Dendrochronologia 72 (2022) 125942

Contents lists available at ScienceDirect

Dendrochronologia

journal homepage: www.elsevier.com/locate/dendro

Musical string instruments: Potential and limitations of tree-ring dating and provenancing to verify their authenticity

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ARTICLE INFO

Keywords:
Dendrochronology
Tree rings
Musical string instruments
Violins
Cross-dating
Dating

ABSTRACT

Authenticity is the prime factor affecting the market value of a work of art. String instruments are among the most valued works of art, particularly those made by the old violin-making masters of northern Italy in the late 17th and early 18th centuries. However, it is difficult to verify the authenticity of string instruments on the basis of style and design alone, as these are often copied or forged. Uncertainties related to craftsmanship can lead to financial and legal controversy, sometimes with even millions of dollars at stake. The authenticity of the Stradivari "Messiah" has long been disputed. Controversies at the end of the 1990s concerning its craftsmanship have enhanced interest in dating this violin. After different dendrochronological analyses provided conflicting tree-ring dates for the front of the violin, a scientifically-sound dendrochronological study eventually established 1682 as *terminus post quem*, i.e., the year when the last ring of the violin front was formed, before which the violin could not have been made. This date is consistent with the attributed date of manufacture, 1716, supporting Antonio Stradivari as the maker of the "Messiah". However, this controversial dating of the "Messiah" sent shockwaves through the violin community. Here, we present the main facts which played a role in this controversy and we show how dangerous the use of dendrochronology can be if investigators do not adhere to well-established techniques and are not versed scholars in the literature. Such controversies threaten the reputation of dendrochronology. Today, many false theories and conceptual mistakes continue to circulate in the violin community. A thorough and scientifically-sound dendrochronological analysis of the wood used to make the instrument is the only analysis that can objectively indicate, if not the exact year an instrument was made, at least the date before which it certainly was *not* made. Here, we describe the importance, in terms of acoustics, of the anatomical characteristics of the wood with which instruments are made and its possible geographical provenance. We review the dendrochronological studies undertaken to assess the authenticity of the instruments made by the old Italian masters. Such studies help to establish the earliest date the tree from which the wood was taken could have been felled, and to determine the source region of the wood. We present the main achievements and challenges that have arisen in the past 50 years of studying the authenticity of string instruments, and discuss the limitations and advantages of using dendrochronological methods to establish the provenance and time period in which a work of art was created. Finally, we describe needs of research in history, wood anatomy and dendrochronology, proposing several new methods that may open up new avenues of research and aid in the assessment of the authenticity of old string instruments.

1. The value of works of art

Works of art are objects made by an artist, someone who creates things with uncommon skill and imagination. Works of art have been highly valued throughout human history and all over the world, from tribal communities to royal courts. As an expression of the creator's technical skills and creativity, the market value of a work of art depends on many factors, including cultural values and comparisons with other

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https://doi.org/10.1016/j.dendro.2022.125942
Received 4 December 2021; Received in revised form 2 February 2022; Accepted 19 February 2022
Available online 23 February 2022
1125-7865/

works. At auction, a work of art may be bought on a whim or reach an astonishingly high price as a result of competition among purchasers. Nonetheless, the prime factor affecting the price of a work of art is its authenticity, the irrefutable attribution to the artist who created it. The "Salvator Mundi", for example, wouldn't have been bought at Christie's for 450.3 million USD in 2017 had there been any doubt in the purchaser's mind that Leonardo da Vinci (1452–1519) painted it around 1500 CE.

Given their market value, paintings, sculptures, and other works of art have been illegally forged for centuries. Art historians and specialists in the field usually attribute a work of art to a certain artist or school after a close examination of its style and design. However, skilled copyists and forgers can produce copies in such magnificent detail that they are all but indistinguishable from the authentic works. The detection of fraudulent art is a very complex chase. It is particularly difficult to discover forgeries in the work of artists whose large numbers of works and superstar status make them especially attractive to those who commit fraud. Pablo Picasso (1881–1973), for example, was a prolific artist. The prestige associated with owning a Picasso and the difficulty of attribution makes forgeries and copies hard to detect.

Works of art that involve wood, such as paintings on panels, sculptures, and furniture, may be dated by analyzing the tree rings of the wood from which they were made. Dendrochronology, the study of tree rings and the variability of their characteristics over time, enables the matching of the ring-width patterns of the wood used in works of art with those of living trees or with tree-ring series built using living trees and crossdated dead wood. Pioneering studies of wooden panels used for paintings during the 14th through the 16th centuries in the Netherlands and England have demonstrated that tree-ring analysis can be used to pinpoint the date the tree used to obtain the wood to make the work of art was felled, and even the region in which the tree had been growing (Eckstein et al., 1975; Fletcher, 1977; Baillie, 1984, 1986; Klein et al., 2014). Using tree-ring analyses, Bauch and Eckstein (1981) determined the felling dates of oaks used for 132 paintings attributed to Rembrandt (1606–1669). They found that some panels were made of wood from trees felled after the death of Rembrandt and therefore could no longer be attributed to him. This study confirmed the authenticity of most of the 132 paintings and revealed some of the limitations of author attribution based on art-historical criteria alone.

