DENDROCHRONOLOGY and DENDROCLIMATOLOGY

Dendrochronology (or tree-ring dating) is the scientific method of dating tree rings (also called growth rings) to the exact year they were formed in a tree.

Dendrochronology derives from the Ancient Greek **dendron** (δένδρον), meaning "tree", **khronos** (χρόνος), meaning "time", and -**logia** (-λογία), "the study of".

As well as dating them, this can give data for dendroclimatology, the study of climate and atmospheric conditions during different periods in history from the wood of old trees.

Dendrochronology is useful for determining the precise age of wood samples, especially those that are too recent for radiocarbon dating, which always produces a range rather than an exact date. However, for a precise date of the death of the tree a full sample to the edge is needed, which most trimmed timber will not provide.

It also gives data on the timing of events and rates of change in the environment (most prominently climate) and also in wood found in archaeology or works of art and architecture, such as old panel paintings.

It is also used as a check-in radiocarbon dating <u>to calibrate radiocarbon ages</u>.

Horizontal cross sections cut through the trunk of a tree can reveal growth rings, also referred to as tree rings or annual rings.

A tree's growth rate changes in a predictable pattern throughout the year in response to seasonal climate changes, resulting in visible growth rings.

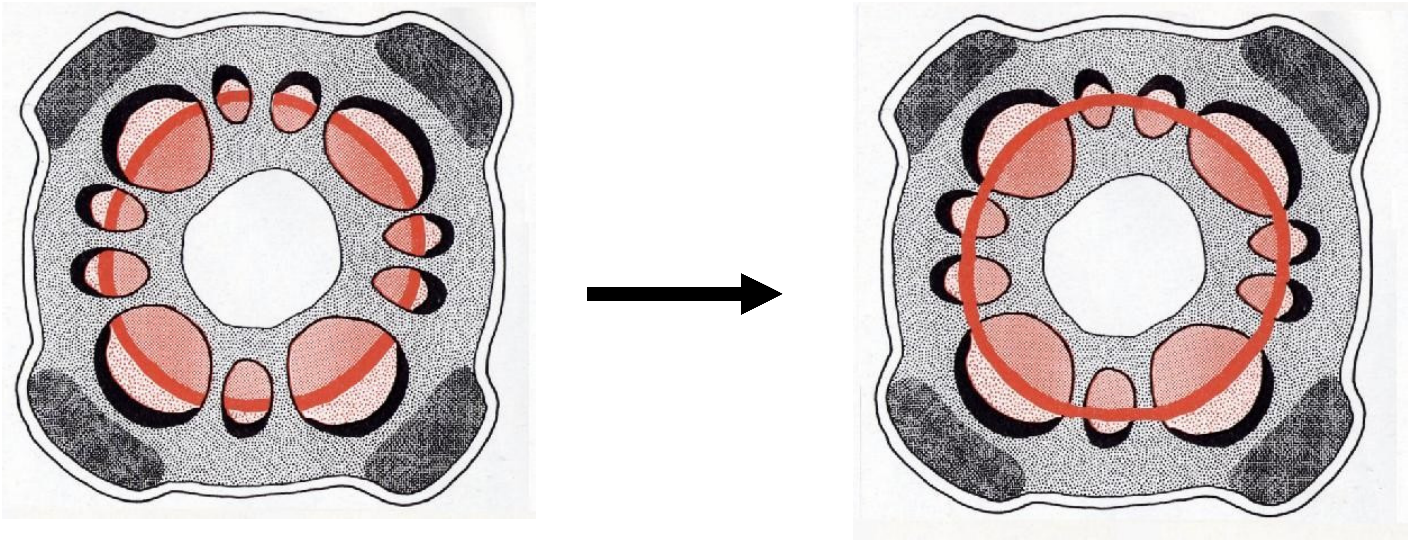
Each ring should mark a complete cycle of seasons, or one year, in the tree's life.

Growth rings result from new growth in the cambium, a layer of cells near the bark that botanists classify as a lateral meristem; this growth in diameter is known as secondary growth.

Visible rings result from the change in growth speed through the seasons of the year; thus, critical for the title method, one ring generally marks the passage of one year in the life of the tree.
Removal of the bark of the tree in a particular area may cause deformation of the rings as the plant overgrows the scar.

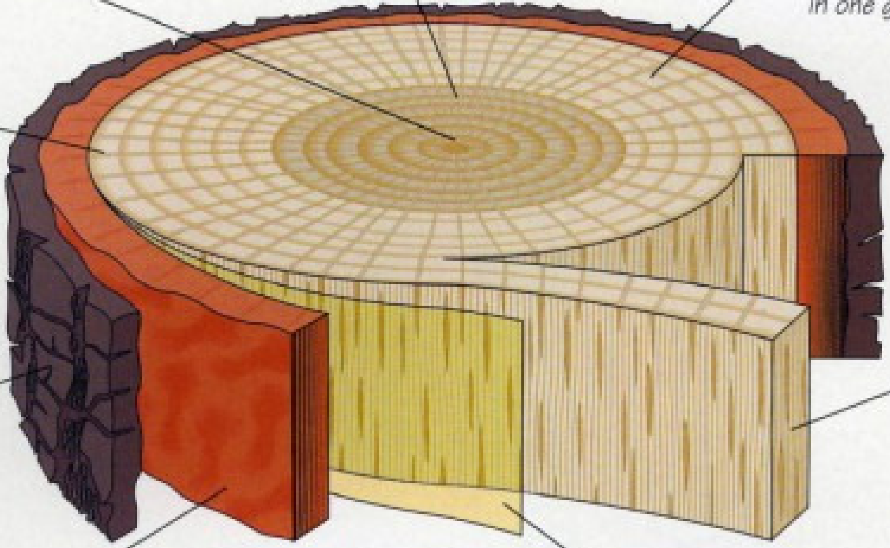
Primary structure → Secondary structure

(woody Dicots and woody Gymnosperm)



🟧 Meristematic tissue

Cribrovascular cambium



Pith
A small and often pulpy core running up the center of the trunk

Heartwood
Sapwood that has been clogged with resins, gums and other extractives; supports tree

Growth ring
A concentric ring divided into earlywood and latewood indicating the amount of wood added to a tree's diameter in one growing season

Ray
Carries nutrients laterally through the wood; also stores nutrients

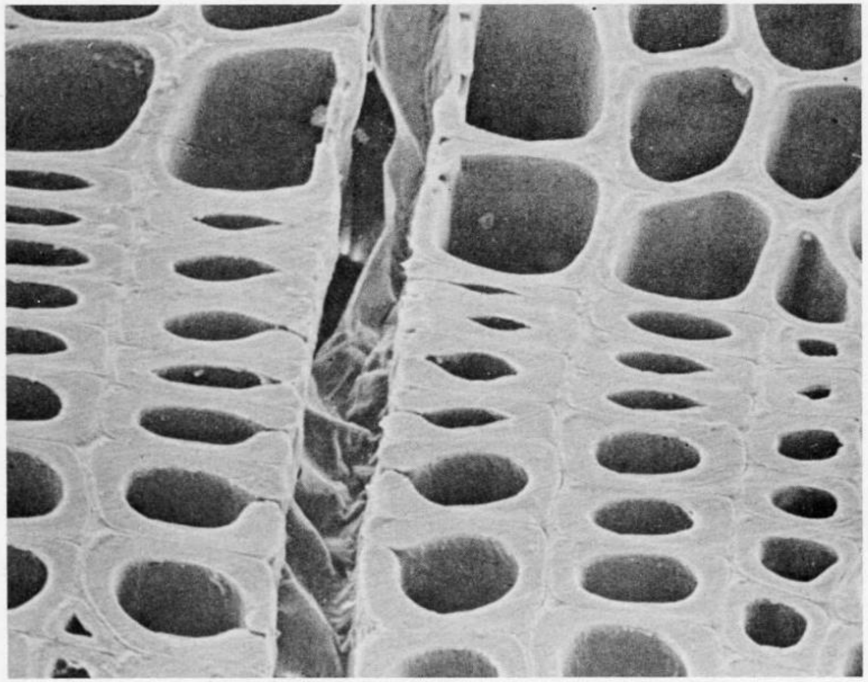
Bark
Insulates tree against temperature extremes; keeps sapwood and phloem from drying out

Sapwood
Active part of the tree's wood through which water and minerals are conducted from the roots to the leaves; also stores nutrients and helps to support the tree

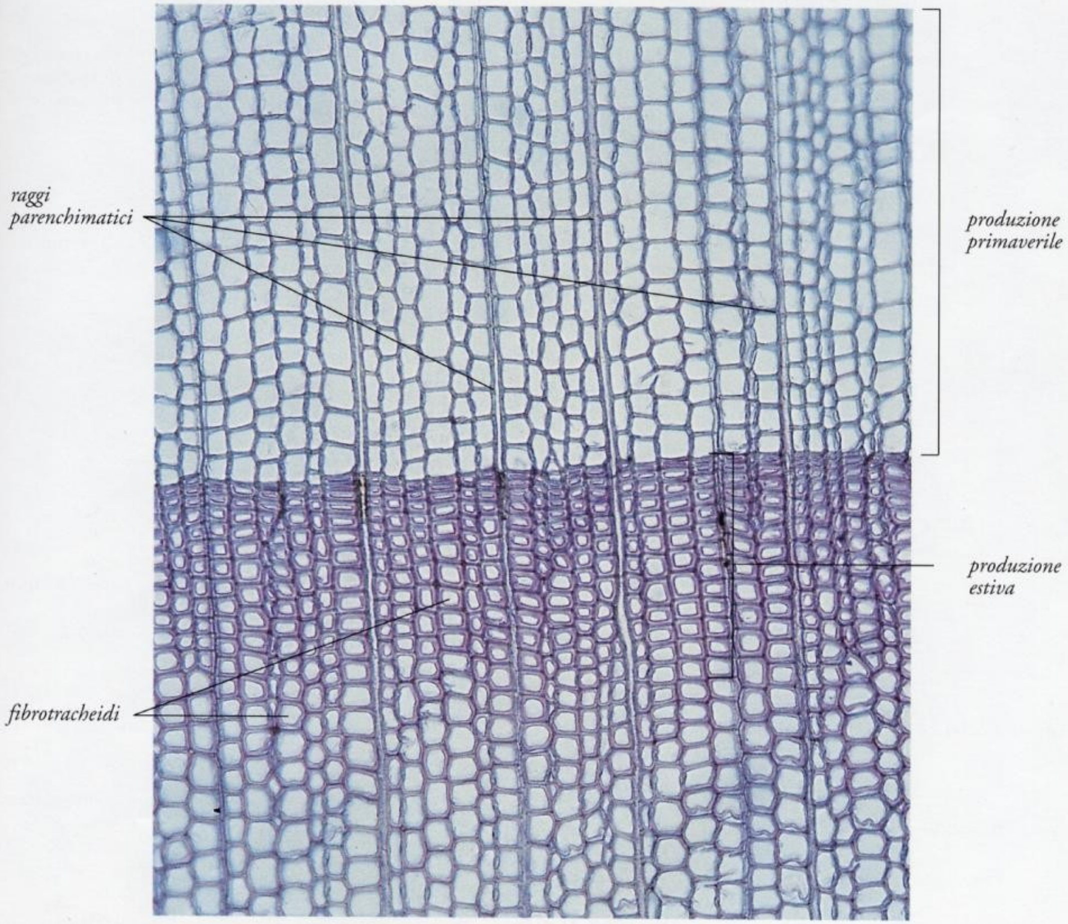
Phloem
A thin, spongy layer of tubes that carry dissolved sugars and growth hormones from the leaves to other parts of a tree

Cambium
A thin reproductive layer that forms new tissue, adding to the phloem and sapwood to increase a tree's girth

The inner portion of a growth ring forms early in the growing season, when growth is comparatively rapid (hence the wood is less dense) and is known as "early wood" (or "spring wood", or "late-spring wood"), typically with vessels of large diameter, because water transport must be high; the outer portion is the "late wood" (sometimes termed "summer wood", often being produced in the summer, though sometimes in the autumn) and is denser, with vessels of smaller diameter, and higher frequency of fibers (in heteroxyl wood only) ; also vessel walls are typically thicker.



