BC, the ratio increases to nearly 70 and then declines to approximately 20 again near 1020 cal BC. These values remain more or less stable until c. cal AD 1090. In Late Roman Times (AD 300), a slight rise in Cu/Sc values is observed. During the High Middle Ages, Cu/Sc increases and reaches its maximum at cal AD 1090 (62.5 ppm). A second peak is recorded at approximately AD 1400/1500.

The As/Sc values are low and remain stable at a mean of 1.35 from the Bronze Age until the high Middle Ages with small peaks at 1160 cal BC (2.14) and c. AD 300 (0.92) (Table 5). In the Late Middle Ages the curve shows a tenfold rise in the values. The maximum is reached at cal AD 1210 with a ratio of 25. At approximately AD 1400 the values increase again, but only slightly, to ratios of 12.

The Sb/Sc curve shows three peaks over time (Fig. 4). The first peak occurs during the Late Bronze Age at c. 1230 cal BC (92 cm) and the ratio is fifty times higher (19.67) than in the underlying layers. A second peak appears during Late Roman Times at approximately AD 300 (68 cm) with values twelve times higher than before (9.34). The third and highest peak occurs in the High Middle Ages from c. AD 1100–1200 (45–50 cm) with about a hundredfold increase in the values (c. 70).

The values of anthropogenic Pb, calculated according to Shotyk et al. (2001), are at a minimum during the Neolithic, Bronze Age and Iron Age. In Late Roman Times, at c. AD 300 (68 cm), the values significantly increase to 26 ppm. A second rise in the values starts at cal AD 1100 and reaches its maximum of over 250 ppm in the High Middle Ages between AD 1200 and 1300 (40–45 cm).

Discussion

Pollen, heavy metals and the accompanying analyses (lithology, micro-charcoals, loss on ignition) illuminate the environmental changes and the moulding of a cultural landscape since the Mesolithic. This study aims to evaluate vegetation changes and their relationship to human activity, particularly specific mining activities.

The LPAZ RAU1, at the base of the pollen diagram, reflects an open forest characterised by a large number of herbal taxa (Caryophyllaceae, Asteraceae) and Poaceae. Additionally, *Botrychium* and *Selaginella selaginoides,* both light-demanding species, growing on open soils, reflects low forest cover. In addition the low AP/NAP index of the two basic samples (1.8 in 160 cm and 1.6 in 163 cm) indicates an open forest with sparse tree cover. Even if the sampling interval in this Sect. (163–133 cm) is coarse, so that 100–500 years are between the samples, it is suggested that the low tree cover is a reaction to the climatic deterioration between 8,100 ± 320 and 7,200 cal BP (6150–5250 cal BC) (Zoller 1960; Valsecchi and Tinner 2010) called the “Misox event” (or identified with the Italian place name Mesolcina). This climatic deterioration is equal to “Bond event 5” at 8,100 cal BP (6150 cal BC, Bond et al. 1997). In 154 cm (c. 4740 cal BC) *Picea* reflects the highest values in the LPAZ RAU1. Together with low

