Charcoal from a prehistoric copper mine in the Austrian Alps: dendrochronological and dendrological data, demand for wood and forest utilisation

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ABSTRACT

During prehistory fire-setting was the most appropriate technique for exploiting ore deposits. Charcoal fragments found in the course of archaeological excavations in a small mine called Mauk E in the area of Schwaz/Brixlegg (Tyrol, Austria) are argued to be evidence for the use of this technology. Dendrochronological analyses of the charcoal samples yielded calendar dates for the mining activities showing that the exploitation of the Mauk E mine lasted approximately one decade in the late 8th century BC. Dendrological studies show that the miners utilised stem wood of spruce and fir from forests with high stand density for fire-setting and that the exploitation of the Mauk E mine had only a limited impact on the local forests.

1. Introduction

The area of Schwaz/Brixlegg (Tyrol, Austria) in the Lower Inn Valley was well-known for silver mining in the late medieval and early modern times, when this region was the world's largest silver producer (Westermann, 1986; Hanneberg and Schuster, 1994; Bartels et al., 2006). However, silver makes up only a small proportion of the metals found in the ores of the Lower Inn Valley, which are dominated by copper (Gstrein, 1979). Today, there are no mining activities in the area of Schwaz/Brixlegg; however, several buildings and landscape features document the long mining history, which is not limited to medieval times. Many mines in this region may be partly attributed to activities in historic periods, but in some places, ore deposits were already being exploited in prehistoric times. These mining activities were first verified by archaeological excavations in the 1990s (Goldenberg and Rieser, 2004). More intensive excavations on prehistoric mining in the Lower Inn Valley have taken place since 2007 (Schibler et al., 2011).

We conducted a detailed investigation of one of these small mines, the so-called *Mauk E* mine, which had initially been explored in the 1990s (Fig. 1).

Of key interest in the investigations at the Mauk E mine was establishing the dates and the duration of ore exploitation. While findings of stone hammer and pottery fragments in the prehistoric layers are rare, an enormous amount of pinewood chips and charcoal could be retrieved from the Mauk E mine. The latter are remains of fuelwood used to weaken the rock by fire-setting, a common technique in prehistoric times for exploiting ore deposits. Charcoal samples can be informative in two ways: (1) the charcoal can be radiocarbon dated and (2) the size and number of tree rings on some pieces, as well as the quantity of the excavated charcoal, make dendrochronological and dendrological investigations possible. By analysing the tree rings of a first group of charcoal samples, we were able to establish a 149-year-long tree-ring chronology that ends in 707 BC (Pichler et al., 2010).

This dendrochronological result agrees in general with the first radiocarbon dates based on charcoals that imply mining activities around the transition from the Late Bronze Age to Early Iron Age (Stöllner, 2009). However, the calibrated ^{14}C results are spread over a time-window of approximately 600 years (ca. 1000–400 BC). This
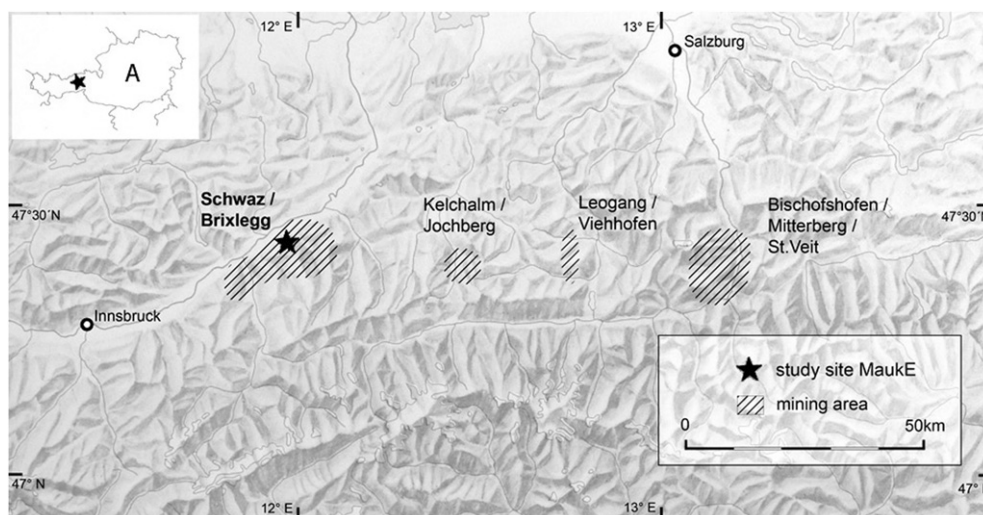
Fig. 1. Location of the study site Mauk E within the mining region Schwaz/Brixlegg. Other prehistoric mining areas in the northern part of the Eastern Alps are also shown (map based on Alpen Reliefkarte − Tirol Atlas).

first set of ^{14}C dates does not make it clear whether this spread indicates an enduring or recurring exploitation of the Mauk E mine or whether the range of dates is related to the limitations of radiocarbon dating (inaccuracy of calibrated radiocarbon dates due to the ^{14}C-Hallstatt plateau) of charcoals (possible *old wood effect*) in the first millennium BC (Pichler et al., 2011). One of the objectives of our study was to either verify a long exploitation period or determine that the spread of the ^{14}C results is merely the result of inaccuracies in radiocarbon dating.

However, our tree-ring analyses performed on charcoal material from the Mauk E mine allowed us to expand the scope of issues beyond dendrochronological dating. By determining the tree species and estimating the diameter of the timber used, we can assess whether the miners preferred a certain type of tree or tree size. Further questions outlined in this paper focus on the demand for fuelwood needed to exploit the mine and the possible impact of the firewood utilisation on the local forests. To gauge the amount of fuelwood needed for underground mining, we included 3D laser-scanning data of the volume of rock exploited in the Mauk E mine as well as data from different fire-setting experiments (O'Brien, 1994; Gätzschmann, 1846; Tereygeol, 2001; Py, 2009). Dendrochronological analyses of mining timber will continue to deepen our knowledge of the history of mining in the Alpine Region, particularly during prehistoric times.

2. Site, material and methods

2.1. Site and archaeological excavations

The Mauk E mine (Fig. 1) is located in the Lower Inn Valley (N 47°26′14″, E 11°57′12″; 997 m a.s.l.) on a north-facing slope in the Northern Alpine Greywacke zone, which holds rich ore deposits of the Fahlore-group minerals, a sulfosalt mineral family that contains copper, silver, iron, zinc, arsenic, antimony, and sulphur. In addition, this Fahlore-group minerals may include mercury, tellurium and other elements (Goldenberg and Rieser, 2004; Krismer et al., 2011).

Today, the entrance to the mine is surrounded by dense woodland dominated by spruce (*Picea abies*) and fir (*Abies alba*). The mine itself has a ramified ground plan (Fig. 2) and reaches approximately 25 m into the rock.