Limite tra due anelli di crescita nel legno di una gimnosperma (pino) visto a forte ingrandimento al microscopio a scansione. In alto, legno primaverile formato da fibrotracheidi a lume largo con funzione prevalentemente di conduzione; in basso, legno estivo dell'anello di crescita precedente formato da fibrotracheidi a lume più stretto e parete più grossa con funzione prevalentemente di sostegno. Si vedono le lamelle mediane che cementano insieme le cellule. Il canale al centro è un raggio midollare.
(Da B.A. Meylan and B.G. Butterfield, «Three-dimensional structure of wood», Chapman & Hall, fig. 38 a pag. 50).



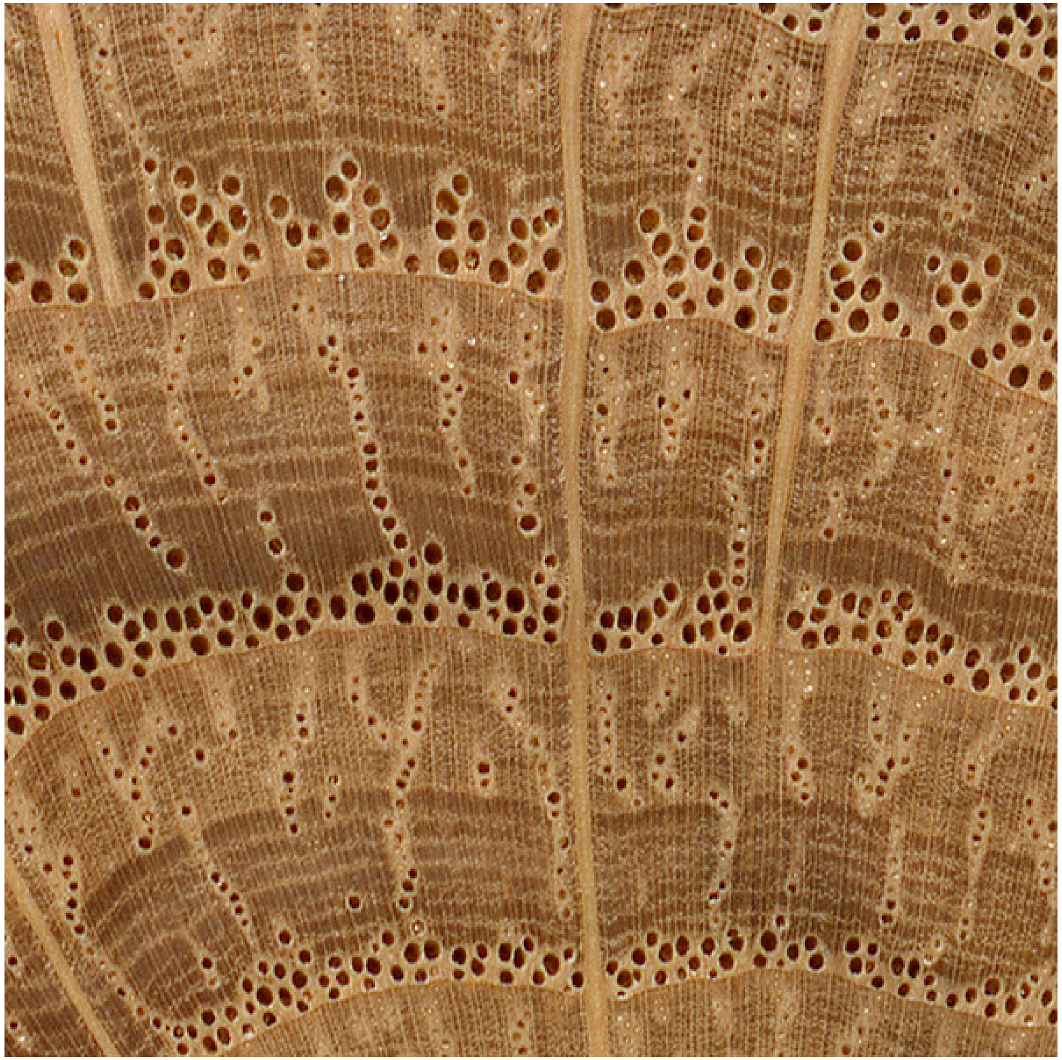
Legno di abete bianco (*Abies alba* Mill., fam. Pinaceae).
Sezione trasversale. x 100 (*120*)
Il taglio trasversale consente di osservare la dimensione minore (il lume) delle fibrotracheidi, e il decorso dei raggi, che mostrano la loro lunghezza e spessore. I vasi della produzione primaverile hanno lume più ampio e parete meno ispessita; quelli della produzione estiva hanno lume ridotto e parete di spessore accentuato.

Spring wood, year 2

Winter pause

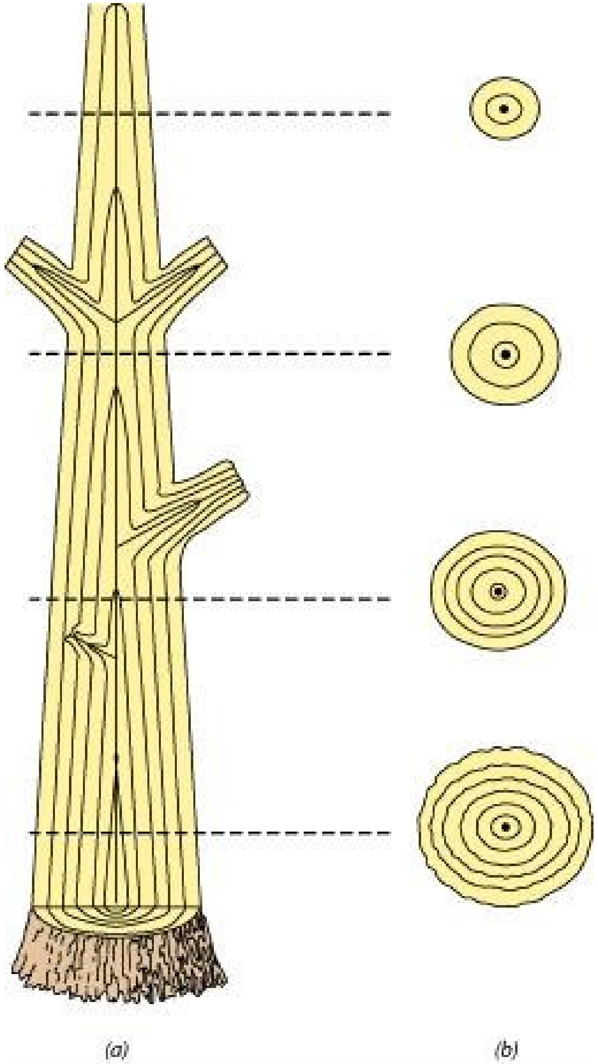
Summer wood

Spring wood, year 1

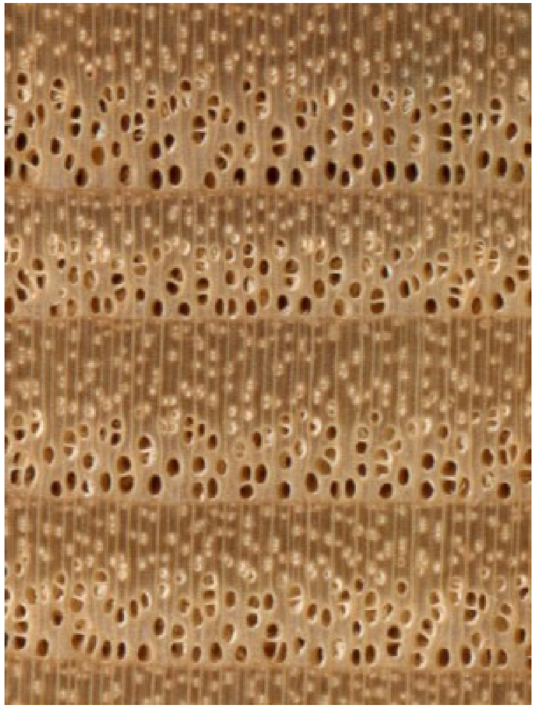


Trees and lignified herbs produce one growth-ring each year, with the newest adjacent to the bark.

Hence, for the entire period of a tree's life, a year-by-year record or ring pattern builds up that reflects the age of the tree and the climatic conditions in which the tree grew.

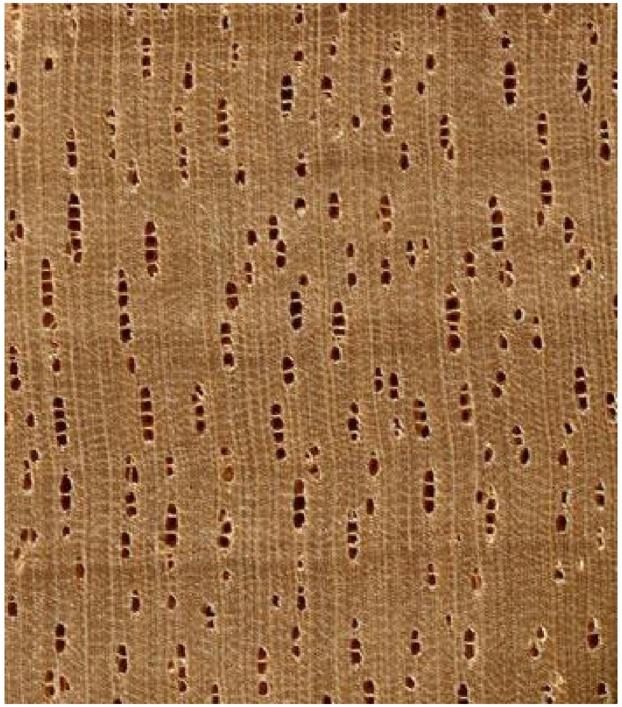


The rings are more visible in trees which have grown in **temperate zones**, where the seasons differ more markedly. Trees from the equatorial areas have a more uniform radial growth, and annual rings are difficult to distinguish. Most tree species from those areas maintain a uniform growth also when planted at our latitudes (e.g. *Citrus* trees).



Ash, *Fraxinus excelsior,*
Germany

Blue gum, *Eucalyptus globosus*,
Australia



Jelutong, *Dyera costulata,*
Malaysia

HISTORY

- The Greek botanist Theophrastus (c. 371 – c. 287 BC) first mentioned that the wood of trees has rings.

- In his *Trattato della Pittura* (Treatise on Painting), **Leonardo da Vinci** (1452–1519) was the first person to mention that trees form rings annually and that their thickness is determined by the conditions under which they grew: *«Li circuli delli rami degli alberi segati mostrano il numero delli suoi anni, e quali furono più umidi o più secchi la maggiore o minore loro grossezza.»*
  Please note that the French writer Michel de Montaigne, who in 1581 was touring Italy, encountered a carpenter who explained that trees form a new ring each year.

- In 1737, French investigators Henri-Louis Duhamel **du Monceau** and Georges-Louis Leclerc **de Buffon** examined the effect of growing conditions on the shape of tree rings. They found that in 1709, a severe winter produced a distinctly dark tree ring, which served as a reference for subsequent European naturalists.

- in 1833 Alexander Catlin **Twining** (1801–1884) suggested that patterns among tree rings could be used to synchronize the dendrochronology of various trees and thereby to reconstruct past climates across entire regions.

- The English polymath Charles **Babbage** proposed using dendrochronology to date the remains of trees in peat bogs or even in geological strata (**1835, 1838**).