2. The value of string instruments made in northern Italy

String instruments, i.e., violins, violas, cellos, and basses, are among the most appreciated and valued works of art. For example, the "Vieuxtemps" Guarneri 'del Gesù' violin sold for over 16 million USD in 2012; the "MacDonald" Stradivari viola put up for auction in 2014 with a minimum bid of 45 million USD; and a Gasparo 'da Salò' viola sold at auction in 2010 for 542,500 USD. Some of the most appreciated string instruments in the history of music are those made by the masters of the old violin-making schools in northern Italy in the late 17th and early 18th centuries. More precisely, Gasparo Bertolotti 'da Salò' (1540–1609) and Giovanni Paolo Maggini (1580–1630), both of Brescia, are considered to be the greatest master viola luthiers, Matteo Goffriller (1659–1742) and Domenico Montagnana (1686–1750), both of Venice, master cello luthiers; and Antonio Stradivari (1644–1737) and Giuseppe Guarneri 'del Gesù' (1698–1744), both of Cremona, master luthiers for violins. Musicians consider instruments from these masters to have exceptional tonal characteristics. However, their appreciation has changed over time, as have the tonal requirements of musicians. For example, Stradivari was famous during his lifetime for making highly appreciated violins (Hill et al., 1902), whereas Guarneri's violins were brought to equal fame only later by Niccolò Paganini (1782–1840), who played the "Cannone" made in 1743 by Guarneri. The old master instruments are reputed to have superior tonal qualities, namely their richness of overtones, as compared to contemporary instruments; as musicians describe it, these instruments have a more "Italian", or clear and fine, tone than other instruments. The designs of the old masters still serve as references for new violins, and nobody would seriously claim to make a better varnish than the old masters; their "secret recipes" (Scott, 1937), if they really exist, remain unknown. This reputation and the reasons for such superiority are still matter of lively debate. Double-blind acoustic tests (e.g., Fritz et al., 2017) have been carried out in which the participating musicians struggle to determine whether they are playing, e.g., a 17th century instrument or a contemporary violin (Vaiedelich and Fritz, 2017). However, some musicians question the value of such tests, on account of the number of times a violin is exchanged between musicians, the music played, and the musicians selected.

An instrument's acoustic properties depend on a number of factors, but the skills of the luthier who made it are certainly a key determinant. For this reason, the market value of an instrument is based mainly on its author, condition and craftsmanship, which is closely related to its value as a collector's item. However, craftsmanship is not always certain, given the many copies and forgeries produced over the centuries by skilled copyists and falsifiers, as well as the prolific activity of some luthiers. For example, Antonio Stradivari, during the Golden Age of the violin, is estimated to have made more than 1000 instruments (Hill et al., 1902). Their authenticity can be questioned because an examination of style, design, construction details, and varnish appearance alone is insufficient to verify the author (Ratcliff and Hoffman, 2014).

The only scientifically objective analysis that can indicate the date after which an instrument could have been made is a dendrochronological, i.e., tree-ring analysis (Fig. 1), of the wood used to make the instrument in question (Cherubini, 2021). For example, several instruments that were once universally accepted by experts as the work of Maggini have now, thanks to dendrochronology, been re-attributed to a later Brescian maker, Giovanni Battista Rogeri (1642–1710) (Ratcliff and Hoffman, 2014). It is, however, possible to obtain tree-ring matches that suggest attribution to more than one maker, usually a contemporary, if both makers used the same source or supplier for their wood. Wood may also be stored and used later or recovered from old houses by violin makers for repair and restoration. For these reasons, dendrochronological dating can only identify the date before which the instrument was certainly *not* made (Cherubini, 2021).

3. The tonal quality of old Italian string instruments

String instruments made by the north-Italian schools are renowned for having been the preferred instruments of many leading professional musicians for centuries, who appreciated their acoustical properties, resonance and ease of response (Cho, 2010). There must be a reason for such a widespread and long-lasting preference for these instruments by virtuosos and talented musicians, who are known to be more sensitive to changes in tonal qualities than non-musicians (Fritz et al., 2007). Why these instruments possess such exceptional acoustic qualities is still unknown, but both the artist's skills and the quality of the wood used to make the instrument certainly play a role (for a review, see Bucur, 2016). One hypothesis about the superiority of old violins is that it may not be true, and this would be the reason why the "secret" is so elusive: it is not there.

Certainly, the doors of theaters and concert halls become easier to open, even for a concert artist of the first order, if a Stradivari or a Guarneri 'del Gesù' is to be played. Ultimately, the violin is a tool for artistic musical interpretation, an investment that has proven to be a source of solid growth and a status symbol that signals success, wealth, and superiority. However, the qualities so highly praised by violin owners, dealers, and lovers cannot all be false. String instruments made by the north-Italian schools are superior.

4. The quality of the wood used

What an instrument is made of is at least as important as *how* it was

Fig. 1. Identifying tree rings on the front of string instruments is possible but not always easy: a violin (a), a viola (b), a cello (c), and a double-bass (d). It mainly depends on the tree rings, the wood condition, and the varnish.

made. The quality of the original timber used to make the instrument is carefully scrutinized by the maker, who chooses wood that will best satisfy her/his aim in the completed instrument (Carlier et al., 2019). In general, wood with a not-too-high density is preferred.

The back, sides, and neck of most modern string instruments, as well as the Classic instruments, are made from maple (*Acer platanoides* L.) or sycamore maple (*Acer pseudoplatanus* L.). The front, i.e., the sounding board or belly, is generally made from Norway spruce (*Picea abies* (L.) Karst.) or silver fir (*Abies alba* Mill.). The tonal quality of an instrument is strongly influenced by its front, so the quality of the wood chosen for this part of the instrument is essential. The selected wood is usually obtained from trees with even and undisturbed growth. Fortunately for dendrochronological purposes, Norway spruce is a commonly analyzed species that offers a longer series of tree rings for analysis than either maple or sycamore maple.

In most cases, the front of a stringed instrument is made from wood obtained from a recently felled tree. The trunk of the tree is quarter-sawn, i.e., radially sawn to produce wedges of wood. Each wedge is split into two halves that are opened like a book and joined so that the youngest rings come together in a joint that forms the centerline of the front of the instrument. The front is therefore usually comprised of two symmetrical pieces, although some fronts are made from a single piece (Ratcliff and Hoffman, 2014). Sometimes, however, much older wood is used to make an instrument, often from wood obtained from centuries-old buildings. In these cases, the dendrochronological date (*terminus post quem*) is much older than the actual date of production. The fronts of some instruments may also be constructed from mismatched halves, and still others have the youngest rings at the outer edges and not at the joint. The Andrea Amati (circa 1505–1577) violin “1566, Charles IX” in the “Museo del Violino” in Cremona has the oldest rings at the center joint, for example. In general, the makers used whatever they had and worked around any wood defects, sometimes causing them to make unconventional decisions so as avoid throwing away a perfectly good piece of tonewood.