Some parts of the Mauk E mine were also exploited in early modern times. Dendrochronological results from wooden remains

provide evidence of mining activities in this location between ca. 1560 and ca. 1600 AD (Pichler and Nicolussi, 2011). After removing stowing from the modern period, archaeological investigations of the prehistoric layers were performed in various parts of the mine (Fig. 2). For this study, we mainly analysed charcoal excavated in sections S1, S3 and S4. Some very small pieces were found in the 1990s during the first small-scale excavations in section S2. The potential for dendrochronological analyses of these charcoal samples was low; instead, the samples were subjected to radiocarbon dating.

2.2. 3D-documentation of the Mauk E mine

Terrestrial laser scanners are state-of-the-art tools for surveying the 3D geometry of objects of any type and shape (Hanke et al., 2010; Kovács et al., 2011). In this case, we wanted to calculate the volume of the Mauk E mine and to create cross-sections. As the space inside the mine is quite narrow, we needed nine individual instrument positions to guarantee a consistent 3D acquisition of the entire structure of the interior part of the Mauk E mine (Fig. 3). Scanning was accomplished with a Trimble GX 3D terrestrial laser scanner with a spatial resolution of 2 cm.
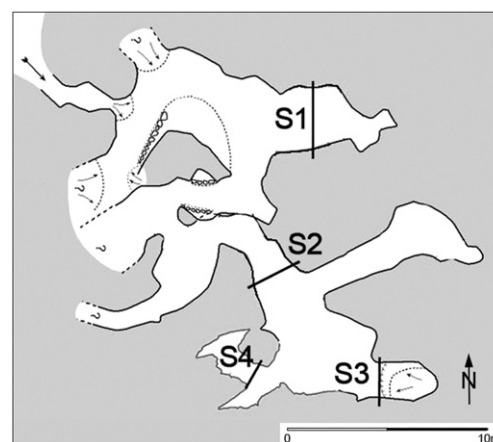

Fig. 2. Ground plan of the fire-set Mauk E mine. S1, S2, S3 and S4 indicate the locations where the samples were discovered.
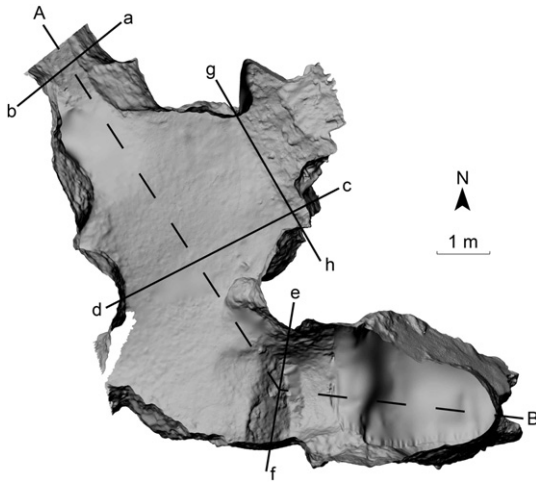
Fig. 3. Modelled ground plan (3D laser-scanning data) of the back part of the Mauk E mine. The continuous lines mark the position of the four cross-sections; the dashed line marks the longitudinal section displayed in Fig. 4.

The first surveys were performed during two days in 2008. In the summer of 2009, another data acquisition episode was completed, and following the excavation works, only the significant volume changes at the cross-section S3 of the Mauk E mine were scanned from three positions. The resulting 3D point clouds of the laser scans were combined, filtered and modelled to achieve a complete 3D surface representation of the entire underground mining gallery. In addition, 58 digital photographs were taken at the site in a panorama-type configuration with a Nikon D200 + 18 mm lens. These photographs were precisely matched to the geometry model to allow successive photorealistic texturing of the interior hull for visualisation and for further archaeological analyses of the entity's surface.

The prehistoric ground surface of the backmost part of the mine was reconstructed for the volume calculation of the prehistoric exploitation (Fig. 4).

2.3. Dendrochronological and dendrological analyses

Archaeological excavations within the Mauk E mine in 2007 and 2008 retrieved an amount of charcoal from the sections S1, S3 and
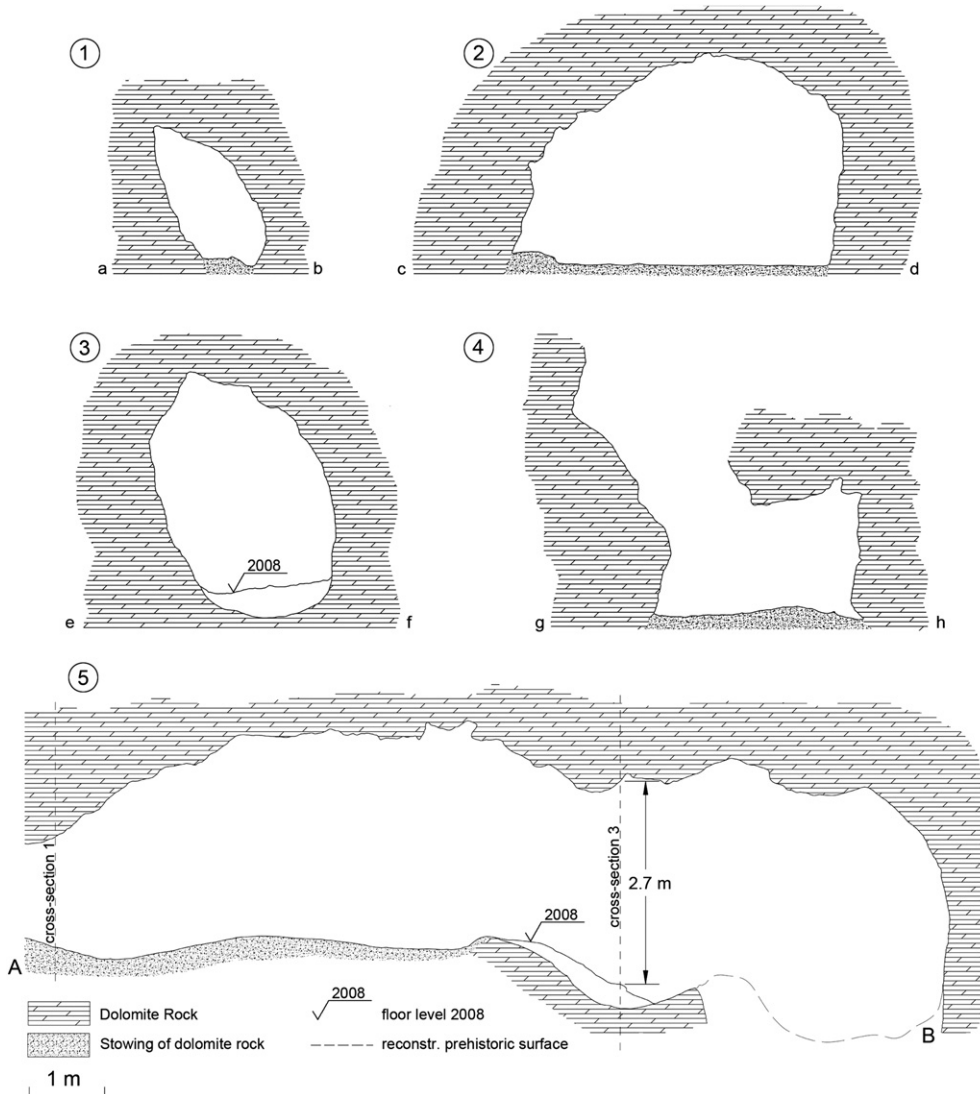

Fig. 4. Cross- and longitudinal sections of the back part of the Mauk E mine. Cross-sections 1 to 4 illustrate the shape and size of the mine at different locations. Cross-section 3 shows the dome-shaped cavity with well-rounded surfaces resulting from Bronze Age fire-setting.