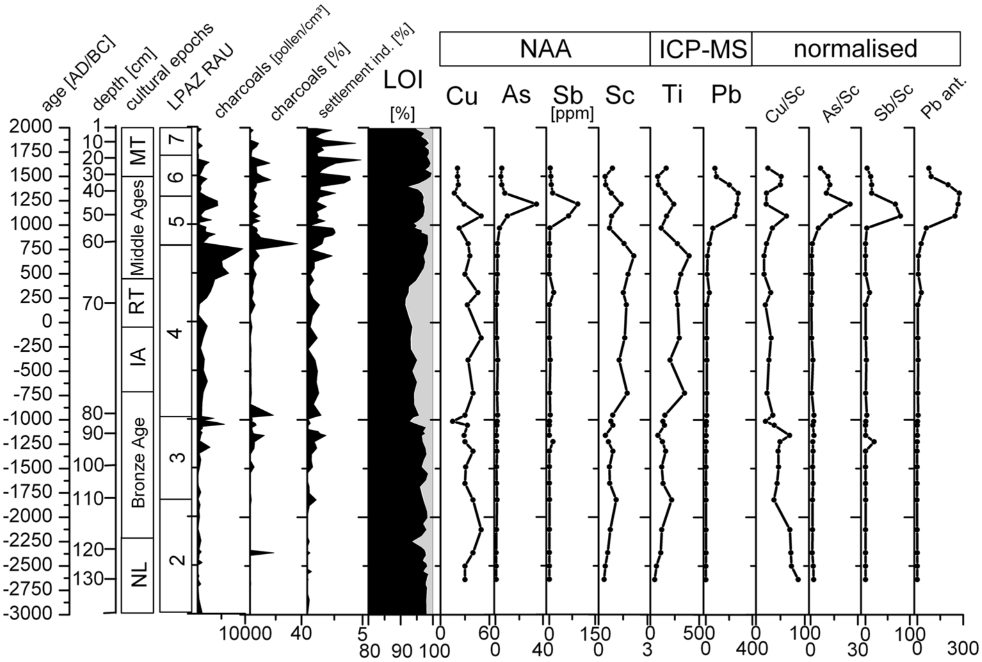


Fig. 4 Results of the heavy metal analyses in relation to the quantified micro-charcoals, settlement indicators as well as the composition of the peat (LOI). Abbreviations for cultural epochs: *MT* Modern Times, *RT* Roman Times, *IA* Iron Age, *NL* Neolithic. Charcoal values are a sum of the *particulae carbonae* classes of >50 and >100 µm, represented as concentrations and as percentages from the defined pollen sum of AP + NAP − Cyperaceae. The loss of ignition values (LOI) sum to 100 % with organic matter in black, carbonate values in white and silicate values in grey. Only the upper 20 % are represented. Cu, As, Sb and Sc are measured with NAA and Pb and Ti with ICP-MS. Sc is the element used for standardisation

Table 5 Results of the heavy metal measurements from the peat column of the Rauber mire using NAA and ICP-MS