The physical and chemical characteristics of the wood used to make an instrument affect its acoustic properties, namely its radiation spectrum (Wegst, 2006; Bissinger, 2008; Cho, 2010; Bucur, 2016). Typically, wood with regular, narrow rings and a straight longitudinal section is preferred for making string instruments (e.g., Spycher et al., 2007). Wood density is one of the most important properties determining the acoustic properties of wood (Stoel and Borman, 2008). Trees growing at higher elevations tend to have slower growth, resulting in narrower rings of uniform width and a low proportion of latewood, which has a positive effect on the acoustic properties of wood for violins. Wood from fast growing trees and wood with a high proportion of latewood and high density is usually avoided because of poorer sound properties (Buksnowitz et al., 2007; Carlier et al., 2019).

5. Methods for achieving the high wood quality of the old Italian instruments

For more than a century, scientists have sought to understand the secret technique used by the violin-making schools of northern Italy to obtain wood of such high tonal quality (Cho, 2010). Many hypotheses have been proposed to explain the unusual sound quality of instruments from these schools. For example, analyses of maple samples from Stradivari and Guarneri instruments have revealed highly distinct organic and inorganic compositions as compared with modern maple samples. This suggests that these masters’ instruments were treated with complex mineral preservatives, a kind of chemical seasoning (Tai et al., 2017). Other proposals speculate that the masters stored wood for a long time before using it, or that they soaked it in water to leach chemicals from the wood tissues (see, e.g., Folland, 2015, Cai and Tai, 2021). However, an experiment by Sonderegger et al. (2008) showed that storing wood under water for three months had no effect on its acoustic qualities. Other proposals suggest that the old schools preferred wood from trees felled in a certain season (Ille, 1976), or that they somehow treated the wood chemically to kill woodworm (Nagyvary et al., 2006). Although several studies have tested these hypotheses, the results remain controversial (Zieger, 1960; Ille, 1976; Schwarze et al., 2008).

One of the most common theories is that special varnishes were used to influence the quality of the wood used to make the instruments. Traditionally, wood used to make musical instruments is treated with varnishes or minerals to stiffen it (Scott, 1937), to improve its vibrational properties (Lämmlein et al., 2019). Such treatment can strengthen the adhesion between cell layers. However, these varnishes also tend to occlude the cell lumina, which increases the density and vibrating mass of the instrument, ultimately reducing the speed of sound. Despite a serious attempt at characterizing Stradivari varnish (Brandmair and Greiner, 2010) and a wide range of studies using cutting-edge techniques (Malagodi et al., 2013), the use of a special varnish by the old Italian schools has yet to be proven (Echard and Lavédrine, 2008; Gilani et al., 2016; Invernizzi et al., 2016; Cai and Tai, 2021). The varnish remains a mystery.

More recently, fungal decay has been proposed as a way to improve the acoustic properties of wood. Schwarze et al. (2008) incubated resonance wood with fungal species that reduce wood density without degrading the middle lamellae. This reduction in density was accompanied by a small change in the speed of sound and an increased radiation ratio, making the wood similar to superior wood grown in a colder climate (Schwarze et al., 2008).

Finally, another hypothesis points to the unique climate situation that existed between AD 1645–1715 as the cause for the exceptional quality of string instruments produced by the old violin-making schools of northern Italy. Known as the Maunder Minimum or the Little Ice Age, this period was characterized by reduced solar activity and lower temperatures, which induced a remarkable reduction in tree growth and thus regular narrow rings. The most prominent Cremonese masters, such as Antonio Stradivari, made their violins with trees that grew during this colder period. It is therefore possible that the acoustic qualities of these instruments are the result of the climatic conditions that prevailed during the trees' lifetimes (Burckle and Grissino-Mayer, 2003). However, this would also imply that all violins from trees that grew during that period should have superior sound, which is not the case.

6. Resonance wood

The wood used to make musical instruments is called "resonance wood" (e.g., Zimmermann, 1996). The reasons for which some trees in some forests form this particularly praised wood are still unknown, as are the criteria used to identify it. However, its qualities have long been appreciated and highly valued (Feuerstein, 1935); for centuries, resonance wood has fetched a higher price than other wood from the same species growing at the same site (Blossfeld et al., 1962). Although resonance wood shows a high radiation ratio in the axial direction, which is associated with the presence of small wood cells with thin cell walls (Spycher et al., 2007), the physical characteristics determining its acoustic properties are still a matter of debate (Buksnowitz et al., 2007). However, it is unanimously recognized that resonance wood produces a superior sound.

The term resonance wood has been used to characterize high-quality wood coming from several different regions, including various parts of the Alps, the Carpathians, and eastern Germany (Zieger, 1960; Blossfeld et al., 1962; Dorsch, 1975; Holz, 1984; Corona, 1998). However, the specific geographical origin of the resonance wood used to make string instruments is usually surrounded by mystery, legend, and anecdotes. Historical studies of archive records, such as reports and forestry accounts covering the past three to four centuries, are still lacking.

The wood used to make string instruments during the 17th and 18th centuries in two of the major violin-making centers in northern Italy, Cremona and Brescia, is thought to have come from subalpine Norway spruce forests in the Dolomites (Trentino, eastern Italian Alps). Here, the Paneveggio forest in the Fiemme Valley (Cherubini et al., 1996) is said to have been one of the most famous forests for the production of resonance wood (Fig. 2) used by the old schools. Legends report that Stradivari himself went to the forest to select the most appropriate wood for his violins, where he recognized the right wood by the sound the timber made as it was slid down-valley (see Bernabei and Bontadi, 2011). Unfortunately, such reports are surrounded by mystery and are not confirmed by any historical records. A systematic search of archives from the Republic of Venice and the Austrian-Hungarian Empire is needed to correctly identify the sources of resonance wood from the eastern Alps.