S4 that weighed a total of 2.8 kg (weight at room temperature). As a result of burning processes and possible dislocations of the burnt wood, the charcoal samples were preserved in fragments only. For the most part, the investigated pieces of charcoal had diameters of only a few centimetres; samples more than five centimetres in diameter (maximum 10 cm) were rare. The assemblage was screened for samples with at least ca. 20 tree rings to establish tree-ring width series of sufficient length for cross-dating purposes and to detect tree-ring patterns that might indicate past fuelwood exploitation strategies. Samples that showed abruptly increasing growth rates (reflecting changes in local ecological conditions) were also selected. Altogether, 240 charcoal samples were analysed and utilised in this study.

The samples were investigated with a stereoscope (Olympus SZ 61) and an incident-light microscope (Olympus BX 40), and the wood taxa were determined following Schweingruber (1990). As a rule, alpine tree species can be clearly distinguished by anatomical criteria. However, larch (*Larix decidua*) and spruce (*P. abies*) present few anatomical differences. To differentiate spruce and larch samples, we considered two other characteristic features: a) a slight modification of the cell size within the early wood and a smooth transition from early wood to late wood, both indicating spruce; b) sequences of abrupt changes in tree-ring width, indicating larch and potentially observable by the examination of the complete section of a sample.

None of the 240 charcoals analysed has preserved pith. We estimated the pith-offset of most of the samples using a diameter stencil to identify the stem size and the tree age of the wood that the miners used for fuel. Usually, when the curvature of the tree rings is stronger, the pith is closer. However, we have to consider that the tree-ring curvature of some samples may have been modified by burning processes.

Before tree-ring width (TRW) measurements were performed on the transverse section, a sample surface was prepared by either breaking (Schweingruber, 1983) or cutting with a standard bandsaw.

TRW measurements were performed by means of the LINTAB IV measuring device linked to a PC and using TSAPWin software. Several radii per sample were compiled, resulting in a sample mean curve. A highpass filter was applied to each established sample series to eliminate the age-related growth trend before they were cross-dated against each other.

2.4. Dating

AMS radiocarbon dating was used for an initial estimate of the time range of the Mauk E charcoal samples (Stöllner, 2009). These results confirm mining activities during the transition from Late Bronze Age (LBA) to Early Iron Age (EIA).

For dendrochronological dating, we used reference chronologies that were available from the Central Alps (Eastern Alpine Conifer Chronology, BC 7109 to AD 2002; Nicolussi et al., 2009) and the Alpine foothills (fir chronology, BC 811 to BC 593; Billamboz and Neyses, 1999). After we had established a local tree-ring chronology based on a tree-ring series of 60 charcoal samples and covering the period from 855 to 707 BC (Pichler et al., 2010), this chronology was primarily used for cross-dating further charcoal samples.

2.5. Demand for wood

Ore exploitation in hard rock in prehistory was primarily accomplished by fire-setting (e.g., Willies and Weisgerber, 2000), which necessitated large amounts of firing wood. One way to quantify the potential demand for fuelwood is to run archaeological

experiments. In addition to data from individual experiments, we also have data from sites where numerous fire-setting experiments have been performed. We were able to ascertain the ratio of rock extraction to fuelwood, based on the results of these experiments. This ratio varies in response to different parameters. According to Timberlake (1990), there are two main groups of factors that affect rock exploitation. First, factors that describe the morphology of the rock, e.g., chemical and mineral composition of the rock, grain size, thermal expansion ratio and internal structure. Second, factors that relate to the fire-setting application, e.g., characteristics of the fuelwood (green or seasoned wood, size, round or split wood, water content, and species), temperature, archaeological experience in the fire-setting technique, ventilation and construction of the wood stack.

Fig. 5 shows the results of different experiments (O'Brien, 1994; Gätzschmann, 1846; Tereygeol, 2001; Py, 2009) on wood consumption and rock extraction. From these results, we derived a generalised rock-to-wood weight ratio (RWR) with a range of approximately 0.7—1.

To estimate the amount of fuelwood needed to exploit the rear part of the Mauk E mine, we calculated the volume of the fuelwood from the weight of the mined rock with the basic Formula (1). We performed the calculation for spruce, which was the dominant tree species in the analysed charcoal assemblage.

$$V_w = \frac{V_r \times \rho_r}{\rho_u} \tag{1}$$

V_w the volume of wood demanded ($[m^3]$ = solid cubic metre),

V_r the volume of mined rock $[m^3]$,

ρ_r the specific gravity of the mined dolomite rock,
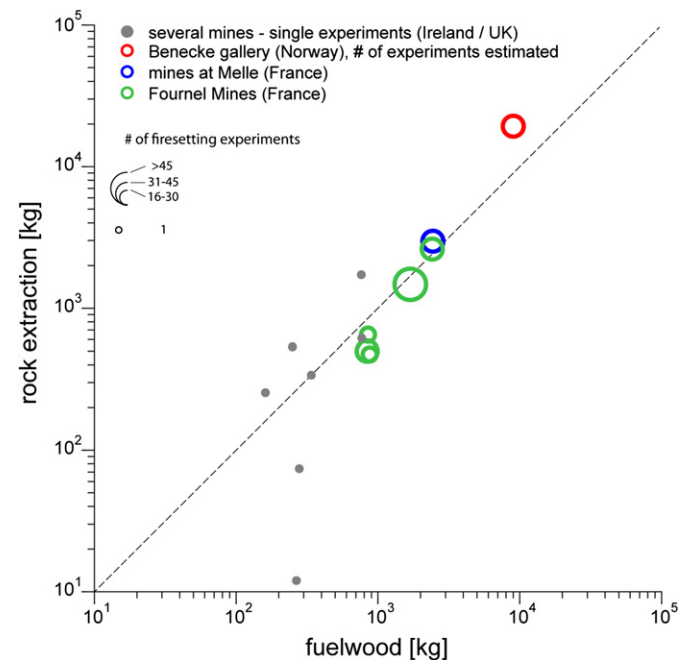

Fig. 5. Rock-to-wood weight ratios of several fire-setting experiments at different locations (Benecke gallery: Gätzschmann, 1846 — only summarised data for wood and rock extraction available, number of fire-setting actions estimated; Fournel mines: summarised in Py, 2009; mines at Melle: Tereygeol, 2001; several mines in Ireland/UK: summarised in O'Brien, 1994). The fire-setting experiments at the Fournel mines were differentiated by an annual campaign.

