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Barbara Viehweider

The palaeoecological effects of prehistoric and historic mining on the vegetation and the environmental implication.

The example of Kitzbühel (North Tyrol, Austria)

ABSTRACT: *In the following, parts of a study that deals with the impact of prehistoric and historic mining on the environment and the effects of the associated subsistence economy on the vegetation in the Kitzbühel region (North Tyrol) are presented. For this study, the reconstruction of the former vegetation and its changes over time plays an essential role.*

In total, three phases of concentrated human impact are defined. A first impact on the local vegetation occurs during the Bronze Age (ca. 1600–800 BCE). At the end of the Latène period (ca. 200 BCE), a second phase of intense human influence on the vegetation with cultivation of cereals and livestock farming takes place. This phase continues until the Middle Roman Period (ca. 160 CE). A further intensification of use starts in the High Middle Ages (ca. 970 CE) and continues until the present.

The anthropogenic phase during the Bronze Age and the first half of the third phase during the Middle Ages and Early Modern Times are characterized by mining activities in the area of Kitzbühel. This is proved by geochemical analysis of the peat and validated by archaeological data and historical sources.

KEYWORDS: POLLEN ANALYSIS, VEGETATION RECONSTRUCTION, HEAVY METAL ANALYSIS, EASTERN ALPS, BRONZE AGE, MINING

Introduction and study area

Since the Neolithic, the natural landscape has been influenced by humans, either by settlement activities (e.g. urban development, agriculture) or by mining activities. This interference in natural regions induces long-lasting ecological changes in the vegetation of the affected area.

The Eastern Alps hide a multiplicity of mineral raw material deposits which have been exploited since the last ice age. The investigation area comprises the mining district of Kitzbühel (Fig. 1) which constitutes, together with the mining regions of Mitterberg in Salzburg and Schwaz-Brixlegg in North Tyrol, a significant supra-regional production area of copper.

The objective of the study presented here was to evaluate the consequences of single mining activities (exploitation, ore beneficiation, smelting) and associated settlement and agricultural activities on the local vegetation, based on pollen analysis. The palynological analysis of peat deposits allows vegetation reconstructions since the Neolithic and bridges the gap between the times (Bortenschlager, 1976; Behre, 1981; Behre and Kucan, 1986). In order to relate vegetation changes to mining activities, additional geochemical analyses were conducted on peat deposits (Shotyk, 1996; Martínez-Cortizas, et al., 2002; Breitenlechner, et al., 2010, 2013, 2014; Mighall, et al., 2002a, 2002b).

Therefore, three mires in the Kitzbühel region were palynologically and geochemically investigated. The “Rauber” mire (RAU) is located in immediate vicinity to the prehistoric exploitation site of Kelchalm (Pittioni, 1930, 1933, 1935, 1936, 1937, 1938, 1948, 1951, 1959, 1967; Klaunzer, 2008; Koch Waldner 2016) on 1754 m a.s.l. (Fig. 2). The second mire studied, called “Untermoosberg” (UMB), is located in the bottom of the valley (858 m a.s.l.) in the surroundings of prehistoric ore beneficiation and smelting sites at Jochberg. The third mire, called “Bichlachmoor” (BLM), is situated on the Lebenberg (Scheiber, 2011) near the pond “Gieringer” (790 m a.s.l.), east of the town Kitzbühel, and is studied with regard to the impact of agriculture and settlement activities in connection with mining (Fig. 2).

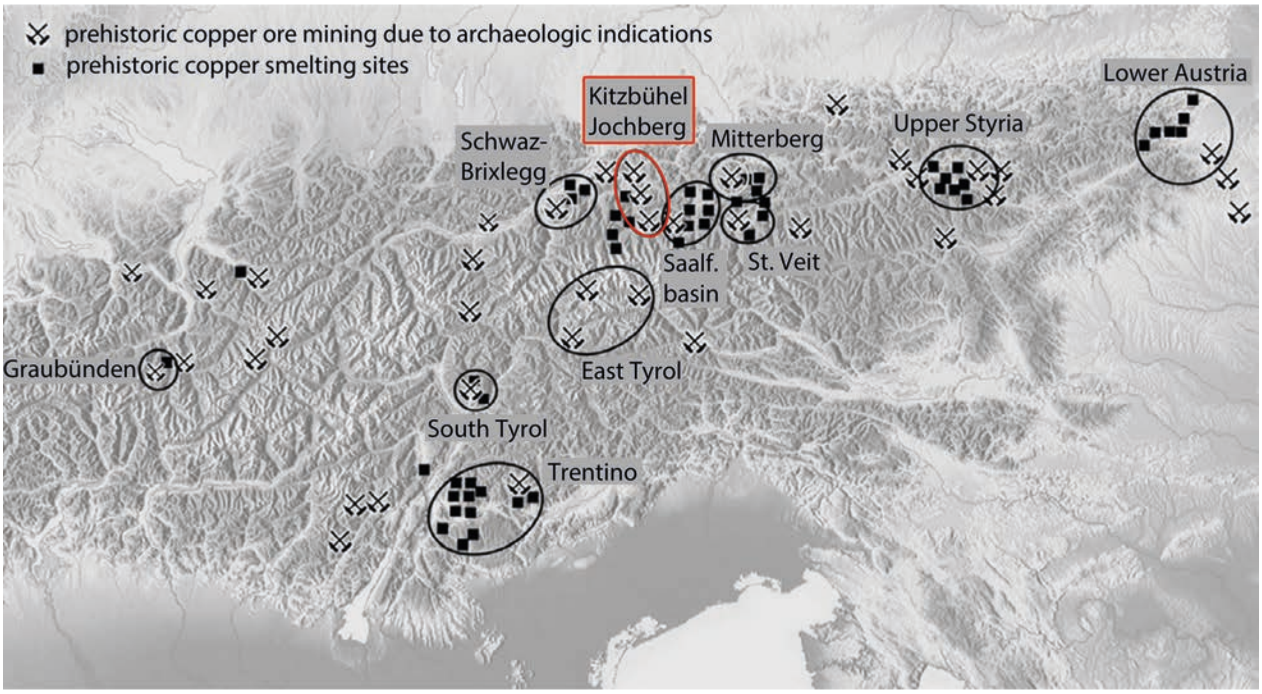

Fig. 1. Copper ore deposits and mining centres with evidence of prehistoric exploitation in the Alps (modified from Bartelheim, 2007 and Stöllner, 2009 with additions). The red circle indicates the investigation area Kitzbühel.

Material and Methods

Laboratory Methods

Former changes in the vegetation and land use are reconstructed by a pollen analysis from peat deposits. This is possible because pollen is distributed homogeneously by the wind, is chemically resistant and well preserved in peats and lake sediments (Faegri and Iversen, 1993).

