OCCURRENCES OF FALSE RINGS AND IADFS IN PINE IN NORTHWEST MEXICO

A Thesis

Presented to the Faculty of the Graduate School

of Cornell University

In Partial Fulfillment of the Requirements for the Degree of

Master of Arts

by

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May 2020

ABSTRACT

Dendrochronology is an under-utilized tool for archaeological research in Northwest Mexico due to the frequency of IADFs and false rings. This project seeks to understand the appearances and causes of this phenomenon through charting these abnormalities in modern pine and looking for correlations. This investigation reveals useful insight to simplify the reading of *Pinus* in this region. A collection of ten sampled trees from the Malpaso Valley were used to make a chronology. I also compare the appearances of ring abnormalities with gridded precipitation values of the region to identify large-scale climate factors for false rings and IADFs. I demonstrate a relationship between resin duct position and false boundaries as well as a correlation with cambial age and abnormal ring formations. Comparison with precipitation reveals little correlation with the frequency, type, or location of these abnormalities. However, many of avenues are available to continue this investigation as discussed in this thesis.

BIOGRAPHICAL SKETCH

Kelli Eileen Breeden received a artium baccalaureus in Classical and Near Eastern Studies at Bryn Mawr College before studying archaeology at Cornell University, beginning in 2016. She is interested in dendrochronology, landscape archaeology, archaeological theory, ancient writing systems and the archaeology of Mesoamerica.

ACKNOWLEDGMENTS

I thank the Cornell Institute of Archaeology and Material Studies for supporting my work at Cornell and in the field. I especially thank Dr. Sturt Manning and Dr. Frederic Gleach for their support and guidance with this thesis as well as for their invaluable advice and insightful comments. I also thank Dr. Paula Turkon, Dr. Carol Griggs, and the entire staff of the Northwest Mexico Project. I thank my family, my husband Andrew Crocker, my colleagues at Cornell, especially Polly Anna Burnette and Kevin Bloomfield, Chelsea Murphy, Lucy Breeden, and Diana Crocker for their support.

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Introduction

Dendrochronology, the study of tree-rings, is a well-developed approach informing a variety of fields (i.e. archaeology, history, ecology, botany) in virtually every geographical area. However, there are still gaps in existing knowledge. One such gap is in the dendrochronological and dendroclimatological study of common species in the Mesoamerican region. Using modern samples of Pinus within the Northwest Mexico Project, led by Dr. Paula Turkon and Dr. Sturt Manning, this thesis investigates the complications arising from growth irregularities within tree-ring sequences. In particular, I examine occurrences of density fluctuations, placement of resin ducts within an annual ring, and appearance of multiple rings for a single year. Through the creation of an absolute chronology using modern samples analyzed by the project, the growth irregularities are linked to specific years. The data set used in this thesis consists of 11 trees from the Malpaso Valley, Zacatecas, Mexico cored in 2010. Comparing these growth patterns with nearby weather station data, I attempt to correlate multiple types and locations of these abnormalities with annual and seasonal precipitation records and the biological age of the tree. Similar research has been conducted with varying degrees of success in pine species in Europe and Northeastern United States; by extending these tests to the Northwest Mexico region, tree-ring sequences can better aid archaeological work through the production of more precise chronologies supporting the dating of specific materials.

Dendrochronology is instrumental in many archaeological contexts for determining relative and absolute dates for sites and objects, reconstructing ancient environments, and dating major enviro-historical events. It is widely applied in the

American Southwest (e.g. Fritts 1976; Fritts et al. 1991; Windes 2010), Europe (e.g. Baillie 1982; Haneca et al. 2009; Hellman et al. 2017) and more recently the Mediterranean (e.g. Kuniholm & Striker 1983; Manning et al. 2001; Rich et al. 2016). In some cases, scholars build chronologies reaching back up to 10,000 years. This work requires intricate studies to account for abnormal ring formation, multiple rings per year, and density fluctuations in species throughout the globe. In the European context in particular, dendrochronologists have connected environmental factors to these abnormalities, thus giving a richer picture to the chronologies (Edmondson 2010; Rozas et al. 2011; Novak et al. 2013; Campelo et al. 2015).

In the Mesoamerican region, however, dendrochronology has been underutilized. While scholars have demonstrated the value of dendroclimatological research in the Mesoamerican region with Douglas Fir and Montezuma bald cypress (e.g. Cleaveland et al. 2003; Therrell et al. 2006; Stahle et al. 2011; Stahle et al. 2016), growth abnormalities have limited study of other common species in this area. The work of Prof. Paula Turkon, Prof. Sturt Manning and Dr. Carol Griggs, assisted by Cindy Kocik, demonstrates that Pinus (pine) species from this region, despite the frequency of false boundaries and other irregular growth patterns, can be crossdated to form a chronology and develop a direct correlation between average ring width and climate data, most specifically rainfall (NSF application 2012). During the summer of 2017, Turkon and Manning sought to expand this finding from four samples of pine to a more robust chronology of ten samples, building an absolute chronology using modern pine with the goal of applying this methodology to historical and prehistoric samples.

The robust chronology developed by this project provides an opportunity to explore growth abnormalities within these samples. The benefits of studying these abnormalities are two-fold: first, identifying physical characteristics that indicate when conditions cause disruption in annual growth increments (i.e. multiple "rings" in a single year and/or sudden changes in density), and defining the context in which misleading boundaries and irregular cells form. The former eases the reading of pine samples, ideally enabling dendrochronologists and archaeologists alike to employ them in future studies. If one identifies the conditions under which abnormalities occur, these data may be more easily incorporated into the broader dendrochronological discourse. Understanding the conditions behind abnormal ring development would thus allow scholars to fill gaps in climate data, create climate reconstructions down to the seasonal level, and expand existing timelines. Through this, scholars would be able to utilize dendrochronology more frequently at individual sites and throughout the region. The use of pine in particular will prove useful in dating structures and wooden artifacts. Additionally, a firm understanding of how pine exhibits abnormal rings could help scholars tackle species where confusing ring growth is more prevalent, such as juniper in Northwest Mexico.

This thesis explores the types of rings that complicate reading and the correlation of abnormal ring typologies with fluctuations in annual and seasonal rainfall, evaporation, and temperature data. An investigation of abnormal ring formation in pine of Northwestern Mexico has the potential to yield more detailed information from pine samples in a variety of ways. First, if ring abnormalities can be correlated with seasonal weather precipitation, the presence of such can be used to link floating chronologies together, providing an extra level of confirmation to supplement ring width indices. This would also provide a better sense of seasonal weather fluctuations, which have influence on crop growth, the spread of illness, migrations of peoples, and how communities react to the landscape, to name only a few applications of climate data in archaeology (e.g. Haug et al. 2003; Buckley et al. 2010; D'Andrea et al. 2011). With Turkon's pine chronology, we have been able to confidently identify false rings and distinguish abnormalities from true rings. By outlining these differences and defining the conditions in which abnormal ring growth occurs, this thesis will provide a means of reading and interpreting such growth patterns more quickly and allow comparative study with other species in the area.

I begin by discussing the Northwest Mexico Project from which the data used in this thesis are derived. I then put this project, as well as this thesis, into context by discussing growth abnormalities generally, then focusing on research correlating pine featuring these irregular growth patterns with environmental triggers. Subsequently, I present the methodology utilized in this thesis, describing how patterns are identified in the following analysis. Finally, results are presented together with a discussion on their significance and future applications in dendrochronological and archaeological contexts.

The Northwest Mexico Project

This thesis analyses the modern pines sampled during the summer of 2010 in the Malpaso Valley of Zacatecas, Mexico and its surrounding regions. Modern pine was chosen for its definitive end date (2010), the ability to record each sample's exact location, and knowledge that these samples are from the same area. The project also collected charred remains from the archaeological sites of La Quemada and Los Pillaros, also in the Malpaso Valley. These samples are currently under study with the aim of creating a floating chronology of that time (Turkon et al. 2018). Ideally, the study of modern pine will help inform the ancient samples.

I assisted with developing the modern chronology, mounting previously un-analyzed 2010 samples and serving as a second or third reader when creating a chronology. This work was complicated by a variety of different abnormalities in ring formation, all which required intense study to unravel. Pine, a widely-used resource historically, nevertheless has not been fully utilized in dendrochronological studies in Northwest Mexico, offering a vast new area for research if these problems can be resolved. However, the abnormalities that create difficult reading also have the potential to provide expansive knowledge surrounding seasonal weather patterns.

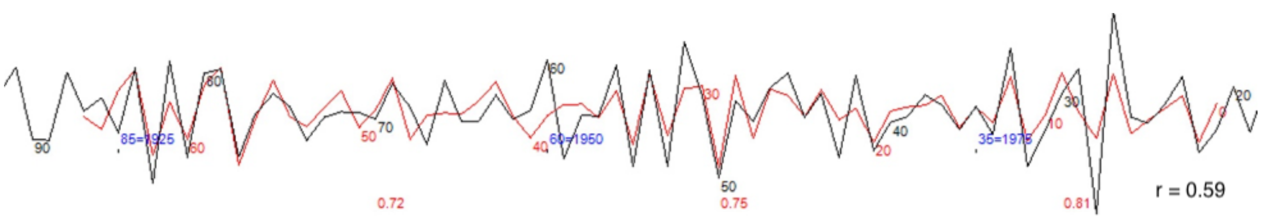

Figure 1: MTG Chronology vs. Nov-May Gridded Precip. values[1]

The climate data used in this research are gridded precipitation values from an area defined by the boundaries 100W, 103W, 20N and 24N, derived by the project from weather station data provided by the Mexican Departmento de Hidrometorologia . The most accurate data spans 1921-1989. Outside of this range, I refer to the closest

[1] This graph was generated in CDendro, using normalization based on P2YrsL.

weather station to the sampled trees, the Malpaso weather station, located 22 ° 37 ' 19 "N, 102° 45 ' 49 "W (Departmento de Hidrometeorologia, Mexico). Its recorded data spans 1975-2009 with limited interruptions.

State of the Field

"Tree-ring chronologies are thus as good as a natural chronometer can be" (Bradley 2011: 5). Bradley's comments on the accuracy of dendrochronological data highlight the utility and even necessity when examining the palaeo-climate. This is partially due to the widespread availability of tree-ring sequences. However, dendrochronological research has been under-deployed in Mesoamerica. In particular, dendroclimatological research has been successful, but has not been applied to pine species in Mesoamerica.

This has been done successfully in other species in the Mesoamerican region (e.g. Cleaveland et al. 2003; Therrell et al. 2006; Stahle et al. 2011; Stahle et al. 2016) and allowed scholars to reconstruct droughts and other climate events. However, it can be used more widely in this area. Understanding when and why abnormalities form will provide a richer picture of past climate, how trees have developed in response to climate stresses, and could aid in the formation of regional master chronologies.

