# Pivotal Aspects of Organology of Stradivarius Violins and their Contribution to Higher Formant Frequencies

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# Contents

**Introduction**

This paper will explore the organology of Stradivarius violins and how such aspects affect their acoustic quality and thus the formant frequencies.

A master luthier is in his workshop in Cremona, known by the name of Antonio Stradivari (1644-1737). He is sat at his workbench masterfully carving the scroll of his next violin, which will be played by the virtuosi of not only his era, but for centuries to come.

The exact date of when the violin was invented is unknown. However, there is evidence of the existence of early violins in the fifteenth-sixteenth centuries. Paintings by Gaudenzio Ferrari (1475-1546) depict a three-string violin, bearing resemblance to today's modern violin. In the painting 'Madonna of the Orange Trees' (1529-30) an infant is playing the violin. Such paintings suggest the existence of the violin dating back to the early sixteenth century[1].

By 1550 the popularity of the violin had grown significantly and it was an acclaimed instrument by 1563, increasing the demand for master luthiers. This is shown by King Charles IX of Spain requesting twenty four violins to be made by Andrea Amati (c.1505-1577) [2].

In Italy, during this era, there were many schools of violin making. Each regional area had a school, referring to the fact that luthiers who work from each individual area

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[1] Gaudenzio Ferrari, *'Madonna degli Aranci'*, Church of St. Cristoforo, Vercelli, Italy (1529-30)

[2] Roger Hargrave, 'From the Archive: Andrea Amati,1564" Charles IX" Violin from the Ashmolean Museum Collection', *The Strad,* (December 1991)

would share certain characteristics in their craftmanship which could be seen in the execution of the violins made in each area.

Each violin making school and each individual luthier create violins which impart their own individual characteristic design and sound distinguishing each violin school and the makers from one another. Cremona was a prominent violin making school, during the mid-sixteenth to the mid-eighteenth century. This period is sometimes referred to as a golden age of violin making[3].

In Italy between the sixteenth and eighteenth centuries, Cremona was highly regarded for violin making, with many master luthiers working there and these luthiers are still famous centuries later. Luthiers and scholars today have the highest respect for the existing Cremonese instruments, especially those made by Antonio Stradivari, whose prolific output surpassed the quantity of other makers, yet with detailed and masterful craftsmanship.

Both Andrea Amati and Gasparo Bertolotti, known more commonly as Gaspar da Salo (1540-1609), have been credited with inventing the modern violin[4].

The names of Amati and Stradivari are widely recognised, even amongst those who are not experts in the violin. From the sixteenth to the eighteenth centuries, there were four hundred and fifty violin makers, who are identifiable by name actively making violins throughout Italy at this time. These makers worked in the fifty towns which were home to violin making during this period and these makers along with many whom

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[3] Hwan-Ching, Tai et al., 'Acoustic Evolution of Old Italian Violins from Amati to Stradivarius', *Proceedings of the National Academy of Sciences*, Vol. 115, no.23 (2018), 5930

[4] ibid.

cannot be identified by name but who would have also been active in this craft are largely forgotten and unrecognised today[5].

There have been attempts to alter the shape and construction of violins since the Amati model, but no instrument has managed to match the tonal capabilities of the violin model designed by Andrea Amati[6]. The overall form of the violin was set by Amati and became the basis upon which many successive luthiers such as Stradivari today base their violins on.

Stradivari and his contemporaries in the seventeenth and eighteenth centuries owned neighbouring shops in Cremona. There is a common belief that amongst the violins with a superior acoustic quality are those made by Antonio Stradivari, Giuseppe Guarneri del Gesù and the Amati family[7].

There is little documented evidence about the early life of Antonio Stradivari. The earliest evidence known of him comes from a violin from 1666 inscribed with the label 'Alumnus Nicolai Amati'. Stradivari is widely considered to have been apprenticed to Nicolò Amati from a young age. He is believed to have worked in the workshop of Nicolò Amati, until his master's retirement in 1680[8].

There are however conflicting views on how and where Stradivari first learnt his craft. One alternative proposal is that rather than being fully apprenticed to Nicolò Amati in

[5] Greilsamer et al., 'On Old Violins', *The Musical Quarterly*, (1927), 411

[6] Hwan-Ching Tai et al., 'Acoustic Evolution of Old Italian Violins from Amati to Stradivarius', *Proceedings of the National Academy of Sciences*, Vol. 115, no.23 (2018), 5926

[7] Karel, Jalovec, *Italian Violin Makers*, (1958) New York

[8] Mariana Dominica, Stanciu, et al., 'X-Ray Imaging and Computed Tomography for the Identification of Geometry and Construction Elements in the Structure of Old Violins', *Materials* 14, no. 20 (2021), 5926.

his youth, he first worked as an apprentice woodcarver and inlayer in the shop of Francesco Pescarolli, whose workshop was close to Amati's, in the Piazza San Domenica in Cremona. When not working for Pescarolli, he would work in Nicolò Amati's shop and learn the art of violin making[9].

Stradivari's earliest years are often considered to be his Amati period (1666 -1690), during this time his instruments show considerable influence of the Amati family's practices and aesthetics. The decade 1690-1700 is commonly referred to as Stradivari's period of experimentation[10]. During this period, Stradivari made longer length violins, which became known as the long pattern violins.

With the turn of the eighteenth century, the violins which Stradivari made became shorter and the arching flatter. Stradivari evolved the model of the violin and the cello to their current form today. He also made many other stringed instruments including violas, harps and guitars. Stradivari gave most attention and time to making and developing the form of violins, demonstrated through his numerous violins still in existence today.

As the role of the solo violinist became increasingly popular with the evolving taste of music at the time, Stradivari lowered the arching of the violin, allowing for a fuller sound, with a greater capacity to project the music into large concert halls. This period is known as Stradivari's golden period. Violins made during the golden period (1700-1720) are often considered to be the most exquisite instruments of his career, with the

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[9] Arnalso Baruzzi, *La Casa Nuziale: The Home of Antonio Stradivarius 1667-1680*, translated by Desmond Hill (London, 1962) 65-6

[10] Lloyd Burckle, and Henri D Grissino-Mayer Henri D, 'Stradivarius, Violins, Tree Rings, and the Maunder Minimum: a Hypothesis', *Dendrochronologia*, 21, no. 1 (2003), 41-45

most superior tonal qualities[11]. During the lifetime of Stradivari, his artistic and technical prowess was admired by both fellow luthiers and performers[12]. Virtuosi such as Arcangelo Corelli and Giuseppe Torelli owned and played Stradivarius violins in his lifetime.

Jean Baptiste Vuillaume (1798-1875) and Simone Sacconi (1895-1973) are two influential figures in lutherie after Stradivari, who both studied and made copies of Stradivarius violins. Sacconi, (1895-1973) was one of the most prominent violin and string instrument restorers of the twentieth century. Luthier Sacconi was of the opinion that Stradivari was an expert, acutely aware of how the geometry of the violin affected acoustics and sensitive to what variations in the structure of the elements of the violin may create in terms of differences to acoustic quality[13].

In the late nineteenth century, the myth of Stradivari's creations sprouted and was particularly propagated by market actors, dealers, performers[14] and in particular by Abbé Sébastien-Andre Sibire. The myth continued to strengthen in France through luthier Jean-Batiste Vuillaume (1798-1875), who extensively studied and made copies of Stradivarius instruments, and Francois-Joseph Fétis (1784-1871), a well-respected violinist. The popularity of Stradivarius instruments rose to such a height, that copies

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**11** Hwan-Ching Tai et al.,'Acoustic Evolution of Old Italian Violins from Amati to Stradivarius', *Proceedings of the National Academy of Sciences*, Vol. 115, no.23 (2018), 5926

12 Aaron S Allen, 'Fatto di Fiemme: Stradivari's Violins and the Musical Trees of the Paneveggio. in L. Auricchio et al. Eds. Invaluable trees: Cultures of Nature, 1660-1830' 301-316

13 Sacconi Simone F., *The Secrets of Stradivarius* (Cremona, 1979)

14 Aaron S Allen, 'Fatto di Fiemme: Stradivari's Violins and the Musical Trees of the Paneveggio. in L. Auricchio et al. Eds. Invaluable trees: Cultures of Nature, 1660-1830' 301-316

of his instruments were made in large volume, while original Stradivarius were being collected by museums and investors, who began to display and loan these instruments, further leading to their superior mythical status[15].

The cult of Stradivarius violins becoming almost magical mythological objects has led to multiple experiments and tests being conducted on them, to uncover the secrets behind recreating a Stradivarius today. However, research on Stradivarius instruments is difficult to carry out due to the challenges of attaining samples. It took researcher Nagyvary twenty-five years to acquire the small samples of Stradivarius violins used in his experiments[16].

Today Stradivarius violins are often used not only to play baroque music but also to play more contemporary music and the setup of these violins have been modified to accommodate the playing of a wider range of music, including music of more modern styles.

Virtuosi today hold Stradivarius violins in the highest esteem[17]. Modern virtuosi who play on Stradivarius instruments include Yo-Yo Ma, Itzhak Perlman, Joshua Bell and Nicola Benedetti. Rudolf Kreutzer famously played Beethoven's Opus 47 violin sonata on a Stradivarius violin. The violin played by Kreutzner is named after him and is played today by virtuoso, Maxim Vengerov.

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[15] ibid. 313

[16] Joseph A Nagyvary et al., 'Mineral Preservatives in the Wood of Stradivarius and Guarneri', *PLoS ONE*, 4 (2009), e4245

[17] Hwan-Ching Tai et al., 'Acoustic Evolution of Old Italian Violins from Amati to Stradivarius', *Proceedings of the National of Sciences*, Vol. 115, no.23 (2018), 5930

Stradivarius violins are often the choice of virtuosi today, due to their unique acoustic quality. As expressed by virtuoso Maxim Vengerov, not all violins are equal and Stradivarius violins sound different to other violins[18]. Since Stradivari, despite many luthiers making copies and intimately studying Stradivari violins, the sound of his violins has not been recreated by luthiers.

Maxim Vengerov expresses how playing the Stradivarius violin taught him how to play the violin. He explains that learning how to play a Stradivarius violin takes time and that it is not the same as playing any other violin. Vengerov recounts that when he first began to play a Stradivarius, on complaining to his father that the sound was not good, his father told him that it was because he had not yet learnt how to play it. Vengerov's father continued to explain that once Vengerov had mastered the art of playing a Stradivarius, he would have greater artistic expression available to him than with any other instrument[19].

This account may explain why some people believe that Stradivarius violins being superior is a myth. If even a professional violinist plays a Stradivarius, until they have spent a long time learning how to play it, they may not be able to fully appreciate the violin's acoustic qualities, leading the violinist to not give a Stradivarius violin the recognition it deserves.

To fully appreciate the quality of a Stradivarius, Vengerov explains that first the violinist needs to have a high level of proficiency in playing the instrument. Next the violinist needs to have the time and patience to learn how to play the Stradivarius. Each new

[18] Maxim Vengerov, 'Me and my Strads', https://www.thestrad.com/lutherie/maxim-vengerov-me-and-my-strads/7925.article (accessed: 23rd August 2023)

[19] ibid.

violin requires a period of adaptation, but Vengerov's story explains that the time needed to be given to understand and learn how to unlock the expression of the Stradivarius violin may be longer. Vengerov did not immediately get the unique acoustic quality which Stradivari violins are renowned for, yet after learning how to unlock the expression of a Stradivari, the brilliance of the instrument shone through.

Stradivarius instruments have been modified to meet the demands and requirements of modern violinists such as Maxim Vengerov who play contemporary music. Consequently Stradivarius instruments have in many cases been altered by successive generations and have undergone irreversible changes. There are approximately five hundred Stradivarius violins in existence, many of which have been restored. Many luthiers consider only twenty percent of these five hundred to be in a suitable condition for playing today[20].

Violins made by master luthiers of the late seventeenth and early eighteenth centuries are often considered to have a superior tonal quality when compared to more modern instruments[21]. Nagyvary et al. and Burckle and Grissino-Mayer hold the opinion that there have been many attempts by luthiers in subsequent centuries to match the Cremonese instruments, whose standard of lutherie is unsurpassed[22] [23].

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[20] Tai Hwan-Ching et al., 'Acoustic Evolution of Old Italian Violins from Amati to Stradivarius', *Proceedings of the National of Sciences*, Vol. 115, no.23 (2018), 5930

[21] Lloyd Burckle, and Grissino-Mayer, Henri D, 'Stradivarius, Violins, Tree Rings, and the Maunder Minimum: a Hypothesis', *Dendrochronologia*, 21, no. 1 (2003), 41-45

[22] Joseph A Nagyvary et al., 'Mineral Preservatives in the Wood of Stradivarius and Guarneri', *PLOS ONE*, 4 (2009)

[23] Lloyd Burckle, and Henri D Grissino-Mayer, 'Stradivarius, Violins, Tree Rings, and the Maunder Minimum: a Hypothesis', *Dendrochronologia*, 21, no. 1 (2003), 41-45

Since Stradivari, despite many luthiers making copies and intimately studying Stradivari violins the sound of his violins has not been recreated by luthiers. The Hills in assessing the quality of copies of Stradivarius violins made by modern luthiers comment that 'the best of these display excellent craftsmanship, they look like the originals, but do not sound like them'[24].The Hills explain that whilst modern luthiers are able to make violins that have the aesthetic appearance of a Stradivarius, they have not been able to recreate the same acoustic quality.

Luthier Paul Gosling recounts that the sound of a Stradivarius today is different to the sound of a Stradivarius in its conception, due to the natural ageing of the instrument and its set up which have been altered to meet the needs of modern music repertoire today. Through the natural ageing process of the violins, the wood density and chemical properties have changed through the oxidation of the wood, thus altering the acoustic quality of the instruments[25]. In a similar way, the chemical composition of the varnish can affect the acoustic quality of the violin as the varnish changes over decades and centuries.

Gosling believes that the sound which many luthiers try to recreate today is the sound of Stradivari, which may not exactly resemble the sound of a Stradivarius violin in its conception. As we cannot know what a Stradivarius sounded like during his lifetime, we can only try to recreate the sound of a Stradivarius which we hear today[26].

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[24] W H, Hill, A F, Hill, A E, Hill, *Antonio Stradivari: His Life and Work* (1644-1737), (NewYork,1902)

[25] Paul Gosling, Personal Communication, 15th September 2023

[26] ibid.

In Gosling's view, luthiers today when making a violin strive to match the sound of a Stradivarius[27]. Although it is true that not all luthiers wish to recreate the sound of Stradivarius, many desire to capture aspects if not the full sound of a Stradivarius in the way in which we hear Stradivarius today.

Paul Gosling is a luthier who trained and worked at the Newark School of Violin Making for many years. He has his own workshop 'The Luthier's Valse' where he makes and restores violins. Throughout his career he has worked in many prestigious workshops allowing him to study many precious antique violins including those of Antonio Stradivari. Gosling has himself made many copies of Stradivari violins and has an intimate knowledge of Stradivari violins. He has given me permission to discuss the conversations which I have had with him and attribute it to his name in my research. I have spoken to Gosling informally several times including during repairs to my violin and on successive visits to his workshop, which included choosing wood from which to make my own violin.

Gosling spoke about the process involved in making a violin and the repairs which he has carried out on many prestigious instruments, including those by Stradivari. This provided me with detailed information on the aspects of organology on the Stradivarius violins which Gosling has repaired. This knowledge is rare as few people have had the opportunity to work on Stradivarius and other antique Cremonese violins.

Gosling discussed the relationship between Stradivari to other contemporary makers, which provided me with a foundation upon which to build my knowledge of lutherie. He also recounted the challenges a luthier has when working on Stradivarius violins.

[27] ibid.

He highlighted the importance of choosing the best wood for violin making. I had the opportunity to have several telephone conversations with Gosling to clarify questions or have his opinion on particular aspects of research which I was working on. During my conversations I learnt how a luthier views and judges a violin. He explained how he regards violin making as a craft and an art form.

Instrumental music and especially violin music has long been compared to the human voice as it is able to capture and imitate its expression. Through researching the formant frequencies produced by violins, the acoustic quality of them can be understood, with the resulting spectral analysis showing how, why and if a comparison of violin playing to the human voice is possible.

Thus far, research has not found any violins which are not made by Stradivari to exhibit formant frequencies which resemble those of the female voice; rather, other violins tested have exhibited formant frequencies which are lower than those of Stradivarius violins, resembling the male voice[28]. However the mystery as to why and how these higher formant frequencies in Stradivarius violins are present is unanswered.