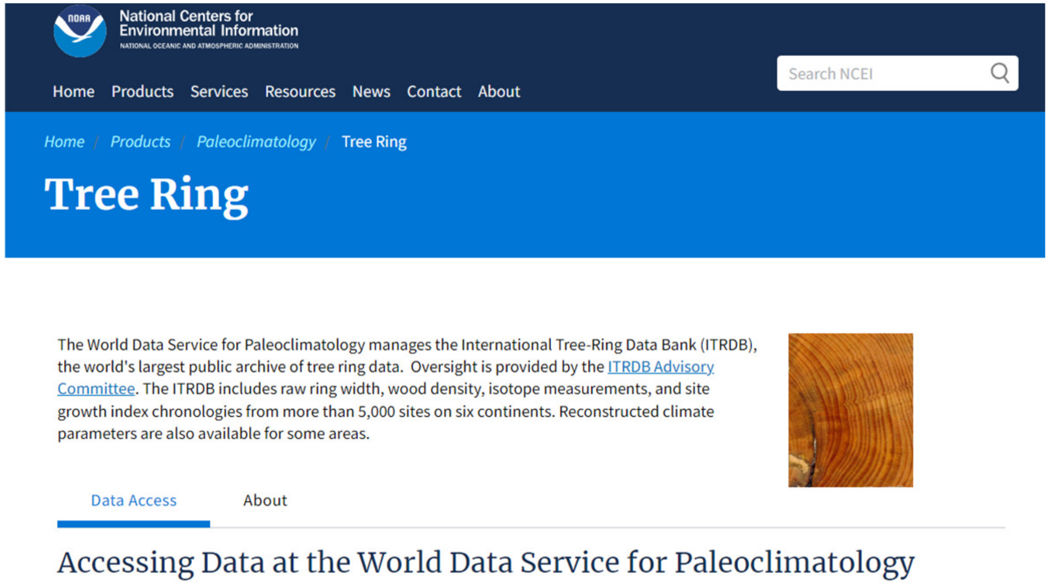
During the latter half of the nineteenth century, the scientific study of tree rings and the application of dendrochronology exploded.

- In **1859**, the German-American Jacob Kuechler (1823–1893) used crossdating to examine oaks (*Quercus stellata*) in order to study the record of climate in western Texas.
- In **1866**, the German botanist, entomologist, and forester Julius Theodor Christian Ratzeburg (1801–1871) observed the effects on tree rings of defoliation caused by insect infestations.
- By **1882**, this observation was already appearing in forestry textbooks.
- In **the 1870s**, the Dutch astronomer Jacobus Kapteyn (1851–1922) was using crossdating to reconstruct the climates of the Netherlands and Germany.
- In **1881**, the Swiss-Austrian forester Arthur von Seckendorff-Gudent (1845–1886) was using crossdating.
- **From 1869 to 1901**, Robert Hartig (1839–1901), a German professor of forest pathology, wrote a series of papers on the anatomy and ecology of tree rings.
- In **1892**, the Russian physicist Fedor Nikiforovich Shvedov (Фёдор Никифорович Шведов; 1841–1905) wrote that he had used patterns found in tree rings to predict droughts in 1882 and 1891.
- During the first half of the twentieth century, the astronomer A. E. Douglass founded the **Laboratory of Tree-Ring Research** at the University of Arizona. Douglass sought to better understand cycles of sunspot activity and reasoned that changes in solar activity would affect climate patterns on earth, which would subsequently be recorded by tree-ring growth patterns (i.e., sunspots → climate → tree rings).

Following the First International Workshop on Dendrochronology, in **1974 Hal Fritts** through the Laboratory of Tree-Ring Research at the University of Arizona, with a grant from the US National Science Foundation, established the ITRDB, the **International Tree-Ring Data Bank.** ITRDB is a data repository for tree ring measurements that has been maintained **since 1990** by the United States' National Oceanic and Atmospheric Administration Paleoclimatology Program and World Data Center for Paleoclimatology.

The ITRDB accepts all tree ring data with sufficient metadata to be uploaded, but its founding focus was on tree ring measurements intended for climatic studies.

Specific information is required for uploading data to the database, such as the raw tree ring measurements, an indication of the type of measurement (full ring widths, earlywood, latewood), and the location. However, the types of data and the rules for accuracy and precision of the primary data, tree-ring width measurements, are decided by the dendrochronologists who are contributing the data, rather than by NOAA or any other governing organization.



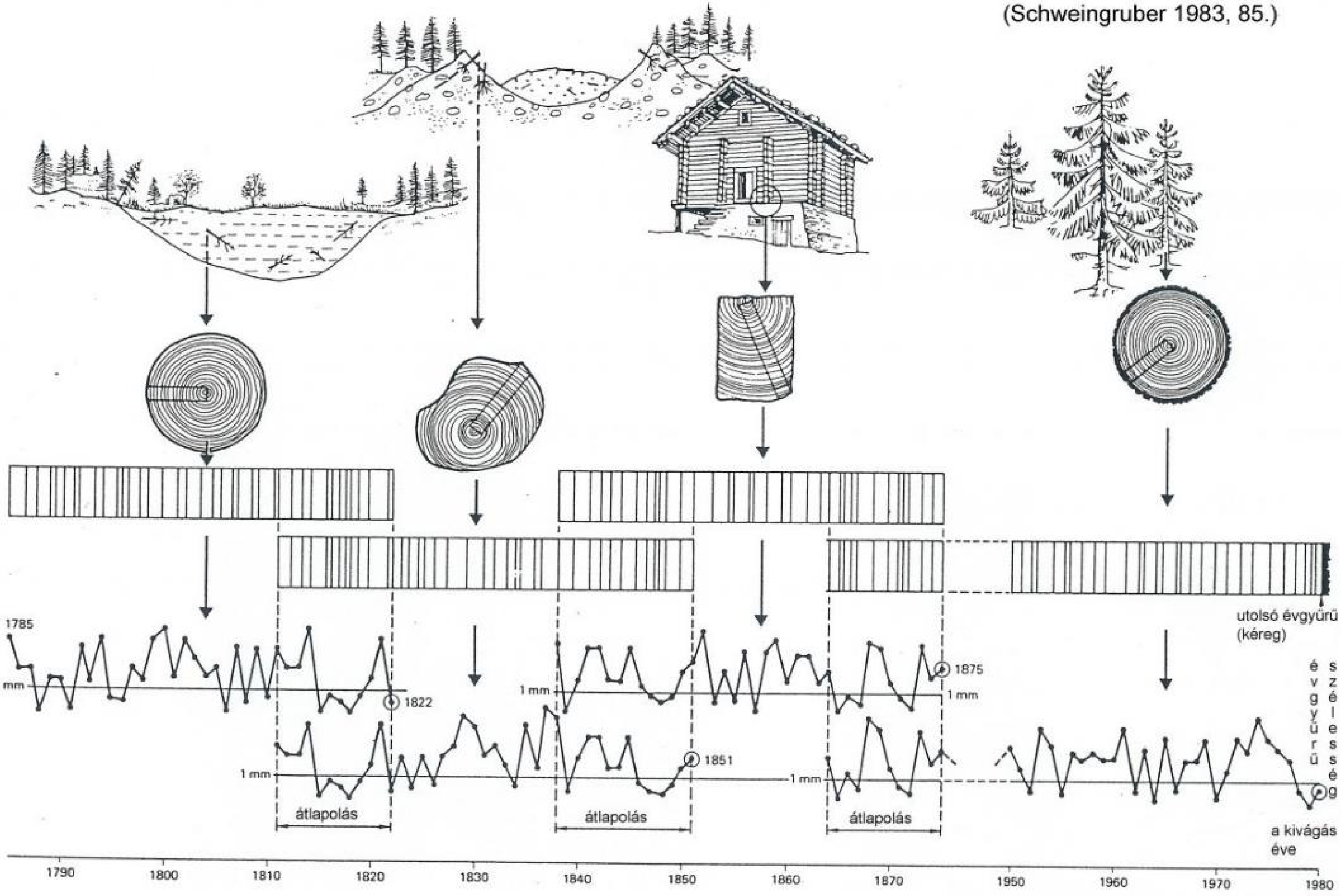
Tree Ring

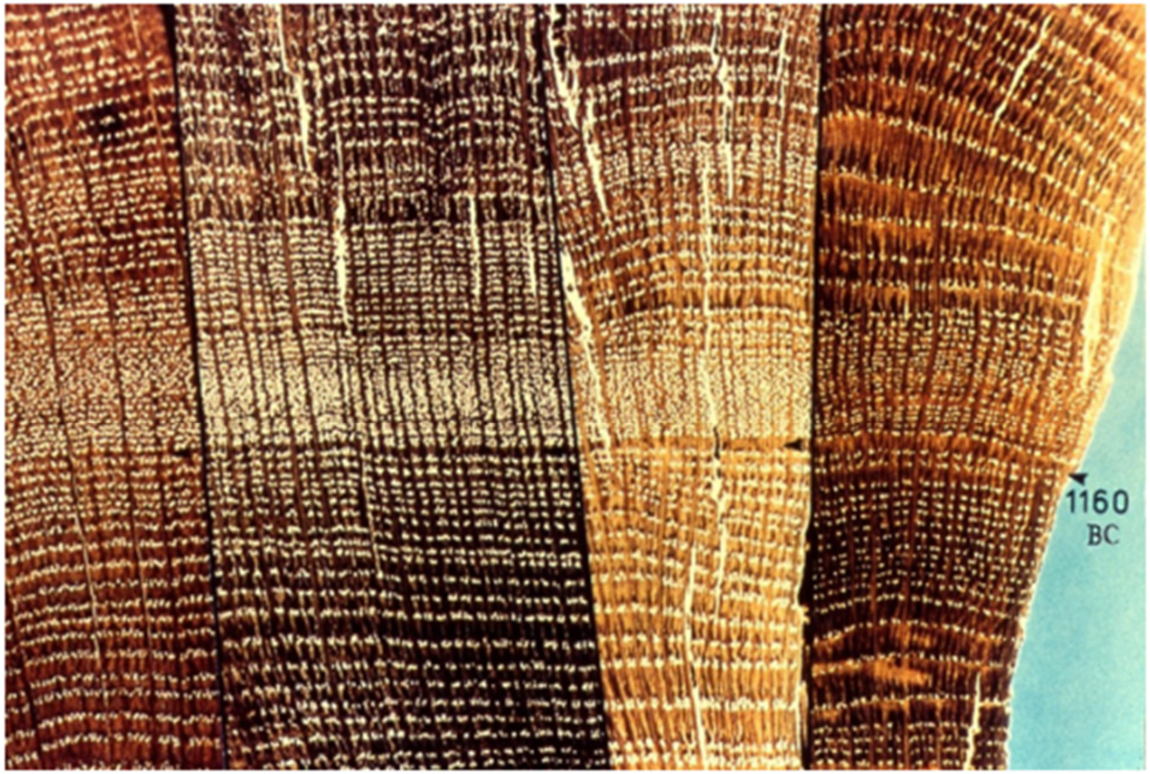
The World Data Service for Paleoclimatology manages the International Tree-Ring Data Bank (ITRDB), the world's largest public archive of tree ring data. Oversight is provided by the ITRDB Advisory Committee. The ITRDB includes raw ring width, wood density, isotope measurements, and site growth index chronologies from more than 5,000 sites on six continents. Reconstructed climate parameters are also available for some areas.

Accessing Data at the World Data Service for Paleoclimatology

Sample collection

Tree rings must be obtained from nature, frequently from
remote regions.
Generally, tree rings are collected using a hand-held borer device, that
requires skill to get a good sample (figs. 1,2), consisting in a rod that
not always intercepts the center of the trunk.
Indeed, the best samples come from felling a tree and sectioning it (fig. 3).
However, this requires more danger and does damage to the forest. It may not
be allowed in certain areas, particularly with the oldest trees in undisturbed sites
(which are the most interesting scientifically).


(Schweingruber 1983, 85.)

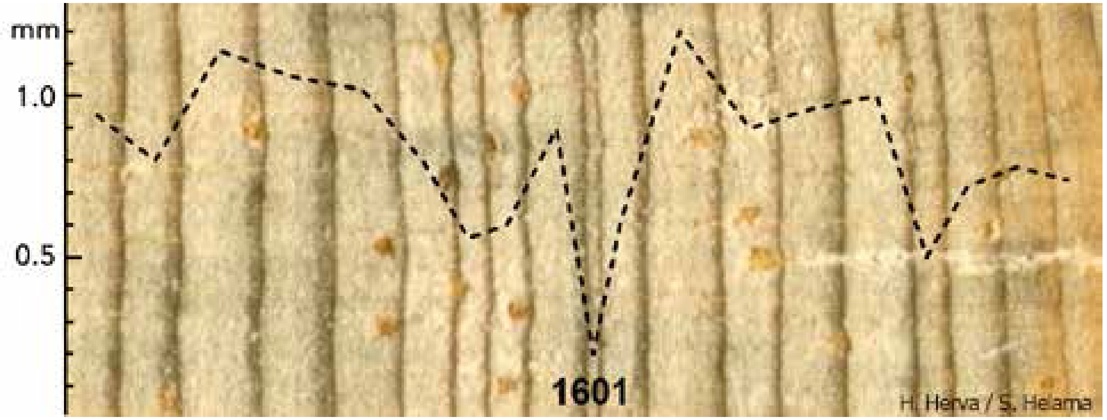


4 Irish bog oaks from different sites

Belfast Laboratory Dendro Dataset
Most of the tree-ring data in this dataset is Irish oak material; these can be bog oak, archaeological and building samples and modern material. There are also bog pine samples from Ireland as well as sundry samples used in Irish houses that are from Britain or the European mainland and America. The dataset also contains a large number of bog oak samples from England that make up the English prehistoric chronology.