ρ_u　　the specific gravity of wood with 20% moisture (e.g., spruce: ca. 0.48 g/cm^3); the calculation of the specific gravity of wet spruce wood is accomplished by a Formula (2) documented in DIN 52182 (German Institute for Standardisation).

Here, $V_r \times \rho_r$ is the weight of the mined rock ("Schwazer dolomite"), based on a specific gravity of 2.7 g/cm^3 (pers. comm. M. Krismer, Department of Mineralogy and Petrography, University of Innsbruck). The variable ρ_u describes the specific gravity of wood with a wood moisture content of 20% (e.g., spruce: ca. 0.48 g/cm^3); according to Grosser (1977), completely dry spruce wood (ρ_0) shows a variable specific gravity between 0.30 and 0.64 g/cm^3 and its mean specific gravity is ca. 0.43 g/cm^3. Generally, green wood contains considerable amounts of water: depending on the external drying conditions (temperature, relative humidity and air velocity) and the duration and type of the storage (open air drying or under shelter; logs or split wood), the wood moisture content may decrease. For example, the water content of piled wood (quartered) left in the open for one year is ca. 26% (Py, 2009) and may fall to 13–15% during longer storage periods. Formula (2) can be applied to calculate the volume of the wood demand for different moisture contents.

$$\rho_u = \rho_0 \frac{100 + u}{100 + (0.85 \times \rho_0 \times u)} \qquad (2)$$

ρ_0　　the mean specific gravity of wood with 0% moisture (oven dry): e.g., spruce: 0.43 g/cm^3 (Grosser, 1977),
ρ_u　　the specific gravity of wet wood [g/cm^3],
u　　the wood moisture content at standard atmosphere [%].

The Formula (1) is valid if the RWR equals 1. In all other cases (where RWR ≠ 1), a modified Formula (3) is applied.

$$V_w = \frac{V_r \times \rho_r}{\rho_u \times \text{RWR}} \qquad (3)$$

RWR　　the rock-to-wood weight ratio.

In our calculations, we used RWR values ranging from 0.5 to 1.2 to outline the wide spread of the fuelwood demand under different basic assumptions.

In addition to calculating the demand for fuelwood used in the rear part of the Mauk E mine, we attempted to estimate the corresponding number of individual trees utilised by the prehistoric miners. In modern silviculture, one can use a Formula (4) established by Denzin (Marschall, 1992) to translate a volume of wood to the corresponding number of trees. This simple expression requires only the diameter of a tree at breast height (DBH) to calculate the volume of the tree. Using the recorded pith offsets – together with the cumulated width of the measured tree rings – the minimum stem diameter, as well as the theoretical volume of the tree, could be retrieved. For example, a tree with a DBH of ca. 31.6 cm provides a theoretical wood volume of 1 m^3.

$$V_t = d^2/1000 \qquad (4)$$

V_t　　volume of the tree [m^3],
d　　diameter at breast height [cm].

3. Results

3.1. 3D documentation

The cavity representing the volume of the exploited rock encompasses the rear part of the mine and is 63.7 m^3 (Fig. 3; from cross-section 1 towards the backmost part of the mine). Because of the two field campaigns at the Mauk E site in 2008 and 2009, it is possible to document the evolution of the archaeological activities – e.g., at section S3 (Fig. 4.3 and 4.5). Arbitrary profiles and cross-sections, derived from the computer model, show the spatial situation and the shape of the archaeological site (Fig. 4).

3.2. Dendrochronological and dendrological results

Four species are present in the dendrochronologically analysed charcoal assemblage (240 samples). The results indicate that softwood was almost always used for fuel. Of the identified species, spruce (88% of the samples) is the most abundant, with minor proportions of fir (A. alba, 10.4%), larch (L. decidua, 0.4%) and alder (Alnus spp., 0.4%). Two charcoal samples (0.8%) are ambiguous and are either spruce or larch. Thus far, no other species have been documented.

After screening each of the excavated charcoal samples, only two pieces could be classified as the remains of twigs or branches (these samples were only dendrologically investigated). The remainder of the charcoal samples did not present the characteristic features of twigs or branches (e.g., strong bending of the tree rings, compression wood); hence, these samples were identified as stem wood.

The lengths of each of the analysed tree-ring series ($n = 240$ samples) range from 6 to 138 rings. The median value ($m = 35$) indicates that most of the samples have short tree-ring series, suggesting that the majority of fragmentary preserved charcoals have similarly short tree-ring series.

3.3. Dating

Previous dendrochronological studies (Pichler et al., 2010) evaluate TRW measurements from charcoals that mainly originate from sections S3 and S4. Now, newly established tree-ring data exist from section S1 of the mine. As a result of these new tree-ring data, the number of cross-dated tree-ring series from charcoal pieces has increased from 60 to 133. Fig. 6a and b document these tree-ring series ($n = 133$) related to sections S1, S3 and S4 and their corresponding tree species.

The TRW chronology from Mauk E covers the time period from 855 to 707 BC. In the time period 813–714 BC, this chronology shows a sample depth of >20. A maximum replication with 101 tree-ring series was reached in the year 754 BC. With the well-replicated tree-ring width chronology, the statistical cross-dating results can be improved even beyond those based on two reference chronologies (Table 1).

Generally, accurate felling dates on wooden samples can be determined in cases where the outermost tree ring (waney edge) is well preserved. As a result of burning processes or probable depositional damage, charcoals found in the course of

Table 1
Statistical parameters from a comparison of the Mauk E chronology with the Eastern Alpine Conifer Chronology (EACC, Nicolussi et al., 2009) and the TA_Mag1i (Billamboz and Neyses, 1999).

