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A Dendrochronological Study of Violins Made by Antonio Stradivari

John Topham

In the past two decades a well established scientific technique has been able to provide assistance in the attribution of old musical instruments. Dendrochronology, or tree-ring analysis, is a powerful method of dating wood that has been used in many fields of research, including archaeology, climatology, forest management, ecology, and art history. In musical instrument research, not only has dendrochronology been shown to be an incisive method for dating wood used in musical instruments, particularly those from the violin family, but it has also provided a glimpse of the way instrument makers of the past chose their wood, something that has hitherto not been recorded.[1]

Dendrochronology relies on the identification and assessment of the growth pattern of the wood's grain. This can be done only on trees growing in a temperate climate where a pronounced seasonal change occurs from summer to winter. This pattern is measured, recorded as a series of numbers, and compared using standard pattern cross-matching,[2] graphical, and statistical methods with dated reference material, thereby enabling a date for the youngest ring on the piece of wood to be obtained.[3] The fundamental strength of dendrochronology, in contrast with other methods such as carbon dating, is its precision: if a positive dendrochronological date is obtained for a piece of wood, it is a single date rather than a range of possible dates, as is the case with carbon dating. Dendrochronological dating is based on the principle that the width of the annual rings of a tree is influenced by the conditions the tree is subjected to while it is growing, and that these conditions prevail over a large area. These conditions include constants such as latitude and alti-

1. Peter Klein, "Dendrochronological Analysis of European String Instruments," *CIMCIM Newsletter* 14 (1989): 37–41; John Topham and Derek McCormick, "A Dendrochronological Investigation of British Instruments of the Violin Family," *Journal of Archaeological Science* 25 (1998): 1149–57.

2. Cross-matching involves comparing the ring-width pattern of different wood specimens. Samples with visually and statistically similar patterns are said to cross-match.

3. Fritz Schweingruber, *Tree Rings: Basics and Applications of Dendrochronology* (Dordrecht: Kluwer Academic Publishers, 1988).

tude, and variables such as rainfall and temperature. The history of the tree's growth is therefore, in a sense, encoded in the pattern of the tree rings.[4]

The similarity of growing conditions in a particular area, often reflected in similar grain patterns, allows the matching of wood from different trees. If the felling date of a particular tree is known, an exact pattern match with an undated neighboring tree can be found and a date for the wood from that tree can be established. Wood from a variety of musical instruments can be subjected to similar analyses using long sequences[5] of measurements known as reference chronologies and dates of the wood used for the fronts of these instruments can be fixed.

A reference chronology (sometimes also known as a master chronology) is usually established with data taken from trees of known felling date from a certain location such as a particular valley in the Alps. The subsequently compiled series of ring-width measurements is extended backwards in time by finding overlapping cross-matching series of measurements taken from older timbers, such as those found, for example, in old (and datable) buildings known to have used local wood.[6]

In most of the initial studies of ring-width series taken from musical instruments, two reference chronologies have been used to establish dates. One of these is based on series of spruce timbers taken from the Ötztal valley east of Innsbruck in Austria, and the other is based on larch timbers (*Larix decidua* Mill, a species which shows a growth pattern very similar to spruce) that originated from a region in the Dolomite Alps in northern Italy.[7]

4. Ring width is defined as the width of an annual growth ring measured from the beginning of the pale earlywood growth to the end of the darker and more dense latewood growth. It may be measured in transverse view as seen on a cut tree trunk or in tangential section as on a quarter-sawn violin front.

5. A sequence, or series, is a string of ring-width measurements taken from one piece of wood. The data are usually stored as column of numbers in a computer file, and can also be represented graphically as a ring-width curve. The year of each ring width is plotted evenly along the x-axis of a graph and the width of the growth ring is plotted along the y-axis.

6. Many reference chronologies have been developed, particularly by universities throughout Europe. These chronologies are valued information and are not generally available to those not associated with the university, although some have been published. Recently, on the retirement of the noted dendronchronologist Fritz Schweingruber, many of his chronologies were made available on the internet (*www.ngdc.noaa.gov/paleo/treering-wsl.html*).

7. See Veronika Siebenlist-Kerner, "Der Aufbau von Jahrringchronologien für Zirbelkiefer, Larche, und Fichte eines alpinen Hochbirgsstandortes," *Dendrochronologia*

Most stringed instruments of the violin family are constructed using maple (and other woods of the genus 'Acer') for the back, sides, and neck. The front, however, is generally made from Norway spruce (*Picea abies* (L.) Karsten), which, as a result of its stiffness-to-weight ratio, possesses what are regarded as the optimum acoustic properties for this kind of musical instrument. The making process usually results in a two-piece front with the youngest year-rings coming together at a longitudinal joint in the center of the instrument (fig. 1).

It is the spruce front that is used for dendrochronological investigation, as maple is unsuitable for this kind of testing, due largely to its erratic growth. What is remarkable about spruce, with its very clear annual growth behavior, particularly at high altitude, is that this similarity of grain pattern can extend to trees grown hundreds of kilometers apart, thus allowing wood taken from large regions to be matched. Because most violin makers in Europe have traditionally obtained their wood from the alpine region, covering many thousands of square kilometers, most research has concentrated on that area.

Antonio Stradivari and Denrochronology

Of all violin makers in the world, past and present, certainly the most famous is Antonio Stradivari, who lived in the northern Italian town of Cremona between 1644 and 1737. Revered for his superb craftsmanship, he is reputed to have made about 1200 instruments, of which only about 600 survive. Much has been written about these instruments, particularly his violins, many of which have been given names to identify them as they changed hands over the generations. Books such as those by Herbert Goodkind and the Hill family, which list instruments made by Stradivari, serve as detailed references and a testament to the prolific nature of his work.[8] The way these and other authors have written

2 (1984): 9–29, and Wulf Hüsken, *Dendrochronologische und ökologische Studien an Nadelhölzern im Gebiet der pragser Dolomiten (Südtirol/Italien)* (Berlin and Stuttgart: J. Cramer, 1994). For more information on reference chronologies and other aspects of dendrochronology consult the web-sites *http://www.ngdc.noaa.gov/paleo/treering.html* (an American site that leads to many other dendrochronological sites) or *http://www.btinternet.com/~j.topham/dendro.htm* (the author's site, where most of the papers cited are listed).

8. Herbert K. Goodkind, *Violin Iconography of Antonio Stradivari, 1644–1737* (Larchmont, New York: H. K. Goodkind, 1972); W. Henry Hill, Alfred F. Hill, and Arthur E. Hill, *Antonio Stradivari: His Life and Work (1644–1737)* (London: William E. Hill and Sons, 1902; reprint New York: Dover Publications, 1963).

