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A dendroarchaeological re-examination of the "Messiah" violin and other instruments attributed to Antonio Stradivari

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Abstract

The "Messiah" violin is considered by many to be the finest work by Antonio Stradivari and one of the most valuable musical instruments in existence. Questions were recently raised concerning its authenticity on stylistic and historical grounds, especially in light of conflicting sets of tree-ring dates for the spruce top of the violin. To resolve this controversy, we analysed the tree rings on the "Messiah" and those found on five other instruments constructed in the same general period, dating these against a regional chronology that integrated 16 alpine tree-ring chronologies from five countries. We conclusively dated both the "Archinto" (1526–1686) and "Kux"/"Castelbarco" (1558–1684) violas against the regional chronology. We could not directly date the "Messiah" against the regional master chronology, but found that its tree rings dated well against both the "Archinto" and "Kux"/"Castelbarco" violas. Our results strongly suggest that the tree rings of the "Messiah" violin date between 1577–1687, dates that support the attribution to Antonio Stradivari and the label date of 1716. We hypothesize the wood used to make the "Messiah" came from a low-elevation tree growing distant from the high alpine areas, whereas the wood used to make the two violas likely came from an intermediate, mid-elevation location.

Keywords: Dendroarchaeology; Tree rings; Musical instruments; Messiah; Antonio Stradivari

1. Introduction

Dendrochronological techniques for the dating of musical instruments were first applied by Lottermoser and Meyer [16], who conducted simple comparative analyses of tree-ring patterns between instruments. The first true dendrochronological analyses that generated precise dates for tree rings from musical instruments were conducted by Corona [2,3], and later by Klein et al. [13], Mehringer [17], and Klein et al. [14]. These and more recent studies [4,15,21] were primarily conducted to confirm or reject label dates and attribution, especially in the case of stringed instruments where the provenance (i.e., origin and ownership history) has been questioned. For example, Klein et al. [14] demonstrated that ten stringed instruments of the 75 that could be dendrochronologically dated had outermost dates that were younger than the attribution date. In this case, intent to defraud the buyer or to simply add value to an instrument may be inferred, possibly by inserting a label with an altered, fake, or fictitious label date and/or maker signature into a more contemporary instrument.

In recent years, controversy has surrounded the celebrated violin known as the "Messiah", attributed to the renowned Cremonese maker Antonio Stradivari (1644–1737) [6,18,19,22,24]. The violin has a label date of 1716, being therefore created during Stradivari's "Golden Period" (ca. 1700–1720 [10]). The violin is considered by many to be his finest work. The instrument lies in a near-perfect state of preservation, housed in a glass case at the Ashmolean Museum in Oxford, UK, donated to the British people by Alfred and Arthur

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Hill [5]. The Hills had previously described the physical details of the instrument and its history of ownership since Stradivari's death in 1737 [11]. The description and history further fuelled the controversy as a recent study noted possible inconsistencies in style and provenance of the violin [18], suggesting the violin could be a copy, perhaps made by the famed French violinmaker and copyist, Jean-Baptiste Vuillaume (1798–1875) ([25]; see also the discussion in [24]).

The most convincing argument that the instrument was a copy came from dendrochronological analyses of the tree rings from the spruce top of the "Messiah". Two studies conducted independently (though unpublished) both suggested that the youngest tree ring on the "Messiah" was formed during the year 1738 (see the discussions in [18] and [22]; also the article by Whittell [26]), in which case Stradivari could not have made the Messiah, as this date is one year after his death (1737). A subsequent dendrochronological study, published in this journal, provided evidence that the youngest tree ring of the "Messiah" dated to 1682, a date that lent support to the instrument being made by Stradivari [24]. The controversy became further confounded when one investigator retracted their original 1738 date. The controversy surrounding the authenticity of the Messiah then focused on the two different tree-ring dates. At stake was not only the credibility of musical instrument appraisal, but the reputation of dendrochronology and its ability to date accurately each tree ring to one year and one year only.