**My Research Proposal**

In my research I aim to explore which aspects of organology may have contributed to the acoustic quality of Stradivarius violins by investigating what lies behind the higher formant frequencies exhibited by Stradivarius violins.[29] I will bring together research

[28] Hwan-Ching Tai et al., 'Acoustic Evolution of Old Italian Violins from Amati to Stradivarius', *Proceedings of the National Academy of Sciences*, Vol. 115, no.23 (2018), 5929

[29] ibid.

and analysis previously conducted on the organology of Stradivarius violins, to shed light on why or how these formant frequencies are present.

I will present a multi-faceted approach assessing several aspects of organology of Stradivarius violins, which may contribute to their acoustic quality and thus formant frequencies. Previous research by scholars has mostly concentrated on individual scientific research which has focused on one single aspect of organology of Cremonese and Stradivarius violins. There has been little research focused on multi-faceted approaches on the organology of Stradivari violins which compares and draws links between the scientific studies on the organology of Stradivarius violins. If the science of Stradivarius violins is understood, we can get closer to understanding what creates the acoustic quality of these valuable instruments.

Two branches of acoustic analysis exist, psychoacoustic studies and vibroacoustic studies. Psychoacoustic studies research the artistic subjective response of people to music. Vibroacoustic studies present the objective spectral analysis of the vibrations and frequency of the sounds produced by the instrument, object or voice. My paper will view acoustics from a scientific angle, focusing on how aspects of organology may affect the acoustic quality of violins, viewed through the lens of vibroacoustics.

I expect that there are many aspects of organology, besides those which I will explore in my paper and which have been researched by scholars and have potentially contributed to the formant frequencies of Stradivarius violins, however due to the scope of my research I will choose to focus on select aspects of organology in my paper. I view that it is possible that more than one aspect of organology may contribute to the acoustic quality and thus the formant frequencies of Stradivarius violins, making it important to see organology from many perspectives.

I will view the organology of Stradivarius violins from the original perspective by looking at their acoustic quality through the lens of formant analysis which is yet to be explored. Research has not yet been carried out into which aspects of organology may affect the acoustic quality of Stradivarius violins through the lens of formant frequencies.

My experience as a violinist serves as a valuable background. As I progressed with my playing, I was searching for a violin better suited to my small hands. This led me to visit luthiers' workshops. Through this I became interested in violin making and the craftsmanship of Antonio Stradivari. The conversations I subsequently had with luthiers and the interviews which I have conducted, have helped me to understand the aspects of organology which I will discuss in this paper.

**Previous Research on Stradivarius Violins**

In this next section I will briefly outline some of the research on the organology of Stradivarius violins which may also impact their acoustic quality, but which I will not focus on in my paper.

For over two centuries much of the research on Stradivarius violins has centred on the varnish of Stradivarius instruments[30]. Luthiers continue to strive to imitate the varnish on Stradivarius violins which they consider as exceptional[31]. Studies have also researched how the varnish of Stradivarius violins may have impacted upon their acoustic properties. Scholars, such as Dondi believe that the varnishes of the

[30] Piercalo Dondi et al., 'Automatic Analysis of UV-Induced Fluorescence Imagery of Historical Violins', *Computing and Cultural Heritage*, 10, no. 2 (2017), 1-13

[31]Jean-Philippe Echard et al., 'The Nature of the Extraordinary Finish of Stradivarius's Instruments', *Angewandte Chemie*, international edition, 49, no. 1 (2010), 197-201

seventeenth century had the dual task of both protecting the surface of the instruments alongside giving a good aesthetic effect[32].

More recently the research has become much more diverse on the organology of Stradivarius violins and the different aspects which researchers claim may impact upon the acoustic quality of Stradivarius violins.

The broad scope of previous violin research includes studies exploring the vibrational properties of the front and back plates[33], shape and design of the f-holes[34] and the varnish of Stradivarius violins.

Further research is required to find out the totality of the aspects of organology which may have contributed to the acoustic quality and thus the formant frequencies exhibited by Stradivarius violins.

**Outline of my Research**

In this section I will outline the structure of my paper. In Chapter One I will present the various studies which have explored the formant frequencies exhibited by Stradivarius violins, the results of these research papers and how I will use the findings of this research on formant frequencies of Stradivarius violins in my work.

In Chapter Two I will first discuss the work on the dendrochronological studies into the wood used by Stradivari to make his violins. I will examine this by looking at research

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[32] Piercarlo Dondi et al., 'Automatic Identification of Varnish Wear on Historical Instruments: The Case of Antonio Stradivarius Violins', *Journal of Cultural Heritage*, 22 (2016), 968-973

[33] Gough Cohn, 'Science and the Stradivarius', *Physics World*, 13, no. 4 (2000), 27

[34] Hadi T Nia, et al., 'The Evolution of Air Resonance Power Efficiency in the Violin and its Ancestors', *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 471, no. 2175 (2015)

by Burckle and Grissino-Mayer who present the hypothesis that the acoustic quality of Cremonese violins may be significantly enhanced compared to other antique and modern violins, due to the superior wood that grew during a time when temperatures in Western Europe were significantly lower than in the surrounding years[35].

I will next examine the study of Stoel and Borman who have compared the density of the wood of Cremonese violins, including that of a Stradivarius to modern European violins[36]. Finally, I will discuss how the findings of the studies discussed in the chapter have contributed to scholarship. This knowledge will aid understanding into the wood Stradivari used and how it may contribute to the acoustic quality and thus the formant frequencies of Stradivarius violins.

In Chapter Three I will introduce wood treatment of Stradivarius violins and the possibility that Stradivari used wood that was ponded, as explored in the study by Barlow and Woodhouse[37]. I will continue to explore the treatment of wood of Stradivarius violins discussing the findings of a modern luthier Folland, who experiments with ponding, using a method proposed by Stamm[38].

In the final chapter, I will discuss studies on the chemical treatment of wood used by Stradivari by Nagyvary et al. and Tai et al. who suggest that chemical treatments of

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[35] Lloyd Burckle and Henri D, Grissino-Mayer, 'Stradivarius, Violins, Tree Rings, and the Maunder Minimum: a Hypothesis', *Dendrochronologia*, 21, no. 1 (2003), 41-45

[36] Berend C Stoel and Borman Terry M, 'A Comparison of Wood Density Between Classical Cremonese and Modern Violins', *PLoS ONE*, 3, no. 7 (2008), e2554

[37] C Y, Barlow and J Woodhouse, 'Bordered Pits in Spruce from Old Italian Violins', *Journal of Microscopy*, Vol. 160, no. 2 (1990), 203-211

[38] David, Folland, 'Wood Ponding', *The Strad,* February 2015, 24-26

the wood used by Stradivari may have impacted upon the acoustic quality of Stradivarius violins[39] [40] [41].

I will finally conclude on the research of my paper summarising findings of the studies discussed and points of commonality shared between the studies. I will discuss how aspects of organology which have been researched in these studies may have affected the acoustic quality and thus formant frequencies of Stradivari violins.

Sources which I will use for my paper include scientific research, writings from contemporary and twentieth century luthiers, violin experts, contemporary virtuosi and knowledge gained from conversations with luthier, Paul Gosling.

I will not be carrying out experiments on Stradivarius instruments as part of my research due to the need for specialist scientific equipment and the difficulties in accessing his violins or of gaining wood samples from them. Therefore I will approach my research using resources from previous scientific studies alongside the conversations and insights I gained from luthier Paul Gosling.

This research will complement and further existing research on the organology of Stradivarius violins and link the organology of violins to formant frequencies. This could help form the basis of new research on how different aspects of organology may affect the acoustic quality and thus formant frequencies of Stradivarius violins. Such

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[39] Joseph A Nagyvary et al., 'Wood Used by Stradivarius and Guarneri', *Nature*, 444, no. 7119 (2006), 565

[40] Joseph A Nagyvary et al., 'Mineral Preservatives in the Wood of Stradivarius and Guarneri', *PLOS ONE,* 4 (2009), e4245

[41] Hwan-Ching Tai et al., 'Chemical Distinctions Between Stradivarius's Maple and Modern Tonewood', *Proceedings of the National Academy of Sciences*, 114, no. 1 (2017), 27-32

research and collaboration between violinists, scholars, scientists and luthiers will help luthiers to get closer to understanding what creates the acoustic quality of Stradivarius violins and how they could be replicated today.

## Chapter One: The Formant Frequencies of Stradivarius Violins

In this chapter I will examine in greater depth the research by scholars on the acoustic quality of Stradivarius violins through spectral analysis of the formant frequencies exhibited by these violins. Understanding the formant frequencies of Stradivarius violins can help in understanding what the difference in acoustic quality is in terms of vibroacoustics between Stradivari and other violins. I will focus my research on exploring how select aspects of organology may impact upon the formant frequencies of Stradivarius violins.

### Introduction to Formant Frequencies

Standing waves in the vocal tract give rise to specific resonance frequencies or formants which are the most important spectral feature of the human singing voice. Formants are created by a combination of pitch frequency and vowel quality. Typically, men have longer vocal tracts and therefore lower formant frequencies than women who often have shorter vocal tracts creating higher formant frequencies[42].

When the same pitched note is sung by a male or a female voice, the sound or timbre of the note produced has a different acoustic quality. The difference between the two sung notes lies in the formant frequencies behind the sung notes, the formant frequencies which create or define the acoustic quality of the notes[43].

Formants are created according to the size and shape created by the mouth when singing and the standing waves vibrate at different pitches. If the size, shape or

[42] Hwan-Ching Tai et al., ‘Acoustic Evolution of Old Italian Violins from Amati to Stradivarius’, *Proceedings of the National Academy of Sciences*, Vol. 115, no.23 (2018), 5926

[43] ibid. 5926-5931

position of the mouth, tongue or opening is altered, then the formant frequencies 1, 2 and 3 will change accordingly[44]. The original sound source of standing waves in the vocal tract are filtered and manipulated by the formants to change the sound or pitch of the note[45]. Formants 1-4 are affected by gender quality[46].

Formants are usually referred to in the context of singing, however, a similar concept of formants can be applied to violin playing. Formants can be applied to violin playing in that the size and shape, instead of being created in the mouth of a singer, are created inside the violin's sound box where the standing waves vibrate and different pitches are created, depending on the position of the left-hand note being played, varying the length of the string vibrations. Therefore, each violin, having a different size and shape inside its hollow body will produce slightly different formants due to the variation in the size and shape of the sound.

[44] J M Hillenbrand, M J Clark, T M Nearey, 'Effects of consonant environment on vowel formant patterns', *J Acoust Soc Am,* 109, (2001) 748–763

[45] Hwan-Ching Tai et al., ‘Acoustic Evolution of Old Italian Violins from Amati to Stradivarius’, *Proceedings of the National Academy of Sciences,* Vol. 115, no.23 (2018),5926-5931

[46] V G Skuk, L M Dammann, S R Schweinberger, 'Role of timbre and fundamental frequency in voice gender adaptation', 138, *J Acoust Soc Am* (2015), 1180–1193

**Research on the Formant Frequencies of Stradivarius Violins**

Stradivari instruments have been the subject of much research by luthiers and scholars. The sound of Stradivarius violins has been investigated to find out if it resembles the human singing voice. There has been research by Childers, Wu and Hillenband et al. into the initial first four formants of the violin comparing them to formant frequencies of the human voice[47] [48]. Research by Tai et al.[49] [50], Mores[51] Childers, Wu[52], Hillenband[53], have shown that Stradivarius violins are different acoustically to other violins due to the formant frequencies which they exhibit. Stradivarius violins have exhibited formant frequencies higher than those of all other antique and modern violins[54]. Buen has compared the formant frequencies of Stradivarius and del Gesu violins to modern violins. Spectral analysis of Stradivarius

[47] Childers et al., ‘Gender Recognition from Speech. Part II: Fine Analysis’, *The Journal of the Acoustical Society of America*, 90, no. 4 (1991), 1841-1856

[48] J L A Hillenbrand et al., ‘Acoustic Characteristics of American English Vowels’, *Acoustical Society of America*, 97 (1995), 3099–3111

[49] Hwan-Ching Tai et al., 'Stradivarius Violins Exhibit Formant Frequencies Resembling Vowels Produced by Females', *Savart Journal*, J 1 (2012), 1-14

[50] Hwan-Ching Tai,et al., ‘Acoustic Evolution of Old Italian Violins from Amati to Stradivarius’, *Proceedings of the National Academy of Sciences*, Vol. 115, no.23 (2018), 5926

[51] Robert Mores, 'Vowel Quality in Violin Sounds-A Timbre Analysis of Italian Masterpieces', *Studies in Musical Acoustics and Psychoacoustics* (2017), 223-245

[52] Childers et al., ‘Gender Recognition from Speech. Part II: Fine Analysis’, *The Journal of the Acoustical Society of America*, 90, no. 4 (1991), 1841-1856

[53] J L A Hillenbrand et al., ‘Acoustic Characteristics of American English Vowels’, *Acoustical Society of America*, 97 (1995), 3099–3111

[54] Hwan-Ching Tai,et al.,‘Acoustic Evolution of Old Italian Violins from Amati to Stradivarius’, *Proceedings of the National Academy of Sciences*, Vol. 115, no.23 (2018), 5926

violins has shown them to exhibit formant frequencies that are similar to those produced by the female voice.

Bissinger revealed that that the violin produces four main bridge resonance bands[55]. Previous research by Tai[56], Nagyvary[57] and Mores[58] showed that violins exhibit four formants which correspond to Bissinger's model. These studies showed the first four formants of violins possessed characteristics similar to human speech[59 60]. Tai and Mores[61] showed Stradivarius violins to have higher formant frequencies and greater vowel frontness than other antique violins tested[62]. These studies however have not compared violin playing to singing but instead used pre-existing speech data sets. This presented problems as the low frequency of the male voice could not be compared to violin playing accurately and formant zero did not match up properly. This presents a difficulty when trying to compare male speech to violin playing and for some semi-tones in the octave to not be possible, giving an incomplete set of results. Comparing

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[55] George Bissinger, 'Structural Acoustics Model of Violin Radiativity Profile', *J Acoust Soc Am*,124 (2008),4013-4023

[56] Hwan-Ching Tai et al., 'Stradivarius Violins Exhibit Formant Frequencies Resembling Vowels Produced by Females', *Savart Journal*, J 1 (2012), 1-14

[57] Joseph A Nagyvary, 'A Comparative Study of Power Spectra and Vowels in Guarneri Violins and Operatic Singing', *Savart Journal*, J 1, (2013), 1-30

[58] Robert Mores, 'Vowel Quality in Violin Sounds-A Timbre Analysis of Italian Masterpieces', *Studies in Musical Acoustics and Psychoacoustics* (2017), 223-245

[59] Childers et al., 'Gender Recognition from Speech. Part II: Fine Analysis', *The Journal of the Acoustical Society of America*, 90, no. 4 (1991), 1841-1856

[60] J L A Hillenbrand et al., 'Acoustic Characteristics of American English Vowels', *Acoustical Society of America*, 97 (1995), 3099–3111

[61] Robert Mores, 'Vowel Quality in Violin Sounds-A Timbre Analysis of Italian Masterpieces', *Studies in Musical Acoustics and Psychoacoustics* (2017), 223-245

[62] Hwan-Ching Tai et al., 'Stradivarius Violins Exhibit Formant Frequencies Resembling Vowels Produced by Females', *Savart Journal*, J 1 (2012), 1-14

violin playing with speech data sets does present some difficulties as violin playing is arguably more comparable to singing rather than to speech. Male speech presented the biggest issue when compared to violin playing as the low frequencies and results of formant zero are pitches that cannot be played on violins, as they are out of the violin's frequency range [63] [64] [65] .

Previous research by Nagyvary using Linear Predictive Coding analysis showed resemblance to the vowel qualities of singing[66]. The aim of Tai et al. in his paper in 2019 was to research whether Stradivarius and Amati violins could be compared to the human singing voice. Results of these studies have also shown Stradivarius violins to have unique formant frequencies. The resonance frequencies of Stradivarius violins displayed format frequencies higher than those of other antique Italian violins and have also displayed greater frontness of vowels[67].

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[63] ibid.

[64] Joseph A  Nagyvary, 'A Comparative Study of Power Spectra and Vowels in Guarneri Violins and Operatic Singing', *Savart Journal*, J 1 (2013), 1-30

[65]  Robert Mores, 'Vowel Quality in Violin Sounds-A Timbre Analysis of Italian Masterpieces', *Studies in Musical Acoustics and Psychoacoustics* (2017), 223-245

[66]Joseph A Nagyvary, 'A Comparative Study of Power Spectra and Vowels in Guarneri Violins and Operatic Singing', *Savart Journal*, J 1, (2013), 1-30

[67] Hwan-ChingTai et al., 'Stradivarius Violins Exhibit Formant Frequencies Resembling Vowels Produced by Females', *Savart Journal*, J 1 (2012), 1-14

The research of Tai et al. 2018, builds on the previous research which I have outlined above on formant frequencies of Stradivarius violins, further demonstrating the vocal qualities of Cremonese violins through formant analysis[68].