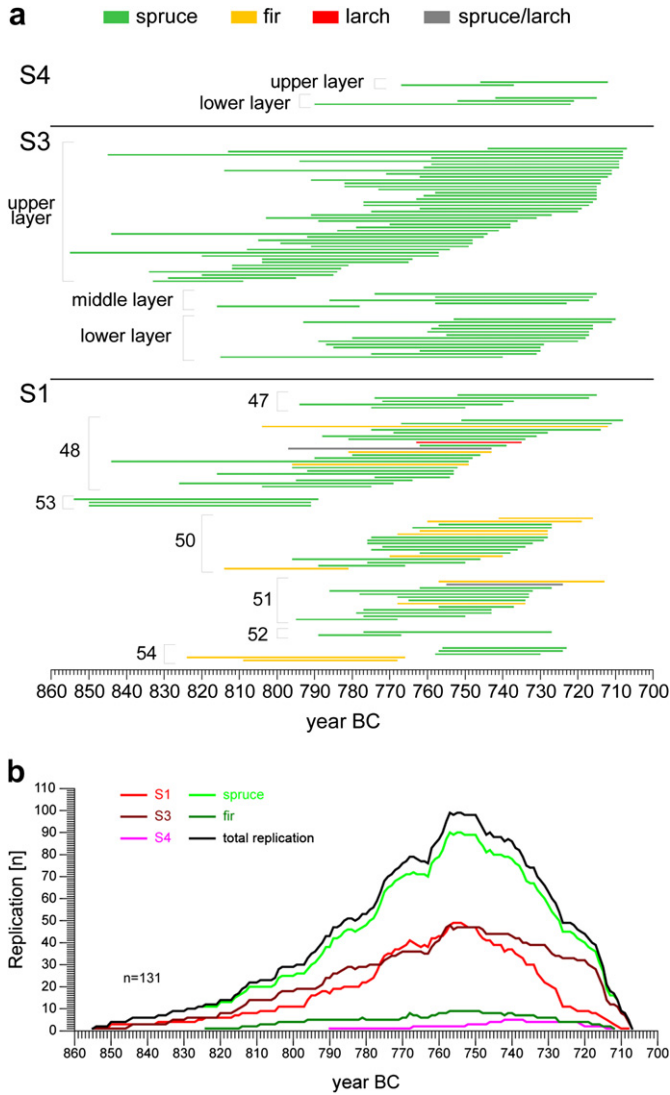| Chronology	Species	Overlap	Gleichläufigkeit [%]	Gleichläufigkeit point interval [%]	t-Value [Baillie & Pilcher]	t-Value [Hollstein]
EACC	Pinus cembra	149	60	65	4.5	4.8
TA_Mag1i	Abies alba	105	72	–	5.0	4.4

Fig. 6. a. The dendrochronologically dated charcoal samples of the fire-set Mauk E mine. Each rectangle represents a sample. The length of the rectangle indicates the length of the tree-ring series obtained from the samples. The samples are grouped according to excavation section and layer. b. Replication of tree-ring series dated according to the cross-section within the Mauk E mine (S1, S3 and S4) and tree species, as well as the distribution of the total replication (*n* = 133).

Fig. 7. Cross-section S3 in the inner part of the Mauk E mine. At that location, three different coloured layers can be distinguished. The dates list the year of the last measured tree ring of a charcoal sample (photo: G. Goldenberg, 21 August 2008).

(708 BC) derives from a sample from layer 48 (Fig. 8). The small spread of end-dates of some of the pieces of charcoal from different layers of the sections S1, S3 and S4 suggests a relatively short working period of approximately one decade around 710 BC during which the copper ore at the Mauk E mine was exploited. The established dendro-dates indicate that the prehistoric mining activities at the Mauk E mine came to an end a few years after 707 BC.

3.4. Groups of TRW series

Even short TRW series of the charcoal samples from the Mauk E mine often show strong correlations with each other. These correlations are not surprising because one can expect that several charcoal samples originated from the same tree and therefore present very similar growth patterns. The fragmentation of wood from a single tree can be explained by the firewood management practiced by the prehistoric miners and the burning

archaeological excavations rarely show this outermost ring. In our study, however, a waney edge could be identified on one charcoal sample, indicating a felling date of 708 BC. Moreover, the last measured tree rings of 15 other samples could be dated to between 707 and 712 BC. For these charcoals, we assume that the felling dates of the trees were close to the date of the last measured tree ring – approximately 710 BC.

The last calendar years established for sections S1 (708 BC), S3 (707 BC) and S4 (711 BC) show a relatively small temporal spread (Fig. 6a and b). This is also the case for the various layers of sections S1 and S3. The last tree rings of charcoal samples from the lower and upper layers of S3 mark the years 710 and 707 BC, respectively (Fig. 7). The few samples from section S4 indicate very similar last tree-ring dates for the lower and upper layers: 715 and 712 BC. The stratigraphy of section S1 (Fig. 8) is more complicated: the basal layer 54 provides only a few cross-dated samples with a last tree ring from 723 BC; the layer above (52) indicates a last ring from as early as 727 BC. The samples from the top layer (47) show tree rings in the year 715 BC, but the youngest tree ring of a charcoal from section S1
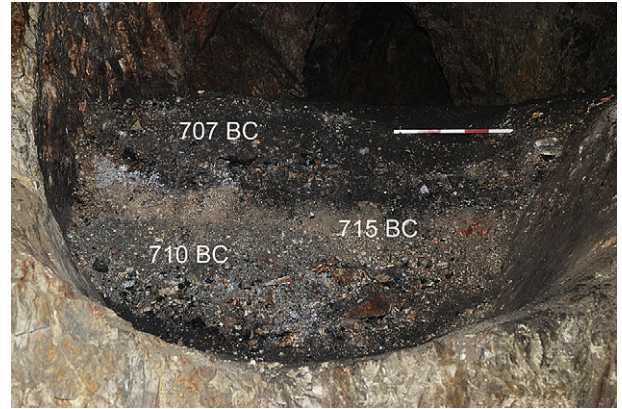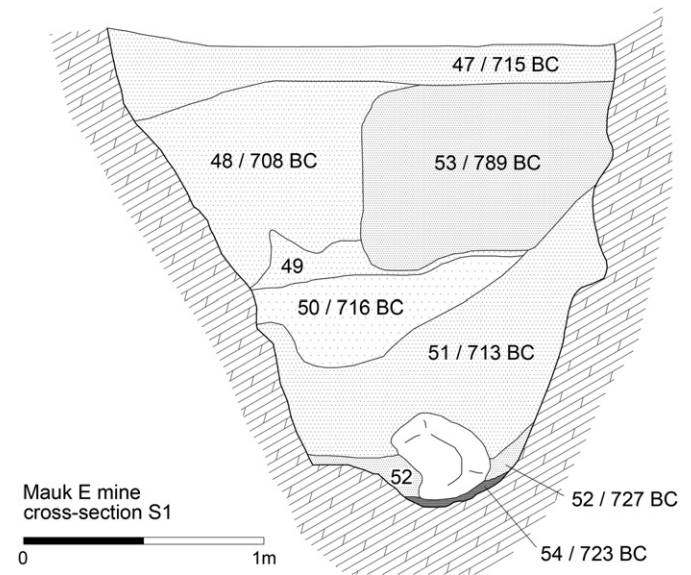

Fig. 8. Cross-section of S1 in the outer part of the Mauk E mine. In each layer except layer 49, charcoal samples were discovered, analysed and dendrochronologically dated. The last measured tree ring of each layer is shown (design by S. Hye/M. Klaunzer/A. Maass, 2009).

processes and possible dislocations of remaining charcoal afterwards.

To identify the charcoal samples that belong to the same log, we used additional features of the TRW series: tree species, growth level, growth trend and year-to-year variability. Based on these dendrotypological features, we combined tree-ring series of 110 samples into 12 different groups, called *trees*. The species of the majority of these *trees* is spruce except for *tree* 9 and *tree* 10 (species: fir). So far, we have not been able to classify the rest of the tree-ring series (n = 130) definitively and we expect more than these 12 utilised *trees*. Fig. 9 displays both the temporal distribution of all cross-dated tree-ring series as well as the replication of the calendrically dated established *trees*.