Lab.No.	Age [AD/BC]	Depth [cm]	NAA [ppm]				ICP-MS [ppm]			Pb [ppm]		Sb/Sc	Cu/Sc	As/Sc
			Cu	As	Sb	Sc	Sc	Ti	Pb	Lithogenic	Anthropog.			
MA-122655	1580	25	21	5.4	3.34	0.85	0.75	163	78.99	3.01	76	3.93	24.71	6.35
MA-122656	1500	30	21	4.5	4.8	0.41	0.39	76	92.4	1.56	90.9	11.82	51.72	11.08
MA-122657	1400	35	22	5.4	6.3	0.44	0.46	84	203	1.82	201.5	14.32	50	12.27
MA-122658	1330	40	17	7.9	11.1	0.78	0.7	153	278	2.81	275	14.23	21.79	10.13
MA-122659	1210	45	29	34.6	93	1.38	1.12	241	271	4.48	266.9	67.39	21.01	25.07
MA-122660	1090	50	50	10.1	63	0.8	0.76	167	250	3.02	246.8	78.75	62.5	12.63
MA-122661	970	55	23	3.4	2.14	0.68	0.58	111	60.9	2.31	58.6	3.15	33.82	5
MA-122662	800	60	34	1.8	0.6	1.57	1.22	277	30	4.87	25.2	0.38	21.66	1.15
MA-122663	680	62	36	1.6	0.81	2.16	1.61	398	13.9	6.45	7.5	0.38	16.67	0.74
MA-122664	500	65	30	1.6	0.46	1.81	1.41	313	11.9	5.66	6.2	0.25	16.57	0.88
MA-122665	300	68	46	1.4	14.2	1.52	1.15	266	30.6	4.59	26	9.34	30.26	0.92
MA-122666	180	70	33	0.9	0.42	1.71	1.24	280	7.92	4.94	3	0.25	19.3	0.53
MA-122667	-160	73	50	1.2	0.86	1.61	1.32	296	8.8	5.3	3.5	0.53	31.06	0.75
MA-122668	-390	75	34	2	3.02	1.27	1.02	202	9.28	4.08	5.2	2.38	26.77	1.57
MA-122669	-730	78	40	1.3	1.31	1.76	1.5	350	9.87	5.99	3.9	0.74	22.73	0.74
MA-122670	-950	80	30	1.9	2.94	0.87	0.82	149	8.57	3.28	5.3	3.38	34.48	2.18
MA-122671	-1020	83	15	1.5	0.7	0.76	0.72	129	4.68	2.86	1.8	0.92	19.74	1.97
MA-122672	-1060	85	33	1.3	0.32	0.88	0.82	145	3.24	3.27		0.36	37.5	1.48
MA-122673	-1160	90	29	0.9	0.3	0.42	0.47	78.4	2.9	1.89	1	0.71	69.05	2.14
MA-122674	-1230	92	30	0.9	12	0.61	0.57	125	1.95	2.26	-0.3	19.67	49.18	1.48
MA-122675	-1320	95	40	1.4	0.26	0.88	0.82	157	1.56	3.3	-1.7	0.3	45.45	1.59
MA-122676	-1480	100	31	0.9	0.25	0.67	0.64	118	1.6	2.57	-1	0.37	46.27	1.34
MA-122677	-1650	105	30	1.1	0.32	0.69	0.66	130	1.25	2.65	-1.4	0.46	43.48	1.59
MA-122678	-1820	110	40	1.4	0.63	1.08	1	218.8	1.67	4	-2.3	0.58	37.04	1.3
MA-122679	-2130	115	50	0.90	0.17	0.72	0.68	117	1.56	2.72	-1.2	0.24	69.44	1.25
MA-122680	-2370	120	40	0.6	0.22	0.56	0.54	107	1.7	2.15	-0.4	0.39	71.43	1.07
MA-122681	-2500	125	30	0.7	0.1	0.41	0.45	63.6	1.35	1.81	-0.5	0.24	72.64	1.69
MA-122682	-2640	130	30	0.7	0.09	0.35	0.38	45.7	1.09	1.53	-0.4	0.26	86.46	2.02

Increased values are indicated with black frames and anthropogenic phases with grey bars

values of Poaceae and other NAP, this pattern suggests a warm period at c. 4600–4400 cal BC (Kofler et al. 2005).

The overlaying depths of the peat core that were analysed indicate another period of climatic deterioration with cold/wet conditions through the low values of *Picea* and charcoals (>50 and >100 µm) from wildfires, as well as the enhanced values for monolete spores (e.g. ferns) and the colony-forming green alga *Botryococcus*. The values of *Picea* are 38 % in 150 cm (c. 4340 cal BC) and 35.5 % in 140 cm (c. 3350 cal BC), the lowest until the Late Bronze Age (92 cm, c. 1230 cal BC). Even if the depths are not dated directly, the two-phase cold period, "Rotmoos I and II", can still be assumed to have occurred (Patzelt 1977; Magny et al. 2006). These cold periods from approximately 6,100–5,700 and 5,500–5,000 cal BP (4150–3750 and 3550–3050 cal BC, respectively) (Hormes et al. 2001) are equal to the "Piora I and II" climatic deterioration events (Zoller 1977a, b) as well as "Bond event 4" (Bond et al. 1997). Although, the mid-Holocene is known as climatically favourable period in relation to the late-Holocene, the percentage values of the climax tree species (mainly *Picea*) are relatively low. This can be attributed to the beginning soil formation, visible in high amount of minerogenic material and low organic material (LOI analysis). A first disturbance in the pollen diagram is observed between c. 2600 and 2300 cal BC. The fluctuating curves of *Abies* and *Picea* without clear increases in Poaceae and/or anthropogenic indicators are ambiguous: (i) The settlement indicators, such as *Plantago lanceolata*-type, *P. major*-type) or Chenopodiaceae as well as charcoals (>100 µm), which would refer to human activities, are represented in the same quantity as in the underlying deposits. The smaller charcoals (>50 µm) show increasing values in one depth (120 cm) which it is suggested to be a natural single fire event. Additionally the first crop pollens (mainly Cerealia) appear later, the absolute pollen limit of cereals is achieved at approximately 2000 cal BC ruling out anthropogenic interference. At the end of LPAZ RAU2 (c. 1800 cal BC) there is a slight increase in pasture indicator, namely, *Ranunculus acris*-type, *Senecio*-type and