For a first exploratory analysis, standardized subsamples with a constant volume of 1 cm³ were taken in intervals of 10 cm. Then, for a more intensive research, the cores were sampled in 5, 2, or 1 cm intervals. Before, chemical treatment tablets (*Lycopodium* sp., Department of Quaternary Geology, University of Lund) with a defined amount of exotic pollen were added to calculate the pollen concentrations (Stockmarr, 1971). The chemical digestion of the samples for the palynological analysis was made following the usual standardized methods by using chlorination (NaCl, HCl), acetolysis (acetic anhydride) and, if necessary, hydrofluoric acid (HF) treatment (Erdtman, 1960; Seiwald, 1980).

Durable mounts were prepared, using glycerine and coloured with fuchsine. The identification and quantification of the pollen was conducted under a light microscope with 400x magnification (in critical cases with 1000x magnification and supported by phase-contrast). For generating robust data quality, every sample was counted until standardized 1000 arboreal pollen (AP) grains. The pollen and spore types were determined with standard identification keys of the central European pollen flora (Punt, 1976; Punt and Clarke, 1980, 1981, 1984; Punt, et al., 1988; Moore, et al., 1991; Reille, 1992, 1995; Faegri and Iversen, 1993; Beug, 2004) and the modern reference collection at the Botanical Institute of the University of Innsbruck. In parallel manner, micro charcoals (*particulae carbonae* of size classes < 50 µm, > 50 µm, > 100 µm) and non-pollen palynomorphs (NPPs) like spores of fungi and zoological micro fossils were recorded as well.

Openness of the landscape

The ratio of arboreal (AP) and non-arboreal pollen (NAP) is an indicator of the openness of the landscape (Aario, 1940; Svenning, 2002; Soepboer and Lotter, 2009) and, in combination with anthropogenic indicators sensu Behre (1981), also a measure of human interference. Herbal taxa percentages of 4-10 % have traditionally been interpreted as an evidence of a landscape fully covered by forests (Vera, 2000). Nevertheless, NAP percentages from interglacial sites correlate well with vegetation openness (Svenning, 2002). Therefore, only taxa with local presence in the respective mire were selected for the calculation. So, the shrubs and the dwarf shrubs were counted to the NAP because they are an additional indicator for open vegetation (Svenning, 2002). A ratio of four, meaning 80 % local climax tree species and 20 % terrestrial, non-arboreal species, respectively a proportion of 4/1, corresponds to the today's open vegetation on the Kelchalm and the surroundings of the mire. If this value is observed in other depths, too, vegetation conditions that are similar to today can be assumed based on uniformitarianism (Lyell, 1830).

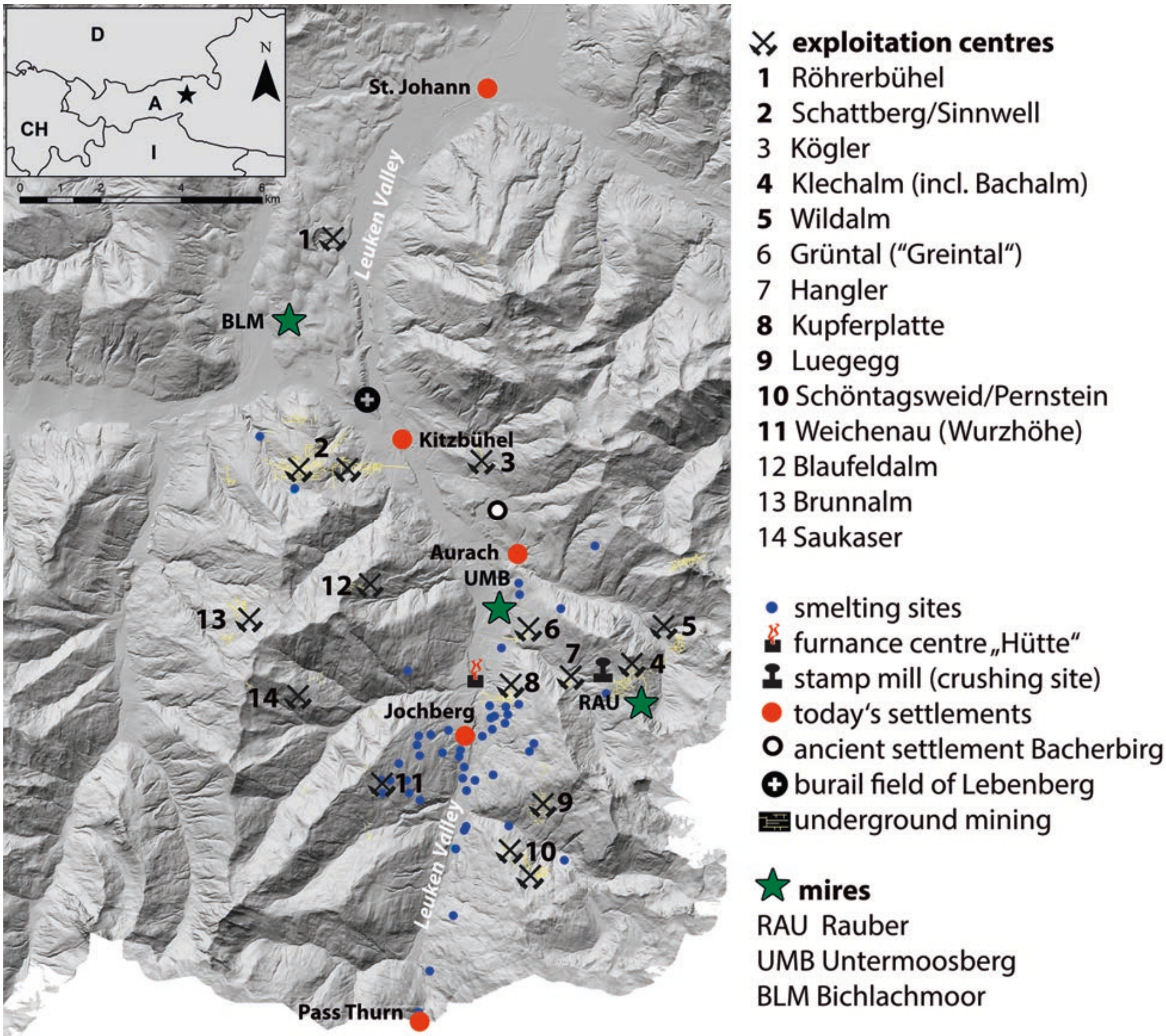

Fig. 2. Investigation area of Kitzbühel with the most important exploitation centres, todays and former settlements, smelting sites and famous archaeological sites. The green stars indicate the three mires analysed (basis map © Land Tirol 2008).

