8 Dendrochronology

Frédéric Guibal and Joël Guiot

Dendrochronology differs from other absolute dating methods in that the age assignment is not based on a simple, automatic count of annual deposits i.e. the rings, but on a set of intercomparisons of a large number of chronologies so as to ensure the annual status of each tree-ring (also known as growth rings), after eliminating the potential pitfall of anomalies in the anatomy of rings which may result, some years, in the absence of a ring or the formation of double rings (also known as false rings).

To understand the principle of this method, some fundamental aspects related to the formation of growth rings in trees in temperate regions should be recalled. Because of the marked climatic seasonal contrast of temperate regions an annual status can be assigned to each ring (with the exception of some accidents in growth).

A Bit of Botany and Ecology

The annual growth of woody plants is composed of an axial component which leads to the lengthening of branches (primary growth) and a radial component which leads to the formation of a ring (secondary growth). The radial growth of the trunk, branches and roots results from a layer of actively-dividing cells, the cambium, immediately beneath the bark. This gives rise to vascular tissues: wood, on the inside, responsible for, among other functions, the upward flow of the sap, and phloem, on the outside, responsible for the downward movement of the elaborated sap (Fig. 8.1). Year after year, the previously formed tissue is pushed inwards for wood and outwards for phloem.

In areas with a temperate climate, fluctuations in the physical aspects of the atmosphere (temperature, humidity, sunshine) mean that vegetation has a period of activity and a period of rest within the same calendar year. Cambial activity is discontinuous in time: in deciduous oaks on the plains in western France, cambial activity lasts from April to September; for larches which grow in the internal Alps above 1500 m, cambial activity extends from mid-June to mid-August.

A ring is made up of two parts: the earlywood which develops at the beginning of the growing season, and the final latewood which develops later in the growing season. These differ in terms of the cells that compose them, their dimensions, their disposition and the thickness of their walls. Variations in the thickness of the cell walls have consequences for the density of the wood, in the form of intra-annual and inter-annual variations more or less linked to changes in climate conditions. These conditions act according to the principle of limiting factors. Growth cannot proceed faster than is allowed by the most limiting factor. This limiting effect may be continuous, variable or sporadic depending on the case. The action of climatic factors is attenuated or amplified by other factors, both abiotic (soil, topography) and biotic (age, competition, pest attacks, phenology).

Crossdating

Aristotle, Buffon and Leonardo mentioned the existence of annual tree rings. Leonardo da Vinci, in particular, observed a relationship between ring widths and the weather conditions of the year. However, it is the American astronomer Andrew E. Douglass (1867–1962) who, in laying out the methodological foundations, is considered the father of

F. Guibal (✉)
Institut Méditerranéen de Biodiversité et d'Ecologie marine et continentale, UMR7 263 CNRS/Aix-Marseille Université/IRD/Univ Avignon, Europôle de l'Arbois, BP 80, 13545 Aix-en-Provence Cedex 04, France
e-mail: Frederic.guibal@imbe.fr

J. Guiot
European Centre for Research and Teaching in Environmental Geosciences CEREGE, Aix-Marseille University, CNRS, IRD, INRAE, Collège de France, BP 80, 13545 Aix-en-Provence Cedex 04, France

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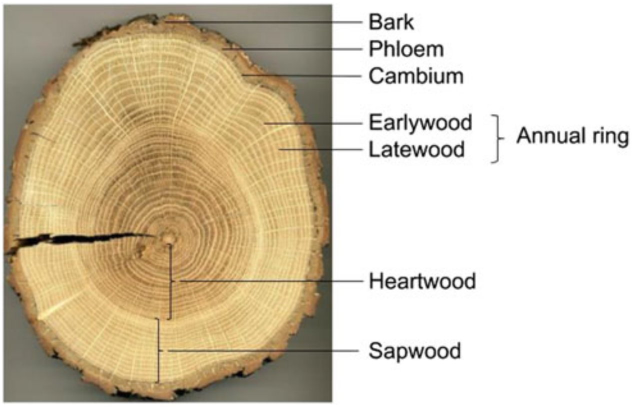