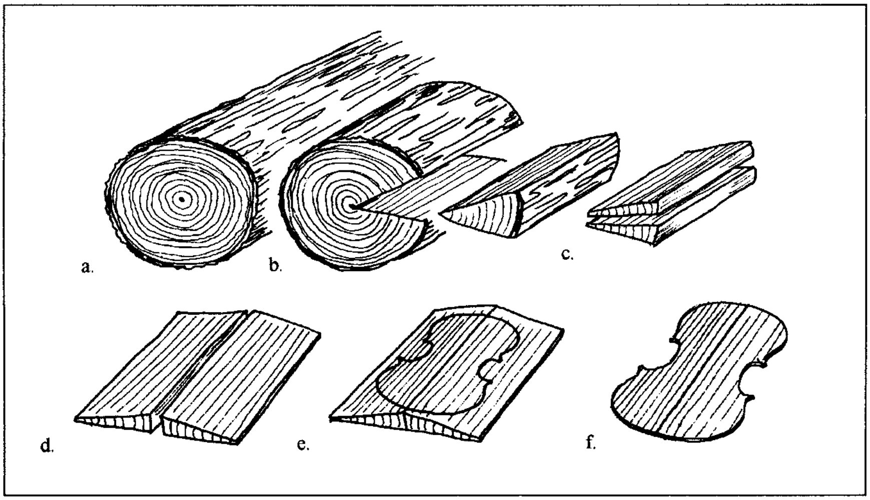

Figure 1. The construction of a violin front from a log of spruce. A thick wedge is first cleaved from the log, then further cleaved or sawn and opened out like a book. The thicker edges are then prepared and joined to form a board ready to be cut out and carved.

about the craftsmanship, tone, and ease of use of his instruments suggests they regard them as some of the most perfect musical objects ever constructed.

However, much remains unknown concerning the methods used to construct his instruments, despite recent books such as Stewart Pollens' study of the wooden forms used by Stradivari, which describes his use of a limited variety of outlines or patterns to define the shape of his instruments.[9] In addition, some of Stradivari's tools and templates still exist and are on display at a museum dedicated to him in Cremona. However, with the exception of information that can be gleaned from the few diagrams that accompany his tools, much of his working method remains a mystery. In particular, despite important recent research on Stradivari's life and his style as a violin maker,[10] we still lack any substantial information about the source of his wood and the criteria used in selecting it,

9. Stewart Pollens, *The Forms of Antonio Stradivari* (London: Biddulph, 1992).

10. Carlo Chiesa and Duane Rosengard, *The Stradivari Legacy* (London: Biddulph, 1998); Charles Beare, *Antonio Stradivari: The Cremona Exhibition of 1987* (London: J. & A. Beare Ltd., 1993).

particularly for the fronts of his instruments.[11] Dendrochronology may cast some light on this particular mystery. For example, it is common practice in violin making today to assume that the fronts of instruments will perform best acoustically when they are made from two pieces taken from a single wedge or plank of wood which is split and joined, with the youngest rings coinciding at the center joint. However, recent research has shown that this may not be entirely the case with Stradivari: in a study of thirty or so Italian instruments, Derek McCormick and I showed that many of the twenty Stradivari instruments we measured appeared to have fronts made of non-matching halves, meaning that the two pieces may not have come from the same tree.[12]

The first recorded application of dendrochronology in the investigation of instruments made by Stradivari was that of Drs. Werner Lottermoser and Jürgen Meyer in a 1958 article entitled "On the possibility of a dendrochronology of old Italian violins."[13] They measured the growth rings on the fronts of three violins by Antonio Stradivari and two by Pietro Guarneri of Mantua, and while their investigation did not succeed in dating the wood, they did find a relative correlation between some of the instruments. In 1991 Prof. Elio Corona published a study on the violin by Stradivari known as "Il Cremonese," dated 1715, in which he revealed that he had been able to provide a *terminus post quem* (oldest possible) date of 1696 for the violin's front—although work done on two other Stradivari instruments was not so successful.[14] Finally, in an article in the *Newsletter of the British Violin Making Association* in 1996, Dr. Peter Klein reported on his examination of three Stradivari violins dated 1698, 1703, and either 1711 or 1717 (the latter ambiguity presumably being due to unclear handwriting on the label). In all three cases the *terminus post quem* dates for the wood used in their fronts—respectively 1679,

11. The Hill brothers stated that, despite suggestions that Stradivari used old material, their own opinion was "rather in favour of the more youthful wood" (*Antonio Stradivari,* 165).

12. John Topham and Derek McCormick, "A Dendrochronological Investigation of Stringed Instruments of the Cremonese School (1666–1757) including 'the Messiah' Violin attributed to Antonio Stradivari," *Journal of Archaeological Science* 27 (2000): 183–192.

13. Werner Lottermoser and Jürgen Meyer, "Uber die Möglichkeit einer Dendrochronologie von altitalienschen Geigen," *Instrumentenbauzeitschift* 12 (1958): 295–296.

14. Elio Corona, "Indagini dendrocronologiche sul violino 'Cremonese' 1715," *Strumenti d'Antonio Stradivari* (Cremona: Ente Triennale Internazionale degli Strumenti ad Arco, 1991), 29–33. The other two instruments were a 1711 cello known as the "Duport" and another cello residing in the Cherubini Museum in Florence.

1680, and 1704—were consistent with the dates found on the instruments' labels, resulting in a difference of nineteen, seventeen, and either seven or thirteen years, respectively, between the attributed manufacture dates and the dendrochronological dates. Klein also showed that only the front of the 1711/1717 violin was made of pieces that came from the same tree, whereas the other two fronts were not.[15] Apart from these studies, it is clear that dendrochronological work done on the instruments made by Stradivari has been limited.

A Survey of Violins made by Antonio Stradivari

As part of a general ongoing investigation into classical Cremonese instruments, I have so far measured 72 instruments by Stradivari, comprising 69 violins and three violas. Measurements were taken directly from the fronts of 65 instruments made available by various individuals, workshops, and institutions in Paris, London, and elsewhere in the U.K. Graphs of sequences from a further seven instruments were provided through the offices of Dr. Lottermoser's laboratory, the Physikalisch-Technische Bundesanstalt in Brunswick, Germany. All the instruments are listed in chronological order in table 1, with those having the same manufacture date listed chronologically according to when they were measured. As most instruments have two-piece fronts (one violin dated 1695 had a one-piece front), a total of 143 sequences were recorded.

When recording the year-ring pattern, measurements of each ring were made on the widest part of the lower section of the front, to maximize the number of growth rings available. This entailed measuring the grain in radial section, i.e., across the face of the front, rather than the more usual cross-section (something not possible with a musical instrument without cutting it in half!). As viewed from the front, with the scroll uppermost, the left and right sides of the spruce front are referred to as the bass and treble sides, respectively. The measurements were made at magnifications of $\times 16$ with a stereo microscope mounted on a horizontal, hand-adjusted travelling carriage under which the instrument was fixed. Measurements to an accuracy of ten micrometers were obtained using an electronic measuring device mounted on the travelling carriage, and were recorded on a laptop computer. The sequences

15. Peter Klein, "Dendrochronology and Violins," *Newsletter of the British Violin Making Association*, Issue 4 (1996): 12–25.

