Original article

Natural disasters written in historical woods: Floods, a thunderbolt fire and an earthquake

Mar Génova\textsuperscript{a,}\textsuperscript{*}, Andrés Díez-Herrero\textsuperscript{b}, Miguel Angel Moreno-Asenjo\textsuperscript{a,}\textsuperscript{b}, Miguel Angel Rodríguez-Pascua\textsuperscript{b}

\textsuperscript{a} Universidad Politécnica de Madrid, Madrid, Spain
\textsuperscript{b} Instituto Geológico y Minero de España, Spain

\textbf{A R T I C L E  I N F O}

\textbf{Article history:}
Received 27 October 2017
Accepted 29 December 2017
Available online 28 February 2018

\textbf{Keywords:}
Dendroarchaeology
Dendrogeomorphology
Natural hazards
Flood
Earthquake
Thunderbolt fire

\textbf{A B S T R A C T}

The present paper analyzes different types of natural disasters recorded in the woody elements from reconstruction or repair works in two World Heritage buildings (the Old Mint and the Cathedral) in Segovia (Central Spain). We employed architectural and historical documentation, along with archaeoseismological analysis techniques in order to frame the events and processes. We analyzed several woody elements from the wooden deck of the Old Mint, including beams, planks and support blocks; and for the Cathedral roof the structural elements analyzed were tiebeams, raised aisles, rafter braces, common rafters and roof battens, as well as many planks and souldaces. For the dating, we combined two methodological approaches based upon dendrochronological techniques (dendroarchaeology and dendrogeomorphology) in an integrated study of the tree-rings series obtained. Furthermore, four wood samples (one from the Old Mint and three from the Cathedral) were dated by means of radiocarbon techniques. The results enable us to detect and corroborate the dates of at least two catastrophic flood events that affected the Old Mint (1695 and 1733). Additionally, we establish the unknown effects to date upon the Cathedral roof of the fire caused by the thunderbolt in 1614 and by the Lisbon earthquake in 1755. From the point of view of cultural heritage, these data are of great interest for the history of the reconstruction of the Old Mint and of the Cathedral of Segovia.

© 2018 Elsevier Masson SAS. All rights reserved.

1. Introduction

Since almost a century ago [1,2], dendrochronology has been commonly employed to establish the age of trees, but it has also been used to date the wood elements of several manmade artefacts such as buildings, boats, furniture, painted panels and even musical instruments (see, among others [3–5]). The results of these studies have enabled the dating and chronological ordering of settlements and artistic styles of archaeological sites (dendroarchaeology [6,7]) and other modern manmade objects (see compilation for the Iberian Peninsula in [8]). Some of these datings have made significant contributions to historical and prehistorical studies because they allow dating to be performed at a one-year resolution as compared with the wider confidence intervals of other dating methods (radiocarbon, luminescence, …). Furthermore, dendrochronological studies are used to calibrate radiocarbon dating curves. Precise tree-ring dating of buildings is even possible, despite the absence of bark [9]. Additionally, dendrochronology can provide more detailed information about the provenance of the timber [4,10]. In summary, dendroarchaeology throws light upon interactions between humans and their natural environment in specific periods of time [8].

Furthermore, since the late 1960s, dendrochronology has been combined with geomorphological analyses in order to date and quantify the magnitude of natural disasters, such as floods, avalanches, landslides, rockfalls, volcanic eruptions, earthquakes, etc. This combination, known as dendrogeomorphology [11], has furthered our knowledge of the frequency of occurrence of these catastrophes in the past, thus enhancing their prevention. A brief compilation of the application of the dendrogeomorphology to natural hazards studies can be found in [12]. These studies usually date and quantify past natural disasters from disturbances and changes in tree-ring sequence and other external and internal evidence in living trees.

Nonetheless, these two approaches in the use of dendrochronological techniques have not been combined to date in an integrated

\* Corresponding author.

E-mail addresses: mar.genova@upm.es (M. Génova), andres.diez@ige.es (A. Díez-Herrero), itollo@gmail.com (M.A. Moreno-Asenjo), ma.rodriguez@igme.es (M.A. Rodríguez-Pascua).

https://doi.org/10.1016/j.culher.2017.12.011 1296-2074© 2018 Elsevier Masson SAS. All rights reserved.
study of natural disasters recorded by means of the tree-ring sequences of timber elements in human constructions. Only the previous studies by [13–16] have explored this interesting line of research.

