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Dendrochronologia 66 (2021) 125814

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ORIGINAL ARTICLE

Prehistoric salt mining in Hallstatt, Austria. New chronologies out of small wooden fragments

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ARTICLE INFO

Keywords:
Prehistoric wood
Dendrochronology
Radiocarbon wiggle matching
Hallstatt
Salt mine
Archaeology

ABSTRACT

The prehistoric salt mine of Hallstatt together with its burial ground is one of the most prominent archaeological sites in the world, and has given its name to the "Hallstatt period", an epoch of European prehistory (800 to 400 BCE). Due to the perfect conservation in rock salt a high number of organic materials have been found, including mostly wooden artefacts and structural timber.

More than 2000 samples were taken from various archaeological sites in the mines as well as at the surface. It was possible to date 763 samples by the means of dendrochronology and by ^{14}C wiggle matching. The dendrochronological dating was possible due to crossdating with various available chronologies (like Villingen-Magdalenenberg or Dachstein/Schwarzer See). The fir (*Abies alba* Mill.) chronologies span the periods: -1232 to -1063; -819 to -425 and -371 to-129. The spruce (*Picea abies* L. Karst.) chronologies span the periods: -1228 to -1063; -813 to -669 and -342 to -123. The larch (*Larix decidua* Mill.) chronologies span the periods: -1393 ± 18 to-1286 ± 18 based on wiggle matching data and -252 to -164. A beech (*Fagus sylvatica* L.) chronology span the time -1182 to -1062.

1. Introduction

The Hallstatt High Valley (Austria) represents one of Europe's oldest cultural and industrial landscapes and forms the center of the UNESCO World Heritage region Hallstatt-Dachstein/Salzkammergut. For millennia this Alpine valley was the demographic and economic center of a wide region with intricate links to regional and trans-regional communities (Kowarik et al., 2015a; Reschreiter and Kowarik, 2017, 2019; Kowarik, 2019). In this landscape the oldest secure evidence for large-scale underground salt mining dates back to the Middle Bronze Age. The extraordinary preservation conditions in the salt-mines allow for unique insights into prehistoric technology, raw-material management, working processes and human-environment relations (Kern et al., 2009; Kowarik and Reschreiter, 2014; Kowarik, 2019). Due to salt preservation a vast amount of organic objects left behind by the prehistoric miners was preserved in perfect condition, e.g. tools and implements made of animal skin and fur, ropes made of grass and lime bast fibres, textiles, and numerous wooden artefacts (Reschreiter et al., 2014; Barth and Lobisser, 2002; Kern et al., 2009; Grabner et al., 2015, 2019). Excavated wooden artefacts include mine timber, constructions, lighting

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https://doi.org/10.1016/j.dendro.2021.125814
Received 3 November 2020; Received in revised form 18 January 2021; Accepted 5 February 2021
Available online 15 February 2021
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chips, tool handles, bowls and cups, and on the surface log basins (a log construction deepened within the soil for curing meat). The inventory of softwood artefacts includes mine timber, lighting chips and wooden containers. Most of these objects are in such good conditions that tool marks, and even the imprints of human teeth are visible (Barth, 1989).

Currently, more than 90 archaeological sites within the mountain range of Hallstatt are known. They were discovered accidentally during modern mining activities (Barth et al., 2019). Only a part of the sites can currently be examined safely. In a large-scale redevelopment project, which is being carried out by Salinen Austria AG, the Federal Office for the Protection of Monuments, the Federal Chancellery and the Province of Upper Austria, the accesses to the most significant find sites are currently being redeveloped and permanently preserved (Reschreiter, 2018).

1.1. The history of dating Hallstatt samples

More than 170 years ago the burial place of the prehistoric miners of Hallstatt was discovered and exploration began. A whole epoch of European prehistory, the older Iron Age (800–400 BCE), was named the Hallstatt period because of the many significant grave goods. The long known traces of prehistoric mining inside the salt dome were automatically associated with the Iron Age miners from the graves - although there was no evidence of this. Despite of this, there are thousands of remains of the mining and transport of the salt (see wooden finds), but almost no pieces of pottery or metal that can be typologically compared with the grave goods from the graves to provide a relative chronological classification. From the 1960s onwards, more and more evidence could be collected, indicating that not all known mining finds date back to the Hallstatt period, but that there were also older mines in Hallstatt. However, there were no possibilities to substantiate the dating. Therefore, Fritz Eckart Barth initiated radiocarbon dating at a very early stage and also sought contact with Ernst Hollstein to initiate tree-ring analysis (Barth et al., 1975; Grabner et al., 2006a). First dendrochronological activities at Hallstatt go back to 1974 (Hollstein, 1974). He took four samples from the Hallstatt period mining place Kilb-Werk (Fig. 2). It was possible to synchronize two fir samples (*Abies alba* Mill.) with the Villingen fir chronology (Hollstein, 1974). Six years later Hollstein corrected the ending dates of his fir samples from 682 BCE to 656 BCE (Hollstein, 1980). Twenty years later Ruoff and Sormaz (1998, 2000) continued sampling. They took 189 samples across all available periods (Bronze Age, Hallstatt period and La Tène period) and came up with crossdatings against the Villingen-Magdalenenberg-chronology (Billamboz and Neyses, 1999) at 724 BCE and 695 BCE (Sormaz and Stöllner, 2005). Also, a number of floating chronologies were established.

Since 2002, the tree ring lab of the University of Natural resources and Life Sciences, Vienna, is continuing the sampling and dating in Hallstatt with support from the University of Innsbruck in Austria and the Dendro Lab of the city of Zürich in Switzerland. Dating of samples is done by both, radiocarbon (^{14}C) and dendrochronology. The first radiocarbon dating of Hallstatt material goes back to 1968 and 1971 (Barth et al., 1975). Stadler (1999) gave an overview on radiocarbon dates of various findings. Most of them were taken from finds lacking enough tree rings for dendrochronological dating, which provided dates for the specific objects. However, now we focused on samples relatively dated between them by dendrochronology, and carried out sampling of selected tree rings for ^{14}C wiggle matching.

For dendrochronological dating of timbers, suitable reference chronologies are needed. Even though the reference tree-ring data network has improved during recent decades due to the general development of dendrochronology in the larger Alpine region, the situation is still challenging, especially for the Late Bronze Age. The forests around Hallstatt, which are the likely source of all timber used in prehistoric salt mining, are situated between 900 and 1500 m asl. However, most currently existing Bronze Age chronologies have been established either with sample material from relatively low elevations, e.g. recovered in lake settlements at around 500 m asl (e.g. Becker et al., 1985; Mäder and Sormaz, 2000; Billamboz et al., 2003), or from much higher elevations in the Alps, around 2000 m asl (e.g. Renner, 1982; Nicolussi et al., 2009; Bernabei et al., 2018). Therefore, we aimed to set up Hallstatt-chronologies and date wooden samples that originate from both, the salt mines and other sites at ground-surface level in Hallstatt.

2. Material and methods

2.1. Hallstatt – the sites at the "Salzberg-valley"

The Hallstatt "Salzberg-valley" is located 300 m above lake Hallstatt and the medieval mining town on the lake shore (532 m a.s.l., 47°33′51″, 13°38′3″ (WGS84), see Fig. 1). The area is situated at the northern rim of the Alps – the Northern Limestone Alps. A pronounced limestone plateau characteristic and high tendency to karst formation dominate the region. The area is characterized by low mean temperatures and high precipitation, with montane spruce - fir - beech forests as the current potential natural vegetation (Mayer, 1974; Böhm, 1992; Auer, 1993; Kilian et al., 1994). In the Subboreal period, *Abies alba* had reached its maximum Holocene range in the Eastern Alps. This was particularly true for montane forests but also for today's subalpine spruce forest regions. Based on a forest zonation presented by Mayer (1974), an Abieti-Fagetum, most likely with a dominance of fir, and an

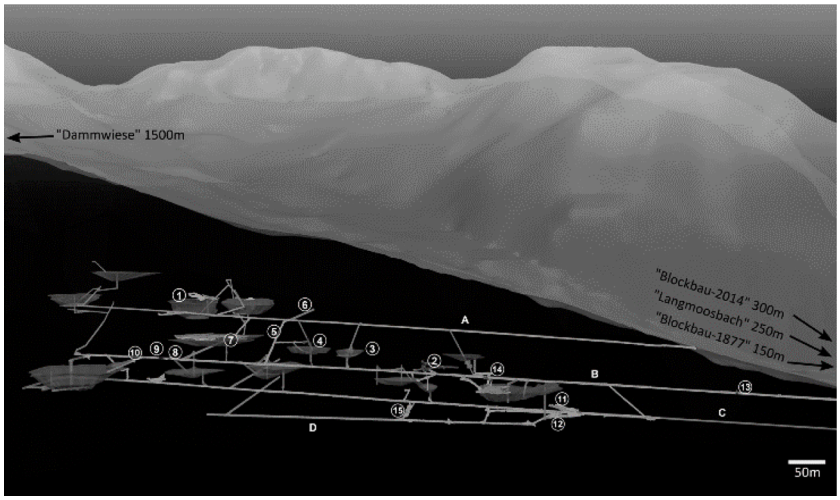

Fig. 2. 3D map of the archaeological sites within the network of the modern mines as well as of the surface. Distances to archaeological sites at the surface outside are indicated.
The Bronze Age sites from 12th to 11th century BCE: 1 "Grünerwerk", 2 "Christian von Tuschwerk, Alter Grubenoffen". The Iron Age sites from the 8th to 7th century BCE: 3" Kilbwerk", 4" Kernverwässerungswerk", 5 "Seeauschurf", 6 "Josefstollen-Querschlag", 7 "Stügerwerk", 8 "Ritschnerwerk-Sinkwerkebentl", 9" Christinastollen-O19", 10 "Enderwerk". The Iron Age sites from the 7th to the 6th century: 11 "Pohl-Schöpfbau", 12 "Bohrlochsonde E-19", 13 "Christinastollen-Tagschurf", 14 "Edlersbergwerk - Sinkwerkebentl", 15 "Schernthannerkehr". The modern tunnel system: A "Kaiser-Josef-Stollen", B "Kaiserin-Christina-Stollen", C "Kaiserin-Maria-Theresia-Stollen", D "Kaiserin-Elisabeth-Stollen" (D. Brandner/NHM Vienna).