Fig. 8.1 Cross-section of deciduous oak

dendrochronology (*dendron*: tree, *chronos*: time, *logos*: study). Dendrochronology remained fairly discreet until it gained in notoriety about 1929, when Douglass succeeded for the first time in dating beams from ruins of Indian buildings in the US state of New Mexico, qualifying it as a dating method with an annual resolution (Robinson 1976). Despite this, it was not until the arrival of the computer in the 1960s, that dendrochronology truly took off, with a proliferation of research laboratories.

In the regions where the first dendrochronological studies were conducted (semi-arid regions of the southwestern USA and cold regions), the existence of a single limiting climate factor (rainfall in semi-arid regions, summer temperatures in cold regions) was instrumental in creating a series of rings whose width varied from one year to the next. However, in regions with a temperate climate, where growth depends on several factors, one factor can compensate for another, and the annual ring width series are less variable, making dendrochronological studies more complicated. In fact, if weather conditions are adequate, year after year, to meet the ecological requirements of the tree, the rings form a temporal series of constant width, and do not provide any chronological information, since it is extreme variations that serve as landmarks.

Dating with dendrochronology is based on a fundamental stage, called crossdating, which is relative dating assuring the proper placement in time of each ring. Crossdating is established by intercomparison of different pieces of wood on which sequences exhibiting similar ring patterns are identified. For this, similar sequences of coinciding narrow and wide rings, that is, separated by the same number of rings, need to be identified. This is possible only with two conditions. Firstly, the limiting factors for radial growth must vary in intensity from one year to another, with an unrepeatable series over time, so that the succession of ring widths are also variable in such a way as to be irreproducible. Secondly, the limiting factors must act in a similar way on trees with the same environmental requirements and over a wide enough geographical area to cause ring widths to vary the same way in many trees. This principle is important because ring widths can be crossdated only if one environmental factor becomes critically limiting.

Crossdating, or synchronization, is essential to check the accuracy of the ring count and the presence of any growth abnormalities. Abnormalities may appear as double rings (false rings) in the same calendar year or as missing rings. Indeed, some years, after a cold winter, possibly followed by a late spring or preceded by severe defoliation in the previous year, the ring may be partially or totally absent. In other years, as a result of the early onset of a summer drought (as in the Mediterranean region), the cambium may develop latewood elements and, then, thanks to improved weather conditions through the summer, may start producing earlywood elements again before producing latewood at the end of the normal growing season. In this case, the “first” ring is identified as supernumerary or false. Crossdating remains largely subjective and various methods have been developed to describe the observed similarities more objectively (McCarthy 2004).

In living trees of the same species, with a confirmed contemporaneity between the samples, synchronization is established by identifying sequences of similar rings over several series under a microscope (in cores or cross sections of trunk), firstly from the same tree, and then, between series from different trees. The operator compares the series from the bark inwards, records the rings and counts the sequences of narrow rings or ones with a distinguishing feature (color or width of the final wood, presence of any traumatic scars or ducts etc.). This stage allows the identification of each ring in terms of its vintage, after any anatomical abnormalities such as missing rings or double rings have been detected. After synchronization of the series has been established, ring width series are measured (1/100–1/1 000 mm).

On samples of unknown date, i.e. samples of wood from trees felled at an unknown date, the measurement of ring width series allows the establishment of digitized series from which graphs are drawn to compare the temporal variations in ring widths. The graphs are then compared in pairs and sequences of similar ring patterns are sought; maximum similarity between two curves is obtained when contemporary years are superimposed: maximum values, minimum values and the number of times two series show the same upward or downward trend in relation to the preceding year.