7. "Hazel" wood

In Paneveggio, not all produced wood is resonance wood. Resonance wood, still the most expensive wood from the forest, is often referred to as "hazel" wood ("Haselwuchs" in German) because of characteristic "hazel" growth (Bonamini and Uzielli, 1998). Also known as "bear claw" due to the wrinkled appearance of the cambium layer that makes the surface of the tree trunk look as through it has been scratched by a bear, "hazel" growth is an abnormal type of wood development characterized by indented growth rings (Fig. 3). Although the physiological processes which induce "hazel" growth are still unclear (Nocetti and Romagnoli, 2008), according to local foresters and anecdotal oral tradition, and supported by its market price, "hazel" wood from Paneveggio has been preferred to other wood by luthiers for centuries (Greyerz, 1919; Feuerstein, 1935; Bonamini and Uzielli, 1998). Although it has never been definitively proven, sound transmission is thought to be slower in wood with "hazel" growth, making the wood more resonant. An early observation of "hazel" growth was made by Vuillaume on the Stradivari "Messiah" (Hill, 1891). Wood reflecting "hazel" growth is commonly seen in instruments by Giovanni Battista Guadagnini (1711–1786), is abundant in a later violin by Francesco Stradivari (1671–1743), and, among several others (see Bonamini and Uzielli [, 1998]), is found in an Antonio Stradivari cello of 1710. However, it is not found in all classical instruments.

Wood with "hazel" growth contains numerous structural irregularities: larger and more numerous rays, distorted or curved rays, distorted and atypical tracheids, and trabeculae (Lev-Yadun and Aloni, 1991; Yaman, 2007). Such anomalies act as knots, making it challenging for the luthier to craft a smooth surface for varnishing. Although it has been studied since the 1950 s (Ziegler and Merz, 1961), it is still not clear why "hazel" wood forms. Although it is rare in both, "hazel" wood forms sporadically in both conifers and dicotyledons. Some studies of xylogenesis have suggested that disturbances in a tree's hormone balance may be responsible, causing anomalies in cambial function (Lev-Yadun and Aloni, 1991). Further experimental research is needed to understand the causes of such hormonal disturbances. Whatever the reasons behind the formation of "hazel" wood, such anomalies lead to a

Fig. 2. Renonance wood: basal cross section of a Norway spruce grown in the Paneveggio forest (Dolomites, eastern Italian Alps) showing a resin pocket, several insect galleries and indented rings, typical feature of "hazel" wood.

Fig. 3. "Hazel" wood in a Norway spruce grown in the eastern Italian Alps (exact provenance unknown), also called "bear claw" due to the wrinkled appearance of the cambium layer that makes the surface of the tree trunk look as through it has been scratched by a bear,.

reduction in anisotropy, which has been shown to be at least partially responsible for the exceptional acoustic quality of the wood (Bonamini et al., 1998; Romagnoli et al., 2003; Buksnowitz et al., 2007, 2012).

In Paneveggio, some other wood-anatomical anomalies have been found in trees characterized by "hazel" wood, i.e., intra-annual radial cracks (Fig. 4), which are probably induced in rings of low density by summer drought (Cherubini et al., 1997; Grabner et al., 2006). Such anomalies could affect the acoustic qualities of the wood, but their influence on the acoustics of string instruments has never been studied. If we want to understand the qualities of wood that produce superior acoustics, we need further studies of the wood of existing quality string instruments.

8. Assessing authenticity: Provenance and dating

Few methods are available to assess the authenticity of a string instrument. Experts often attribute an instrument to an author or a period of time depending on its acoustic properties, style and technical characteristics, or the techniques used to make it. However, a qualified expert cannot identify a maker by these characteristics alone; more objective methods are needed, particularly ones that provide a high temporal resolution. Although it is possible to use radiocarbon dating, this is a destructive method, and cannot provide annual resolution. The only nondestructive, noninvasive, and objective method that may enable the spatio-temporal collocation of a string instrument is the analysis of the tree rings of its wood using dendrochronology (e.g., Ratcliff, 2012). Dendrochronological methods, i.e., the study of the physical characteristics, such as width or density, of the tree rings of the wood used to make the instrument, can help in determining when the instrument was made (e.g., Bernabei et al., 2017), and the origin of the wood from which it was made (Wilson and Topham, 2004). The spruce front of the instrument is typically used for dendrochronological investigation as it offers the opportunity to analyze the longest tree-ring series available (Fig. 1), which is important for achieve results with a

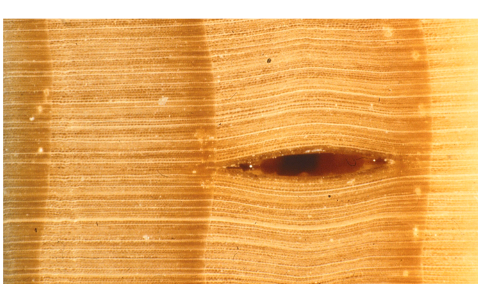

Fig. 4. An intra-annual radial crack on a cross section of a Norway spruce grown in the Paneveggio forest (Dolomites, eastern Italian Alps): what is the influence of such anomalies on the acoustics of string instruments?.

statistically significant confidence (Topham and McCormick, 1998). Neither sycamore nor maple is suitable for dating purposes because long ring-width series are unavailable for these shorter-lived trees.

Dendrochronological dating of wood is achieved by cross-dating different ring-width series (Fig. 5). The year of formation of the last (or youngest) ring on the front of a violin can be identified by comparing the pattern of tree-ring widths measured on the front of the instrument with the ring-width pattern from a chronology built with living trees growing at the site from which the wood was putatively taken. Wood from old buildings or semi-fossil wood can be used to extend the time span of the chronology. The year of formation of the last ring will be the most recent date the tree from which the wood was taken could have been felled, and therefore the *terminus post quem*, i.e., the date after which the instrument could have been made (Ratcliff and Hoffman, 2014; Bernabei and Cufar, 2018) (Fig. 5).

