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Wood as a Biological Time Capsule

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Wood is produced by vascular cambium of woody plants, including trees. Growth of trees follows in seasonal cycles, and the wood produced in each growing season can be distinguished from the wood formed previously. Except many subtropical or tropical trees, which never really stop their growth, trees mark the end of the growing season by a rapid transition from one distinct feature of anatomical structure to a different feature (Telewski, 1998). As a result, trees show periodicity of their growth in the form of wide or narrow rings distinguishable from the previous layers. Tree rings are produced mostly on an annual basis. They reflect conditions under which the tree grew, as they record whether the year was favourable for growth or not.

Besides still growing old trees, wood can survive in the form of wooden products for many hundreds and thousands of years. Subfossil trunks can be deposited in peat bogs or sediments even for several dozen thousands of years. The oldest subfossil kauri (*Agathis australis*) from New Zealand is about 40000 years old. Growth rings are sometimes well preserved also in petrified wood for millions of years. They all contain the history of trees written and saved in their wood structure.

The most important information contained in wood is the time of their formation. The best-known dating method applied to all organic materials is the radiocarbon method. The principle of radiocarbon dating is based on the calculation of the proportion of radioactive isotope ^{14}C to stable carbon ^{12}C. Radiocarbon is formed continuously in the upper layer of the atmosphere mostly in the form of carbon dioxide. All living organisms get carbon, including extremely small quantities of radioactive ^{14}C, through photosynthesis and the food chain. Therefore they have the same $^{14}C/^{12}C$ ratio as the atmosphere during their lifetime. Death stops the absorption of radiocarbon and ^{14}C as an unstable isotope begins to disintegrate (Fig. 1). Half-life of ^{14}C is known and amounts to 5730 years (Mook and Waterbolk, 1985). This means that if modern Vemits about 14 beta particles per minute per gram, then the activity of material at the age of 5730 years is only about 7 disintegrations per minute per gram. In this way a measurement of the ^{14}C decay of the sample leads to an estimation of its

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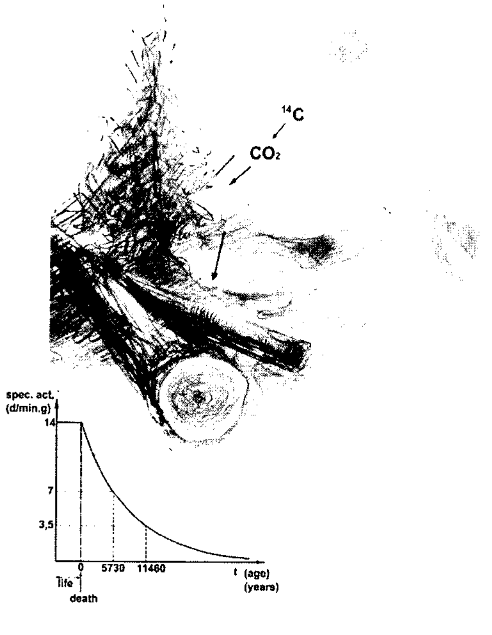

Fig. 1. Absorption and disintegration of Carbon 14 in wood.

radiocarbon age.

In the last years the conventional beta-counting method was replaced by the AMS-method (Accelerator Mass Spectrometry). The AMS-method enables the measurement of radiocarbon age by directly assessing the ^{14}C concentration. Both methods require chemical pre-treatment and they damage the samples. Requirements for the quantity of samples are about 5~20 g of wood for the conventional method and 20~50 mg of charcoal or dry wood in the case of the AMS-method.

The calculated radiocarbon age is not equal to the true calendar age. The major reason for this is that ^{14}C concentration in the atmosphere has not always been stable, as it is influenced by many factors, such as solar activity, changes of the Earth's magnetic field and recently also human activity. Because of the massive input of carbon dioxide without radiocarbon into the atmosphere during the pre-industrial and industrial period as a result of fossil fuel burning, it is difficult to distinguish between material originating from the last 300 years, except for decades after the year 1950, when nuclear tests produced huge amounts of artificial radiocarbon. Calendar age is calculated from the radiocarbon date using the calibration curve. Calibration curve has been built by measuring radiocarbon concentration in single tree-rings of very old trees and of subfossil trunks precisely dated by the dendrochronological method. At present the radiocarbon timescale calibrated by tree-rings reaches 11800 years back and has been extended using laminated marine sediments and corals (Stein et al., 2000).