This analysis allows us to date the year of formation of each ring and identifies the felling date of the tree. The felling date of the tree is ensured when the outermost ring is still present; for species where the anatomical difference between sapwood (functional wood nearest the bark) and heartwood persists over time (oak, ash, elm, larch, etc.), the felling date of the tree is estimated based on the date assigned to the last ring.

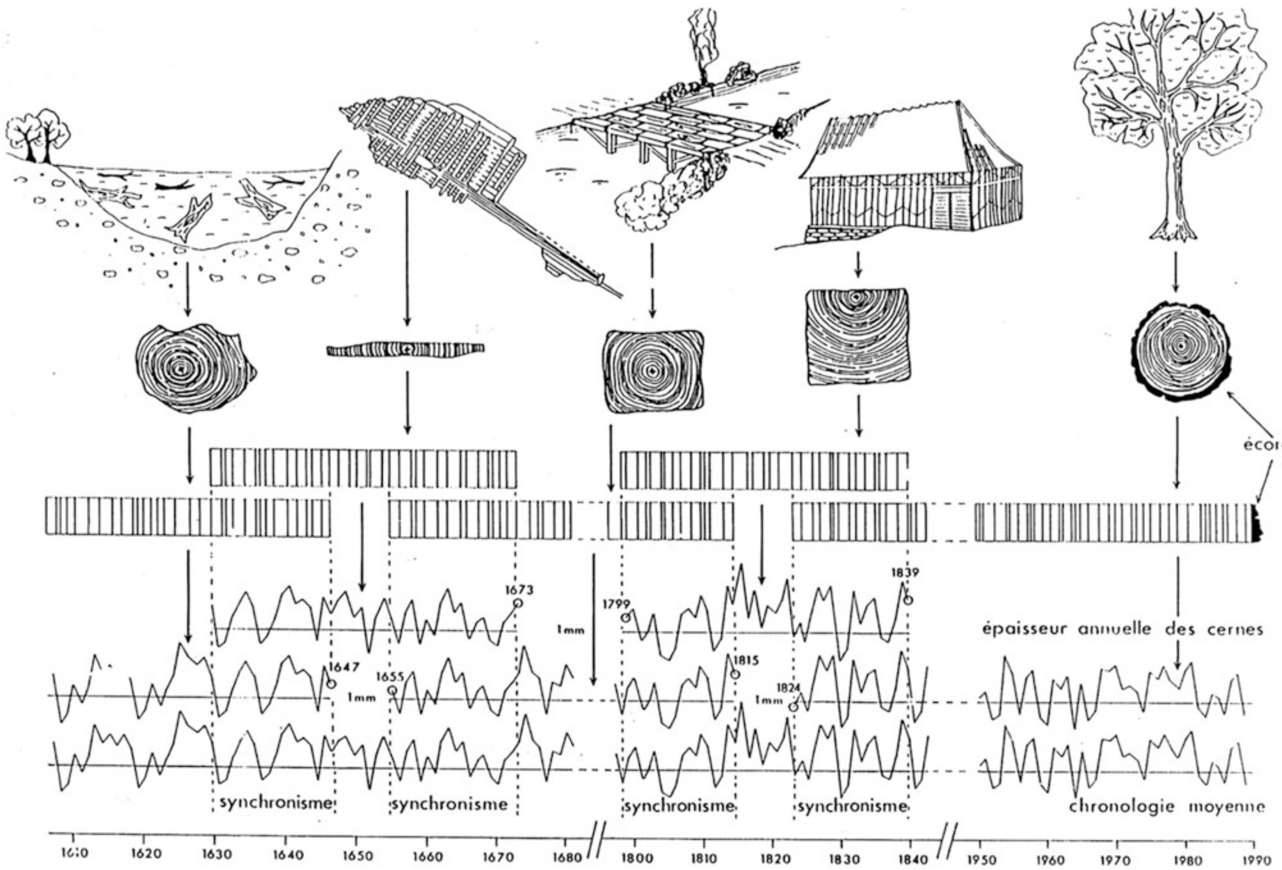

Fig. 8.2 Diagram of the theoretical construction of a master chronology

The dating of samples from trees which died at an unknown date requires synchronization between the analyzed series and a chronology of previously dated ring widths, called a master chronology. This master chronology must be composed of several series of rings from the same tree species as the one to be dated and from trees exposed to the same climatic factors, i.e. geographically close. Building a master chronology involves assembling several mean chronologies, homogeneous in their ecological and geographical origin, partially synchronous, based on the presence of ring patterns common to these timelines, and one of which is constructed from living trees for which the year of formation of the outermost ring is known. This permits each ring in the master to be assigned the year of its formation (Fig. 8.2). The representativity of a master chronology is related to its sample depth, i.e. the number of series included in the calculation of the mean ring width value. Even in climatically homogeneous regions, the geographic area covered inevitably leads to the inclusion of trees from forest stands subject to a variety of local climates, due to differences in altitude, exposure, continental character or even having grown in different site conditions (bedrock, exposure, phyto-ecological communities, degree of clearing of the site etc.) or having experienced more or less different stresses in the form of local disturbances. This summation results in a master chronology that is the average of annual wood layers over time of a given species in a region exposed to the same macro-climate, over a more or less extensive area.

Temporal and Spatial Extension