While the pine of Northwest Mexico is a difficult species for dendrochronological research due to the sheer volume of abnormal ring growths, it does not feature unique abnormalities. Thus, comparisons with other genera may be informative. Many populations throughout the world are affected by climate in more ways than just the width of each ring. Density fluctuations, false rings, and false boundaries have all been documented in numerous studies. Wimmer (2002) explores these variations and lists a number of others: cell size change, resin duct mutations, false rings, IDAFs, or collapse of cell structure (22-24). With the well-documented effects of external factors on wood anatomy, looking at these studies and comparing the conditions in which those species and the pine of the Northwest Mexico Project react similarly, can potentially provide useful insight.

Scholars have demonstrated the connections between rainfall and false rings in pine and other species in the American Southwest and Mediterranean (e.g. Copenheaver et al. 2010; Edmundson 2010; Copenheaver et al. 2017). Copenheaver et al. defines false rings as "intra-annual bands of high density xylem cells that form in response to an environmental condition that causes a tree to form two bands of latewood cells during a single growing season" (2017: 1037). Simply put, a false ring is formed when growth is halted or slowed during the usual growing season, forcing the tree to grow latewood cells, or when trees are able to grow beyond normal times, causing it to once again grow earlywood cells.

This can "serve as a valuable proxy record of specific environmental conditions", often climate related (Copenheaver et al. 2017: 1037). These conditions could be either an abundance or lack of water at any point of the growing season and result in a false ring (Kramer and Kozlowski 1979, Copenheaver et al. 2010). Fluctuations in rainfall allowing growth before the traditional season can result in false boundaries near the beginning of the year's ring (Wimmer et al. 2000). Rainfall extending the end of the growth season is reflected in a false boundary in the later part of the ring (Novak et al. 2013). Copenheaver's study of false rings in bald cypress of the Southwest United States demonstrated that the two conditions of water abundance can be apparent within a single species or even a single sample (2017). Juvenile Bald Cypress was demonstrated to begin growth early and form false boundaries at the beginning of its annual ring. In its mature years, Bald Cypress responds with late season growth more often (1043).

In time of drought, false boundaries can appear when a tree is forced into "cambial dormancy" (Heinrich and Banks 2006). This has been done in a variety of areas such as Heinrich and Banks (2006) also identified the potential for a grouping of vessels if precipitation falters during the growing season.

False rings have also been linked to environmental triggers not associated with rainfall such as insect damage (Schulman 1941), forest fires, disease, injury (Heinrich and Banks 2006, Edmondson 2010), and forest competition (Copenheaver et al. 2006). Edmonson (2010) explored false ring development in Eastern Red Cedar of the American Great Plains. He also determined that the age of the tree affects its formation of false rings; as a cedar ages, its growth is more stable and it forms rings (including false rings) less often. Here, chronologies play a pivotal role by introducing trees of different ages to the timeline, which capture different climate events. Edmonson states that dendrochronologists can infer climate and weather extremes in pre-instrumental records based on the appearance of false rings.

Related phenomena to false rings are "intra-annual density fluctuations" (subsequently IADFs) within a ring. These are defined as the appearance of earlywood cells within the latewood section of a ring, or vice versa. IADFs are the result of a variety of "predisposing and triggering" factors (Marchand and Filion 2012). Like false rings, De Micco et al. (2016) state that IADFs form in response to sudden changes in growth conditions that can occur throughout a growing season and can be isolated based on their location within an annual ring (151).

The most frequent and strongest factors found in studies of Pinus in multiple parts of the world are the tree's cambial age and each individual year's ring width (e.g. Rigling et al. 2001; Copenheaver et al. 2006; Campelo et al. 2015). The age trend, while clearly a factor, offers conflicting results when correlation is tested against IADF formations. Rigling et al. (2001) found that IADFs in Swiss Pinus sylvestris occurred almost solely in younger annual rings but the same species in Russia formed IADFs more evenly throughout its growth. Copenheaver et al. (2006) determined that Pinus banksiana Lamb. in Michigan, USA, featured IADFs more frequently in younger, wider rings, but not exclusively so. The same was documented in Spanish Pinus halepensis (Novak et al. 2013). The study of Pinus pinaster in Portugal by Campelo et al. (2015) demonstrated that IADFs were more common during the biological years 40-140. When they formed at younger ages, they were more frequently in narrower annual rings (24). Pinus pinaster studied in Northwest Spain by Rozas et al. (2011), however, had no correlation between either ring width or age.

The relationship between IADFs and climate is also complicated and varies between locations and species. Campelo et al. (2015) deemed them to be a result of short-term climate variations during the growth season. Novak et al. (2013) traced a connection between the location of IADFs within an annual ring and precipitation changes throughout the growing season. Again, Rigling et al. (2001) found different results dependent on the location of Pinus sylvestris, with only one of six Russian stands showing any correlation between the appearance of IADFs and small-scale precipitation or temperature fluctuations but a relationship between the IADFs and an influx of rainfall just before the growing season in Switzerland. Rozas et al. (2011) documented a relationship between the appearance of IADFs and the precipitation levels of the previous two winters. Copenheaver et al. (2006) found no correlation between either temperature or precipitation (354).

Campelo et al. propose a methodology of isolating the IADFs from age and ring width constraints, but emphasize that their appearance or lack thereof is not standardized due these constraints. All authors mentioned above note that the formation of IADFs may be related to individual tree's stressors. For example, Copenheaver et al. (2006) show a clear connection between sudden density fluctuations and canopy gaps while Rigling et al. (2001) demonstrate IADFs form with different frequencies dependent on the soil composition. These studies also focus specifically on intensely dry areas at the edge of Pinus habitation zones. Rigling et al. (2001) suggest that more clear connections between climate and IADFs and false rings alike may be more apparent in areas of heavier rainfall (29). Copenheaver et al. (2006) suggest that the usefulness of IADFs and false rings to dendroecologists is proportional to the propensity of a species to form these abnormities. Rozas et al. (2011) divided IADFs into sub-types to address the frequency of their appearances to some success.

The Malpaso pine trees sampled in 2010 formed both false rings and IADFs frequently during their growth. The above research suggests that they will therefore have dubious connections with climate conditions if considered in a singular category. However, as some researchers have had success with forming a relationship between climate conditions and abnormalities, there is an opportunity to at least better understand the relationship of Pinus in Northwestern Mexico and small-scale climate fluctuations of Northwest Mexico during the 19th and 20th centuries.

Work done by Diaz et al. (2002) in Chihuaua, Mexico with Douglas fir to better understand the relationship between Mexican weather patterns and ring growth is relevant. They concluded that using November to April precipitation when correlating with growth indices was most effective, due to low evaporation and high soil moisture recharge (239). Usually, this period only accounted for one third of annual growth. This concurs with other studies that suggest that false rings are caused by abnormal access to water outside of the typical growth season (e.g. Fritts 1976: 238-240; Kramer and Kozlowski 1979; Copenheaver et al. 2010; Novak et al. 2013). November-May precipitation exhibited the closest relationship with the MTG chronology as well.

MTG Normalized	Gridded Precip Values			
	Annual	Jun-Oct	Nov-May	Nov-Sep
Correlation Coefficient	0.2	0.2	0.66	0.59
T Test	1.6	1.7	7.2	4.3

Table 1: Average Precipitation Values vs, MTG Chronology

Methodology

Because Dr. Turkon's and Dr. Manning's project seeks to advance dendrochronological research in the Malpaso Valley of Zacatecas, Mexico and its surrounding regions and fill the immense gaps between modern and ancient dendrochronologies of the area, the data from the Northwest Mexico Project is a mix of modern and ancient wood of local juniper and pine, from tree core samples and structural remains.

The samples used in this thesis are strictly modern core samples. The study of modern samples allows a concrete comparison of ring growth and climate due to the following reasons: a) it gives us an absolute end date to the chronology, facilitating a common year between all samples; b) they can be compared with scientifically recorded climate data that does not exist in the past; c) these materials are easier to obtain and often less fragile or fragmented than ancient artifacts; and d) the exact locations of the sampled trees are documented. These conditions fulfill the assumptions necessary to crossdating: 1) the species in question exhibits clear annual growth rings; 2) the trees grew in the same region and relative time as one another; 3) the same environmental stimuli such as rainfall, temperature, soil chemistry, etc. affected each tree in a similar way during its growth; 4) that the samples overlap by at least 50 years (Turkon et al. 2018: 108).

Other studies have used the study of soil chemistry, water tables, among other factors, as stimuli but many artifacts and structural remains are found without context. It stands to reason that local species of wood used in structures would come from a relatively small area before being used in construction, but without the exact locations, factors such as soil chemistry, water retention, forest competition, and access to sunlight must remain unanswered. In contrast, the goal of this thesis is to find ways to read pine from a variety of contexts, ancient and modern. Thus, I assume that the more detailed scientific information used in other studies would be unavailable in a practical scenario. The soil composition mentioned in Novak et al. (2013), canopy class evaluated in Copenheaver et al. (2006), biological age used in Campelo et al. (2015) and slope/elevation mentioned in Fritts (1976: 220-221) could all be a mystery when looking at charcoal or wood planks.

Of the 40 trees sampled in 2010, eleven were chosen for the chronology based on minimal breakage and twisting of cores, the presence of bark in the sample, a length of 100 years or more, and multiple readable radii. Having multiple radii for comparison accounts for any twisting that obscures the rings, serves as confirmation of accuracy, and identifies instances in which pinching, compression, or injury alters the appearance of the rings. The most complete and readable tree-ring sequences and composites were then selected for the final chronology. They are as follows: MTG 3-A-A, composite MTG 5 (radii –B-A, -C-A), composite MTG 7 (-A-A, -B-A ,-C-A), 15-A-A, 16-B-A, composite MTG 17 (-B-A, -C-A), 21-A-A, 27-A-A, composite MTG 28 (-A-A, -B-A, -C-A), 29-C-A, composite MTG 30 (-A-B, -C-A).