I will discuss and analyse the findings of the study by Tai et al., which explores whether antique Cremonese and Brescian violins display characteristics similar to the human voice. Tai et al. conduct their research through analysis of the frequency response curves of fifteen antique Italian violins of masters from Cremona and Brescia, including Antonio Stradivari[69].

**Tai et al: A comparison between the Formant frequencies in Stradivarius and other Antique Italian and modern violins**

At the start of the study, Tai et al. hypothesise that Amati violins may share characteristics of the human voice. In the paper Tai et al. explore the differences between Amati and Stradivarius violins to shed light on why the tonal differences between the violins exists. The research aims to reveal what gives the Cremonese and Brescian violins which were made by the masters their voice-like characteristics. However as the research unfolds, the emphasis of discussion focuses on the difference in the formant frequencies of Stradivarius violins in comparison to those of other antique Italian violins[70]. I will base my analysis and discussions on the formant

68 Hwan-Ching Tai et al., 'Acoustic Evolution of Old Italian Violins from Amati to Stradivarius', *Proceedings of the National Academy of Sciences,* Vol. 115, no.23 (2018), 5926-5931

69 ibid.

70 ibid.

frequencies and vowel qualities of Stradivarius violins, which show significant differences in comparison with other antique Italian violins.

The experiments measure the specific resonance frequency or formants of Stradivarius violins against non-Stradivarius violins to assess their voice-like characteristics using the method of Linear Predictive Coding analysis[71]. In this study both violinists and singers perform the one octave chromatic scale from G#3 to G4. From recordings taken, an analysis of frequency response and harmonics is conducted[72]. The fifteen violins in this study include two of the oldest existing by Andrea Amati and Gaspar da Salo, six violins by the Stradivari family, five by Antonio Stradivari and one by Stradivari's son, Omobono Stradivari and nine by different Cremonese and Brescian masters. The violin recordings are analysed against recordings of eight male and female singers who sing eight English vowel sounds[73].

Each pitch played by the violin displays differences in formants one and two, yet the patterns of formants show characteristics of the human vocalisation of vowel sounds.

The results of Linear Predictive Coding Analysis show that the violins of Andrea Amati and Gaspar da Salo display formants similar to male voices. The Stradivarius violins exclusively, display formants which are higher and akin to the female voice[74].

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[71] ibid. 5926

[72] ibid. 5926- 5931

[73] ibid.

[74] ibid.

**Table 1. Formant frequencies of 15 antique Italian violins**

| Violin | F1, Hz | F2, Hz | F3, Hz | F4, Hz | VTL, cm |
|---|---|---|---|---|---|
| A. Stradivari 1667 | 537 | 1,539 | 2,670 | 3,745 | 16.43 |
| A. Stradivari 1707 | 558 | 1,654 | 2,690 | 3,799 | 16.54 |
| A. Stradivari 1709 | 531 | 1,519 | 2,702 | 3,797 | 15.92 |
| A. Stradivari 1713 | 538 | 1,631 | 2,812 | 3,814 | 15.66 |
| A. Stradivari 1722 | 560 | 1,496 | 2,628 | 3,645 | 16.52 |
| O. Stradivari 1740 | 601 | 1,705 | 2,660 | 3,736 | 15.86 |
| Strad avg. | 554 | 1,591 | 2,694 | 3,756 | 16.15 |
| G. Bertolotti 1560* | 497 | 1,509 | 2,515 | 3,594 | 17.37 |
| A. Amati 1570 | 503 | 1,583 | 2,602 | 3,731 | 16.71 |
| P. Maggini 1610 | 517 | 1,571 | 2,649 | 3,817 | 16.46 |
| N. Amati 1624 | 543 | 1,517 | 2,617 | 3,635 | 16.82 |
| N. Amati 1656 | 505 | 1,360 | 2,582 | 3,707 | 17.54 |
| F. Rugeri 1694 | 482 | 1,314 | 2,436 | 3,681 | 18.35 |
| G. Guarneri 1706† | 492 | 1,582 | 2,733 | 3,774 | 16.60 |
| C. Bergonzi 1732 | 532 | 1,484 | 2,688 | 3,750 | 16.55 |
| B. Guarneri 1733‡ | 525 | 1,585 | 2,559 | 3,744 | 16.73 |
| Non-Strad avg. | 511 | 1,500 | 2,598 | 3,715 | 17.02 |
| Male avg. | 652 | 1,440 | 2,682 | 3,745 | 16.44 |
| Female avg. | 632 | 1,571 | 2,857 | 4,106 | 15.74 |

*Commonly known as Gasparo da Salo.
†Commonly known as Giuseppe Guarneri "filius Andreae."
‡Commonly known as Giuseppe Guarneri "del Gesù." [75]

Table 1 is taken from the study by Tai et al. and shows the formant frequencies in terms of hertz of the first four formants of the fifteen antique violins tested in this study. Table 1 shows the six Stradivarius violins to have higher formants for formants one, two, three and four than non-Stradivarius violins. The average formants for the six Stradivarius violins are as follows for formants one, two, three and four of 554Hz, 1591Hz, 2694Hz and 3756Hz. In comparison the average formants of the nine non-Stradivarius violins are 551Hz, 1500Hz, 2598Hz and 3715Hz For formants three and four, the higher average formant frequencies of the Stradivarius violins are closer to the higher average formant frequencies of the female voice[76].

[75] ibid.

[76] ibid.

Yet there is an inconsistency which is unexplained by Tai et al. that the average formant frequencies of the female voice for formant one is lower than that of the average formant frequencies of the male voice, this may be associated with the vowel quality of Stradivarius violins as formant one is heavily associated with vowel quality[77].

Stradivarius and non-Stradivarius violins have a similar frequency response curve yet with some significant differences of peaks and dips. Stradivarius violins show higher formant frequency of 2766Hz and 3141Hz, which correspond to the central frequencies of the tenor, female alto and soprano voices. There are strong anti formants around 1219Hz and 2344Hz. The results show that the non-Stradivarius violins display a strong formant around 2344 Hz, which is similar to the central frequency of a bass singer. Tai et al. suggest that the higher formants two and three of Stradivarius violins may be partly due to the strong formant peaks and anti formants, findings which reflected the previous results of Buen of formant frequencies in Stradivarius violins[78] [79].

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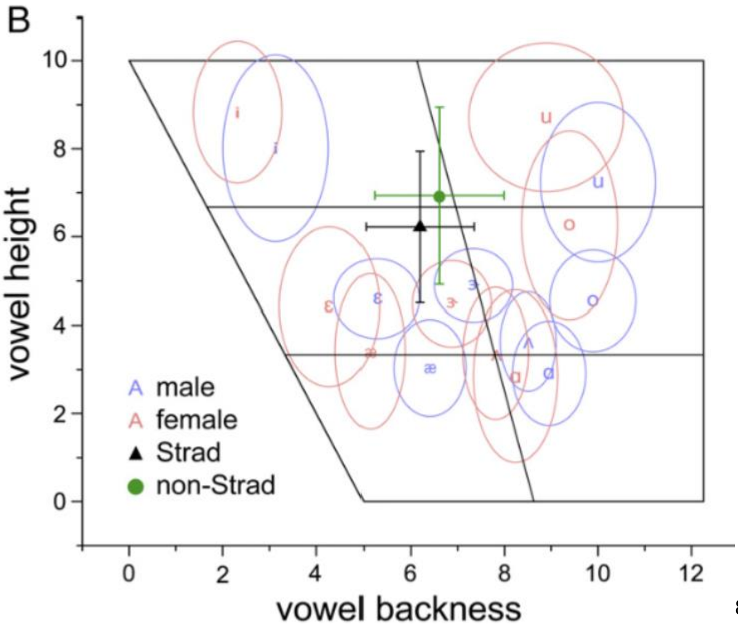
[77] ibid.

[78] ibid.

[79] Buen Anders, ‘Comparing the Sound of Golden Age and Modern Violins: Long Time-Average Spectra’, *VSA* (Summer, 2005), 51-74



[80]

Table 2

Table 2 taken from Tai et al.'s study shows the average backness and height of vowels of Stradivari violins compared to the average vowel height and backness of male and female voices.

The results of the study by Tai et al show an average of female voice in the sung vowels to have lower vowel backness for all vowels and to have increased vowel height for all vowels except for the ⟨ɜ⟩ vowel. When compared, Stradivarius violins showed less average vowel backness to non-Stradivarius violins. Stradivarius violins are more similar to the female voice pattern of having lower vowel backness, yet unlike the female voice pattern in having lower vowel height than non-Stradivarius violins. The average vowel height of Stradivarius violins is lower in comparison to

[80] Tai Hwan-Ching et al., 'Acoustic Evolution of Old Italian Violins from Amati to Stradivarius', *Proceedings of the National Academy of Sciences*, Vol. 115, no.23 (2018), 5926-5931

non-Stradivarius violins, having a vowel height closer to 6 whereas non-Stradivarius violins have a vowel height closer to 7. Stradivarius violins have a vowel backness closer to 6 whereas non Stradivari violins have a vowel backness closer to 7.

The research also addresses the characteristics of the violin resembling the human voice in the vowel qualities they exhibit. The vowel qualities of Stradivarius violins are similar to those of alto and tenor singers, whereas the Italian violins in this study by Andrea and Nicolò Amati III, Giuseppe Guarneri and Giuseppe Guarneri del Gesù, Ruggeri, Maggini, Bergonzi and Gaspar da Salo showed vowel qualities of baritones and basses[81].

**Analysis of the results of Tai et al. 2018**

The research of Tai et al. is conducted with the violins in modern setup, however these violins in their conception were originally made and played with baroque setup. Modern setup significantly changes the sound and capabilities of the violin.

It is likely that the setup of each violin in the study is different due to variations in the setup such as the strings, string tension, bridge height, all of which will affect the sound of the violin in various ways. As a result, a comparison between the violins is therefore not direct and may be influenced by inconsistencies in the set up.

Tai et al. conclude that they are unsure why Stradivari's first four formants are higher than the other Italian violins. They suggest the flatter curve of the violin arching when compared to Amati and Stainer previously may have contributed to the brighter

[81] ibid.

powerful tones[82]. Tai et al. suggest higher formants may be linked to the brilliance often attributed to Stradivari violins.Stradivarius violins are often considered to have a unique sound, possessing the qualities of ’brightness’ or ‘brilliance’[83]. The greater frontness of vowels as in the case of Stradivari violins is associated with brightness[84].

Linear Predictive Coding Analysis is a widely used method of analysing speech in audio signal processing, by taking the ‘buzz’ of the original audio signal and analysing it to estimate the formants. Tai et al. conducted LPC analysis using Praat software, which is a tool used to analyse speech phonetics. Tai et al. assessed that despite being designed to analyse human speech, it proved suitable also for analysing his audio of violin playing and singing from which to extract the formant frequencies.

LPC is able to represent speech signals through modelling the vocal tract and extracting the formant frequencies. LPC works well particularly with vowels and in aiding vowel identification. This is ideal for the study by Tai et al. as the singers sing vowels and a part of the study is to compare and identify the vowels of the sung and played violin notes. However while LPC is designed for the analysis of human speech, it is not designed specifically to identify sung vowels or for violin playing which could potentially make it more difficult for analysis in the study by Tai et al.

LPC is limited in the modelling of complex and nasal sounds. The violin is often compared to having elements of nasality and complexity. LPC is not so effective in the

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[82] W H Hill, A F Hill, A E Hill, *Antonio Stradivari: His Life and Work* (1644-1737), (New York, 1902)

[83] ibid.

[84] Stanley S Newman, 'Further Experiments in Phonetic Symbolism', *The American Journal of Psychology*, 45, 1, (1933), 53-75

use of plosives, the sound of a violin bow when it hits the string is often described as having the consonant ‘k’.

LPC results can be distorted by background noise and small errors in LPC coefficients can make the reconstructed signal inaccurate and distinctly different to the original. Additional factors such as the sound of the player moving their body and arm to put the bow on the strings and play the note can distort LPC results. Therefore the accuracy of the results of the four month analysis of the violin playing could depend on how clearly each note was played by the violinist and how much care and attention was given to minimising noise in the recordings used for LPC.

To directly compare the formants of violins and singers, the range of pitches played and sung in this research was limited to the range of G#3 to G4 (200-400Hz)[85]. The limited range used in the recordings was due to the need to find a range where all voice types in this study were able to sing comfortably without straining their natural voices. However the limited range, whilst suiting the range of tenors, baritones, alto and mezzo sopranos restricts the violin to its lowest octave.

Repertoire for the violin typically extends up to and beyond two octaves higher than the range included in this study. Therefore the range does not fully represent the entire range of the violin’s capabilities. Only the lowest octave of the violin was analysed for formants in this study by Tai et al. Thus whilst results have shown the lowest octave of the violin range to display characteristics of formant frequencies similar to the

[85] Hwan-Ching Tai et al., ‘Acoustic Evolution of Old Italian Violins from Amati to Stradivarius’, *Proceedings of the National Academy of Sciences*, Vol. 115, no.23 (2018), 5930

female voice, I consider that there is no evidence that such results extend to the higher ranges of the violin.

The formant frequencies of the lowest octave of the violins in the study by Tai et al. may however also indicate that similar characteristics of the female voice may be found in the higher ranges of the violins. Further research on the formant frequencies of Stradivarius violins which encompasses a higher range would show if the trends of formant frequencies found by Tai et al. extend to a higher range.

I view the results of the study by Tai et al. to be more in depth and accurate than those of previous studies on formant analysis, as sung vowels are used, rather than speech data sets, as speech does not compare so well to violin playing as singing.

The range of sung notes of singers is more accurately compared to violin playing than the range of speech data sets, where in previous studies certain pitches had to be omitted and formants mis-matched between the bass singer and violins, making the results not so comprehensive or precise. However, the results of the study by Tai et al. back up the previous studies and further show how the violin's formants frequencies exhibit similarities to the human voice. Further, the study backs up findings showing that Stradivarius violins display unique formant frequencies which are higher than the other Italian violins tested in the studies[86]. Therefore, I view that the study by Tai et al. is showing the formant frequencies and comparative range between singers and violins and therefore is a strong indication of the formant frequencies of Stradivarius violins shedding light on revealing their acoustic quality. As the Stradivarius violins which are used in the study by Tai et al. span the spectrum of Stradivari's career, it

[86] ibid.

shows that the results may indicate that higher formant frequencies are representative of many of his violins, not confined to a particular period of his career[87].

To support the findings of the study by Tai et al. and further demonstate the presence of formant frequencies of Stradivarius violins being closer to those of the female voice, this study would need to be repeated to confirm findings remain constant and prove the repeatability of the study. This can however be challenging due to the difficulties of accessing such valuable instruments for research. Many of the antique violins can be found in museums or on long term loans to virtuosi today, so can be difficult to access for research.

In relation to my research, the study by Tai et al. is significant, as it provides groundwork scientific evidence showing the formants and frequencies which are behind the acoustic quality of Stradivarius violins. In my research I will look at what could have led to the acoustic quality of Stradivarius violins by analysing aspects of the organology of Stradivarius violins through the lens of formant frequencies.

**How I will use the study of Tai et al. in my work**

The results of the research by Tai et al. show that Stradivarius violins display higher formant frequencies closer to those of the female voice whereas the other old Italian violins by reputed masters tested in this study displayed formant frequencies closer to the male voice.[88] In my paper I will research and suggest how these higher formant frequencies are present when Stradivarius violins are played, through examining aspects of the organology of the violins.

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87 ibid.

88 ibid.

Despite extensive research by scholars and luthiers into what may cause Stradivarius violins to possess their unique acoustic quality, no consensus has been formed as to why this may be so. The results of the study by Tai et al. offer a perspective on Stradivarius violins showing certain significant divergences from Cremonese modern violins in their formant frequencies that lie behind the notes and acoustic quality. Tai et al. suggest that the formant frequencies produced by Stradivarius violins may contribute to their acoustic quality[89] .

Since Stradivari, luthiers have not been able to recreate the acoustic quality of Stradivarius violins. What differentiates the acoustic quality of Stradivarius violins from the other antique Cremonese and modern violins tested in the study by Tai et al. are the formant frequencies of Stradivarius violins, which resemble the characteristics of the female voice[90]. The formant frequencies which Stradivarius violins exhibit, provide the backbone of the acoustics of Stradivarius violins.

Tai et al. express the need for research to explore which aspects of the violin's organology have led to Stradivarius violins producing higher formants closer to the female voice[91].