To help resolve the controversy, we analysed the tree-ring patterns of the spruce top on the "Messiah" violin using more rigorous dendrochronological techniques than previously applied to determine the date for its youngest tree ring. If the violin was made by Stradivari, the youngest ring should (1) correspond to years when Stradivari manufactured instruments (ca. 1664–1737, see [10]), and (2) occur within a reasonable range of the label date of 1716, given that some sapwood rings were likely removed during the construction process. We emphasize that dendrochronologists can only assign dates to the tree rings. We cannot conclusively prove that the violin was made by Stradivari. Rather, we can only prove that Stradivari could *not* have made the violin should the tree rings post-date his death. Tree-ring dates that are contemporary with his working career and the label date, however, can provide substantive scientific support to the claim that Stradivari made this particular violin.

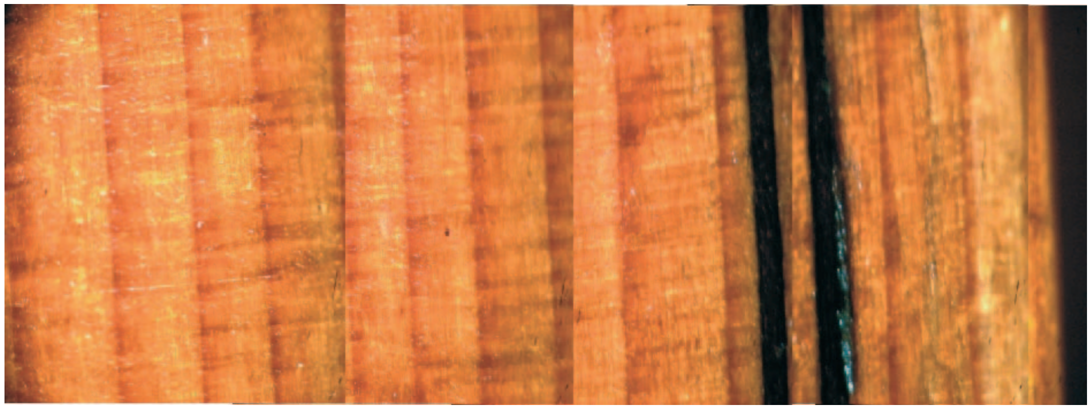
2. Materials and methods

We measured the widths of the spruce tree rings (precise to 0.001 mm) on the "Messiah" top, both the base and treble halves, using a Velmex® measuring stage interfaced to a laptop computer running MeasureJ2X® software. An imaging system mounted on top of the microscope captured digital images of the tree rings of the "Messiah". We also obtained measurements from five other instruments: the "Archinto" viola (Stradivari label, dated 1696); the "Kux"/"Castelbarco" viola (attributed to Stradivari, original label missing, but likely dating ca. 1720; see [20]); the ex "Cipriani Potter" violin (Stradivari label, dated 1683); an unnamed violin attributed to Stradivari (label dated 1666); and an unnamed violin (label dated 1696) attributed to Francesco Ruggeri (1645–1700, also spelled "Ruggieri"). Tree-ring patterns from these additional measurement series could help crossdate the "Messiah" tree rings because the Cremonese violinmakers probably obtained the wood for most of their instruments from nearby forests in northern Italy [24].

Because violin tops are made from "butterflied" halves of quarter-sawn logs [23], tree rings are presented in the radial view (Fig. 1) rather than the transverse (cross-sectional) view preferred in dendrochronology. In the radial view, the stem wood is split along its vertical axis and the cells are viewed from the side instead of the top. Ring boundaries are therefore less distinct, which could make locating all rings, especially very narrow rings, more difficult. To ensure that all tree rings were properly identified and measured, we each made independent sets of measurements on both treble and bass halves of the "Messiah" and ex "Cipriani Potter" violins. We compared sets of measurements by observer statistically for both violins using correlation analysis and the computer program COFECHA [8,12] to help verify that all rings were properly identified.