Table 1. Instruments available for the study (all violins except nos. 11, 51, and 53, which are violas)

Instrument No.	Attributed Date	Name	Side	No. of Rings	Date of Youngest Ring	Difference	Average Ring Width (mm)
1	1666	—	Bass	81	1652	14	1.20
			Treble	85	1657	9	1.13
2	1666	—	Bass	72	—	—	1.33
			Treble	69	—	—	1.37
3	1666	Ashby	Bass	79	1653	13	1.14
			Treble	78	1649	17	1.17
4	1680	—	Bass	75	—	—	1.22
			Treble	78	—	—	1.24
5	1681	Reynier	Bass	74	1675	6	1.28
			Treble	75	1674	7	1.28
6	1682	—	Bass	197	1669	13	0.51
			Treble	202	1653	29	0.48
7	1683	Cipriani Potter	Bass	70	1671	12	1.26
			Treble	75	1677	6	1.17
8	1685	—	Bass	123	1632	53	0.77
			Treble	142	1659	26	0.68
9	1694	Rutson	Bass	116	1679	15	0.83
			Treble	95	1670	24	0.90
10	1695	—	Whole front	191	1666	29	1.00
11	1696	Archinto	Bass	149	1679	17	0.75
			Treble	139	1673	23	0.80
12	1696	—	Bass	192	1670	26	0.49
			Treble	156	1647	49	0.49
13	1698	Joachim	Bass	89	—	—	1.09
			Treble	96	—	—	0.98
14	1699	—	Bass	127	1682	17	0.75
			Treble	138	1679	20	0.68
15	1699	Ex-Crespi	Bass	151	1677	22	0.62
			Treble	148	1679	20	0.64
16	1699	—	Bass	137	1674	25	0.72
			Treble	172	1650	49	0.53
17	1699	Kustendyke	Bass	187	1670	29	0.52
			Treble	203	1681	18	0.47
18	1704	Betts	Bass	97	1662	42	—
			Treble	96	1653	51	—

Instru-ment No.	Attri-buted Date	Name	Side	No. of Rings	Date of Youngest Ring	Differ-ence	Average Ring Width (mm)
19	1707	—	Bass	135	1679	27	0.72
			Treble	154	1694	12	0.63
20	1708	Davidoff	Bass	125	1697	11	0.78
			Treble	119	1687	21	0.82
21	1708	Tua	Bass	104	1698	10	0.93
			Treble	104	1674	34	0.94
22	1708	Ex-Regent	Bass	107	1697	11	0.92
			Treble	101	1697	11	0.97
23	1708	—	Bass	102	1698	10	0.95
			Treble	108	1700	8	0.88
24	1708	—	Bass	152	1684	14	0.65
			Treble	147	1686	16	0.66
25	1708	Havemeyer	Bass	101	1699	9	0.97
			Treble	137	1690	18	0.72
26	1709	La Pucelle	Bass	147	1693	16	0.67
			Treble	134	1690	19	0.73
27	1710	Campo Selice	Bass	88	1688	22	—
			Treble	80	1684	26	—
28	1711	Parke	Bass	95	1704	7	1.05
			Treble	84	1694	17	1.04
29	1711	—	Bass	90	1698	13	1.06
			Treble	94	170	8	1.00
30	1712	Fountaine	Bass	61	1702	10	1.18
			Treble	58	1702	10	1.18
31	1712	Le Brun	Bass	98	1703	9	0.99
			Treble	86	1705	7	1.11
32	1713	Gibson-	Bass	98	1697	16	1.03
		Huberman	Treble	96	1706	7	0.97
33	1713	Baron	Bass	98	1702	11	0.98
		d'Assignies	Treble	89	1692	21	1.08
34	1714	Dolphin	Bass	93	1702	12	1.03
			Treble	92	1704	10	1.06
35	1714	General Kyd	Bass	89	1694	20	1.09
			Treble	90	1700	14	1.07
36	1715	—	Bass	99	1698	17	0.96
			Treble	100	1699	16	0.97

Instrument No.	Attributed Date	Name	Side	No. of Rings	Date of Youngest Ring	Difference	Average Ring Width (mm)
37	1715	Marsik	Bass	78	1697	18	1.24
			Treble	92	1703	12	1.05
38	1715	—	Bass	90	1702	13	1.10
			Treble	92	1701	14	1.06
39	1715	Baron Knoop	Bass	73	1700	15	1.35
			Treble	79	1701	14	1.21
40	1716	Messiah	Bass	93	1682	34	1.05
			Treble	95	1675	41	1.03
41	1716	Milstein	Bass	68	1706	10	1.43
			Treble	74	1699	17	1.18
42	1716	Provigny	Bass	88	1699	17	1.11
			Treble	84	1693	23	1.15
43	1716	Booth	Bass	66	1703	13	1.46
			Treble	74	1704	12	1.30
44	1716	—	Bass	78	1703	13	1.25
			Treble	90	1706	10	1.08
45	1716	de Duranty	Bass	83	1701	15	1.14
			Treble	86	1703	13	1.12
46	1717	—	Bass	93	1699	18	1.02
			Treble	91	1699	18	1.07
47	1717	Sasserno	Bass	82	1665	52	1.19
			Treble	90	1686	31	1.09
48	1717	Park	Bass	72	1662	55	1.34
			Treble	85	1689	28	1.15
49	1717	—	Bass	139	1712	5	0.71
			Treble	138	1714	3	0.72
50	1718	Maurin	Bass	125	1709	9	0.78
			Treble	116	1706	12	0.84
51	1719	Macdonald	Bass	73	1708	11	1.62
			Treble	72	1712	7	1.55
52	1719	Alba Herzog	Bass	119	1704	15	0.75
			Treble	120	1706	13	0.72
53	1720	Kux	Bass	117	1678	42	0.96
			Treble	121	1681	39	0.95
54	1720	Ex Beckerath	Bass	59	1682	38	—
			Treble	63	1692	28	—

Instrument No.	Attributed Date	Name	Side	No. of Rings	Date of Youngest Ring	Difference	Average Ring Width (mm)
55	1721	—	Bass	132	1709	12	0.74
			Treble	115	1710	11	0.85
56	1721	Lady Blunt	Bass	139	1704	17	—
			Treble	111	1698	23	—
57	1721	Prof Lutz 1	Bass	119	1702	19	—
			Treble	118	1695	26	—
58	1722	—	Bass	117	1694	28	0.82
			Treble	100	1662	60	0.97
59	1722	Conte de Chaponay	Bass	142	1713	9	0.71
			Treble	132	1710	12	0.72
60	1723	—	Bass	136	1712	11	0.71
			Treble	114	1673	50	0.87
61	1724	Sarasate	Bass	104	1713	11	0.94
			Treble	96	1711	13	1.02
62	1724	—	Bass	101	1714	10	0.99
			Treble	105	—	—	1.16
63	1724	—	Bass	101	1715	9	0.98
			Treble	105	1716	8	0.94
64	1725	Chaconne	Bass	93	1707	18	—
			Treble	98	1698	27	—
65	1726	Viola d'Amoure	Bass	65	1714	12	1.40
			Treble	76	1715	11	1.30
66	1730	—	Bass	82	1702	28	1.18
			Treble	82	1696	34	1.21
67	1730	Prof. Lutz 2	Bass	103	1691	39	—
			Treble	117	1694	36	—
68	1733	Hamma	Bass	79	1722	11	1.21
			Treble	79	1719	14	1.23
69	1733	Pr. Khevenhuller	Bass	84	1719	14	1.18
			Treble	86	1721	12	1.12
70	1733	Sassoon	Bass	82	1721	12	1.21
			Treble	83	1719	14	1.16
71	1734	Habeneck	Bass	81	1718	16	1.24
			Treble	84	1720	14	1.14
72	1736	Muntz	Bass	73	1716	20	1.30
			Treble	81	1716	20	1.16

of measurements from each piece of wood were subsequently compared and cross-matched with reference chronologies and previously dated sequences from other instruments, using standard dendrochronological techniques.[16] If a match was found that fulfilled the criteria set by normal dendrochronological methods, a date for the youngest ring of the sequence was fixed. Figure 2 shows schematically how this is done. Statistical analysis has a great deal to offer in the cross-matching and dating of sequences of ring-widths with references chronologies and other dated sequences; however, graphs are also used to a great extent in helping the assessment process. Figure 3 schematically shows how these graphs are constructed.