The accuracy of radiocarbon dating depends on the period and at best can give a result within one century. In some periods, as for example in the middle of the 1^{st} millennium BC, disturbances of solar activity (period of the so-called Hallstatt catastrophe) and the resultant shape of the calibration curve does not enable precise age determination. A higher accuracy can be obtained by "wiggle-matching": comparison of a series of ^{14}C-dates of wood samples taken in known intervals against the radiocarbon calibration curve.

A much more precise method of age estimation is dendrochronology, where tree-rings are the subject of the analysis. *Multilingual Glossary of Dendrochronology* (Kaenel and Schweingruber, 1995) defined dendrochronology as "the science of dating tree-rings". In comparison to the radiocarbon method, dendrochronology is limited to wood and charcoal with a preserved ring sequence. The minimum number of required rings depends on the task. On the other hand, with yearly or sometimes seasonal accuracy it is the most precise dating method.

The concept of dendrochronology is very simple. In the temperate zone trees produce a new annual ring every year. So in growing trees the date of formation of every ring can be determined. Parameters of tree-rings vary from year to year with changing environmental conditions, but the patterns are similar within each geographic region. Therefore it is possible to compare tree-ring series of known age (from living trees) with dead trees or timber of overlapping age, and to extend the tree-ring pattern into the past. The construction of well-replicated long-term chronologies is an important task for many laboratories. They have been developed independently for different species and geographic areas.

Thousands of precise dates have been provided for wooden structures of historic and prehistoric periods thanks to the tree-ring calendars. They enable us to obtain ample information from various fields of human activity, as for example:

- settlement history;
- periods of building activity
- history of architecture;
- history of art.

From my professional experience in Poland I would like to mention the most important archaeological site in Biskupin. In 1933 archaeologists discovered very well preserved wooden constructions on a small peninsula of the Lake Biskupin in northwestern Poland. The constructions represent a settlement of the Lusatian culture, which has been built during the Early Iron Age. The timber used for the basement of houses, gate, pathway and breakwater construction were dendrochronologically dated to 722～747 BC. The majority of samples come from the winter cut 738/737 BC. The Biskupin timber provides a well-replicated chronology which covers the years 887～722 BC (Wazny, 1994).

Wood preserves in its structure not only information about the year of formation, but also data about its origin in the sense of geographic region. The use of dendrochronology to determine the provenance of timber, termed "dendroprovenancing", was introduced to solve the questions of imported timber in Western Europe and subsequently for timber from excavated ships (Bonde et al., 1997). The basic requirement for dendroprovenancing is a dense network of chronologies. A high similarity of the tested tree-ring sequence against the master chronology representing a defined geographic region indicate its origin. In this way the provenance of painting panels used by Netherlandish masters (Rembrandt, Rubens and others) was found in the Baltic region (Eckstein et al., 1986).

According to Eckstein (1998) "dendrochronology is a science of extracting chronological and non-chronological information from dated tree-rings". The most important information has already been mentioned: age and origin. They are only two of many records saved in wood structure. Tree-ring patterns preserved in wood reflect also environmental conditions around the tree. The year-to-year variability of tree-rings is a combined effect of many factors, such as:

- soil and air temperature;
- humidity and precipitation;
- solar radiation;
- length of growing season;
- soil conditions and properties;
- ground stability;
- wind;

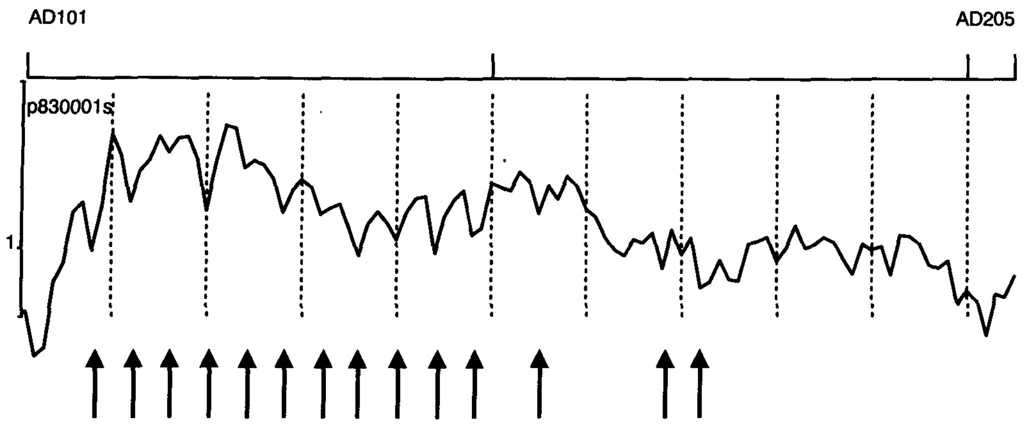

Fig. 2. Floating oak chronology from the 1st millenium BC. Arrows show cyclic growth disturbances appearing as narrow tree-rings. Four-year frequency indicates defoliation caused by cockchafer.