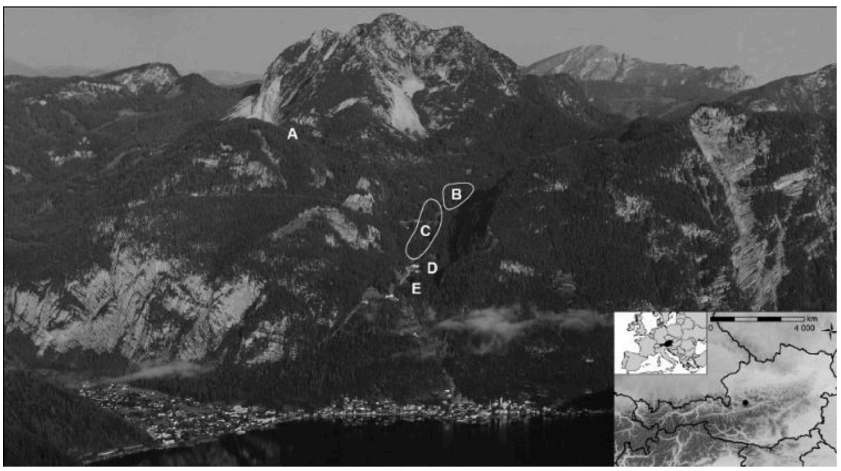

Fig. 1. The "Salzberg valley" above the mining town Hallstatt with the main archaeological sites: A "Dammwiese", B area of Bronze Age mining activities, C area of Iron Age mining activities, D "Blockbau-1877", E "Blockbau 2014" and "Langmoosbach" – both at the border of the well-known cemetery. The inset indicates the location of Hallstatt within Austria and Europe. (D. Brandner, J. Klammer/NHM Vienna; Map data: SRTM DEM (90 m): CGIAR-CSI; countries: Natural Earth).

Abietetum above around 1200 m altitude can be expected as the dominating forest association in the "Salzberg-valley".

Through pollen analysis at the nearby mount Dachstein it was possible to reconstruct the forest composition over time down to local scales. The palyonological analysis clearly shows anthropogenic changes in the variation of different tree species. The proportion of Norway spruce (*Picea abies* L. Karst.) increased since the beginning of human cultivation of forest environments, while Silver fir and European beech (*Fagus sylvatica* L.) decreased to one third of their natural potential (Mayer, 1974).

The "Salzberg-valley" offers only a restricted area and is difficult to access as it is closely confined by steep mountains to the North, South and West and by a steep slope in the east descending towards lake Hallstatt (Kowarik, 2019). This specific topographic situation restricts the area, where logs can be transported with relative ease to 900–1500 m a.s.l. (Grabner et al., 2006a, 2007). Considering the challenging entrance route to the "High Valley" the import of timber seems unlikely, at least in a modern perspective. But the evidence for regular large-scale transport activities of raw materials (e.g. salt) and objects (e.g. tools, textiles, bronze objects) needs also to be taken into account (Kowarik et al., 2015b; Kowarik, 2019).

2.1.1. *The bronze age sites*

The Bronze Age site "Christian von Tuschwerk, Alter Grubenoffen" is situated at the level of the modern mining gallery "Kaiserin Christina Stollen" (930 m a.s.l.) and 100 m below surface (see Fig. 2 and Table 1). The archaeological excavations there started in 1992 (Barth et al., 2003). At this point, a Bronze Age shaft system can be proven, with several horizontal mining chambers - one above the other. These chambers were over 25 m wide, more than 50 m long and had a height of up to 14 m (Reschreiter and Kowarik, 2019).

Other Bronze Age sites (see Fig. 2 and Table 1) from which wood was successfully dated (dendrochronology or radiocarbon) are: the mine "Grünerwerk" and from the surface a log-construction, the "Blockbau-1877" as well as a newly found log basin ("Blockbau-2014").

The site "Grünerwerk" is the lower end of another huge Bronze Age shaft, which reached a depth of 160 m. This pit is more than 400 m away from the pit around the "Christian von Tuschwerk, Alter Grubenoffen". First collections of finds were made 100 years ago in the early 20th century. Intensive archaeological investigations took place between 1985 and 1991 (Barth, 1986).

Since 2014, the Natural History Museum has been excavating and examining a wooden structure that is sealed in dense and airtight clay

Table 1
The archaeological sites at which wooden finds were dated.

site name	dating period	type of excavation	elevation (m asl)	Code Fig. 2	main wooden artefacts	nr of dendro samples
Grünerwerk	Bronze Age	mining	988	1	mining timber, lighting chips, bases	48
Christian von Tuschwerk, Alter Grubenoffen	Bronze Age	mining	940	2	mining timber, lighting chips	989
Blockbau 1877	Bronze Age	surface	900	–	roundwood	19
Blockbau 2014	Bronze Age	surface	845	–	roundwood	16
Kilbwerk	Iron Age	mining	970	3	lighting chips, mining timber	449
Kernverwässerungswerk	Iron Age	mining	970	4	lighting chips	224
Seeauschurf	Iron Age	mining	970	5	lighting chips	3
Josefstollen-Querschlag	Iron Age	mining	981	6	lighting chips	15
Stügerwerk	Iron Age	mining	964	7	lighting chips	16
Ritschnerwerk-Sinkwerkebentl	Iron Age	mining	946	8	lighting chips	16
Christinastollen-O19	Iron Age	mining	947	9	lighting chips	13
Enderwerk	Iron Age	mining	948	10	lighting chips	124
Pohl-Schöpfbau	Iron Age	mining	901	11	lighting chips	57
Bohrlochsonde E-19	Iron Age	mining	890	12	lighting chips	15
Christinastollen-Tagschurf	Iron Age	mining	931	13	lighting chips	19
Edlersbergwerk - Sinkwerkebentl	Iron Age	mining	937	14	lighting chips	23
Schernthannerkehr	Iron Age	mining	893	15	lighting chips	1
Langmoosbach	Iron Age	surface	840	–	shingels	161
Dammwiese	La Tène	surface	1350	–	roundwood, bases of vessels	63

("Blockbau-2014", see Fig. 2 and Table 1). This structure is located within the area of the long-known Hallstatt cemetery, underneath the examined burial horizon from around 500 BCE. As the wooden structure is not excavated completely up to now, the function has not yet been determined. There are some similarities to the known log basins (Pucher et al., 2013). The part examined so far consists of a block construction, which is particularly distinctive due to the triangles notched in the round beams. It presumably encompasses another approx. 2.50 by 2.50-meter-wide wooden block construction, in the interior of which, under fine sediment layers, numerous pieces of wood that are still well preserved can be found. Due to its good state of preservation, it gives an insight into the multifaceted craftsmanship of the Bronze Age.

2.1.2. The iron age sites

Several sites could be dated to this first Iron Age period (see Fig. 2 for the localization and Table 1 for an overview).

The sites "Stügerwerk", "Seeauschurf", "Kernverwässerungswerk" and "Kilbwerk" are considered to be different outcrops of a single huge mining chamber. This chamber was originally up to over 20 m high, five to at least 27 m wide and about 300 m long (Barth and Reschreiter, 2019). The many exposed finds from these sites allow a very detailed reconstruction of the working and living environment of prehistoric miners (Reschreiter et al., 2013a).

The site "Josefstollen-Querschlag" is located about eight meters above this huge mining chamber. Its function in the Iron Age mine building has not yet been clarified.

The three sites "Enderwerk", "Ritschnerwerk-Sinkwerkebentl" and "Christinastollen-Tagschurf" are considered to be part of a horizontal gallery only about two meters wide. This gallery is seen as a development route for a mining area which has not yet been discovered, but is assumed to be south of the "Enderwerk" site.

Below the mining chamber from "Stügerwerk" to "Kilbwerk", the "Edlersbergwerk - Sinkwerkebentl" site is known. And even deeper, the sites "Pohl-Schöpfbau", "Bohrlochsonde E-19" and "Schernthannerkehr" were excavated.

The site "Christinastollen-Tagschurf" is the only known access tunnel from the Iron Age (Barth, 1984). Here a narrow inclined tunnel with a slope of about 45° using mine timber as shoring was investigated.