We crossdated individual series by instrument using COFECHA to place each series against each other in its correct temporal location. These placements were graphically confirmed using superimposed line plots. Once the bass and treble sides were crossdated by instrument, we combined the measurements into separate instrument chronologies using the computer program CRONOL [1], which detrends individual measurement series before averaging the resulting indices for each year. Detrending tree-ring series is necessary because (1) low-frequency trends arise from normal physiological aging, (2) changes in growth rates may occur within and between trees due to local disturbances, and (3) some trees simply grow faster than others [7]. These effects are well-known to introduce trends that may hamper crossdating efforts. CRONOL detrended the original measurement series by fitting negative exponential curves or regression lines to each series, then generated indices of growth for each year by dividing the actual measurement with that value obtained from the trend line or curve.

Yamaguchi and Allen [29] and Yamaguchi [28] have shown that crossdating autocorrelated tree-ring series



mm	1.836	1.514	1.264	1.310	1.130	1.196	1.300	1.254	1.708	1.492	1.234	1.428	*
yr	1589	1588	1587	1586	1585	1584	1583	1582	1581	1580	1579	1578	1577

Fig. 1. Photomosaic of the "Messiah" tree rings in radial view, treble side, lower bout, with measurements in mm above the years. Tree growth is from right to left. The tree ring for 1577 (*) is an incomplete ring. The dark bands to the right are the purfling around the edge of the violin.

against a reference chronology can result in many "false positives", i.e., a placement may be found for the chronology being dated that is temporally incorrect. High autocorrelation, a common property of tree-ring series [7], occurs because tree growth in any one year can be strongly influenced by tree growth from previous years, i.e., "biological inertia". The effects of this property are apparent in the two possible dates (early 1680s and late 1730s) suggested for the youngest rings on the "Messiah" during previous investigations. To remove autocorrelation in the detrended series, CRONOL performed autoregressive (AR) modelling to produce a final residual tree-ring chronology for each instrument with all autocorrelation removed, thus increasing the likelihood that the correct temporal placements of the chronologies would be found.

Dated reference chronologies from nearby sites are required to successfully date "floating" (i.e., undated) chronologies. At least 16 dated chronologies from five countries exist in the higher portions of the nearby Alps. To increase the likelihood that the tree rings from the instruments would be successfully dated, we developed a region-wide reference chronology based on these 16 chronologies, representing information from several hundred trees from three different species (Table 1). An assessment of the interseries crossdating indicated some chronologies had a few, short innermost and outermost segments that had low correlations with the corresponding segments from the remaining chronologies. This is expected because low sample depth in these earlier or later segments causes individual tree dynamics (e.g., competition from nearby neighbouring trees) to outweigh effects caused by the common macroclimatic signal necessary for region-wide crossdating. Therefore, these short, disassociated segments were not used in our analyses. Some of the longer chronologies were simply truncated at AD 1500 because earlier years were of little use for dating instruments made in later centuries. Final interseries correlations were statistically significant (Table 1), indicating a strong regional climate signal stretching from western France to southern Germany, a distance of approximately 600 km.

To date each individual instrument chronology, we relied primarily on the computer program COFECHA, entering the reference chronology as the dated series and the instrument chronologies as undated series. COFECHA uses "segmented time series correlation analysis" [8] by breaking down the series being dated into shorter, overlapping segments and searching for possible dates for these segments. Because of the relatively short tree-ring series on the instruments, we examined 40-year segments lagged 10 years (i.e., rings 1–40, 11–50, 21–60, etc.). This short lag allowed us to determine more precisely the beginning and ending years of segments with significant correlations, thus allowing us to more precisely identify problem segments. Using segmented and lagged time series is advantageous because many more tree-ring sequences can be tested and problem segments and rings (if any) can be more easily identified and localized. Further, individual tree dynamics may cause erratic ring patterns in the instrument series being dated. The use of multiple, shorter segments can circumvent the effects of these problems during crossdating attempts. A possible match was indicated when (1) COFECHA specified the same systematic dating position for most of the segments, and (2) the correlations associated with these suggested placements were statistically significant. We also used graphical techniques to verify the placements suggested by COFECHA by creating line graphs from the instruments being dated and overlaying these against each other and against the reference chronology. Suggested

Table 1
Individual chronologies obtained from the International Tree-Ring Data Bank (ITRDB, [9]) used in this study

