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Wieliczka Salt Mine and its history written in annual growth rings of spruce wood

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This paper presents results of dendrochronological analysis of spruce wood from the Wieliczka Salt Mine, one of the oldest mines in Poland. The wood came from the first level of the mine, from casings of drifts, chambers, mineshafts, short shafts, galleries and chapels. The oldest wood, representing spruce trees cut down in the 15th century, appears in the Wałczyn, August and Dusząca chambers, Bąkle chamber and Powroźnik gallery, as well as the cast between the Kaczorowski and Sroki chambers. Younger wood, from the 16th and 17th century, was recognized in the Krupiński, Dusząca, Reyna and Weszki chambers, the Leszno and Karol galleries, the Sułów short shaft, and the Lizak chapel. The 18th–19th century wood appears in the August, Wałczyn, Dusząca, Rex and Kloski chambers, the Klemens gallery, the Piżmowa chapel, and the Wałczyn short shaft. In two excavations of the August and Weszki chambers, fragments of 20th century wood were recognized. Wood from old mines is a valuable source of information on history of the mining excavations or tools used in the mines. It also allows extending the scope of research of the mining archaeology.

Key words: *Picea abies*, Wieliczka Salt Mine, mining casings, annual growths, dendrochronology, mining archaeology.

INTRODUCTION

The Salt Mine in Wieliczka, situated in the Badenian (Middle Miocene) salt-bearing formation of the Polish Carpathian Foredeep (Garlicki, 1979), is one of the oldest mines in Poland; beginnings of its mining activity reach back to the 13th century. Since that time, it has incessantly operated and the excavations formed at the salt exploitation constitute valuable historic substance. The oldest of them are situated in the first level Bono, at a depth of about 58 m relative to the Kinga mineshaft. Mediaeval objects, among others, drifts, shafts, chambers, galleries and underground chapels, hide in themselves the history of the aged mine. They are invaluable, even in spite of the current condition of the excavations, in places far from perfect. They are a rich source of knowledge on the development of techniques of the deposit exploitation, and they also yield the image of knowledge and abilities of generations of the miners. This historical value was confirmed by listing the Wieliczka Salt Mine in the UNESCO World Cultural and Natural Heritage List. Remains of the ancient mining are investigated by the mining archaeology. To a considerable degree, it is supported by dendrochronology, which is of key importance for reading the information written chronologically in tree rings, year after year. Therefore, wood preserved in old mines is so valuable; once introduced into the mining excavations allows to follow the chronology of functioning of devices, excavation casings, their reconstructions or renovations. Analysis of annual growth rings allows determining the age of trees, from which wooden elements were made, with the accuracy of a single year. Dendrochronology is helpful in reconstructing the chronology of mine excavations, it also provides useful, exact information for establishing the history of the mines. In Europe, only several selected tree species are used for dendrochronological analysis: *Abies alba*, *Picea abies*, *Pinus sylvestris*, *Larix decidua*, *Quercus* sp., *Ulmus* sp., *Fagus sylvatica* and *Alnus* sp. Over 700 years of mining activity in the Wieliczka Salt Mine resulted in vast amounts of wood gathered within that period of time. Wood was delivered to the mine from various areas; in the beginning from close to Wieliczka, then, with elapse of time, from more and more distant mountains, like the Island Beskids (Beskid Wyspowy) or Silesian Beskids (Beskid Śląski). Various provenances of wood in the mine creates high potential of exploiting this advantage in further dendrochronological research. The wood was used as material for the excavation casings, as well as for construction of transport devices, production of mining tools (blockheads, hoes), or construction of draining devices (gutters, pipes). The investigations carried out by the authors were aimed at reaching and sampling the oldest wood from the mine to determine its age. This, in turn, should help in establishing the time of formation of the excavations, their history, and the time of functioning. Wood from the mine is an excellent store of potential material to establish dendrochronological standards, for coniferous tree species in particular.

