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ORIGINAL ARTICLE

Analysis of the fuel wood used in Late Bronze Age and Early Iron Age copper mining sites of the Schwaz and Brixlegg area (Tyrol, Austria)

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Abstract Charcoal analysis was carried out as part of an interdisciplinary project focusing on the copper mining history of the former mining area of Schwaz and Brixlegg, a region pivotal as a copper source in prehistoric Europe. The goal was to use remains of carbonised wood to investigate environmental implications of prehistoric mining, as well as to gain new insight about the ancient mining technique of fire-setting. Charcoal samples from seven copper mining sites (Late Bronze Age to Early Iron Age) were analysed. The results reveal a strong preference for coniferous wood as fuel in fire-setting, but not in ore smelting/roasting processes. Species composition at the ore-processing sites indicates moderate forest degradation processes caused by human intervention.

Keywords Charcoal analysis · Bronze Age · Iron Age · Fire-setting · Copper mining history · Alps

Introduction

The Eastern Alps contain a high number of profitable ore deposits and are thus a region with a long tradition of mining (Eibner 1992; Höppner et al. 2005). The most prominent prehistoric mining areas were the Mitterberg near Salzburg, the region of Schwaz and Brixlegg in the lower Inntal, and the Kelchalpe near Kitzbühel. In the area of Schwaz/Brixlegg, man has been extracting copper ores from the bedrock since at least the Early to Middle Bronze Age (Goldenberg 1998, 2001), and the local use of copper for creating artefacts is already documented for the beginning of the fourth millennium B.C. (Matuschik 1997; Huijsmans et al. 2004).

The local geology is dominated by the Northern Alpine Greywacke zone (Fig. 1 inset, hatched areas; Brandner 1980) which holds deposits of the tetrahedrite–tennantite type (fahlore/grey copper ore), a mineral closely associated with dolomite rock (Rieser 2000). Dolomite is represented in this area by a local variety, the Schwazer Dolomit. Prehistorical and historical exploitation of these deposits has left traces across the landscapes around Schwaz and Brixlegg (Pirkl 1961; Gstrein 1986, 1988; Goldenberg and Rieser 2004). Along the south bank of the lower Inntal, hundreds of former mines and pits from prehistoric times (Fig. 2) to the Middle Ages can still be found up to high altitudes, for example, the mines of Gratlspitze at 1,899 m a.s.l., a site which is also included in this investigation.

Most of the prehistoric mines close to the surface seem to have been created using the fire-setting technique (Goldenberg 1998). Aside from tools driven by human strength, this was one of the principal methods of working into the rock during the millennia preceding the use of explosives. This did not occur until the seventeenth century, when in 1627 the first confirmed use of gunpowder in mining took place in Banska Stiavnica, Slovakia (Weiss 2005).

Fire-setting takes advantage of the susceptibility of dolomitic rock to heat. A fire is lit close to the wall (Fig. 3) causing the surface layers to crack, thus easing further processing with stone or metal tools. The pits created in dolomite in this way are of a characteristic, dome-like shape. As demonstrated in an experimental approach by Rieser (2000), this treatment can cause ra-

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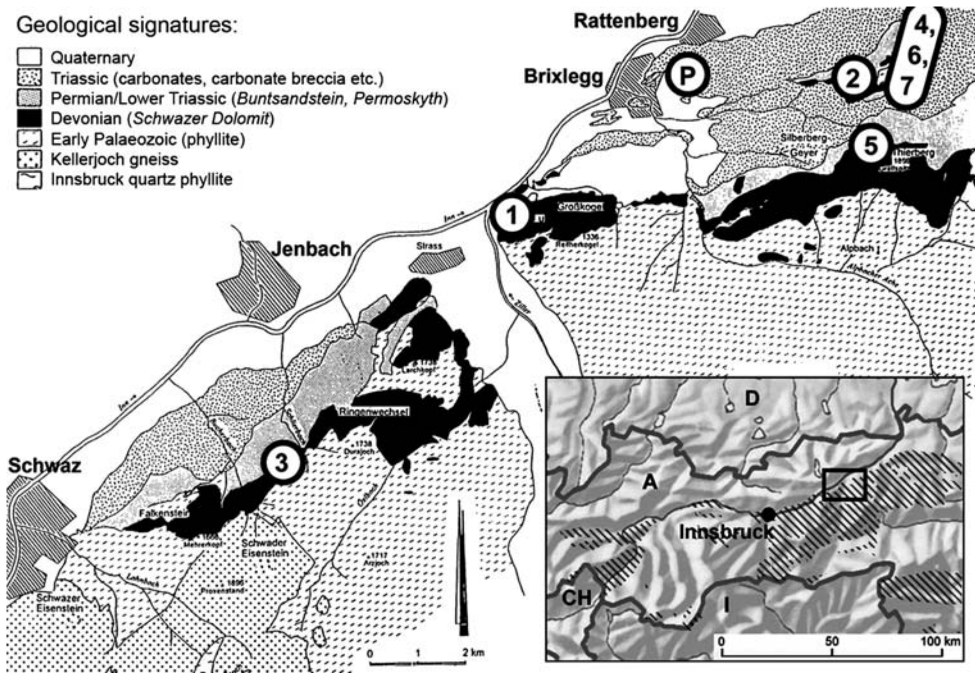


Fig. 1 Site locations (Arlt 1994, modified). *Inset* area investigated, *hatched pattern* Alpine Greywacke zone (Spiess 2002, modified; Brandner 1980, modified). *1* Kleinkogel (970 m a.s.l.), *2* Moosschrofen (1,150 m), *3* Blutskopf (1,200 m), *4* Mauken B (1,200 m), *5* Gratlspitze (1,899 m), *6* Mauken A (950 m), *7* Mauken D (1,020 m), *P* Oberkienberg pollen profile (757 m)

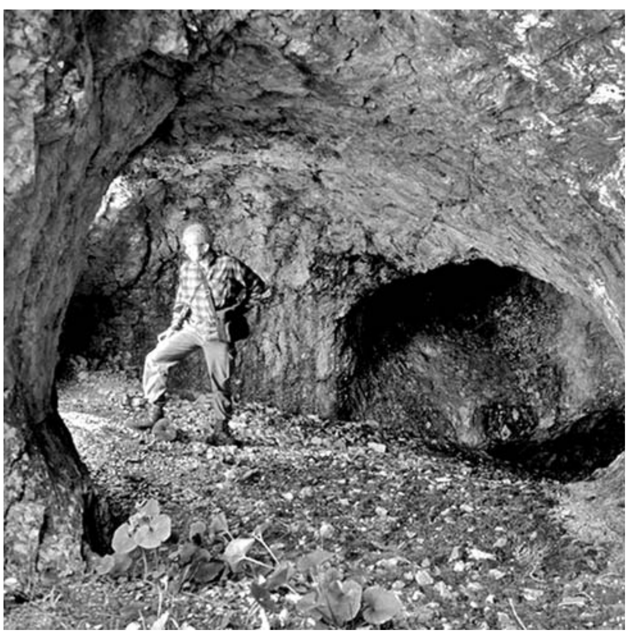


Fig. 2 The pit ''Zwei Fenster'' at Gratlspitze (*photo* Gert Goldenberg)