Of the 72 instruments measured, 69 (96%) significantly cross-matched the reference material, allowing the establishment of dates for 136 sequences from these instruments, which are listed in table 1. In each case the date of the youngest ring was earlier than the label date of the instrument. However, there is a wide range of variation between the dendrochronological dates and the attributed dates of the instruments' manufacture, from as few as three to as many as 60 years, with an average interval of approximately 25 years; these numerical differences are also listed in table 1. These intervals can be assumed to result from the combination of two factors: seasoning time before manufacture, and the removal of some of the outermost rings during the process of joining the two halves of the front. In our paper on Italian instruments, McCormick and I indicated that those makers evidently did not think it important to allow a long seasoning period; previously Dr. Peter Klein had shown that in the instruments he studied by Giuseppe Guarneri del Gesù, the interval between the date of the youngest ring and the date of manufacture was as low as three years.[17] However, whereas that article went on to suggest that this may have been due to Guarneri's hasty and not overly careful workmanship, the discovery that one of the Stradivari instruments in the present group also has an interval of only three years suggests that the choice of short seasoning times was perhaps a more common practice.

Seven sequences of the 143 measured for the current study were not dateable. Six of these come from violins that were made before 1700,

16. See above, pp. 72–73 and notes 3–7.

17. Peter Klein and Stewart Pollens, "The technique of dendrochronology as applied to violins made by Giuseppe Guarneri del Gesù," in Peter Biddulph, ed., *Giuseppe Guarneri del Gesù* (London: Biddulph, 1998), 159.

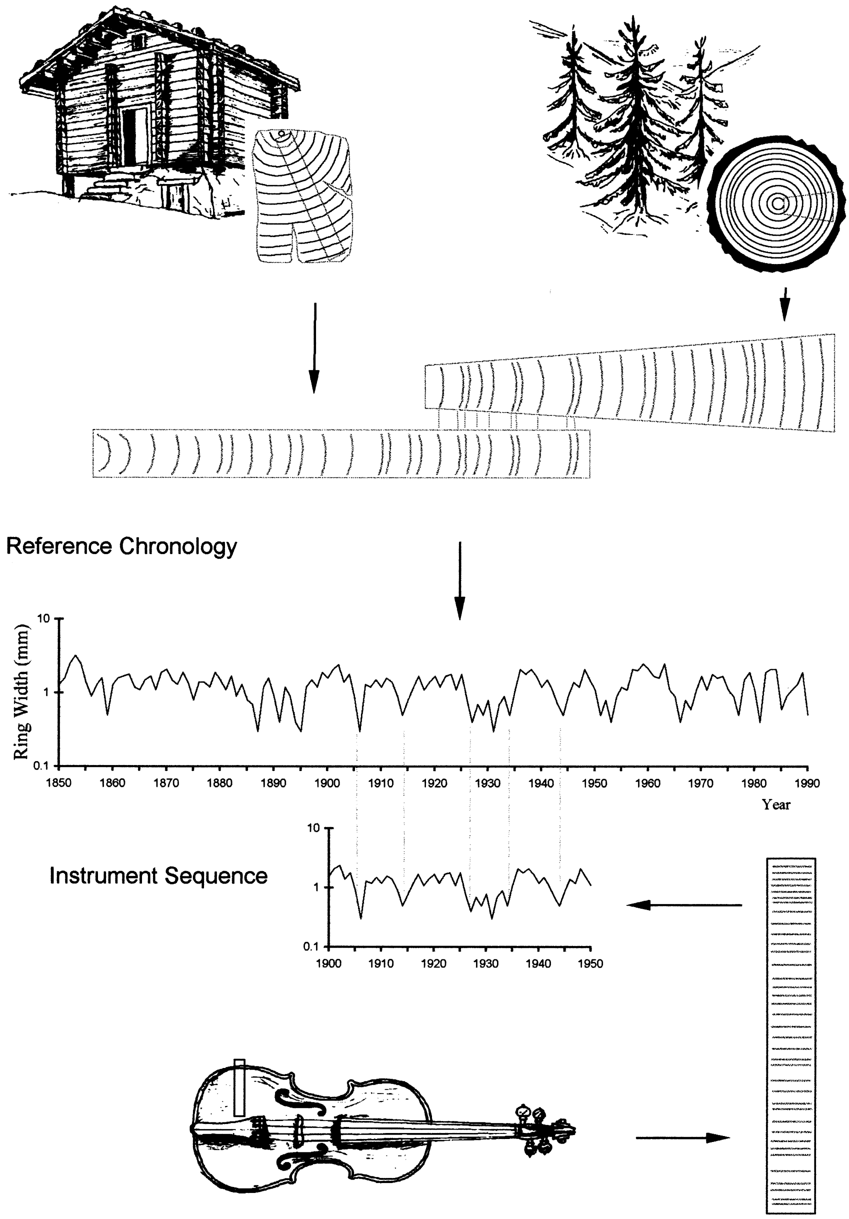

Figure 2. Schematic representation of the construction of a reference chronology and its comparison against a sequence of ring widths taken from the front of a violin.