2016 parts of a shingle-roof were excavated at the border of the cemetery at the high valley, close to the stream "Langmoosbach". The processed wooden fragments (including shingles and round logs) can be described as part of a building. The finds are dated to the late Hallstatt period. This collapsed construction may be the first indication of the settlements, which was located uphill, in the northwest of the excavation site. Due to the heavy damage, no specific function can be assigned to the construction.

2.1.3. The La Tène site

The site "Dammwiese" is located in a raised bog at 1350 m a.s.l. on a saddle above the "Salzberg-valley" (Kern et al., 2009; see Fig. 2 and Table 1). Excavations on the "Dammwiese" undertaken in the 1880s and the first half of the 20th century revealed a settlement of miners with numerous dwelling houses. A tunnel entrance was also discovered. Since the corresponding mining area is located farther uphill than the other known prehistoric mines, it was the first to be exploited in the course of the historic mining activities in the 16th and the 17th centuries, which advanced systematically downhill. None of the sites are accessible today.

2.2. The wooden finds

2.2.1. Mine timber

The group of mine timber contains roundwood timbers or slightly manufactured timbers (Grabner et al., 2009a) for the shafts, platforms and other purposes. In most cases, timber from the platforms (and staircases) had collapsed. So far the only wooden structure found in situ is the Bronze Age wooden staircase (Reschreiter and Barth, 2005; see Fig. 3). However, there are also parts of other stairs between the collapsed mine timbers.

Most of the samples are from the Bronze Age "Christian von Tuschwerk, Alter Grubenoffen". In addition to this, there are few more samples from Bronze Age mines and some from the older Iron Age.

2.2.2. Lighting chips

One of the preconditions for working below ground is enough light. For this purpose, the prehistoric miners used lighting chips in vast amounts (Kowarik et al., 2015b). Therefore, one can find the burned-out remains in innumerable quantities in the operational waste of the prehistoric mines (see Fig. 4). Since they were not made of resinous pine (*Pinus sylvestris*) as expected, the name "lighting chips" or "Leuchtspäne" opposed to the German name "Kienspäne" (as used for pine chips) was deliberately chosen (Klein, 2006). The burnt remains of these shavings are found in all Bronze Age as well as older Iron Age mining areas. These chips with either a square or rectangular cross section and a length of 80–100 cm were split off the logs – mainly in a radial direction (Klein, 2006; Morton, 1927).

2.2.3. Log basins

In the "Salzberg-valley", a total of eight block-type constructions have been discovered so far (Barth and Lobisser, 2002; Pucher et al., 2013). Two of them have been archaeologically examined and documented. Pieces of wood from these log basins are in the collection of the Natural History Museum in Vienna. These are the basins uncovered in 1877 by a landslide and the one excavated by Friedrich Morton in 1939 (Pucher et al., 2013). In general, these are basins that were dug into the surface and then buried later on, thus conserving the wood. These buildings belong to the Bronze Age era.

2.2.4. Tree stumps

In total eight tree stumps (Sycamore maple and European beech) were found at the "Christian von Tuschwerk" – showing roots as well as felling traces about half a meter above ground level (Reschreiter et al., 2010). They were brought into the mine during a catastrophe, when the existing caverns and galleries were filled up with material from the surface (soil, stones, tree stumps). The felling traces look quite fresh – no degradation of the wood due to UV and/or fungi is visible. Therefore, they would date the catastrophe quite precisely.

2.2.5. Shingles

At the excavation close to the small stream "Langmoosbach" in 2016 wooden shingles were uncovered. They were split out of fir tree trunks.

2.2.6. Wooden containers, bentwood boxes, bins and buckets

So far more than 20 bentwood boxes (the bent bands were split out of



Fig. 3. The Bronze Age staircase from the "Christian von Tusch-Werk". (A. Rausch/NHM Vienna).

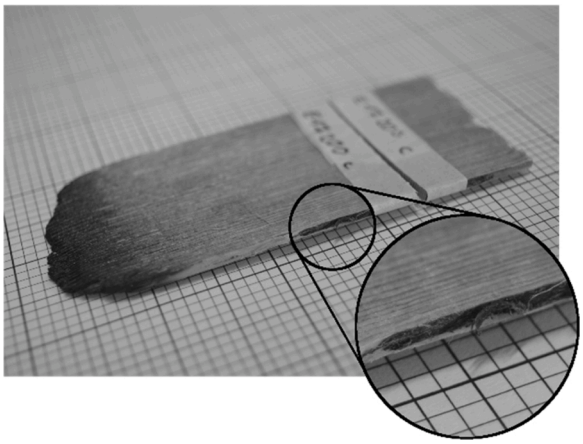

Fig. 4. A burnt remnant of a lighting chip showing waney edge proven by some small particles of bast at the outermost tree ring. (fir wood, appr. 40 × 20 mm, 46 tree rings, dated to -575).

ash wood) have been found from the Iron Age sites (Kern et al., 2009; Reschreiter et al., 2009, 2013b). These bentwood boxes were finely decorated and may have served to store food. Bins and buckets are transport containers that were found exclusively in Bronze Age mining. The bin (together with the scraper) was used to pick up the hewn salt (Kowarik and Reschreiter, 2010; Kern et al., 2009; Grabner et al., 2010; Klein, 2006). At one end, a transverse board is sewn in with fur strips or leather. The base of a bentwood box, bin and bucket consists of a tangentially or radially split board which is fixed with wooden nails in the wall.

2.2.7. Spoons and shovels

There are tools from the Early Iron Age that are described as a wooden spoon. From the Bronze Age and the La Tène period there are finds that are interpreted as shovels. See Fig. 5 for an example from the "Dammwiese".

2.3. Sampling

Mine timber and the logs of the log basins were mainly sampled using a regular dry-wood corer and a power drilling machine, leaving a core of 7 mm in diameter. The wet cores were glued onto wooden sticks and dried carefully. Usually one core per log was taken. In some cases – especially logs with high number of tree rings – another one or two cores were sampled. Most of the samples which were taken from the 1970-ies onwards up to 2001 were taken as discs. These samples were re-measured.

Lighting chips and shingles were cut with the help of a very thin saw into two pieces (see Fig. 4) and processed as above.

As it was not justified to cut the spoons, shovels and bases of baskets, bins and buckets, X-ray CT was applied. X-ray computed tomography is a widely used method for nondestructive visualization of the interior of different materials. Unlike common applications very high resolution is needed to use such CT images in dendrochronology and to evaluate wood species. In dendrochronology big samples (up to 50 cm) have to be scanned and the required resolution is – depending on the species – about 20 µm. Different devices were used to scan the wooden findings from Hallstatt: National Institute of Cultural Properties, Nara, Japan - SMX-100CT-D, Shimadzu Corporation (see Fig. 5); Upper Austria University of Applied Sciences, Wels - RayScan 250E (Ray Scan Technology, Meersburg, Germany (Grabner et al., 2009b; Okochi et al., 2007)). The resolution of these scans was between 272 and 8 µm (see Grabner et al., 2009b for details).

2.4. Measurements

Dry disks and mounted cores were sanded (up to grid 600) until individual tracheids became visible. Wood species were identified by microscopic analysis (Wagenführ, 1989) and the tree-rings were measured to the nearest 0.01 mm using the LINTAB measuring device (www.rinntech.de). Since 2011 the samples have been measured with the help of 1200dpi scans and the measurement software WinDENDRO 2009 (Regent Instrument, Quebec, Canada) to the nearest 0.001 mm. The digital X-ray CT pictures were measured using the same software.

2.5. Data treatment

Ring width series were standardized to remove low-frequency variability that included age-related trends, stand development and local disturbances (Cook et al., 1990). A cubic smoothing spline with 50 % cut-off at 30-year wavelength was applied to each series and the originally measured values were divided by the fitted curve values (Cook and Peters, 1981).

Tree-ring series were dated using t-values and the sign test (Gleichläufigkeit) computed by the TSAP software (www.rinntech.de), supplemented by visual checking. The first step was to crossdate the unknown samples against each other, following Baillie (1995). These floating series were checked against existing chronologies (see Table 2 for the list of chronologies).

Hallstatt chronologies were compiled by calculating mean values of dated and indexed tree-ring series, and comparing them with reference chronologies using TSAP (www.rinntech.de). Dating quality was also

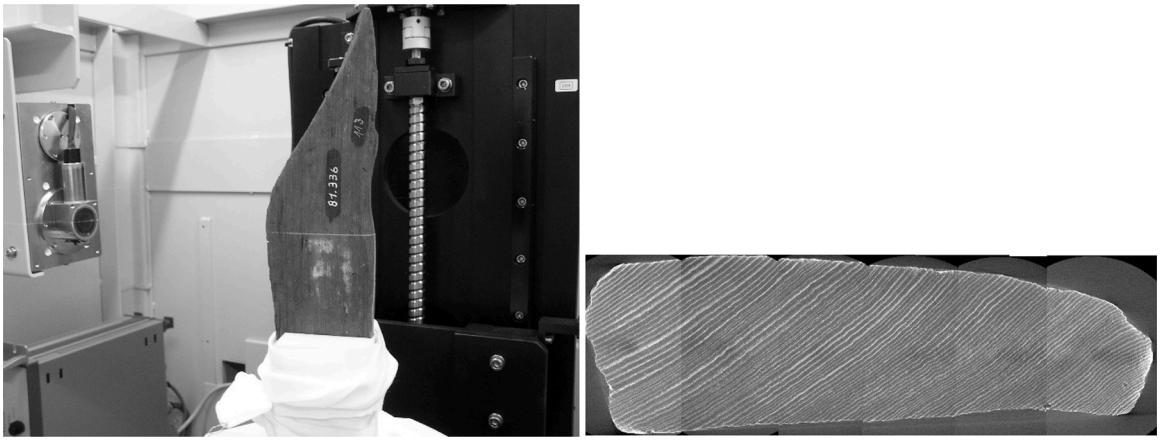

Fig. 5. A broken shovel (Inv-nr. 81336 NHM Vienna) inside the X-ray CT machine in Nara, Japan, and the resulting CT image. This shovel was made out of spruce wood shows 113 tree rings and was successfully dated to -167.