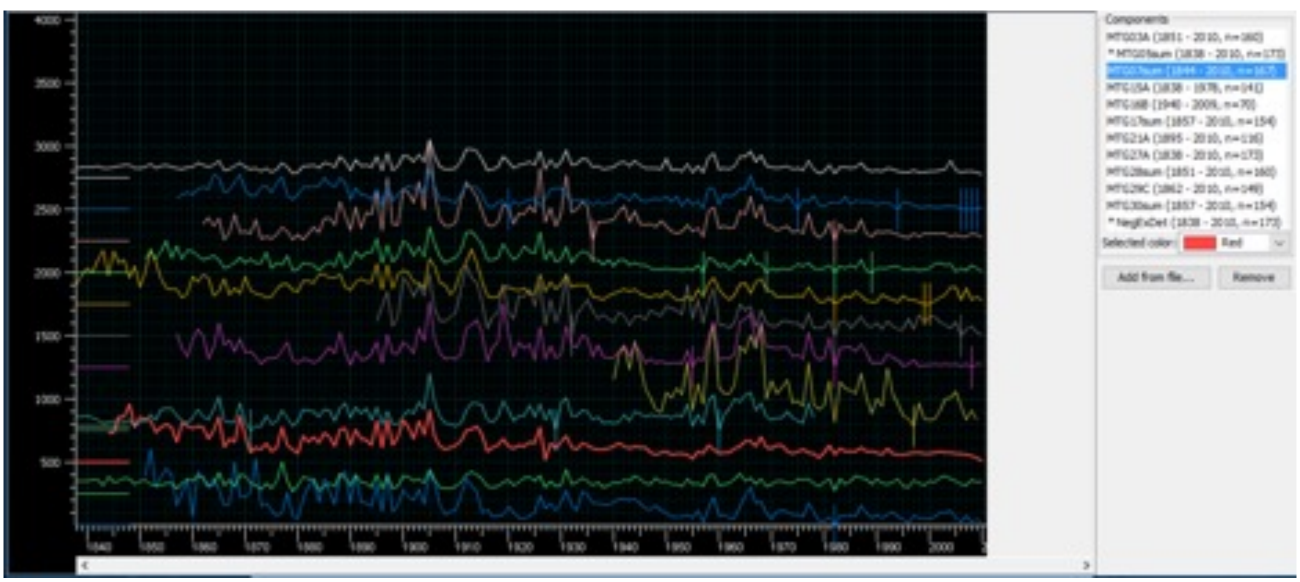

Figure 2: Samples within the MTG Chronology. Each color represents a distinct sample.

Measurements were taken of every potential ring within each sample and graphed to illustrate the changes in ring width from year to year. For this initial reading, each boundary was treated as indicative of an annual ring until evidence suggested otherwise. Then, by comparing the different samples taken from the same tree, false boundaries were identified to reach agreement between the intra-tree samples. The clearest samples of each tree were then compared against one another.

A number of conditions indicated when a boundary was false, including if they: a) were absent in other radii of the same tree, b) lacked a gradual transition from early- to latewood (characterized by cells growing steadily smaller and cell walls becoming thicker, resulting in a darker color), c) were fainter than surrounding boundaries, d) were disrupted by the formation of resin ducts, e) were followed by latewood cells leading to a boundary rather than earlywood cells, or f) differed vastly from ring width indices of other samples (of the same tree or another) that they otherwise matched. While any one of these conditions may occur in a true boundary, the presence of two or more constitutes a false boundary.

Once a false boundary is identified, it must then be assigned as part of a ring. As we read the rings with the bark on the left in this project, the false boundary is accompanied by the span of cells immediately to its right but after the last boundary. The false boundaries and accompanying cells were considered part of the next true boundary to the left.

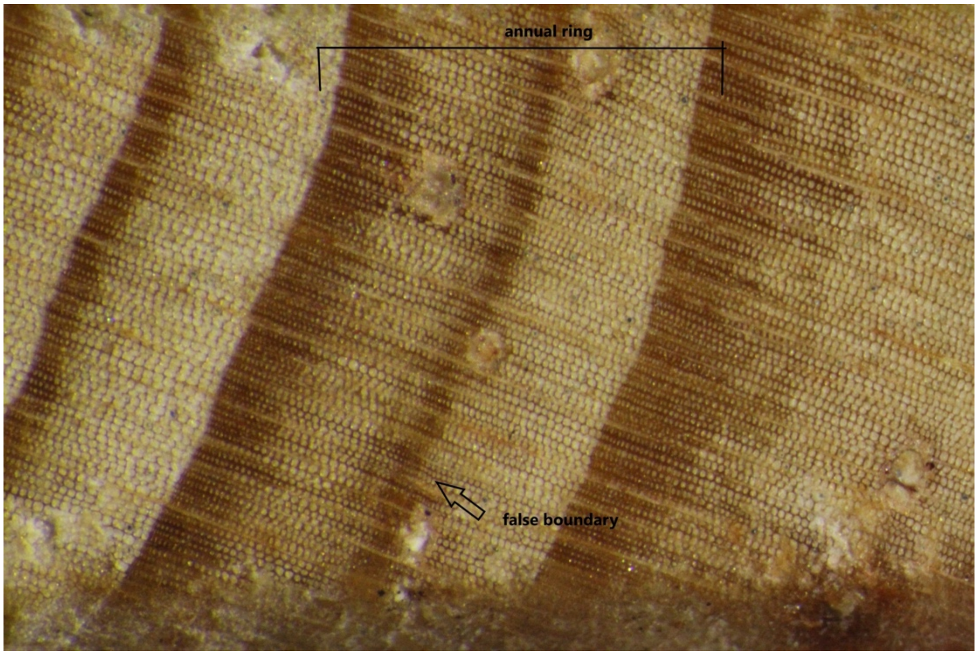

Figure 3: MTG 5-B-A, RY 64

The exact positioning of these false boundaries varied widely, from early in the ring to just before the true boundary. This draws parallels with other studies (Fritts 1976: 238-240; Wimmer et al. 2000; Copenheaver et al. 2010; Novak et al. 2013; Copenheaver et al. 2017) in that these appeared to form during different parts of the year. There was also a wide variety in how much boundaries clearly presented or lacked gradual cell transitions, which may suggest that climatic events related this growth were either rapid and intense, thus not allowing a tree to form latewood, or stretching throughout a season, leading to the presence of earlywood between a false and true boundary, or at least allowing latewood transitions to occur.

The major groups are resin ducts and false boundaries. Resin ducts are common in these samples, but three positions stood out: (i) straddling a boundary, (ii) on a boundary, causing the latewood cells to bulge out around it, (iii) one of several in a row along a boundary (all illustrated in Appendix 9). While seemingly random in their frequency, these resin ducts can assist in identifying false versus true boundaries. I define false boundaries loosely as the change in cell size that typically denotes a new annual ring, but is in fact still part of the same ring. There may or may not be the appearance of cell wall thickening characteristic of latewood growth. However, there is always a steady shrinking of cells per the tree's usual growth that is interrupted by the sudden growth of larger earlywood cells (see Appendix 8 for examples). This can occur at any point in the ring's formation, from just after the previous year's boundary to within the latewood of an annual ring. For the sake of classification, an annual ring was divided into four parts, the first, middle, last thirds of earlywood and the latewood. The cell wall thickness is gauged based on how close to a true boundary the false one resembles. Some cell size transitions are completely without cell wall change, while others feature enough cell wall thickening that a line is visible at the row of cells immediately preceding the suddenly larger cells, but no more than a row or two wide and not quite solid. Less common are boundaries that exhibit the gradual cell wall thickening typical of latewood growth. Appendix 7-9 illustrate these different appearances.

As previously mentioned, scholars have linked false rings and IADFs with small scale climate fluctuations throughout the year (Rigling et al. 2001; Novak et al. 2013; Campelo et al. 2015). Even with the high percentage of extraneous ring abnormalities and inconsistent appearances between radii of the same tree, there are some years with overwhelming numbers of abnormalities. Comparison of these false boundaries with seasonal changes to account for the varying positioning could provide new insight.

Analysis and Findings

a. Data Set Issues

The data set had some limitations. Several were subject to breakage and others to twisting of the cores leading to their exclusion from the chronology. Even the final samples, chosen specifically for their clarity and continuity, have some unclear portions.

Some samples, however, despite being in good condition, simply didn't agree. One tree in particular, MTG-27, fit the selection criteria (long ring sequence, multiple radii, relative clarity, etc.) but did not read well despite several different approaches. The radii matched one another, but clashed utterly with the chronology for nearly all years. This may suggest that pine is more reactive to immediate environmental concerns, such as soil composition or proximity to a consistent water source, which overshadows the effects of larger climate conditions.

Most of these trees were far older than our modern climate record. As the ring abnormality formations appear to peak in biological age 40-70, several trees' peaks fell outside of the available climate data. Additionally, by 2010, the year of sampling, most of the trees had largely ceased forming false boundaries.

b. Frequency of Abnormalities

Overall, abnormalities were frequent throughout the MTG pine samples. They occurred in 14.61-42.07% of total annual rings in each tree sampled. The variation in frequency between trees highlights the lack of an immediate relationship between climate and abnormal ring growth but rather a complex set of conditions taking effect. The high percentages also demonstrate that these formations do not only occur during extreme conditions. Of course, this is not surprising, given the difficulty they cause when reading samples.

Ring abnormalities further complicate analysis due to their inconsistency. When 3 radii were available, abnormalities appeared in all radii of the same annual ring a mere 25% of the time, with abnormalities present in only one radius of three in 53.4% of all cases. This poses a major problem when data sources are limited, like with charcoal samples. If one must assume that half of abnormalities are extraneous, it becomes incredibly difficult to gain any useful information, particularly when only one radius is available, never mind readable.

Another possible explanation of inconsistency is that abnormalities are related to their location within the tree. As water distribution and growth occur from the top of a tree moving down, abnormalities may be more common in the bottom of the trunk. Alternatively, areas of pinching may be less apt to form false boundaries (Fritts 1976: 220). These possible explanations, however, would only be convincing if false boundaries were concretely tied to an abundance of water availability and represent an opportunity for growth outside of the typical growth pattern.

c. Patterns in Multiple Radii Samples

Several inter-tree samples shared very similar IADF formations. This phenomenon may suggest that IADFs are caused by more localized environmental factors than precipitation, such as proximity to a water source, the slope of the earth, or access to sunlight. This conclusion is supported by the irregularity in which abnormalities occur as well. These pairs are not nearer one another geographically than with other samples, which suggests soil chemistry or water tables may have less of an effect on the formations.

However, the similarities between these samples may actually be more related to the sampled trees having multiple radii, which emphasize years where all radii exhibit abnormalities and cause them to stand out from trees with a single radius. If more samples had multiple radii, more may reflect the patterns of these samples. Appendices 13-15 illustrate these ideas by comparing MTG 28 against two multiple-radii samples, MTGs 5 and 7, and against the nearest tree geographically, MTG 27.

d. Abnormality Heavy Years

Multiple years are marked by a large number false boundaries across all samples. These are the most promising when looking at the climate data. Due to our limited climate data, my initial testing of these years was limited to those occurring between 1921 and 1989. Years with over five trees showing false boundaries: 1928, 1932, 1933, 1937, 1954, 1964, 1966, 1968 and 1977. These do not match the years of unusually high or low precipitation. Therefore, if it is unlikely that these false boundaries are caused by water availability related to precipitation.

e. Age Trend

These samples indicate stronger abnormal ring frequencies in the juvenile rings than more mature rings. This correlation between age and false rings has been demonstrated in other studies of pine in several regions (Rigling et al. 2001; Copenheaver et al. 2006; Campelo et al. 2015). Using each sample's relative age (distance from the pith or my best approximation), I graphed the average number of abnormalities in all radii in decadal increments. This is to adjust for the estimated cambial ages. While the frequency of ring abnormalities does decline over time, there is first an increase of abnormality from relative ages 40 through 70. When types related to resin ducts are removed from this graph, this pattern holds (see Appendix 16 for illustration). There are several possible reasons for a decline in ring abnormality of time, such as the more erratic growth patterns of juvenile trees (e.g. Novak et al. 2013) or the diminishing opportunities for extra growth within a season as a stand ages or new competition is introduced to the stand (e.g. Copenheaver et al. 2006).