All Stradivarius violins are unique in their own way, with small nuances in acoustic quality which are different to each other, yet all the six Stradivarius violins tested in the research by Tai et al. exhibited formant frequencies which show characteristics of the female voice, in contrast to the other Cremonese and modern violins exhibiting

[89] ibid.

[90] ibid. 5926-5931

[91] ibid.

characteristics resembling the male voice[92]. Therefore, I propose that there must be some unifying factor or factors of organology which unite the Stradivarius violins in acoustic quality to exhibiting formant frequencies similar to the female voice. I view that the findings by Tai et al. of formant frequencies in Stradivarius violins may exemplify the acoustic quality of Stradivarius violins.

If a greater knowledge on the aspects of organology of Stradivarius violins which contribute to their acoustic quality can be understood, and thus the formant frequencies which resemble the female voice can be understood, then this knowledge could be used by modern luthiers to help them get closer to creating the acoustic quality of a Stradivarius violin today. Such knowledge may be applied in a wide range of ways for lutherie today benefitting luthiers, beyond those who wish to get closer to recreating the acoustic quality of Stradivarius violins today.

[92] ibid.

## Chapter Two: The Source of Stradivari's Wood, the Maunder Minimum and Density Differentials

**C**hapter two will discuss the organology of Stradivari violins by looking at the origin of the wood, dendrochronological studies, how the climatic conditions affected tree growth and density differentials to consider how they may have impacted on the wood used to make Stradivarius violins and their subsequent effects on acoustic quality and formant frequencies.

### The Source of Stradivari's Spruce and Maple

Violins soundboards are made from two pieces of spruce, with the youngest tree rings at the centre of the violin. Maple is used for the back, ribs and the scroll of the violin as it is a strong, durable and resonant wood.

The study of dendrochronology determines the age of wood and its source. Dendrochronological studies on violin wood have mostly been conducted on the spruce fronts of violins where the tree rings are clear[93].

Studies on dendrochronology of over seventy of Stradivari's spruce soundboards have shown specific groups of year patterns, suggesting that in making his instruments, Stradivari had a small number of logs from which he made many of his instruments[94]. Scholars believe that Stradivari and his contemporaries may have sourced their

[93] P Klein, 'Dendrochronological Analysis of European String Instruments', (1987), 37-38

[94] John C Topham, 'A Dendrochronological Study of Violins Made by Antonio Stradivari', 29, *The America Musical Instrument Society*, (2003), 72-96

spruce from the Fiemme Valley in the Southern Italian Alps as it is famous for its resonant spruce[95] [96].

The period before 1684 saw Stradivarius instruments to have maple of plainer appearance but with superior acoustic qualities. The Hills speculate that the maple used before 1684 by Stradivari was of homegrown origin and that it was only after 1684 that there was the possibility of obtaining more aesthetically pleasing figured wood, that was much used in later violins. The Hills suggest that after 1684 Stradivari may have been paid greater sums to make his violins which may have allowed for the possibility of sourcing European grown maple with flamed figuration[97].

The source of Stradivari's maple is believed to be Bosnia. Nagyvary found that the ratios of calcium and magnesium in the Slovenian tone wood were closer to those displayed by the Stradivarius and the Guarneri del Gesù wood samples, rather than the Bosnian tone wood[98]. As a consequence of this, Nagyvary et al. suggest that unless magnesium salts were extracted from the Stradivarius and the Guarneri del Gesù wood before use, that it is more likely that Stradivari and Guarneri del Gesù sourced maple from Slovenia.

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[95] Lloyd Burckle, and Grissino-Mayer, Henri D, 'Stradivarius, Violins, Tree Rings, and the Maunder Minimum: a Hypothesis', *Dendrochronologia*, 21, no. 1 (2003), 41-45

[96] Aaron S Allen, 'Fatto di Fiemme: Stradivari's Violins and the Musical Trees of the Paneveggio. in L. Auricchio et al. Eds. Invaluable trees: Cultures of Nature, 1660-1830' 301-316

[97] W H Hill, A F Hill, A E Hill, *Antonio Stradivari: His Life and Work* (1644-1737), (NewYork,1902) 164

[98] Lloyd Burckle, and Grissino-Mayer Henri D, 'Stradivarius, Violins, Tree Rings, and the Maunder Minimum: a Hypothesis', *Dendrochronologia*, 21, no. 1 (2003), 41-45

Grissino-Mayer proposes that Stradivari used old wood sourced from buildings such as castles and cathedrals from which to make his instruments[99]. However this hypothesis has been shown this to be incorrect, as dendrochronological analysis carried out on instruments made by Stradivari dates the spruce wood from the time of Stradivari's lifespan [100] [101] [102]. This would mean that Stradivari used wood felled during his lifetime rather than using older wood.

### The Ideal Properties of Wood for Violin Making

The use of spruce for instrument soundboards is due to the properties of the wood from this species[103]. Luthier Beare explains that such wood needs to be 'light and resonant' and that the properties that give rise to such characteristics are high density wood, where the tree rings are tightly packed together, alongside being light weight; these properties are found in spruce[104]. Gosling explains that conditions which lead to

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[99] ibid.

[100] 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*, Volume 27, Issue 3, (March 2000) 183-192

[101] John C Topham, 'A Dendrochronological Study of Violins Made by Antonio Stradivari', 29, *The America Musical Instrument Society*, (2003), 72-96

[102] Lloyd Burckle, and Grissino-Mayer Henri D, 'Stradivarius, Violins, Tree Rings, and the Maunder Minimum: a Hypothesis', *Dendrochronologia*, 21, no. 1 (2003), 41-45

[103] Voichita Bucur, 'Theory of and Experimental Methods for the Acoustic Characterization of Wood', *Acoustics of Wood*, 2nd ed. (2006), 39-104

[104] Beare Peter, 'Crafting a Violin from a Tree', Orchestra of the Age of Enlightenment (2021), https://oae.co.uk/how-to- (accessed: 07/09/23)

the growth of ideal violin wood, are those where trees grow slowly at high altitude, where temperatures are cooler and the trees are grown close together[105].

I will now introduce periods of climatic change in history which may have affected the growth and properties of the wood used by Stradivari and other contemporary Cremonese violin makers

**The Little Ice Age and the Maunder Minimum**

The Little Ice Age spanned three periods of time which were 1458-1552, 1600-1720 and 1840-1880. During the Little Ice Age the Arctic sea water travelled further south, and alpine glaciers covered farmland[106]. The Maunder Minimum occurred during the second period of the Little Ice Age.

The Maunder Minimum gave rise to cooler temperatures than the Little Ice Age. During the Maunder Minimum the weaker sun caused less ultraviolet light to be emitted into the earth's atmosphere and decreased ozone layer formation[107]. The reduced solar activity and decreased radiation emitted from the sun reaching the earth during the Maunder Minimum coincided with the Little Ice Age[108].

During this period there were few sunspots on the sun's surface coupled with a slight decrease in the overall activity and temperature of the sun·. The Maunder Minimum

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[105] Lloyd Burckle, and Henri D Grissino-Mayer, 'Stradivarius, Violins, Tree Rings, and the Maunder Minimum: a Hypothesis', *Dendrochronologia*, 21, no. 1 (2003), 41-45

[106] Nasa, https://earthobservatory.nasa.gov/images/7122/chilly-temperatures-during-the-maunder-minimum (accessed: 10th June 2023)

[107] ibid.

[108] Lloyd Burckle, and Henri D Grissino-Mayer, 'Stradivarius, Violins, Tree Rings, and the Maunder Minimum: a Hypothesis', *Dendrochronologia*, 21, no. 1 (2003), 41-45

paired with the period of the Little Ice Age led to cooler temperatures across Europe and North America[109]. Estimates of the magnitude of cooling during the Little Ice Age range from 0.5+/- degrees Celsius[110]. In comparison estimated cooling during the Maunder Minimum ranged from 1-2 degrees Celsius[111]. The Maunder Minimum gave rise to cooler temperatures than the Little Ice Age. During the seventy year span of the Maunder Minimum, summers were wetter and cooler. Towards the latter years of the Maunder Minimum cooler temperatures remained for decades[112].

During the Maunder Minimum, the rate of tree growth in Western Europe decreased during the period 1645-1715. During this time, solar activity was less, leading to an overall annual decrease in temperature with extended winters and colder summers. During this colder period, decreased tree growth had the impact of creating trees with narrow rings, ideal characteristics for the soundboards of violins.

**A Dendrochronological Study of Tree Rings**

Grissino-Mayer et al. 2003 conducted dendrochronological research into the spacing of tree rings from trees grown at high elevation in the forest stands in the European Alps which grew during the Maunder Minimum. Collating information from several

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[109] Nasa, https://earthobservatory.nasa.gov/images/7122/chilly-temperatures-during-the-maunder-minimum (accessed: 10th June 2023)

[110] Rind D and J Overpeck, 'Hypothesized causes of decade-to-century-scale climate variability: Climate model results', *Quat Sci Rev* 12, (1993), 357-374,

[111] D T Shindell et al., 'Solar forcing of regional climate change during the Maunder Minimum', *Science*, 294, (2001), 2149-2152

[112] Luterbacher J, 'The Late Maunder Minimum (AD 1675–1715) – Climax of the Little Ice Age in Europe', in Jones, P. D., Davies, T. D., Ogilvie, A. E. J., and Briffa, K. R. (eds.),Climate (2000) Impacts: The Last 1000 Years, Climatic Research Unit, University of East Anglia, Norwich

hundred trees grown across five countries from western France to Southern Germany, results showed that across sixteen sites from 1625-1720 there was a long period of reduced growth rates in tree rings. The tree species involved in the study were Norway Spruce, European Larch and Swiss Stone Pine[113].

The study revealed Norway spruce from the European alps to show a long period where the tree rings had decreased growth from the period 1625-1720, this period coincided with the Maunder Minimum[114].

The Maunder Minimum Hypothesis and its Effects on Wood for Violin Making

Burckle and Grissino-Mayer: The Maunder Minimum Hypothesis and its impact on violin lutherie used Grissino-Mayer's study from 2003 on tree rings as the basis for the Maunder Minimum hypothesis[115] [116]. They hypothesise that the high quality, narrow ringed spruce wood used for the soundboard of instruments that was grown in the Maunder Minimum may have contributed to the acoustic quality of Cremonese violins.

Burckle and Grissino-Mayer believe that past studies focused on discovering the reason for the exceptional acoustic quality of Cremonese instruments presenting the Maunder Minimum hypothesis as an explanation were flawed.

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[113] Grissino-Mayer H D, Sheppard P R, Cleaveland M K, 'A dendroarchaeological re-exam ination of the "Messiah" violin and other instruments attributed to Antonio Stradivari', 21, 1, Journal of Archaeological Science (2003)

[114] ibid.

[115] ibid.

[116] Lloyd Burckle, and Grissino-Mayer Henri D, 'Stradivarius, Violins, Tree Rings, and the Maunder Minimum: a Hypothesis', *Dendrochronologia*, 21, no. 1 (2003), 41-45

The authors acknowledge that many of the great violin makers were active in Cremona during the period of the Maunder Minimum, one of them being Antonio Stradivari who was born the year prior to its beginning. Burckle et Grissino-Mayer consider that the coincidence of the unique environmental and macroclimatic conditions in which the wood grew in The Paneveggio Forest alongside the superior craftsmanship of the Cremonese masters is the key to the acoustic quality of the Cremonese violins.

Burckle and Grissino-Mayer offer the hypothesis that the reason for the superior acoustic quality of Cremonese violins, such as those by Stradivari and his contemporaries is due to the high quality of the spruce wood used for the sound board. Burckle and Grissino-Mayer hypothesise that several environmental characteristics of the topography, soil conditions and elevation of the forests alongside the macroclimatic conditions of the Maunder Minimum impacted upon wood growth of the trees in The Paneveggio Forest[117]. Therefore, the trees which Stradivari sourced may have grown at a slower rate during this prior cooler period.

Stradivari’s contemporaries also used similar wood, grown during the Maunder Minimum, therefore the acoustic quality of Stradivari's sound cannot be attributed to the effect of the Maunder Minimum on the wood he used. However, it is generally considered that antique Cremonese instruments are superior to modern ones in acoustic quality, therefore perhaps the Maunder Minimum may have contributed to the overall acoustic quality of the Cremonese instruments made by Stradivari and his contemporaries.

The Fiemme Valley is renowned for its fir trees which have superior resonant properties for violin making. The most resonant trees for violin making are those which

[117] ibid.

produce high density wood, the result of growth at high elevation on north facing slopes and where the soil is nutritionally poor[118]. The trees of highest resonance wood have narrow tree rings due to slower growth, which increases their strength and density.

An issue which arises is that Stradivari may not have exclusively used wood grown during the Maunder Minimum. The extent to which the wood used by Stradivari was grown during the Maunder Minimum depends on whether all the wood he used was felled during his lifetime and on the age of the trees when cut down.

An aspect which Burckle and Grissino-Mayer have not considered is that prior to the Maunder Minimum the weather was also cooler due to the Little Ice Age. There were cooler temperatures during the periods of the Little Ice Age, both before and after the Maunder Minimum, including a later period which followed it, known as the Dalton Minimum. The authors do not investigate whether this cold period, the Dalton Minimum affected the wood's growth in a similar way to the Maunder Minimum. Burckle and Grissino-Mayer do not discuss or make reference to the wood, violin making or luthiers, during other colder periods. The omission of information on the wood used for violin making and lutherie in other cooler periods, raises the possibility of whether the authors are biased.

Burckle and Grissino-Mayer consider that the topography, soil conditions and elevation of the forest stands all impacted upon wood growth[119]. As there is no analysis of how any of the factors mentioned have impacted upon tree growth, further research

[118] ibid.

[119] ibid.

is required as to how such factors may inflence wood growth and affect the acoustic quality of the wood.

The hypothesis proposed by Burckle and Grissino-Mayer does not provide evidence that the spacing of tree rings has a direct correlation to the acoustic properties of the wood and violins[120]. Such research would reveal if and how ring spacing affects the acoustic quality of an instrument. A later study by Stoel and Borman explores how the density of wood and density differentials may affect the acoustic quality of antique Cremonese and modern violins[121].

The Maunder Minimum hypothesis provides an insight into how climatic conditions may have affected the properties of the spruce which may have contributed to the acoustic quality of Cremonese instruments, and therefore also the instruments of Stradivari.

**Density and Density Differentials in Cremonese Violins**

Stoel and Borman explore the average density and density differentials between Cremonese and modern violins to assess whether such factors could impact upon the acoustic quality of violins[122].

The research was conducted by Stoel, a medical doctor and Borman, a luthier. Stoel designed a computer programme using computerised tomography (CT) scanning which allowed for the density of the front and backs of violins to be measured using a

[120] ibid.

[121] Berend C Stoel, and Borman Terry M, 'A Comparison of Wood Density Between Classical Cremonese and Modern Violins', *PLOS ONE*, 3, no. 7 (2008)

[122] ibid.

non-invasive method. Stoel and Borman's methodology shows density at growth ring level, providing greater detail and accuracy of plate densities of the violins.

Five Cremonese violins, three of which were made by Giuseppe Guarneri del Gesù, two by Antonio Stradivari and seven modern violins and one modern viola were scanned and average density and density differentials were analysed and compared. The density of plate thickness and sound box volume were calculated, plate thickness was observed to have no effect[123].

After genetic factors, the greatest factor influencing the density of the wood is the microclimate and location of where the tree grew. High density wood grows slowly due to cool temperatures, limited exposure to the sun, little access to water and a nutrient poor soil, conditions which produce the most resonant and preferable sounding wood for violins.

The authors chose to focus discussion of results on spruce, giving little attention to the results of the maple. The reason given for the attention on spruce given by Stoel and Borman is that below 800 Hertz, the entire violin sound box acts as a resonating hole for the violin vibrations to sound, whereas above 800Hz most of the vibrations are hitting the spruce plate of the violin[124]. The resulting density maps display the median densities taken from the left and right upper and lower bouts and the centre of the violin, five areas in total, with any areas of repair work avoided.

Density differentials are the difference in density between the amounts of early and late growth in the wood. This may affect the mechanical and vibrational properties in

[123] ibid.
[124] ibid.

which the wood vibrates. The wood vibrates in three directions horizontally, vertically and slab wise directly or perhaps through different levels of stiffness or characteristics of levels of sound damping.