Table 2
The reference chronologies which were used for dating of the Hallstatt samples.

reference chronology	species	time span	lab	reference
East-Austria	fir	976 to 1997	University of Natural Resources and Life Sciences, Vienna	Wimmer and Grabner, 1998; Grabner and Wimmer, 2006b
East-Austria	spruce	1005 to 2006	University of Natural Resources and Life Sciences, Vienna	Wimmer and Grabner, 1998; Grabner and Wimmer, 2006b
East-Alpine	fir	856 to 2012	University of Natural Resources and Life Sciences, Vienna	Wimmer and Grabner, 1998; Grabner and Wimmer, 2006b
East-Alpine	spruce	−959 to 2012	University of Natural Resources and Life Sciences, Vienna	Wimmer and Grabner, 1998; Grabner and Wimmer, 2006b
East-Alpine	larch	−276 to 2009	University of Natural Resources and Life Sciences, Vienna	Wimmer and Grabner, 1998; Grabner and Wimmer, 2006b
Schwarzen See	spruce,larch	−1475 to 2012	University of Natural Resources and Life Sciences, Vienna	Wimmer and Grabner, 1998; Grabner and Wimmer, 2006b
Southern Germany	fir	820 to 1985	University Stuttgart Hohenheim	
Villingen-Magdalenenberg	fir	−811 to −593	Landesamt für Denkmalpflege Hemmenhofen	Billamboz and Neyses, 1999
Middle European	oak	−5100 to 1996	Labor für Dendrochronologie Zürich and University Stuttgart Hohenheim	Becker et al., 1985
Urseren	spruce	−1198 to −957	WSL Birmensdorf	Renner, 1982; Nicolussi et al., 2009
Eastern Alpine Conifer	cembran pine, larch, spruce	−8071 to 2002	Department of Geography, Universität Innsbruck	Nicolussi et al., 2009; 2015
Trentino section II	larch, spruce	−1198 to −957	Laboratorio di Dendrocronologia, Trees and Timber Institute – National Research Council of Italy (CNR-IVALSA)	Bernabei et al., 2018
Chollerpark	fir	−1249 to −860	Labor für Dendrochronologie Zürich	Eberschweiler, 2004
sfAlp	spruce	−1361 to −957	Department of Geography, Universität Innsbruck	Renner, 1982; Nicolussi et al., 2009; Bernabei et al., 2018
Tirol	larch	−3309 to 2011	Department of Geography, Universität Innsbruck	Nicolussi et al., 2009; 2015

checked by running the COFECHA software (Holmes, 1983).

2.6. ^{14}C data

A tree-ring radiocarbon "wiggle matching" method was used in our work for a precise placement of floating chronologies in time with a much smaller relative error. The method of fitting curves provides much higher precision than individual radiocarbon dates. The success of a wiggle matching fit depends on the length of the sequence, number of tree-ring sequenced data, measurements precision and the shape of the radiocarbon calibration curve (Bronk Ramsey et al., 2001; Galimberti et al., 2004).

After crossdated sequences were combined into chronologies, samples were carefully chosen for radiocarbon dating and submitted for accelerator mass spectrometry (AMS) ^{14}C dating analysis. All together two or more wood samples were chosen from each chronology. From each sample a single ring or series of ring segments were selected and cut for ^{14}C analysis. Then a ^{14}C compiled dataset was placed along the same timeline as their respective tree ring segments and matched to the IntCal13 calibration curve (Reimer et al., 2013). The result of the wiggle matching is presented as the OxCal agreement index A (Bronk Ramsey et al., 2001). This is a calculation of the overlap of the simple calibration distribution with the distribution after Bayesian modeling. A suitable acceptance threshold for the OxCal agreement index is ca. 60 % (Bronk Ramsey, 1995). Wiggle match dating was performed with the OxCal software using the D_Sequence function (Bronk Ramsey et al., 2001) and the international radiocarbon calibration curve IntCal13.

Radiocarbon measurements were performed in three different laboratories during the last 18 years of research. Some samples were measured at the VERA (Vienna Environmental Research Accelerator) AMS facility at the University of Vienna in Austria. Other samples were dated at the ETH (Swiss Federal Institute of Technology) accelerator facility in Zurich in Switzerland. The latest samples were dated at Poznan Radiocarbon Laboratory (PRL) in Poland (Poz-). Samples dated by these laboratories were processed following the acid/base/acid (ABA) protocol, combusted to carbon dioxide and graphitized. At the end the mixture of graphite and graphitization catalyst was pressed into sample holders and then measured. All three mentioned radiocarbon laboratories offer ^{14}C dating using the technique of accelerator mass spectrometry (AMS). The conventional ^{14}C ages were calibrated to calendar ages using the IntCal13 atmospheric data set.

Altogether 81 radiocarbon measurements of the wood samples were performed. 42 of them were used in the wiggle match analysis and presented in this paper. The other single samples were chosen for ^{14}C dating because of their archaeologically meaningful contexts.

All resulting dates are given in astronomical year numbering, including the year 0 (zero). To convert the negative dates into Gregorian dates, the negative sign must be inverted and one year added: e.g. −1163 corresponds to 1164 BCE.

3. Results and discussion

Up to the year 2019, 2271 samples have been taken and measured (see Table 3). 55.9 % were determined as fir wood, followed by 20.1 % Norway spruce, 12.7 % European beech (*Fagus sylvatica* L.) and minor amounts of European larch (*Larix decidua* Mill.), maple (*Acer* spp.), ash (*Fraxinus excelsior* L.), alder (*Alnus* spp.) and yew (*Taxus baccata* L.).

It was possible to date 763 samples (33.9 %) by dendrochronology (see Table 3). 23 samples are included in floating chronologies dated by

Table 3
Details about the wood species share and the amount of dated samples (as percentage of the measured ones). Here are just the major wood species, which were possible to date given.

time period	species	species share	nr of samples	% dated
Bronze Age	spruce	31.8	341	29.6
	fir	32.3	346	30.6
	beech	22.9	246	54.1
Iron Age	spruce	8.7	99	7.1
	fir	79.8	907	40.6
La Tène	spruce	41.3	24	58.8
	fir	42.9	25	64.7
	beech	11.1	10	0.0
	larch	4.8	4	50.0

^{14}C wiggle matching. The reason for the low number of successful dating is partially the wood species (see above – like ash or alder), but especially the low number of tree rings per sample. The average number of rings per sample (across all species) is 64.5 for the dated and 54.7 for the not dated. The threshold of the minimum number of tree rings per sample was set to 30. 245 samples did not meet this requirement. The highest number of rings per sample was 207 (fir from the "Dammwiese" excavation).

3.1. The bronze age

1072 samples were taken from wooden samples archaeologically dated to the Bronze Age period. The same amount of samples were from fir and Norway spruce – 32 % each, followed by beech 23 % and minor amounts of European larch, maple, ash and yew (Table 3).

The Bronze Age samples are mainly mine timber, logs from the log basins and some lighting chips as well as chipping residues.