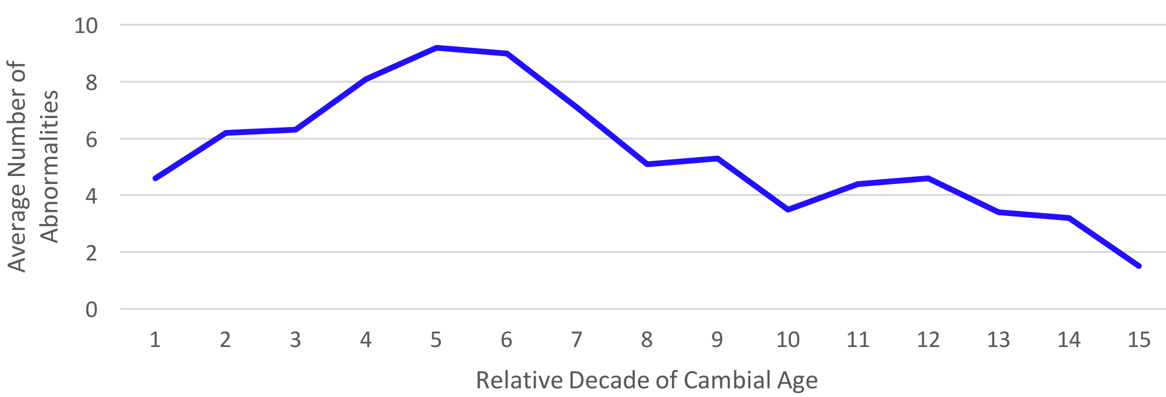

Figure 4: All abnormalities compared with Cambial Age

f. False Boundary Typology

I consider the ring abnormalities in two groups: the types of false boundaries and IADFs that occur and resin ducts that help identify false and true boundaries. False boundaries and IADFs were categorized based on their location within a ring and relative clarity. By clarity I mean a scale from just a change in cell size with little to no cell wall thickening to a very convincing boundary with a gradual transition into seemingly latewood cells. These cells have been proven to only appear visually as latewood cells but actually having the same cell wall thickness as the surrounding rows of cells (Vaganov et al. 2006) (Hereforth described as latewood for clarity). The clarity is in part based upon the appearance of true boundaries on either side. If the sample generally exhibits brief early- to late-wood transitions, less transition is needed to be considered 'convincing'. In terms of categorizing location, the earlywood is split into thirds and the latewood is its own category. The most common placements of false boundaries were in the first third of the ring's earlywood, near the previous ring's boundary. These boundaries became less common the later in the annual ring they occur. Latewood abnormalities, for example, make up less than 5% of documented abnormalities. Again, there was not uniformity in either the solidity or location within the ring in any single year. Abnormalities appeared in the same location within the ring between radii of the same tree 45% of the time.

The degree of cell wall thickening was examined for patterns with the thought that more extreme weather conditions (particularly lack of water access) would result in a more pronounced false boundary. There was little to no consistency between radii or trees in terms of how dark the false boundaries appeared. Not a single annual ring has the same solidity across all radii when three are available for study. 41% of annual rings presenting abnormalities in two samples share the same solidity. This may be an effect of sample quality, causing the obscuring of these boundaries, but that does not appear to be the case. Many of these differences occurred in samples where all radii were of good clarity.

g. Resin Ducts

Boundary types I and II represent two possible positions of resin ducts along a boundary. These abnormalities appear to occur randomly throughout each tree's growth, with no correlation to temperature or rainfall and few shared appearances between radii or samples. Where multiple radii are available for study, less than 7% of Boundary II occurrences are shared across the same annual ring[2] and less than 1% of Boundary I occurrences respectively. There is little continuity of Boundary II resin ducts appearing across samples, with the most being three of ten trees showing these types of ducts in a single year.

Boundary I contains a resin duct that cuts through a boundary, one half within the latewood of one ring and the earlywood of the next. It occurred at least twice in every tree sampled. Of the 2982 recorded rings from all radii, 120 instances of resin ducts severing a boundary were identified. Our readings show that boundaries associated with Boundary I resin ducts prove false in all but five cases.

Boundary II rings exhibit a resin duct the grows along a boundary that causes the latewood to bend around it, creating a bulge. This may only be a few cells wide, but is marked by the resin duct's right edge having a dark outline versus the light outline of Boundary I. This too occurred multiple times in every tree sampled for a total of 178 instances. All but three appearances of a Boundary II resin duct were associated with definitively true boundaries. This type also helped identify several micro-rings, where the space bulging around the resin duct contained a row or two of earlywood cells. These two positions of resin ducts within the latewood of a ring

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[2] This excludes one tree in which 45% of Boundary II appearances were in both radii.

proved more reliable than identifying true and false boundaries by how dark or gradual the latewood appeared. A few (less than a dozen) resin ducts were difficult to categorize whether they were truly on the boundary or just before it, in which instances we used agreement with the other radii to inform our chronology, but relied on our best judgement of the resin duct's appearance.

Due to the high consistency of Boundary I resin ducts with false boundaries and of Boundary II resin ducts with true boundaries, this is a useful tool in reading samples both modern and ancient. While boundaries with Boundary II resin ducts are a small portion of all boundaries documented (6.9%), Boundary I resin ducts are present in 28.4% of the boundaries in our study. It is important to note that these types of resin ducts must lay on the boundary itself as resin ducts near a boundary, but not touching it, are associated with false and true boundaries alike.

h. Connections with Climate

In order to evaluate the relationships between ring abnormalities and climate, a series of correlation tests were performed. The gridded precipitation values from 1921-1989 were used in annual, seasonal, and monthly increments. The seasons are based upon typical growth patterns: November-May and June-October. Temperature values were averaged within the area of 100W, 103W, 20N and 24N from 1950-1990 and also considered annually, seasonally, and monthly. This data is even less complete and further outside the bulk of the ring abnormalities than the precipitation records, greatly limiting its effectiveness in this project's applications. Abnormality frequencies were divided into each type individually (location, clarity, and resin ducts) and total abnormalities, both when matching across intra-tree radii and not[3]. These resulted in no plausible correlations between these conditions and types of abnormalities. The strongest relationship was demonstrated between total number of IADFs and average February rainfall at a 0.35 correlation coefficient. Appendix 6 shows the comparisons between monthly, seasonal, and annual precipitation values.

Future Directions and Conclusions

This research project, while not having totally successful results, has provided some useful approaches to the abnormalities present in Northwest Mexican pine species. Most immediately applicable is that the placement of resin ducts along a boundary can be trusted as an indicator for a true or false boundary, when present. This is limited by the infrequency of the boundary resin ducts in the annual rings of this study, but are almost uniformly associated with one or the other. However, this is not infallible and should be confirmed with crossdating.

Several trees have relatively similar patterns of false boundaries and abnormalities. However, they are not the closest to one another geographically. This suggests that conditions specific to each individual tree are more likely to be related to these formations. The frequency of irregular growth patterns also supports this conclusion. Abnormalities and false boundaries were present every year within the chronology in at least one tree. However, some years exhibit a much stronger presence of abnormalities than others, indicating that larger environmental conditions have at least some effect in the formation of abnormalities.

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[3] If only false boundaries present in all possible radii were used in this comparison, there would be too few to be useful.

While this approach wasn't wholly successful with pine in Northwest Mexico, there are other genera where this might apply. For instance, the MTG juniper may be studied in a similar manner, but the abnormalities are much more common and diverse in this species. These approaches may be productive for examining such diversity as caused by multiple conditions.

Further study is needed to truly understand the relationship between tree ring abnormalities and external factors. Primarily, more data and a larger sample size would be helpful, especially in terms of multiple radii per tree. This would solidify the frequency with which abnormalities do not match across radii, which would ultimately determine the usefulness of considering these abnormalities as climate induced or by more localized factors, such as competition for sunlight exposure or soil moisture. Slightly more than half (53.4%) of the abnormalities present in this data set seem random, appearing in approximately only one in three radii. If these abnormalities were the product of an external factor, the same abnormalities should appear in all three radii. Thus, the seemingly random pattern could be the result of intra-tree conditions, such as proximity to pinching or injury.

Large-scale environmental conditions are not the sole factor in ring abnormalities. The next logical step is to investigate other causes demonstrated in studies of other species. The sheer number of abnormalities removes the likelihood of rare and extreme conditions as cause and the lack of damage within the samples negates injury or insect infestations. Further, local environmental factors such as slope, sun exposure, drainage may play important roles that should be explored.

The variation of formation puts severe limits on abnormalities' usefulness in creating a chronology between ancient samples. It is not guaranteed or even likely that there will be enough samples from charcoal with multiple radii to filter helpful abnormalities from distracting ones. If an abnormality appears in a single sample, it cannot be used to correlate to an absolute year with specific climate conditions. Nor can the pattern of appearances be used to help connect samples to one another, even if the indices already match up. However, if a direct influence on the development of false rings is identified, the application of this study to ancient samples would still provide useful insight.

While the approaches explored in this thesis did not completely solve the issue of false ring boundaries in pine, there are still potentially fruitful avenues of study. I divided the false boundaries based on relative clarity and position within the ring, but these avenues did not produce statistically significant correlation. Future studies should focus on smaller portions of the ring abnormalities, which could potentially yield closer correlation. This could be based on the degree of size difference between the cells leading up to a false boundary and after it, which may reflect the intensity of fluctuations in precipitation or evaporation. Another category may be to divide by Pine types (I-IV), as this may account for the close similarities in abnormality between groups of two or three samples. Conducting a field study with particular focus on the local conditions, such as the soil chemistry or forest competition would identify patterns between those conditions and the appearance of false boundaries. Selecting for younger trees, to ensure their peak abnormality forming years are within the range of modern climate data would also allow better identification of correlation.

Scholars have examined the effects of various environmental conditions, such as temperature and canopy class, yet this research has not been conducted on the pine species found in Northwestern Mexico. The results of this thesis could be further built upon by evaluating such data, including modern and historical sources. This would require a deep search of journals and other written accounts that describe unusual weather patterns or other climate events that may correlate with abnormal ring formation. Again, with the sheer number of abnormalities, this would most likely need to be done in tandem with more clearly limited categories than the ones used in this thesis.