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MATERIALS AND METHODS

Wood gathered in the mine is excellent material for dendrochronological investigations. However, difficult conditions at some sites of the mine: tight or too dangerous excavations, collapse threats, tightened roofs and walls, or crumpled casings effectively make it impossible to reach the sites at which huge trunks appear. Moreover, in spite of their impressing sizes, they appear not to be suitable for analyses, because they are either strongly cracked or crushed (Fig. 1).

Therefore, sampling had to be limited to the sites. Samples were taken with a wood handsaw and a Pressler increment borer. Combustion saws and drillers could not be used because of the methane gas present in the mine.

Sampling was made in the oldest mediaeval excavations from the first level, stretching at a depth of 57.4 m relative to the Kinga shaft (Jodłowski, 1988). These are eleven chambers (Reyna, Krupiński, Powroźnik, Wałczyn, August, Mortis, Dusząca, Weszki, Rex, Fortynbark, between the Gębaliński gallery and the Boża Wola mineshaft), three short shafts (Wałczyn, Zigler, Sułów), three galleries (Leszno, in front of the Piżmowa chapel, Bąkle), two perpendicular galleries (Karol, Powroźnik), as well as the Kloski and Stara Stajnia chambers and the Lizak chapel. The sampled wooden elements that form circular slices or cores were analysed with a stereoscopic microscope; 67 of them represent spruce. They came from casings of excavation walls or casts that appear there (Fig. 2).

Measurements of annual growth width, with 0.01 mm accuracy, were made using a *DENDROLAB1.0* apparatus at the Dendrochronological Laboratory of the AGH University of Science and Technology in Kraków (Poland). The measurements were registered and the annual growth sequences were graphically presented using a package of *TRMEAS* programs (Krawczyk and Krąpiec, 1995). Pearson's coefficient of the linear correlation *r* and the value *t* (Baillie and Pilcher, 1973) were calculated with the software of *TREE-RINGS* (Krawczyk and Krąpiec, 1995) and *COFECHA* (Holmes, 1999). When identifying the best fitting positions of the individual sequences, high *r* and *t* values, as well as visual resemblance to the dendrochronological curves were considered.

Individual sequences were dated against spruce master chronologies constructed for:

– southern Poland (1390–2001 AD) (Szychowska-Krąpiec, 2004);

Fig. 1. Examples of huge, strongly cracked and crushed trunks (photograph by J. Przybyło)

Fig. 2. A spruce wood cast, sampled for dendrochronological analysis (photograph by J. Przybyło)

– Bohemia and Moravia (1279–1997 AD) by T. Kyncl and J. Kyncl (unpubl.).

Taking into account that all the samples analysed were devoid of their last, youngest rings, developed directly under the bark, only a terminus post quem dating was possible (Zielski and Krąpiec, 2004). Evaluation of the number of lacking rings is difficult, although in most cases of samples taken from round beams it is less than twenty.

RESULTS

The individual ages of spruce trees used for casings vary from 30 to 177 years, however, most of timbers (60%) come from trees between 61 and 177 years. Generally, the tree rings were regularly developed, without disorders. Double or missing rings have not been found. At the microscopic inspection, the anatomical structure of wood was visible satisfactorily enough to carry out the measurements of width of the annual growth rings. Cell walls of the tracheids were clearly marked, without mechanical distortions: crumpling or damages. Borders between the tracheids of early and late wood were legible. Coniferous wood, susceptible to absorb salty damp, was well-preserved, without traces of decaying. Excellent condition of the spruce wood, with clear anatomical structure and distinct borders between the annual growth rings, enabled effective dating.

Absolute dating was made on 34 samples (Fig. 3 and Table 1). For every piece of wood analysed, corresponding numbers of tree rings, dating of individual sequences, and (estimated) dates of cutting the trees down are presented in Table 1, together with exact locations of the excavations, from which the timbers were sampled. The investigations were carried out in the northern, southern, eastern, western, and central part of the Bono level. Most of the timbers dated came from the northern part, in which also most of the oldest, 15th century wood was identified.