Fig. 3 Fire-setting as depicted by Georgius Agricola in his *De re metallica libri XII* from 1549 (Schiffner 1928). A burning pile of wood, *B* Bärte (frayed pieces of wood for kindling fire), *C* mine shaft

ther large chunks (up to 10 cm in diameter) to come off the rock by themselves, and allows the miner to process the now-fissured dolomite wall with tools as simple as wooden rods and stone mallets. Historical sources frequently mention the use of cold water for quenching the heated rock and thus enhancing the effect. Roman authors such as Titus Livius (*Ab urbe condita*, *Liber XXI*, *XXXVII*; Spillan and Edmonds 1868) and Gaius Plinius Secundus (*Naturalis historia*, *Liber XXXIII*, *LXXI*; von Jan 1860) even wrote of vinegar as a quenching agent instead of water. However, experimental approaches have not been able to verify unequivocally the efficacy of quenching (Rieser 2000; Craddock 1995, cited by Rieser 2000).

During Middle to Late Bronze Age new technological and cultural influences coming from the Mediterranean spread across Europe. Archaeological evidence suggests a kind of ''early industrialisation'' impulse in the Eastern Alps based on the rising demand for bronze in Europe and also newly introduced techniques of smelting and alloying (Goldenberg 1998). It is to be expected that during this period

1. a higher demand for copper led to an increase in copper production, which resulted in
2. a higher population and larger settlements, and
3. an increase in agriculture and trade, leading to the expansion of arable land and of the road network.

Furthermore, a noticeable impact on local forest ecosystems in the mining areas is to be expected because of the timber needed for ore winning and processing.

To investigate these cultural and social as well as environmental changes, an interdisciplinary project on Bronze Age fahlore mining in the Schwaz and Brixlegg region was launched in 1997. Since then, test excavations have been carried out at numerous mining sites throughout the area, resulting in a number of publications on copper ore mining in the Eastern Alps (Goldenberg 1998, 2001; Goldenberg and Rieser 2004; Höppner et al. 2005; Rieser 2000). Similar multidisciplinary investigations including charcoal analysis are available from, for example, Cabrières in southern France (Ambert 2002; Ambert et al. 2002), or from Goleen in south-eastern Ireland (O'Brien 2003).

The goal of the charcoal analyses performed in the current project was to investigate some of the general conditions and consequences of mining, and of fire-setting in particular:

- Does the species composition of the fuel wood reflect local vegetation at Late Bronze Age and Early Iron Age, derived from the available pollen record?
- Is there any evidence on changes in forest cover or even on vegetation degradation?
- Could the data possibly contain any evidence on specific selection of certain woody taxa?
- What do dendrological features tell us about the quality of wood used?

Similar anthracological investigations of human impact and forestry management, as well as of details of the underlying technical processes have already been carried out for other periods: Imperial Roman bloomery furnaces in northern Germany (Dörfler and Wiethold 2000), Roman to modern times settlements, mining and kiln sites in the Black Forest (Ludemann 1996, 1999, 2002, 2003; Ludemann et al. 2004) and in the Bavarian Forest (Nelle 2003), and various sites from modern times analysed in large-scale investigations in Great Britain (Gale 2003).

The area investigated

Charcoal was collected from five fire-set pits at different locations (Fig. 1) and at different altitudes as described below, as well as from two other archaeological sites. These were a Middle to Late Bronze Age ore-processing site and the surroundings of a late Bronze Age mine shaft (Fig. 1). Detailed account of the topography, geology and actual vegetation can be found in Rieser (2000) and in Heiss (2001).

The first pit is located at *Kleinkogel* (970 m a.s.l.), the most north-westerly outpost of the Kitzbüheler Alpen at the entrance of the Zillertal. Its northern aspect is characterised by numerous screes and steep rock faces (*Heidstein*, the ''heathen rock'') pierced with prehistoric mines. Actual vegetation on the northern face is a mixed montane forest similar to that described for the Mauken area, but interrupted by azonal stands of mugo pine (*Pinus mugo*) in the screes.

The *Moosschrofen* is a small inselberg in the Mauken region, completely composed of Schwazer Dolomit and with numerous fire-set pits. Samples were taken from the pit ''Grube Ost'' (1,150 m a.s.l.) at the northern face of Moosschrofen (Rieser 2000). The rocky areas contain Scots pine (*P. sylvestris*), whereas the surrounding vegetation is composed of spruce forest and pastures.

The pit sampled at *Blutskopf*, a mountain at Hochgallzein in the east of Schwaz, lies about 100 m below the peak (at 1,200 m a.s.l.), on a scarp called Vogelsang. Local vegetation is dominated today by (supposedly) natural spruce woods, with frequent occurrence of larch.

Mauken (Hintersommerau) is a small region on the south bank of the Inntal, in the vicinity of Brixlegg. In a narrow, gorge-like valley in that area, the Maukengraben, a fire-set pit (*Mauken B*) at about 1,200 m a.s.l., was sampled. Some distance downhill, excavation campaigns revealed the slag dump from an ore-processing site (*Mauken A*, 950 m a.s.l.) and several collapsed mine shafts (*Mauken D*, 1,020 m a.s.l.). Charcoal was collected from both sites for analyses. The actual vegetation of the area is very heterogeneous due to debris cones and anthropogenic clearings (e.g. the gravel access road). However, it is dominated by a montane mixed forest of spruce (*Picea abies*), fir (*Abies alba*) and beech (*Fagus sylvatica*), with Scots pine (*P. sylvestris*) and larch (*Larix decidua*) occurring frequently.

The prehistoric mines at *Gratlspitze* (1,899 m a.s.l.) are also very close to the peak, where a pit (''Zwei Fenster'', Rieser 2000) on the northern face was sampled. Local woody vegetation is restricted to patches of mugo pine (*P. mugo*). Beneath the timberline (at about 1,800 m), woods of the typical subalpine spruce–larch type dominate the landscape.