The results showed no significant divergence in average density between Cremonese and modern violins. However there is a significant difference in the wood density between early and late growth, that is the density differential. The violins of Stradivari and Guarneri del Gesu are more equal in the amount of early and late growth wood than in the modern violin[125]. The Cremonese violins showed a much greater homogeneity between the densities of the early and late wood growth on both the spruce soundboard and the maple back plate, therefore giving a low density differential from approximately 140kg/m3 to 205kg/mg3, whereas the modern soundboards with the exception of one result around 140kg/m3 showed density differentials much higher ranging from 250kg/m3 to 415/m3. There appears to be an inconsistency in one of the modern soundboards as noted by Stoel and Borman with a low density differential of 140/m3 matching the lowest density differential of the Cremonese soundboards. Stoel and Borman explain that the supplier of the wood used to make this violin sometimes treated wood prior to use and sometimes did not know if the wood had been pre-treated. The Cremonese back plates exhibited density differentials between 110/kg/m3 to 120kg/m3, whereas the modern back plates showed density differentials between approximately 115kg/m3 to 140kg/m3[126].

[125] ibid.

[126] ibid.

However the density differential is significantly lower for the soundboard of Cremonese violins, with a smaller but discernible differential in the back plates. The modern violins in contrast displayed a higher density differential. Stoel and Borman suggest that the lower density differentials of the Cremonese violins may affect their acoustic quality[127].

Stoel and Borman have not been able to evidence that density differentials affect acoustic quality or what may cause the density differentials. They suggest various reasons which may have led to the density differentials in the study, such as natural ageing and the stewing or fuming of wood[128].

Stoel and Borman speculate on the causes for the lower density differentials shown in the results for the Cremonese violins. They discuss how ponding decomposes wood and causes bacteria and fungi to enter changing its composition. The effect of bacteria or fungi attacking the wood may have caused the wood's degradation due to ponding, impacting its density causing it to decrease. The amount of degradation and decreased density would depend upon the treatment used for the ponding as to how it could affect the density differentials[129].

Stoel and Borman conclude that the density differentials of wood may impact on the acoustic qualities of the violin, and that the acoustic qualities of antique Italian violins may be due to the low density differentials they exhibit.[130]

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[127] ibid.
[128] ibid.

[129] Eriksson Karl-Erik L et al., 'Morphological Aspects of Wood Degradation by Fungi and Bacteria', *Microbial and Enzymatic Degradation of Wood and Wood Components* (1990), 1-87

[130] Berend C Stoel and Borman Terry M, 'A Comparison of Wood Density Between Classical Cremonese and Modern Violins', *PLOS ONE*, 3, no. 7 (2008),

Bucur explains that natural ageing causes decomposition of the wood and less hemicellulose thus lowering the density of wood. Decomposition of the wood of violins may have lowered the density. Studies have also found that chemically treated wood shows decomposition[131].

Studies by Nagyvary et al. and Tai et al. have shown the presence of chemical treatment in wood. Nagyvary et al suggest treatment of the wood was likely by chemicals to preserve the wood and protect it from fungi and woodworm and potentially to enhance the acoustic properties of the wood[132] [133].

Su et al. focus on the findings of Stoel and Borman's research that density differentials between early and late wood are significantly smaller in Cremonese spruce, yet not such great density differentials in maple. Su et al. suggest possible reasons for low density differentials being recorded in spruce in comparison to maple. Su et al. suggest that as the Cremonese violins are likely to have been chemically treated, the metal salts for these treatments may have caused the more porous, less dense early wood to absorb the metal salts more than late wood. Consequently the early wood may have absorbed the x-rays to a greater extent than the late wood and thus it may appear falsely that the density differential is small. Su et al. also propose that the density of the maple may have been overestimated by Stoel and Borman as the tree rings of

[131] Voichita Bucur, 'Theory of and Experimental Methods for the Acoustic Characterization of Wood', *Acoustics of Wood*, 2nd ed. (2006), 39-104

[132] Joseph A Nagyvary et al., 'Mineral Preservatives in the Wood of Stradivarius and Guarneri', PLOS ONE, 4 (2009), e4245

[133] Cheng-Kuan Su et al., 'Materials engineering of violin soundboards by Stradivarius and Guarneri' Angewandte Chemie ,133, no. 35, (2021), 19293-19303.

maple are not as clear as the spruce and hence that these results may not be accurate[134].

The inconsistency in the one result of modern soundboards which matched the lowest of the Cremonese violins, the only one which had a density differential which comes close to or in the case matches the density of Cremonese soundboards of 140kg/m3 is a point of investigation. The reason provided for the low result is that the wood may have been treated prior to use. There is therefore the possibility that treated wood may cause lower density differentials. The results of Tai et al. and Nagyvary et al. showed that Cremonese wood exhibited unnatural chemical composition and altered matrix and therefore may have been treated prior to use[135].

There are several reasons why a difference in density and density differentials may be found in wood growth naturally. Depending on which part of the tree trunk vertically the wood is cut and the distance to the pith, the density of spruce wood varies. This suggests that there would normally be a significant density differential in a cross section of wood.

Bucur states that the vibrational and sound radiation of a violin are affected by the geometry and constitutional properties of the wood. The type of wood growth affects the density differentials. Typically early spring growth is less dense and more porous due to its role of transporting water, whilst later summer growth is denser with tightly grouped tracheids due to the more structural role of the late wood as a support[136].

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[134] ibid.

[135] Hwan-Ching Tai et al., 'Chemical Distinctions Between Stradivarius's Maple and Modern Tonewood', *Proceedings of the National Academy of Sciences*, 114, no. 1 (2017), 27-32

[136] Voichita Bucur, 'Theory of and Experimental Methods for the Acoustic Characterization of Wood', *Acoustics of Wood*, 2nd ed. (2006), 39-104

Therefore I view from Bucur's research that the less dense growth in spring and the denser growth in summer would usually create a density differential between wood growth.

The results of Stoel and Borman's study show that there is little significant difference in average density between the antique Cremonese violins and the modern violins. The most important finding results is that the Cremonese violins have a significantly lower density differential when compared to modern violins. While it is possible that this may be due to the treatment or the ponding of the wood, it may also be because of the environmental factors where the wood grew.

Tree rings in a given piece of wood would typically vary in thickness depending on the climate throughout the year. However Stoel and Borman's results show more even growth between the early and late wood growth. This suggests a factor in the environment where the wood grew, caused unusually uneven growth throughout the year. I suggest that the factor which may have caused the unusually low density differentials in Cremonese violins may be the climatic factors in which the wood grew. This is as the conditions which favour the low density differentials, or even growth of early and late growth, are the climatic conditions which were exhibited during the Maunder Minimum.

Burckle and Grissino-Mayer assert that as wood grown during the Maunder Minimum had little nutrients available, growth would have been slow. However outside the Maunder Minimum, a density differential between early and late growth would be normal, as with more nutrients available to the tree, growth would be greater and more rapid. Poor conditions generate slow growth and high average density in the wood[137].

It is unclear why Stoel and Borman conclude that environmental factors do not affect median density, density differentials or the sound quality of a violin, as it appears to be unexplained and lacking in evidence as to why they consider this to be so. The absence of reference to the climatic conditions or location of where the wood grew may be an oversight. Stoel and Borman conducted research on the average density and density differentials of wood but did not do any acoustic experiments or reference Burckle and Grissino-Mayer's work.

I consider it important to reference that the low density differential of Cremonese wood may be due to the conditions of the Maunder Minimum under which the Cremonese wood is believed to have grown at slow rates with more even growth[138]. Therefore the climate and environmental factors under which a tree grows may affect the properties of the wood, a potential consideration which Stoel appears to have overlooked.

In presenting the results of this study, Stoel has anonymised the Cremonese and modern violins, citing the reason being common medical practice[139]. However by anonymising the results, it is not possible to know which results pertain to which instruments or maker, thus making it not possible to compare findings between makers or to assign trends to a maker. This excludes the reader from drawing any conclusion as to the density, density differentials or practice of violins made by Stradivarius.

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[137] Lloyd Burckle, and Grissino-Mayer Henri D, 'Stradivarius, Violins, Tree Rings, and the Maunder Minimum: a Hypothesis', *Dendrochronologia*, 21, no. 1 (2003), 41-45

[138] ibid.

[139] Berend C Stoel, and Borman Terry M, 'A Comparison of Wood Density Between Classical Cremonese and Modern Violins', *PLoS ONE,* 3, no. 7 (2008),

The results of the study could be more pertinent to my research if further repetitions of such a methodology were tested on a greater number of Stradivarius instruments to see if the results confirm low density differentials, and in addition if the results were individually listed for each violin, the results of the Stradivari violin separate from the other Cremonese violins could be studied. Data could then be more accurately attributed to the Stradivarius violins in particular.

Amongst the eight modern instruments used for comparison to the Cremonese in this study, one of the instruments is a viola while the remainder are violins. The study is titled ‘A Comparison of Wood Density between Classical Cremonese and Modern Violins’, thus it appears as an inconsistency with the aim of the study to include a viola and include it in the category of modern violins for comparison. The viola is an instrument with different properties, size, acoustics and range. Moreover, within a study of a comparison between violins, a viola cannot be substituted for a violin for direct comparison of density and density differentials. In addition, there is an inequality between the number of Cremonese and modern instruments used for comparison in the study with only five Cremonese to the eight modern instruments. Consequently, the comparison seems unequally proportioned as there is a higher percentage chance of evening out fluctuations in the modern violins results due to the higher number of them in this study.

Previous methods of density analysis have involved the immersion of wood in water, covered in a plastic outer layer, a potentially risky method which was not able to produce such accurate results on density and density differentials. Therefore the methodology of CT scanning may be a more accurate way of measuring the density and density differentials of violins. However wood density can vary for each 0.1 millimetres, a resolution which CT cannot decipher. The density value of early and late growth may consequently not be accurate as a surrogate grain density measure had to be used instead to work out the density differentials in the wood. Further research using a more accurate methodology to study density differentials would provide results on whether the findings in this study are precise.

The research by Stoel and Borman has provided valuable data showing that density differentials in Cremonese violins are lower than those of modern violins. The lower density differential may contribute to their acoustic quality which is often considered desirable by violinists today. However as results of the study have been anonymised, it is not possible to know whether Stradivarius violins present a significant difference in density differentials to the other Cremonese violins, as all of the Cremonese violins exhibit density differentials which are lower than those of untreated modern violins.

The conditions in which the trees grew affected all the luthier's wood in Cremona impacting the acoustic quality. The anomaly of the potentially treated modern wood displaying lower density differentials also suggests that research by modern luthiers today into treating wood in various ways such as by soaking wood may reveal further insight into whether the treated wood has lower density differentials. This could indicate whether Cremonese wood may have lower density differentials due to treatment.

**A Discussion on the Findings of the the Studies and the Implications They Hold for my Research**

The research of Burckle and Grissino-Mayer focused on the climatic conditions and location of where the spruce grew, and Stoel and Borman focused on the density and density differentials in Cremonese violins. The study of Stoel and Borman is anonymised, and the hypothesis of Burkle and Grissino-Mayer pertains to Cremonese luthiers in general and to the source of Cremonese spruce, so both studies represent a more overall discussion of how the growth and density of wood has impacted upon Cremonese makers.

The two studies link together as the low density differentials of Cremonese violins may be explained by the Maunder Minimum put forward by Burckle and Grissino-Mayer. It appears that low density differentials and the conditions of the Maunder Minimum may have impacted upon the wood used in antique Cremonese violins and therefore the violins of Stradivari affecting their acoustic quality and thus their formant frequencies.

## Chapter Three: The Aqueous Treatment of Stradivari's Wood

Chapter Three will first introduce the topic of wood treatment, which will be explored in both Chapters Three and Four. Wood treatment is the process of physically or chemically altering its properties. Chapter Three will focus on the aqueous treatment of wood. Chapter Four will continue the discussion on wood treatments by analysing the chemical treatments and chemical composition of the wood used by Stradivari in closer detail. Scholars such as Nagyvary, have proposed that the wood used to make Cremonese violins had in some way been treated prior to use, and consequently this may have impacted upon the acoustic quality and thus the formant frequencies of these violins.

In this chapter I will explore the aqueous treatment of wood by looking specifically at ponding by discussing the studies of Barlow and Woodhouse, and Folland, who have researched whether the wood Stradivari used was ponded before use.

The consensus of many luthiers today is that fungi, which may be introduced as a consequence of wood treatments, can lead to degradation in wood. Luthiers today tend to view degradation in a negative light, and many choose to not treat their wood either chemically or by aqueous treatment. If wood decreases in density, which is a possible consequence of degradation or fungi, Beare explains that it could negatively impact on the acoustic quality of a violin. Consequently many luthiers today do not treat their wood or introduce any chemicals or fungi directly or indirectly into the wood.

Many modern luthiers do not treat violin wood, except for leaving the wood to season for a period of time before use, which can vary, depending on the type of wood and time of harvesting. Seasoning dries out the wood, so that enough moisture from the wood has evaporated prior to use. Gosling explains that the length of time to season wood depends upon the thickness of the pieces of wood. Scholars, Topham and McCormick, deduce that Stradivari seasoned his wood for between seven and thirty-two years[140].

Luthier Paul Gosling from the Luthiers Valse, explained that he seasons spruce and maple wood with a depth of 25 ml for a year. During the year, he alters the amount of air flow between the wood in the winter and summer. He allows for greater spacing between the planks of wood in the summer, always drying the wood in the open air outside, without a metal roof. He explains that many planks of wood can be thicker than 25 ml, which lead to extended drying times[141].

Beare, an experienced luthier, explains that the wood intended for the use of making instruments, needs to be seasoned by being air-dried instead of being dried in a kiln, to make sure that the cell structure remains intact. If dried in a kiln, it could result in a loss of density[142].

Wood treatments are carried out before any carving or shaping of the instrument is done. The wood treatments which scholars have suggested may have been used by luthiers such as Stradivari include the following: treating wood with chemicals by direct application onto the wood's surface, permeation by fumigation, soaking or the ponding

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[140] 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, Volume 27, Issue 3, (March 2000) 183-192

[141] Paul Gosling, Personal Communication, *The Luthiers Valse*, 23rd July 2023

[142] Beare Peter, 'Crafting a Violin from a Tree', Orchestra of the Age of Enlightenment (2021), https://oae.co.uk/how-to- (accessed: 07/09/23)

of the wood in chemical solutions, baking, burning or the physical manipulation and storage of wood in particular environments after seasoning the wood. Treatment of wood may have consisted of one treatment or a combination of treatments.

Wood has been preserved for centuries for use in shipbuilding and cabinet making. Shipbuilders soaked wood in sea water to strengthen it. The soaking of wood in fresh or salt water increases its permeability allowing preservatives to better soak into the wood for commercial use. When wood is soaked in fresh water the structural chemical composition of the wood is altered[143].

There is disagreement as to when it may be that the practice of treating wood, apart from simple seasoning was common practice. Nagyvary documents an account by the aristocratic patron of Joannes Baptista Guadagnini (1711-1786), which emphasises the importance of only using air dried wood, rather than using wood which has been subject to other treatments. Given that Guadagnini was one of the later celebrated Cremonese luthiers, this suggests that wood treatment was no longer practised from the mid-eighteenth century. Further, treatises from the eighteenth and nineteenth centuries do not mention chemical treatment, thus suggesting such practices were not followed during this time[144].

Scholars such as Nagyvary et al., Tai et al. and Su et al. speculate that the wood used by Antonio Stradivari and his contemporaries, Giuseppe Guarneri del Gesù, Nicolò

[143] C Y Barlow and J Woodhouse, 'Bordered Pits in Spruce from Old Italian Violins', *Journal of Microscopy*, Vol. 160, no. 2 (1990), 203

[144] Joseph A Nagyvary et al., 'Mineral Preservatives in the Wood of Stradivarius and Guarneri', *PLoS ONE*, 4 (2009)

Amati and other Cremonese luthiers was treated before use. They also suggest that such treatment may affect the acoustic quality of the instruments [145] [146] [147].

Tai et al. 2016 consider the treatment of maple to have not been a widespread practice by many luthiers. Chemically treated wood appears to be unique to Cremona. Wooden artefacts from this area, unlike some from other Italian cities, did not suffer from woodworm damage[148].

**The Ponding of wood**

Ponding is a type of aqueous treatment, where wood is submerged in salt or fresh water. Freshly felled wood during the lifetime of the master Italian luthiers was transported using the waterways, consequently ponding the wood. Wood is also ponded for commercial reasons, to increase the permeability of wood, allowing preservatives to penetrate it.

The research by Barlow and Woodhouse on ponding and bordered pits explores the hypothesis put forward by Nagyvary in 1988, that spruce used in Italian violins may have been ponded, through submersion in water for soaking or treatment[149]. Barlow and Woodhouse examined thirteen samples of spruce from thirteen antique Italian violins using SEM to see if the membranes of the bordered pits showed signs of

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[145] ibid.

[146] Cheng-Kuan Su et al., ‘Materials engineering of violin soundboards by Stradivarius and Guarneri’ *Angewandte Chemie* ,133, no. 35, (2021), 19293-19303.