Table 2 outlines several parameters of the *trees* established so far, comparing these values, for instance, with those of the unclassified samples. One can see that the mean segment length of the unclassified samples is lower (29.8) than that of *trees* 1 to 12. This is one explanation for why many investigated charcoal samples could not be attributed to one of the existing *trees* or used to build up a new, coherent sample series. Fig. 10 shows the distribution of selected parameters (mean, maximum and minimum TRW) of all analysed samples. Each bar represents a sample. Most of them return low mean increment rates and a small variation between minimum and maximum TRW, as is typical of older trees. We suggest that samples with such features are from the outer part of a tree, close to the waney edge.

The growth patterns and annual increment rates of these *trees* contain information on stand characteristics and the dynamics of the forests harvested for firewood. Based on the tree-ring widths of the *trees,* the stand density of the exploited forest can be derived. Minimum values of the utilised *trees* range from 0.09 mm to 0.68 mm (Table 2). For example, the lowest width of a tree-ring sequence derives from *tree* 4 (species: spruce) and documents an inferior site (most likely with additional individual disturbance), as is found in naturally grown forests (Fig. 11). *Tree* 4 recovered from poor conditions in subsequent years due to anthropogenic or naturally forced clearings. Towards the end of the TRW series, the annual increment increased to almost 0.8 mm, which seems to be the maximum that could be reached at these growing sites. Compared to *tree* 4, the TRW series of *tree* 1 (species: spruce) shows slowly declining overall increment rates (Fig. 12). Here, with the exception of the juvenile phase, the annual width increment generally declines with increasing age of the tree (Bräker, 1981). The lowest increment of *tree* 1 is recorded close to the end of the measured series. Such a growth pattern can be attributed to trees that do not suffer from disturbances. *Tree* 1 most likely displays growth conditions that might be considered "normal" for trees growing in the vicinity of the Mauk E mine.

Some tree-ring series of *tree* 9 (species: fir) present an abrupt doubling in radial growth, which starts some years before the last measured tree ring. The increase of the TRW in *tree* 9 is obviously related to better growth conditions. The sudden change points to an alteration in the status of this tree from a suppressed to a free-standing tree, e.g., in a clearing. The direct consequence is a higher availability of light, which causes an increase in the increment during the following years. However, we have to bear in mind that the effects observed in *tree* 9 are not necessarily related to human activity but could be a result of natural events (e.g., windbreaks). Fig. 12 compares the increment evolution of *tree* 1 and *tree* 9. As a result of clearings (anthropogenic or natural) that must have occurred before 720 BC, the TRW increased to twice the increment of previous periods.

3.5. Minimum diameter of utilised stems (without consideration of shrinkage)

Fig. 13 outlines the estimated stem diameters of the established *trees*, which reflect stem size. One can assume that primarily small trees were exploited by the miners. The estimated diameters range from ca. >13 cm to 27 cm, with a mean diameter value of approximately 20 cm. However, these values take into account neither the shrinkage of charred wood nor the relative position of the sampled charcoals within the utilised stems. (As it is not possible to determine precisely where the charcoals come from, one might also expect larger stem diameters.) Studies attest to a change in radial and tangential direction within a 12.6%–24.9% range (Brown, 1945; Schläpfer and Brown, 1948). In these studies, samples of deciduous and coniferous wood were investigated. It was discovered that the coniferous samples did not shrink as much as the deciduous samples. The calculated tree diameters presented here (Fig. 13) are therefore minimum values.

3.6. Rock extraction, demand for wood and impact on the forest

The rock-to-wood weight ratio, together with the 3D laser-scanning data, allowed us to estimate the amount of wood needed to exploit the Mauk E mine. The total weight of the rock exploited (specific gravity = 2.7 g/cm^3) in the back part of the mine (volume 63.7 m^3) is approximately 172 tons. This figure indicates a total demand of 358 m^3 of fuelwood, given a rock-to-wood weight ratio of 1:1 and a specific gravity for spruce of 0.48 g/cm^3 (Table 3).

The calculated demands for wood given in Table 3 are based on a variety of values of the rock-to-wood weight ratio. We also calculated the amount of wood needed annually for different exploitation times. Several factors (the volume of the back part of the mine, the specific gravity of the rock and of the fuelwood and the water content of the wood) are relatively constant. Hence, they do not greatly affect the amount of wood needed and have been excluded from the calculations.
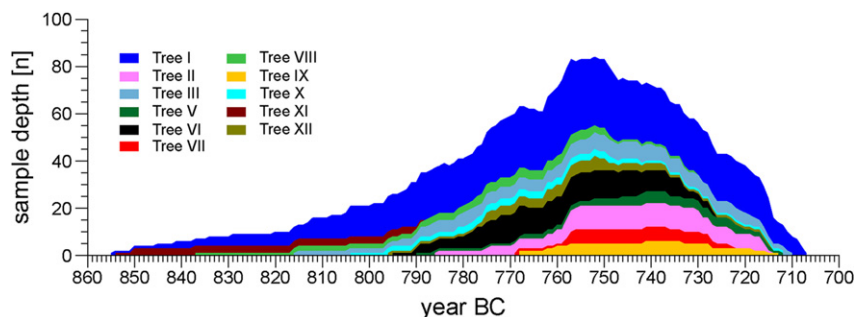

Fig. 9. Sample depth of the established and dendrochronologically dated groups of tree-ring series, called *trees*. The replication of each *tree* is added to the following ones, which results in an overall replication that peaks (n = 84) in the year 752 BC.

Table 2

Breakdown of the different parameters of the so-called *trees* 1 to 12 in relation to the total number of analysed samples ($n = 240$). The parameters of the unclassified spruce (PCAB) and fir (ABAL) samples are indicated. The last two columns show parameters of all analysed spruce and fir samples.