Direct reading of tree ring chronologies is a complex science, for several reasons. First, contrary to the single-ring-per-year paradigm, alternating poor and favorable conditions, such as mid-summer droughts, can result in several rings forming in a given year.
In addition, particular tree species may present "missing rings", and this influences the selection of trees for study of long time-spans. For instance, missing rings are rare in oak (*Quercus*) and elm (*Ulmus*) trees, whereas missing rings and additional rings are frequent in poplar (*Populus*) trees.

As a first approximation, adequate moisture and a long growing season result in a wide ring, while a year characterized by drought or low temperatures may result in a very narrow one.



The dendrochronological equation defines the law of growth of tree rings. The equation was proposed by Russian biophysicist Alexandr N. Tetearing in his work "Theory of populations" in the form:

$$\Delta L(t) = \frac{1}{k_v\, \rho^{\frac{1}{3}}} \frac{d\left(M^{\frac{1}{3}}(t)\right)}{dt}$$

where ΔL is width of annual ring, t is time (in years), ρ is density of wood, k_v is some coefficient, $M(t)$ is function of mass growth of the tree.

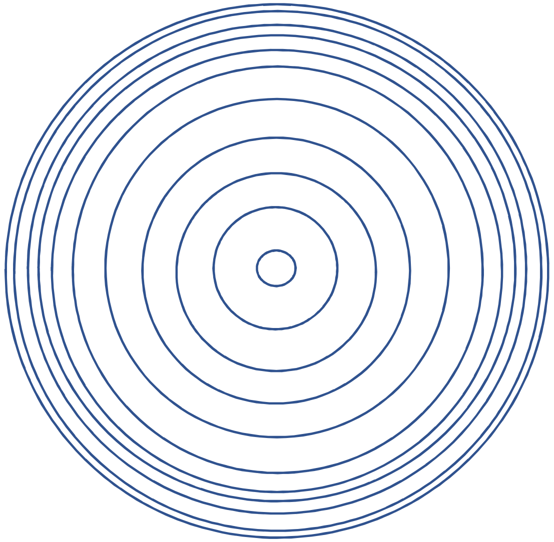
Ignoring the natural sinusoidal oscillations in tree mass, the formula for the changes in the annual ring width is:

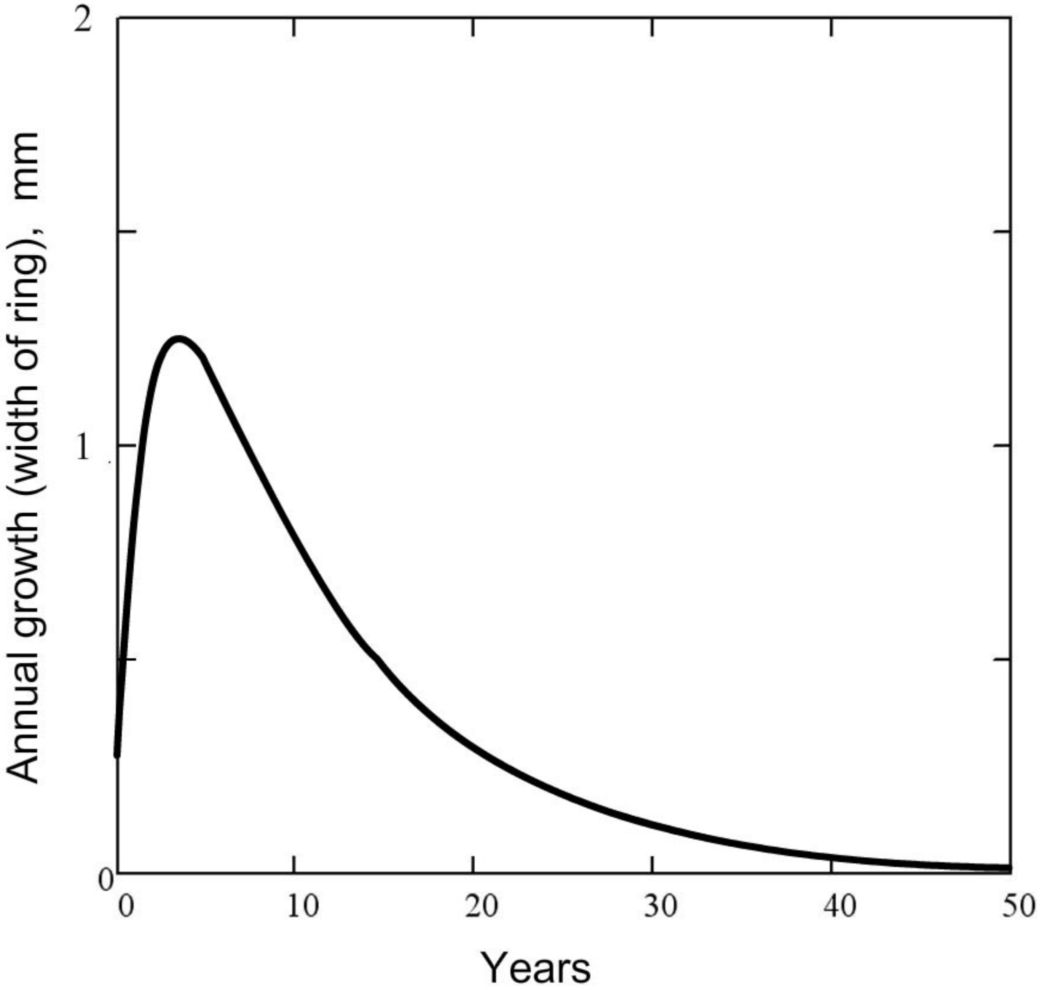
$$\Delta L(t) = -\frac{c_1 e^{-a_1 t} + c_2 e^{-a_2 t}}{3 k_v \rho^{\frac{1}{3}} \left(c_4 + c_1 e^{-a_1 t} + c_2 e^{-a_2 t}\right)^{\frac{2}{3}}}$$

where c1, c2, and c4 are some coefficients, a1 and a2 are positive constants.
The formula is useful for correct approximation of samples data before data normalization procedure.

The typical forms of the function ΔL(t) of annual growth of wood ring are shown in the figure (right).

In accordance with the dendrochronological equation, there is an increase in the width of wood ring at initial stage, then a constant decrease with the tree aging.

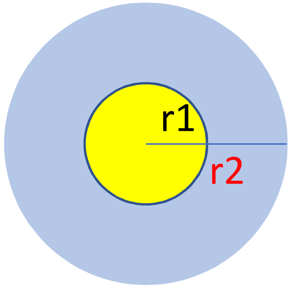


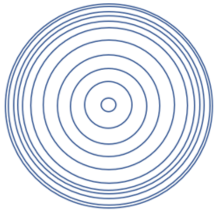


The variation in growth depends by many factor, internal and external.

Among the internal ones:

- Geometry
- Age of the plant: in the first growth phase, energies are concentrated in buiding up the body of the plant, in order to win the competition for space/light/nutrients; the functions of water transport and support prevail; later on, the adult plant will devote most of its net income in producing seeds; when senescent, new wood growth is at its minimum, and only water transport is needed, support being assured by the dead wood mass.
- Wood type (hard/soft wood)
- wood density





Crown area= $\pi(r2^2-r1^2)$

r2	r1	delta	area (*pi greco)	
3,5	3	0,5	3,25	
15,5	15	0,5	15,25	
30,5	30	0,5	30,25	

Among the external ones (Memento: growth depends directly on the net income of photosynthesis)

- Water availability
- Temperature regimes (mean, minimum and maximum temperatures)
- Defoliation by animals (e.g. carterpillers, fungi, mammals etc.)
- Defoliation by wind, hail etc.

Critical to the science, trees from the same region tend to develop the same patterns of ring widths for a given period of chronological study. Researchers can compare and match these patterns ring-for-ring with patterns from trees which have grown at the same time in the same geographical zone (and therefore under similar climatic conditions). When one can match these tree-ring patterns across successive trees in the same locale, in overlapping fashion, chronologies can be built up—both for entire geographical regions and for sub-regions.

Moreover, wood from ancient structures with known chronologies can be matched to the tree-ring data (a technique called **cross-dating**), and the age of the wood can thereby be determined precisely.

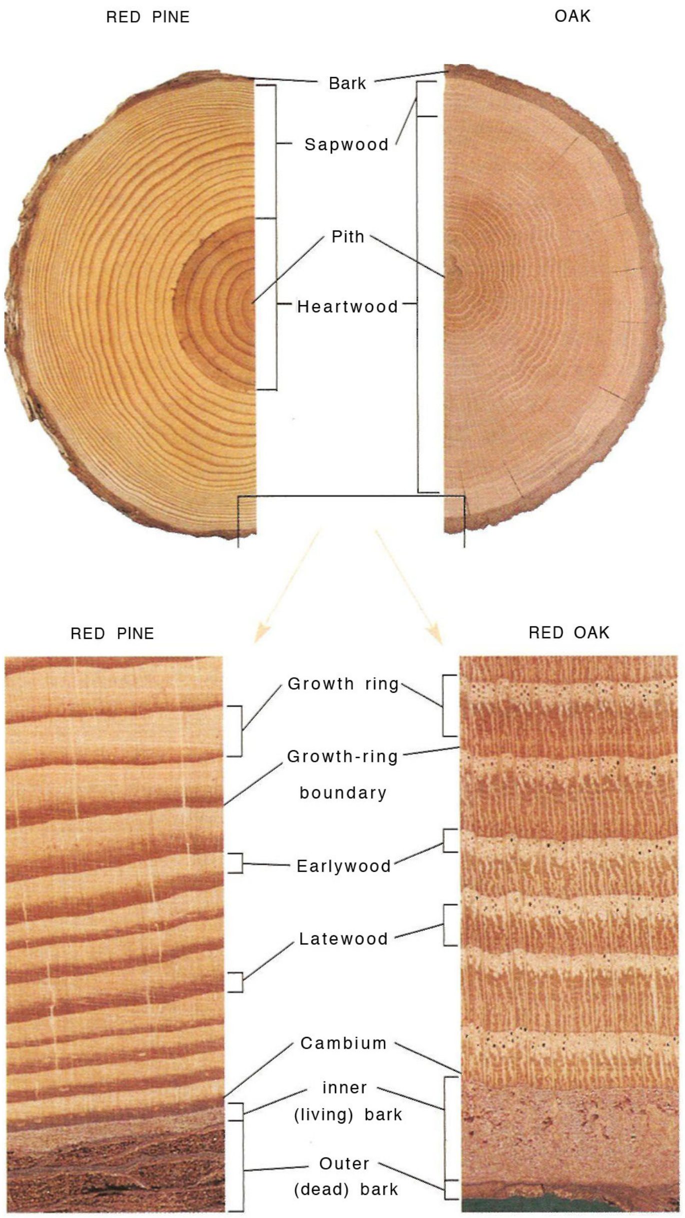
Dendrochronologists originally carried out cross-dating by visual inspection; more recently, they have harnessed computers to do the task, applying statistical techniques to assess the matching.

To eliminate individual variations in tree-ring growth, dendrochronologists take the smoothed average of the tree-ring widths of multiple tree-samples to build up a ring history, a process termed replication.

A tree-ring history whose beginning- and end-dates are not known is called a **floating chronology**. It can be anchored by cross-matching a section against another chronology (tree-ring history) whose dates are known.

As of 2020, securely dated tree-ring data for the Northern Hemisphere are available going back **13,910 years**.

A fully anchored and cross-matched chronology **for pine and oak in central Europe** extends back **12,460 years**.