For the Holocene period, the longest chronologies, covering several thousand years, come from North America (Ferguson 1969; Ferguson and Graybill 1983), the British Isles (Pilcher et al. 1984; Baillie and Brown 1988), Central Europe (Leuschner 1992; Krapiec 1998; Schaub et al. 2008; Kaiser et al. 2011), North-West Europe (Eronen et al. 2002; Grudd et al. 2002) and Siberia (Naurzbaev and Vaganov 1999; Rashit et al. 2002). In the southern hemisphere, several groups have built thousand-year chronologies in Argentina and Tasmania (Barbetti et al. 1995; Roig et al. 1996; Cook et al. 2000).

In the same way that the representativeness of a master chronology is related to the quality of the climate signal evidenced by a high frequency of pointer years, the

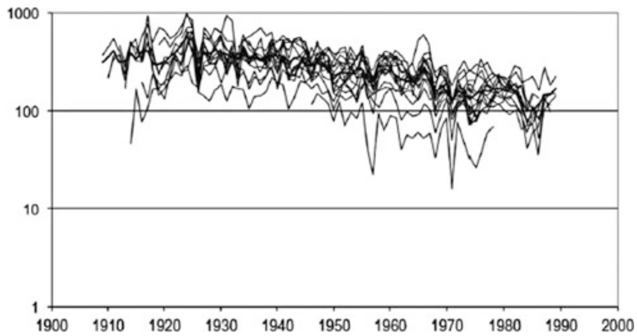

Fig. 8.3 Mean chronology (thick line) built up from multiple synchronous ring-width series of variable length (in line with the custom in dendrochronology, the y-axis is shown on a logarithmic scale to make the thinner rings more distinct)

chronological representativeness of the sample to be dated depends on the number of pointer years it contains. For this reason, trying to date a chronology composed of too few rings is usually an exercise doomed to failure. For a given site, a multiplicity of samples is essential to acquire a representative mean chronology for the site in which individual variances are minimized; in the field, this means sampling at least a dozen cases presumed to be contemporaneous, in order to achieve, whenever possible, a mean chronology of at least 80 years (Fig. 8.3). This methodological requirement explains the negative outcome of repeated attempts to date isolated pieces of wood, regardless of the context of their discovery, even if, in certain exceptional conditions (very long ring series, particularly well-documented period), statues and dugout canoes may have been dated by dendrochronology (Arnold 1996; Eckstein 2006)!

Synchronization between different tree species, called heteroconnexion, although discouraged because of differences in climate response and ecological requirements between species, is sometimes carried out between species with very similar ecological requirements. For example, comparisons are commonly made between oak and chestnut, oak and elm, larch and spruce.