356 samples (33.6 %) were dendrochronologically dated (Table 3 for details). Three dendrochronologically dated chronologies were set up: fir from -1232 to -1063; spruce from -1228 to -1063 and beech from -1182 to -1062 (see Table 4 and Fig. 6). All three chronologies show a high mean series intercorrelation between 0.59 and 0.64. The replication is high, as all of them represent more than 100 samples. The spruce trees had wider rings and longer series than fir and beech. The dating of these Hallstatt chronologies was not possible against the geographically close (about 15 km) Dachstein/Schwarzer See chronologies (Grabner

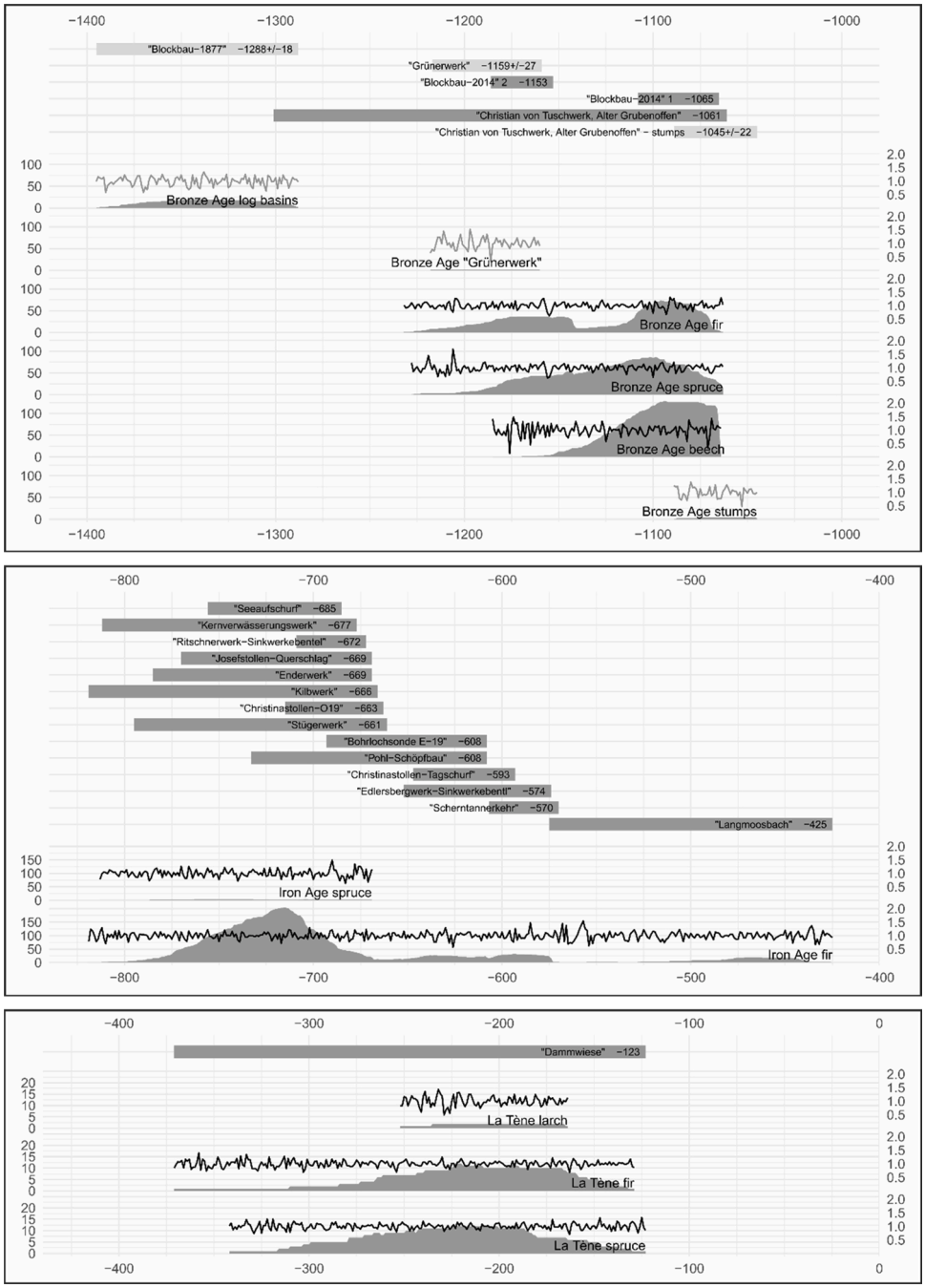

Fig. 6. Sites and established chronologies for the Bronze Age, Hallstatt and La Téne period. The species-specific chronologies are presented as mean curves on the base of standardized samples series together with the sample depth. The bars indicate the temporal extension of the mean-curve for the different sites (wood species are here mixed). Dark-grey bars indicate dendro-dated chronologies, light-grey boxes indicate floating chronologies based on ^{14}C dates.

et al., 2007), which consist of just a few larch trees at this time. The dendrochronological dating of the Bronze Age Hallstatt conifer chronology is based on the crossdating of a mean curve of selected spruce and fir series with a reference chronology based on subfossil spruce. These spruce samples originate from several sites in the Austrian (Nicolussi et al., 2009), Italian (Bernabei et al., 2018) and Swiss Alps (Renner, 1982) and thus from elevations between about 1400 and 2000 m asl (Table 2 and 4).

The Bronze Age beech chronology was built out of 130 samples and is 121 years long (see Fig. 6). For a wiggle matching analysis 13 wood samples from nine dendrochronological cores were chosen. All of them were synchronized to a floating beech chronology having the same date end (later dated to -1062). In seven cases a single-ring was selected for ^{14}C dating. In another six cases three-ring fragments were cut for ^{14}C analysis (see Table 5). Conventional ^{14}C ages together with the calendar ages are reported in Table 5. It includes also the relative dating information provided by tree-ring analysis, e.g. that Poz-104480 is five years younger than Poz-104485. The chronological model for the dating of all samples is shown in Fig. 7. The model has an overall agreement (Acomb = 56.1 %) near acceptable threshold of ca. 60 %. 11 samples showed very good overall agreement, well above the satisfactory threshold value of 60. The fit is good for almost all samples though two samples (T14050Ba, T04119B1) are slightly more scattered than one might expect (although there is a very good dendrochronological match between the samples). The youngest measured fragment taken for the wiggle matching analysis (ring 121 - sample T12157Ba) corresponds also to the last ring of the beech chronology. Application of the wiggle match methodology placed the last ring of the beech chronology at cal -1090 to -1043 (-1074 ± 24) with 68.2 % probability. The Hallstatt beech series are dendrochronologically dated on the one hand with the local spruce and fir series, but also significantly with a Swiss fir reference series (Chollerpark – see Table 2 and 4; Eberschweiler, 2004). As the dendrochronological dating was done with reference chronologies of other species, ^{14}C wiggle matching was performed to assure the dendrochronological dates. They are within the 68.2 % confidence range of the ^{14}C wiggle match (cal -1090 to -1043 (-1074 ± 24)). The Bronze Age beech chronology spans the time -1182 to -1062.

Three floating chronologies were set up where dendrochronological dating was not possible: 20 samples from the "Blockbau-1877" with the end date -1286 ± 18; four maple samples from the "Christian von Tuschwerk, Alter Grubenoffen – stumps" with the end date -1044 ± 22 and a single sample from the "Grüner-Werk" with the ending date -1158 ± 27 (see Fig. 6).

The oldest wood comes from the site "Blockbau-1877". It was possible to set up a floating chronology from 20 samples, 108 years in length. The wiggle matching analysis of this site is based on five radiocarbon measurements corresponding to five larches. The result showed a very good overall agreement Acomb = 88.2 %, well above the threshold value of 60. The date for the mid-point of the last dated segment, sample B77081La (the last six growth rings but without a bark ring), is fitted to cal -1304 to -1276 with 68.2 % probability (cal -1288 ± 18). Adding the two missing rings to the waney edge, the date for the mean curve can be estimated to the range of -1302 to -1274 (-1286 ± 18)

Due to their high archaeological relevance, four stumps from the "Christian von Tuschwerk, Alter Grubenoffen" showing a low number of rings were subjected to radiocarbon dating. Six samples were taken by cutting a single-ring sample. The fit is very good for most of the samples (A above 100 %) and the overall agreement with the calibration curve passes the statistical test (Acomb of 67.6 %). Only two segments showed poor overall agreement (about 50 %) although there is a very good dendrochronological match between them. The date of the last dated ring is fitted to cal -1074 to -1009 with 68.2 % probability. Since the last wiggle matched ring is also the outermost ring showing bark of the sample T09070Aa, we can deduce that the trees were felled within the range cal -1044 ± 22 (see Fig. 6).

From the site "Grünerwerk'' we have wiggle matched four decades

Table 4
Description of the chronologies. The dates of floating chronologies based on ^{14}C-dates are given by the mean value (μ) with ± the standard deviation (σ) calculated by the OxCal software. Reference = reference chronology at which the Hallstatt chronology show the best match; GLK = "Gleichläufigkeit" – sign test; tvBP = t-value based on Baillie-Pilcher; tvH = t-value based on Hollstein. * Crossdating is based on selected series.

Description	Length	Date begin	Date end	Species	Nr. of samples	mean number of members	Mean series length	Average mean sensitivity	Mean series intercorrelation	Mean_tree_trw	Reference	Overlap	GLK	tvBP	tvH
Bronze Age log basins	108	−1395 ± 18	−1288 ± 18	larch	20	13	72.1	0.27	0.63	0.99	–	–	–	–	–
Bronze Age "Grünerwerk"	59	−1217 ± 27	−1159 ± 27	spruce	1	1	59.0	–	–	1.63	–	–	–	–	–
Bronze Age fir *	170	−1232	−1063	fir	115	30	43.9	0.20	0.64	0.79	sfAlpSpruce	153	63	3.2	4.3
Bronze Age spruce *	166	−1228	−1063	spruce	110	42	63.7	0.20	0.59	1.10	sfAlpSpruce	111	71	3.9	5.4
Bronze Age beech *	121	−1182	−1062	beech	130	61	56.2	0.32	0.64	0.80	Chollerpark	90	67	5.2	4.9
Bronze Age stumps	45	−1089 ± 22	−1045 ± 22	maple	4	4	40.0	0.18	0.56	1.57	–	–	–	–	–
Iron Age fir	395	−819	−425	fir	378	39	40.9	0.20	0.64	0.62	MagdalAA	219	69	9.6	11.1
Iron Age spruce	145	−813	−669	spruce	6	3	61.8	0.19	0.46	0.80	MagdalAA	142	66	4.7	4.5
La Tène fir	243	−371	−129	fir	13	5	98.5	0.18	0.42	1.03	SwsLDPA	242	65	4.4	3.9
La Tène larch	89	−252	−164	larch	2	2	79.5	0.21	0.44	0.99	TirolLD	89	63	4.0	3.5
La Tène spruce	220	−342	−123	spruce	15	7	96.7	0.17	0.42	1.06	SwsPA	220	67	9.1	8.7

Table 5
Wiggle-matching radiocarbon dates for the Bronze Age site chronologies. Analyzed samples, conventional ^{14}C ages, corresponding calibrated time ranges and modelled dates. The table present only data of well dendrochronologically synchronized samples; the others are not shown.