- snow cover.

The major characteristic of growth dynamics is tree-ring width. According to the model worked out by Cook (1990), ring width R of a tree growing in a particular forest stand is a function of five basic components:

$$R_t = A_t + C_t + \delta D1_t + \delta D2_t + E_t ,$$

where A is the age trend resulting from the increasing stem diameter, C is the climatic signal, D1 is the disturbance impulse affecting single trees in the stand (for example wounds), D2 is the disturbance impulse affecting the whole stand (for example fire or flood), E is an unexplained component, t is time (year), and δ is a binary index of presence or absence of the disturbance. Component D2 is very important for dendroecology, while from the point of view of dendrochronology as a dating method, all components except C are disturbance components and they reduce the value of tree-ring records for further examination.

Insect outbreak is an interesting example of exogenous disturbance factors. Effects of defoliation caused by insects are reflected by periods of growth reduction (Asshoff et al., 1998-1999). In the case of European cockchafer (*Melolontha melolontha*) they are easy to recognize due to their periodicity (Christensen, 1987). In some regions of Poland cockchafer causes defoliation of oak stands every 4-5 years; in northern Germany and Denmark the cycles are shorter: 3~4 years. Periodic growth suppression is visible as characteristic peaks in tree-ring series occurring repeatedly every 4 years. Traces of such outbreaks, which occurred 2700 years ago, are well preserved in timber from the above-mentioned settlement in Biskupin and a neighbouring settlement from the same period in Izdebno (Fig. 2). They provide additional interesting environmental information recorded in prehistoric wooden constructions.

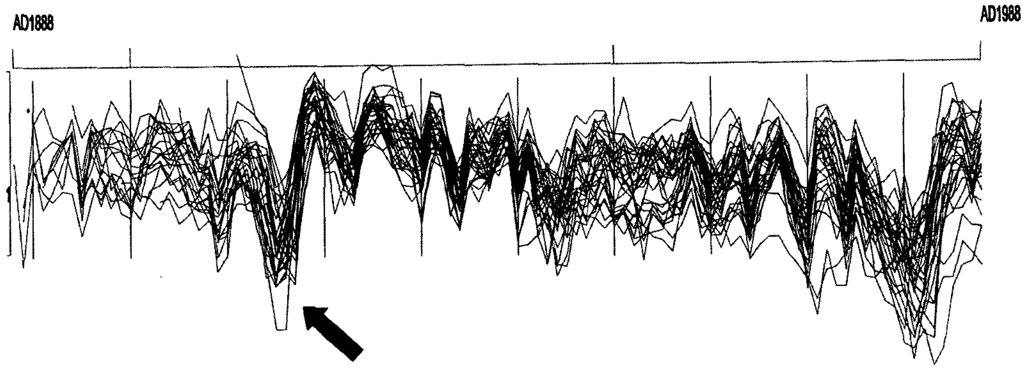

Fig. 3. Tree-ring series of oaks growing on Krotoszyn Plateau (Poland). Arrow denotes period of deep growth reduction 1913~1917 AD. Climatic effect of Katmai eruption 1912 AD?

Prevailing disturbance components make cross-dating of tree-ring sequences and dendrochronological examination of wooden materials more difficult and often impossible. Occurrence of growth anomalies and intensity of disturbing the normal growth rhythm depend on species. The sensitivity of each tree species to their influence is different, which results in its greater or lesser usefulness for dendrochronology. Grissino-Mayer (1993) provides list of 573 species that have been investigated in tree-ringresearch. The Crossdating Index (CDI) informes about their usefulness for dendrochronology. All possible modifications of tree-ring structure with their environmental interpretation have been juxtaposed by Schweingruber (2001).

Environmental records stored in tree-ring patterns have a various range and significance. Some of them - such as a changes in the ground water level (Verlage and Breckle, 1989), flooding (Yanosky, 1982), glacial movements (Kaiser, 1993), mass movements (Denneler and Schweingruber, 1993), forest fires (Swetnam, 1993) - are local or have a regional character, while others reflect events on a global scale. Volcanic eruptions belong to the most important disturbance phenomena. The influence of volcanic eruptions is mostly indirect: a powerful eruption can cause a long sequence of climatic events around the world. Huge amounts of volcanic dust in the upper level of the atmosphere cause an unusually cool weather and formation of very narrow rings or frost rings in trees from different parts of the world. For example, trees in the northern hemisphere - from Scandinavia to California - were markedly affected by the Santorini eruption in 1627 BC (LaMarche and Hirschboeck, 1984; Grudd et al., 2000), and European trees reacted to the eruption of volcano Katmai on Alaska in 1912 AD (Fig. 3). Still very controversial and mysterious is the history of the deep growth reduction of 536~540 AD, which was studied by Baillie (1994, 1995). It was a period of famines from Europe to China, and Baillie (1995) found in Chinese records that "stars were not seen" then.