Teleconnection or comparison of tree ring series over long distances, from areas subjected to different climate conditions, although theoretically just as frowned upon as the previous exercise is nevertheless, often done if the study is initiated in an area previously never investigated and for which there is no knowledge base.

In this way, the first master chronologies of oak representing the North East of France and Brittany were initiated. In a first example, master chronologies already in place for the South West of Germany were used to calibrate the first samples in Franche-Comté and Burgundy, which were analyzed by the Laboratory of Chrono-Ecology in Besançon, in the early 1980s. In a second example, master chronologies representative of the South West of England have allowed dating of sites located in the Loire valley, the Penthièvre and the Rennes basin by the City of London Polytechnic and Queen's University Belfast.

We should also mention that before starting to crossdate a piece of wood, it is often necessary to start with an approximate age of the piece, provided by ^{14}C dating which crossdating will then refine until accuracy to the year is achieved. It should also be noted that although dendrochronology is an absolute dating process accurate to a single year, this does not prevent occasional dating failures, especially when master chronologies for the species and/or region are lacking.

Contribution of ^{14}C to Calibration

Extremely valuable for its ability to date wood vestiges by establishing, under the conditions detailed above, the year of formation of each ring, even the year of death of the tree, dendrochronology has the undeniable advantage of contributing to the calibration of radiocarbon dates by converting ^{14}C age to the true calendar age.

In the 1950s, when the first radiocarbon datings were obtained on objects from past human societies, the match between the ^{14}C dates and the calendar dates was considered adequate. However, the archaeological material used was not very well dated or very old, and the ranges of uncertainty were so great that they masked potential minor deviations. According as the accuracy of ^{14}C dating improved and the body of datings grew, it quickly became obvious that the ^{14}C dates obtained were more recent than the dates obtained independently, in particular those obtained from remains from ancient Egypt. Given that any uncertainty inherent in relative dates obtained on such material could not be ruled out, and that in a living tree, only the outermost ring has a ^{14}C content in balance with that of the atmosphere, a program of ^{14}C dating of tree rings dated to the year by dendrochronology was initiated on long-living Methuselah pine (*Pinus aristata*) from the slopes of the White Mountains in California (Fig. 8.4). The results confirmed the disparity between ^{14}C dates and calendar dates (de Vries 1958). Irregular fluctuations were noted in the dates obtained, and led Suess (1965) to establish a calibration procedure for the ^{14}C dating of tree rings, in order to express the raw dates (conventional dates) in chronometrically calendar dates (calibrated dates). Measurements carried out on sequences of five or ten consecutive rings collected on the California pines have shown that the gap between the two calendars, ^{14}C years and actual years, remained low for the last 2500 years,

Fig. 8.4 View of a several thousand year old Methuselah pine (*Pinus aristata*) from the White Mountains (California)

but that from 500 BC, the gap increased sharply to almost 800 years at 5500 years BC.

A systematic study of this phenomenon was then carried out in the 1980s and 1990s by several laboratories on blocks of rings from American pines, oaks and European Scots pines. After publication in 1993, these curves, called radiocarbon calibration curves, established by thousands of measurements, constituted the basis on which corrections are now possible for the entire Holocene period, and currently, for the past 12,400 years (Stuiver et al. 1998). Extended into the past through the dating of tropical reef corals, varved sediments and speleothems (see Chap. 4), the calibration curves obtained from tree ring data are now being extended using series of dated tree rings series from Bølling Allerød and from Younger Dryas in Germany, the area around Zürich, Northwest Italy and watersheds of tributaries in the mid Durance valley (France).

The correction curve for ^{14}C dates in calendar years shows that the actual time seems compressed by about 15% before the sixth millennium BC, that there are plateaus along the curve (for example, around 500 BC. or during the ninth and tenth millennia BC.), and that multiple small fluctuations can, for some periods, affect the rectilinear shape of the curve. The practical consequences of these types of variations, showing that variations in concentration of atmospheric ^{14}C have been erratic, are very different: small fluctuations, after correction, can result in particularly inaccurate dates; but in some cases, very precise dates can be achieved for those periods particularly affected by fluctuations in the atmospheric content of ^{14}C.