Dendrochronology requires the measurement of tree-ring characteristics, most commonly the ring width. This is usually measured on samples (cores or stem disks) taken from trees and it is therefore destructive. Nevertheless, tree-ring widths can also be measured non-destructively using images of the tree rings. The sounding boards are made from radial sections of wood; ring widths can therefore be measured either directly on the table or indirectly via high-resolution photographs after removing the bridge, strings, and tailpiece.

9. Cross-dating the instrument against reference ring-width chronologies

In temperate climates, trees grow during the mild season and stop growing during the cold winter, forming one (and only one) ring each year. Tree-ring physical characteristics such as width and density reflect the environmental conditions in which the tree was growing. Tree growth at each site is limited by specific environmental factors. During a rainy summer, for example, a tree growing at a normally dry site will build a wider ring. During a hot dry summer, trees at dry sites will suffer more, whereas trees at cold and humid sites will take advantage of the warmer conditions by forming wider rings.

In the Alps, luthiers have searched for wood for string instruments in subalpine forests at elevations between about 1600 and 1800 m a.s.l. At these elevations, tree rings are typically regular and narrow and summer temperature is the limiting factor (Corona, 1998). Several studies have shown that moisture availability is the dominant factor affecting Norway spruce growth at lower elevations. At higher elevations and at upper tree-line sites, air temperature is generally the factor limiting growth (e.g., Hughes, 2002). At these sites, trees will grow better and form wider rings during a year characterized by high summer temperatures. Wilson and Topham (2004) showed that a strong climatic signal exists in tree-ring data from violins; this data can be used to identify the source regions of the wood used by luthiers.

Climatic variability influences tree growth at the site level such that different trees growing at the same site have similar tree-ring patterns. All trees growing at a site, particularly those of the same species, will form rings of similar widths depending on whether the meteorological conditions of that specific year increase or decrease growth. The most basic element of dendrochronology is cross-dating, or the comparison of ring-width patterns. If the time series is long enough, the patterns caused by climatic variation will be unique and there will be only one correct placement in time of each tree-ring series (Fig. 5). The two ring-width series are matched using first visual, then statistical methods (if the time series is long enough). Statistical cross-dating depends strongly on time series with prominent high-frequency (mostly climatic) signals. Cross-dating provides the statistical confidence level one should accept the result of such analysis (Grissino-Mayer et al., 2010).

The strong temperature signal present in tree-ring series from high-elevation sites makes possible the cross-dating of string instruments with chronologies from trees growing at those sites (Wilson and Topham, 2004). However, given the limited spatial variability of

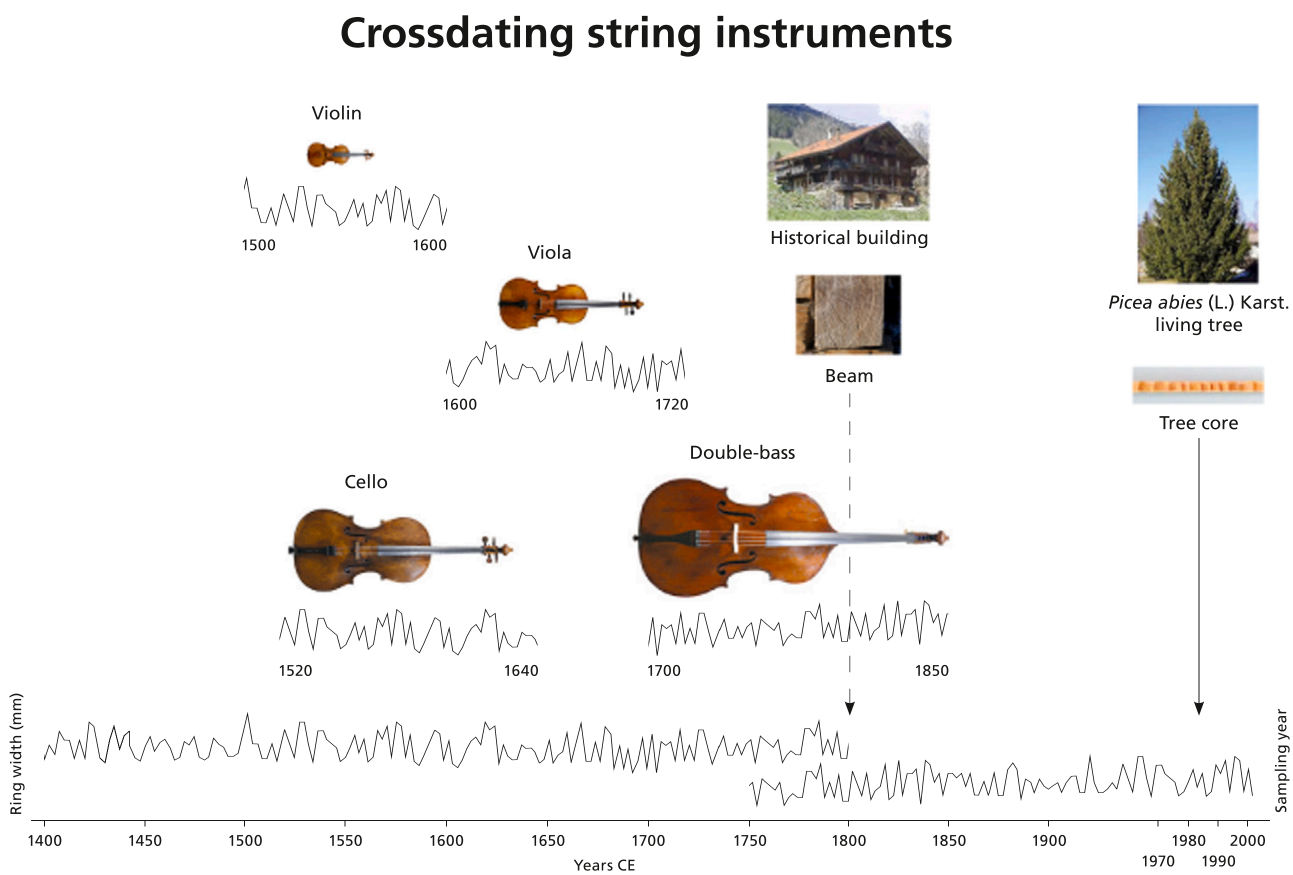

Fig. 5. Crossdating string instruments.

summer air temperatures at a regional scale, this very prominent high-frequency signal can be found in high-elevation Norway spruce tree-ring series over a very large region. This lack of regional heterogeneity may explain some of the uncertainties related to using tree rings to determine the origin of the wood.