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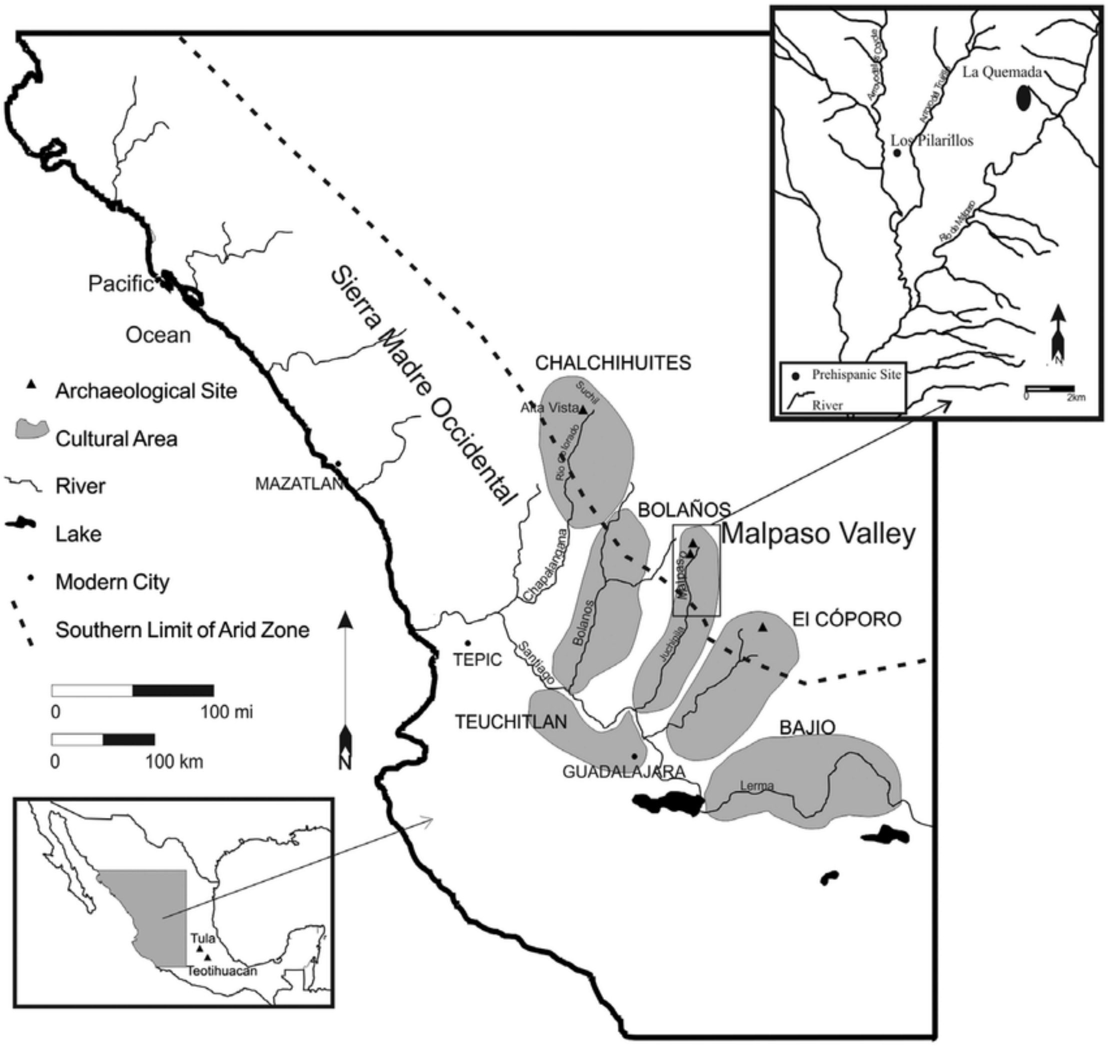
APPENDIX



Appendix 1: Map of the Malpaso Valley from Turkon et al. 2017

Sample	n =	First AY in Ring Sequence	End AY in Sequence
3-A-A	160	1850	2010
5-B-A	157	1853	2010
5-C-A	92	1852	1944
7-A-A	91	1850	1941
7-B-A	154	1856	2010
7-C-A	160	1850	2010
15-A-A	130	1850	1980
16-B-A	68	1940	2008
17-B-A	156	1854	2010
17-C-A	110	1894	2004
21-A-A	111	1899	2010
27-A-A	160	1850	2010
28-A-A	144	1866	2010
28-B-A	187	1851	2010
28-C-A	88	1891	1979
29-C-A	149	1861	2010
30-A-A	97	1887	1984
30-C-A	146	1855	2001

Appendix 2: Samples within MTG Chronology

Tree:	Zone:	Northing:	Easting:	Elevation:
MTG 3	13 N	2458277	13,742,787	2722m
MTG 5	13 N	2458291	13,742,797	2728m
MTG 7	13 N	2458461	13,742,898	2693m
MTG 15	13 N	2458403	13,742,830	2694m
MTG 16	13 N	2548435	13,743,527	2696m
MTG 17	13 N	2458418	13,743,582	2705m
MTG21	13 N	2458181	13,742,842	2732m
MTG 27	13 N	2458191	13,742,892	2733m
MTG 28	13 N	2458202	13,742,869	2725m
MTG 29	13 N	2458231	13,742,880	2723m
MTG 30	13 N	2458309	13,742,901	2700m

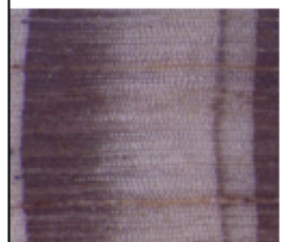
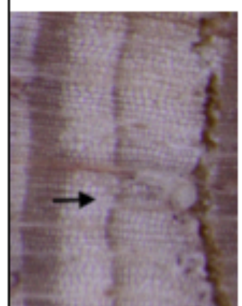
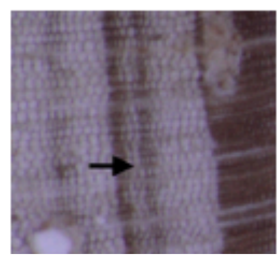
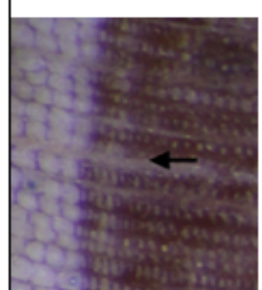
Appendix 4: Location of Trees Sampled

Sample		MTG-3-A	MTG-5-sum	MTG-7-sum	MTG-15-A	MTG-16-B	MTG-17-su	MTG-21-A	MTG-27-A	MTG-28-su	MTG-29-C	MTG-30-sum	
MTG-3-A			.50 / 7.2	.54 / 7.9	.53 / 6.9	.71 / 8.0	.51 / 7.2	.39 / 4.4	.43 / 6.0	.43 / 5.9	.63 / 9.7	.41 / 5.3	
MTG-5-sum		.50 / 7.2		.69 / 12.2	.71 / 11.7	.65 / 7.0	.61 / 9.3	.49 / 6.0	.37 / 5.1	.54 / 8.0	.65 / 10.1	.48 / 6.5	
MTG-7-sum		.54 / 7.9	.69 / 12.2		.72 / 11.7	.60 / 6.1	.58 / 8.7	.62 / 8.4	.45 / 6.4	.52 / 7.5	.56 / 10.1	.44 / 6.0	
MTG-15-A		.53 / 6.9	.71 / 11.7	.72 / 11.7		.79 / 7.6	.68 / 9.9	.66 / 7.8	.53 / 7.3	.61 / 8.3	.60 / 7.9	.59 / 7.8	
MTG-16-B		.71 / 8.0	.65 / 7.0	.60 / 6.1	.79 / 7.6		.68 / 7.3	.43 / 3.8	.57 / 5.5	.36 / 3.0	.64 / 6.6	.39 / 3.3	
MTG-17-sum		.51 / 7.2	.61 / 9.3	.58 / 8.7	.68 / 9.9	.68 / 7.3		.61 / 8.1	.55 / 7.9	.50 / 7.0	.62 / 9.4	.42 / 5.5	Corr / Ttest
MTG-21-A		.39 / 4.4	.49 / 6.0	.62 / 8.4	.66 / 7.8	.43 / 3.8	.61 / 8.1		.51 / 6.2	.52 / 6.3	.65 / 8.9	.34 / 3.6	
MTG-27-A		.43 / 6.0	.37 / 5.1	.45 / 6.4	.53 / 7.3	.57 / 5.5	.55 / 7.9	.51 / 6.2		.35 / 4.6	.37 / 4.7	.38 / 4.8	
MTG-28-sum		.43 / 5.9	.54 / 8.0	.52 / 7.5	.61 / 8.3	.36 / 3.0	.50 / 7.0	.52 / 6.3	.35 / 4.6		.57 / 8.2	.36 / 4.6	
MTG-29-C		.63 / 9.7	.65 / 10.1	.56 / 10.1	.60 / 7.9	.64 / 6.6	.62 / 9.4	.65 / 8.9	.37 / 4.7	.57 / 8.2		.40 / 5.0	
MTG-30-sum		.41 / 5.3	.48 / 6.5	.44 / 6.0	.59 / 7.8	.39 / 3.3	.42 / 5.5	.34 / 3.6	.38 / 4.8	.36 / 4.6	.40 / 5.0		

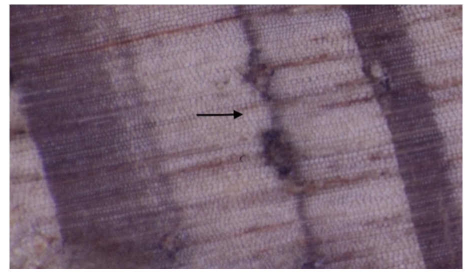
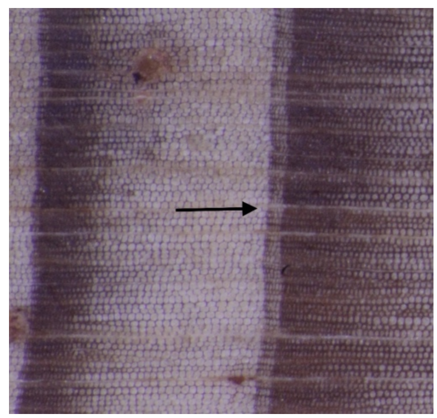
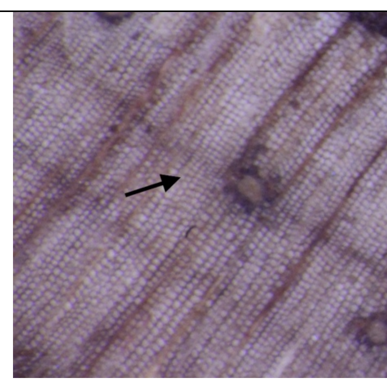
Appendix 5: Cross Correlations with Negative Exp. Detrending