^{14}C Lab Code	Dendro Code	Ring Nr.	^{14}C Age (BP)	Calibrated Date ± CE (ISO-8601 yrs) (68 % confidence)	Mean curve for Wiggle-Matching	Modelled Date cal ± CE (ISO-8601 yrs) (68 % probability)	Dendro Date C14 sample (Date WK) ±CE (ISO-8601 yrs)
B-6367	B77019La	31–51 (41)	3010 ± 30	−1368 to −1208 (−1253 ± 59)	Bronze Age log basins	−1369 to −1341 (−1353 ± 18)	–
ETH-19927	B77081La	81–86 (84)	3020 ± 45	−1381 to −1207 (−1267 ± 75)	Bronze Age log basins	−1304 to −1276 (−1288 ± 18)	–
B-6366	B77016La	83–107 (95)	3050 ± 30	−1384 to −1262 (−1315 ± 51)	Bronze Age log basins	−1312 to −1284 (−1296 ± 18)	–
ETH-19926	B77009La	71–80 (76)	3070 ± 40	−1394 to −1281 (−1329 ± 54)	Bronze Age log basins	−1308 to −1280 (−1292 ± 18)	–
Poz-104478 (2018)	B77016L2	66	3085 ± 30	−1406 to −1300 (−1345 ± 43)	Bronze Age log basins	−1350 to −1322 (−1334 ± 18)	–
Poz-104469 (2018)	G00012F1	13	2940 ± 30	−1211 to −1109 (−1143 ± 52)	Bronze Age "Grünerwerk"	−1229 to −1184 (−1203 ± 27)	–
Poz-104472 (2018)	G00012F1	58	2940 ± 30	−1211 to −1109 (−1143 ± 52)	Bronze Age "Grünerwerk"	−1184 to −1139 (−1158 ± 27)	–
Poz-104471 (2018)	G00012F1	48	2945 ± 30	−1211 to −1113 (−1150 ± 51)	Bronze Age "Grünerwerk"	−1194 to −1149 (−1168 ± 27)	–
Poz-104468 (2018)	G00012F1	1–4 (3)	3025 ± 30	−1372 to −1220 (−1280 ± 58)	Bronze Age "Grünerwerk"	−1240 to −1195 (−1214 ± 27)	–
Poz-104481 (2018)	T00049B2	59–61 (60)	2860 ± 35	−1106 to −974 (−1029 ± 57)	Bronze Age beech	−1118 to −1071 (−1102 ± 24)	−1089 (−1064)
Poz-104483 (2018)	T04199B1	14–16 (15)	2880 ± 35	−1113 to −1006 (−1060 ± 58)	Bronze Age beech	−1166 to −1119 (−1150 ± 24)	−1137 (−1064)
VERA-53006 (2015)	T12157Ba	70	2885 ± 40	−1123 to −1001 (−1068 ± 64)	Bronze Age beech	−1090 to −1043 (−1074 ± 24)	−1061 (−1061)
VERA-53003 (2015)	T14030Ba	22	2885 ± 45	−1152 to −998 (−1069 ± 70)	Bronze Age beech	−1123 to −1076 (−1107 ± 24)	−1094 (−1063)
Poz-104480 (2018)	T00049B2	26–28 (27)	2905 ± 35	−1154 to −1020 (−1095 ± 58)	Bronze Age beech	−1151 to −1104 (−1135 ± 24)	−1122 (−1064)
Poz-104482 (2018)	T04199B1	4–6 (5)	2925 ± 35	−1191 to −1054 (−1122 ± 58)	Bronze Age beech	−1176 to −1129 (−1160 ± 24)	−1147 (−1064)
VERA-53002 (2015)	T14051Ba	7	2930 ± 50	−1207 to −1053 (−1130 ± 76)	Bronze Age beech	−1131 to −1084 (−1115 ± 24)	−1102 (−1062)
Poz-104485 (2018)	T04199B1	24–26 (25)	2935 ± 30	−1208 to −1088 (−1136 ± 53)	Bronze Age beech	−1156 to −1109 (−1140 ± 24)	−1127 (−1064)
VERA-53005 (2015)	T09042Ba	53	2955 ± 40	−1255 to −1110 (−1163 ± 65)	Bronze Age beech	−1101 to −1054 (−1085 ± 24)	−1072 (−1062)
Poz-104479 (2018)	T00049B2	1–3 (2)	2965 ± 35	−1255 to −1120 (−1177 ± 59)	Bronze Age beech	−1176 to −1129 (−1160 ± 24)	−1147 (−1064)
VERA-53001 (2015)	T14022Ba	10	2965 ± 40	−1256 to −1119 (−1177 ± 66)	Bronze Age beech	−1144 to −1097 (−1128 ± 24)	−1115 (−1062)
VERA-53004 (2015)	T14050Ba	40	2990 ± 45	−1280 to −1126 (−1218 ± 77)	Bronze Age beech	−1113 to −1066 (−1097 ± 24)	−1084 (−1063)
VERA-53000 (2015)	T13052Ba	1	2995 ± 50	−1366 to −1126 (−1226 ± 83)	Bronze Age beech	−1160 to −1113 (−1144 ± 24)	−1131 (−1063)
VERA-6184 (2015)	T13208T	1–7 (4)	3027 ± 37	−1375 to −1218 (−1281 ± 65)	Bronze Age spruce and fir	−1245 to −1209 (−1227 ± 14)	−1225 (−1145)
Poz-104475 (2018)	T08042Fa	23	2960 ± 35	−1226 to −1116 (−1169 ± 58)	Bronze Age spruce and fir	−1224 to −1188 (−1206 ± 14)	−1204 (−1076)
Poz-104476 (2018)	T08042Fa	33	2930 ± 35	−1194 to −1056 (−1129 ± 58)	Bronze Age spruce and fir	−1214 to −1178 (−1196 ± 14)	−1194 (−1076)
Poz-104477 (2018)	T08042Fa	43	2920 ± 35	−1191 to −1050 (−1116 ± 58)	Bronze Age spruce and fir	−1204 to −1168 (−1186 ± 14)	−1184 (−1076)
VERA-6185 (2015)	T13216F	28–38 (33)	2997 ± 47	−1367 to −1127 (−1229 ± 80)	Bronze Age spruce and fir	−1171 to −1135 (−1153 ± 14)	−1151 (−1143)
ETH (2012)	T00221Fa2	3–8 (6)	3015 ± 50	−1379 to −1132 (−1257 ± 81)	Bronze Age spruce and fir	−1166 to −1130 (−1148 ± 14)	−1147 (−1080)
VERA-6183 (2015)	T00257Ta	76–80 (78)	2951 ± 36	−1223 to −1109 (−1157 ± 59)	Bronze Age spruce and fir	−1164 to −1128 (−1146 ± 14)	−1145 (−1143)
VERA-6186 (2015)	T13222F	29–31 (30)	3002 ± 37	−1367 to −1130 (−1239 ± 68)	Bronze Age spruce and fir	−1163 to −1127 (−1145 ± 14)	−1144 (−1143)
VERA-0037 (1997)	T00090Fa1	36–45 (41)	2940 ± 40	−1214 to −1057 (−1142 ± 64)	Bronze Age spruce and fir	−1148 to −1112 (−1130 ± 14)	−1130 (−1091)
ETH (2012)	T00355Fa	69–78 (74)	2960 ± 50	−1260 to −1091 (−1171 ± 80)	Bronze Age spruce and fir	−1127 to −1091 (−1109 ± 14)	−1109 (−1064)
VERA-0036 (1997)	T00090Fa2	70–79 (75)	2920 ± 50	−1206 to −1045 (−1116 ± 76)	Bronze Age spruce and fir	−1114 to −1078 (−1096 ± 14)	−1096 (−1091)
VERA-53013 (2015)	T07054Fm1	51	2895 ± 40	−1126 to −1009 (−1082 ± 64)	Bronze Age spruce and fir	−1092 to −1056 (−1074 ± 14)	−1074 (−1064)
VERA-6127 (2014)	T07054Fm2	52–61 (57)	2926 ± 26	−1191 to −1055 (−1124 ± 50)	Bronze Age spruce and fir	−1086 to −1050 (−1068 ± 14)	−1060 (−1064)
	T15035F1	59					−1064 (−1063)

(*continued on next page*)

Table 5 (*continued*)