An **oak chronology** goes back **7,429 years in Ireland and 6,939 years in England**.
Comparison of radiocarbon and dendrochronological ages supports the consistency of these two independent dendrochronological sequences.

N.B. - European chronologies derived from wooden structures initially found it difficult to bridge the gap in the fourteenth century when there was a building hiatus, which coincided with the Black Death.

Another fully anchored chronology that extends back **8,500 years** exists **for the bristlecone pine in the Southwest US** (White Mountains of California)

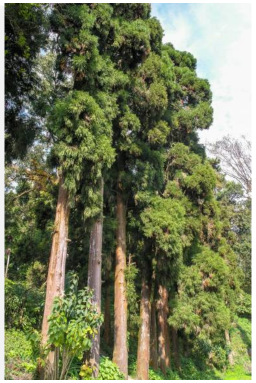
The term bristlecone pine covers three species of pine tree (family Pinaceae, genus *Pinus*, subsection Balfourianae: *P. aristata, P. balfouriana*, and *P. longaeva*). All three species are long-lived and highly resilient to harsh weather and bad soils. One of the three species, *P. longaeva*, is among the longest-lived life forms on Earth. The oldest of this species is **Methuselah**, which has a verified age of **4,855 years**, making it the oldest known individual of any plant species; located in the Inyo National Forest in Eastern California (but specific location is a closely guarded secret).

Dendrochronology allows specimens of once-living material to be accurately dated to a specific year.
Dates are often represented as estimated calendar years B.P., for before present, where "present" refers conventionally to **1 January 1950**.

Timber core samples are sampled and used to measure the width of annual growth rings; by taking samples from different sites within a particular region, researchers can build a comprehensive historical sequence.

The techniques of dendrochronology are more consistent in areas where trees grew in marginal conditions such as aridity or semi-aridity where the ring growth is more sensitive to the environment, rather than in humid areas where tree-ring growth is more uniform (complacent). In addition, some genera of trees are more suitable than others for this type of analysis.

A **Miyake event** is an observed sharp enhancement of the production of cosmogenic isotopes by cosmic rays. It can be marked by a spike in the concentration of radioactive carbon isotope ^{14}C in tree rings, ^{10}Be and ^{36}Cl in ice cores, which are all independently dated.
At present, five events are known (7176 BCE, 5259 BCE, 660 BCE, 774 CE, 993 CE). They were first identified by the Japanese physicist Fusa Miyake (as a doctoral student!) when dating Japanese cedars (*Cryptomeria japonica*) tree samples.



Isotopic time markers

A relatively new method is based on measuring variations in oxygen isotopes in each ring, and this 'isotope dendrochronology' can yield results on samples which are not suitable for traditional dendrochronology due to too few or too similar rings. But from the ‘50s Dendrochronology is strictly associated to Carbon isotopic measurements. Actually, **the most recent part of IntCal20 (the "Radiocarbon Age Calibration Curve"**, which provides a calibrated carbon 14 dated sequence going back 55,000 years) **is based on tree rings: It goes back 13,900 years!**

Fixed reference points are due to cosmic radiation. They are known as **Miyake events**, such as the ones in 774 and 993. They appear as spikes in carbon 14 in tree rings for that year all round the world, and therefore they can be used to date historical events to the year.

For example, wooden houses in the Viking site at L'Anse aux Meadows in Newfoundland were dated by finding the growth ring with the 993 spike, which showed that the wood is from a tree felled in 1021.

Frost rings

Frost ring is a term used to designate a layer of deformed, collapsed tracheids and traumatic parenchyma cells in tree ring analysis. They are formed when air temperature falls below freezing during a period of cambial activity. They can be used in dendrochronology to indicate years that are colder than usual.

Art history

Dendrochronology has become important to art historians in the dating of panel paintings. However, unlike analysis of samples from buildings, which are typically sent to a laboratory, wooden supports for paintings usually have to be measured in a museum conservation department, which places limitations on the techniques that can be used.

In addition to dating, dendrochronology can also provide information as to the source of the panel.

Many Early Netherlandish paintings have turned out to be painted on panels of "Baltic oak" shipped from the Vistula region via ports of the Hanseatic League. Oak panels were used in a number of northern countries such as England, France and Germany. Wooden supports other than oak were rarely used by Netherlandish painters. Since panels of seasoned wood were used, an uncertain number of years has to be allowed for seasoning when estimating dates.
Panels were trimmed of the outer rings, and often each panel only uses a small part of the radius of the trunk. Consequently, dating studies usually result in a "**terminus post quem**" (earliest possible) date, and a tentative date for the arrival of a seasoned raw panel using assumptions as to these factors.

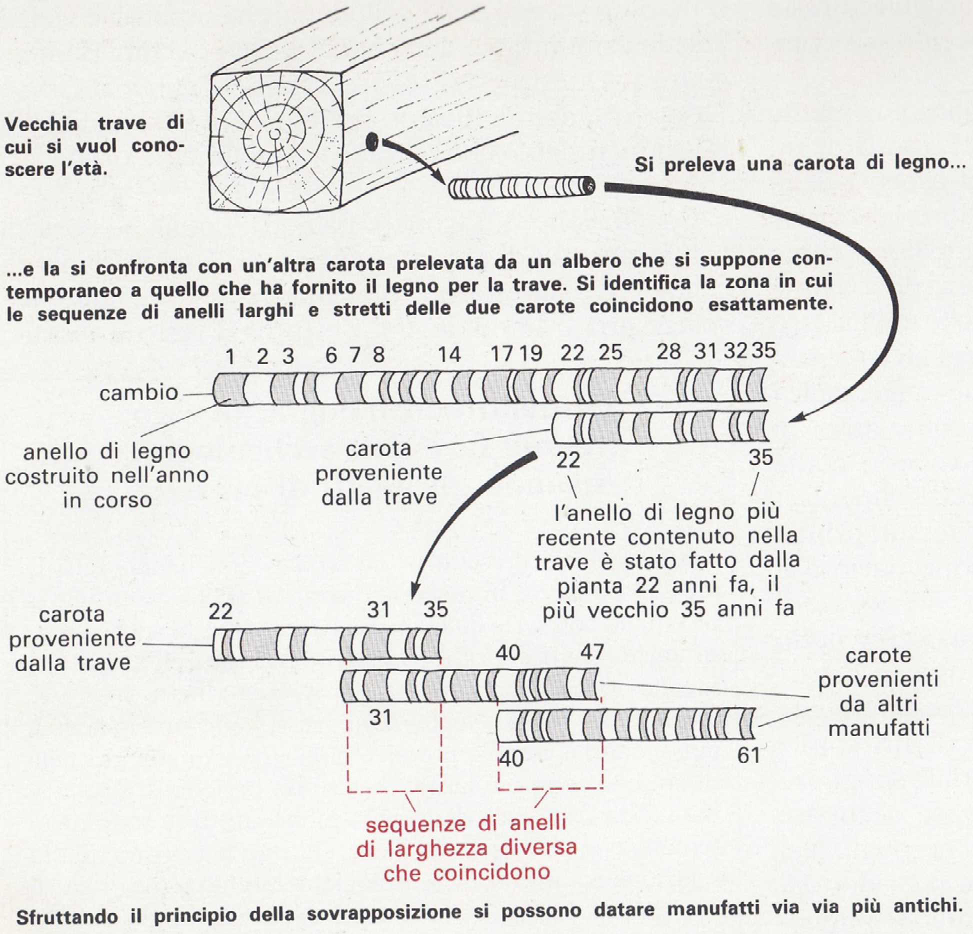
As a result of establishing numerous sequences, it was possible to date 85–90% of the 250 paintings from the fourteenth to seventeenth century analysed between 1971 and 1982; by now a much greater number have been analysed.

A portrait of Mary, Queen of Scots in the National Portrait Gallery, London (left) was believed to be an eighteenth-century copy. However, dendrochronology revealed that the wood dated from the second half of the sixteenth century. It is now regarded as an original sixteenth-century painting by an unknown artist.

On the other hand, dendrochronology was applied to four paintings depicting the same subject, that of Christ expelling the money-lenders from the Temple (right). The results showed that the age of the wood was too late for any of them to have been painted by **Hieronymus Bosch**, the putative author.

While dendrochronology has become an important tool for dating oak panels, it is not effective in dating the poplar panels often used by Italian painters because of the erratic growth rings in poplar (see above).

The dating of buildings with wooden structures and components is also done by dendrochronology; dendroarchaeology is the term for the application of dendrochronology in archaeology.



...e la si confronta con un'altra carota prelevata da un albero che si suppone contemporaneo a quello che ha fornito il legno per la trave. Si identifica la zona in cui le sequenze di anelli larghi e stretti delle due carote coincidono esattamente.

l'anello di legno più recente contenuto nella trave è stato fatto dalla pianta 22 anni fa, il più vecchio 35 anni fa

sequenze di anelli di larghezza diversa che coincidono

Sfruttando il principio della sovrapposizione si possono datare manufatti via via più antichi.

FIG. 9.46 • Il metodo dendrocronologico per la datazione di manufatti in legno. Esso si basa sul fatto che la sequenza di anelli di crescita larghi e stretti è identica per tutti gli alberi vissuti in una certa zona e in un determinato periodo. Nella figura (che è un esempio immaginario) ho fortemente ridotto per motivi di spazio le età a cui si può risalire con questo metodo.

Arched Attic of an old church with domed ceiling from the 16th century in the Netherlands

While archaeologists can date wood and when it was felled, it may be difficult to definitively determine the age of a building or structure in which the wood was used; the wood could have been reused from an older structure, may have been felled and left for many years before use, or could have been used to replace a damaged piece of wood. The dating of building via dendrochronology thus requires knowledge of the history of building technology.

Many prehistoric forms of buildings used "posts" that were whole young tree trunks; where the bottom of the post has survived in the ground these can be especially useful for dating.

Examples:

- The Post Track and Sweet Track, ancient timber trackways in the Somerset levels, England, have been dated to 3838 BC and 3807 BC.
- Navan Fort where in Prehistoric Ireland a large structure was built with more than two hundred posts. The central oak post was felled in 95 BC.
- The Fairbanks House in Dedham, Massachusetts. While the house had long been claimed to have been built circa 1640 (and being the oldest wood-framed house in North America), core samples of wood taken from a summer beam confirmed the wood was from an oak tree felled in 1637–8, as wood was not seasoned before use in building at that time in New England. An additional sample from another beam yielded a date of 1641, thus confirming the house had been constructed starting in 1638 and finished sometime after 1641 .
- The burial chamber of Gorm the Old (first king of Denmark), who died c. 958, was constructed from wood of timbers felled in 958.

DENDROCLIMATOLOGY

Dendroclimatology is the science of determining past climates from trees (primarily properties of the annual tree rings).
Tree rings are wider when conditions favor growth, narrower when times are difficult (L. da Vinci: “*la maggiore o minore grossezza [del]li circuli delli rami degli alberi segati mostra […] quali [anni] furono più umidi o più secchi»)*.

Other properties of the annual rings, such as maximum latewood density (MXD) have been shown to be better proxies than simple ring width, but there are more difficult to measure.

Using tree rings, scientists have estimated many local climates for hundreds to thousands of years previous. By combining multiple tree-ring studies (sometimes with other climate proxy records), scientists have estimated past regional and global climates.

Tree rings respond to multiple climatic effects (temperature, moisture, cloudiness), so that various aspects of climate (not just temperature) can be studied. However, this can be a double-edged sword.

Limitations

Along with the advantages, there are some limitations. Among others:

- confounding factors
- geographic coverage
- annular resolution
- collection difficulties.

The field has developed various methods to partially adjust for these challenges.

Confounding factors

There are multiple climate and non-climate factors as well as nonlinear effects that impact tree ring width. Methods to isolate single factors (of interest) include botanical studies to calibrate growth influences and sampling of "limiting stands" (those expected to respond mostly to the variable of interest).

Climate factors

Climate factors that affect trees include **temperature, precipitation, sunlight, and wind**.
To differentiate among these factors, scientists collect information from **"limiting stands“.**
An example of a limiting stand is **the upper elevation treeline**: here, trees are expected to be more affected by temperature variation (which is "limited") than precipitation variation (which is in excess).
Conversely, lower elevation treelines are expected to be more affected by precipitation changes than temperature variation.
This is not a perfect work-around as multiple factors still impact trees even at the "limiting stand," but it helps. In theory, collection of samples from nearby limiting stands of different types (e.g. upper and lower treelines on the same mountain) should allow mathematical solution for multiple climate factors.