Reconstruction of human impact

The cumulative curves such as pasture/settlement/cultural indicators, charcoals and coprophilous fungi are indicating a human impact. To standardize the pollen data from all three mires investigated (RAU, UMB, BLM), the percentage values were transformed into z-scores, whereby the mean corresponds to zero and the standard deviation is one. This method is a statistical measurement of the data’s relationship to the mean in a group of scores. Negative values are below and positive values are above the mean.

Scores which are higher than zero were interpreted to be indicative for human activities, negative scores were considered as natural occurrence of the taxa included in the cumulative curves. This method enables us to undertake the direct comparison of the chronological development of human activities at different sites, located in different altitudinal zones.

Vegetation reconstruction

Surface pollen samples from moss cushions are used to detect the recent pollen rain in an investigation area. The reconstruction of past vegetation is performed by the “modern analogue technique” (Overpeck, et al., 1985). Here, fossil pollen spectra are compared and numerically evaluated with recent surface pollen samples from different vegetation types in the investigation area, for a similarity measure. This serves a better interpretation of the fossil pollen spectra (Gaillard, et al., 1992; Hjelle, 1997, 1999; Mazier, et al., 2006; Mazier, et al., 2009).

For the reconstruction of the former vegetation, the pollen calibration data set of the recent surface samples was compared with the subfossil samples. Thereby, the data of the three mires (RAU, UMB, BLM) and data from additional three mires (HAS, WAS, FIB), analysed in the past and located in the surroundings of the investigation area, were integrated in the reconstruction (Bortenschlager, 1976; Eidenhammer, 1999). First, a cluster analysis was conducted to find similarities and to build clusters of vegetation types. In a second step, the defined clusters underwent a Euclidian distance analysis. This analysis reveals similarities of the samples whereby the most likely group membership of a fossil sample or a depth to a recent surface sample was calculated and graphically displayed.

AMS-Radiocarbon dating

Radiocarbon dating is indispensable for the creation of a detailed chronology of the pollen and geochemical sequences by which a temporal sequence of the environmental changes caused by mining activities is made visible.

The radiocarbon dating of ten samples from the peat core Rauber has been conducted at the VERA-Laboratory of the Isotope Research at the Faculty of Physics, University of Vienna, Austria. The dating of the other two mires Untermoosberg (13 samples) and Bichlachmoor (10 samples) was done in cooperation with the Klaus-Tschira-Laboratory for Radiometric Dating Methods at the Curt-Engelhorn-Centre for Archaeometry in Mannheim, Germany.

The calculations concerning the age-depth model were done at a 95 % confidence range with 1000 iterations. The calibrated age values correspond to a 2σ-confidence interval. The calendar age point estimates for depths were based on weighted average of all age-depth curves with a linear interpolation between the dated levels. These chronologies were used for drawing time linear pollen diagrams and for all temporal indications (converted in BCE/CE) in the text.

Geochemistry – Heavy Metal Analysis

Parallel to the pollen analysis, geochemical analysis of copper (Cu), arsenic (As), antimony (Sb), scandium (Sc), titanium (Ti) and lead (Pb) were conducted on the peat samples of the Rauber and Untermoosberg mires. From the peat core Rauber, 30 samples, each of a dry weight of 0.2-1 g, were taken every 2-5 cm between 25 and 150 cm. The mire Untermoosberg provided 29 samples with a dry weight of 0.2-4.7 g taken every 2 cm between 4-28 cm and every 2 or 6 cm between 40 and 82 cm depth. The peat samples for geochemical analysis were lyophilized for 24 h and packed in plastic boxes for the transport to the laboratory of the Curt-Engelhorn-Centre for Archaeometry in Mannheim, Germany.

For both mires, Rauber and Untermoosberg, the elements Cu, As, Sb and Sc were analyzed by neutron activation analysis (NAA) according to Perlman and Asaro (1969) and Kuleff and Djingova (1990).

Since the elements Ti and Pb cannot be measured by NAA, they were analysed by help of a Quadrupole Inductively Coupled Plasma-Mass Spectrometer (Thermo XS II Quadrupole equipment, Q-ICP MS) (Houk, et al., 1980; Shotyk, et al., 1997, 1998).

For the discussion of the geochemical data measured, the values of the volatile metal Cu and the metalloids As and Sb were normalized by the conservative element Sc (Shotyk, et al., 1998; Shotyk, et al., 2001), because 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, 1999a). The Sc values of both measurements, NAA and ICP-MS, are highly congruent, so the NAA Sc values were used to normalise because the concerned elements were measured with the same method.

Results and Discussion

Openness of the landscape

In the surroundings of the Rauber mire (RAU), the AP/NAP ratio of the local climax species indicates several forest openings in the past. In ca. 4300 and again in 3300 BCE, the values of NAP increase, resulting in a ratio of 4 (Fig. 3). This reflects a sparse tree covering. Then, the forest becomes denser, for more than 2000 years. In ca. 1100 and 900 BCE further openings are reflected by the AP/NAP ratio. During Roman Times around 170 CE, a change in the forest vegetation is visible, too. Since ca. 900 CE, the human impact on the forest has been obvious and a general opening, clearing and decimation of the forest takes place.

In the lowermost samples of the Untermoosberg (UMB) peat core, an AP/NAP ratio of 5 reflects open vegetation. Then, at about 5000 BCE, the NAP increases, but in an insufficient manner, to a ratio of 5 (84%/16%) or less. Another opening of the vegetation is visible in ca. 1200 BCE which is additionally underlined by a ratio of 5. After ca. 1460 CE, a fundamental and consistent decline of the forest is reflected. From ca. 1700 CE on, even a ratio of 4 is achieved (Fig. 3).

Between ca. 1300 and 580 BCE, the peat core of the Bichlachmoor mire (BLM) reflects a slight opening of the vegetation with a rise of NAP from 1 % to 5 % on average. Nonetheless, a ratio of 5 was not achieved. During the Iron Age and Roman Times, the NAP decreases again. Since the Late Roman Times at ca. 300 CE, higher values with an average of 7.5 % of NAP have been reflected (Fig. 3). In the High Middle Ages, since ca. 1300 CE, the opening of the landscape has been sustained by an AP/NAP ratio of 4 (80%/20%).