Site name	Country	Begin year[a]	End year[a]	Species code[b]	ITRDB code	Interseries correlation[c]
Les Merveilles Site 1	France	1500	1964	LADE	FRA 010	0.57
Les Merveilles Site 2	France	1500	1964	LADE	FRA 009	0.57
L'Orgere Site 1	France	1523	1958	LADE	FRA 012	0.64
Berchtesgarden	Germany	1551	1947	LADE	GER 019	0.49
Fodara Vedla Alm	Italy	1559	1990	LADE	ITA 024	0.74
Fodara Vedla Alm	Italy	1563	1990	PICE	ITA 023	0.62
L'Orgere Site 2	France	1563	1972	LADE	FRA 011	0.65
Obergurgl	Austria	1591	1971	PICE	AUS 002	0.70
Obergurgl	Austria	1604	1972	LADE	AUS 004	0.68
Fodara Vedla Alm	Italy	1640	1990	PCAB	ITA 025	0.64
Cortina d'Ampezzo Sud	Italy	1709	1975	PCAB	ITA 007	0.60
Arosa Tritt Nord	Switzerland	1718	1975	PCAB	SWI 107	0.61
Cortina d'Ampezzo Nord	Italy	1759	1975	PCAB	ITA 006	0.56
Milderaun Alm	Austria	1776	1975	PCAB	AUS 007	0.59
Patscherkofel	Austria	1816	1967	PICE	AUS 101	0.59
Katscherpass	Austria	1864	1975	PCAB	AUS 005	0.58

[a] Some inner and outer rings removed due to low correlations arising from low sample depth.
[b] ITRDB species codes used: LADE=*Larix decidua* Mill.=European larch; PCAB=*Picea abies* (L.) Karst.=Norway spruce; PICE=*Pinus cembra* L.=Swiss stone pine.
[c] The correlation of the chronology against the chronology developed from all remaining sites. All values are statistically significant ($P<0.0001$).

Table 2
Comparisons of ring measurements between three independent observers on two violins

Comparison	Correlation coefficient[a]	
	Bass	Treble
"Messiah"		
Observer 1 vs Observer 2	0.92	0.90
Observer 1 vs Observer 3	0.90	0.77
Observer 2 vs Observer 3	0.90	0.79
ex "Cipriani Potter"		
Observer 1 vs Observer 2	0.88	0.84
Observer 1 vs Observer 3	0.88	0.71
Observer 2 vs Observer 3	0.87	0.75

[a] All correlations are statistically significant ($P<0.0001$).

Table 3
Correlation analysis between the "Kux"/"Castelbarco" residual chronology and the "Archinto" residual chronology, comparing 40-year segments lagged 10 years

Chronology segment	Correlation coefficient
1–40	0.40[a]
11–50	0.43[b]
21–60	0.52[c]
31–70	0.60[c]
41–80	0.64[c]
51–90	0.60[c]
61–100	0.66[c]
71–110	0.58[c]
81–120	0.64[c]

[a] $P<0.05$.
[b] $P<0.01$.
[c] $P<0.001$.

placements had to be convincing both statistically and graphically.

3. Results

Our inter-observer comparison of ring identification and measurement precision revealed significant correlations among all measured series (bass and treble sides) for both the "Messiah" and ex "Cipriani Potter" violins (Table 2). We therefore were confident that we had identified all rings in the radial view and that our ring measurements were reproducible.

We found a statistically significant series of correlations when we compared 40-year segments of the "Kux"/"Castelbarco" residual chronology against the "Archinto" residual chronology (Table 3). The graphical comparison (Fig. 2, B and C) also indicated a strong match between the two chronologies. We therefore adjusted the ring numbers of the "Kux"/"Castelbarco" to correspond to those found on the "Archinto". COFECHA also found a statistically significant association between the "Archinto" residual chronology and the regional residual chronology over a 100-year period (Table 4). Correlations between the "Kux"/"Castelbarco" residual chronology and the regional residual chronology were also statistically significant over an 80-year period (Table 4), and were only slightly