Non-climate factors

Non-climate factors include soil, tree age, fire, tree-to-tree competition, genetic differences, logging or other human disturbance, herbivore impact (particularly sheep grazing), pest outbreaks, disease, and CO_2 concentration.

For factors which vary randomly over space (tree to tree or stand to stand), the best solution is to collect sufficient data (more samples) to compensate for confounding noise. Tree age is corrected for with various statistical methods: either fitting spline curves to the overall tree record or using similar aged trees for comparison over different periods (regional curve standardization).

Careful examination and site selection helps to limit some confounding effects, for example picking sites undisturbed by modern man.

Non-linear effects

In general, climatologists assume a linear dependence of ring width on the variable of interest (e.g. moisture). However, if the variable changes enough, response may level off or even turn opposite. The home gardener knows that one can underwater or overwater a house plant: The same holds true for precipitations.
In addition, it is possible that interaction effects may occur (for example "temperature times precipitation" may affect growth as well as temperature and precipitation on their own.

Botanical inferences to correct for confounding factors

Botanical studies can help to estimate the impact of confounding variables and in some cases guide corrections for them.
These experiments may be either ones where growth variables are:

- all controlled (e.g. in a greenhouse or in a cabinet, top right);
- partially controlled (e.g. fre-air CO_2 Concentration Enhancement facility, right);
- monitored in nature.

In any case, the important thing is that multiple growth factors are carefully recorded to determine what impacts growth. With this information, ring width response can be more accurately understood and inferences from historic (unmonitored) tree rings become more certain. <u>In concept, this corresponds to a sort of calibration</u>.

Geographic coverage

Trees do not cover the Earth. Polar and marine climates cannot be estimated from tree rings. In perhumid tropical regions, Australia and southern Africa, trees generally grow all year round and don't show clear annual rings. In some forest areas, the tree growth is too much influenced by multiple factors (no "limiting stand") to allow clear climate reconstruction.

In areas without trees the coverage difficulty is dealt with by acknowledging it and by using other proxies (e.g. **ice cores, corals**).

In some cases it can be shown that the parameter of interest (temperature, precipitation, etc.) varies similarly from area to area, for example by looking at patterns in the instrumental record. Then one is justified in extending the dendroclimatology inferences to areas where no suitable tree ring samples are obtainable.

Annular resolution

In general, the ring width is used to infer the overall climate change during the corresponding year. This is clearly an approximation.

Climate changes deep in the dormant season (winter) will not be recorded. In addition, different times of the growing season may be more important than others for ring width (at our latitudes: May versus September, i.e the starting growth season vs. the late growth season).

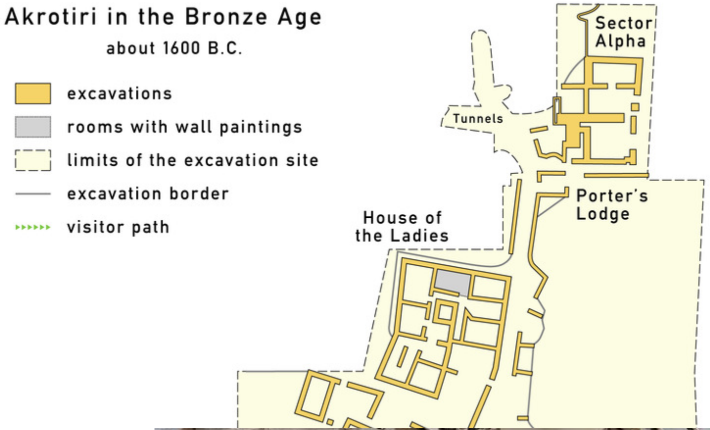
Another problem is "memory" or autocorrelation. A stressed tree may take a year or two to recover from a hard season, caused e.g. by defoliation by animals or a strong hail event. This problem can be dealt with by more complex modeling (a "lag" term in the regression) or by reducing the skill estimates of chronologies.

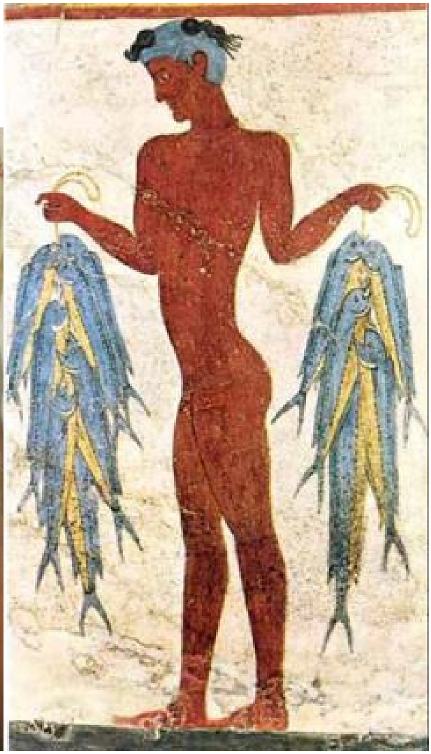
Collection difficulties

Tree rings must be obtained from nature, frequently from remote regions. This means that special efforts are needed to map sites properly. In addition, samples must be collected in difficult (often sloping terrain) conditions.

As with all experimentalists, dendroclimatologists must, at times, decide to make the best of imperfect data, rather than resample.

This tradeoff is made more difficult, because sample collection (in the field) and analysis (in the lab) may be separated significantly in time and space. These collection challenges mean that data gathering is not as simple or cheap as conventional laboratory science.


Akrotiri in the Bronze Age
about 1600 B.C.
excavations
rooms with wall paintings
limits of the excavation site
excavation border
visitor path
Sector Alpha
Tunnels
Porter's Lodge
House of the Ladies
Xeste 3
South Building



The Minoan eruption was a catastrophic volcanic eruption that devastated the Aegean island of Thera (also called Santorini) circa 1600 BCE, which was entombed in a layer of pumice. Hypotheses have been proposed based on archaeological evidence found on Crete indicating that a tsunami, likely associated with the eruption, impacted the coastal areas of Crete and may have devastated the Minoan coastal settlements. Another hypothesis is that much of the damage done to Minoan sites resulted from a large earthquake and the fires it caused, which preceded the Thera eruption.

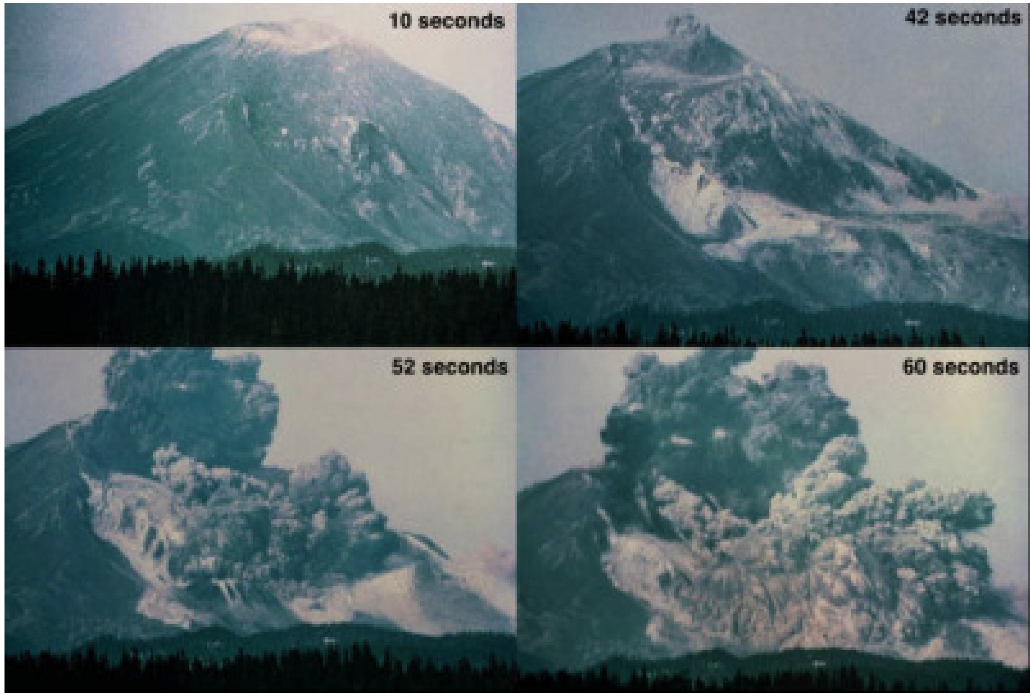
Some Minoan sites were abandoned or settlement systems significantly interrupted in the immediate aftermath of the eruption. Some archaeologists speculate that the eruption caused a crisis in Minoan Crete, opening it to Mycenaean influence or even conquest.

The impact of the eruption in terms of a civilization collapse is perhaps recalled inthe myths of the Titanomachy in Hesiod's Theogony, and in Plato's story of Atlantis (the latter view is not supported by current scholarship).

Phaistos Disc, side A (top), side B (bottom).

With a VEI magnitude of a 6, resulting in an ejection of approximately 28–41 km^3 (6.7–9.8 cu mi) of dense-rock equivalent (DRE), the eruption was one of the largest volcanic events in human history. Since tephra from the Minoan eruption serves as a marker horizon in nearly all archaeological sites in the Eastern Mediterranean, its precise date is of high importance and has been fiercely debated among archaeologists and volcanologists for decades.

This eruption is comparable with the Mount Tambora volcanic eruption of 1815, Mount Samalas eruption of 1257, Lake Taupo's Hatepe eruption around 230 CE, and the Paektu Mountain eruption of 946 CE, which are among the largest eruptions during the Common Era.



On Santorini, there is a 60 m (200 ft) thick layer of white tephra that overlies the soil clearly delineating the ground level before the eruption. This layer has three distinct bands that indicate the different phases of the eruption. Studies have identified four major eruption phases, and one minor precursory tephra fall. The thinness of the first ash layer, along with the lack of noticeable erosion of that layer by winter rains before the next layer was deposited, indicate that the volcano gave the local population a few months' warning. Since no human remains have been found at the Akrotiri site, this preliminary volcanic activity probably caused the island's population to flee. It is also suggested that several months before the eruption, Santorini experienced one or more earthquakes, which damaged the local settlements

The eruption was of the **Ultra Plinian type**, and it resulted in an estimated 30 to 35 km (19 to 22 mi) high eruption column which reached the stratosphere. In addition, the magma underlying the volcano came into contact with the shallow marine embayment, resulting in violent phreatomagmatic blasts.

The eruption also generated **35 to 150 m high tsunamis** that devastated the northern coastline of Crete, 110 km away. The tsunami affected coastal towns such as Amnisos, where building walls were knocked out of alignment. On the island of Anafi, 27 km to the east, ash layers 3 m deep have been found, as well as pumice layers on slopes 250 m above sea level.

Elsewhere in the Mediterranean are pumice deposits that could have been sent by the Thera eruption. Ash layers in cores drilled from the seabed and from lakes in Turkey show that the heaviest ashfall was towards the east and northeast of Santorini.