Pioneering work by Bauch and Eckstein (1981) showed that it is possible to date historical artifacts by comparing the tree-ring patterns in works of art with ring-width chronologies from living trees (if the trees are old enough) coming from the same forests from which the wood used to make the artifact is thought to have originated. Cross-dating uses statistical techniques that alert one to dating uncertainties and to the likelihood of dating errors (Wigley et al., 1987; Bernabei et al., 2017). However, this method depends on the availability of reference chronologies, i.e., chronologies from the same species and the same climatic area as the wood in question (Baillie, 1984).

To date instruments from the old Italian schools, Alpine ring-width chronologies are usually used. Such chronologies are built either by public institutions, e.g., laboratories of Universities, and are often made publicly available, or by private laboratories, usually not publicly available. Thousands of ring-width chronologies are available to the public through the International Tree Ring Data Bank (ITRDB; National Oceanic and Atmospheric Administration NOAA, Boulder, Colorado, U. S. Department of Commerce, U.S.A.). Founded in 1974 as an *ante litteram* open-access databank, the ITRDB is a repository where dendrochronological data from all around the world are stored. Unfortunately for the purposes of dating old string instruments, however, only a few chronologies of sufficient length are available from sites close to where wood was harvested for luthiers (e.g., Becker and Giertz-Siebenlist, 1970). The most commonly used chronologies are reported in Table 1.

The lack of publicly available reference chronologies for the Italian Alps limits the application of tree-ring dating. In the past two or three decades, some private laboratories specialized in dendrochronological dating of string instruments have been established. They operate worldwide and own private collections that comprise thousands of ring-width chronologies, built with both living trees and old string instruments. This allows them the spatial and temporal resolution to date old instruments with a high degree of accuracy, as well as to identify the wood source of many instruments. For example, violins from private collections in Slovenia were dated using a database from a private laboratory that contains around 4000 ring-width series (Cufar et al., 2010). The authors admit that it would not have been possible to date most of the instruments using only chronologies available through the ITRDB.

Table 1
Ring-width chronologies frequently used to crossdate tree-ring patterns of string instruments in order to find the *terminus post quem* of a given instrument.

Time span	Location	Author/s
982–1976	Lauenen (Switzerland)	Schweingruber
1276–1974	Obergurgl (Austria)	Giertz-Siebenlist
1537–1995	Obersaxen Meierhof (Switzerland)	Schweingruber
1540–1995	Falkenstein (Germany)	Wilson
1573–1961	Kreuth (Germany)	Becker
1598–1990	Fodara Vedla (Italy)	Huesken/Schirmer
1660–1975	Cortina (Italy)	Schweingruber

10. Determining the wood origin

The source region of wood used to make high-value instruments is surrounded by mystery; although there are many hypotheses, anecdotes, tales, and legends, there is no written evidence to support them. The absence of archival studies is also remarkable. In some cases, cross-dated ring-width chronologies derived from instruments with reference chronologies derived from living trees (in part) has enabled the identification of the wood source. For example, dendrochronology enabled the identification of the provenance of the wood of the entire collection of the "Luigi Cherubini Conservatory at the Accademia Gallery" in Florence, Italy (37 instruments) (Bernabei and Bontadi, 2011). The tree-ring patterns of the instruments were compared with those of 95 ring-width master chronologies from across Europe using dendrochronological methods. The comparisons showed that most of the instruments were made of resonance wood coming from Obersaxen and surrounding areas in Switzerland, the Bavarian Alps, northern Bavaria, and the eastern Italian Alps in the area around Paneveggio and Cortina D'Ampezzo (Bernabei and Bontadi, 2011). This confirms that the wood used to make instruments was sometimes sourced far from the place where the instrument was actually made (Topham and McCormick, 1998; Lauw et al., 2021). The same areas were found to be the source of wood used during the 19th and 20th centuries to make string instruments now housed at the "Theatre Museum Carlo Schmidl" in Trieste, Italy (Bernabei et al., 2017).

11. Dating the last ring on the front

The growth pattern on the front of an instrument can be compared with available ring-width chronologies of the same species from a number of different regions to determine the year in which the last ring was formed (e.g., Bernabei et al., 2017). It can be assumed that the instrument was made shortly after the last ring was formed; in any case, the last ring represents the earliest year in which the instrument could have been made (the last year that the tree was, with certainty, still standing in the forest). Additional years can still be added to account for the seasoning of the wood and the removal of the outermost layers with a plane to prepare the center joint. This method of establishing the *terminus post quem* has been used since the middle of the last century. In an inspiring and pioneering work, Lottermoser and Meyer (1958) compared ring-width patterns of instruments by Stradivari and Guarneri and found good correlations, showing that the instruments from both were made at the same time. Using a Tyrolean (Ötztal) chronology, Corona (1980) was the first to date two violins made by Giovanni Battista Gabbrielli (1716–1771), who worked in Florence between 1739 and 1770, and identified the Fiemme Valley in the eastern Italian Alps as the possible source region for the "Bimbi" viola (Corona, 1981). Later, Corona (1998) also dated violins, violas, cellos, and double basses from the "Collezione dell'Ospedaletto della Pietà" in Venice. Major advancements were made by Klein et al. (1986), who built new chronologies from various forest sites in order to better attribute the spruce growth patterns in instruments to specific geographical areas. They analyzed 134 instruments dating from the 16th to the 20th centuries, ultimately dating the fronts of 75 instruments. For 65 of these, the date of the most recent ring was earlier than the date of musical-historical attribution, thus confirming the attribution of the instrument. In the remaining 10 instruments, the ring was formed later, requiring a reappraisal of the date of manufacture. These works show the importance of building chronologies from many forest sites to increase the likelihood of dating and dendroprovenancing (Klein et al., 1986).