Materials and methods

Sampling

The excavator (G. Goldenberg) took 11 samples of fire-setting rubble from the 5 fire-set pits, their volumes ranging between 25 and 120 ml. The soil samples from the Mauken A and D sites were significantly larger and ranged between 42 and 2,660 ml. All material was packed in airtight polyethylene bags immediately after sampling and stored at +5°C until analysis.

Radiocarbon dating

Several charcoal samples were AMS dated at the Vienna Environmental Research Accelerator (VERA) laboratory at the Institute for Isotope Research and Nuclear Physics of the University of Vienna. Radiocarbon data calibration was carried out with OxCal 3.10 (Bronk Ramsey 1995, 2001) using the IntCal04 calibration curve (Reimer et al. 2004).

Sample processing and identification

Extraction of plant macro remains from the soil material followed standard flotation procedure (Jacomet and Kreuz 1999), and the resulting material was split into four fractions using staggered sieves at mesh sizes of 0.25, 0.5, 1 and 2 mm. Uncarbonised and carbonised plant remains from all fractions were then analysed. Results from the macrofossil analyses from Mauken have already been published (Heiss 2001; Schatz et al. 2002; Heiss and Oeggl 2005).

As charcoal analysis had originally only been planned as a minor component of the investigations, the following measures were taken in order to keep within the scheduled time frame:

- Charcoal analysis was limited to fragments from the largest fraction (>2 mm)
- Subsamples of 50 fragments (where possible; Table 1) per sample were randomly collected and analysed.

Identification of the charcoal fragments was carried out using an episcopic microscope (Zeiss Axioskop). An interactive identification key (Heiss 2000 onwards) was also used in addition to the standard literature (Schweingruber 1990).

In addition to identification, some dendrological and taphonomical features were recorded for the charcoal analysed to gain some insight into the quality of wood used. The radius of the outermost growth ring for each charcoal fragment was measured by adjusting the growth ring curvature and wood ray angle of the charcoal pieces to a diameter stencil (Ludemann 1996). As a simplified stencil was used, only a qualitative differentiation between ''small'' (≤25 mm) and ''large'' (>25 mm) radii was made in this current study. Additionally, the maximum growth ring width per fragment (i.e. the dimension of the widest growth ring) was recorded.

Wood-decaying fungi are destroyed during carbonisation, but their former presence is often indicated by imprints of hyphae in the cell wall tissue of the host plant. This fact can be used to gain further information on the quality of the fuel wood, and whether intact or decaying wood had been used (Schweingruber 1976). Unidentified fragments (recorded as ''hardwood indet.'' and ''softwood indet.'') were excluded from this analysis. Charcoal pieces containing modern hyphae material (probably from edaphic fungi) were considered as not containing any ancient hyphae imprints. This approach implies a bias, possibly causing under-representation of fungus-infested material in the data.

Results

Radiocarbon dating

The results indicate ages ranging from Late Bronze Age to Early Iron Age (Fig. 4) and an obvious temporal difference between the ore-processing sites at Mauken A and D and the five fire-set pits. However, these seemingly younger sites lie within the Hallstatt plateau of the calibration curve. This is caused by a sudden rise in atmospheric ^{14}C content between ca. 2750 B.P. and 2450 B.P. (van Geel et al. 1996; Reimer et al. 2004; Guilderson et al. 2005) which renders radiocarbon data from that period rather unreliable. Consequently, it cannot be stated with certainty whether the material from the fire-set pits investigated is of Late Bronze Age (Urnfield Culture) or Early Iron Age (Hallstatt) origin.

Moreover, the charcoal material from Kleinkogel dates to modern times. Although sampling focused on the lower layers of the fire-setting rubble (G. Goldenberg, personal communication), the charcoal had most probably been contaminated with modern material. This may be explained by the fact that both tourists and locals sometimes use the prehistoric mines as campfire sites. Nevertheless, the results from the Kleinkogel samples are also included in this study as a modern analogue for the prehistoric sites.

Charcoal analysis

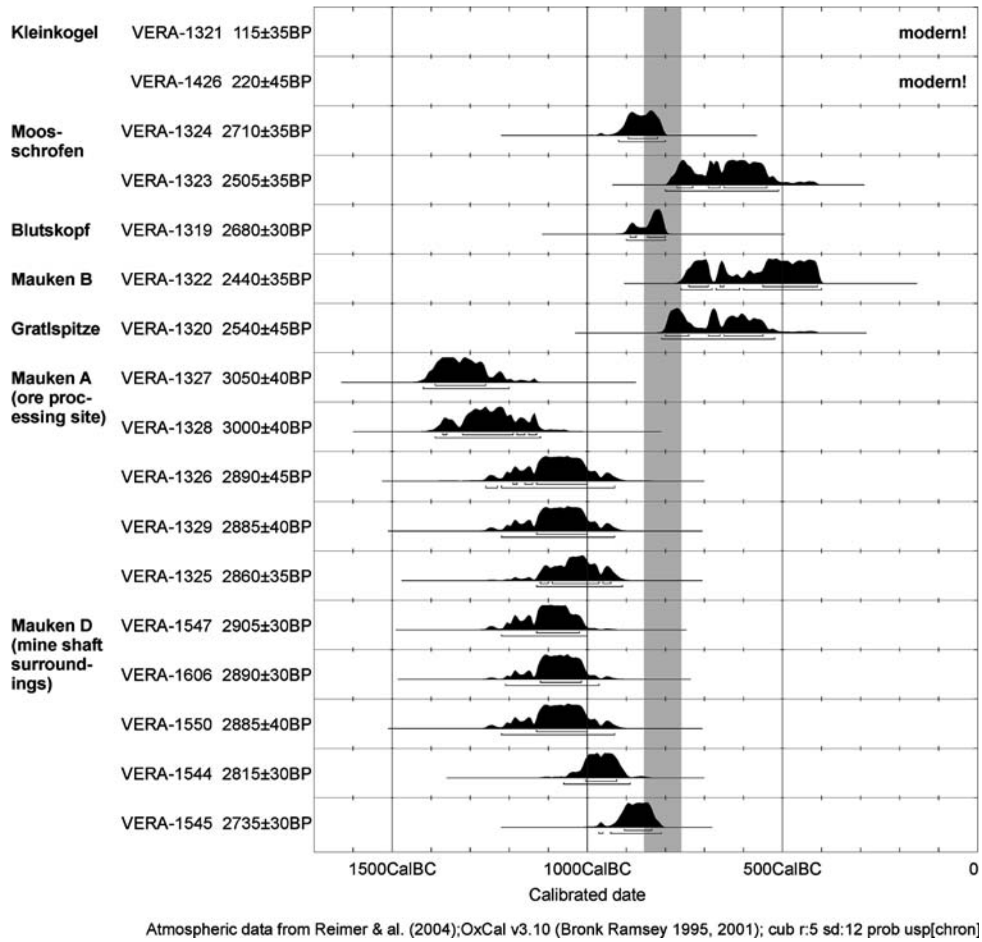
A total of 520 charcoal fragments was analysed from the Late Bronze Age (LBA) sites of Mauken A and D (Table 1). The samples were dominated by the taxa *Abies*, *Picea*/*Larix* type and *Fagus*. Small quantities of the light-demanding pioneer woody taxa *Betula*, *Pinus* and *Sambucus* occurred, as well as the highly shade-tolerant *Taxus*.