^{14}C Lab Code	Dendro Code	Ring Nr.	^{14}C Age (BP)	Calibrated Date ± CE (ISO-8601 yrs) (68 % confidence)	Mean curve for Wiggle-Matching	Modelled Date cal ± CE (ISO-8601 yrs) (68 % probability)	Dendro Date C14 sample (Date WK) ±CE (ISO-8601 yrs)
Poz-104473 (2018)			2850 ± 35	−1053 to −934 (−1014 ± 55)	Bronze Age spruce and fir	−1081 to −1045 (−1063 ± 14)	
VERA-53007 (2015)	T05167Aa	37	2825 ± 35	−1014 to −923 (−980 ± 49)	Bronze Age stumps	−1076 to −1012 (−1045 ± 22)	–
VERA-53008 (2015)	T09036Aa	31	2855 ± 35	−1072 to −938 (−1022 ± 56)	Bronze Age stumps	−1075 to −1011 (−1044 ± 22)	–
Poz-104486 (2018)	T10060A3	1	2870 ± 35	−1110 to −1000 (−1045 ± 58)	Bronze Age stumps	−1108 to −1044 (−1077 ± 22)	–
VERA-53009 (2015)	T09070Aa	35	2900 ± 45	−1187 to −1010 (−1090 ± 70)	Bronze Age stumps	−1074 to −1010 (−1043 ± 22)	–
Poz-104487 (2018)	T10060A3	10	2920 ± 35	−1191 to −1050 (−1116 ± 58)	Bronze Age stumps	−1099 to −1035 (−1068 ± 22)	–
Poz-104488 (2018)	T10060A3	20	2940 ± 30	−1211 to −1109 (−1143 ± 52)	Bronze Age stumps	−1089 to −1025 (−1058 ± 22)	–

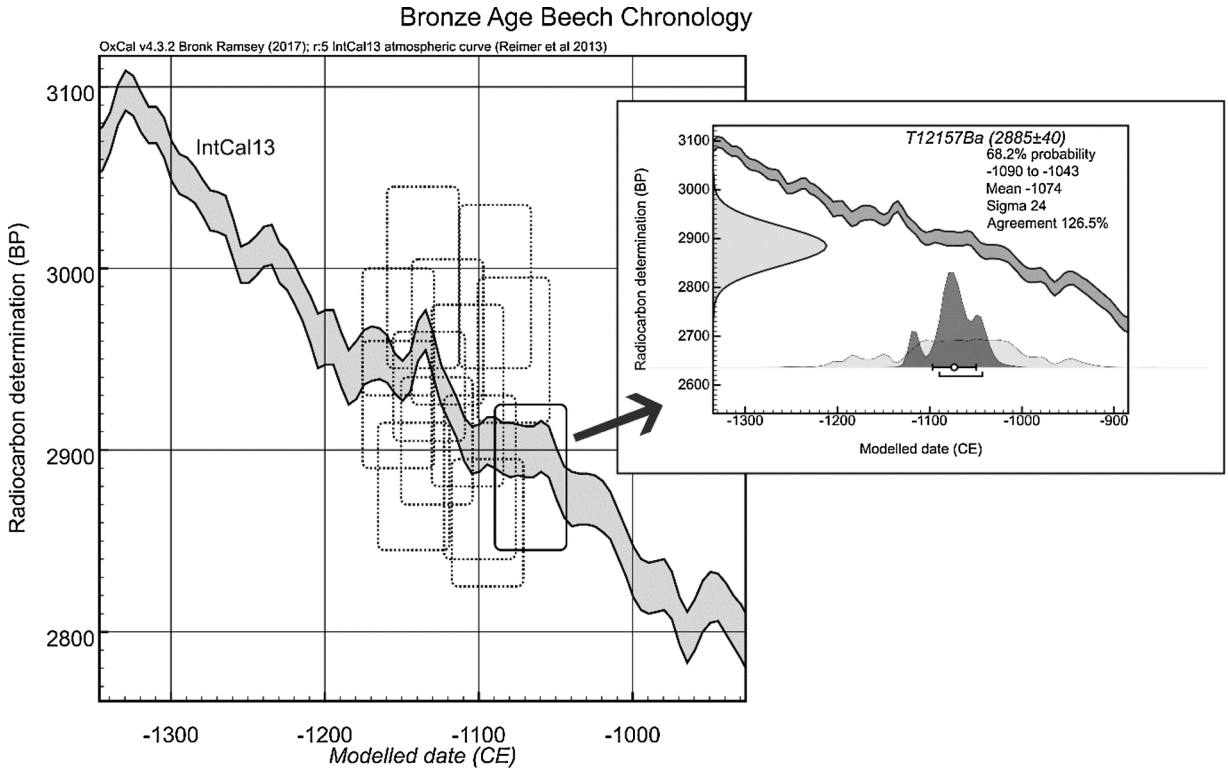

Fig. 7. Radiocarbon wiggle-match of the Bronze Age beech chronology. Main panel: placement of the tree-ring sequenced ring segments of the Bronze Age beech chronology on the IntCal13 radiocarbon calibration curve (Reimer et al., 2013). The boxes indicate the 68.2 % probability ranges of the ^{14}C dates (y axis) and the 68.2 % modeled calibrated calendar age ranges (x axis). Inset: modeled calibrated calendar age probabilities for the youngest measured fragment (the bold box) taken for the wiggle-matching analysis (ring 121 - sample T12157Ba). It corresponds also to the last ring of the beech chronology. Data from OxCal 4.3.2 (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

from a 59-year-long tree ring sequence from a spruce timber. The fit is very good for all samples and the overall agreement with the calibration curve passes the statistical test (Acomb = 95.1). The date of the last dated ring Nr.58 is fitted to cal -1184 to -1139 with 68.2 % probability. Since the last wiggle matched ring is also the outermost ring of the sample G00012F1, we can deduce that the tree was felled within the range cal -1158 ± 27 (see Fig. 6). Unfortunately, it was not possible to match it with the Bronze Age spruce chronology.

While the intercorrelation between the Bronze Age fir and spruce chronology is supported by good statistics (GLK = 73; tvBP = 9.3, tvH = 7.9 for an overlap of 132 rings), we present here one joined wiggle matching dating model for both chronologies. All together 225 samples of fir and spruce were crossdated and combined to form the Bronze Age fir/spruce chronology which is 170 years long and show an end date at -1063. The radiocarbon wiggle matching method supports the dendrochronological crossdating. For a wiggle matching analysis 12 different timbers were selected – ending in 14 segments of tree-rings chosen for ^{14}C dating. The results of wiggle matching showed a very satisfactory overall agreement Acomb of 68,2.5 %, well above the threshold value of 60. The youngest segment included in the wiggle matching model (ring No.59 from the sample T15035F1) placed the ring No. 59 at cal -1081 to -1045 with 68.2 % probability. Since the samples T15035F1 has 60 measured rings, we have to add one more ring to the outermost ^{14}C dated segment. In this case we can deduce that the tree was felled within the range cal -1063 ± 14. This is also the last ^{14}C wiggle match dated ring of the fir/spruce chronology. This fits very well to the dendrochronological date of -1064 for the ^{14}C sample (meaning -1063 for the last ring of the Bronze Age spruce and fir chronologies). The

dendrochronological dating of the Bronze Age samples was complicating due to missing reference chronologies in former times. During the dating process various ^{14}C wiggle matching samples were taken and dated for internal dendrochronological dating. These ^{14}C wiggle matching dates finally assured the dendrochronological dates of the new chronology.

Most of the Bronze Age dates from the Hallstatt salt mine which were published by Grabner et al. (2007) had to be changed. Due to the lower number of samples at that time, the internal set up of the chronology was not perfect and therefore a dating against the Dachstein/Schwarzer See chronology was erroneous – even with quite high statistical figures.

All dendrochronologically dated samples from the Bronze Age originate from the "Christian von Tuschwerk, Alter Grubenoffen" – with the exception of three samples from the "Blockbau-2014" (see Fig. 6). The majority of samples came from mine timbers and logs (231 pieces); 64 samples were identified as lighting chips; the others were undefined wooden fragments (like chipping residues).

The only construction which was found and excavated in situ and which was not destroyed is the stair case – see Fig. 3. The staircase consists of 64 pieces. All elements – except one piece made of European beech – are made of softwood. Except two pieces, all elements were measured – using cores as well as X-ray CT images. 14 elements did not meet the minimum requirement of 30 rings. Finally, 28 samples were dendrochronologically dated with the end date of -1143. Just six pieces date a little bit older to -1144 and -1145. One piece is dating to -1142. Interestingly, one tread dated to -1111, which is located at the lower third of the construction – below a breakage of the right string. The original position was most likely within the shaft. A break of a string with a diameter of about 30 cm is not possible if the construction is laying on the floor (which is the case at the find spot). The date of -1111 could give the time of the rebuilding of the staircase after the damage. Interestingly, there is no evidence (based on high t-values) that any of the timbers came from the same tree.

The dating clearly shows that mining and the meat curing at the log basins were already active in Hallstatt in the 13th century BC. The two dated log basins prove that this way of meat preservation was practiced in Hallstatt over a long period of time and that it was of immense relevance - over eight of these basins are known up to now.

In the "Grünerwerk" it is assumed that the timbers which were dated (-1158 ± 27, see Fig. 6) belong to the last operating phase of this mining area and thus the date of the burial of this area can be roughly determined. It is assumed that the start of mining at this location is much earlier. Above the "Grünerwerk" site there are still almost 100 m of exploitable salt rocks. It is difficult to say how long the prehistoric miners mined salt in this part of the deposit before they reached the depth of the "Grünerwerk".