Pteridium aquilinum as well as micro-charcoals (>50 µm) and Poaceae, which since c. 2000 cal BC points to human activities in the surroundings of the mire (Fig. 3). It is suggested that small kin groups frequented the valley and the surrounding montane and subalpine altitudes for hunting or trading (e.g. Pass Thurn, Assmann 1967). (ii) Furthermore in 2600/2500 cal BC, the advance of the *Pasterze* glacier in the Eastern Alps, the *Gepatschferner* glacier in the Central Alps (Nicolussi and Patzelt 2000; Nicolussi et al. 2009) and the *Unteraar* glacier in the Western Alps (Hormes et al. 1998) is known to have occurred. Additionally the diminished micro-charcoal values (>50 and >100 µm) due to reduced local natural fire before 2400 cal BC indicate wetter and cooler conditions (Clark 1988; Tinner et al. 1999; Cubizolle et al. 2012). Therefore, these variations in the forests at approximately 2500 cal BC are likely due to both climatic reasons and beginning anthropogenic influence (Damm 1998).

Distinct evidence of an opening of the forest canopy in the mire's surroundings is found in the Early Bronze Age, approximately 2000 cal BC, in the gradually decreasing values of *Picea* and subsequently increasing values of Poaceae, pasture indicators (e.g. *Plantago lanceolata*-type) and slightly increasing charcoals (>50 µm). This development takes approximately 170 years (Fig. 3; Table 6), and then a secondary succession with *Alnus* and *Betula* begins. In lower altitudes, *Corylus* also shows higher values because of the more open vegetation and resulting higher pollen record. This is clear evidence of colonisation in the region around Kitzbühel. Also the charcoal values show that the opening of the forest coincides with intentional fire activity. However at approximately 2000 cal BC, a climatic timberline depression of approximately 100 m has been documented in the Kauner Valley by Nicolussi et al. (2005). Due to unfavourable climate conditions a fluctuation of the timberline between 100/150 m (Patzelt 1975; Lang 1993) and 300 m (Burga 1991) is described. As mentioned above, *Alnus* is increasing because of the better growing conditions, damp soils and lower evaporation (Moore et al. 1984), caused by the decline of the forest. So the increase of *Alnus* underlines a climatic explanation in addition to the anthropogenic factors. At approximately 4,200 cal BP (2250 cal BC), the cold/wet climatic deterioration "Bond event 3" occurs (Bond et al. 1997; Wanner et al. 2008). Since the Early Bronze Age, a few archaeological findings, such as a flanged axe, a grip plate sword or winged axes, prove human presence in the area (Plank 1968). In addition transhumant activities are conceivable. According to Oeggl (1988), the first human disturbance of the vegetation of eastern Tyrol occurs at 1850 cal BC and includes moderate activities, such as forest clearing with possible pasturing.