Also important is the construction of ring-width chronologies using old string instruments. For example, 37 instruments in the collection of the "Luigi Cherubini Conservatory at the Accademia Gallery" in Florence were used to build a chronology (1396–1953) to date other instruments (Bernabei et al., 2010). Topham and McCormick (1998) investigated 17 violins, 2 violas, and 21 cellos, all attributed to British makers from the 17th to the early 19th centuries. In doing so, they demonstrated that dendrochronology can be a highly reliable and nondestructive means of dating string instruments (Topham and McCormick, 1998). They confirmed some but not all of the previously formulated attributions based on stylistic and technical analyses. In other cases, the authenticity of certain instruments has been more difficult to confirm. For example, Grissino-Mayer et al. (2005) used four reference chronologies developed from tree-line species in the European Alps to anchor the dates for the tree rings found on the front of the "Karr-Koussevitzky" double bass. They found that the last ring of the double bass was formed in 1761, indicating that the instrument could not have been made in 1611 by the Amati workshop as previously thought. These examples, as well as more recent ones (e.g., Bernabei et al., 2017, Lauw et al., 2021), show how important dendrochronology is for confirming (or not) the authenticity of instruments.

12. Doubts about dendrochronological dating

The authenticity of the Stradivari of 1716 known as the "Messiah" ("Salabue" or "le Messie"), one of the most famous violins accredited to the Master, has long been disputed. One of the reasons for this controversy is probably the long-troubled history of the violin, which passed from one owner to the next many times over the centuries (Hill, 1891). The "Messiah" was made, or is thought to have been made, in 1716 by Antonio Stradivari (Scott, 1937) and apparently remained in his workshop until his death in 1737, when it passed to his son Paolo. Paolo then sold it to Count Cozio di Salabue in 1775, who sold it in 1827 to Luigi Tarisio, a collector and dealer who extolled its qualities in Paris without showing it. Reportedly, this was the reason for which it was called "Messiah", because it never appeared but everyone was speaking about it. When Tarisio died, the famous violinist Jean-Baptiste Vuillaume (1798–1875) went to Italy and bought it from Tarisio's heirs. When Vuillaume died, his sisters sold it. After being bought and sold by several more owners, it finally arrived at W.E. Hill & Sons, a firm of violin makers, restorers, and dealers, who later presented it to the Ashmolean Museum, Oxford, UK, where it is now kept on display. Vuillaume was not only a virtuoso violin player but also a famed violinmaker and copyist, and was long thought by some to be the maker of the "Messiah" (Hill, 1891; Hill et al., 1902).

Controversy concerning the provenance of the "Messiah", related in particular to supposed stylistic inconsistencies and the unexpectedly early final ring year, have spurred renewed interest in this violin. Pollens (1999) reported an apparent contradiction between an inscribed letter in the pegbox and the mould from which it was made. This discrepancy made him suspicious about the violin's provenance. Measuring the ring widths on a photograph of the violin's front, Pollens dated the youngest ring to 1738, a year after Stradivari's death. The 1738 date was later retracted without a clear explanation, further confounding the controversy. At the request of well-known experts Charles Beare and Andrew Hill, Topham and McCormick (2000) measured the ring widths directly on the instrument's front. They then cross-dated the resulting chronology against that of two undisputed Stradivari violins and found a significant correlation. They were eventually able to use two existing chronologies from Austrian and Italian eastern Alps (Siebenlist-Kerner, 1984; Hüsken and Schirmer, 1993) to date the treble side (1581–1675) and the bass side (1590–1682) of the instrument. The *terminus post quem* was therefore 1682, a date consistent with the attributed date of manufacture, 1716, supporting Antonio Stradivari as the maker of the "Messiah" (Topham and McCormick, 2000).

Cross-dating with five other instruments and against a regional chronology integrating 16 Alpine chronologies revealed that the "Messiah" correlates not only with the regional chronology, but also with the "Archinto" (1526–1686) and "Kux-Castelbarco" (1558–1684) violas. These instruments have a *terminus post quem* of 1687, which still supports the attribution to Antonio Stradivari (Grissino-Mayer et al., 2002, 2003, 2004). Nevertheless, this controversial dating of the "Messiah" sent shockwaves through the violin community. Questions concerning the authenticity of the "Messiah" remain and are based on stylistic and historical inconsistencies, such as the conflicting sets of tree-ring dates for the spruce front of the violin.

In 2009, Mondino and Avalle (2009) entered into this controversy and attributed the "Messiah" to Vuillaume, also based on an examination of tree rings. Their study was shown to be technically, methodologically, and statistically flawed and was promptly rebutted

(Grissino-Mayer et al., 2010). Nonetheless, the booklet published by Mondino and Avalle (2009) created intense confusion regarding tree-ring dating among the community of violinmakers, dealers, and lovers. This shows how dangerous the use of dendrochronology can be if investigators do not adhere to well-established techniques and are not versed in the literature. Many false theories and conceptual mistakes (e.g., Mondino and Avalle, 2009) continue to circulate in a community where publications, even if based on scientifically sound studies (e.g., Fioravanti et al., 2009, Bucur, 2016), are usually not peer reviewed. Unfortunately, such controversial results threaten not only the credibility of musical appraisal, but also the reputation of dendrochronology as a scientific discipline capable of attributing each individual tree ring to a single year.

It is important for musicians and art collectors to know how much confidence they can place in the dendrochronological authentication of fine violins. Correctly dendrochronologically-dated rings are always precisely dated; there is never a question of the assigned date being "within one or two years" of the actual date, as stated by Baillie (1984). The amount of confidence one can have in the accuracy of dendrochronological dates is reflected in the statistical significance of the correlation coefficients when dating the instrument against several reference chronologies (Wigley et al., 1987; Grissino-Mayer et al., 2010).