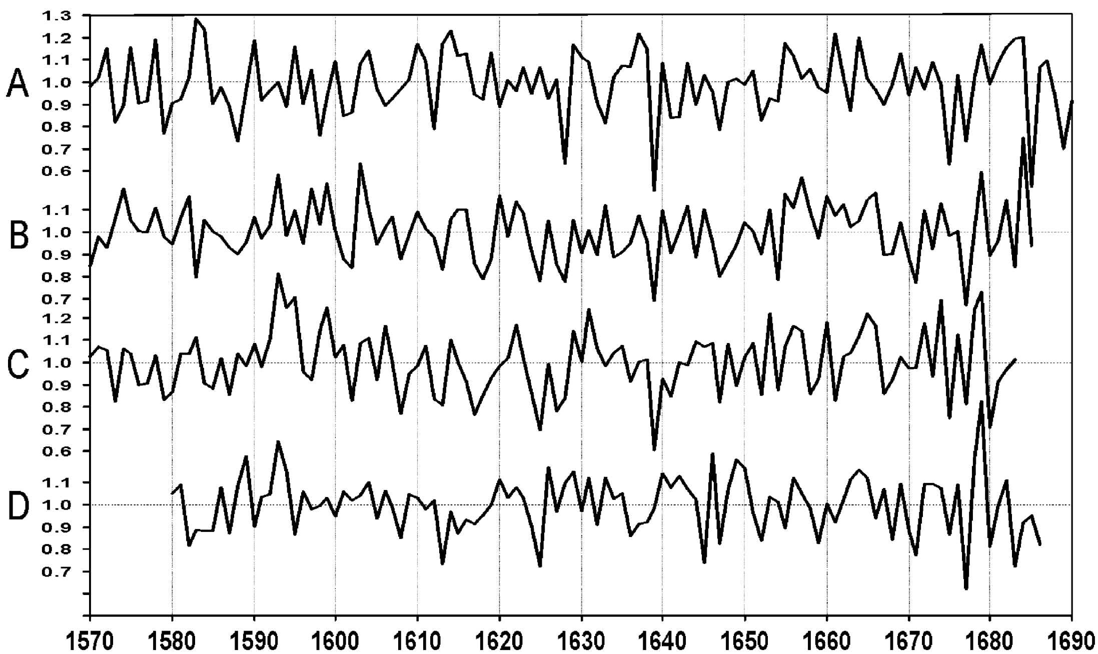


Fig. 2. Comparisons of the regional composite residual chronology (A) with the "Archinto" (B), "Kux"/"Castelbarco" (C), and "Messiah" (D) residual chronologies, showing the high degree of association among all series.

weaker than those found for the "Archinto". Graphical comparisons also clearly indicated firm dating (Fig. 2). Correlations for the innermost ring segments on both the "Archinto" and the "Kux"/"Castelbarco" were not significant, which likely reflects the effect of complacent ring sequences (i.e., with little year to year variability) that formed during juvenile growth [7]. These results strongly suggest that the youngest measured, complete tree ring of the "Archinto" is 1685, while the youngest measured, complete tree ring of the "Kux"/ "Castelbarco" is 1683. Partial rings were therefore present for the year 1686 on the "Archinto" and 1684 on the "Kux"/"Castelbarco".

Table 4
Correlation analysis between the "Kux"/"Castelbarco" and "Archinto" residual chronologies against the regional residual chronology, comparing 40-year segments lagged 10 years

Chronology segment	Correlation coefficient	
	"Kux"/"Castelbarco"	"Archinto"
61–100	0.09[a]	0.35[b]
71–110	0.12[a]	0.31[b]
81–120	0.42[c]	0.47[c]
91–130	0.45[c]	0.54[d]
101–140	0.46[c]	0.65[d]
111–150	0.43[c]	0.57[d]
121–160	0.40[c]	0.47[c]

[a] $P>0.05$ (not significant).
[b] $P<0.05$.
[c] $P<0.01$.
[d] $P<0.001$.