After 170 years of forest regeneration, a second opening (c. 1700–1500 cal BC) is observable in the pollen diagram. Local logging is distinctly observable from approximately 1400–1140 cal BC (Fig. 3; Table 6). This clearing is represented by decreasing values of *Picea* and *Abies* and increasing values of charcoals (in particular >100 µm), all of which suggest local fire caused by man (Fig. 5). Moreover settlement indicators are apparent, especially the spread of *Plantago lanceolata*-type and cereal pollen, indicating farming activities in the vicinity. Additional archaeological findings, such as a beater for butter-making (Preuschen and Pittioni 1937) indicate alpine pastoralism. This pattern is again visible from 1050-950 cal BC and indicates a typical clearing. A product moment correlation indicates that *Abies* is highly negatively correlated with charcoals > 50 µm ($r = 0.3$; $P < 0.01$). The indicator curve for pasture remains at low values; so mining activities are obvious—as opposed to land reclamation for pasturing—because the Kelchalm exploitation area is located 1 km from the Rauber mire. Furthermore at approximately 1230–1160 cal BC, the heavy metal analysis of the peat sequence shows enhanced values for Cu/Sc, Sb/Sc, (Fig. 4) and also slightly higher for As/Sc (Table 5). Considering the adjacent copper ore deposit, this suggests increasing pollution by heavy metals as a consequence of ore exploitation activities in the vicinity of the mire. Additionally since c. 1000 cal BC, the rising mineral values of the LOI analysis indicate more erosion caused by forest clearing and mobilization of bare soil. Moreover the *Botryococcus* peak suggests higher water levels in the mire and so wetter conditions. This effect can be tied to the multiphase climatic deterioration, "Löbben", from 1800 to 1300 cal BC (Patzelt and Bortenschlager 1973; Patzelt 1977) or 2200–1410 cal BC (Nicolussi and Patzelt 2000). The additive human impact is validated by archaeological findings that confirm mining activities during the Late Bronze Age. A multitude of archaeological artefacts specific to ore exploitation, such as mallets, a trough for ore panning, and spoons or shovel fragments made of *Picea* or *Abies* prove that the Kelchalm was a mining centre in the Middle Bronze Age (Preuschen and Pittioni 1937; Klaunzer et al. 2010). Dendrochronological analyses of these items date several wooden artefacts to between 1389 and 1237 cal BC (Pichler et al. 2009, 2010). Furthermore, stray finds, such as a bronze median-winged axe (TLMF 1830) or a bronze lance head (TLMF 1891; Vogl 1929), in the region of Kitzbühel date back to the Urnfield period between 1330 and 1080 cal BC. Previous studies from other bogs in the study area—Giering near Kitzbühel (Bortenschlager and Bortenschlager 1981) and Wasenmoos near the Pass Thurn (Bortenschlager 1976)—reveal anthropogenic influence on the vegetation on a regional scale (end of LPAZ RAU2 and RAU3, c. 1800–970 BC).

The peak in heavy metals Cu/Sc, Sb/Sc and anthropogenic Pb during Roman Times (Fig. 4) cannot be linked

Table 6 Opening and clearing cycles determined from the pollen diagram of the Rauber mire

Opening or clearing	Depth [cm]	Analysed strata (*n*)	Time [AD/BC]	Lpaz (RAU-)	*Picea*	*Abies*	Charcoal (>50, >100 µm)	Pasture indicators	Settlement indicators	Cultural indicators
13th	6-2	3	1900-1975	7	↙	↙	↗	↙	↗	↗
12th	18-10	5	1700-1840	7	↙	↙	↗	↗	↗	↗
11th	28-24	3	1530-1601	6	↙	↙	↙	↗	↗	↗
10th	36-30	4	1400-1500	6	↙	↙	↗	↙	↗	↗
9th	44-40	3	1240-1330	5/6	↙	↙	↗	↗	↗	↗
8th	53-50	4	1000-1100	5	↙	↗	↗	↗	↗	↗
7th	59-56	4	8700-945	5	↙	↙	↙	↗	↗	↗
6th	61-60	2	750-800	5	↙	↙	↗	↗	↗	↗
5th	72-70	3	-50-180	4	↙	↙	↗	↗	↗	↙
4th	85-80	8	-1050--950	3/4	↙	↙	↗	↗	↗	↙
3rd	98-89	6	-1400--1140	3	↙	↙	↗	↗	↗	↗
2nd	106-100	4	-1700--1500	3	↙	↗	↗	↗	↗	
1st	113-110	4	-2000--1820	2	↙	↙	↗	↗	↗	↙