The oldest trees represented by the samples were felled in the 15th, and the youngest ones in the 20th century. The

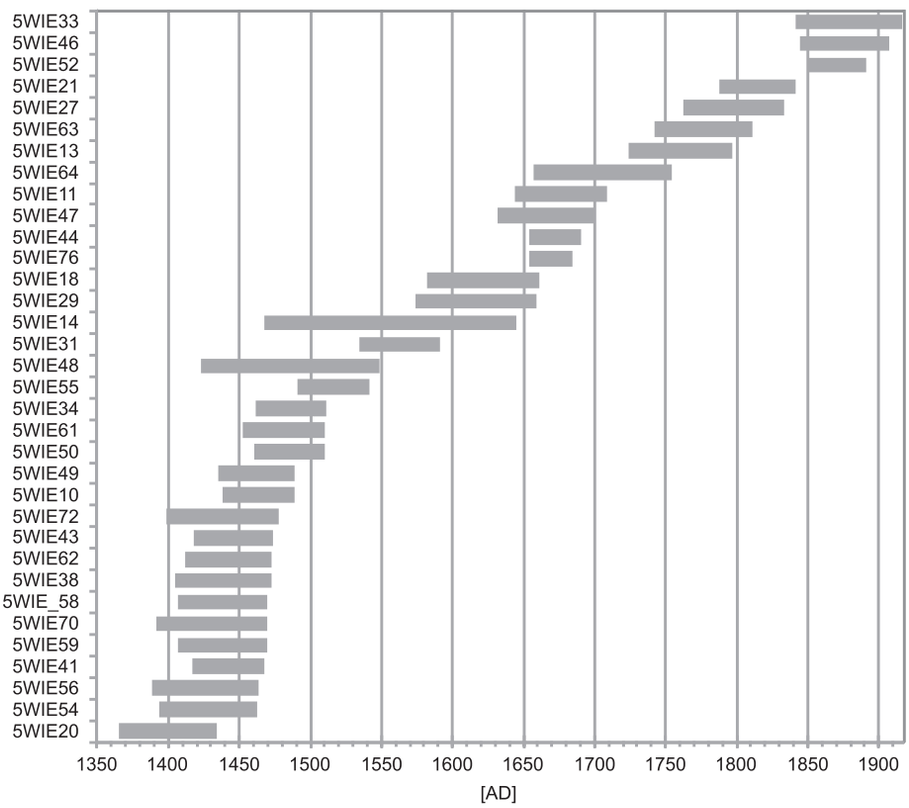

Fig. 3. Temporal extent of growth sequences of spruce trees, sampled from the Wieliczka Salt Mine

amounts of samples representing the following centuries are presented in Figure 4.

Amongst the wood, most timbers represented trees cut down in the 15th century (40.6%), particularly in its second half, and only one timber came from a spruce cut in the first half of the century. The 15th century wood was recognized in the Wałczyn (1470 AD, 1473 AD), August (1468 AD, 1473 AD, 1474 AD) and Dusząca (1463 AD, 1464 AD, 1470 AD, 1489 AD) chambers, the Bąkle (1464 AD, 1489 AD) and Powroźnik (1470 AD) galleries, and in the cast between the Kaczorowski and Sroki chambers (1478 AD) (Fig. 5).

Significantly less wood came from the 16th (18.7%) and 17th (15.6%) centuries. Six wooden elements coming from spruces cut down in the first half of the 16th century were found in the Krupiński and Dusząca (1510 AD), Weszki (1511 AD) and Dusząca (1542 AD) chambers, and in the Leszno gallery (1549 AD), whereas one timber, from the short shaft of Sułów, represented a spruce cut down later – in 1591 AD (Fig. 6).