However, dendrochronological dating does *not* provide an absolute date for the creation of a work of art; dendrochronology can only provide the *terminus post quem*, i.e., the date of the outermost ring on the front of the instrument. This date is the earliest possible year in which the tree from which the timber used to make the instrument could have been felled (Hughes et al., 1981). The outermost ring represents the last year during which the wood used to make the instrument was certainly still in a living tree. Dendrochronology cannot provide information about how many years passed between the time the tree was felled and when it was crafted into an instrument, nor can it indicate how much of the outermost wood was lost when the wood was crafted. According to Klein et al. (1986), wood may be seasoned for as many as 25 years before it is used to make an instrument.

In the past decade, many precious instruments have been sold with an accompanying report by a dendrochronological expert (Ratcliff and Hoffman, 2014). However, the quality of these reports is sometimes questionable (Cufar et al., 2017). In order to be reliable, dendrochronological dating needs to be done using sound analytical methods, robust statistical analyses, and a solid dataset of reference ring-width chronologies (e.g., Cufar et al., 2010, Bernabei et al., 2017, Lauw et al., 2021). Only a few laboratories worldwide are able to provide such rigorous expertise (e.g., Cufar et al., 2017).

13. Future perspectives and new methods

The utility of dendrochronological methods for dating instruments is limited by the availability of reference ring-width chronologies. Reference chronologies are lacking for many regions, mainly due to the lack of wood (from living trees, buildings or other sources) from the same area old enough to build such references. Few chronologies go back to 1500 or 1400. However, many new chronologies have recently been added to the ITRDB and are now publicly available. Dendrochronological references for spruce from the 15th and 16th centuries are still scarce but future studies will hopefully expand on both the quantity and geographic and temporal coverage of such chronologies. Both living trees and the wood of string instruments can contribute to this effort (Bernabei et al., 2017).

For the purposes of identifying the luthier who made a given instrument, it would be helpful to date the back of an instrument along with its front. To do so, it is necessary to expand the availability of ring-width chronologies for maple and sycamore maple from different sites in Europe. Maple and sycamore maple, reportedly from the Balkans, were often used for the back of string instruments by the masters of the northern Italian schools.

Moreover, wood densitometry has long been known to be superior to ring-width measurements for detecting climatic signals in high-elevation conifers (Hughes et al., 1984; Briffa et al., 1990; Hughes, 2002). To date, tree-ring density has seldom been used for the analysis of string instruments although the measurement of wood density needs not be destructive. Indeed, instruments can be x-rayed or analyzed by newly developed image analysis techniques, such as computed tomography or neutron imaging, or by synchrotron facilities (Sodini et al., 2017). The lack of densitometric studies to date is likely due to the limited availability of wood densitometrical and computed tomography facilities in the past (Sirr and Waddle, 1997), but in the future they may be expanded because of the availability of cheaper and better analytical techniques (Sodini et al., 2017), such as for example neutron imaging (Lämmlein et al., 2019).

Other techniques can be used to assess and confirm wood sources. For example, recent genetic analyses of maternally-inherited mitochondrial DNA across the distribution of Norway spruce in the Alps revealed highly diverse populations in the eastern Alps and monomorphic populations in the western Alps. The variation in tree genetics allows for the separation of northern populations from southern, and is useful for assessing population diversity at the regional or local scale (Gugerli et al., 2001; Tollefsrud et al., 2009). Although further research is still needed, this approach is promising for establishing the wood source (Jansen et al., 2017).

Moreover, other biochemical analyses offer promising means of determining wood sources. For example, X-ray fluorescence spectroscopy analysis is a particularly promising not destructive method to achieve precious information on the wood chemical element composition (Rovetta et al., 2019). Other analyses, such as those of wood strontium isotopes (e.g., Reynolds et al., 2005) and carbon and oxygen stable isotopes (Gori et al., 2015) provide information about the specific local environmental conditions and physiological characteristics of the tree population growing at a certain site (Cherubini et al., 2021). Such methods require some wood for analysis and are therefore somewhat destructive. However, collection curators and luthiers should keep in mind that if some wood pieces do become available, for example during restoration efforts (Fig. 6), such methods may provide precious information.

Dendrochronology is indispensable to string instrument experts, dealers, and collectors because it enables the objective verification of date attributions made on the basis of art history and stylistic criteria. For the purposes of dating precious string instruments, dendrochronological methods offer a unique nondestructive, scientifically-sound analytical technique. Such methods must, however, be rigorously applied paying attention to the technical, methodological, and statistical tenets of dendrochronology.

Declaration of Competing Interest

The authors declare that they have no known competing financial

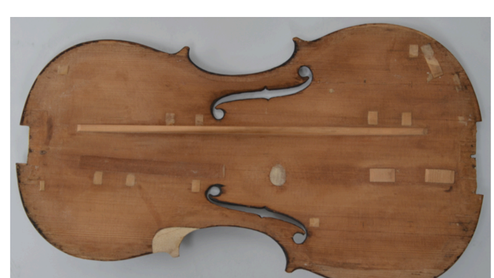

Fig. 6. Backside of the front of a viola (*terminus post quem*: 1643) attributed to the Antonio Mariani (1635–1695) school: during repair and restoration some wood pieces may become available for destructive analyses.

interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

P.C. thanks Piero Piussi (Università di Firenze, Italy) for having introduced him, when P.C. was still a PhD student, through the fabulous violin forest in Paneveggio (Dolomites, Trentino, Italy), Lisa Wingate (INRAE, Bordeaux, France) for sharing her views regarding "hazel" wood, Francesca Sedran (lawyer in Venice, Italy) for revealing some secrets related to the market of string instruments, Jacqueline Annen (WSL) for preparing the artwork (Fig. 5), and Erin Gleeson (ScienceEdit.ch) for help revising a previous draft of the manuscript. P.C. dedicates this paper in memory of Dieter Eckstein (Universität Hamburg, Germany), sadly passed away in 2021, who always inspired him in the study of the secrets recorded in the tree rings, and motivated him to study string instruments.

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