Indeed, when the elements of buildings (i.e., roof) and other constructions (i.e., canals) made of wood were used after natural disasters or catastrophic events in reconstruction or repairs, dating of these timber elements suggests the occurrence of the natural disaster, as well as the date thereof.

This approach constitutes a highly original way of studying historical (and prehistorical) catastrophic events ‘written in wood’, because it does not use disturbances in the tree-ring sequence of living trees (as is habitual in dendrogeomorphology), but rather the dendrochronological dating of manufactured woods (timber elements). In addition to establishing terminus post quem dates, i.e., the year in or after which structures were built, dendroarchaeology can assist in the study of remodeling and other alterations to buildings, including the use of timber salvaged from older structures or the replacement thereof [17].

Additionally, these integrated dendrochronological studies permit us to research more than one different type of natural disasters in a wooden building, because the timber elements might have been replaced following several different catastrophes such as floods, thunderbolt fires, earthquakes, etc. In a natural environment, it is not easy to find a forest with trees presenting different external evidence and disturbances in tree-ring sequences caused by different natural disasters and which can be studied with the use of classical dendrogeomorphological methodologies. Furthermore, in the event of various natural disasters recorded in the same forest, it would be difficult to distinguish and separate the different types of events by means of conventional techniques [12].

Historical buildings several centuries old present a complex history of construction involving different timber elements that can be affected by natural disasters over a wider time span. This is the case of the Gothic Medieval cathedrals in European countries, usually tall and thin and prone to be struck by lightning or affected by distant earthquakes (high-wavelength and low-frequency oscillations). This is also true for water-powered industries located in river valley bottoms, such as mills and hydroelectric plants, which are often affected by river floods and other mass movements from the slopes (rockfalls, landslides, avalanches, etc.).

2. Research aim

The present research aims to study three different types of natural disasters (floods, a thunderbolt fire and an earthquake) recorded in the wood elements of two different historical buildings in Segovia, Central Spain (the Old Mint and the Cathedral). In both cases, recent restoration works have provided a unique opportunity to sample their wood elements. The archaeological studies, revealing the presence of deteriorated wood elements (decay and putrefaction) that needed to be replaced, enabled sampling to be conducted in coordination with the building works.

Our specific aims are:

• to compile information from several data sources, such as documentary archives and archaeoseismology, about the effects of different natural disasters in the historical construction of these buildings;
• to assign dates, as precise as possible, using dendrochronological and radiocarbon techniques, to the wooden deck of the Old Mint and the Cathedral roof;
• to establish relationships between the timber dates and floods on the wooden deck and the effects of the 1614 fire and the 1755 earthquake on the Cathedral roof and complete the existing information and;
• to promote the use of multidisciplinary techniques in order to contribute with novel findings to the knowledge of historical heritage.

3. The wooden deck of the Old Mint and the wooden roof structure of the Cathedral of Segovia

The materials were collected from two important monuments of the town of Segovia (Central Spain, 60 km North of Madrid; Fig. 1), both declared as World Heritage sites by UNESCO in the year 1986: the Old Mint and the Cathedral. Both buildings rank among the four main monuments of the town, along with the Roman Aqueduct and the Medieval Castle, known as the Alcázar.

The Old Mint, situated in the Eresma river floodplain, was remodeled and put into operation during the reign of King Felipe II by the architect Juan de Herrera (1583–1585). Different minting processes were used here for almost three hundred years to mint coins, until its closure in 1809, when it became a flour mill [18–20]. Some of the minting processes, such as lamination, were powered by water from the nearby Eresma river, by means of a weir, canals and water wheels. During the archaeological research work for its restoration, a wooden deck over the Herrera canal was discovered. It was made of transverse beams and planking nailed in the direction of the canal, and support blocks for the canal structure [14] (Fig. 2a).