[147] Hwan-Ching Tai et al., 'Chemical Distinctions Between Stradivarius’s Maple and Modern Tonewood', *Proceedings of the National Academy of Sciences,* 114, no. 1 (2017), 27-32

[148] Joseph A  Nagyvary, et al., 'Mineral Preservatives in the Wood of Stradivarius and Guarneri', *PLoS ONE,* 4 (2009), e4245

[149] Joseph Nagyvary, ‘The chemistry of a Stradivarius’, *Chemical & Engineering News* 66 21, (1988) 24–31

bacterial degradation, which if present would suggest that the wood had been submerged in water for some time before use. Amongst the instrument samples were violins made by Gaspar Da Salo, Maggini, Amati and Stradivari[150].

Recently felled green wood which has not been dried out and has been ponded shows significant effects of ponding after only a few days. Wood is typically ponded for four to twelve weeks. Ponding has been used to strengthen the wood and to prevent woodworm.

Previous research on ponded wood shows that bacteria and enzymes selectively destroy sections of the wood structure, leaving the membranes of bordered pits in the wood degraded or missing[151]. As wood degrades, the density decreases[152]. Such signs of degradation provide evidence for the wood being ponded.

The results of the study by Barlow and Woodhouse show all membranes of the thirteen spruce samples to be intact with no missing or degraded membranes[153], unlike the typical properties exhibited by wood which has been ponded[154]. Barlow and Woodhouse state that most of their samples appear to look the same as modern air-dried spruce used for violin making, with the only exceptions being samples which were lacking strength or were falling apart and crumbling. However, even these

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[150] C Y Barlow and Woodhouse J, 'Bordered Pits in Spruce from Old Italian Violins', *Journal of Microscopy*, 160, no. 2 (1990), 203-211

[151] Ibid.

[152] Paul Gosling, Personal Communication, *The Luthiers Valse*, 23rd July 2023

[153] ibid.

[154] A J, Bolton and J A Petty, ‘Structural Components Influencing the Permeability of Ponded and Unponded Sitka Spruce’, *J.Microscrospy*, 104, 33-46

samples showed membranes to remain intact, leading Barlow and Woodhouse to the conclusion that ponding was not the reason for the weakness of these samples. Barlow and Woodhouse conclude that it is likely that the spruce used for the violin fronts was not ponded[155].

Yet Barlow and Woodhouse highlight a complication to the interpretation of their results and conclusions of the study. If the wood had been heart wood or wood which had been aspirated and air-dried prior to the study, then it is not normal for signs of degradation of the wood to be present if the wood had been ponded, unless ponding had been for an extensive period. Therefore, it would be difficult to test for whether wood had been ponded if it had been aspirated. The high presence of salt shown in previous chemical analysis suggests that the wood may have been ponded or submerged in water or waterways.

Barlow and Woodhouse point out that the purpose of ponding is often to degrade pit membranes to increase permeability[156]. Therefore, without pit membranes degrading, it puts into question why wood would be ponded if it did not have the result of degrading the membranes for chemical treatment to penetrate further into the wood. Therefore, it puts into question why wood would be aspirated before ponding, if degradation is desirable. However, there may have been other reasons behind why wood was ponded, other than for increasing permeability, such as for storage or transportation purposes[157].

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155 C Y Barlow and Woodhouse J, 'Bordered Pits in Spruce from Old Italian Violins', *Journal of Microscopy,* 160, no. 2 (1990), 203-211

156 ibid.

157 ibid. 203

Barlow and Woodhouse acknowledge that although the results of their study show no evidence of degradation, suggesting that wood was not ponded, they cannot be certain that Stradivari's wood was not ponded. This is because degradation would not normally be evident if the wood had been aspirated[158].

Despite having limited samples, Barlow and Woodhouse consider their study to be representative of the spruce used for violin fronts from the lifetime of the Italian master luthiers and from their golden periods. This is due to the wide representation of samples in the study from makers from various regions, with samples coinciding with luthiers' golden periods, despite inconsistencies in the quality and quantity of sample sizes.

Depending upon the rivers where the wood would be floated, the wood would be immersed in different chemicals and solutions and thus would have absorbed different chemicals[159]. This may account for the diversity of chemicals and minerals found in the violin wood of antique Cremonese instruments. Gosling's explanation of differences in the quality of water in the different rivers, canals and sea, may explain the varying chemical compositions between the violin wood in different instruments. As Gosling has suggested that wood was transported by waterways, the suggestion by Tai et al. of minerals having been taken in or washed out of the wood may have occurred, perhaps not just through treatment but as a consequence of the method of transporting the wood in water. The different chemical compositions of the wood of Cremonese violins may affect their acoustic quality and formant frequencies.

[158] ibid.

[159] ibid.

Further research into the chemical composition of Stradivari's wood compared to other Cremonese makers could give insight into whether Stradivari's wood in general showed differences to other makers. If the chemical analysis of Stradivari's wood is different to other makers or showed the presence of certain minerals or chemicals, this may suggest that his wood was handled differently or that his unique acoustic quality was due to a separate or an additional chemical treatment.

**An Experiment in Ponding of Wood by a Contemporary Luthier**

David Folland, a modern luthier was impressed by the tonal strength of bridges made by Stamm who used wood which he had ponded. Folland decided to experiment using the method of ponding as proposed by Stamm to see what effects ponding may have on the acoustic quality of violin. Folland ponded twelve spruce fronts and twenty five maple backs in distilled water for three months as detailed in experiments by Stamm. Folland made the violins over a period of four years[160].

Folland conducted experiments to reveal whether ponding of the wood affected the density or speed of sound travel in the spruce and maple. Results showed both the ponded spruce and maple to have no difference in the speed of sound. The spruce retained the same relative density, whereas the maple slightly decreased in relative density by 0.02. Additionally Folland made two identical violins, one from unponded spruce and maple and one from spruce and maple which was ponded, to directly compare the tonal characteristics of the violins[161].

[160] David Folland, 'Wood Ponding', *The Strad,* February 2015, 24-26

[161] ibid.

When tested by violinists periodically, the tone between the two violins was considered as similar. Some players detected minor differences in the tone of the violins, without regarding one violin tone as distinctly better than the other. Folland also detected no change in the speed of sound[162].

Folland concludes that his findings are limited due to the lack of repetition of the experiment to consolidate the results, suggesting the value in other luthiers testing for differences in ponded versus unponded wood to discover the potential benefits that the ponding of wood may have for violin making[163].

In Folland's method he soaked the wood for two months and then proceeds to dry the wood, first in an outbuilding at about 50% humidity for four to five weeks and then in a drying cabinet at 15% humidity. He finishes the drying of the wood in his loft for two months, to accustom the wood to normal room temperature and humidity. Usually spruce is seasoned for three years and maple for five years, a significantly longer period of time than Folland dried the wood for which he used in this experiment[164].

I view that immersing the wood fully in water for two months, as Folland did, would make the moisture levels in the wood much greater than when the wood was first felled, which may suggest that drying time would need to be extended. The drying times of freshly felled wood is much greater than those used in Folland’s experiments[165], where the drying time has been and Folland has contracted these and as a result the wood may not be fully dried before being used to make a violin.

[162] ibid.

[163] ibid.

[164] ibid.

[165] Paul Gosling, Personal Communication, *The Lutheirs Valse*, 30th August 2023

Therefore, despite the accelerated drying of the wood, due to the use of the drying cabinet, it is questionable whether the wood which Folland used was fully dried before he made the violins, which may affect the acoustic quality, impacting upon the results of his experiments.

Another aspect which I question in Folland's methodology, is that the ponded wood was partially dried in a drying cabinet, which again is not a usual practice for drying wood. Wood for making violins is usually seasoned at room temperature to avoid the properties of the wood being adversely affected, by drying the wood in hotter or less humid conditions[166]. Therefore, I view Folland's method of using a drying cabinet with a lower humidity of 15% as having the potential to affect the properties of the wood, which could impact upon its acoustic quality. Due to the methodology of drying out the wood followed by Folland, I view his results as potentially being impacted by having the wood with a short drying time and also under unnatural conditions of drying out the wood. The results therefore, may not show the effect of ponding on the acoustic quality of fully dried wood under room temperature conditions under which most wood is seasoned for the purpose of violin making.

Folland's study shows the potential effects of ponding wood in water without any added chemicals. This may not be representative of water or solutions which may have been used on the wood by the Cremonese makers during Stradivari's lifetime. If the wood was ponded by submersion in water or when transported or stored in waterways,

[166] ibid.

which may have been polluted or have had additional chemicals or minerals present, these chemicals and minerals may have been absorbed by the wood.

An additional aspect, which is important in viewing Folland's study results, is the method used for detecting the acoustic quality of ponded and unponded instruments. The human memory retention of sound is shorter than the time taken to switch playing instruments[167], therefore leading to the possibility of inaccurate results as to whether the acoustic quality between the ponded or unponded woods of violins is different. If recordings were made of the ponded and unponded violins being played and directly compared against one another, then the results of perceived acoustic quality would have greater accuracy and validity.  However, the methodology using subjective opinion puts the study in the field of psychoacoustics, which is harder to evaluate.

Although the players agreed that there were not significant differences in the acoustic quality of ponded and unponded wood, scientifically this is not concrete, as no spectrogram showing resonance frequencies has been used to back up the subjective opinion on the acoustic quality of the violins. I would therefore suggest results would have been stronger if analysis of spectrogram frequencies were conducted using vibroacoustics, alongside psychoacoustic studies of players' judgement on the acoustic quality of the violins.

I view Folland's study as valuable for a modern luthier in testing for the potential effects of ponding wood regarding the acoustic quality of a violin. If a different method of ponding or solution or a varying timescale, for ponding had been used by Folland,

[167] James Bigelow and Amy Poremba, ‘Achilles’ Ear? Inferior Human Short-Term and Recognition Memory in the Auditory Modality’, 2, *PLoS ONE* (2014) 9

results may have been different. Therefore, I view this study as a valuable preliminary study on ponding, however, as suggested by Folland, further research would need to done to see if the results varied on repetition, or if an alternative methodology yielded the same results. Therefore, from Folland's study, without further research, I view it is not possible to see whether Cremonese wood was ponded.

Folland's research backs up the research of Barlow and Woodhouse, that Cremonese wood may not have been ponded[168], as little discrepancy in acoustic quality was discernible in Folland's results between the violins made with ponded or unponded wood. The results of the study by Barlow and Woodhouse are inconclusive as they are unable to assess whether the wood was aspirated prior to ponding. The research by Folland does not use any spectral analysis or scientific measurement to assess the difference in sound, relying upon psychoacoustic studies for sound perception. Therefore there are no scientific results to show any differences in sound between the ponded and unponded violins. Further research is necessary to verify whether the wood of Cremonese violins was ponded and whether this could have impacted the acoustic quality of the violins.

[168] C Y Barlow and Woodhouse J, 'Bordered Pits in Spruce from Old Italian Violins', *Journal of Microscopy*, 160, no. 2 (1990), 203-211

## Chapter Four: The Chemical Treatment and the Chemical Composition of the Wood of Stradivari Violins

Chapter four will discuss the research by Nagyvary et al. and Tai et al. who explore whether the wood of Stradivari and other Italian master luthiers of the seventeenth and eighteenth centuries was chemically treated using a variety of scientific methods, including scanning electron microscopy, light microscopy, and transmission electron microscopy.

Topics of discussion will include if, how, why and by whom was the wood used by Stradivari treated. I will conclude by looking at the chemical treatment which may affect their acoustic quality and the formant frequencies.

### Investigations into the Chemical Treatment of Stradivari's wood

Nagyvary is a chemist, luthier and researcher of seventeenth and eighteenth century lutherie, specialising in copying and researching the instruments of Antonio Stradivari and Giuseppe del Gesù. In 1978, Nagyvary began a new field of study into the organology of Stradivarius violins, suggesting that the composition of the workman's materials, could be more important than the craftsmanship in determining the acoustic quality of a violin. The suggestion was first met with mixed reception from fellow scholars and luthiers in the field[169].

Nagyvary proposes that previous research on the violin's geometry, shape, thickness, varnish and the tuning of violin plates only reveals one side of how these makers

[169] Joseph A Nagyvary, 'History and interpretation of chemical knowledge available to violin makers', *J Violin Soc Amer* IV(3&4), (1978), 147–176

crafted instruments. Nagyvary suggests that there is a large unexplored avenue of wood treatment which may affect the acoustic quality of Cremonese violins[170].

Initial investigations of Nagyvary found that the violins made by Antonio Stradivari and Guarneri del Gesù showed signs of chemical treatment and that this affected the mechanical and acoustical properties of the violins. Nagyvary suggests that the local pharmacy in Cremona may have supplied a solution for pre-treating wood to inhibit infestations of woodworm, as there was a significant outbreak of woodworm in Cremona during this period[171].

Nagyvary proposes that the superior acoustic quality of Stradivari and Guarneri del Gesù violins may be as a result of a pretreatment of the wood to prevent woodworm infestation, rather than an intentional chemical treatment which improved the acoustic quality[172]. Nagyvary states that in other parts of Europe the same level of craftsmanship and knowledge was present as in Cremona and that treatment may have been a need to preserve wood, which gave the Cremonese violins their acoustic properties[173].

Further research by Nagyvary centred on taking SEM observations of three wood samples taken from the spruce plate of Stradivarius 'The Betts' 1704 violin, the Guadagnini 1750 violin and the Guarneri del Gesù 1735 violin. Results showed many inorganic residues and high amounts of salt in the wood. Nagyvary proposes that the

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[170] ibid.

[171] ibid.

[172] ibid.

[173] ibid.

wood had been soaked in sea water, causing the high amounts of salt present. This may also have changed the wood structure and introduced microorganisms into the wood[174].

In 2006, Nagyvary et al. proceeded to conduct experiments to investigate whether the wood used by Antonio Stradivari and Guarneri del Gesù, a highly respected Cremonese luthier contemporary to Stradivari, was chemically treated. The experiments were conducted using nuclear magnetic resonance and infrared spectroscopy to analyse the organic matter in the wood of the instruments by Antonio Stradivari and Guarneri del Gesù[175].

The instruments used for this study were a violin by Antonio Stradivari from 1717, a violin by del Gesù from 1741 and a cello by Stradivari from 1741. The wood from antique Italian instruments was compared against the wood from a violin made by Gand-Bernardel in Paris 1840, a viola by Henry Jay in London 1769 and new tone woods from Bosnia and central Europe. The wood used was maple wood shavings from the backs of the instruments.

The Stradivarius and del Gesù violins differed when chemically analysed to the London and Paris instruments and also to the tone woods. In contrast, the Stradivarius cello showed much smaller differences when analysed and compared with the London and Paris instruments and tone wood. The 1717 Stradivarius violin's results were close in spectrum to the del Gesù violin. The Stradivarius cello only showed a small variation

[174] ibid.

[175] ibid.

from the Bosnian maple and the London and Paris instruments and to those of the wood of the boiled and baked Bosnian maple sample[176].

Nagyvary et al. conclude that the wood in the Stradivarius and Guarneri del Gesù violins is possibly chemically treated but note that the differences between the composition of the two violin makers may be due to the way in which the wood was preserved[177].

Explaining the high concentrations of calcium and magnesium in Stradivarius maple Nagyvary et al. suggest that the maple may have been soaked in mineral water[178]. Nagyvary et al. suggest that chemical treatments such as oxidation and ponding may have been used to change the properties of the Stradivarius and del Gesù woods. The Paris and London instruments and the Stradivarius cello may have natural ageing as a reason behind the chemical changes which occurred to these woods rather than treatment. Nagyvary et al. suggested an examination of the minerals present in the wood may reveal further information[179].

The aim of the study by Nagyvary et al. 2009 was to follow up on the 2006 study, to identify the minerals and chemical composition of samples of maple ashes taken from Antonio Stradivarius and Guarneri Del Gesù instruments. The samples used in this study are the same as used in a previous study by Nagyvary et al. in 2006 which are

[176] ibid.

[177] ibid.

[178] Joseph A Nagyvary, 'Investigating the Secrets of the Stradivarius', *Education in Chemistry*, 42, no. 4 (2005), 96-98

[179] Joseph A Nagyvary et al., 'Wood Used by Stradivarius and Guarneri', *Nature*, 444, no. 7119 (2006), 565

compared against samples of modern maple tone woods which had been untreated and naturally seasoned from Bosnia, Slovenia and China[180].

The methods of analysis were back scattered electron imaging, x-ray fluorescence maps for individual elements, wave-length dispersive spectroscopy, energy dispersive spectroscopy and qualitative microprobe analysis[181]. Results indicated that there was evidence of all four Cremonese instruments showing chemical treatment. The minerals found included barium sulphate, calcium fluoride borate and zirconium silicate. The results show differences between the London and Paris instruments and only the Cremonese instruments differed to the commercial tone woods[182].