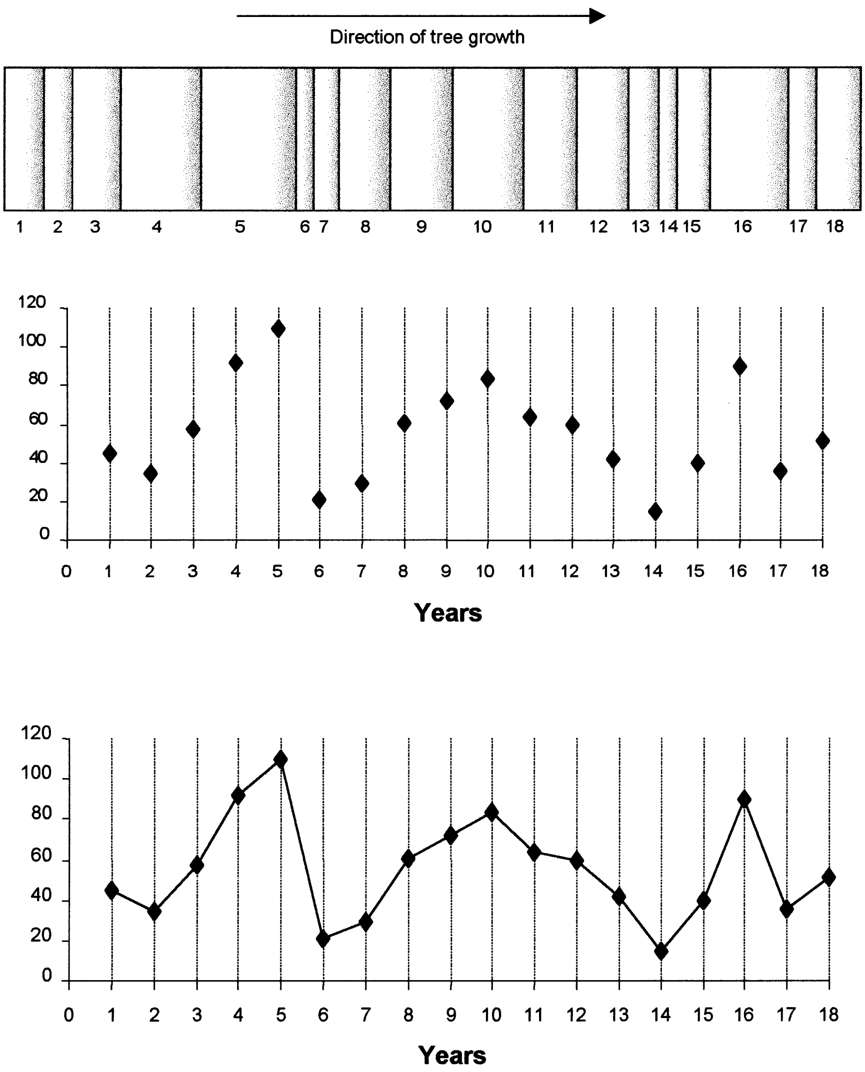

Figure 3. The ring widths measured from the front of an instrument (top diagram) are plotted sequentially, with each ring representing one year (middle diagram). The width of each ring is represented by how high the point is plotted against vertical axis calibrated in hundredths of a millimeter. The points are joined together with straight lines to show the pattern of the ring widths more clearly (bottom diagram).

while the seventh comes from the treble side of an instrument dated 1724 (no. 62 in table 1). Not being able to date the wood suggests that its source was very different from that used by Stradivari for the other instruments. From surveys of other Italian instruments a similar trend also emerges, particularly with instruments made by the Amati family, who also worked in Cremona. The dating of sequences from Italian instruments made before around 1700 is patchy, whereas those made after then, particularly in the eighteenth century, are relatively easy to date. One factor that could account for this is the nature of the wood trade in the northern and central alpine regions. As far as I have been able to determine, no documentary evidence is available relating to trade in this specialized wood during this period. However, based on opinions of some of the violin experts in the U.K., it is plausible that prior to 1700 or thereabouts no particular centralized network existed, so that artisans would have acquired wood from a variety of sources. After 1700 perhaps merchants in one particular region established some kind of organized dealing in wood, of which Stradivari then took advantage.

Properties of the Wood Used by Stradivari

The grain structure of all the dated and undated pieces used for the fronts studied here varies a great deal. Although it is difficult to draw any concrete conclusions based on the limited number of instruments studied, various patterns do appear which are worth noting.

Nowadays, violin makers tend to follow certain criteria when choosing wood, particularly for their fronts. First they look at the quality of the wood, specifically considering the closeness and evenness of grain, the lightness yet strength of the wood, and its capacity to ring when lightly knocked. Secondly they check for the ease of working, that is, how well it carves and how well it finishes when smoothed using either a plane or a scraper. Lastly, makers often make sure that the front comes from one piece of wood, i.e., a single thick wedge, which is either bought as such or cleaved from a larger piece. This thick wedge is then further cleaved or sawn in half and opened like a book, and its outer edges are prepared and joined to produce a board ready to be cut out and carved (fig. 1). The idea here is to maintain a kind of symmetry across the face of the front, which is thought to enhance the front's tonal quality. When all these factors are correct in the maker's mind, he or she can be fairly confident that the resulting instrument's sound will be of high quality.

Although dendrochronology cannot be used to study all these factors, some significant characteristics can be examined directly, such as the closeness and evenness of grain, and to some degree also whether the maker chose symmetrical pieces.

Closeness of grain. As the two pieces of wood making up the instrument's front are roughly the same width, particularly on violins, the closeness of grain can be measured by recording the number of rings on each piece and computing the average ring width for each sequence. The average number of rings on the 143 sequences shown in table 1 is approximately 117, with the highest number being 203 and the lowest 58. The average ring width for the same sequences is approximately 1.00 mm, with the widest being 1.62 mm and the narrowest 0.47 mm.[18] These minimum, maximum, and average values are typical of all the sequences (nearly 2000 at the time of writing) measured so far from a variety of instruments from all over Europe and suggest that in this respect the wood used by Stradivari had no particular special property.

Sequences from some of Stradivari's violins made before 1700 have very narrow ring widths, far less than the average. For example, the instrument having the narrowest average ring width (0.47 mm) and the greatest number of rings (203) on one side of the front is the 1699 "Kustendyke" belonging to the Royal Academy of Music in London (no. 17 in table 1). Others in the survey with similar ring widths and a large number of rings per piece include violins made in 1682 and 1696. The narrow-grain wood used by Stradivari is not unique to him, however: two other instruments, one made by Francesco Ruggeri in 1683 (privately owned) and another by Pietro Guarneri of Mantua c. 1685 (sold at Sotheby's auction in 2001), also utilized similar wood. In fact, there is a distinct dendrochronological relationship between at least two of the sequences. The two sides of the "Kustendyke" front cross-match quite well, but upon closer visual inspection it can be seen that the structure of the treble side corresponds more closely to the bass side of the Guarneri front (fig. 4). Stradivari appears not to have used such wood in his later instruments, and it is possible that these examples are the result of a

18. Numbers of rings and average widths were obtained from the 65 instruments measured directly. Average widths from the seven Brunswick Laboratory graphs could not be calculated directly as the scales on the graphs were not calibrated correctly. The pattern and structure of ring widths were nevertheless very clear, and dendrochronological dates were obtainable.