Table 1 Results of the charcoal analyses for the Late Bronze Age mining sites

	Mauken A: ore-processing site											Mauken D: mine shaft surroundings								
												Fireplace				Refuse pit				
Sample no.	1	2	14	19	21	25	30	31	32		%	35	36		%	26	33	34		%
Total sample volume (ml)	790	610	42	2,634	1,330	2,125	1,405	430	590	9,956		2,660	690	3,350		1,430	1,630	2,090	5,150	
Total charcoal weight >2 mm (g)	2.30	1.33	0.1	27.56	2.98	57.34	12.18	0.58	3.92	108	100	1.35	6.29	8	100	12.04	7.14	4.41	24	100
Analysed charcoal weight >2 mm (g)	0.35	0.43	0.1	5	0.58	9.25	2.31	0.27	2.12	20	19	0.69	1.92	3	34	2.1	2.57	1.88	7	28
Mean fragment weight (mg)	7	9	10	100	12	185	46	27	42			23	38	33		42	51	38	44	
Abies alba	28	26	5	22	24	40	25	7	21	198	53.5	13	15	28	35	7	9	11	27	18
Larix decidua	2	–	–	–	4	–	–	–	3	9	2.4	–	–	–	–	–	1	5	6	4
Picea/*Larix* type	15	16	2	13	12	3	7	1	9	78	21.1	8	21	29	36.3	24	19	20	63	42
Pinus non *cembra*	–	–	–	–	–	–	2	–	1	3	0.8	3	1	4	5	–	1	–	1	0.7
Taxus baccata	–	–	–	–	–	–	–	–	–	–	–	2	–	2	2.5	–	–	–	–	–
Coniferous wood (indet.)	2	4	1	3	1	–	3	–	4	18	4.9	–	–	–	–	2	3	2	7	4.7
Betula sp.	–	–	–	–	–	–	2	–	–	2	0.5	–	–	–	–	–	–	2	2	1.3
Fagus sylvatica	3	4	–	10	7	5	10	2	10	51	13.8	4	8	12	15	16	16	9	41	27.3
Sambucus sp.	–	–	–	–	–	–	–	–	–	–	–	–	2	2	2.5	–	–	–	–	–
Broad-leaved wood (indet.)	–	–	2	2	2	2	1	–	2	11	3	–	3	3	3.8	1	1	1	3	2
Analysed charcoal (total)	50	50	10	50	50	50	50	10	50	370	100	30	50	80	100	50	50	50	150	100

Values given are fragment numbers unless otherwise stated

Fig. 4 Results of the radiocarbon dating. The *grey bar* indicates the Hallstatt plateau



From the fire-set pits, 476 specimens of charcoal were analysed. In comparison to the LBA sites, the results for the prehistoric samples display a starkly diverging species composition: all the charcoal originated exclusively from softwoods (Table 2, Fig. 6) with either *Abies* or the *Picea/Larix* type dominating. The modern samples from Kleinkogel pit show in turn an additional proportion of *Fagus* wood similar to the LBA sites.

Discussion

Species composition

According to the palynological analyses performed on a peat profile from the nearby Oberkienberg (Walde 1998, 1999), forest vegetation in the Brixlegg area during the LBA was very similar to modern conditions. After the arrival of *Fagus* during the transition Atlantic-Subboreal (ca. 4000 cal B.C.), all main tree taxa were present in the area, indicating that montane mixed forests were already fully formed at the beginning of LBA.

Proportions of the dominant tree taxa in the LBA sites of Mauken A and D (*Abies*, *Picea/Larix* type, *Fagus*; Table 1, Fig. 5) more or less match the expected natural composition of montane mixed-forest stands. Species composition at these two sites does not give any evidence of selection of fuel wood.

The presence of some pioneer taxa in the Mauken A and D charcoal samples might indicate that succession processes were taking place, probably induced by anthropogenic influence on the local forest ecosystems (comparable to the modern situation at Mauken). As expressed in the basic hypothesis stated above, small-scale clearings are to be expected in the surroundings of ore-processing and mining facilities, as there was need for fuel wood and traffic routes to be set up in order to facilitate work and transport. However, the obviously very small proportion of these pioneer taxa (0.54–2.5% of charcoal fragments per site) is within the range of natural conditions and does not necessarily imply human impact (T. Ludemann, personal communication). In any case, their low proportions in the firewood point to sufficient availability of the taxa forming the climax forest, and consequently a rather low or, at the most, a moderate influence of mining activities on the local forest ecosystems.

As already described, hardwoods were completely missing from the prehistoric material from the fire-set pits. Widely varying amounts of *Abies* were recorded, from a

Table 2 Results of the charcoal analyses for the Early Iron Age fire-set pits

	Kleinkogel (modern!)				Moosschrofen					Blutskopf				Mauken B				Gratlspitze			
Sample no.	6	11		%	4	5	7		%	8	9		%	3	10		%	12	13		%
Total sample volume (ml)	120	66	186		31	67	25	123		39	86	125		74	35	109		46	29	75	
Total charcoal weight >2 mm (g)	17.39	27.58	44.97	100	14.56	19.92	9.97	44.45	100	13.60	27.26	40.86	100	18.48	13.88	32.36	100	28.48	13.62	42.1	100
Analysed charcoal weight >2 mm (g)	3.03	15.96	18.99	42	14.56	12.95	5.15	32.66	73	5.35	17.39	22.74	56	7.27	5.03	12.3	38	20.92	12.21	33.13	79
Mean fragment weight (mg)	61	319	190		14,560	259	103	323		107	348	227		145	101	123		418	488	442	
Abies alba	32	13	45	45	–	36	5	41	41	8	4	12	12	11	35	46	46	1	–	1	1
Larix decidua	–	–	–	–	–	–	–	–	–	1	–	1	1	–	–	–	–	5	2	7	9
Picea/Larix type	13	31	44	44	1	14	43	58	57	35	45	80	80	39	12	51	51	43	23	66	88
Coniferous wood (indet.)	–	–	–	–	–	–	2	2	2	6	1	7	7	–	3	3	3	1	–	1	1
Fagus sylvatica	2	6	8	8	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Broad-leaved wood (indet.)	3	–	3	3	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Analysed charcoal (total)	50	50	100	100	1	50	50	101	100	50	50	100	100	50	50	100	100	50	25	75	100