		All IADFs	Earlywood I	Earlywood II	Earlywood III	Latewood	Opaque	Faint	Cells Only	Boundary I	Boundary II	Row	
Annual		.01 / 0.0	-.09 / -0.6	-.02 / -0.1	not	not	-.13 / -.06	-.14 / -0.9	.12 / 0.8	-.38 / -2.0	-.02 / -0.1	not	
Jun-Oct		.01 / 0.0	-.03 / -0.2	-.09 / -0.5	enough	enough	-.15 / -0.7	-.05 / -0.3	.06 / 0.4	-.31 / -1.5	-.05 / -0.3	enough	
Nov-Sep		.05 / 0.4	-.04 / -0.3	-.11 / -0.7	occurrences	occurrences	-.09 / -0.4	-.02 / -0.1	.07 / 0.4	-.20 / -1.0	-.14 / -0.9	occurrences	
January		-.01 / -.1	-.12 / -0.8	.09 / 0.5	to accurately	to accurately	.14 / 0.6	-.17 / -1.0	.16 / 1.0	-.35 / -1.8	-.01 / 0.0	to accurately	
February		.35 / 2.7	.18 / 1.2	-.19 / -1.1	correlate	correlate	.17 / 0.8	.16 / 1.0	.03 / 0.2	.31 / 1.6	-.12 / -0.8	correlate	
March		.22 / 1.6	.11 / 0.7	.19 / 1.1			.13 / -0.6	-.04 / -0.2	-.08 / -0.5	.18 / 0.9	.02 / 0.1		Corr.Ttest
April		.13 / 1.0	-.05 / -0.3	.20 / 1.2			-.25 / -1.2	-.05 / -0.3	.02 / 0.1	.02 / 0.1	-.42 / -3.2		
May		-.16 / -1.2	-.10 / -0.7	.22 / 1.3			.04 / 0.2	-.29 / -1.9	.07 / 0.4	-.08 / -0.4	-.18 / -1.5		
June		.00 / 0.0	.12 / 0.8	-.23 / -1.4			.36 / 1.7	.13 / 0.8	-.20 / -1.2	-.05 / -0.3	-.13 / -0.9		
July		.08 / 0.6	-.15 / -1.0	-.05 / -0.3			-.43 / -2.1	-.10 / -.06	.14 / 0.9	-.11 / -0.5	.08 / 0.5		
August		-0.05 / -0.4	.03 / 0.2	-.27 / -1.7			-.19 / -0.8	.09 / 0.6	-.05 / -0.4	-.20 / -1.0	.13 / 0.9		
September		.02 / 0.2	-.04 / -0.3	.20 / 1.2			-.10 / -0.5	.01/ 0.1	.11 / 0.7	-.13 / -0.6	-.16 / -1.1		
October		-.03 / -0.2	.12 / 0.8	.18 / 1.0			-.09 / -0.4	-0.15 / -0.9	-.02 / -0.1	-.16 / -0.8	.07 / 0.5		
November		-.04 / -0.3	-.14 / -1.0	.27 / 1.6			-.26 / -1.2	-.36 / -2.4	.23 / 1.5	-.29 / -1.4	.10 / 0.7		
December		-.03 / -0.2	-.13 / -0.9	-.08 / -0.5			.33 / 1.6	.10 / 0.6	-.01 / 0.0	-.11 / -0.5	-.29 / -2.4		

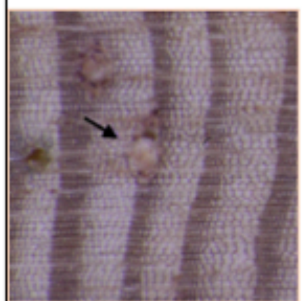
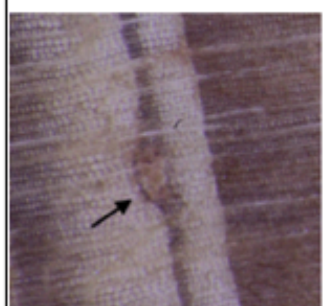
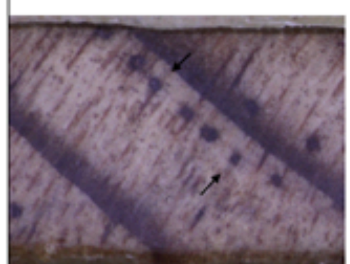
Appendix 4: Cross Correlations of Abnormal Ring Formations and Gridded P Values

Ring Typology Based on Location within the Ring		
Ring Type:	Description:	Example:
Earlywood I	False boundary within the first third of the earlywood. Often a thin boundary (a few rows of cells) with little to no transition into latewood cells.	 3-A-A, RY 93
Earlywood II	False boundary within the middle of the earlywood. Varying degrees of width, gradual transition, and cell size change.	 17-B-A, RY 72
Earlywood III	False boundary within the last third of the earlywood. Varying degrees of width, gradual transition, and cell size change. Differentiates from Latewood type because it occurs	 16-B-A, RY 48
Latewood	False boundary within the latewood of the cell. Ring demonstrates a gradual transition into latewood that is interrupted by a few rows of larger cells. These enlarged cells may be replication of earlier stages of latewood cells. Discernable from Earlywood III due to location firmly within latewood transition.	 5-B-A, RY 80

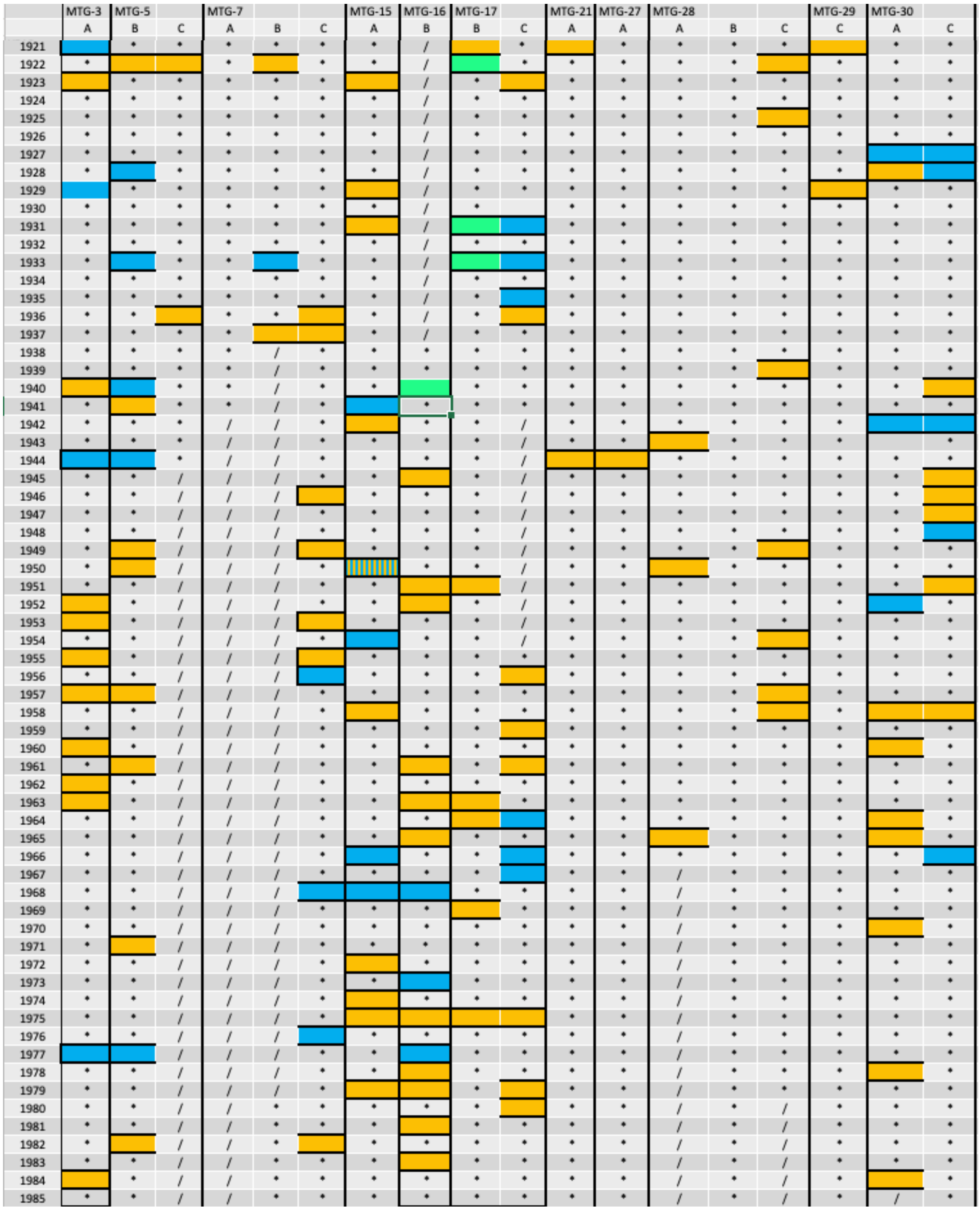
Appendix 6: IADF Categories

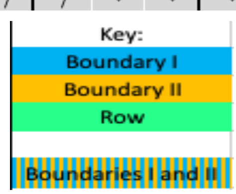
Ring Typology Based on Density of Cell Walls and Cell Shrinkage		
Ring Type:	Description:	Example:
Opaque	This is a dark false boundary with both shrinking of cells and thickening of cell walls. May have a gradual latewood transition leading to the false boundary.	 17-B-A, RY 49
Faint	This boundary has both shrinking of cells and thickening of cell walls but not enough to be mistaken for a true boundary. Often lacks a gradual transition into latewood-resembling cells.	 3-A-A, RY 83
Cell Shrinkage Only	A sudden appearance of enlarged cells that is not associated with any thickening of cell walls. Not a true false boundary.	 5-C-A, RY 3

Appendix 7

Ring Types Based on Placement of Resin Ducts		
Ring Type:	Description:	Example:
Boundary I	A resin duct disrupts the ring boundary. It touches latewood on its right and earlywood on its left and has no effect on the formation of the boundary. Often indicative of a false boundary.	 17-B-A, RY 95
Boundary II	A resin duct on the edge of the ring causes the boundary to bulge out. Latewood cells surround this boundary on all sides. Typically indicative of a true ring boundary.	 25-A-A, RY 46
Row	Row of resin ducts at any point in the ring. Three ducts or more constitute a row – does not need to be in a perfect line. Cell size shrinks surrounding the ducts, but may not occur in a straight line (thus not considered type vii).	 6-C-A, RY 4