Combining both sets of measurements from the treble and bass sides of the "Messiah" violin, we developed a 107-year-long residual "floating" chronology from the 109 measured rings (the AR modelling resulted in the "loss" of the two oldest rings). We could not directly crossdate the "Messiah" residual chronology, however, with the master reference chronology we developed for this study. Attempts at dating the violin against each of the individual 16 chronologies were also unsuccessful. This result suggests the wood used to make the "Messiah" violin likely did not come from close proximity to the higher alpine areas where these chronologies were developed.

We next compared the residual chronology for the "Messiah" against both chronologies for the "Kux"/ "Castelbarco" and the "Archinto" separately, the chronologies of each viola acting as a new reference chronology, a common strategy employed in dendroarchaeological dating. COFECHA found a statistically significant match for the "Messiah" against both chronologies, although the relationship with the "Kux"/ "Castelbarco" chronology was stronger (Table 5). The same suggested temporal placement was suggested against both chronologies independently. Statistically significant correlations were found for all but one of the 40-year segments tested (Table 5). Comparisons of the graph of the "Messiah" chronology against both viola chronologies were also convincing, especially the

Table 5
Correlation analysis between the "Messiah" residual chronology and the "Kux"/"Castelbarco" and "Archinto" residual chronologies, comparing 40-year segments lagged 10 years

Chronology segment	Correlation coefficient	
	"Kux"/"Castelbarco"	"Archinto"
1–40	0.46[c]	0.23[a]
11–50	0.56[d]	0.42[c]
21–60	0.54[d]	0.40[c]
31–70	0.37[b]	0.29[a]
41–80	0.35[b]	0.26[a]
51–90	0.26[a]	0.14[a]
61–100	0.51[d]	0.46[c]
71–107	0.63[d]	0.54[d]

[a] $P>0.05$ (not significant).
[b] $P<0.05$.
[c] $P<0.01$.
[d] $P<0.001$.

noticeable "sawtooth" signature pattern in the youngest rings of the "Messiah" chronology (Fig. 2). These compelling statistical and graphical analyses strongly suggest that the youngest complete tree ring on the "Messiah" violin is the year 1686, with an incomplete, partial ring for the year 1687. These dates are in agreement with the 1682 outermost date found by Topham and McCormick [24]. The difference between their outermost dates and ours occurred because we found more rings near the pin on the lower bout.

Three of the six instruments we analysed could not be conclusively dated. The unnamed 1666 Stradivari violin could not be dated because the top appeared to consist of two adjoined pieces of wood, perhaps due to a defect in the wood that required removal, or because the original stem was too narrow in diameter. The short series (<60 rings) and potential missing rings precluded successful dating. The 1696 violin made by Ruggeri was problematic because measurement series from the treble and bass sides did not crossdate with a high degree of confidence against each. This suggests that different trees were used to make this violin rather than using "butterflied" halves of quarter-sawn logs. We were also unable to date each series separately against our master chronology. Lastly, the ex "Cipriani Potter" violin appeared to crossdate against the "Kux"/"Castelbarco" ($r=0.41$, $n=78$, $P<0.001$) with a suggested outermost date that supports its label date (1683). It did not date against either the "Messiah" or "Archinto", however. Comparisons with other dated instruments would be required to ensure this temporal placement, so we consider this violin undated pending further analyses.

4. Discussion

We found more inner and outer rings on the "Messiah", "Archinto" and "Kux"/"Castelbarco" than had previous studies. The importance of these additional rings should not be overlooked for two reasons. First, the longer chronologies made possible with these additional rings increase the likelihood of successful dating. Second, the interval between the youngest ring and the manufacture date is indicative of the seasoning period, which can vary by maker [24]. We found and measured three additional inner rings on the "Messiah" violin by carefully examining the area around the purfling (the inlaid wood or ebony that reinforces the edges of the violin, seen to the right in Fig. 1). After measuring as many rings as possible along a straight transect on the top of the violin, we noticed the rings were not parallel to the centreline, but instead formed an inverted "V" with a very shallow angle. This inverted "V" can occur due to the "conical" nature of tree growth upward and outward, or due to the quarter-sawn wood section being cut from the log off-vertical. This indicated that additional rings could be found in the area around the pin on the lower bout, where we indeed found four additional outer rings on the "Messiah". We found ten more rings on the "Archinto" (four inside and six outside) and two more outer rings on the "Kux"/"Castelbarco" than had previous studies.