Nagyvary et al. suspected the use of insecticides or fungicides to chemically treat the wood of Stradivarius and Guarneri del Gesù violins. Nagyvary et al. focused specifically on searching for evidence of insecticide and fungicide treatment in the samples. Significant levels of boron were found in the samples of Stradivarius instruments and the Guarneri del Gesù early violin, however not in the late Guarneri del Gesù violin. None of the samples of maple tone wood show the presence of boron. Notably levels of sodium chloride were found to be higher in the Stradivari violins than would naturally be present in maple[183].

Nagyvary et al. interpret the high levels of boron and the presence of fluoride to be evidence of chemical treatment from a pesticide for the purpose of protecting the wood from fungus and woodworm, both of which are commonly used in modern pesticide

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180 Joseph A, Nagyvary et al., 'Mineral Preservatives in the Wood of Stradivarius and Guarneri', *PLOS ONE,* 4 (2009), e4245

181 ibid.

182 ibid.

183 ibid.

solutions. Elevated levels of sodium chloride were interpreted by Nagvyary et al. as potential evidence for the soaking of wood in water. The chemical composition of the sample of Stradivarius wood is shown to be notably different to all the tone wood samples. The Stradivarius wood displays significantly higher levels of sodium oxide in comparison to the tone woods. Higher levels of chlorine, silicon dioxide, sulphur trioxide, barium oxide, iron oxide and copper oxide were also found. An unnatural ratio of potassium to sodium was revealed. Compared to the tone woods, decreased levels of calcium oxide, magnesium oxide and phosphate were also found to be present in the Cremonese wood.

The greatest decomposition of the wood was evident in the Stradivarius and Guarneri del Gesù instruments, despite the composition being contrastingly different between the two instruments. Thus, as the chemical compositions vary, it is not clear which chemicals are responsible for the wood's structural changes[184]. It is therefore likely in my opinion that the instruments may have been treated differently to one another which may explain their contrasting composition and presence of chemicals.

The sample from the Stradivarius cello showed natural levels of phosphate to be present, suggesting the same method of potential chemical treatment may not have been employed by Stradivari for violins and cellos[185].

Nagyvary et al. base their hypothesis of chemical treatment on Nagyvarys observations of violins from Cremona and Milan. Nagyvary et al. noticed that the violins from Milan show significant sign of damage from woodworm, whereas such damage was not evident in Cremonese violins. Therefore, Nagyvary et al. propose

[184] ibid.

[185] ibid.

that the Cremonese violin wood may have been treated in some way, to prevent damage from woodworm and that this practice was not common in Milan[186].

I view the premise for the hypothesis by Nagyvary et al. to be a possible proposition, as during this time the treating and preserving of wood was a practice in other trades, such as furniture making during the same period. Additionally, the chemicals found to be present in the wood of Stradivari reflect many of the chemicals found in pesticide solutions. It is possible that Stradivari's wood was chemically treated for preservation reasons and to inhibit attacks of woodworm.

Within the tone woods used as a control in the study, variation was present, potentially due to the varying nutrients available in the soil where the trees grew and from the spraying the trees with pesticides or from accidental contamination. Therefore it could be argued that due to the variation in tone woods, there is no constant control to compare the Cremonese samples against. Despite the inconsistency of the tone woods, results of chemical composition of Cremonese instruments are significantly divergent. Results showed that the Cremonese wood in the instruments is significantly different to all the other tone woods.

The study was unable to uncover a specific recipe for chemical treatment used by both Stradivari and Guarneri del Gesù. Even between the Stradivarius violin and cello, results of chemical analysis differed greatly, perhaps due to their size difference and the difficulties which would have been associated with treating longer and larger pieces of wood.

I suggest that the stronger chemical treatment of violins compared to the cello found in the study by Nagyvary et al. may be due to the size difference of the instruments

[186] ibid.

and the difference in pitch range. Gosling explained that it is more important to have a quality wood for violins due to the high frequency vibrations produced by them than for cellos which have lower vibrations[187].

Nagyvary et al. speculate that crushed crystal salts may have been used to treat wood in Cremona to harden its structure[188]. The wood may have been submerged in aqueous solutions of the salts or boiled to inhibit woodworm. Alternatively a crystal salt solution may have been able to penetrate through the maple, being applied on top of the surface of the wood as fillers. The use of salt solutions to submerge the wood would explain the higher levels of sodium chloride detected in some of the violins.

While growing, trees have been reported to have suffered damage and degradation when sprayed with pesticides containing sea salt and salts of iron, copper, chromium, zinc and selenium[189]. Nagyvary et al. believe it is likely that several soluble salts are the reasons for the degradation found in the wood samples of the Cremonese instruments.

Nagyvary et al. pursue the premise that the wood may not have been intentionally treated for acoustic purposes, as it may have been bought pretreated or the local chemist may have provided a ready-made solution for the treatment of wood, rather than the luthier preparing his own solution for treatment[190]. I view this approach by Nagyvary et al. suggesting that the luthier himself may not be responsible for the

[187] Paul Gosling, Personal Communication, *The Luthiers Valse*, 30th August 2023

[188] ibid.

[189] ibid.

[190] ibid.

treatment of wood affecting the acoustic quality of a violin to be a hypothesis in need of exploring further. As Cremonese wood was pretreated chemically, for the cabinet making industry, then it is possible that the hypothesis by Nagyvary et al. could hold significance in considering how Stradivari's wood may have been treated.

Nagyvary et al. conclude that across the Stradivarius and Guarneri del Gesù violins, signs of chemical treatment are present, therefore increasing the likelihood that the presence of such chemicals would not be restricted to only the instrument samples used in the study[191]. Thus, I view that it is likely that chemical treatment may have been a process used on many of the violins by Stradivari and Guarneri del Gesù. I suggest that further study is needed on a wider sample of Stradivarius instruments to support evidence of chemical treatment in the wood of Stradivarius violins as a common practise of Stradivari.

I consider that as the difference in chemical composition of Stradivari's wood is significantly different from that of modern violins tested in the study, there may have been deliberate treatment by either the sellers of the wood or the makers in Cremona either for preservation or acoustic purposes. This makes it, in my view, more likely that treatment may have been a standard practice. It is unlikely in my opinion, that this treatment was applied to only one or a few select violins, as no particular Stradivari or known select number of Stradivarius violins are signalled out as having significantly different aesthetics or properties to others, despite each Stradivarius violin having its own unique attributes.

[191] Joseph A Nagyvary et al., 'Mineral Preservatives in the Wood of Stradivarius and Guarneri', *PLoS ONE*, 4 (2009), e4245

It is pertinent to note the identified variations in chemical composition between the two Guarneri del Gesù violins[192]. Such results suggest that luthiers may not have had a defined recipe for chemical treatment for an instrument type, with varying chemical treatments between batches or instruments present.

The unnatural levels of chemicals which Nagyvary has found in Stradivarius violins have effected the chemical composition and thus may have impacted upon the acoustic quality and consequently the formant frequencies of Stradivarius violins.

**Further Research into the Chemical Composition and Properties of Stradivarius Violins**

The research by Tai et al. 2017 is based on previous findings from Nagyvary et al. 2009[193] exploring the chemical treatment of Stradivarius violins, alongside common beliefs held by luthiers, concerning the reasons why Stradivarius violins may have superior tonal qualities to other violins, and are thus often held in high esteem and are the choice of many virtuosi today.

Tai et al. studied maple samples taken from the Cremonese instruments of Antonio Stradivari and Guarneri Del Gesù which they compared to European modern maple tone wood recently acquired from Italy. The Cremonese instrument samples were obtained through previous repair work on back plates and from samples previously

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[192] Joseph A Nagyvary et al., 'Mineral Preservatives in the Wood of Stradivarius and Guarneri', *PLOS ONE,* 4 (2009), e4245

[193] Joseph A Nagyvary et al., 'Mineral Preservatives in the Wood of Stradivarius and Guarneri', *PLOS ONE*, 4 (2009), e4245

used in research by Nagyvary et al. alongside samples from an original violin neck taken from non-contact areas[194].

The samples of the Cremonese instruments were taken from one Stradivarius violin back from 1717, two Stradivarius cello backs from 1707 and 1731, one Guarneri violin back from 1741 and an original neck from a 1725 violin. Samples were also taken from the neck extension fixed to the 1725 violin c.1800. Tai et al. carried out research into the composition of organic fibre, cellulose crystallinity, amount of moisture, thermo-oxidative properties and composition of inorganic elements in the maple of the Stradivarius and Guarneri samples, c.1800 replacement neck and five modern maple tone wood controls[195].

Tai et al used solid-state spectroscopy in their investigations. The results showed that one third of hemicellulose was decomposed in Cremonese samples comparison to in the modern maple and showed evidence of lignin oxidation due to sunlight exposure during the drying of the violins and oxidation due to light exposure over time[196].

Thermooxidation patterns of the Cremonese samples differed from modern tone woods and were similar to the exothermic properties typical of degraded wood which has been attacked by fungus. Tai et al. suggest that the wood may have been soaked in a solution, allowing the penetration of chemicals[197]. In my view the findings showing

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194 Hwan-Ching Tai et al., 'Chemical Distinctions Between Stradivarius's Maple and Modern Tonewood', *Proceedings of the National Academy of Sciences,* 114, no. 1 (2017), 27-32

195 ibid.

196 ibid.

197 ibid.

fungal degradation are strong and that a potential reason for such degradation could be aqueous chemical treatment.

The samples of maple from Cremonese instruments showed evidence of potential chemical treatment using elemental analysis by inductively coupled plasma mass spectrometry. Twenty five elements and minerals were found in the 1731 Stradivarius cello and the original 1725 neck. The neck extension, which is circa 1800 on the 1725 Stradivarius violin showed little or no evidence of metal content with only 2000 ppm, whereas unusually high amounts of metal were present in the original Stradivarius 1725 neck and 1731 cello at a measurement of 9000ppm. The 1725 Stradivarius original neck and 1731 cello displayed similar amounts of the increased presence of potassium, sodium, calcium, copper and zinc. The original Stradivarius neck had increased levels of aluminium and the cello an increased quantity of boron[198]. The presence of unnaturally high amounts of metal in the original 1725 Stradivarius neck, compared to the circa 1800 neck extension shows that chemical treatment may have been carried out to the 1725 wood, but not the 1800 wood. This suggests that by 1800, wood may no longer have been treated with chemicals.

The findings of Nagyvary et al. of reduced hemicellulose in Stradivarius and Guarneri Del Gesù instruments indicates that the instruments have been chemically treated. When testing the same wood samples as Nagyvary et al., Tai et al. found similar results with only differences in hemicellulose and lignin detected[199] [200].

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198 Hwan-Ching Tai et al., 'Chemical Distinctions Between Stradivarius's Maple and Modern Tonewood', *Proceedings of the National Academy of Sciences*, 114, no. 1 (2017), 27-32

199 ibid.

200 Joseph A Nagyvary et al., 'Mineral Preservatives in the Wood of Stradivarius and Guarneri', *PLOS ONE*, 4 (2009), e4245

Thus, chemical treatments used by Stradivari may have included chemicals of aluminium, calcium, copper, sodium, potassium and zinc. Results showed the maple of Stradivari and Guarneri to be significantly different to the modern maple used by luthiers today. Tai et al. also suggest the changes to the organic and inorganic composition of the wood from Stradivarius and Guarneri instruments displayed in the results of the study, could be due to the natural ageing and the force of vibrations on the wood when the instrument was played over time[201].

Scholars have suggested that chemical changes previously found in wood shavings of Stradivarius and Guarneri instruments may be due to the use of surface application of minerals and elements. However, Tai et al. believe the mineral infusion of surface application to have only been possibly used for treatments of small quantities of fungicides by surface application. Tai et al. suggest that significant increases in elements found in the samples may be due to liquid infusion via the process of soaking the wood or sap displacement, before the wood was fully dried when the growth of microorganisms is stopped[202]. Treatment of wood in aqueous solutions has the effect of increasing porosity and permeability and to a greater degree this is the case in early wood.

Therefore if the early wood was treated in an aqueous solution, or as Gosling suggested the wood had been transported through waterways, the penetration of chemicals or minerals may have been strong and highly effective[203]. Tai et al. believe

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[201] Hwan-Ching Tai et al., 'Chemical Distinctions Between Stradivarius's Maple and Modern Tonewood', *Proceedings of the National Academy of Sciences*, 114, no. 1 (2017), 27-32

[202] ibid.

[203] Paul Gosling Personal Communication, *The Luthiers Valse*, 30th August 2023

that wood is likely to have been pre-treated before luthiers received it[204]. Nagyvary et al. also suggest that pre-treatment of the wood may have happened perhaps without deliberate intention to affect the acoustic quality through the transportation or preservation of the wood.

Tai et al. believe that the elements and minerals which would have been originally present in the chemical treatments may have been washed away during subsequent treatment to the wood[205]. Therefore the elements and minerals found when analysing the wood may not reveal the full story of the treatment methodology or composition.

Tai et al. express the need for further research to establish the relationship between ageing wood and exposure long term to vibrations. Yet Tai et al. believe that the changes to the maple in Stradivarius violins are due to the high-frequency vibrations, yet I view that it is important to consider that this is applicable to all violins of the same age[206].

Tai et al.'s findings show decomposition in the wood, with one third of hemicellulose being decomposed and similar exothermic properties of degraded would being exhibited by Stradivari violins[207]. Stoel and Borman also suggested that decomposition of Cremonese wood may have occurred, leading to the wood having lower density

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[204] Hwan-Ching Tai et al., 'Chemical Distinctions Between Stradivarius's Maple and Modern Tonewood', *Proceedings of the National Academy of Sciences*, 114, no. 1 (2017), 27-32

[205] ibid.

[206] ibid.

[207] ibid.

differentials. Both studies suggest that the use of aqueous ponding may have caused such degradation in the wood of Cremonese instruments.

The altered matrix, elevated chemical composition and decomposition of the wood may be in part responsible for the properties of Stradivari's wood which contributed to the acoustic qualities and higher formant frequencies of his violins.

**A Comparison Between the Findings of the Studies and the Implications They Hold for my Research**

Tai et al.'s results concur with the results of Nagyvary et al. that the violins of Stradivari exhibit unnatural chemical composition alongside showing evidence of matrix decomposition. I view that the suggestion by Tai et al. of the chemical treatment method being that of soaking the wood or sap displacement as a potential reason for the chemicals being present in the wood. Alongside this, Tai et al. suggest that during the process of soaking or sap displacement, the chemicals or the minerals which were first present in the wood, may have been washed out and replaced with chemicals in the solution in which the wood was soaked during treatment[208]. This may be a reason why certain minerals are depleted while other minerals and chemicals are unnaturally present or found in greater concentrations in the chemical analysis of the wood of Stradivarius violins.

Alternatively if the wood was ponded in rivers for transportation purposes, elements such as magnesium would be present, and that unnaturally occurring chemicals in waterways could be present due to pollutants which may have infiltrated the wood.

[208] ibid.

The possibility exists that the quantity of samples used for the studies by Nagyvary et al. in 2009 and Tai et al. in 2017 could hinder the accuracy of the results as much of the wood of the Cremonese violins was obtained whilst the violins were undergoing repairs. The wood shavings obtained were small in quantity varying from 30-300mg[209]. The wood shavings have been obtained from different parts of the violins, making a comparison between the results difficult.

Despite the findings by Barlow and Woodhouse that ponding of Cremonese wood is unlikely[210], I view that the wood may have been ponded as the results were inconclusive as it is unknown if the wood was aspirated. Due to the high amounts of chemicals shown in the analysis by Nagyvary et al. and Tai et al., one of the easiest and that effective ways of penetrating the wood, would have been by soaking[211]. This may explain the unnatural levels and presence of the chemicals and minerals shown in the analysis by Nagyvary et al.,[212] who have suggested that chemicals may have been added to the wood during treatment, whereas Tai et al. suggest that some elements may have also been washed away during treatment[213].

Although the samples used by Barlow and Woodhouse are limited, many of the Cremonese masters such as Stradivari, Amati, Guarneri, Maggini, Gaspar da Salò are included in this study, representing many of the influential luthiers from the

[209] ibid.

[210] C Y Barlow and Woodhouse J, 'Bordered Pits in Spruce from Old Italian Violins', *Journal of Microscopy*, 160, no. 2 (1990), 203-211

[211] ibid.