Values given are fragment numbers unless otherwise stated

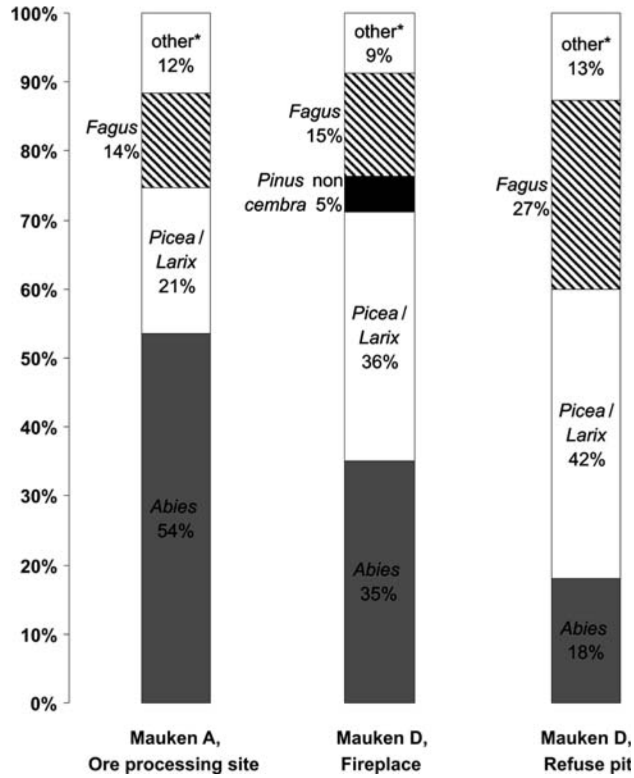


Fig. 5 Taxon percentages for the Late Bronze Age (LBA) mining sites. * = Taxa with per-site percentages below 5%, subsumed as ''other'' (see Table 1 for details)

maximum of 46% at Mauken B to only a single find at the Gratlspitze pit. When considering the differences in altitudes between the sites (bottom of Fig. 6), it becomes obvious that natural altitudinal distribution of *A. alba* may

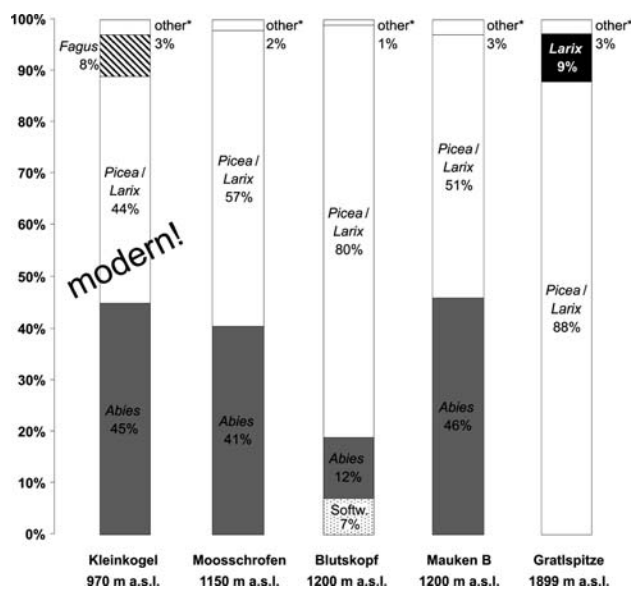


Fig. 6 Taxon percentages for the Early Iron Age fire-set pits. * = Taxa with per-site percentages below 5%, subsumed as ''other'' (see Table 2 for details)

be the reason. Noteworthy amounts of *Abies* charcoal occur only in the material from the montane pits.

By and large two approaches seem possible when seeking explanations for the species compositions being so markedly different to the LBA sites. Either these divergences are the consequence of the very different archaeological contexts and the different uses of the fuel wood (ore smelting/roasting in contrast to fire-setting), or major changes in local vegetation must have taken place between the LBA and Early Iron Age.

Taking the pollen record into account, then at least for the surroundings of the three Iron Age pits at montane altitudinal zones (Moosschrofen, Mauken B, and Blutskopf) the availability of sufficient wood from hardwood species (e.g. *F. sylvatica*) for fire-setting can be considered. The Oberkienberg pollen profile (Walde 1998, 1999) documents human impact on local vegetation by a steady increase of anthropogenic indicators (Cerealia, *Plantago lanceolata* and *Rumex* pollen types) and decreasing values for arboreal pollen since the Subboreal. However, there is apparently no evidence whatsoever for major degradation processes in local forest vegetation during the Bronze and Iron Ages, such as would result in a collapse of hardwood species populations. Consequently, their complete absence in all of the charcoal samples ought to be interpreted as evidence of the deliberate selection of coniferous taxa for fuel wood.