Construction of the gothic Cathedral, located at the top of a hill, began during the reign of King Carlos I (1525), following destruction of the old romanesque Cathedral during the Comunidades Civil War (1520–1521). Although designed in the Gothic style, during the three Centuries it took to be finished, Renaissance and baroque elements were gradually incorporated. The roof of the main nave of the Cathedral was completed at the beginning of the 17th Century and it comprised a structure of wooden trusses [21]. On September 18, 1614, a thunderbolt struck the spire crowning the cathedral bell tower, causing a fire that spread to the library and the naves. The tower (at the time the highest one in Spain), as well as most of the roof structure, succumbed to the fire and had to be replaced [21]. Moreover, the Cathedral was subsequently affected by the Lisbon Earthquake, on November 1, 1755. This was the most destructive earthquake in the history of Western Europe, affecting the entire Iberian Peninsula. The city of Lisbon was devastated and many historical buildings in Spain were damaged. The effects of this earthquake were recorded in the survey conducted by King Fernando VI several months later and in many other documents of the time [22]. The damage recorded in the Cathedral of Segovia involved cracks and fractures in the walls and general damage to the chapels (documentary sources: Proceedings of the Chapter of the Cathedral describing the effects of the 1755 earthquake on the building [15]).

The current roof trusses of the Cathedral comprise a unique timber frame (not the typical Spanish armature with rafters and ridge plate), because it is made up of two common rafters, one tiebeam, one collar and two queen struts; additionally, there are rafter braces and raised aisle trusses [23] (Fig. 2b). The whole roof structure is covered by wooden planking and over this, a roof made of tiles. The trusses were tilted and diagonal soulices between adjacent trusses were added to counteract the inclination and prevent the collapse of the armature [15,24]. In 2014, rehabilitation and renovation work was carried out on the roof of the Cathedral of Segovia (Fig. 1), of which various pieces were replaced due to being in a poor state of conservation; moreover, the soulices were removed. These wood samples therefore constitute valuable records of the history of both buildings and of the town affairs.
4. Material and methods

4.1. Historical and archaeoseismological information

We analysed historical documents from several archives, libraries and newspaper archives of the city and province of Segovia and at national level, to gather information on works and repairs conducted in the studied buildings in which wood was used, including the origin thereof. Moreover, we searched for records of historical disasters such as floods, slope movements (landslides, collapses, etc.), fires and earthquakes that affected both buildings. Specifically, systematic searches were made in the following archives: the General Archive of Simancas (AGS), the General Archives of the Palace (AGP), the Historical Archive of Segovia (AHPS), the General Register of the Stamp (RGS), the Historical Military Archive of Segovia (AHMS), the Municipal Archive of Segovia (AMS) and the Archive of the Cathedral of Segovia (ACS). We also consulted newspaper archives and libraries, such as the local press from the end of the 19th century (Eresma, Adelantado de Segovia, etc.) and historical magazines in which news or reviews could be found (Estudios Segovianos). We used each document to create a simple file with the documentary typology (municipal acts, Cabildo minutes, newspaper reports, etc.). A transcription was made by means of paleographic techniques where necessary, and temporary data were extracted (date or time interval), as well as the magnitude and intensity thereof and the damages caused. All these records were used to construct a database.

Strain structures detected in archaeological sites affecting buildings, monuments, cathedrals, etc., can be caused by different factors, for example those of seismic origin, intervening slope process, unstable soils, differential overburden during the burial process, or simply collapsed remains resulting from eventual building abandonment or war destruction, etc. For this reason, it is necessary to identify the trigger mechanism of the damaged structure in order to assign a seismic origin.

The anisotropy inherent to the seismic wave (i.e. the direction of the seismic ray propagation) generates a strain field constrained by the seismic source parameters: distance from the archaeologi- cal site to the epicentre, magnitude of the earthquake, hypocentral depth, type of arrival wave, etc. This fact implies that the ductile and brittle structures affecting monuments, walls and buildings can be analysed by means of the classic structural geology techniques. The results obtained from these analyses enable us to reconstruct the mean direction of ground movement. Earthquakes can generate different deformation structures, which affect archaeological sites. In consequence, we collected the data concerning the Earthquake Archaeological Effects (EAEs) [25] and the geological structural analysis proposed by [26]. This classification was created for use in archaeological sites and historic buildings to distinguish seismic effects from other causes. The geological tool employed for this purpose involved analysis of seismic strain structures. All of these deformational structures have been classified and studied according to the geological structural analysis of brittle deformation in order to estimate the orientation of the maximum horizontal movement of the ground. The initial hypothesis requires that most of the seismic damage must be oriented in relation to the seismic ground movement. Hence, we can compare oriented seismic deformation with other damage.
the bark (tiebeams, raised aisles and soulaces), whereas the most elaborate pieces (planking, rafter braces, common rafters and roof battens) lack numerous outer rings. Given that these wood pieces come from the rehabilitation works, the outer portions of the pieces are seen to be affected by different degrees of decay.