[212] Joseph A Nagyvary et al., 'Mineral Preservatives in the Wood of Stradivarius and Guarneri', *PLOS ONE,* 4 (2009)

[213] Hwan-Ching Tai et al., 'Chemical Distinctions Between Stradivarius's Maple and Modern Tonewood', *Proceedings of the National Academy of Sciences*, 114, no. 1 (2017), 27-32

seventeenth to the mid-eighteenth century, which I view as a reasonable representation of Italian luthiers. However, the shortcomings of the results lie in the inability of the methodology to test whether wood which has been aspirated or was from the heart had been ponded, unless ponding had happened over a long period of time. Experiments by Folland also showed no supporting results for the ponding of Stradivari's wood[214], however further research could confirm or refute the results of the experiments by Folland.

Tai et al. agree with other research that the decomposition and cellulose rearrangement of the wood may have been altered by chemical treatment. However, they also suggest that aspects such as natural ageing of the wood, the composite nature of wood and high vibrations which the wood is exposed to when playing the violin may have an effect. Tai et al. suggest that when the violin is played, it is exposed to high frequency vibrations which may have accelerated the decomposition of the wood and altered the cellulose structure. As all antique violins have been exposed to these high frequency vibrations when played, I suggest that the high frequency vibrations may not account for the unique sound of Stradivarius violins.

The study by Stoel and Borman using computer tomography to measure the density and density differentials of wood suggested that the findings of the Cremonese violins having lower density differentials could be due to the aqueous treatment of the wood[215].

[214] David Folland, 'Wood Ponding', *The Strad,* (February 2015), 24-26

[215] Stoel Berend C and Borman, Terry M, 'A Comparison of Wood Density Between Classical Cremonese and Modern Violins', *PLOS ONE*, 3, no. 7 (2008)

Research by Tai et al. and Nagyvary et al. has shown that wood was likely to be treated chemically due to the presence of unnatural elements and inorganic elements. The researchers consider how these unnaturally occurring chemicals came to be in the samples taken from the instruments[216] [217]. Some researchers such as Tai et al. hold the belief that the wood may have been deliberately treated with aqueous treatment, a direct application or solution of chemicals or fumigation, while opposing views are held by Nagyvary et al. that the presence of chemicals in the wood affecting the acoustic quality may be accidental and non-intentional on the part of luthiers[218].

Nagyvary et al. suggest that the wood may have been treated prior to purchase for preservation reasons, suggesting that trees may have been sprayed with fungicides and that the wood could have been contaminated in some way accidentally, perhaps from the spraying of nearby crops[219]. I consider it less possible, that many trees at different times and logs acquired by different makers, all would have accidental contamination of several chemicals. While I consider that chemical treatment of violin wood may have been performed intentionally, it may not have been done with the aim of altering the acoustic quality.

The absence of woodworm in the Cremonese instruments and the boron which was found present, points to some form of fungicide or preservative treatment being used

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216 Hwan-Ching Tai et al., 'Chemical Distinctions Between Stradivarius's Maple and Modern Tonewood', *Proceedings of the National Academy of Sciences*, 114, no. 1 (2017), 27-32

217 Joseph A Nagyvary et al., 'Mineral Preservatives in the Wood of Stradivarius and Guarneri', *PLOS ONE*, 4 (2009)

218 Cheng-Kuan Su, et al., 'Materials engineering of violin soundboards by Stradivarius and Guarneri' *Angewandte Chemie* ,133, no. 35, (2021), 19293-19303

219 Joseph A Nagyvary et al., 'Mineral Preservatives in the Wood of Stradivarius and Guarneri', *PLOS ONE*, 4 (2009),

on the wood, be it by farmers, a chemist, or the luthiers themselves[220]. The chemicals have been able to penetrate into the wood, which is most likely to have happened after the wood was felled, this would allow for the more porous wood beyond the hard bark to be penetrated more easily.

I view that the difference between the chemical elements found between different violins and different makers, seems to suggest that no set formula existed for the purpose of preserving or treating violins by any maker.I would argue this may validate the hypothesis by Nagyvary presented that the chemist may have solutions to the luthiers which was convenient at the time, rather than the makers having their own solutions to treat their wood.

An interesting point arises that the Stradivarius violins did not show signs of all being treated with the same chemicals, yet all Stradivarius violins hold Stradivarius acoustic qualities. Further research would need to be done I view, to see if a trend of similarities emerges between the chemicals present in a wider sample of Stradivarius violins and then to see if these violins could be tested for the presence of high format frequencies to see if any correlations occur.

Tai et al. concur with the suggestion by Nagyvary et al.[221] that the wood may have been pre-treated prior to the luthier receiving it. Tai et al.[222] propose that because of the high amounts of inorganic chemicals found in the wood, that the wood is likely to

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[220] ibid.

[221] Joseph A Nagyvary et al., 'Mineral Preservatives in the Wood of Stradivarius and Guarneri', *PLOS ONE*, 4 (2009), e4245

[222] Hwan-Ching Tai et al., 'Chemical Distinctions Between Stradivarius's Maple and Modern Tonewood', *Proceedings of the National Academy of Sciences*, 114, no. 1 (2017), 27-32

have been subject to soaking or sap displacement, which backs up the suggestions of Su et al.[223] and Nagyvary et al.[224] that wood may have been ponded in some way. Tai et al. explain that surface application of fungicides would have been using a smaller amount of chemicals than what was found in the analysed wood samples of the Stradivarius and Guarneri violins[225].

I suggest that the unnatural chemical composition in Stradivari's wood may affect its acoustic properties and thus its formant frequencies. I propose that the unique acoustic quality and the higher formant frequencies which in Stradivarius violins may in part be due to the unnatural chemical composition, altered properties and decomposition of Stradivari's wood, as evidenced by Nagyvary et al.[226] and Tai et al[227].

I suggest that there is sufficient evidence to support the view that Stradivari's wood was treated with chemicals. Whether to deliberately affect the acoustic quality or as a consequence of transportation or purposes of preservation, results show unusually high levels of unnaturally occurring chemicals in the wood of Stradivari alongside

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[223] Cheng-Kuan Su et al., 'Materials engineering of violin soundboards by Stradivarius and Guarneri' *Angewandte Chemie* ,133, no. 35, (2021), 19293-19303.

[224] Joseph A Nagyvary et al., 'Mineral Preservatives in the Wood of Stradivarius and Guarneri', *PLOS ONE*, 4 (2009), e4245

[225] Cheng-Kuan Su et al., 'Materials engineering of violin soundboards by Stradivarius and Guarneri' *Angewandte Chemie* ,133, no. 35, (2021), 19293-19303.

[226] Joseph A Nagyvary et al., 'Mineral Preservatives in the Wood of Stradivarius and Guarneri', *PLOS ONE*, 4 (2009), e4245

[227] Hwan-Ching Tai et al., 'Chemical Distinctions Between Stradivarius's Maple and Modern Tonewood', *Proceedings of the National Academy of Sciences*, 114, no. 1 (2017), 27-32

altered chemical structures and evidence of oxidation and degradation. These changes to the natural wood properties and composition found by Nagvary et al. and Tai et al. may account for or contribute to the unique acoustic quality and unique formant frequencies of Stradivarius violins. The difference in wood properties and chemical composition between Stradivarius and non-Stradivarius may explain the differences in acoustic quality between these violins and why each of Stradivarius violins sound unique. Further research needs to be carried out into how Stradivari may have treated his wood or how his wood came to show unnatural chemical composition, altered properties and decomposition.

**Conclusion**

Research into Stradivarius violins has not yet understood why his violins possess a unique acoustic quality. Stradivarius violins are often the choice of virtuosi today due to their special acoustic quality.

Scholars such as Tai et al. have conducted spectral analysis to show the formant frequencies of antique Italian violins including those of Stradivari. Their research has revealed that Stradivari violins have higher formant frequencies closer to the female voice, than those of other antique violins which had formant frequencies closer to baritone and bass voices. Tai et al. suggested that although they found the formant frequencies of Stradivarius violins to be higher, they did not know why they were present. Tai et al. proposed further research into the organology of Stradivarius violins could uncover which aspects could create the higher formant frequencies[228].

I have contributed to research in this field by looking at how select aspects of organology have advanced research into why formant frequencies have been found to be higher in Stradivarius violins. My research has included the dendrochronology, density differentials, aqueous and chemical treatment of Stradivari violins.

The climatic conditions in which the trees grew were unique to the period of Cremonese violin making with the cooler temperatures of the Maunder Minimum causing the trees to grow in a way which yielded exceptional acoustic quality[229]. This

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[228] Hwan-Ching Tai et al., 'Acoustic Evolution of Old Italian Violins from Amati to Stradivarius', *Proceedings of the National Academy of Sciences*, Vol. 115, no.23 (2018), 5926

[229] Lloyd Burckle, and Grissino-Mayer, Henri D, 'Stradivarius, Violins, Tree Rings, and the Maunder Minimum: a Hypothesis', *Dendrochronologia*, 21, no. 1 (2003), 41-45

will have contributed to the superior standard of violins of Stradivari and his contemporaries.

The lower density differential in the wood used by the Cremonese makers which Stoel and Borman discovered supports the exceptional quality of Cremonese violins[230]. However because the results of the study were anonymised we do not know the density differential of Stradivarius violins compared to the other violins in the study. If the Stradivari violins had a lower density differential to the other violins, it would suggest that Stradivari treated his wood. How far the density differentials have impacted upon the acoustic quality of Stradivarius violins depends upon how significant the difference in density differential of Stradivarius violins is to the other Cremonese violins.

There has been a question over whether Stradivari's wood was ponded before use. The bordered pits of Stradivarius violins have remained intact, which unless previously aspirated would have degraded if ponded[231]. Therefore there is a strong case that the wood was not ponded, however without knowing if it was aspirated, no definite conclusion can be drawn. Folland's experiments on ponding wood showed there to be no discernible difference in acoustic quality from the violins made with ponded wood and those which were not.

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[230] Berend C Stoel and Borman Terry M, 'A Comparison of Wood Density Between Classical Cremonese and Modern Violins', *PLOS ONE,* 3, no. 7 (2008),

[231] Hwan-Ching Tai et al., 'Chemical Distinctions Between Stradivarius's Maple and Modern Tonewood', *Proceedings of the National Academy of Sciences*, 114, no. 1 (2017), 27-32

The wood used in Stradivarius violins has an unnatural chemical composition[232]. Scholars have suggested the chemicals found may be due to aqueous or chemical treatment of the wood. The wood used by Stradivari may have been unintentionally ponded during storage or transportation, when minerals may have been washed out of the wood and other minerals present in the water may have been absorbed into it.

The wood used by craftsman was often transported through the waterways during Stradivari's lifetime as it was a cheap method of transport, consequently it is possible that it could be due to the method of transport that Stradivari's wood was treated. The difference in chemicals found in Stradivarius violins may be due to the varying levels of minerals and chemicals in the waterways at different times and places. This may explain the non-uniform composition of chemicals found in Stradivarius violins. However ponding in waterways may be undermined by the findings of the study by Barlow and Woodhouse. They found that the bordered pits of Stradivari violins showed no signs of degradation indicating that the wood was not immersed in water. However as we do not know if the wood of Stradivari was aspirated, it is still possible that if the wood were aspirated prior to transportation in the waterways, it would not show signs of degradation.

Further research on a larger sample of Stradivarius violins would yield more information about the chemical composition of Stradivari's wood and whether signs of degradation are present in more of his violins. If research were conducted to further the experiments of Folland, with a modified methodology, where the wood is air dried rather than dried in a drying cabinet, alongside results being measured acoustically

[232] C Y Barlow and J Woodhouse, 'Bordered Pits in Spruce from Old Italian Violins', *Journal of Microscopy*, Vol. 160, no. 2 (1990), 203-211

using a quantifiable methodology such as spectral analysis, greater knowledge could be found on the effects of ponding wood. The experiments could be repeated both with or without the wood being aspirated prior to being ponded, to observe the effects of the degradation, properties and acoustic quality on the wood.

Research conducted by Nagyvary et al. on the chemical treatment of Stradivarius violins has shown unnatural chemical composition with elevated and depleted levels of minerals[233]. Nagyvary et al. suggest solutions of fungicides or pesticides may have been sold by the local chemist to the luthiers or wood merchants to treat the wood. This is a creditable possibility as the violins of Cremona do not have woodworm damage, whereas violins from elsewhere such as Milan do show woodworm.

Whilst Stradivarius violins may have been pretreated for preservation, it is likely that other violins made by other master luthiers were treated similarly. Therefore the difference in chemical composition and acoustic quality between Stradivarius and non-Stradivarius violins could be due to some additional treatments or the absorption of chemicals during transportation. The decreased level of certain minerals indicates that some may have been washed away in aqueous treatment.

Further research into aqueous and chemical treatments such as fumigation would provider further information on the types of treatments. Additional research into Stradivarius and other antique violins may show patterns of chemical composition in the violins between makers and over differing time periods could show if wood treatment varied. Research into other aspects of organology such as how the shape of the violin, the f holes and the thickness of the violin plates may influence acoustic

[233] Joseph A Nagyvary et al., 'Mineral Preservatives in the Wood of Stradivarius and Guarneri', *PLoS ONE*, 4 (2009), e4245

quality, alongside archival research may reveal additional information about luthiers' practices during the lifetime of Stradivari which could show how they impacted the acoustic quality and thus the formant frequencies of Stradivarius violins.

While the climatic and environmental conditions affected the trees and consequently the wood used by Stradivari, it did not affect the acoustics of Stradivarius violins exclusively. It is possible that the acoustic quality and formant frequencies of Stradivarius violins were affected by the aqueous or chemical treatment of the wood, either deliberately or accidentally due to the methods used to transport or preserve the wood.

Despite all of Stradivarius violins having their own unique characteristics, as the research by Tai et al. has shown, all six of Stradivarius violins exhibited higher formant frequencies closer to the female voice. I view that there must therefore be some unifying factor of organology or craftsmanship which has led to Stradivarius violins displaying unique higher formant frequencies.

Tai et al.'s study in 2017 show Stradivari violins to exhibit decomposition of hemicellulose which supports Stoel and Bormans suggestions that Stradivari violins may have been attacked by fungus and undergone decomposition, thus creating low density differentials in Cremonese violins.

The high metal content of 9000ppm in the original Stradivari 1725 neck shows unnatural levels of metals in the wood, yet not in the 1800 neck replacement, suggesting treatments in some form have allowed these metals to penetrate into the wood of the original neck in high concentration[234].

While other methods of treatment are possible, Tai et al. Suggest ponding would best have been able to get such high amounts of metal to penetrate the wood, which has also previously been suggested by Nagyvary et al. [235] [236] Yet Barlow and Woodhouse's results show no degradation of pit membranes in Stradivari violin wood, which would mean that unless previously aspirated the wood had not been ponded[237].

Since Stradivari, luthiers have managed to create the aesthetics of a Stradivarius violin but have not been able to reproduce its acoustic quality. My research has aimed to shed some light on how the acoustic quality and the higher formant frequencies are present in his violins. I have researched the origin, aqueous and chemical treatment of Stradivari's wood which may have impacted upon the acoustic quality of his violins. My research is original as I have viewed the acoustic quality of Stradivarius violins through the lens of formant frequencies by looking at how aspects of the organology may have contributed to their higher formant frequencies. My research has begun to explore which aspects of organology in the field of vibroacoustics may have impacted upon the acoustic quality and thus the formant frequencies of Stradivarius violins. I

[234] Hwan-Ching Tai et al., 'Chemical Distinctions Between Stradivarius's Maple and Modern Tonewood', Proceedings of the National Academy of Sciences, 114, no. 1 (2017), 27-32

[235] Hwan-Ching Tai et al., 'Chemical Distinctions Between Stradivarius's Maple and Modern Tonewood', Proceedings of the National Academy of Sciences, 114, no. 1 (2017), 27-32

[236] Joseph A Nagyvary et al., 'Mineral Preservatives in the Wood of Stradivarius and Guarneri', PLOS ONE, 4 (2009), e4245

[237] C Y Barlow and J Woodhouse, 'Bordered Pits in Spruce from Old Italian Violins', *Journal of Microscopy*, Vol. 160, no. 2 (1990), 203-211

have taken a multi-facetted approach looking at the organology of Stradivarius violins, as it is probable that more than one aspect has contributed to the acoustic quality and thus the higher formant frequencies.

This paper is a preliminary study into the area and further research particularly into how aqueous and chemical treatments can alter the properties of spruce and maple would provide useful insights how the wood Stradivari used may have been treated. This knowledge would provide information on the working practices of Stradivari and could help luthiers today to recreate the sound of his violins today.

This paper began by introducing the figure of Antonio Stradivari, a luthier in his workshop, mid-seventeenth century in Cremona, revered not only during his lifetime but centuries later also. Much speculation has arisen about what lies behind the acoustic quality of Stradivarius violins, this paper has aimed to contribute to researching how the violins made by the Cremonese luthier came to have their acoustic quality.

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