|	All series	Tree 1	Tree 2	Tree 3	Tree 4	Tree 5	Tree 6	Tree 7	Tree 8	Tree 9	Tree 10	Tree 11	Tree 12	Not classified	Total	Total
Species	—	PCAB	PCAB	PCAB	PCAB	PCAB	PCAB	PCAB	PCAB	ABAL	ABAL	PCAB	PCAB	—	PCAB	ABAL
Number of series	240	40	10	8	4	5	15	6	4	6	3	3	6	130	213	23
Mean segment length	38.9	57.4	46.8	59.5	62	39	37.5	32	59.8	37.3	60	62	33.8	29.8	39.6	32.6
Length of combined series	—	149	72	107	95	79	69	47	107	56	93	66	82	—	—	—
Dating [year BC]	—	855–707	786–715	816–710	—	790–712	796–717	769–723	837–731	768–713	804–712	854–789	796–715	—	—	—
TRW, mean [mm]	0.86	0.81	0.45	0.49	0.52	1.04	0.61	0.70	1.13	0.78	0.36	0.60	0.76	1.04	0.84	1.13
TRW, max. [mm]	5.32	1.94	0.78	0.84	1.39	1.76	0.98	1.02	2.17	1.72	0.75	1.17	1.67	5.32	5.32	4.86
TRW, min. [mm]	0.03	0.25	0.22	0.21	0.09	0.68	0.35	0.42	0.55	0.24	0.11	0.24	0.32	0.05	0.03	0.08
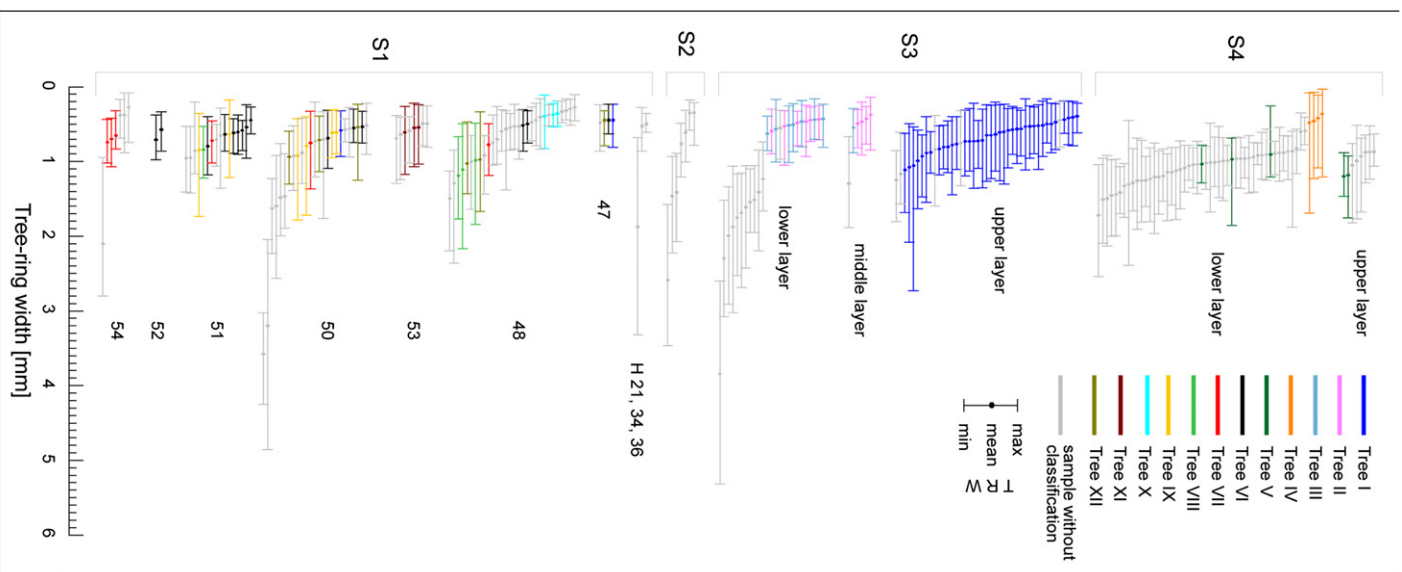
Fig. 10. Comparison of the annual increments of the analysed charcoal samples related to the archaeological layers and sections, showing maximum, minimum and mean values of the measured tree-ring width. S1, S2, S3 and S4 indicate the positions of the samples discovered in the Mauk E mine.

Assuming an operation period of 5–10 years as well as a varying rock-to-wood weight ratio (0.7–1), the demand for fuelwood by the exploitation of the Mauk E mine ranges from ca. 102 m³ to 36 m³ per year. We estimated the number of trees needed to meet this demand assuming timber of ca. 30 cm in diameter (see Section 3.5). After Denzin, a volume of 0.9 m³ per tree can be expected, resulting in a demand for ca. 40 to 114 trees per year (corresponding to the marked zone of Table 3). This number
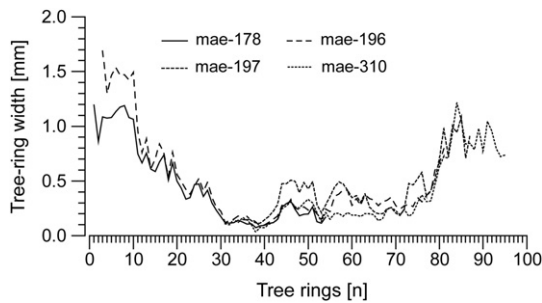
Fig. 11. Tree-ring series of four charcoal samples (cross-section S4) integrated into *tree* IV. The plotted series show similar dendrotypological features.

suggests a limited effect on the forests involved. Even if we suppose that the underground mining occurred over a period of only five years, the timber required could easily be supplied from the local forests.

This assumption can be confirmed by recent woodland management parameters ascertained in Tyrolean forests. Depending on local site conditions, one can expect an annual increment of 5 m³–10 m³ per year per ha (pers. comm. F. Riccabona, forest department, government of Tyrol). This means that a forested area of ca. 4 ha, for example, would yield enough fuelwood (based on 10 years of operation and rock-to-wood weight ratio 1:1) without unsustainable harvesting of wood.

4. Discussion

The charcoal samples from the Mauk E mine represent the remains of fire-setting in this copper mine and allow calendar dating of these activities. Generally, the pieces of preserved charcoal are too small to yield dendrochronological data. However, there are a few larger excavated samples with a higher number of tree rings. The dendrochronological results provide a more detailed insight into small-scale mining during the Early Iron Age.

The dating results obtained from 133 charcoals from different layers of three sections suggest that the exploitation of the Mauk E mine lasted approximately one decade in the late 8th century BC. The last tree-ring date marks the year 707 BC. This is contrary to the results of the first radiocarbon testing (Stöllner, 2009; Pichler et al., 2011). The corresponding calibrated results were spread over more
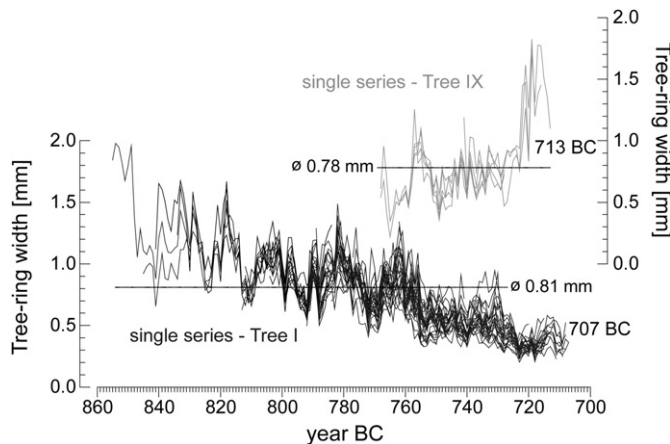