Appendix 8: Resin Duct Categories

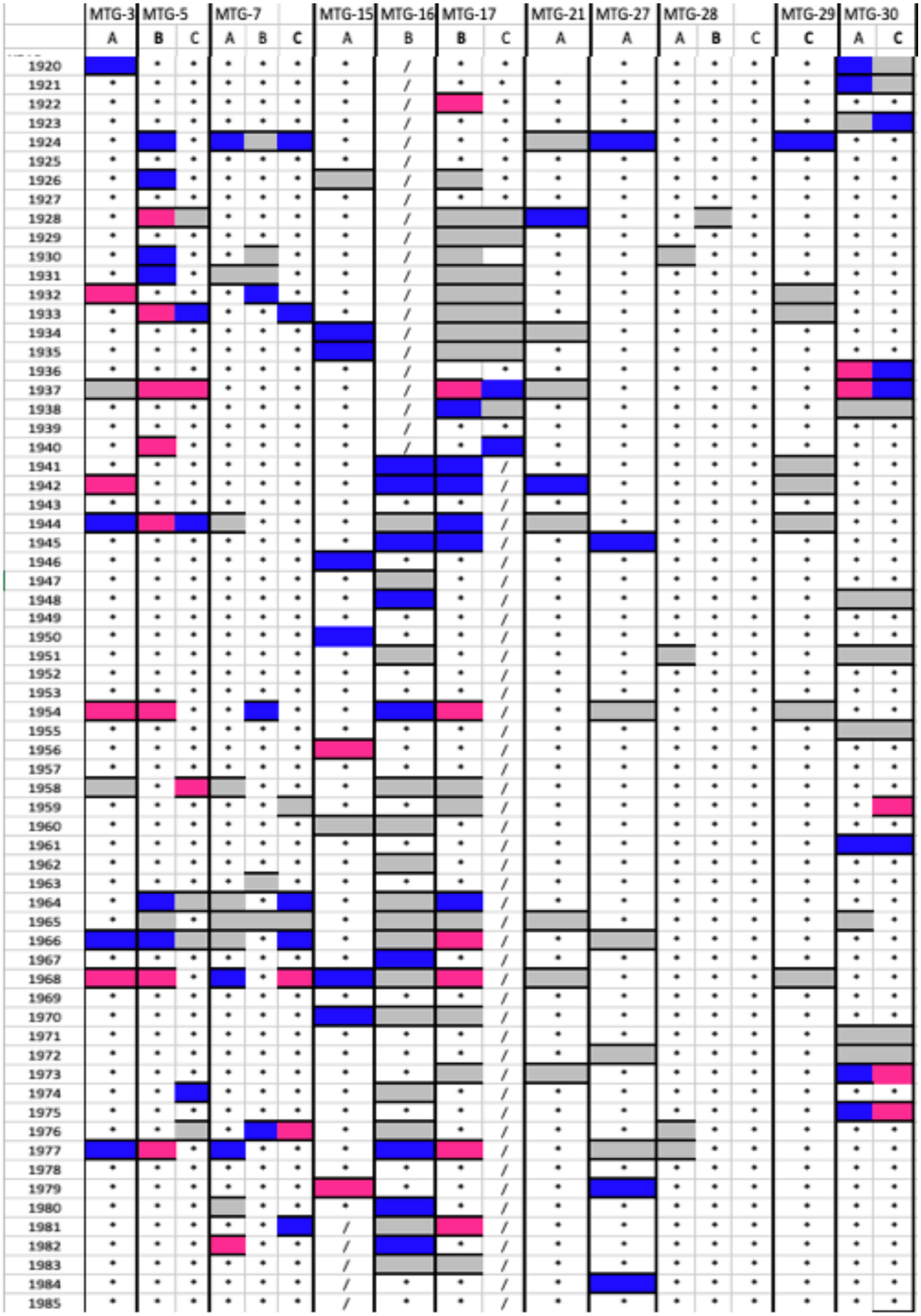




Appendix 9: Appearances of Resin Duct Types 1921-1985

	MTG-3	MTG-5		MTG-7			MTG-15	MTG-16	MTG-17		MTG-21	MTG-27	MTG-28			MTG-29	MTG-30	
	A	B	C	A	B	C	A	B	B	C	A	A	A	B	C	C	A	C
1921	*	*	*	*	*	*	*	/	*	*	*	*	*	*	*	*		
1922	*	*	*	*	*	*	*	/		*	*	*	*	*	*	*	*	*
1923	*	*	*	*	*	*	*	/	*	*	*	*	*	*	*	*		
1924	*		*				*	/	*	*			*	*	*		*	*
1925	*	*	*	*	*	*	*	/	*	*	*	*	*	*	*	*	*	*
1926	*		*	*	*	*		/		*	*	*	*	*	*	*	*	*
1927	*	*	*	*	*	*	*	/	*	*	*	*	*	*	*	*	*	*
1928	*			*	*	*	*	/				*	*		*	*	*	*
1929	*	*	*	*	*	*	*	/			*	*	*	*	*	*	*	*
1930	*		*	*		*	*	/			*	*		*	*	*	*	*
1931	*		*			*	*	/			*	*	*	*	*	*	*	*
1932		*	*	*		*	*	/			*	*	*	*	*		*	*
1933	*			*	*		*	/			*	*	*	*	*		*	*
1934	*	*	*	*	*	*		/				*	*	*	*	*	*	*
1935	*	*	*	*	*	*		/			*	*	*	*	*	*	*	*
1936	*	*	*	*	*	c cv v	*	/		*	*	*	*	*	*	*		
1937				*	*	*	*	/				*	*	*	*	*		
1938	*	*	*	*	*	*	*	/			*	*	*	*	*	*		
1939	*	*	*	*	*	*	*	/	*	*	*	*	*	*	*	*	*	*
1940	*		*	*	*	*	*	*	*		*	*	*	*	*	*	*	*
1941	*	*	*	*	*	*	*			/	*	*	*	*	*		*	*
1942		*	*	*	*	*	*			/		*	*	*	*		*	*
1943	*	*	*	*	*	*	*	*	*	/	*	*	*	*	*	*	*	*
1944					*	*	*			/		*	*	*	*		*	*
1945	*	*	*	*	*	*	*			/	*		*	*	*	*	*	*
1946	*	*	*	*	*	*		*	*	/	*	*	*	*	*	*	*	*
1947	*	*	*	*	*	*	*		*	/	*	*	*	*	*	*	*	*
1948	*	*	*	*	*	*	*		*	/	*	*	*	*	*	*		
1949	*	*	*	*	*	*	*	*	*	/	*	*	*	*	*	*	*	*
1950	*	*	*	*	*	*		*	*	/	*	*	*	*	*	*	*	*
1951	*	*	*	*	*	*	*		*	/	*	*		*	*	*		
1952	*	*	*	*	*	*	*	*	*	/	*	*	*	*	*	*	*	*
1953	*	*	*	*	*	*	*	*	*	/	*	*	*	*	*	*	*	*
1954			*	*		*	*			/	*		*	*	*		*	*
1955	*	*	*	*	*	*	*	*	*	/	*	*	*	*	*	*		
1956	*	*	*	*	*	*		*	*	/	*	*	*	*	*	*	*	*
1957	*	*	*	*	*	*	*	*	*	/	*	*	*	*	*	*	*	*
1958		*			*	*	*			/	*	*	*	*	*	*	*	*
1959	*	*	*	*	*		*	*		/	*	*	*	*	*	*	*	
1960	*	*	*	*	*	*			*	/	*	*	*	*	*	*	*	*
1961	*	*	*	*	*	*	*	*	*	/	*	*	*	*	*	*		
1962	*	*	*	*	*	*	*		*	/	*	*	*	*	*	*	*	*
1963	*	*	*	*		*	*	*	*	/	*	*	*	*	*	*	*	*
1964	*				*		*			/	*	*	*	*	*	*	*	*
1965	*		*				*			/		*	*	*	*	*		*
1966					*		*			/	*		*	*	*	*	*	*
1967	*	*	*	*	*	*	*		*	/	*	*	*	*	*	*	*	*
1968			*		*					/		*	*	*	*		*	*
1969	*	*	*	*	*	*	*	*	*	/	*	*	*	*	*	*	*	*
1970	*	*	*	*	*	*				/	*	*	*	*	*	*	*	*
1971	*	*	*	*	*	*	*	*	*	/	*	*	*	*	*	*		
1972	*	*	*	*	*	*	*	*	*	/	*		*	*	*	*		
1973	*	*	*	*	*	*	*	*		/		*	*	*	*	*		
1974	*	*		*	*	*	*		*	/	*	*	*	*	*	*	*	*
1975	*	*	*	*	*	*	*	*	*	/	*	*	*	*	*	*		
1976	*	*		*			*		*	/	*	*		*	*	*	*	*
1977			*		*	*	*			/	*			*	*	*	*	*
1978	*	*	*	*	*	*	*	*	*	/	*	*	*	*	*	*	*	*
1979	*	*	*	*	*	*		*	*	/	*		*	*	*	*	*	*
1980	*	*	*		*	*	*		*	/	*	*	*	*	*	*	*	*
1981	*	*	*	*	*		/			/	*	*	*	*	*	*	*	*
1982	*	*	*		*	*	/		*	/	*	*	*	*	*	*	*	*
1983	*	*	*	*	*	*	/			/	*	*	*	*	*	*	*	*
1984	*	*	*	*	*	*	/	*	*	/	*		*	*	*	*	*	*
1985	*	*	*	*	*	*	/	*	*	/	*	*	*	*	*	*	*	*