Reconstruction of Human Impact

A comparison of the three investigated mires (Bichlachmoor, Untermoosberg and Rauber) indicates that the anthropogenic phases are synchronous, with exception of the phase during the Iron Age/Roman Times, which expresses a generally weak signal. These phases of intense human activities are characterized by positive

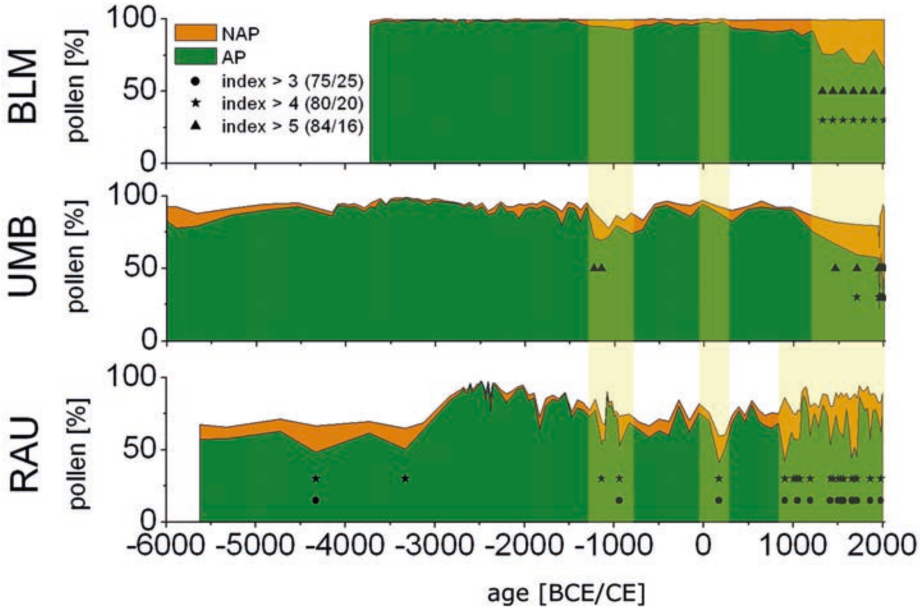

Fig. 3. Percentages of local arboreal (AP) and non-arboreal pollen (NAP) of the Rauber mire (RAU), the Untermoosberg mire (UMB) and the Bichlachmoor mire (BLM). The three different indices are presented with symbols, a ratio of > 3 is displayed in form of dots, > 4 in form of asterisks and > 5 in form of triangles. The yellow shaded bars indicate the phases of increased human impact.

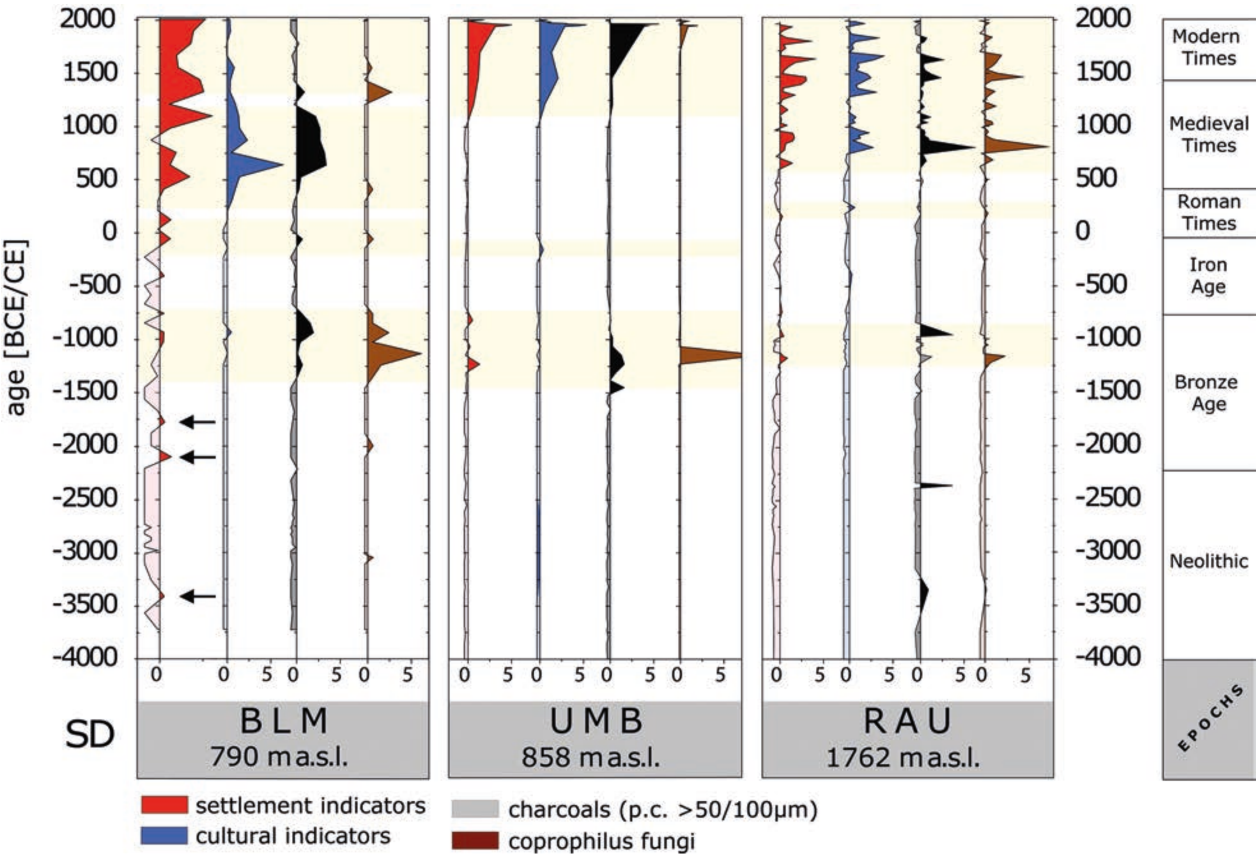

Fig. 4. Z-transformation (mean value = 0, SD = 1) of the following cumulative curves received from analysis of the peat of the three mires Rauber (RAU), Untermoosberg (UMB) and Bichlachmoor (BLM): settlement/cultural indicators, charcoals (particulae carbonae > 50/100 µm), coprophilous fungi. The yellow shaded bars indicate the phases of increased human impact.

z-scores of the settlement indicators as well as cultural indicators (mainly Cerealia). In addition, values above the mean of large sized charcoals (*particulae carbonae* > 50/100 µm) and of coprophilous fungi give evidence of human presence (Fig. 4). In contrast, the percentage values of the climax trees (*Picea* and *Abies*) decrease.