The depth layers, numbers of strata documenting the glade, the duration of the openings or clearings and the local pollen assemblage zones (LPAZ) are indicated on the left. On the right, the biostratigraphy of single arboreal taxa, charcoals and indicator species are represented. Symbols: ↙ decreasing, ↗ increasing, grey arrows (11.5 %) indicate deviations from the opening/clearing pattern

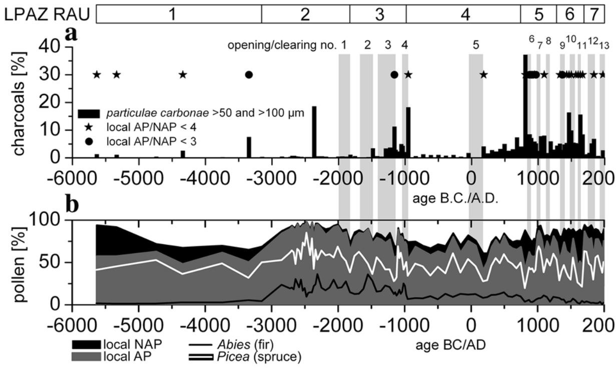


Fig. 5 The AP/NAP index as an indicator of landscape openness. **a** Charcoals, represented as percentages from the defined pollen sum of AP + NAP – Cyperaceae (*black column*) as a proxy of fire activity, opening/clearing cycles (*grey sections*), index values higher than four (*asterisk*) and higher than three (*dot*), **b** Percentage values of local NAP (*black silhouette curve*) and AP (*grey silhouette curve*) as well as percentage curves of *Picea* and *Abies*

to local mining activities. The pollen diagram reflects human activities as represented by settlement, pasture and cultural indicators, and the utilisation of the forests is visible due to a clearing phase (50 cal BC–cal AD 180) and decreasing values of *Picea*. In addition the charcoals (>50 and >100 µm) remain at low levels, so the small heavy metal peak during Roman Times is likely an extra-regional signal. The signal is visible in comparable studies, e.g. of the Greenland ice core (Hong et al. 1994; Rosman et al. 1997) and peat sediments in Switzerland (Shotyk et al. 1998, 2001), the United Kingdom (De Vleeschouwer et al. 2010), Sweden (Renberg et al. 1994; Bränvall et al. 1997) and Spain (Martinez Cortizas et al. 1997, 2002). Additionally there is no archaeological information about ore exploitation during this time. However this does not exclude ongoing moderate exploitation activities since the Iron Age, as opposed to a booming mining industry.