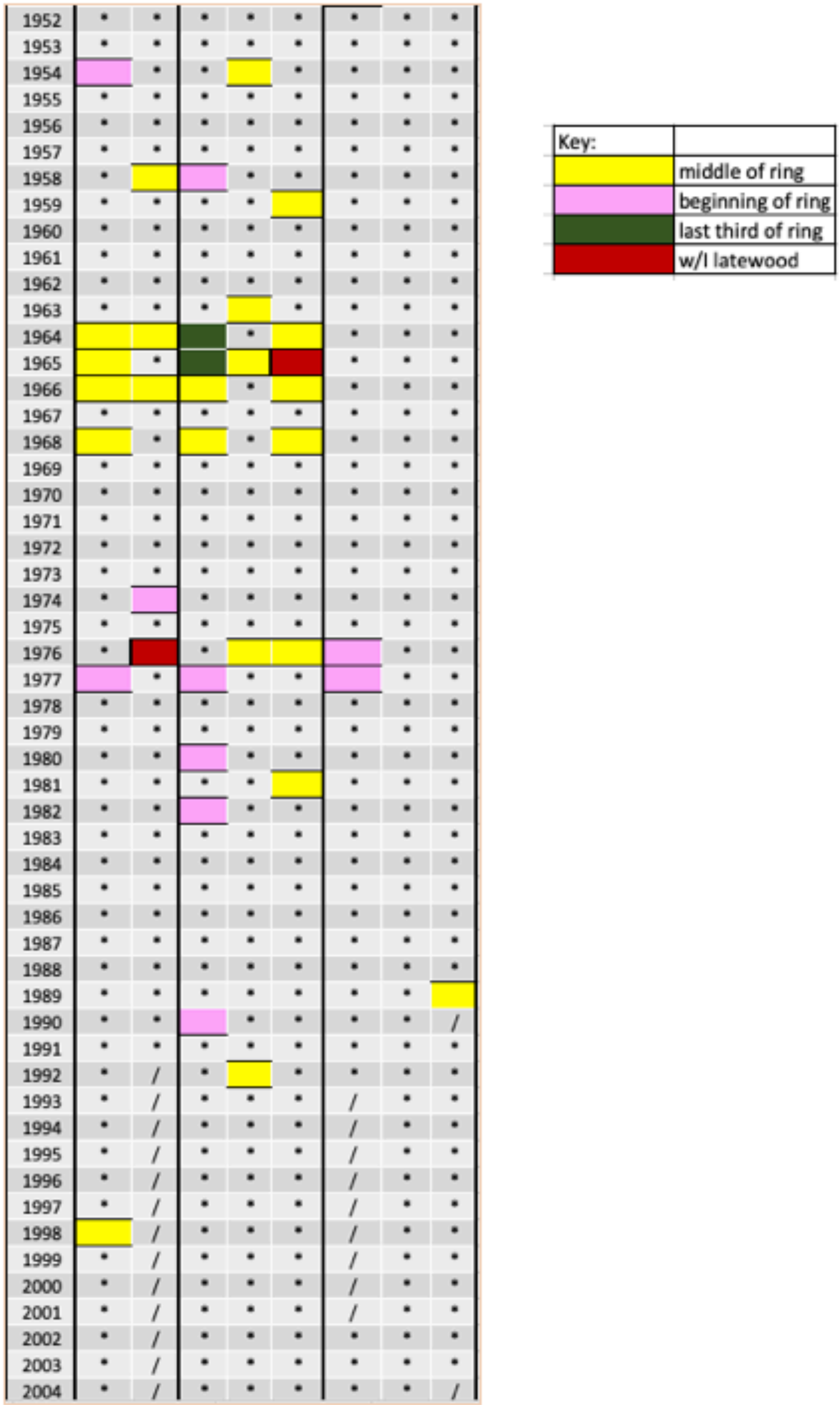
Appendix 10: IADF Appearances 1921-1985



Appendix 11: IADFs by Clarity 1920-1985

	MTG-5		MTG-7			MTG-28		
YEAR	B	C	A	B	C	A	B	C
1850	/	/	•	/	•	/	/	/
1851	/	/	•	/	•	/	•	/
1852	/		•	/	•	/	•	/
1853	•	•	•	/	•	/	•	/
1854	•	•		/		/		/
1855		•		/	•	/		/
1856		•		•	•	/		/
1857			•	•	•	/	•	/
1858			•	•	•	/	•	/
1859		•				/	•	/
1860	•	•	•	•	•	/	•	/
1861	•	•	•			/	•	/
1862			•			/	•	/
1863	•	•	•	•	•	/	•	/
1864				•		/	•	/
1865	•		•	•	•	/	•	/
1866		•	•	•	•	•	•	/
1867			•	•	•	•	•	/
1868			•	•	•	•		/
1869	•	•			•	•	•	/
1870	•		•	•	•	•	•	/
1871					•	•		/
1872	•	•	•	•	•	•	•	/
1873	•	•	•	•	•			/
1874	•	•			•	•	•	/
1875	•	•	•	•	•	•	•	/
1876			•	•	•	•	•	/
1877	•	•	•	•	•	•		/
1878		•	•	•	•	•	•	/
1879	•	•	•	•	•	•	•	/
1880	•		•	•	•	•	•	/
1881	•	•						/
1882				•				/
1883		•	•	•	•	•	•	/
1884	•	•	•	•	•	•	•	/
1885	•	•				•	•	/
1886								/
1887	•	•	•	•	•	•	•	/
1888		•					•	/
1889		•				•		/
1890	•	•	•	•	•	•	•	/
1891						•	•	•
1892						•		•
1893			•	•	•	•		•
1894	•	•	•	•	•	•		•
1895	•	•	•			•	•	•
1896	•	•	•	•	•	•	•	•
1897		•				•	•	•
1898	•		•	•	•	•		
1899	•	•	•	•	•	•	•	•
1900		•	•	•			•	•
1901								
1902			•	•		•		•
1903							•	•
1904	•	•		•	•	•	•	•
1905	•	•	•	•	•	•	•	•
1906								
1907			•	•	•	•	•	•
1908			•	•	•	•	•	•
1909	•	•	•	•	•	•	•	•
1910	•	•	•	•	•	•	•	•
1911		•	•	•	•	•	•	•
1912	•	•				•	•	•
1913		•				•	•	•
1914	•	•	•	•	•	•	•	•
1915								
1916	•	•	•	•	•	•	•	•
1917	•	•	•	•	•	•	•	•
1918	•	•	•	•	•	•	•	•
1919						•	•	•
1920	•	•	•	•	•	•	•	•
1921	•	•	•	•	•	•	•	•
1922	•	•	•	•	•	•	•	•
1923	•	•	•	•	•	•	•	•
1924		•				•	•	•
1925	•	•	•	•	•	•	•	•
1926		•	•	•	•	•	•	•
1927	•	•	•	•	•	•	•	•
1928			•	•	•	•		•
1929	•	•	•	•	•	•	•	•
1930		•	•		•		•	•
1931		•			•	•	•	•
1932	•	•	•		•	•	•	•
1933			•	•		•	•	•
1934	•	•	•	•	•	•	•	•
1935	•	•	•	•	•	•	•	•
1936	•	•	•	•	•	•	•	•
1937			•	•	•	•	•	•
1938	•	•	•	•	•	•	•	•
1939	•	•	•	•	•	•	•	•
1940		•	•	•	•	•	•	•
1941	•	•	•	•	•	•	•	•
1942	•	•	•	•	•	•	•	•
1943	•	•	•	•	•	•	•	•
1944				•	•	•	•	•
1945	•	•	•	•	•	•	•	•
1946	•	•	•	•	•	•	•	•
1947	•	•	•	•	•	•	•	•
1948	•	•	•	•	•	•	•	•
1949	•	•	•	•	•	•	•	•
1950	•	•	•	•	•	•	•	•
1951	•	•	•	•	•		•	•

Appendix 12: Comparison of IADFs in Samples with Multiple Radii 1850-1898

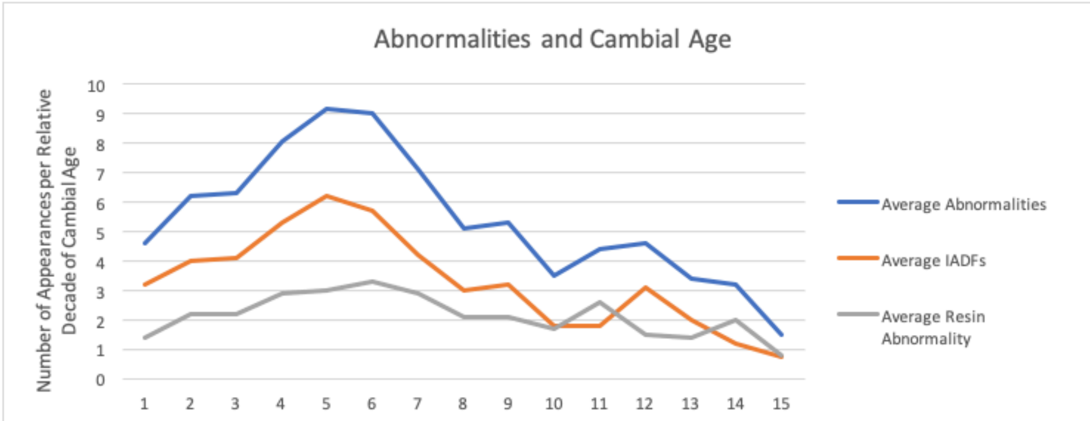


Appendix 13: Comparison of IADFs in Samples with Multiple Radii 1952-2004

	MTG-28			MTG-27
YEAR	A	B	C	A
1850	/	/	/	
1851	/	•	/	•
1852	/	•	/	•
1853	/	•	/	•
1854	/		/	•
1855	/		/	
1856	/		/	•
1857	/	•	/	•
1858	/	•	/	
1859	/	•	/	•
1860	/	•	/	
1861	/	•	/	
1862	/	•	/	•
1863	/	•	/	
1864	/	•	/	•
1865	/	•	/	•
1866	•	•	/	•
1867	•	•	/	
1868	•		/	
1869	•	•	/	•
1870	•	•	/	
1871	•		/	
1872	•	•	/	
1873			/	•
1874	•	•	/	•
1875	•	•	/	•
1876	•	•	/	•
1877	•		/	•
1878	•	•	/	
1879	•	•	/	
1880	•	•	/	
1881			/	•
1882			/	•
1883	•	•	/	•
1884	•	•	/	•
1885	•	•	/	•
1886			/	•
1887	•	•	/	•
1888		•	/	
1889	•		/	•
1890	•	•	/	•
1891	•	•	•	•
1892	•		•	
1893	•		•	•
1894	•		•	•
1895	•	•	•	•
1896	•	•	•	•
1897	•	•	•	•
1898	•			•
1899	•	•	•	•
1900		•	•	•
1901				•
1902	•		•	
1903		•	•	•
1904	•	•	•	•
1905	•	•	•	•
1906				•
1907	•	•	•	
1908	•	•	•	•
1909	•	•	•	•
1910	•	•	•	•
1911	•	•	•	•
1912	•	•	•	•
1913	•	•	•	•
1914	•	•	•	•
1915				
1916	•	•	•	•
1917	•	•	•	•
1918	•	•	•	•
1919	•	•	•	•
1920	•	•	•	•
1921	•	•	•	•
1922	•	•	•	•
1923	•	•	•	•
1924	•	•	•	
1925	•	•	•	•
1926	•	•	•	•
1927	•	•	•	•
1928	•		•	•
1929	•	•	•	•
1930		•	•	•
1931	•	•	•	•
1932	•	•	•	•
1933	•	•	•	•
1934	•	•	•	•
1935	•	•	•	•
1936	•	•	•	•
1937	•	•	•	•
1938	•	•	•	•
1939	•	•	•	•
1940	•	•	•	•
1941	•	•	•	•
1942	•	•	•	•
1943	•	•	•	•
1944	•	•	•	•
1945	•	•	•	
1946	•	•	•	•
1947	•	•	•	•
1948	•	•	•	•
1949	•	•	•	•
1950	•	•	•	•
1951		•	•	•
1952	•	•	•	•
1953	•	•	•	•
1954	•	•	•	
1955	•	•	•	•
1956	•	•	•	•
1957	•	•	•	•
1958	•	•	•	•
1959	•	•	•	•
1960	•	•	•	•
1961	•	•	•	•
1962	•	•	•	•
1963	•	•	•	•
1964	•	•	•	•
1965	•	•	•	•
1966	•	•	•	
1967	•	•	•	•
1968	•	•	•	•
1969	•	•	•	•
1970	•	•	•	•
1971	•	•	•	•
1972	•	•	•	
1973	•	•	•	•
1974	•	•	•	•
1975	•	•	•	•
1976		•	•	•
1977		•	•	
1978	•	•	•	•
1979	•	•	•	
1980	•	•	•	•
1981	•	•	•	•
1982	•	•	•	•
1983	•	•	•	•
1984	•	•	•	
1985	•	•	•	•
1986	•	•	•	•
1987	•	•	•	•
1988	•	•	•	•
1989	•	•		•
1990	•	•	/	•
1991	•	•	•	•
1992	•	•	•	•
1993	/	•	•	•

Key:	
	middle of ring
	beginning of ring
	last third of ring
	w/l latewood

Appendix 14: Comparison of MTG 28 with MTG 27



Appendix 15: Cambial Age vs. Abnormality Frequency