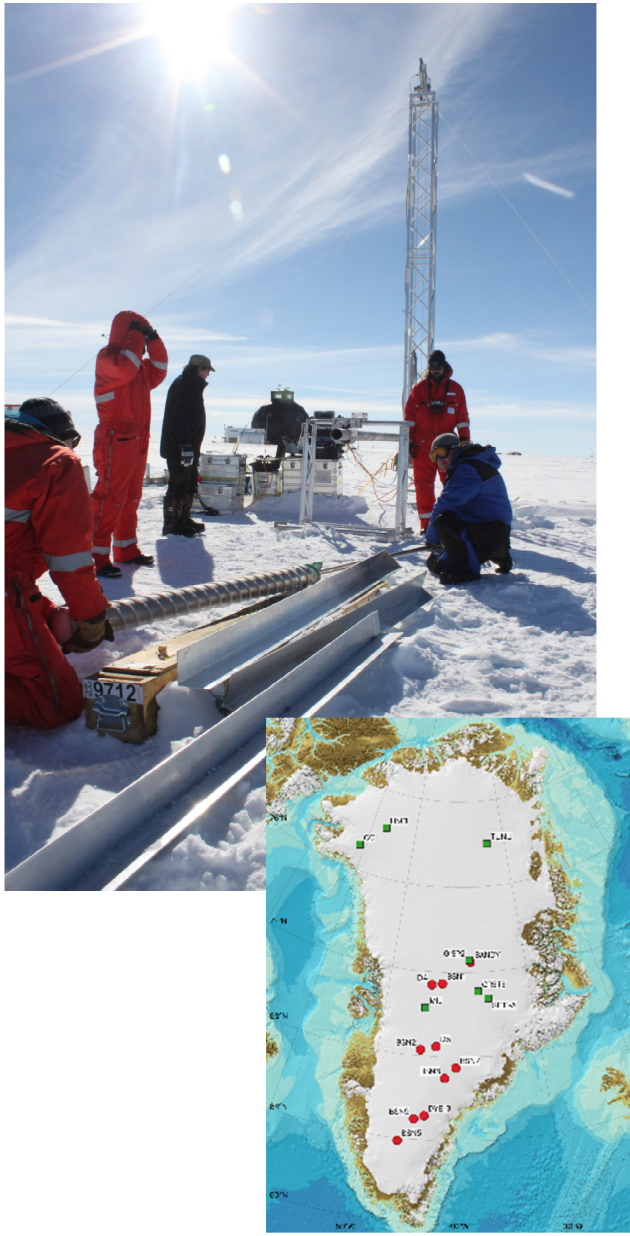
The Minoan eruption is an important marker horizon for the Bronze Age chronology of the Eastern Mediterranean realm. It provides a fixed point for aligning the entire chronology of the second millennium BCE in the Aegean, as evidence of the eruption is found throughout the region.
Yet, archaeological dating based on typological sequencing and the Egyptian chronology is significantly younger than the radiocarbon age of Minoan eruption, by roughly a century.
This age discrepancy has resulted in a fierce debate about whether there is an upheaval in the archaeological synchronization between the Aegean and Egypt.

Raw radiocarbon dates are not accurate calendar years of the event and this has to do with the fact that the level of atmospheric radiocarbon fluctuates. Raw radiocarbon ages can be converted to calendar dates by means of calibration curves which are periodically updated by international researchers. Derived calibrated calendar date ranges are highly dependent on how accurately calibration curve represents radiocarbon levels for the time period. As of 2022, the most updated calibration curve is IntCal20. Radiocarbon dating has built a strong case for an eruption date in the late 17th century BCE. The table below summarizes the history and results of radiocarbon dating of volcanic destruction layer with pre-2018 calibration curves:

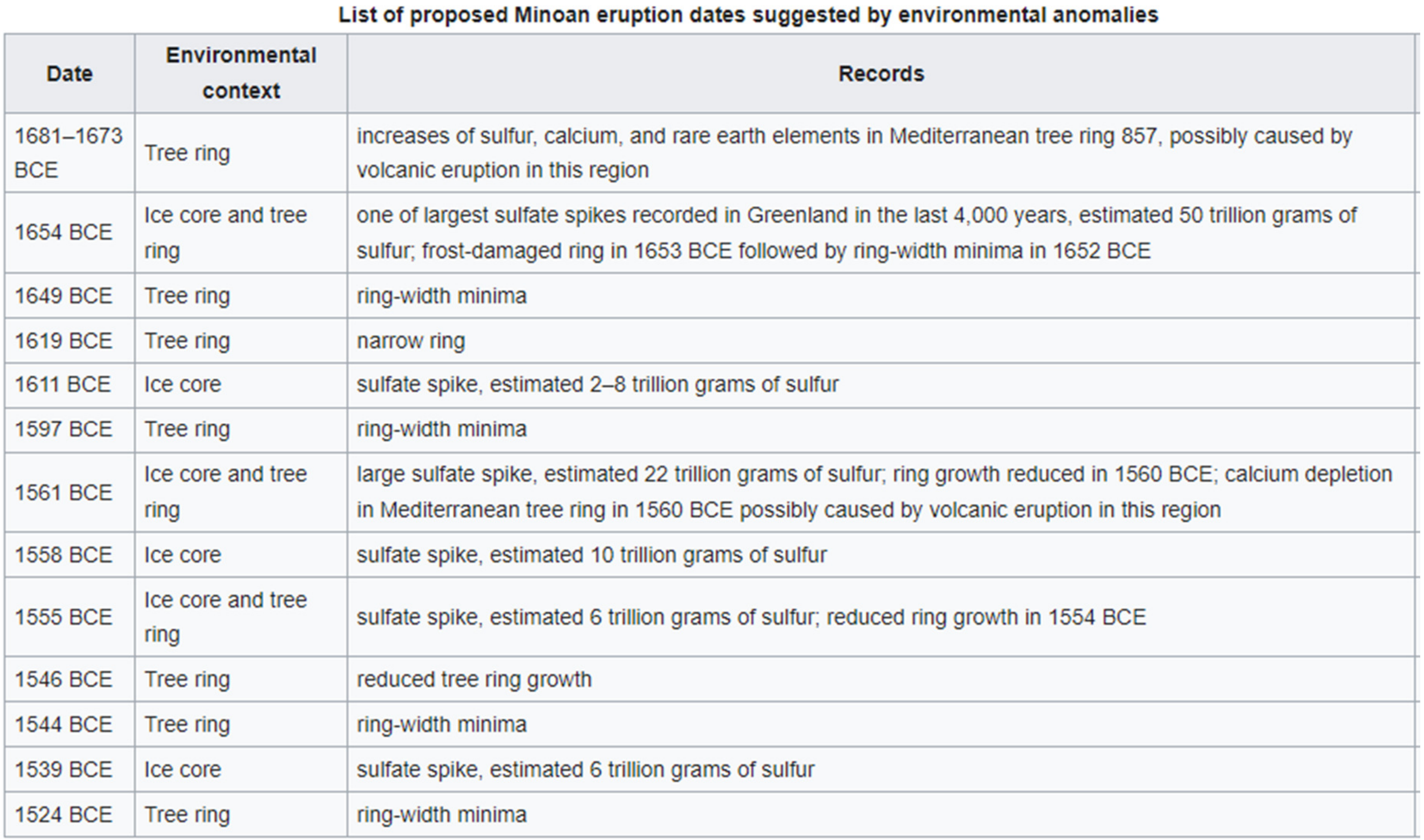
An eruption of Theran magnitude is expected to leave detectable signal in various environmental records like ice core and tree ring. Petrologic constraints on Minoan magma yields a range of 0.3–35.9 trillion grams of sulfur release. The higher end of the estimate could cause severe climatic change and leave detectable signals in ice cores and tree rings. Notably, tree ring dating allows extremely precise dating to the exact calendar year of each ring with virtually no age uncertainty, and from properties of the annual tree rings local climate record could be reconstructed down to sub-annual precision.

In 1987, a major Greenland sulfate spike in 1644 ± 20 BCE in ice core chronology was hypothesized to be caused by Minoan eruption based on the early radiocarbon results of Hammer et. al.[46] In 1988, a major environmental disruption and extreme global-cooling/forst-ring in 1627 ± 0 BCE were also revealed through precisely dated frost ring and too were hypothesized to be related to Minoan eruption.

Archaeologists who preferred late 16th century BCE eruption date were neither convinced by the 1644 ± 20 BCE sulfate spike nor by the 1627 BCE frost ring because evidence of causality between the two events and Minoan eruption was absent.



In the light of much younger radiocarbon dates and revised ice core chronology, several possible ice core and tree ring signals in the 17th and 16th century BCE have been proposed.[75][79][80] The list below summarizes the tree ring and ice core signals that may have been caused by Minoan eruption:



List of proposed Minoan eruption dates suggested by environmental anomalies

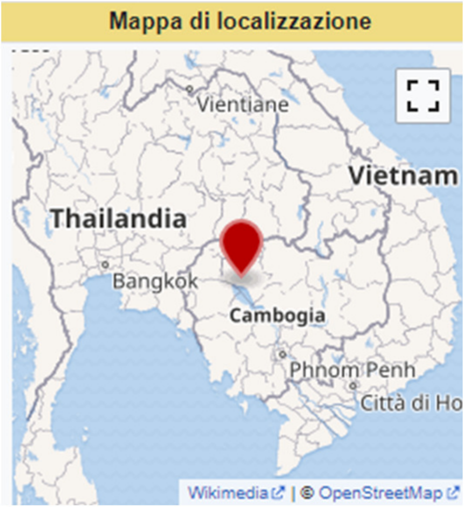
Date	Environmental context	Records
1681–1673 BCE	Tree ring	increases of sulfur, calcium, and rare earth elements in Mediterranean tree ring 857, possibly caused by volcanic eruption in this region
1654 BCE	Ice core and tree ring	one of largest sulfate spikes recorded in Greenland in the last 4,000 years, estimated 50 trillion grams of sulfur; frost-damaged ring in 1653 BCE followed by ring-width minima in 1652 BCE
1649 BCE	Tree ring	ring-width minima
1619 BCE	Tree ring	narrow ring
1611 BCE	Ice core	sulfate spike, estimated 2–8 trillion grams of sulfur
1597 BCE	Tree ring	ring-width minima
1561 BCE	Ice core and tree ring	large sulfate spike, estimated 22 trillion grams of sulfur; ring growth reduced in 1560 BCE; calcium depletion in Mediterranean tree ring in 1560 BCE possibly caused by volcanic eruption in this region
1558 BCE	Ice core	sulfate spike, estimated 10 trillion grams of sulfur
1555 BCE	Ice core and tree ring	sulfate spike, estimated 6 trillion grams of sulfur; reduced ring growth in 1554 BCE
1546 BCE	Tree ring	reduced tree ring growth
1544 BCE	Tree ring	ring-width minima
1539 BCE	Ice core	sulfate spike, estimated 6 trillion grams of sulfur
1524 BCE	Tree ring	ring-width minima

The Khmer Empire was a Hindu-Buddhist empire in Southeast Asia, centered around hydraulic cities in what is now northern Cambodia. Known as Kambuja by its inhabitants, it grew out of the former civilisation of Chenla and lasted from 802 to 1431. Historians call this period of Cambodian history the Angkor period, after the empire's most well-known capital, Angkor. The Khmer Empire ruled or vassalised most of mainland Southeast Asia and stretched as far north as southern China. At its peak, the Empire was larger than the Byzantine Empire, which existed around the same time

The Khmer Empire (Kambuja), c. 900

Angkor Wat

The site of Angkor is perhaps the empire's most notable legacy, as it was the capital during the empire's zenith. The majestic monuments of Angkor, such as Angkor Wat and Bayon, bear testimony to the Khmer Empire's immense power and wealth, impressive art and culture, architectural technique, aesthetic achievements, and variety of belief systems that it patronised over time. Satellite imaging has revealed that Angkor, during its peak in the 11th to the 13th centuries, was the most extensive pre-industrial urban complex in the world. Researchers have also concluded that the Khmer Empire invented the world's first healthcare system, which included 102 hospitals.