The Bichlachmoor mire, which is an archive of a regional pollen signal, indicates settlement activities in the wider surroundings of the investigation area already during the Neolithic Times and Early Bronze Age (ca. 3400, 2100 and 1800 BCE). Nevertheless, the other two analyzed mires don't show any human impact on a local scale

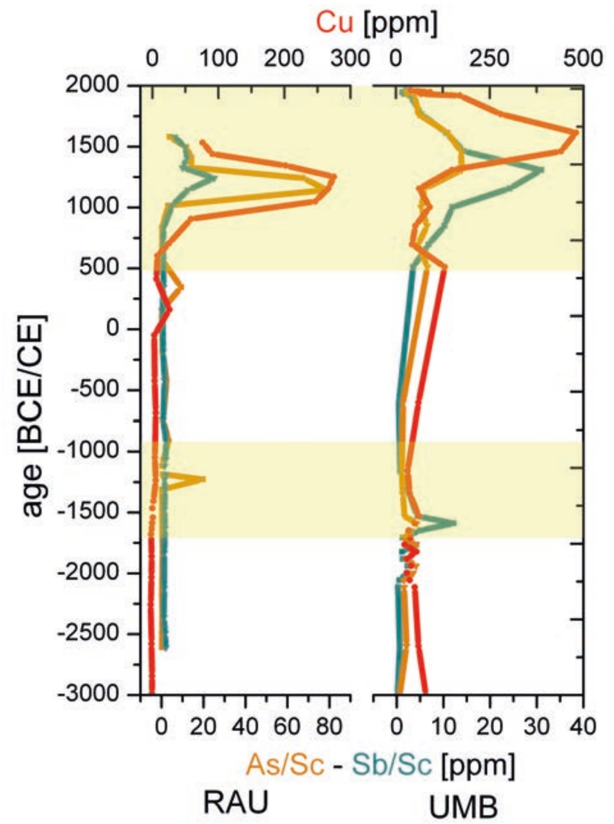

Fig. 5. Summary of the heavy metal analysis. The yellow bars indicate the mining activities in the research area during the Bronze Age and Medieval Times. Cu, As, Sb, and Sc were measured with NAA. Sc is the element used for standardization.

(Leuken Valley), apart from the charcoal peaks of the Rauber mire which can be interpreted as natural fire events, too.

A first phase of enhanced human activity with effects on the vegetation occurs during the Bronze Age (ca. 1250–700 BCE). This phase is associated with mining activities based on geochemical analysis showing increased values of Sb/Sc, As/Sc and Cu/Sc between ca. 1200 and1000 BCE (Fig. 5). Then, during the Iron Age, the cumulative curves, especially of settlement indicators, fall below the average, suggesting that the anthropogenic impact is reduced. Only at the end of the Latène period (ca. 200 BCE), a second phase of intense anthropogenic influence on the environment with crop cultivation and animal husbandry is recorded in the pollen diagram of UMB. This second period continues until the Middle Roman Times (ca. 200 CE).

A further intensification of human influence on the environment occurs in the Early Middle Ages (ca. 500 CE). Here, the values show a maximal standard deviation between four and six (RAU 3.9; UMB 5.3; BLM 6.3, Fig. 4). This anthropogenic phase and utilisation of the area continues until today. Since the High Middle Ages (ca. 1200–1550 CE), elevated heavy metal values indicate a further mining phase (Fig. 5). Archaeological finds and findings (Leib, 2013; Pichler et al., 2009) and numerous historical sources as well (Mutschlechner, 1968; Widmoser, 1967; Rupert, 1976) validate the palynological and geochemical results.

In determined time periods, namely in the Neolithic, Late Bronze Age, and Early Modern Times, the cumulative curves (settlement indicators, crops and charcoals) show single events of increased human impact during the cultural epochs. An intensification of agriculture over time is evident, too. This is also manifested in the development of the AP/NAP index, where the herbaceous proportion increases over time indicating an opening of the landscape.

Vegetation reconstruction

The analysed mires are located in different altitudes and in different vegetation belts of the investigation area. That is why each of the sites reflects a different vegetation development. The mires Hasenmoos (HAS), Fieberbrunn (FIB) and Bichlachmoor are located in the low montane level beneath 800 m a.s.l. The mires Untermoosberg and Wasenmoos are located below 1300 m a.s.l., that is to say at the high montane altitude. Only the Rauber mire is situated in the low sub-alpine zone with more than 1750 m a.sl.

The similarity analysis shows that since 5000 BCE, *Picea* has already been immigrating into the study area and evolving spruce forests (Piceetum). About 4500 BCE, Abies immigrates and establishes in the forests; spruce-fir forests (Abieti-Piceion) develop. In the Rauber mire during the Bronze Age and in the UMB mire during Iron Age, forests with an even higher abundance of *Abies*, so called fir-spruce forests (Piceeto-Abietetum) are displayed. In low montane regions (mires BLM, FIB, HAS) mixed spruce-fir forests with beech (Abieti-Fagetum) are manifested (Fig. 6).

Since the High Middle Ages, the species-rich mixed forests are substituted by pure spruce forests (Piceetum).

Conclusion

Settlement and change of land use

The results concerning the colonization of the investigation area provide the following conclusions:

i) When comparing the vegetation development of the three mires analysed (Rauber, Untermoosberg, Bichlachmoor) it becomes apparent that the phases of anthropogenic impact are synchronous during the Bronze Age and Medieval Times. These periods are characterized by decreasing values of the climax-tree species spruce (*Picea*) and fir (*Abies*) and increasing values of pasture, settlement, and cultural indicators, as well as micro-charcoals.

ii) The first human impact on the vegetation is detected in the Early Bronze Age (ca. 2000 BCE) in the two mires Rauber and Bichlachmoor. The values of spruce (*Picea*) descend and settlement as well as rising pasture