Tree-ring widths usually reflect climatic conditions. Trees growing near the limit of their existence are the most sensitive to climatic change. For example, the trees from the northern treeline or from high mountain localities respond sensitively to temperatures (Briffa et al., 1990). Similarly, the trees of desert areas of south-western USA record the precipitation history in their annual rings (Grissino-Mayer, 1996). The strength of relationship between tree-rings and climate depends on species and its genetic preferences. Research on those relationships and the high correlation with instrumental climate records enables us to provide a reconstruction of climate components and spatial variations in climate (Fritts, 1976). Historic timber as well as subfossil logs from peat bogs, lakes and rivers preserve climate records from the pre-instrumental time. For example growing in Korean forests *Pinus densiflora* Sieb. et Zucc. (Japanese red pine) used for reconstruction of Kyungbok Palace in Seoul and originated form central or eastern part of the Korean Penisula (Ważny et al., 2001) shows significant growth

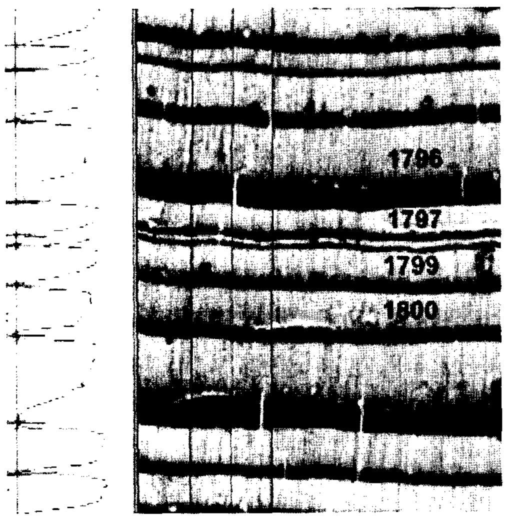

Fig. 4. Example of growth reduction found in *Pinus densiflora* used as construction timber for reconstruction of Royal Palace in Seoul.

reduction in 1798 (Fig. 4) caused probably by drought around the Yellow Sea (Liu, 2000, pers. comm.).

Tree-ring width is only one of many potential variables describing tree-rings. Environmental data recorded in wood can be "read" by a combination of dendrochronological techniques, including measurements of wood density or concentration of stable isotopes ^{13}C or ^{18}O in individual tree-rings. Wimmer and Grabner (2000) tested 16 anatomical variables of conifer trees:

- ring width, density and latewood proportion;
- maximum and minimum latewood density;
- maximum and minimum earlywood density;
- resin duct density;
- tracheid length in earlywood and latewood;
- cell-wall proportion in earlywood and latewood;
- microfibril angle in earlywood and latewood;
- total number of ray cells per unit area;
- height of uniseriate rays.

Those authors also analysed the strength of the climatic signal of those variables. Their results confirmed that especially the maximum latewood density appeared to be the best indicator of climatic conditions.

Deciduous species and their anatomical variables have also been a subject of dendroclimatological and dendroecological study. Variability of the vessel parameters with resulting conductive area of a tree show the strongest relationship with climatic data (Sass and Eckstein, 1992; Pumijumnong and Park, 1999).

Gindl et al. (2000) looked deeper into the anatomical and chemical structure of wood and properties of tree-rings. The subject of their study was the latewood lignin content compared with the total ring width and maximum density of trees growing at the Alpine treeline in Austria. All the tested variables were strongly correlated with temperature, but in different time intervals. The total ring width reflected the period from mid-July till late August, the maximum latewood density was positively correlated with mean temperatures of August and September, whereas the latewood lignin content was influenced by the period from September to the third week of October. That study demonstrates that also lignification of cell walls reflects climatic variability and determines new directions for dendrochronological research in years to come.

Wood is the only organic material which registers the date of its formation with yearly or seasonal resolution. Wood structure and chemical composition record environmental data from the lifetime of the tree. The high durability of wood and wooden products as well as favourable conditions that slow down their biodegradation, enable the preservation of these records for thousands of years. Owing to dendrochronology we are able to open this time capsule and to reconstruct the saved data. Information preserved in wood is of enormous value for historical research, climatology, paleoecology, geology, biology and many other branches of science.

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