The 17th century spruce wood was observed in the Dusząca (1645 AD, 1662 AD) and Reyna (1684 AD) chambers, the Karol gallery (1691 AD), and the Lizak chapel (1659 AD). These trees were cut down mainly in the second half of the 17th century, except one spruce which was most probably felled somewhat earlier – in 1645 AD. That tree, however, was of great age – over 177 years (Fig. 7).

Younger, 18th and 19th century wood proved to occur in lower amounts – only 12.5% from each of these centuries. The 18th century timbers were found in the August chamber (1700 AD), Klemens gallery (1709 AD), Piżmowa chapel (1797 AD) and the short shaft of Wałczyn (1754 AD) (Fig. 8), whereas the 19th century ones – in the Wałczyn (1811 AD), Dusząca (1891 AD), Rex (1833 AD), and Kloski (1841 AD) chambers (Fig. 9).

Individual sequences were relatively short and contained from 41 to 97 growth rings. The youngest, 20th century wood (August chamber – 1907 AD, and Weszki chamber – 1916 AD) came from spruces cut down in the 1920s; they were over 60 and 70 years old.

There is also the presence of deciduous, scattered-vascular wood of the *Fagus sylvatica* species. That beech wood has been preserved in a very good condition, with regularly developed core rays and distinct annual growths. It is characterized by several zones of narrow growths in its older part, whereas the younger rings are wider. The beech timber consists of over 100 tree rings. Unfortunately, hetero-connection with the oak regional standard for southern Poland and with the south Polish fir standard was unsuccessful.

DISCUSSION

Most of the wood pieces were identified as 15th century timbers, which are the oldest ones. Considerable amount of the 15th century wood can be related to technological changes that took place in the mine at that time. At the turn of the 14th century, more advanced devices were applied, so-called hand crosses, which considerably facilitated transport in the mineshafts and draining of the excavations. Soon, in the second half of the 15th century, other changes occurred; hand crosses were replaced by horse gears, which significantly contributed to the increase of the output (Przybyło and Sadkiewicz, 2013). Production growth required collateral security measures and, consequently, more and more increasing supplies of wood, which was used, among others, to construct mining casings and devices, and to secure the excavations.

In addition to increased supplies, there is also evidence for secondary use of older wood in the mine. An interesting example is the Weszki chamber, most probably dug out before

Table 1

Results of dating of spruce wood in the first-level excavations of the Wieliczka Salt Mine