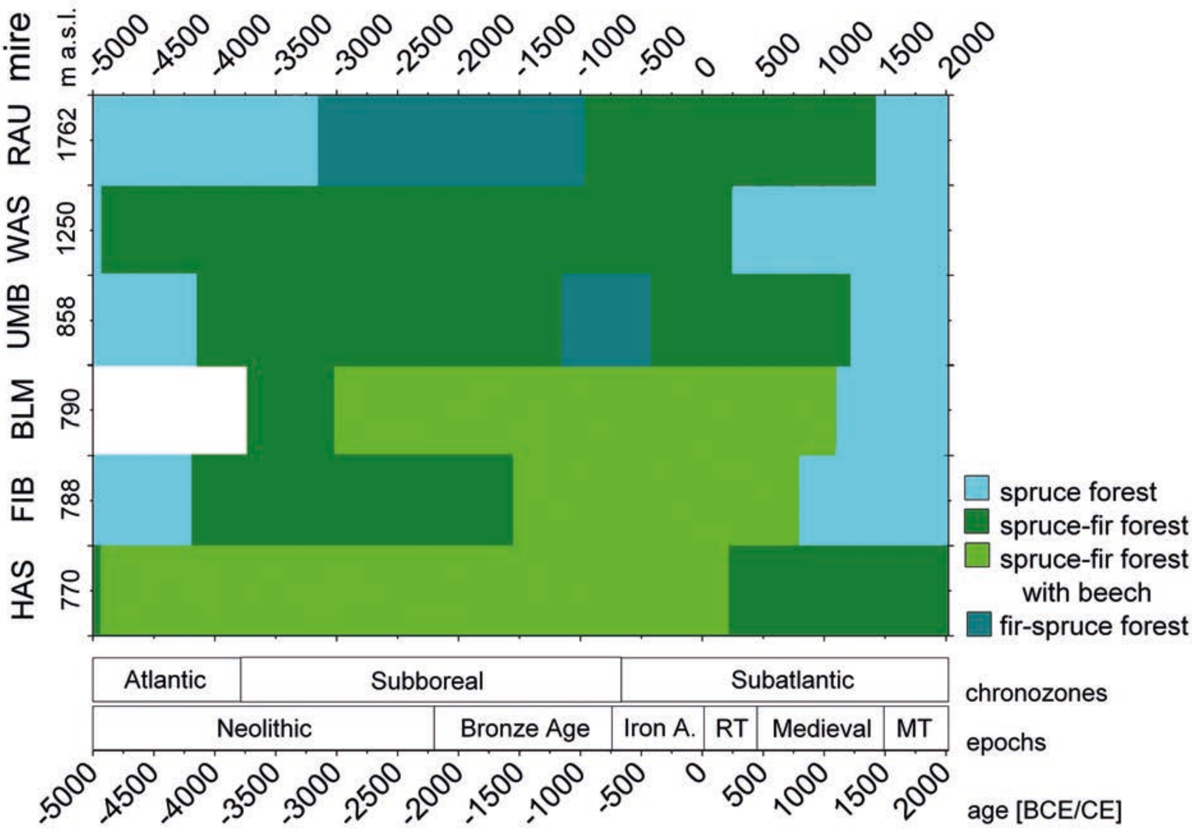

Fig. 6. Vegetation development of the Kitzbühel area in different altitudes since the Middle Neolithic. Abbreviations: HAS = Hasenmoos, FIB = Fieberbrunn, BLM = Bichlachmoor, UMB = Untermoosberg, WAS = Wasenmoos, RAU = Rauber, RT = Roman Times, MT = Modern Times.

indicators proves the human presence, together with grazing livestock. The next decline in spruce values (ca. 1400–1100 BCE) is synchronous with the appearance of cereals at ca. 1200 BCE. These are the first indications of permanent settlements suggesting that this is the period when the colonization of the area with animal husbandry and agriculture started. The reason for the stronger anthropogenic impact might be the exploitation of the abundant copper ore deposits. On the other hand, the colonisation of the Leuken Valley occurs earlier and is not connected with mining.

iii) A total of three phases of extensive human impact could be detected. A first opening of the landscape due to anthropogenic activities occurs during the transition from the Middle to the Late Bronze Age (ca. 1300 BCE). During the Iron Age, the human impact declines. A second phase of intensification begins at the end of the La Tène Period (ca. 100 BCE), visible in the pollen spectra of the mires Bichlachmoor and Untermoosberg. The phase is characterized by cereal cultivation and livestock farming as well. This intense utilization continues until the Middle Roman Times (ca. 150 CE). The Rauber mire reflects an intensification of human impact since 100 CE. A further intensification with interference with the environment is detected in the High Middle Ages (ca. 970 CE) and continues until the present.

iv) The areas of the Kelchalm that are located at higher altitudes, in close proximity to the mining activities, may also have been used for alpine pasture since the Bronze Age, as reflected by increasing pasture indicators and archaeological artefacts like a beater for butter-making.

v) Comparing the human interventions in prehistory and Early Modern Times it is conspicuous that, in more recent times, the disappearance of forest takes place in shorter intervals and for shorter durations indicating an intensification of forest use over time. Since the Early Middle Ages (ca. 800 CE), recent vegetation conditions on the Kelchalm area have been indicating the cultivation of cereals.

Exploitation, dressing and smelting

It was possible to detect two mining phases over time. The palynological and geochemical analysis leads to the following conclusions:

i) The first mining phase in prehistory is synchronous with the first phase of intense human impact in the investigation area during the Middle Bronze Age. A second mining phase could be detected in Early Modern Times.

ii) The consequences of ore exploitation on the Kelchalm are still visible today. The large ore-processing heaps leave a devastated landscape in which the vegetation regenerates slowly. Due to the collapsed galleries, small ponds characterize the landscape around the exploitation area.

iii) The anthropogenic influence may have caused changes in the vegetation and a reduction of the forest but was never limited, because of the demand for resources. After the regression of mining activities, forests in the surrounding area began to regenerate so that an active reforestation was not necessary. At all times, the miners had enough wood for ongoing exploitation and processing activities. However, since the Early Modern Times, a supply of wood has been undertaken from the surrounding valleys; but this may have been due to economic reasons or represent a tactical distribution of tasks.

Bibliography

Aario, L., 1940. Waldgrenzen und subrezente Pollenspektren in Petsamo, Lappland. *Ann. Acad. scient. Fenn. Ser. A*, *54(8)*, pp.1-120.

Bartelheim, M., 2007. *Die Rolle der Metallurgie in vorgeschichtlichen Gesellschaften.* Forschungen zur Archäometrie und Altertumswissenschaft, Bd. 2. Rahden/West.: Marie Leidorf, pp.33-82.

Behre, K.-E., 1981. The interpretation of anthropogenic indicators in pollen diagrams. *Pollen et Spores*, *23*, pp.225-245.

Behre K.-E. and Kucan, D., 1986. Die Reflektion archäologisch bekannter Siedlungen in Pollendiagrammen verschiedener Entfernung – Beispiele aus der Siedlungskammer Flögeln. In: K.-E. Behre, D. Kucan, eds. *Anthropogenis indicators in pollen diagrams*. Rotterdam, pp.95-114.

Beug, H.-J., 2004. *Leitfaden der Pollenbestimmung für Mitteleuropa und angrenzende Gebiete*. München: Dr. Friedrich Pfeil.

Bortenschlager, I., 1976. Beiträge zur Vegetationsgeschichte Tirols II: Kufstein – Kitzbühel – Pass Thurn. *Berichte des naturwissenschaftlich-medizinischen Vereins in Innsbruck*, *63*, pp.105-137.

Breitenlechner, E., Hilber, M., Lutz, J., Kathrein, Y., Unterkircher, A. and Oeggl, K., 2010. The impact of mining activities on the environment reflected by pollen, charcoal and geochemical analyses. *Journal of Archaeological Sciences, 37*, pp.1458-1467.