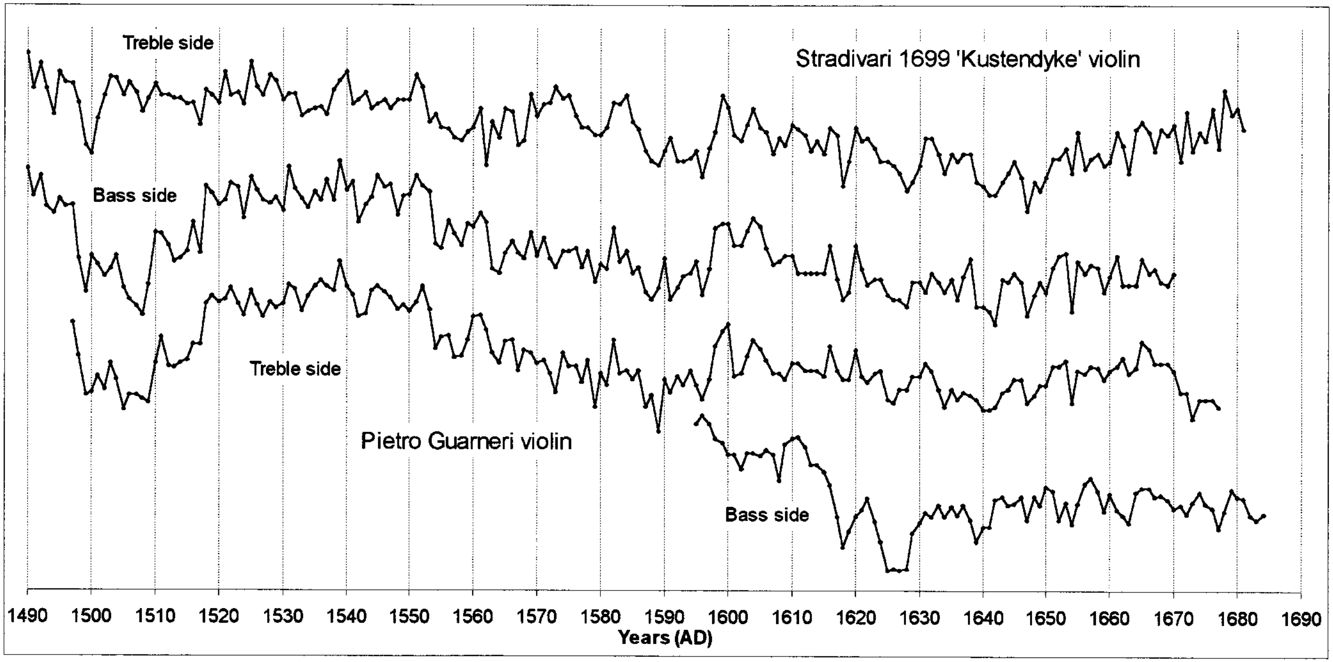

Figure 4. Sequences from the front of the 1699 "Kustendyke" violin by Antonio Stradivari compared with those from the front of a violin by Pietro Guarneri of Mantua. The similarities between grain structures of the bass side of the "Kustendyke" and the treble side of the Guarneri strongly suggest that these two pieces of wood came from the same tree.

consignment of narrow-grained wood from a particular high-altitude area, from which other makers also benefited.

Evenness of grain. Whereas most makers would prefer a completely even grain profile across the whole face of the front, it appears that Stradivari may have been less discriminating. A noticeable feature of some of the later instruments is his choice of wood that has distinct clusters of narrow rings. One set of sequences that exhibits this behavior comes from ten instruments that were made between around 1717 and 1723, including notable instruments such as the 1721 "Lady Blunt" violin (fig. 5). Figure 6 shows a typical sequence taken from the treble side of the "Conte de Chapony" violin, dated 1722 (instrument no. 59). As can be seen, it includes a short series of about six rings with the narrowest having a width of 0.25 mm dating to 1625. This short series at this date does not appear on other instruments from different periods and seems to be the result of Stradivari choosing wood from a particular region with a distinct local climate. The climate must have varied enough in this period, which lasted about a decade, to cause the trees to lay down narrow rings. The average ring-width for these instruments is also distinct, being about 0.77 mm, with the number of rings per piece averaging about 130.

Another short series of narrow rings appears on four other instruments made in the years 1724 and 1725, including the 1724 "Sarasate" violin (instrument no. 61, belonging to the Musée de la Musique in Paris) and the 1725 "Chaconne" violin (instrument no. 64, in a private collection). Figure 7 shows a typical example coming from an unnamed instrument made in c. 1724 (instrument no. 62). The series, which is slightly more extensive than the 1625 group, appears to extend from 1658 to 1677, with the narrowest ring having a width of 0.29 mm and dating to 1666. This series is also unique to this period and again suggests a particular source of wood that is different from the others. In spite of the narrow rings, the average ring width for sequences from this set is approximately a millimeter.

One-piece and two-piece fronts. Of the 72 instruments in the survey, only one violin has a one-piece front (no. 10 in table 1, dated 1695). It is not known how many of the 1200 or so instruments Stradivari made had one-piece fronts but it may have been a quite few. In Charles Beare's book on the Stradivari Exhibition (see note 10), it can be clearly seen from the photographs that at least two additional violins, dated 1702 and 1703, also have one-piece fronts. Stradivari appears not to have been too concerned about the orientation of the grain on his one-piece fronts.

Figure 5. The bass side of the 1721 “Lady Blunt” violin (courtesy of Charles Beare). Photo: Linea Tre, Cremona.

Some present-day makers hold the view that in such cases there may be a specific tonal advantage to having the older, wider grain set on the bass side of the front to enhance the lower harmonics of the sound. If this traditional view was advocated by older makers, it appears Stradivari did not subscribe to it: while the grain on the 1695 and 1702 violins is oriented with the oldest rings on the bass side, that of the 1703 instrument is oriented in the opposite direction. It is difficult to generalize about Stradivari’s preference for a particular grain orientation based on just three instruments, but to see a difference on such a small sample suggests he was not that concerned about it.

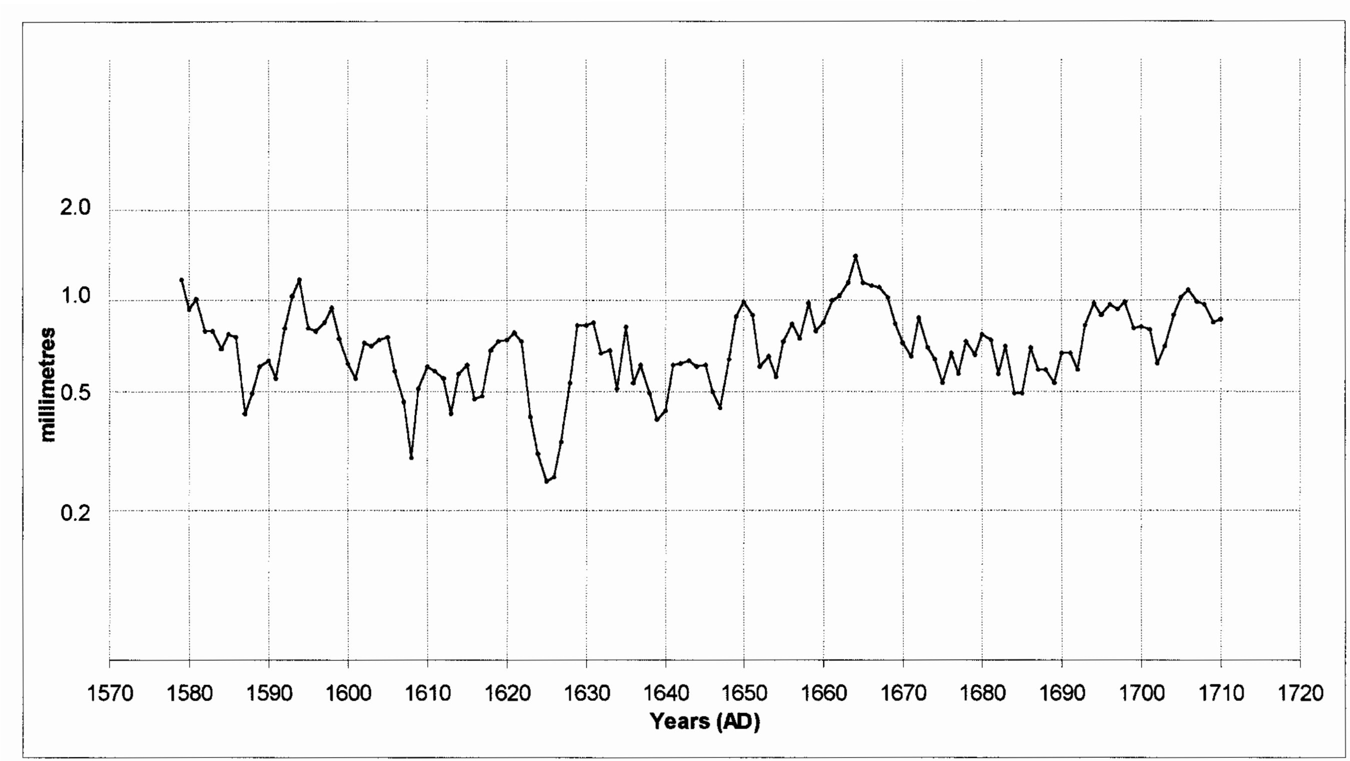

Figure 6. Graph of the sequence from the bass side of the 1722 “Conte de Chapony” violin, showing a series of narrow rings around 1625.