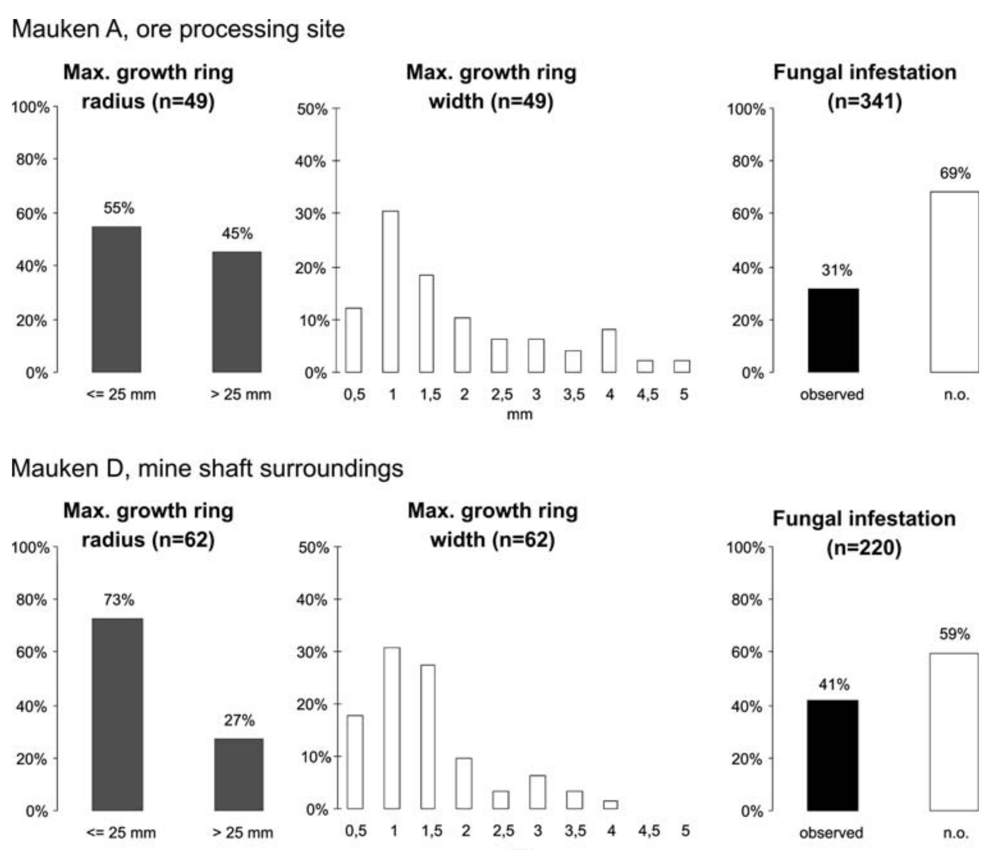
This possible evidence for the selection of fuel wood in fire-setting may also be corroborated by historical written sources, for example, Rösler (1700) cited by Rieser (2000) strongly suggests the exclusive use of fir and spruce wood for fire-setting, due to their ''hotter flames''. Such preference for coniferous wood cannot be substantiated by measurement—in reality burning temperatures are not species dependent (Ten Wolde et al. 1988, cited by Ragland et al. 1991). Nevertheless, if our conclusions on Early Iron Age fire-setting in the Schwaz/Brixlegg area are correct, taking these together with the sixteenth century document, we have a strong indication of a tradition of fire-setting remaining nearly unchanged for more than two millennia, at least in terms of fuel wood selection.

The modern charcoal material from Kleinkogel pit, strongly deviating from this pattern of an exclusive presence of softwood taxa, more or less resembles the taxa proportions typical of the modern, montane mixed-forest stands in the area (Table 2). It can be presumed that no selective processes had guided the wood gatherers.

Wood quality

The data resulting from the dendrological analyses are displayed in Figs. 7 and 8. For each site, the maximum growth ring radius, a histogram of maximum growth ring

Fig. 7 Dendrological features of the LBA mining sites charcoal. n.o. = not observed



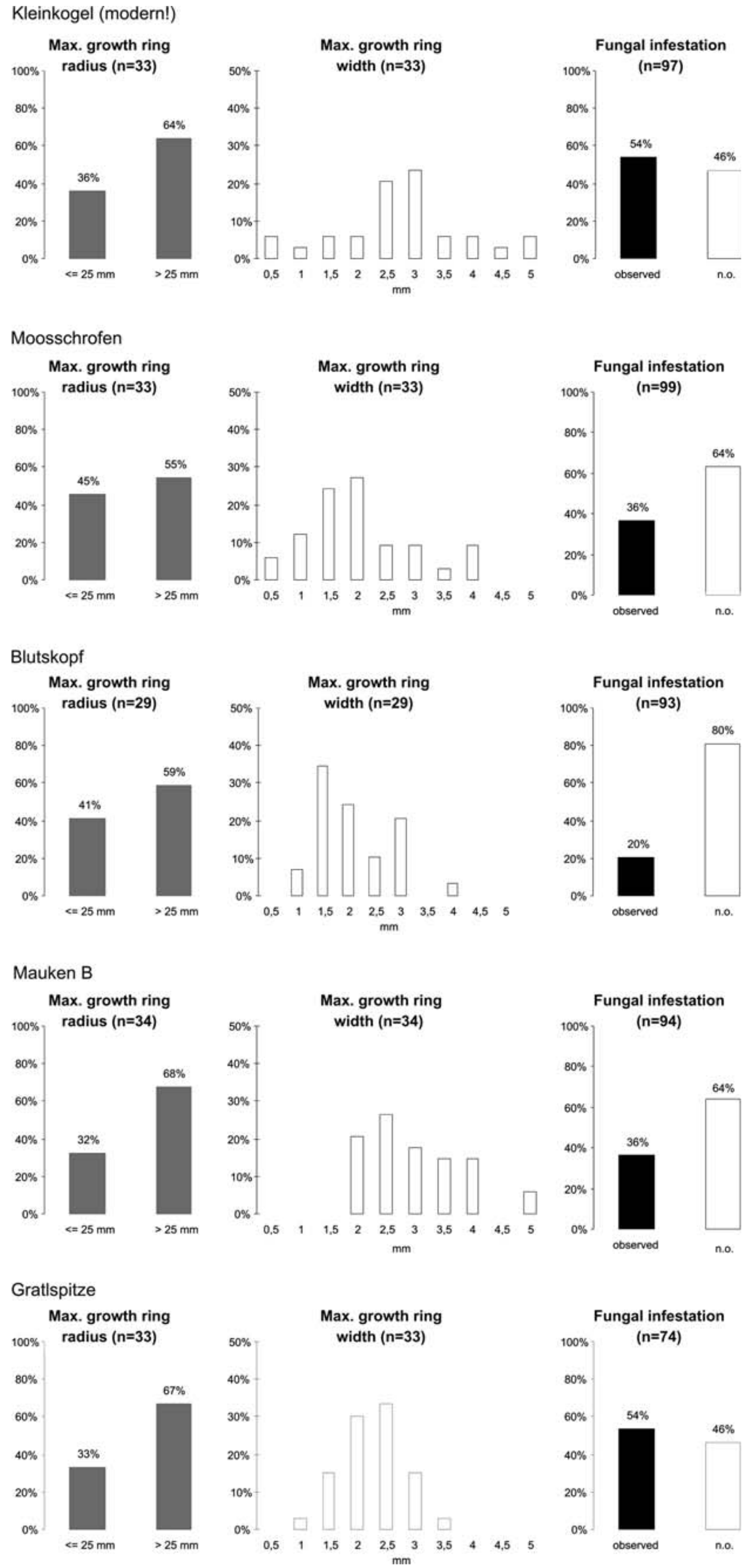


Fig. 8 Dendrological features of the Early Iron Age fire-set pits charcoal. n.o. = not observed

widths and the proportion of fungus-infested wood are shown.