Due to the many dates of the site "Christian von Tuschwerk, Alter Grubenoffen" it is possible to give a rough idea of the operating phase and the end of this mining activity. The oldest mine timbers date around -1160 (see Fig. 6). Most of them, however, come from the broken shaft lining and the staircase. It seems possible that some of the operational waste is older. In the next few years, further excavations in the entire find area should lead to the lowest and thus presumably oldest layer. While the beginning of mining activity in this area has not yet been completely clarified, the end can be determined exactly. In -1062 (due to the beech-dating, or -1044+-22 due to the dating of the stumps) this mine was buried by a kind of landslide.

After the landslide it was more than 300 years before dendrochronologically dated woods once again appear (Fig. 6). However, since some of the techniques seen in Bronze Age mining at Hallstatt appear in the Iron Age operation from -740 onwards, it is assumed that there was actually no disruption to mining here. It is assumed that after the catastrophe in the 11th century BC new mines were opened but the whereabouts of these mines are unknown.

3.2. The iron age

1136 samples were taken from wooden samples archaeologically dated to the Iron Age period (see Table 3). 79.8 % of the samples were identified as fir wood, followed by 8.7 % spruce and minor amounts of European larch, maple, ash, yew and alder (*Alnus* spp.).

376 samples were dendrochronological dated – 33.1 % (Table 3 for details).

The samples were taken from various different archaeological sites (Table 1). In the Iron Age period, most of the dated samples were lighting chips which accounted for 326 pieces. 19 pieces were fragments of shingles from the excavation at the "Langmoosbach" and just 31 samples came from mine timber and other findings.

The chronologies of the Iron Age period consist of almost 87 % lighting chips – small wood fragments (see Fig. 4). These chips were selected out of several thousand. The selection criterion was the number of tree rings, which was set to 30 as minimum. The number of rings varied between two (measured with at least 30 rings) and 94 (average 39.6). 118 out of 326 (36 %) showed a waney edge, which is possible to determine by residues of bast at the outermost tree ring - see Fig. 4. Studying 530 randomly taken lighting chips - not for dendrochronological dating, but to study the variability of ring width and diameter of the trees used to split the chips - from the Iron Age period showed that 16.7 % of the samples presented waney edge. The mean number of tree rings was 23.2. It can be hypothesized, that part of the lighting chips without waney edge are broken pieces, resulting in a higher number of waney edges of the selected samples (above 30 rings). It is obvious that these small pieces have the highest relevance for the archaeologists as they present the date of felling the trees and were used shortly afterwards. This makes it possible to determine the operating phases very precisely. These small remnants stay precisely localized – they did not crash down during the process of backfilling of the mines. Mine timber on the other hand may have been moved and reused as is the case for the staircase – see above.

Two chronologies were set up: fir from -425 to -819; spruce from -669 to -813 (see Fig. 6). As most of the dated samples are lighting chips with fir as major species, this chronology shows a high number of samples (307), but a low mean number of members (39; see Table 4). Another reason for the low mean number of members is the short mean series length of 40.9 rings. This fir chronology shows high mean series intercorrelation (0.64) and the smallest mean ring width (0.62 mm). The low growth of the fir trees will be due to higher age of the trees as the lighting chips were split off the outermost part of the tree trunk.

The dating was done against the Villingen-Magdalenenberg fir chronology (-810 to – 592; Billamboz and Neyses, 1999) with very high statistical figures – see Table 4. Even with a long distance of these two sites, a perfect match can be obtained. Villingen is located in the "Schwarzwald", Germany, at an elevation of 740 m a.s.l. So, the climatic conditions are comparable, leading to a perfect crossdating possibility for Hallstatt. The spatial dating signal of fir plays an important role for the success of dating, too. As the Villingen-Magdalenenberg chronology is covering just the Iron Age period, a dating of the Bronze Age and the La Tène period samples from Hallstatt is not possible (see Table 2).

Just six samples of spruce were dated and put together to form the spruce chronology (-813 to -669). This chronology is dated with the Villingen-Magdalenenberg fir chronology (Table 2) as well, but with low statistical values (see Table 4). But the crossdating with the Hallstatt Iron Age fir chronology confirms the date (OVL = 145, GLK = 72, TvH = 8.2, TvBP = 9.1).

Mining in the older Iron Age can now be easily divided into individual phases of operation due to the many dated sites (Fig. 6). The assumption, based on the finds, that the sites "Stügerwerk", "Seeauschurf", "Kernverwässerungswerk" and "Kilbwerk" belong to one single huge mining chamber (Barth and Reschreiter, 2019) is supported by the dating. It seems exciting that the three sites "Enderwerk", "Christinastollen-Tagschurf" and "Ritschnerwerk-Sinkwerkebentl" also date to the

same operational phase (Fig. 6), although they are located somewhat lower down (Fig. 2). The site "Josefstollen-Querschlag" is about 10 m above the huge mining chamber between the "Stügerwerk" and the "Kilbwerk" (see Fig. 2). As this is a single outcrop, it is difficult to classify this site at the moment. All these areas of the older Iron Age mining are probably part of one operational phase and were buried around -662.

After an interruption, mining activities can soon be detected again, but now deeper. The next most recent data are provided by the sites "Pohl-Schöpfbau" and "Bohrlochsonde E19"; and even more recent are the sites "Edlersbergwerk" and "Schernthannerkehr" (Fig. 6).

The find site "Christinastollen-Tagschurf" can be interpreted as one of the entrances to the resumption of mining after the interruption.

There are currently no sites in the mine that can be dated earlier then -570. However, the shingles in the "Langmoosbach stream" and the more recent burials in the cemetery prove that construction was carried out in the lower part of the "Salzberg-valley" and that the cemetery was still in use. After about -350 there are no more graves at the cemetery.

3.3. The La Tène period

63 samples were taken from wooden samples archaeologically dated to the La Tène period (see Table 3). 42.9 % of the samples were identified as fir wood, followed by 41.3 % spruce, 4.8 % larch and 11.1 % beech.

31 samples were dendrochronologically dated – 49 % (Table 3 for details).

All samples originate from the "Dammwiese" excavations. Most of the samples were measured by the help of X-ray CT and do belong to the group of tools and wooden container bases.

Three chronologies were set up: fir - from -129 to -371; spruce from -123 to -342 and larch from -164 to -252. The fir and spruce chronologies are well replicated (13 and 15 pieces); larch is just represented by two examples, which were dated against the spruce samples. The La Tène fir chronology is dated with low statistical values (see Table 4). But the crossdating with the Hallstatt La Tène fir spruce chronology confirms the date (OVL = 188, GLK = 68, TvH = 7.6, TvBP = 9.7).

The "Dammwiese"-site is located at about 1350 m a.s.l – about 450 m higher than the main "Salzberg-valley" area (Fig. 2). That is more or less the elevation where the sampling for the Dachstein/Schwarzer See chronology took place. The hypothesis is, that due to catastrophes at the "Salzberg-valley" the miners went upwards to the "Dammwiese" site, which is characterized by a much colder climate and therefore for slow growth of the trees. This is possible to be seen in a much higher mean number of tree rings per sample – up to 98.5 (see Table 4). Due to the much higher comparability to the Dachstein/Schwarzer See area, the dating with these chronologies was possible with high statistical figures (see Table 4).

There were no actual mining or archaeological activities at the "Dammwiese", just wooden artefacts which were excavated mostly in the 1880's and 1936 and are stored at the Natural History Museum in Vienna. These artefacts consisted of tools, spoons, shovels and container bases. Therefore, it was not possible to drill or cut samples out of these objects. The only possibility to perform dendrochronological measurements was using X-ray CT images (see above). Fig. 5 shows an example of a broken shovel made of spruce wood. This broken piece had 113 tree rings and was successfully dated to -167.

After about -350 there are no more known graves at the cemetery. A little later, around -150, the oldest data at the much higher "Dammwiese" are known. Thus it is now also confirmed by dendrochronology that the mining district and mining settlement were moved in the Early Iron Age.

4. Conclusions

Over the last 18 years intensive sampling (2271 samples) has been carried out at the various archaeological sites in Hallstatt, Austria. Due to the lack of reference chronologies which allow a secure crossdating, the dating process took a long time. Thanks to intense ^{14}C wiggle matching dating and a combination of various dendrochronological samples it was possible to establish yearly-based dates. Various chronologies within the time frame of -1232 to -123 (with gaps) for spruce, fir, larch and beech are now available. These chronologies represent forest sites at the northern rim of the Alps and can therefore be a "bridge" between the High Alpine archaeological sites (like Steiner et al., 2009) and the low elevation archaeological sites (like Billamboz and Martinelli, 2015).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank Andre Billamboz (Hemmenhofen, Germany) for providing the Villingen-Magdalenenberg chronology. The dating of the prehistoric samples was supported by the Natural History Museum, Vienna, the Salzwelten GmbH, Salinen Austria AG, the Hochschuljubiläumsstiftung of the City of Vienna and the government of Upper Austria (Kulturabteilung). We are thankful to a numerous group of colleagues for help in sampling, measurement and crossdating over the last 18 years of dendrochronological research.

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