No.	Laboratory code	Location	Tree ring number	Dating of the sequence
1	5WIE41	August chamber, E part of the deposit, Piżmowa chamber area	51	1418–1468
2	5WIE38	August chamber, E part of the deposit, Piżmowa chamber area	68	1406–1473
3	5WIE43	August chamber, E part of the deposit, Piżmowa chamber area	56	1419–1474
4	5WIE47	August chamber, E part of the deposit, Piżmowa chamber area	69	1632–1700
5	5WIE46	August chamber, E part of the deposit, Piżmowa chamber area	62	1846–1907
6	5WIE54	Dusząca chamber, N part of the deposit, Regis shaft area, Bąkle complex	69	1395–1463
7	5WIE56	Dusząca chamber, N part of the deposit, Regis shaft area, Bąkle complex	75	1390–1464
8	5WIE70	Dusząca chamber, N part of the deposit	78	1393–1470
9	5WIE49	Dusząca chamber, N part of the deposit, Regis shaft area, Bąkle complex	54	1436–1489
10	5WIE50	Dusząca chamber, N part of the deposit, Regis shaft area, Bąkle complex	50	1461–1510
11	5WIE55	Dusząca chamber, N part of the deposit, Regis shaft area, Bąkle complex	51	1492–1542
12	5WIE14	Dusząca chamber, N part of the deposit, Regis shaft area, Bąkle complex	177	1469–1645
13	5WIE18	Dusząca chamber, N part of the deposit, Regis shaft area, Bąkle complex	79	1584–1662
14	5WIE52	Dusząca chamber, N part of the deposit, Regis shaft area, Bąkle complex	41	1851–1891
15	5WIE21	Kloski chamber, N part of the deposit, Regis shaft area	53	1789–1841
16	5WIE61	Krupiński chamber, casts, S part of the deposit, Powroźnik gallery area	58	1453–1510
17	5WIE76	Reyna chamber, cast, E part of the deposit, Piżmowa chamber area	30	1655–1684
18	5WIE27	Rex chamber, central part of the deposit, Powroźnik gallery area	71	1763–1833
19	5WIE_58	Wałczyn chamber, W part of the deposit	63	1408–1470
20	5WIE62	Wałczyn chamber, W part of the deposit	61	1413–1473
21	5WIE63	Wałczyn chamber, W part of the deposit	69	1743–1811
22	5WIE34	Weszki chamber, E part of the deposit, Piżmowa chamber area	50	1462–1511
23	5WIE33	Weszki chamber, E part of the deposit, Piżmowa chamber area	75	1842–1916
24	5WIE72	cast between Kaczorowski and Sroki chambers	79	1400–1478
25	5WIE29	Lizak chapel, N part of the deposit, Lizak–Sułów complex	85	1575–1659
26	5WIE20	Bąkle chamber, N part of the deposit, Regis shaft area, Bąkle complex	69	1366–1434
27	5WIE10	Bąkle gallery, N part of the deposit, Regis shaft area, Bąkle complex	51	1439–1489
28	5WIE44	Karol gallery, N part of the deposit, Regis shaft area	37	1655–1691
29	5WIE11	Klemens chamber area, N part of the deposit, Regis shaft area, Museum complex, ca. 20 m W from Karol gallery	65	1645–1709
30	5WIE48	Leszno chamber, W part of the deposit, area of crossroad with Blum gallery	126	1424–1549
31	5WIE13	gallery in front of Piżmowa chapel, E part of the deposit, Piżmowa chamber area	73	1725–1797
32	5WIE59	Powroźnik chamber, central and S part of the deposit	63	1408–1470
33	5WIE31	Sułów chamber	57	1535–1591
34	5WIE64	Wałczyn chamber shaft, central and S part of the deposit, Powroźnik gallery area	97	1658–1754

1499 AD (Jaworski et al., 1984), whereas the wood analysed represented spruces cut down in 1511 AD. This could be due to repair of already existing casings. Such a situation took place in the Wałczyn chamber. This chamber, according to the source data (Jaworski et al., 1984), was formed at the beginning of the 18th century, however spruce pieces came from trees cut down in the 1470s (1470, 1473 AD).

The greatest amounts of the spruce wood were identified in the Dusząca chamber (Szychowska-Krąpiec, 2003a) situated in the northern part of the mine, where the oldest excavations were encountered (Jodłowski et al., 1988). In wall casings of the Dusząca chamber, apart from spruce, fir wood is also abundant, which came from fir trees cut down in the 14th, 15th, 16th, 17th, and 19th centuries (Szychowska-Krąpiec, 2000). Amongst the excavations, the Dusząca chamber merits particular attention. It belongs to the complex of Bąkle excavations situated in the oldest part of the mine.

Apart from the Dusząca chamber, the wood of coniferous species, *Picea abies*, *Abies alba* and *Pinus sylvestris*, appears in the mine in other excavations of the oldest level Bono (Szychowska-Krąpiec, 2003a). Samples from subsequent centuries are less frequent, however, their presence indicates that wood was being delivered to the mine in a continuous way, which, in turn, points to a considerable using up of this material. It may be supposed that wood supplies were particularly high in periods of increased salt production and development of the mine. Beside coniferous wood, which was most often used in mining casings in Wieliczka, particularly in casts, deciduous wood (*Fagus sylvatica*, *Quercus* sp.) was encountered as well. It was a good material for making various mine devices. In the Bochnia Salt Mine, the situation looks somewhat different; in mining casings, in addition to coniferous wood, wood of deciduous species, especially alder and birch, is relatively frequent (Szychowska-Krąpiec, 2003b).