From c. cal AD 1200 on, the heavy metal values (Sb/Sc, Cu/Sc, As/Sc and anthropogenic Pb) again show higher values until c. cal AD 1560 (Fig. 4; Table 5). This is too early for mining activities in the Kitzbühel region because the historical sources mainly show silver mining southwest from Kitzbühel to the Röhrerbühel and Schattberg/Sinnwell since the 15th/16th century (Mutschlechner 1967, 1968). Additionally there is archaeological evidence of exploitation activities near the analysed mire at the mining site (Kelchalm) in Early Modern Times from 1769 (Posepny 1880) to 1908 (Preuschen and Pittioni 1937). In addition dendrochronological analyses (Pichler et al. 2009) of wooden artefacts, namely two boards, split wood and one round timber (all *Picea*) from the archaeological excavation of Preuschen and Pittioni (1937; Klaunzer et al. 2010), date between cal AD 1450 and 1565. So the rise in the geochemical values cannot be connected with an erosive effect because the LOI analyses show relatively stable organic matter values of 95 %. Additionally the values for charcoals (>50 and >100 µm), which can hint at slash and burn activities, are lower than earlier when the low heavy metal values occur. So the explanation for these elevated values during the 13th/14th century is either (i) water level oscillation and redeposition of the elements, or (ii) a certain mobility of the elements in sparsely decomposed and compacted peat. Water levels can fluctuate by approximately 30 cm (Hölzer 1977), so heavy metals can be remobilised. Clymo et al. (1990) showed a downward movement of Pb and Cu depending on the concentration of H_2S in a peat deposit, and Urban et al. (1990) were able to detect clear evidence of Pb mobility in the upper layers of peat lands. Additionally Hölzer and Hölzer (1987, 2003) and Damann (1978) discuss the displacement of trace elements and/or the enrichment of the groundwater level. Therefore the detected peaks could originate from the mining activities in the 15th/16th century but are displaced downwards.

Except for the forest around the exploitation area Kelch alm shows a change from a spruce-fir forest (Piceeto-Abietetum), with more or less full coverage to a spruce forest (Piceetum) over time, so wood was never a limiting resource. The combined values of *Picea* and *Abies* never fall below 23 %. For all samples, *Abies* reaches an average of 11 % and *Picea* 49 %. According to Huntley and Birks (1983), *Abies* pollen values of ≥5 % are assumed to indicate a significant presence in the surrounding forests, and *Picea* pollen values of ≥25 % are assumed to represent areas where spruce-dominated forests are abundant. The conclusion that the amount of wood was sufficient for mining, settlement and agricultural activities is comparable to other studies from Killarney Valley (Ross Island/Ireland, Mitchell and Cooney 2004) and Brixlegg (Mauken/Austria, Breitenlechner et al. 2013) and with a study of more massive land use change also from the Mitterberg (Bischofshofen/Austria, Breitenlechner et al. 2014).

Conclusions

In this multi-proxy study we combined analyses of pollen, micro-charcoals and heavy metals to represent vegetation changes caused by mining activities and land use changes due to settlement and agricultural activities in the area of Kitzbühel. In order to validate the results, archaeological and dendrochronological analyses were used. It was possible to confirm with palynological and geochemical methods the two mining phases during the Bronze Age and Early Modern Times. The palynological analysis warranted the following conclusions:

(i) The first human impact on the vegetation is assumed to be in the Early Bronze Age (c. 2000 cal BC). The values of *Picea* drop, and settlement as well as pasture indicators begin to rise to indicate human presence together with grazing livestock. The next decline in *Picea* values (c. 1400–1100 cal BC) is synchronous with the appearance of cereals at c. 1200 cal BC. Therefore this is the period where the area was settled with animal husbandry and agricultural activities. The reason for an augmented immigration of people might be the abundant copper ore deposits, but the colonisation of the Leuken Valley occurs earlier and was not connected with mining.

(ii) The high altitudes of the Kelchalm, which are next to the mining activities, might have also been used for alpine pasture since the Bronze Age, as reflected by an increasing pasture indicator curve and archaeological artefacts, such as a beater for butter-making.

(iii) The anthropogenic influence may have caused changes in the vegetation and a reduction of the forest but was never limited by demand for resources. After the regression of mining activities, the forests in the surrounding area began to regenerate and reforestation was not necessary. At any time, the miners had enough wood for ongoing exploitation and processing activities. However from Early Modern Times a supply of wood is known to have come from the surrounding valleys, but this may have been due to economic reasons or represented a tactical distribution of tasks.

(iv) If we compare the human interventions in prehistory and Early Modern Times it is conspicuous that in more recent times, the removal of the forest is taking place at shorter intervals and for shorter durations (Table 6), which shows an intensification of forest use over time.

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