As for the wood radii, only very limited interpretation is possible since only two radius categories were used. As a significant volumetric loss in wood tissue during carbonisation has to be considered, especially in the radial and tangential directions (12–25%, Schweingruber 1976; Slocum et al. 1978), the measured growth ring data (radius as well as growth ring width) also cannot be equated with uncarbonised wood.

Generally, for the fire-set pits the amount of ''large'' radius wood is above 50%, suggesting the presence of thicker stems and branches (>5 cm diameter) in the charcoal material. However, the Mauken A and D sites display a reverse proportion, with a dominance of ''small'' radius wood. Analyses with a higher resolution (e.g. using five radius categories instead of only two) should reveal whether there has been any preference for twigs and thin branches at Mauken A and D.

The histograms show the distribution of growth ring width categories in the charcoal material. Branches commonly display less radial growth than do young stems of the same diameter. The figures show markedly heterogeneous results that do not display a common trend within the fire-set pits, very unlike the species composition or the wood diameters. However, the LBA sites at Mauken A and D again stand out, because of the increased occurrence of low radial growth with a simultaneous decrease in large growth rings. This, too, points to a prevalent use of twigs and thin branches in the fuel wood.

The presence of fungus-infested charcoal fragments was also recorded for all the sites investigated. The proportions in the fire-set pits are rather heterogeneous, with 20 to 54% of the material containing hyphae imprints, indicating varying quantities of gathered/stored wood in contrast to freshly felled material.

The only prehistoric site exceeding a value of 50% was Gratlspitze (54%). Given a possible under-representation of hyphae-containing fragments (see Methods section) we have to consider the use of a substantial amount of fungus-infested (and thus, partly decayed) wood/charcoal for fire-setting. Considering the altitude of the mine it seems very plausible to assume that the low availability of fuel wood had led the miners to use (gathered?) wood of poor quality, which they had to transport to the pit from the forests below.

The same analyses carried out for the Mauken A and D sites resulted in roughly one-third of the charcoal material showing hyphae imprints, indicating a moderate proportion of gathered/stored wood.

Conclusions

The results from the LBA sites of Mauken A and D suggest that the fuel wood utilised for smelting/roasting processes as well as for daily use (Mauken A, D) was most probably taken from the environment at random, but may have undergone a selection process by branch thickness. The implication of the charcoal record of human impact on local forest ecosystems points to a possible influence due to clearings and wood use, but still suggests a broad availability of climax forest taxa and consequently the presence of more or less intact forest vegetation.

The situation at the Early Iron Age fire-set pits is rather different, clearly showing deliberate selection of fuel material on the basis of hardwood/softwood, with the sole use of coniferous woods for setting fire possibly being due to their putative combustion properties.

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References

Ambert P (2002) Utilisation préhistorique de la technique minière d'abattage au feu dans le district cuprifère de Cabrières (Hérault). C R Palevol 1:711–716

Ambert P, Coularou J, Cert C, Guendon J-L, Bourgarit D, Mille B, Dainat D, Houlès N, Baumes B (2002) Le plus vieil établissement de métallurgistes de France (III^{e} millénaire av. J.-C.): Péret (Hérault). C R Palevol 1:67–74

Arlt T (1994) Geologie und Vererzungen im Raum Schwaz-Brixlegg, Tirol. Lapis VII/VIII (20)

Brandner R (1980) Tirol-Atlas, Geologische Übersichtskarte von Tirol. Institut für Landeskunde, Universität Innsbruck

Bronk Ramsey C (1995) Radiocarbon calibration and analysis of stratigraphy: the OxCal Program. In: Cook GT, Harkness DD, Miller BF, Scott EM (eds) Proceedings of the 15th International ^{14}C Conference. Radiocarbon, vol 37, pp 425–430

Bronk Ramsey C (2001) Development of the radiocarbon program OxCal. Radiocarbon 43:355–363

Dörfler W, Wiethold J (2000) Holzkohlen aus den Herdgruben von Rennfeueröfen und Siedlungsbefunden des spätkaiserzeitlichen Eisengewinnungs- und Siedlungsplatzes am Kammberg bei Joldelund, Kr. Nordfriesland. In: Haffner A, Jöns H, Reichstein J (eds) Frühe Eisengewinnung in Joldelund, Kr. Nordfriesland. Ein Beitrag zur Siedlungs- und Technikgeschichte Schleswig-Holsteins. Teil 2: Naturwissenschaftliche Untersuchungen zur