The dates for the youngest partial rings for the "Archinto" (1686) and "Kux"/"Castelbarco" (1684) violas are remarkably similar. In addition, the statistical (Table 3) and graphical (Fig. 2) comparisons indicate very close agreement between the two chronologies, which strongly suggests that the two violas were likely made from trees that grew in the same forest stand, and perhaps were harvested during the same year. Interestingly, the label date for the "Archinto" (1696) is considerably earlier than the suggested manufacture date for the "Kux"/"Castelbarco" (ca. 1720). The label on the latter was either accidentally lost or purposely removed at some point since its manufacture, and the assigned date is based solely on stylistic evidence [20]. If the 1720 date is accurate, this suggests that the wood used to create the "Kux"/"Castelbarco" perhaps sat in Stradivari's Cremona workshop for 20+ years before being used. Long-term storage of wood before the manufacture of instruments is also suggested for the "Messiah" violin by the difference between its youngest partial ring (1687) and its label date (1716).

Despite the success in dating these instruments, we faced a perplexing situation that required resolution. The "Kux"/"Castelbarco" and the "Archinto" both dated against the regional reference chronology, while the "Messiah" did not. Yet, the "Messiah" dated against both the "Kux"/"Castelbarco" and the "Archinto". Logic infers that the "Messiah" therefore should have dated against the regional reference chronology. The explanation to this lies in the topographic position of the trees harvested to make these instruments and the probable differences in microclimate associated with these locations. Wilson and Hopfmueller [27] conclusively demonstrated that Norway spruce trees respond differently to local microclimate depending on their elevation. Spruce trees from the Bavarian Alps growing in low elevation (<680m) locations responded much differently to climatic variation compared to trees growing in mid-elevation (780–970m) and high elevation (>970m) locations. Based on these findings, spruce trees growing at lower elevations in the foothills of the Alps may not be easily crossdated using tree-ring chronologies developed from higher elevation trees [27].

We hypothesize that the spruce tree harvested and eventually used to manufacture the "Messiah" violin therefore might not have come from the higher locations in the Alps. If it had, our region-wide reference chronology, based on several hundred high-elevation trees from five countries, should have been capable of dating it. We suggest the spruce tree came from a location lower in elevation, in a different climate zone altogether. The trees used to make the "Archinto" and the "Kux"/"Castelbarco" perhaps came from an intermediate location, one that had climate characteristics of both the higher alpine areas and the lower areas in the foothills closer to Cremona. Therefore, the two violas would date against both the "Messiah" and the regional chronology, while the "Messiah" would date only against the two violas and not against the regional chronology.

5. Conclusions

We successfully dated three of the six instruments analysed in our study. We exclusively used residual chronologies (i.e., with autocorrelation removed) for dating floating dendrochronological series to minimize the possibility of a "false positive" occurring. We also used segmented time series analysis available through the COFECHA software, which provided statistical diagnostics that helped ensure correct temporal placements of the floating chronologies developed from the instruments. The "Archinto" viola contains tree rings formed between 1526–1686, the outermost date in agreement with its label date of 1696. The "Kux"/"Castelbarco" contains tree rings that formed between 1558–1684. Although the outermost date agrees with its suggested label date of 1720, the long interval (36 years) suggests long-term wood storage prior to manufacturing the viola. The "Messiah" violin contains tree rings that formed between 1577–1687, confirming the dates originally published by Topham and McCormick [24]. The difference between its outermost date and its label date (29 years) again suggests long-term wood storage. We could not date three of the instruments we measured, but the percentage of successfully dated instruments in our study is comparable to that found in two previous studies [14,24]. Because the "Messiah" dated against both violas, but not against the regional chronology, we hypothesize that the wood used to manufacture the "Messiah" came from a lower-elevation site while the wood used to manufacture the violas came from an intermediate, perhaps mid-elevation location.

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