Breitenlechner, E., Goldenberg, G., Lutz, J., and Oeggl, K., 2013. The impact of prehistoric mining activities on the environment: A multidisciplinary study at the fen Schwarzenbergmoos (Brixlegg, Tyrol, Austria). *Vegetation History and Archaeobotany, 22*, pp. 351–366.

Breitenlechner, E. Stöllner, Th., Thomas, P., Lutz, J. and Oeggl, K., 2014. An interdisciplinary study on the environmental reflection of prehistoric mining activities at the Mitterberg main lode (Salzburg; Austria). *Archaeometry,* 56, pp.102-128.

Eidenhammer, S., 1999. *Palynologische Untersuchungen zur holozänen Vegetationsentwicklung im Raum Fieberbrunn und Brandenberg unter besonderer Berücksichtigung des anthropogenen Einflusses*. Universität Innsbruck, Diplomarbeit (diploma thesis).

Erdtman, G., 1960. The acetolysis method. A revised description. *Svensk Botanisk Tidskrift, 54*, pp. 561-569.

Faegri, K. and Iversen, J., 1993. *Bestimmungsschlüssel für die nordwesteuropäische Pollenflora.* Jena: Gustav Fischer.

Gaillard, M.J., Birks, H.J.B., Emanuelsson, U., Berglund, B.E., 1992. Modern pollen/land-use relationships as an aid in the reconstruction of past land-uses and cultural landscapes: An example from south Sweden. *Vegetation History and Archaeobotany, 1*, pp.3-17.

Hjelle, K.L., 1997. Relationships between pollen and plants in human-influenced vegetation types using presence-absence data in western Norway. *Review of Palaeobotany and Palynology, 99*, pp.1-16.

Hjelle, K.L., 1999. Modern pollen assemblages from mown and grazed vegetation types in western Norway. *Review of Palaeobotany and Palynology, 107*, pp.55-81.

Houk, R.S., Fassel, V.A., Flesch, G.D., Gray, A.L. and Taylor, E., 1980. Inductively coupled argon plasma as an ion source for mass spectrometric determination of trace elements. *Analytical Chemistry,* 52(14), pp.2283-2289.

Klaunzer, M., 2008. *Studien zum spätbronzezeitlichen Bergbau auf der Kelchalm und Bachalm, Bezirk Kitzbühel, Nordtirol*. Universität Innsbruck, Diplomarbeit (diploma thesis).

Koch Waldner, T., 2016. *Charakterisierung einer alpinen bronzezeitlichen Bergbaulandschaft anhand von archäologischen Befunden, Geländeanalysen und überregionalen Vergleichen. Räumliche und zeitliche Struktur des Bergbaureviers Kitzbühel.* Universität Innsbruck, Dissertation (doctoral thesis).

Kuleff, I. and Djingova, R., 1990. Activation Analysis in Archaeology. In: Z. Alfassi, ed. *Activation Analysis, 2*. Boca Raton, Florida: CRC-Press Inc., pp.427-489.

Land Tirol, 2008. *Amt der Tiroler Landesregierung; Abteilung Geoinformation,* LiDAR-Daten. [online]. Available at: <portal.tirol.gv.at/LBAWeb/luftbilduebersicht.show>.

Leib, S., 2013. Ein Streiflicht auf frühneuzeitliche Bergbauartefakte aus dem Raum Schwaz (Tirol). In: Montanwerke Brixlegg AG, K. Oeggl, V. Schaffer, eds. *Cuprum Tyrolense. 5550 Jahre Bergbau und Kupferverhüttung in Tirol*. Brixlegg: Edition Tirol, pp.189-205.

Lyell, C., 1830. *Principles of Geology, being an attempt to explain the former changes of the earth's surface, by reference to causes now in operation*. London: J. Murray.

Martínez Cortizas, A., García-Rodeja, E., Pontevedra Pombal, X., Nóvoa Muñoz, J.C., Weiss, D. and Cheburkin, A., 2002. Atmospheric Pb deposition in Spain during the last 4600 years recorded by two ombrotrophic peat bogs and implications for the use of peat as archive, *The Science of the Total Environment,* 292, pp.33-44.

Mazier, F., Galop, D., Brun, C. and Buttler, A., 2006. Modern pollen assemblages from grazed vegetation in the western Pyrenees, France: a numerical tool for more precise reconstruction of past cultural landscapes. *The Holocene,* 16, pp.91-103.

Mazier, F., Galop, D., Gaillard, M.J., Rendu, C., Cugny, C., Legaz, A., Peyron, O. and Buttler, A., 2009. Multidisciplinary approach to reconstructing local pastoral activities: an example from the Pyrenean Mountains (Pays Basque). *The Holocene, 19(2)*, pp.171-188.

Mighall, T.M., Abrahams, P.W., Grattan, J.P., Hayes, D., Timberlake, S., and Forsyth, S., 2002a. Geochemical evidence for atmospheric pollution derived from prehistoric copper mining at Copa Hill, Cwmystwyth, mid-Wales, *U.K. Science of the Total Environment,* 292, pp.69-80.

Mighall, T.M., Timberlake, S., Clark, S.H.E. and Caseldine, A.E., 2002b. A Palaeoenvironmental Investigation of Sediments from the Prehistoric Mine of Copa Hill, Cwmystwyth, mid-Wales. *Journal of Archaeological Science,* 29, pp.1161-1188.

Moore, P.D., Webb, J.A., Collison and M.E., 1991. *Pollen Analysis*. 2^{nd} ed. Oxford: Blackwell Science.

Mutschlechner, G. 1968. *Kitzbüheler Bergbaugeschichte. Stadtbuch Kitzbühel, Band 2. Vorgeschichte und Bergbau.* Kitzbühel: Stadtgemeinde Kitzbühel, pp.138-225.

Overpeck, J.T., Webb, T. and Prentice, C., 1985. Quantitative Interpretation of Fossil Pollen Spectra: Dissimilarity Coefficients and the Method of Modern Analogs. *Quaternary Research,* 23, pp.87-108.

Perlman, I. and Asaro, Z., 1969. Pottery Analysis by Neutron Activation. *Archaeometry,* 11, p.21.

Pichler, T., Nicolussi, K., Goldenberg, G. and Klaunzer, M., 2009. Die Hölzer des bronzezeitlichen Bergbaus auf der Kelchalm bei Kitzbühel. Dokumentation und erste Ergebnisse dendrochronologischer Analysen. *Archäologisches Korrespondenzblatt,* 39, pp.59-75.