Metallurgie- und Vegetationsgeschichte. Universitätsforsch. Prähist. Archäol, vol 59. Habelt, Bonn, pp 217–262
Eibner C (1992) Der Kupferbergbau in den Österreichischen Alpen in der Urzeit. Archäol Österreichs 3:12–16
Gale R (2003) Wood-based industrial fuels and their environmental impact in lowland Britain. In: Murphy P, Wiltshire PEJ (eds) The environmental archaeology of industry. Symposia of the Association for Environmental Archaeology vol 20, pp 30–47
Geel B van, Buurman J, Waterbolk HT (1996) Archeological and paleoecological indications for an abrupt climate change in The Netherlands and evidence for climatological teleconnections around 2650 BP. J Quat Sci 11:451–460
Goldenberg G (1998) L'exploitation du cuivre dans les Alpes Autrichiennes à l'âge du Bronze. In: Mordant C, Pernot M, Rychner V (eds) L'Atelier du bronzier en Europe du XXe au VIIIe siècle avant notre ère. Actes du colloque international Bronze '96, Neuchâtel et Dijon. Tome II. Paris, CTHS, pp 9–24
Goldenberg G (2001) Bronzezeitlicher Kupferbergbau in Nordtirol. In: Brunn A, Steinacker C, Jordan T (eds) Archäologie Online. Retrieved March 29, 2004 from the WWW. URL: http://www.archaeologie-online.de/thema/2001/02/
Goldenberg G, Rieser B (2004) Die Fahlerzlagerstätten von Schwaz/Brixlegg (Nordtirol). Ein weiteres Zentrum urgeschichtlicher Kupferproduktion in den österreichischen Alpen. Alpenkupfer Rame delle Alpi Der Anschnitt, Beiheft 17:37–52
Gstrein P (1986) Geologie–Lagerstätten–Bergbautechnik. In: Egg E, Gstrein P, Sternad H (eds) Stadtbuch Schwaz. Natur–Bergbau–Geschichte. Schwaz, pp 9–77
Gstrein P (1988) Geologie, Mineralogie und Bergbau des Gebietes um Brixlegg. In: Brixlegg, eine Tiroler Gemeinde im Wandel der Zeiten. Brixlegg, pp 11–62
Guilderson TP, Reimer PJ, Brown TA (2005) The boon and bane of radiocarbon dating. Science 307:362–364
Heiss AG (2000 onwards) Anatomy of European and North American Woods—an interactive identification key. Version 2005–03–09. http://www.holzanatomie.at/
Heiss AG (2001) Anthrakologische und paläoethnobotanische Untersuchungen im bronzezeitlichen Bergbaugebiet Schwaz-Brixlegg (Tirol). Unpublished diploma thesis, Innsbruck
Heiss AG, Oeggl K (2005) The oldest evidence of *Nigella damascena* L. (Ranunculaceae) and its possible introduction in central Europe. Veget Hist Archaeobot 14:562–570
Höppner B, Bartelheim M, Huijsmans M, Krauß R, Martinek K-P, Pernicka E, Schwab R (2005) Prehistoric copper production in the Inn Valley (Austria), and the earliest copper in central Europe. Archaeometry 47:293–315
Huijsmans M, Krauß R, Stibich R (2004) Prähistorischer Fahlerzbergbau in der Grauwackenzone—Neolithische und bronzezeitliche Besiedlungsgeschichte und Kupfermetallurgie im Raum Brixlegg (Nordtirol). Alpenkupfer Rame delle Alpi Der Anschnitt, Beiheft 17:53–62
Jacomet S, Kreuz A (1999) Archäobotanik. Ulmer, Stuttgart
von Jan L (ed) (1860) *C. Plini Secundi Naturalis historiae libri XXXVII*. Libb. XXXIII–XXXVII. Teubner, Leipzig
Ludemann T (1996) Die Wälder im Sulzbachtal (Südwest-Schwarzwald) und ihre Nutzung durch Bergbau und Köhlerei. Mitt Ver Forstl Standortsk Forstpflanzenzücht 38:87–118
Ludemann T (1999) Zur Brennstoffversorgung einer römischen Siedlung im Schwarzwald. In: Brather S, Bücker C, Hoeper M (eds) Archäologie als Sozialgeschichte. Studien zu Siedlung, Wirtschaft und Gesellschaft im frühgeschichtlichen Mitteleuropa (Festschrift Steuer). Internationale Archäologie (Studia honoraria), vol 9, pp 165–172
Ludemann T (2002) Anthracology and forest sites—the contribution of charcoal analysis to our knowledge of natural forest vegetation in south-west Germany. In: Thiébault S (ed) Charcoal analysis. Methodological approaches, palaeoecological results and wood uses. Proceedings of the 2nd International Meeting of Anthracology, Paris, France, September 2000. BAR International series, vol 1063, pp 209–217
Ludemann T (2003) Large-scale reconstruction of ancient forest vegetation by anthracology—a contribution from the Black Forest. Phytocoenologia 33:645–666
Ludemann T, Michiels H-G, Nölken W (2004) Spatial patterns of past wood exploitation, natural wood supply and growth conditions: indications of natural tree species distribution by anthracological studies of charcoal-burning remains. Eur J For Res 123:283–292
Matuschik I (1997) Der neue Werkstoff—Metall. In: Planck D (ed) ALManach 2, Archaeologisches Landesmuseum Baden-Württemberg. Theiss, Stuttgart, pp 16–25
Nelle O (2003) Woodland history of the last 500 years revealed by anthracological studies of charcoal kiln sites in the Bavarian Forest, Germany. Phytocoenologia 33:667–682
O'Brien W (2003) The Bronze Age copper mines of the Goleen area, Co Cork. Proc R Irish Acad 103:13–59
Pirkl H (1961) Geologie des Trias-Streifens und des Schwazer Dolomits südlich des Inn zwischen Schwaz und Wörgl (Tirol). Jb Geol Bundesanstalt 104:1–150
Ragland KW, Aerts DJ, Baker AJ (1991) Properties of wood for combustion analysis. Bioresour Technol 37:161–168
Reimer PJ, Baillie MGL, Bard E, Bayliss A, Beck JW, Bertrand CJH, Blackwell PG, Buck CE, Burr GS, Cutler KB, et al. (2004) IntCal04 Terrestrial radiocarbon age calibration, 26–0 ka BP. Radiocarbon 46:1029–1058
Rieser B (2000) Urgeschichtlicher Kupferbergbau im Raum Schwaz-Brixlegg. Eine Untersuchung urgeschichtlicher Bergbauspuren und Werkzeugfunde—mit Experimenten. PhD thesis, Innsbruck
Schatz I, Schatz H, Glaser F, Heiss AG (2002) Subfossile Arthropodenfunde in einer bronzezeitlichen Grabungsstätte bei Radfeld (Tirol, Österreich)—Acari: Oribatida; Insecta: Coleoptera, Hymenoptera: Formicidae. Ber Nat Med Ver Innsbruck 89:249–264
Schiffner C (1928) Georg Agricola. Zwölf Bücher vom Berg- und Hüttenwesen (translated). VDI, Berlin. http://www.digitalis.uni-koeln.de/agricola/
Schweingruber FH (1976) Prähistorisches Holz—Die Bedeutung von Holzfunden aus Mitteleuropa für die Lösung archäologischer und vegetationskundlicher Probleme. Academica helvetica. Haupt, Bern
Schweingruber FH (1990) Anatomie europäischer Hölzer. Haupt, Bern
Slocum DH, McGinnes EA Jr, Beall FC (1978) Charcoal yield, shrinkage, and density changes during carbonization of oak and hickory wood. Wood Sci 11:42–47
Spiess E (ed) (2002) Schweizer Weltatlas. Neuausgabe 2002. Lehrmittelverlag des Kantons Zürich, Zürich. http://www.educeth.ch/geographie/weltatlas/
Spillan D, Edmonds C (eds) (1868) The History of Rome, by Titus Livius. Books 9 to 26. eBook. http://www.gutenberg.org/etext/10907
Walde C (1998) Palynologische Untersuchungen zur Vegetations- und Siedlungsentwicklung im Raum Kramsach-Brixlegg (Tirol). Unpublished diploma thesis, Innsbruck
Walde C (1999) A contribution to the vegetation and settlement history in the region of Kramsach-Brixlegg (Tyrol, Austria). Ber Nat Med Ver Innsbruck 86:61–79
Weiss A (2005) Der Pulverturm von Arzberg und das Sprengen mit Schwarzpulver—the Arzberg explosives magazine and blasting with gun powder. Joannea Geol Paläont 7:127–145