Chronological record of the history of mines written in tree rings may be observed not only in salt mines, but also in mines of polymetallic ores (Szychowska-Krąpiec, 2007), as well as gold mines (Szychowska-Krąpiec, 2005) of Lower Silesia. Unfortunately, wood appears in these mines in considerably smaller amounts, and its state of preservation is not so good as in the salt mines.

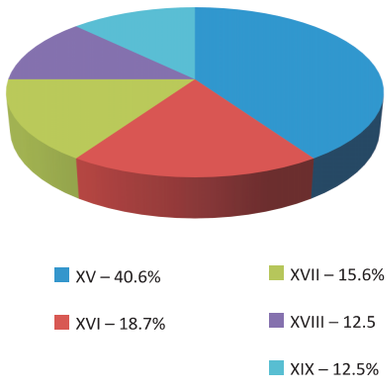

Fig. 4. Percentage of samples from particular centuries

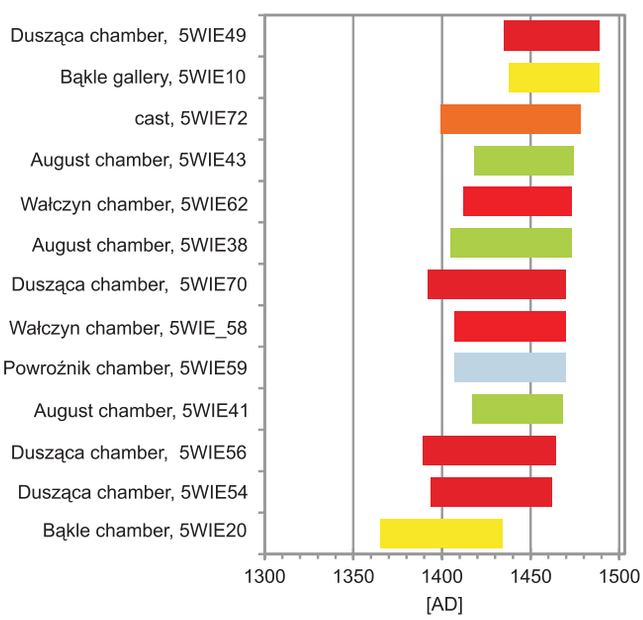

Fig. 5. Temporal extent of 15th century wood samples from various excavations in the Wieliczka Salt Mine

Significantly wider chronological record in annual growths of trees was registered in the Hallstatt salt mines (Grabner et al., 2007) and in the Kelchalm copper mine near Kitzbühel (Pichler et al., 2009) in Austria. In both Austrian mines, wooden artefacts originate from the Bronze Age all the way to the historic times, and they present remains of ancient mining works. In studies of such artefacts, dendrochronological analysis has proved to be very useful. In combination with the radiocarbon method, spruce wood from the copper mine in Tyrol was dated to 1237 BC (Pichler et al., 2009), and from the Hallstatt salt mine – to 1245 BC (Grabner et al., 2007). In both cases, it provided valuable information on the history and mining activity in Austria in the Bronze Age.

Systematic investigations of wood are valuable sources of knowledge, they also allow broadening the scope of research in mining archaeology, rapidly developing since the 1960s, e.g., in the Czech Republic (Kundrač, 1977; Kundrač and Michalek,

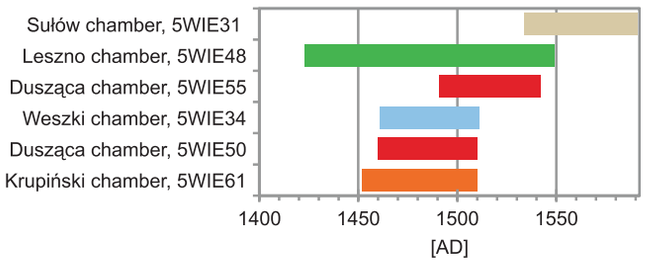

Fig. 6. Temporal extent of 16th century growth sequences, sampled from excavations in the Wieliczka Salt Mine