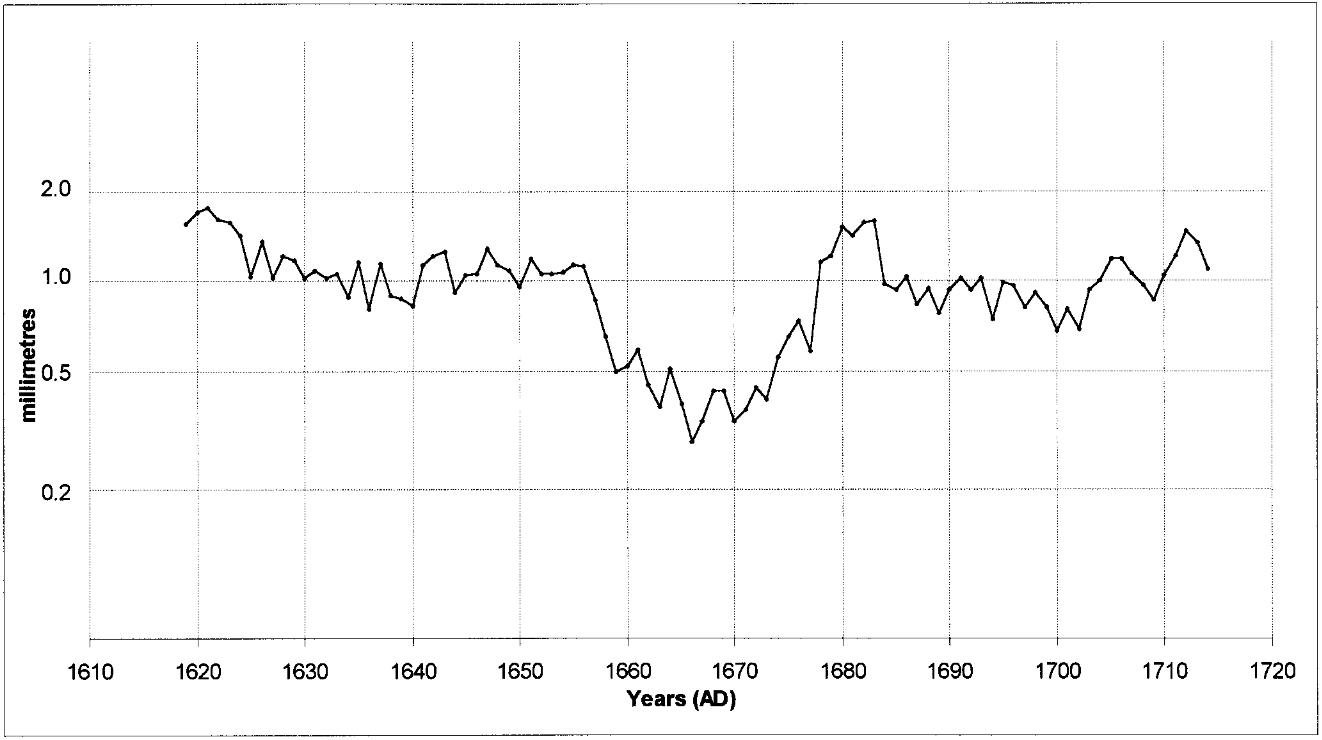

Figure 7. Graph of the sequence from the bass side of the unnamed c. 1724 violin, showing a series of narrow rings from 1658 to 1677.

With respect to violins with two-piece fronts, in general, makers tend to seek a perfectly symmetrical pair (two adjacent pieces cleaved from one piece of wood), believing such a combination to be tonally advantageous. From dendrochronological studies on instruments and evidence about the known practice of modern makers using or not using pieces of wood from the same tree, as well as other associated tree-ring cross-matching studies (see note 1), a relatively clear judgement can be made as to whether or not a maker used pieces from the same tree. It appears that Stradivari was more discriminating in this respect than in his choice of wood based on its evenness of grain. However, there are a few notable exceptions, such as the 1708 "Davidoff" violin (instrument no. 20), where the two sides of front of are statistically and visually very different (fig. 8). This suggests Stradivari may have been concerned only with matching the appearance of the wood, with no regard to the specific origin of the two halves, which may well have come not merely from two different places in the same tree but even from two different trees. Other violins in which the front appears to be constructed from unmatched pieces include the 1708 "Havemeyer" (instrument no. 25), the 1716 "Milstein" (no. 41), the 1733 "Sassoon" (no. 70), and an unnamed c. 1724 violin (no. 62). In the last of these, in fact, the front consists of pieces so different that one side cannot be dated. It is not necessary for each side to cross-match the other to establish a date, but it helps a great deal, particularly if, as is true in certain cases, one side is somewhat different from the main chronologies.

In the majority of his other instruments, Stradivari appears to have been interested in choosing fairly closely matching halves for most of the fronts. A typical pair from the unnamed 1730 violin (instrument no. 66) is shown in figure 9; here the average ring width of the sequences is approximately 1.20 mm with 82 rings per piece. In addition, a clue as to how Stradivari may have joined his pieces together is shown in figure 10. The graph shows the sequences from three instruments from this period, the 1711 "Parke" (instrument no. 28), the 1714 "Dolphin" (no. 34) and the undated "Marsick" (no. 37) violins.[19] Apart from their general similarity, which strongly suggests that all pieces came from the same

19. Figures 9 and 10 not only show how close the pieces are, but also show a type of wood typically chosen by Stradivari. Instruments made between 1708 and 1716 and between 1730 and 1736 show characteristics similar to this instrument. In addition to the similarity they have with each other, there is a set of four narrow rings at 1639, 1677, 1685, and 1689 with ring-widths of approximately half a millimeter.