Examined more closely, the radiocarbon calibration curve with its very twisted appearance reflects a stochastic process which constitutes, at certain times, a particularly valuable

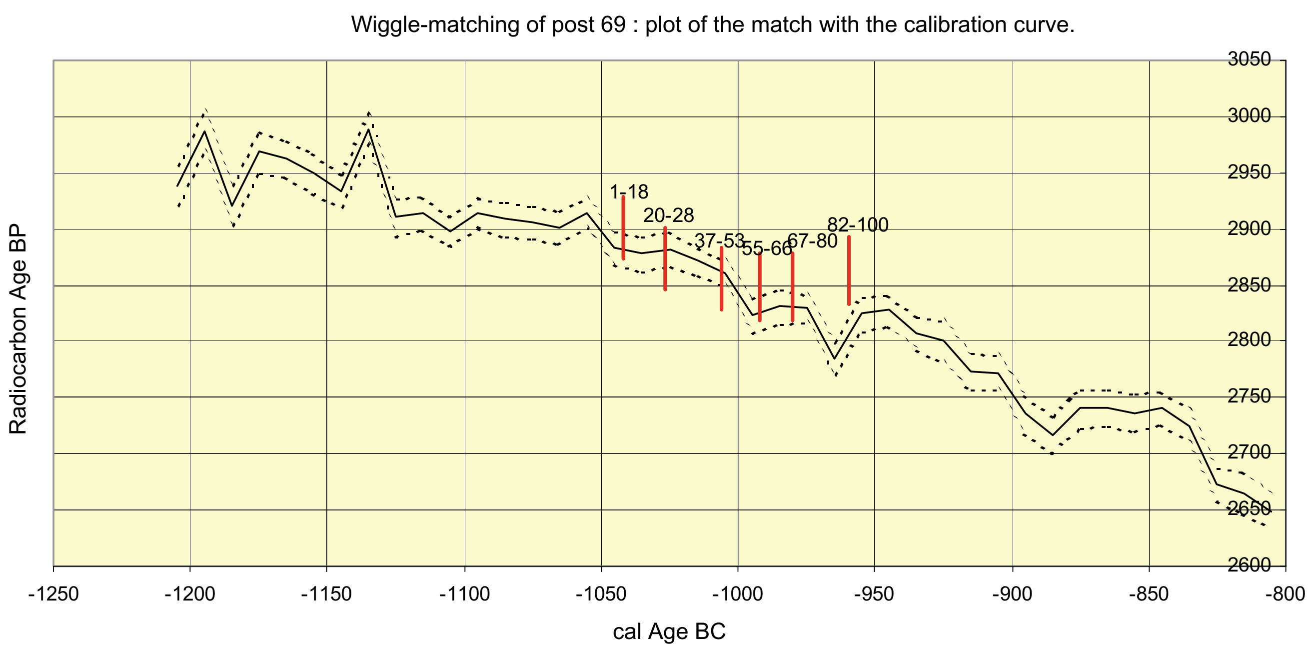

Fig. 8.5 Dating by wiggle-matching of the late Bronze age oak post n○ 69 from the submerged coastal habitat of Montpenèdre, Hérault (Oberlin et al. 2004). The x-axis corresponds to the calendar years; the y-axis corresponds to radiocarbon years. Vertical lines = standard deviation of the measure

chronological marker. Indeed, the matching of these kinks (known as wiggles), based on a multiplicity of ^{14}C dates obtained from blocks of tree rings, separated by a known number of calendar years, allows, by the method of "wiggle-matching" (Pearson 1986), a greatly improved accuracy of radiocarbon dating, as illustrated by the example of the post n○ 69 (Fig. 8.5) from the submerged coastal habitat of Montpenèdre (Hérault, France).

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