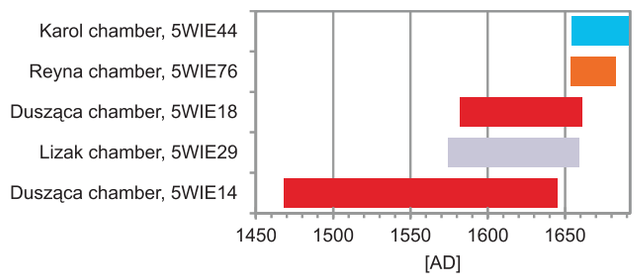

Fig. 7. Temporal extent of 17th century wood samples from excavations in the Wieliczka Salt Mine

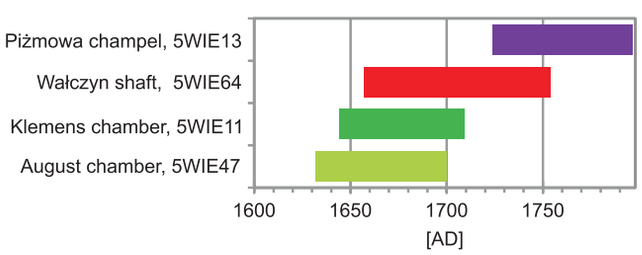

Fig. 8. Temporal extent of 18th century growth sequences, sampled from excavations in the Wieliczka Salt Mine

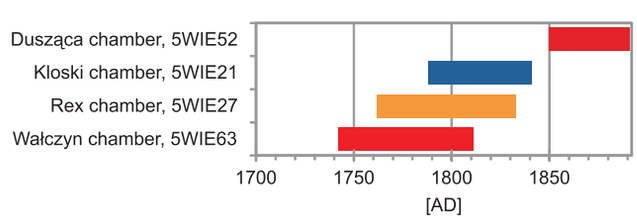

Fig. 9. Temporal extent of 19th century wood samples from excavations in the Wieliczka Salt Mine

1993) and in Poland (Madziarz and Sztuk, 2005; Firszt, 2006; Stolarczyk, 2006). Dendrochronological studies allow for more precise dating, as in the case of the Silberloch adit (Stysz et al., 2012), or revision of hypotheses on chronology of mining excavations (Szychowska-Krąpiec, 2007).

Finally, the record of climatic conditions contained in annual growth rings is a good material for climate reconstruction, in particular the temperature, rainfall, and solar exposure (Szychowska-Krąpiec, 2010; Koprowski and Duncker, 2012).

CONCLUSIONS

1. Both Polish and Austrian mines discussed demonstrate high potential of the dendrochronological analysis of wood appearing in historic and prehistoric mines. The Wieliczka Salt Mine, with its 700-years history, presents an extraordinarily rich store of spruce wood. Dendrochronological analysis of 67 spruce samples allowed for absolute dating of 34 elements. The spruce timbers dated represent a broad time interval – from 1434 AD to 1916 AD.

2. Apart from the historic record, wood from mines presents excellent material for construction of regional dendrochronological standards.

3. The investigations carried out yielded the information supplementing hitherto chronological determinations. They allowed to determine the time of cutting down spruce trees used for construction of the excavation casings. They also allowed to point out times of introduction of new wooden elements into the existing casings, at the repairs or partial exchange of fragments used up.

4. Examples of secondary using of wood in the mine were recognized. Relatively late mining excavations proved to contain wood coming from spruces cut down considerably earlier. This, in turn, proves re-using of wood and economic management of the Cracow Salt Works with this expensive raw material.

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