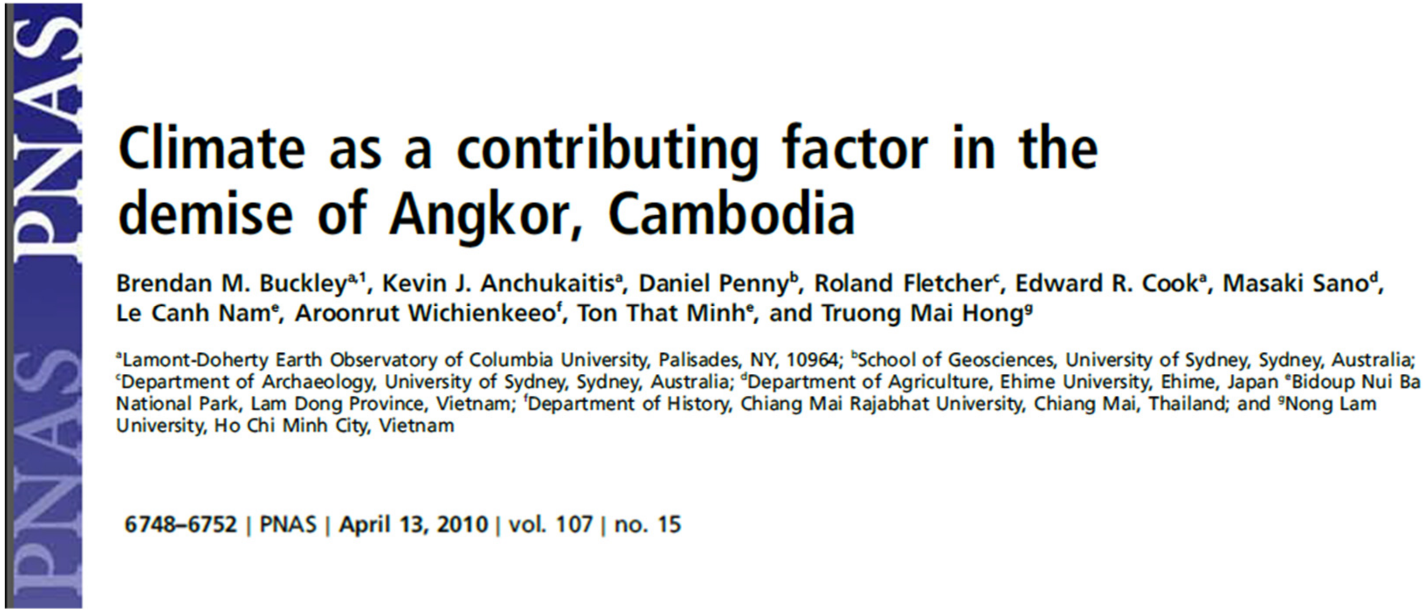


Although the end of the Khmer Empire has traditionally been marked with the Fall of Angkor to the Siamese Ayutthaya Kingdom in 1431, the reasons for the empire's collapse are still debated amongst scholars.

By the 14th century, Kambuja suffered a long, arduous, and steady decline. Historians have proposed different causes for the decline: the religious conversion from Hinduism to Buddhism, that affected social and political systems, incessant internal power struggles among Khmer princes, vassal revolt, foreign invasion, plague, and ecological breakdown.

As usual, more than one cause is involved, but ecological failure and infrastructural breakdown are probably at the base of internal riots, which are at the base of internal power struggles and vassal revolts, which favored or allowed foreign invasion.

The Khmers had an elaborate system of reservoirs and canals used for trade, transportation, and irrigation. The canals were used for harvesting rice. As the population grew there was more strain on the water system. To adapt to the growing population, trees were cut down from the nearby Kulen hills and cleared out for more rice fields. That created rain runoff carrying sediment to the canal network. Any damage to the water system would have enormous consequences. Violent floods due to monsoons damaged the infrastructure impacting the water management system during the fourteenth and fifteenth centuries, followed by periods of drought which led to decreases in agricultural productivity.



Climate as a contributing factor in the demise of Angkor, Cambodia

Brendan M. Buckley[a,1], Kevin J. Anchukaitis[a], Daniel Penny[b], Roland Fletcher[c], Edward R. Cook[a], Masaki Sano[d], Le Canh Nam[e], Aroonrut Wichienkeeo[f], Ton That Minh[e], and Truong Mai Hong[g]

[a]Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY, 10964; [b]School of Geosciences, University of Sydney, Sydney, Australia; [c]Department of Archaeology, University of Sydney, Sydney, Australia; [d]Department of Agriculture, Ehime University, Ehime, Japan [e]Bidoup Nui Ba National Park, Lam Dong Province, Vietnam; [f]Department of History, Chiang Mai Rajabhat University, Chiang Mai, Thailand; and [g]Nong Lam University, Ho Chi Minh City, Vietnam

6748–6752 | PNAS | April 13, 2010 | vol. 107 | no. 15

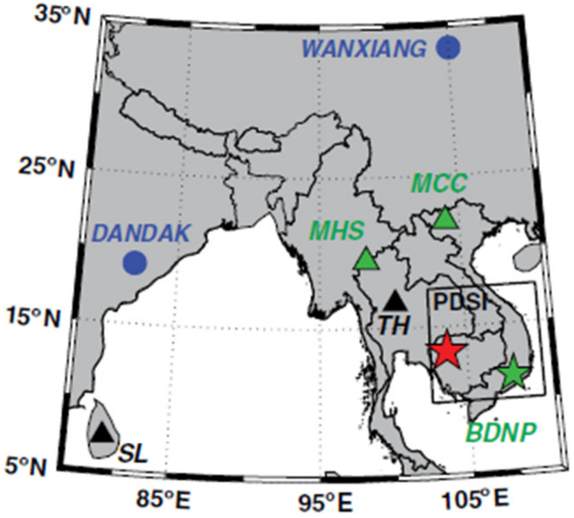
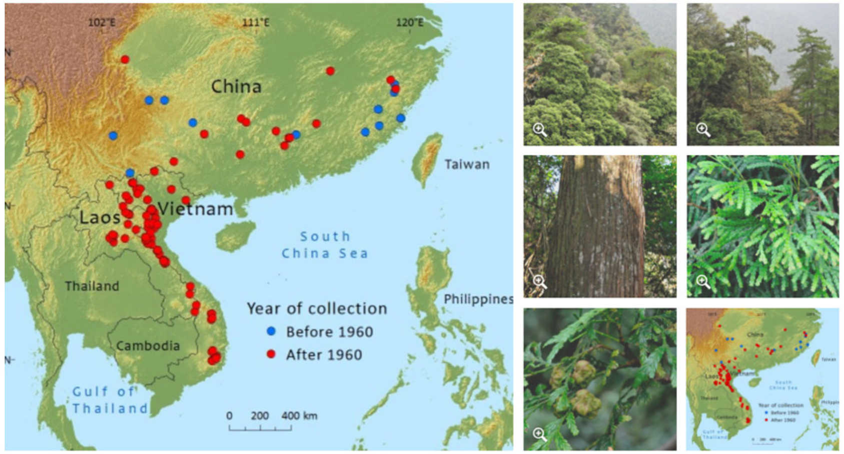


Fig. 1. Geographic context for the present study. The location of Angkor is marked by the red star in Cambodia. The map indicates the locations of the three tree-ring climate reconstructions discussed in the text with green symbols: MHS (10), MCC (11), and the BDNP *Fokienia hodginsii* site (this study, the green star in southern Vietnam) presented in this paper. Speleothem proxy records covering the fourteenth and fifteenth centuries are found at Dandak Cave in India (17) and Wanxiang Cave in China (18) as indicated by blue circles. Additional historical, documentary records of the fourteenth and fifteenth century droughts come from Phitsanulok in modern Thailand (TH) and Sri Lanka (SL) (14, 16), and whose locations are indicated by black triangles. The nine PDSI grid boxes that were used for paleoclimate reconstruction are shown by the box (15).

«a 979-year (1030–2008 CE) ring-width record from the rare cypress *Fokienia hodginsii* growing at two sites in the highlands of Vietnam’s Bidoup Nui Ba National Park (BDNP, **Fig. 1**) is presented. From this record a robust, well-validated, and absolutely dated 759-year (1250–2008 CE) reconstruction of early monsoon (March to May) Palmer Drought Severity Index (PDSI; Fig. 2C) is proposed, which passes all of the rigorous calibration and verification tests used in dendroclimatology [...]”



https://threatenedconifers.rbge.org.uk/conifers/fokienia-hodginsii

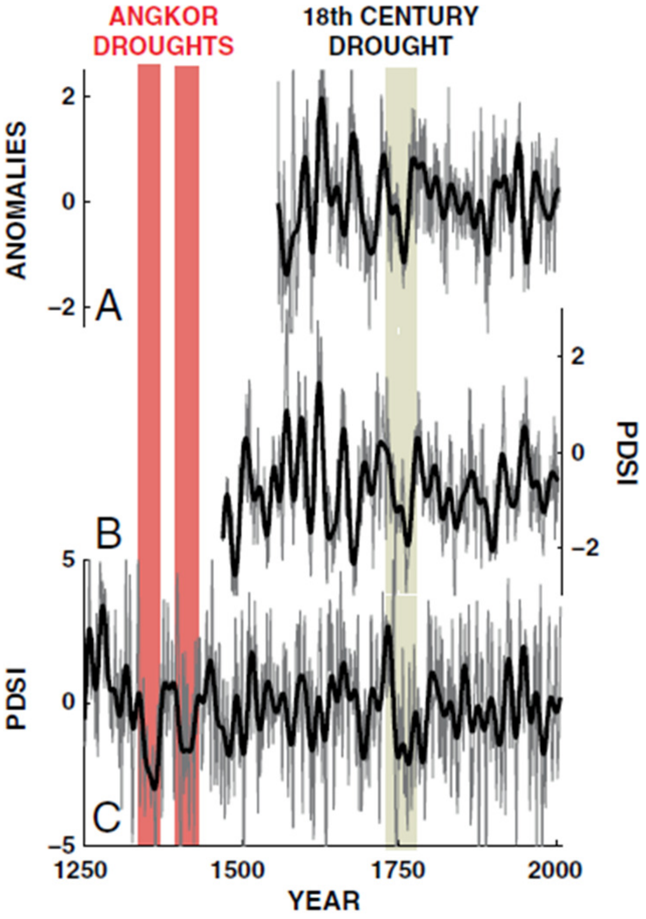


Fig. 2. Tree-ring reconstructed drought from Southeast Asia. (*A*) MHS-inferred PDSI normalized anomalies (10) from teak, (*B*) MCC reconstructed PDSI (11) from Po Mu (*Fokienia hodginsii*), and (*C*) the new BDNP reconstructed PDSI from Po Mu (*F. hodginsii*). The two Angkor Droughts in the late fourteenth and early fifteenth centuries are indicated by red vertical bars. A more recent drought in the middle of the eighteenth century is indicated in each reconstruction by the brown bar.

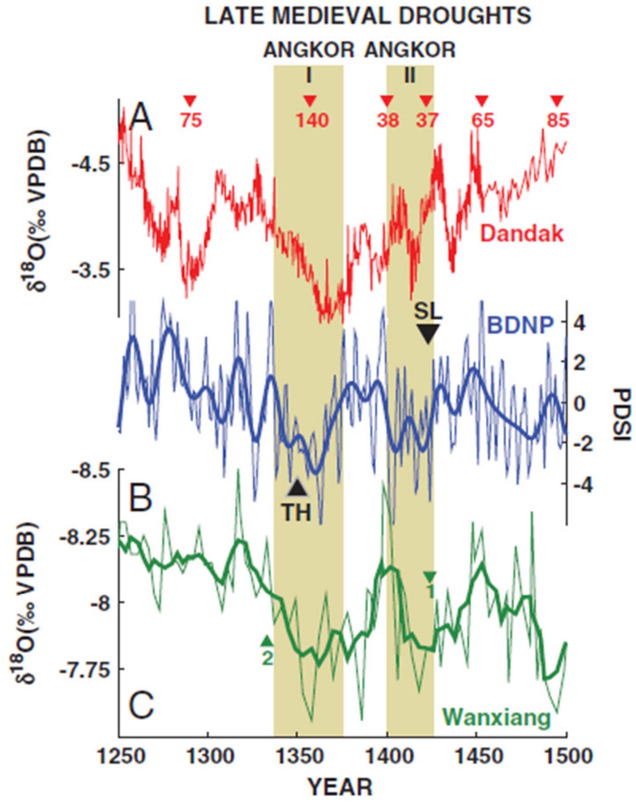


Fig. 3. Regional paleoclimate records of Medieval Drought in Southeast Asia. Dandak Cave δ^{18}O record (*A*) from the core monsoon region of India (17, 52), our Bidoup Nui Ba National Park (BDNP) PDSI reconstruction (*B*, with heavy line 15-year Butterworth filter from southern Vietnam), and the speleothem δ^{18}O record from Wanxiang Cave (*C*, heavy line, five-point boxcar filter) in China (18). Note that axes for both speleothem records are inverted such that drier conditions are down. U/Th dates for speleothems are shown by filled triangles of the same color with analytical error estimates (±years) shown by the accompanying number. The fourteenth and early fifteenth century Angkor droughts are indicated by the brown shaded bars. Historical records of the fourteenth and fifteenth century droughts come from Phitsanulok in modern Thailand (TH) and Sri Lanka (SL) (14, 16) and are indicated by black triangles.