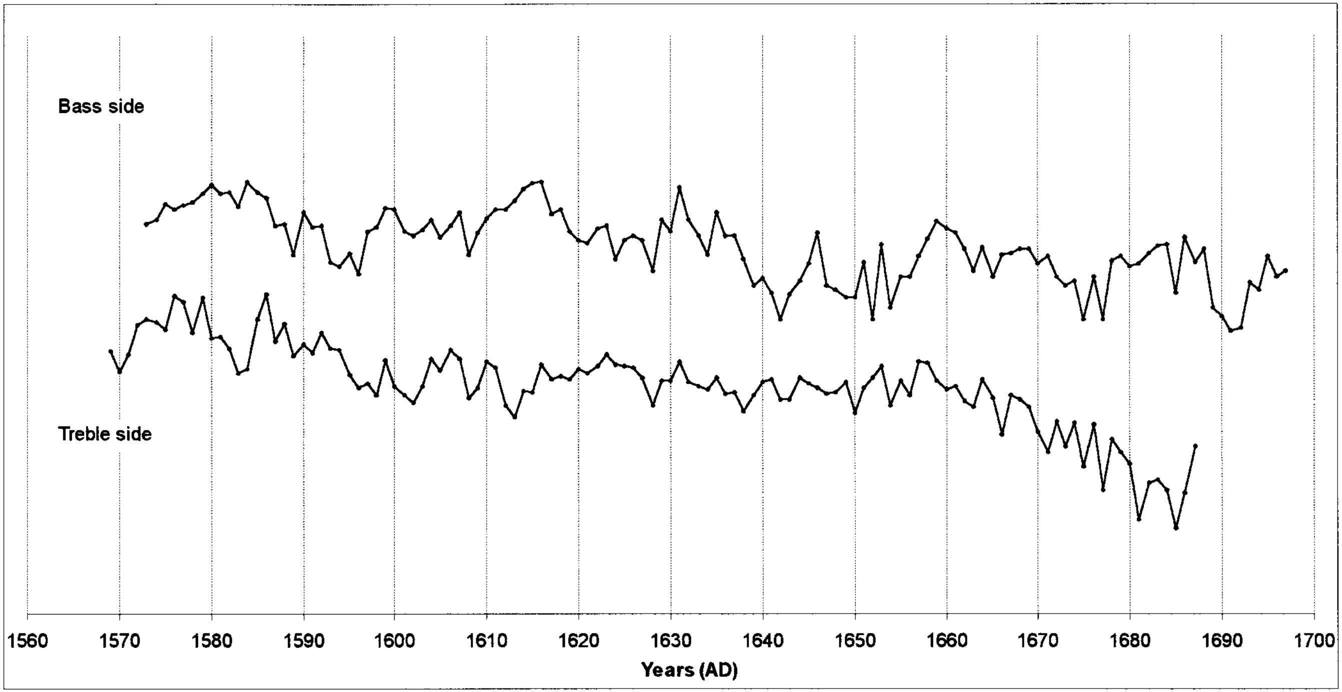

Figure 8. Graph of the sequences from the 1708 “Davidoff” violin, showing the different structures of the treble and bass sides.

Figure 9. Graph of the sequences from the unnamed 1730 violin (instrument no. 66).

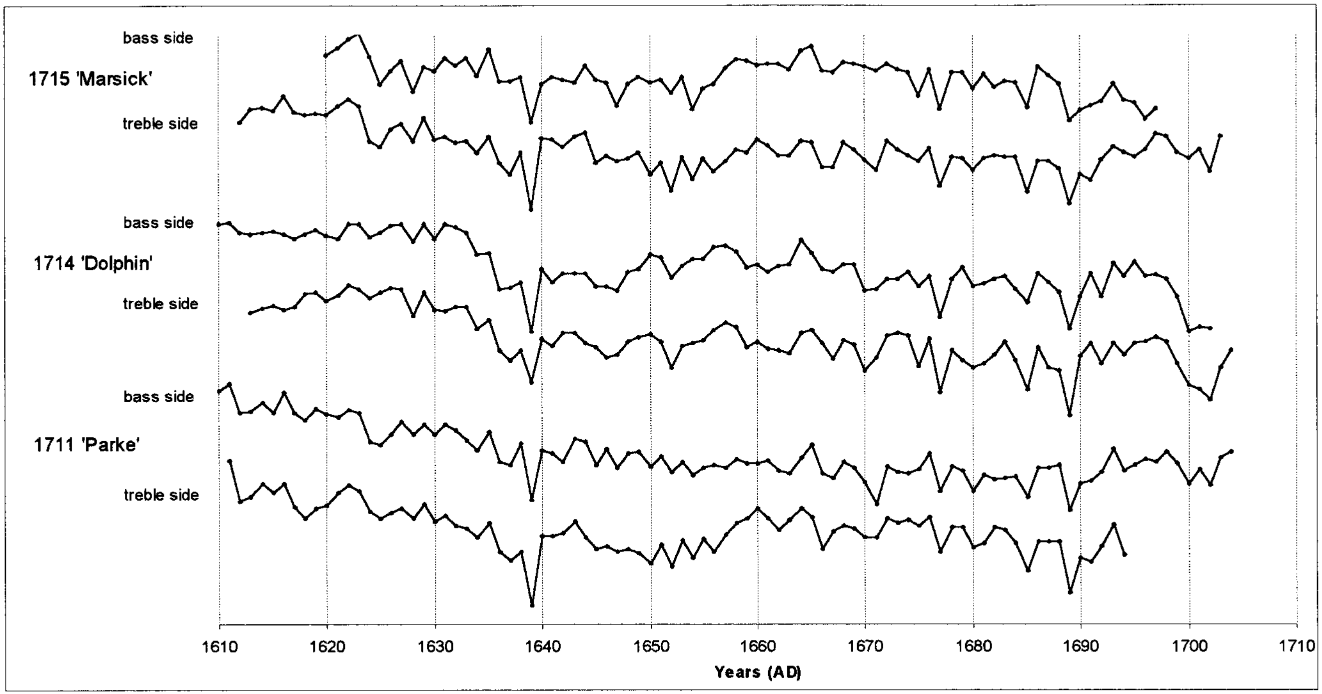

Figure 10. Graph of the sequences from the 1711 "Parke," the 1714 "Dolphin," and the c. 1715 "Marsick" violins.

tree, it would seem that for each instrument a matching adjacent pair of pieces was chosen. However, on closer inspection of figure 10, it can be seen that the sequences from the fronts of the treble sides of the "Parke" and "Marsick" violins match each other more closely than they do their respective other halves. This suggests that these two sides were split from closer positions in the tree than the other four. Together with evidence from other violins, particularly in the period 1717 to 1723, this would suggest that rather than pairs being split from adjacent positions of the same tree, Stradivari split off single pieces and joined pairs together without too much regard to choosing specifically adjacent pairs.

Conclusion

The above results may cast light on some aspects of Stradivari's choice of wood, at least as far as the construction of the fronts of his instruments is concerned. This evidence is probably the only way we will know anything of his constructional ideas, since, like many other makers, Stradivari left little or no documentary evidence as to how he actually chose his wood and made his instruments. However, the above evidence does suggest a certain systematic working procedure, particularly after 1700.

Clearly, 72 instruments is not a sufficient number to prove that this was his common practice, but the fact that strong similarities do occur in such a small sample may indicate a distinct trend. Dendrochronological work to analyze all of Stradivari's instruments would be a major task indeed, but such an analysis would go a long way in shedding further light on the poorly-documented methods and practices not only of a craftsman who is revered the world over, but also of other makers and craftsmen who worked at the same time.[20]

20. I wish to thank all the people and institutions who allowed me to measure and assess the instruments, notably Charles Beare, Peter Biddulph, and the Royal Academy of Music in London. I would also like to thank the Musée de la Musique (Paris) for allowing me to see five violins in their collection (the 1708 Davidoff, 1708 Tua, 1724 Saraste, 1724 Provigny, and an unnamed 1699 violin, with inventory numbers E.1111, E.1932, E.1729, E.1730, E.1375, and E.1217 respectively). Finally, I would like to thank Derek McCormick for his help and support in the writing of this article.