Pittioni, R., 1930. Neue Funde von der Kelchalpe in Nordtirol. *Wiener Prähistorische Zeitschrift,* 17, pp.121-130.

Pittioni, R., 1933. Kelchalpe, Gde. Aurach, BH. Kitzbühel. *Fundberichte aus Österreich,* 1, p.193.

Pittioni, R., 1935. Aurach, GB und VB Kitzbühel. *Fundberichte aus Österreich,* 2, pp.46-47.

Pittioni, R., 1936. Kelchalpe, Gde. Aurach, GB u. VB Kitzbühel. *Fundberichte aus Österreich,* 2, p.103.

Pittioni, R., 1937. Kelchalpe, Gde. Aurach, GB u. VB Kitzbühel. *Fundberichte aus Österreich,* 2, p.178.

Pittioni, R., 1938. Aurach, GB und VB Kitzbühel. *Fundberichte aus Österreich,* 2, p.287.

Pittioni, R., 1948. Kelchalpe, Gde. Aurach, Pol. Bez. Kitzbühel. *Fundberichte aus Österreich,* 3, p.35.

Pittioni, R., 1951. Untersuchungen im Bergbaugebiete Kelchalpe bei Kitzbühel, Tirol (2. Bericht), in: *Mitteilungen der Prähistorischen Kommission, 5*, pp.37-99.

Pittioni, R., 1959. Aurach, BH Kitzbühel. *Fundberichte aus Österreich,* 5, p.71.

Pittioni, R., 1967. Aurach bei Kitzbühel, BH Kitzbühel. *Fundberichte aus Österreich,* 6, p.53.

Punt, W., 1976. *The Northwest European Pollenflora*, vol. 1. Amsterdam: Elsevier.

Punt, W. and Clarke, G.C.S., 1980. *The Northwest European Pollenflora*, vol. 2. Amsterdam: Elsevier.

Punt, W. and Clarke, G.C.S., 1981. *The Northwest European Pollenflora*, *vol. 3*. Amsterdam: Elsevier.

Punt, W. and Clarke, G.C.S., 1984. *The Northwest European Pollenflora*, *vol. 4*. Amsterdam: Elsevier.

Punt, W., Blackmore, S. and Clarke, G.C.S., 1988 *The Northwest European Pollenflora*, *vol. 5*. Amsterdam: Elsevier.

Reille, M., 1992. *Pollen et spores d'Europe et d'Afrique du nord*. Marseille: Laboratoire de Botanique Historique et Palynologie.

Reille, M., 1995. *Pollen et spores d'Europe et d'Afrique du nord, Suppl. 1*, Marseille: Laboratoire de Botanique Historique et Palynologie.

Rupert, M., 1976. Zur Geschichte des Berg- und Hüttenwesens in der Herrschaft Kitzbühel bis ins 17. Jahrhundert, Teil II/3. *Archaeologie Austriaca,* 59/60, pp.273-437.

Scheiber, E.-M., 2011. *Das spätbronzezeitliche Gräberfeld am Lebenberg bei Kitzbühel, Tirol*. Universität Innsbruck, Diplomarbeit (diploma thesis).

Seiwald, A., 1980. Beiträge zur Vegetationsgeschichte Tirols IV: Natzer Plateau, Villanderer Alm. *Ber. Nat.-med. Verein, Innsbruck,* 67, pp.31-72.

Shotyk, W., 1996. Natural and anthropogenic enrichment of As, Cu, Pb, Sb, and Zn in ombrotrophic versus minerotrophic peat bog profiles, Jura mountains, Switzerland. *Water Air Soil Pollut 90*, pp.375-405.

Shotyk, W., Cheburkin, A., Appleby, P.G., Fankhauser, A. and Kramers, J.D., 1997. Lead in three peat bog profiles, Jura Mountains, Switzerland: Enrichment factors, isotopic composition, and chronology of atmospheric deposition. *Water Air Soil Poll,* 100, pp.297-310.

Shotyk, W., Weiss, D., Appleby, P.G., Cheburkin A.K., Frei, R., Gloor, M., Kramers, J.D., Reese, S. and van der Knaap, W.O., 1998. History of atmospheric lead deposition since 12,370 14C yr BP recorded in a peat bog profile, Jura Mountains, Switzerland. *Science,* 281, pp.1635-1640.

Shotyk, W., Weiss, D., Kramers, J. D., Frei, R., Cheburkin, A. K., Gloor, M. and Reese, S., 2001. Geochemistry of the peat bog at Etang de la Gruère, Jura Mountains, Switzerland, and its record of atmospheric Pb and lithogenic trace metals (Sc, Ti, Y, Zr, and REE) since 12,370 14C yr BP. *Geochimica et Cosmochimica Acta,* 65(14), pp.2337-2360.

Soepboer, W. and Lotter, A.F., 2009. Estimating past vegetation openness using pollen-vegetation relationships: A modelling approach. *Review of Palaeobotany and Palynology,* 153, pp.102-107.

Stockmarr, J., 1971. Tablets with spores used in absolute pollen analysis. *Pollen and Spores,* 13, pp.615-21.

Stöllner, Th, 2009. Die zeitliche Einordnung der prähistorischen Montanreviere in den Ost- und Südalpen – Anmerkungen zu einem Forschungsstand. In: K. Oeggl, M. Prast, eds. *Die Geschichte des Bergbaus in Tirol und seinen angrenzenden Gebieten – Proceedings zum 3. Milestone-Meeting des SFB HiMAT vom 23.-26.10.2008 in Silbertal*. Innsbruck: Innsbruck university press, pp.37-60.

Svenning, J.-C., 2002. A review of natural vegetation openness in north-western Europe. *Biological Conservation,* 104, pp.133-148.

Vera, F.W.M., 2000. *Grazing Ecology and Forest History*. Oxon: CABI Publishing.

Weiss, D., Shotyk, W., Cherburkin, A.K., Gloor, M. and Reese, S., 1997. Atmospheric lead deposition from 12,400 to ca. 2000 yrs BP in a peat bog profile, Jura Mountains, Switzerland. *Water, Air and Soil Pollution,* 100, pp.311-324.

Weiss, D., Shotyk, W., Appleby, P.G., Cheburkin, A.K. and Kramers, J.D., 1999a. Atmospheric Pb deposition since the Industrial Revolution recorded by five Swiss peat profiles: enrichment factors, fluxes, isotopic composition, and sources. *Environ Sci. Technol, 33*, pp.1340-1352.

Widmoser, E., 1967. Das Kitzbühler Salbuch von 1416, in: *Stadtbuch Kitzbühel, Band 1*. Raum und Mensch. Kitzbühel: Stadtgemeinde Kitzbühel, pp.111-193.