Fig. 12. Comparison of the increment evolution of the samples that compose *tree* I and *tree* IX. While *tree* I reflects environmental conditions of a naturally grown forest, *tree* IX shows an abrupt growth increase not later than 720 BC as a result of clearings.
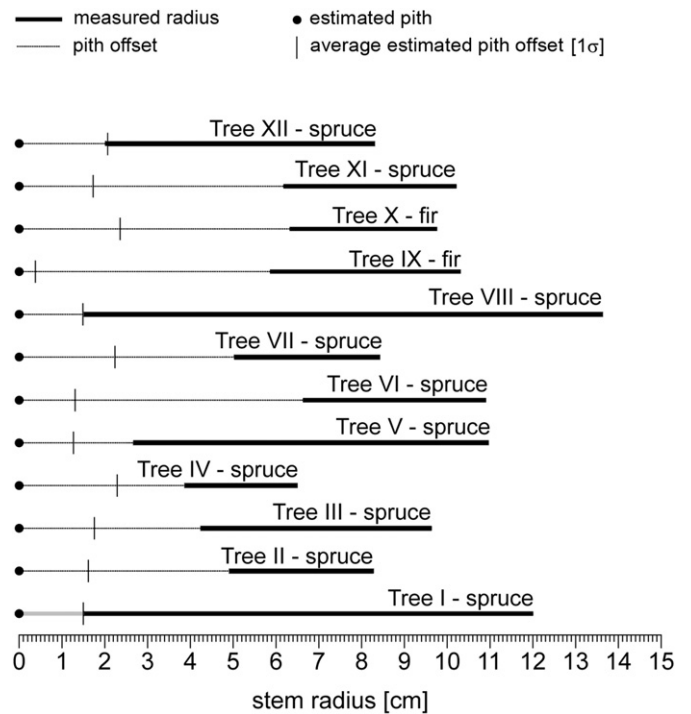

Fig. 13. Estimated stem radii of the different *trees*. The calculated radii are composed of the summarised tree-ring measurements as well as the estimated pith offset. In addition, the average of all pith-offset estimates of a *tree* is shown, together with the error of these pith offset estimates (1σ).

than five centuries (between ca. 1000 BC and 400 BC). However, this broad time range must be attributable to the cumulative effects of the old wood effect and the well-known Hallstatt ^{14}C plateau.

The results of the analyses of the charcoal samples indicate that as a rule softwood was used for fire-setting in the EIA Mauk E mine. Other species have not been documented so far, except for one sample of alder found in the front part of the Mauk E mine. These observations are confirmed by the results of the analyses performed on charcoals discovered at mines of similar age near Mauk E (Heiss and Oeggl, 2008). This study also points to selective fuelwood gathering. The fact that no pieces of hardwood were found cannot be attributed to a lack of such species in the nearby grown forests. Dendrochronological analyses on wooden remains from the early 9th century ore processing site Schwarzenberg Moos (linear distance to Mauk E ca. 1.5 km) (Nicolussi et al., 2010) do indeed provide evidence for the use of hardwood. In this study, the species composition is dominated by the common Alpine conifer species spruce, fir and larch, as well as wood from six different deciduous trees (alder, beech, white willow, common ash, acer and silver birch). Moreover, a local pollen study at Kogelmoos fen, a few kilometres west, performed by Breitenlechner et al. (2010), confirms this heterogeneity of the woodland composition at the transition from the Bronze Age to the Iron Age. Taking these results into account, we suggest a preference of the prehistoric miners for coniferous species for fuelwood at the Mauk E mine.

The trees selected by the prehistoric miners had diameters between ca. 15 cm and 30 cm. The absence of evidence for bigger stems to date may be attributable to tool handling and transportation. Timbers with a smaller diameter seem to be more easily tooled. At other prehistoric mining sites, timbers with larger diameters are documented. The diameters of timbers documented at the ore processing site Schwarzenberg Moos, close to the Mauk E site, range from 4 cm to 38 cm (Nicolussi et al., 2010). Trees of larger

Table 3
Estimated overall and annual demand for wood [m³] for several rock-to-wood weight ratios (0.5–1.2) and operation times (1–10 years). The more probable assumptions are highlighted.

	1	2	3	4	5	6	7	8	9	10	Total
0.5	716.63	358.31	238.88	179.16	143.33	119.44	102.38	89.58	79.63	71.66	716.63
0.7	511.88	255.94	170.63	127.97	102.38	85.31	73.13	63.98	56.88	51.19	511.88
0.8	447.89	223.95	149.30	111.97	89.58	74.65	63.98	55.99	49.77	44.79	447.89
0.9	398.13	199.06	132.71	99.53	79.63	66.35	56.88	49.77	44.24	39.81	398.13
1	358.31	179.16	119.44	89.58	71.66	59.72	51.19	44.79	39.81	35.83	358.31
1.2	298.59	149.30	99.53	74.65	59.72	49.77	42.66	37.32	33.18	29.86	298.59

size (up to 70 cm) were cut to build the two troughs excavated at the Kelchalm site near Kitzbühel (Pichler et al., 2009). Timbers excavated in the middle Bronze Age mine Arthurstollen (mining area Mitterberg) have diameters of up to 45 cm (pers. comm. P. Thomas, Deutsches Bergbaumuseum, Bochum). The trees used to construct the wet-tye at the Troiboden (Stöllner et al., 2012) had diameters between ca. 45 cm and 50 cm. However, the timbers with the largest diameters were found to make specific pieces of equipment, e.g., troughs. The most common values fall into the same range as the reconstructed diameters of the fuelwood trees of Mauk E.

The analyses of the charcoals also allow the impact on the local forest to be assessed. The impact was limited even assuming that the exploitation activities only lasted a few years. The prehistoric miners were obviously able to fully meet their demand using locally growing coniferous wood. The dendrological results from the charcoals suggest that wood from deciduous trees, which is also suitable for fire-setting (O'Brien, 1994), was not required.

The assumption of small-scale clearings is further supported by the finding that charcoals from very few *trees* (e.g., *tree* 9) show clearing effects. Moreover, the observed effects are not necessarily related to anthropogenic impact but could instead be the result of natural events, e.g., windbreaks. Furthermore, the dominance of samples with relatively small tree-ring widths (the median of all measured TRW series from Mauk E is 38.9) indicate the use of naturally grown forests with high stand densities by the prehistoric miners.

5. Conclusion

The dendrochronological and dendrological results presented provide insight into a fire-set mine in the prehistoric mining area of Schwaz/Brixlegg:

i) Tree-ring data provide an accurate dating of the mining activities in the Mauk E mine in the late 8th century BC (last measured ring 707 BC), suggesting a duration of approximately one decade around the year 710 BC,

ii) Selective wood procurement (only softwood species and primarily stem wood of limited diameter) was common,

iii) TRW analyses imply the use of naturally grown forests (high stand density) on a small scale,

iv) The demand for wood for fire-setting activities was limited and could be met by exploiting only local forests.

Acknowledgements

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