All these timber elements involve Scots pine (*Pinus sylvestris*), according to their anatomical characteristics [27]. In addition, the historical documentation indicates that both the wooden deck of the Old Mint and the reconstructed wooden roof structure of Segovia’s Cathedral after the fire of 1614, come from the nearby pine forests of *P. sylvestris* known as Valsaín [20,21] (Fig. 1a).

### 4.3. Sample collection, preparation, measurement and elaboration of tree-ring series

In order to analyze the tree-ring series of the different construction elements available for sampling, we employed the most common procedures of the dendrochronological study of historical and archaeological woods [6]. Once the pieces were cleaned, we obtained from 1 to a maximum of 3 cross-sections of each element with the chainsaw, drying them all slowly to gradually reduce the moisture content of the wood. The cross-sections were sanded and polished very precisely, with belt sanders (rotary orbital and manual), using progressively finer grit sandpaper until all the tree rings could be adequately visualised. We then selected several measuring radii using visual procedures, from 2 to 6 in each section, depending on the shape and size of the sections, and we generally measured a larger number of radii in the larger or irregular cross-sections.

The ring widths were measured to an accuracy of 1/100 mm with a digital LINTAB positioning table connected to a stereomicroscope and TSAPWin software. The measured tree-ring radii series were cross-dated with TSAPWin software and the COFECHA program facilities, in order to detect false, incomplete, or missing rings, as well as to eliminate possible errors or anomalies, with the aim of finding the correct dated position in time [28–30]. We first crossdated and averaged the tree-ring series of the same section; we then crossdated and averaged the tree-ring series of each piece. Next, we crossdated the series corresponding to each type of element, and then the tree-ring series corresponding to each architectural structure. We determined the raw data by first fitting them to a negative exponential function and then to a 25-year spline function (ArstanWin program [31]). Finally, we developed average series of indices, rejecting individual series whose intercorrelation values were lower than the critical value of 0.32.

### 4.4. Dendrochronological dating

Selecting a suitable reference chronology is crucial to the success of the dating procedure. Master chronologies should be of the same tree species, deriving from roughly the same geographical area as the wood to be dated and should obviously be long enough to include the prospective time-period covered by the wood sample [32]. As already indicated in section 4.2, all the construction elements analyzed, both from the Old Mint and the Cathedral, come from trees felled in the nearby Valsaín pine forest. This *P. sylvestris* forest is located on the north-facing slope of the Sierra de Guadarrama Mountains, near the city of Segovia (Fig. 1). Numerous dendrochronological studies over decades in the Sierra de Guadarrama have enabled the elaboration of a regional tree-ring chronology (1462–2005 [33]). Therefore, taking into account both the origin of the wood and the approximate dates of its use in the architectural structures (see section 3), we used this tree-ring chronology as a reference. For the dendrodatation of the tree-ring indices of the architectural structures, we contrasted the Cofecha intercorrelation with the statistical parameters of TSAPWin values (see section 4.3).

---

**Table 1**

<table>
<thead>
<tr>
<th>Site</th>
<th>Structure Type</th>
<th>Number of Pieces</th>
<th>Mean Radius (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mint canal</td>
<td>Wooden deck</td>
<td>6</td>
<td>18</td>
</tr>
<tr>
<td>Mint canal</td>
<td>Wooden deck</td>
<td>3</td>
<td>17</td>
</tr>
<tr>
<td>Mint canal</td>
<td>Support block</td>
<td>4</td>
<td>16</td>
</tr>
<tr>
<td>Cathedral</td>
<td>Wooden truss</td>
<td>15</td>
<td>26</td>
</tr>
<tr>
<td>Cathedral</td>
<td>Raised aisle</td>
<td>3</td>
<td>18</td>
</tr>
<tr>
<td>Cathedral</td>
<td>Rafter brace</td>
<td>2</td>
<td>14</td>
</tr>
<tr>
<td>Cathedral</td>
<td>Common rafter</td>
<td>2</td>
<td>26</td>
</tr>
<tr>
<td>Cathedral</td>
<td>Roof batten</td>
<td>3</td>
<td>13</td>
</tr>
<tr>
<td>Cathedral</td>
<td>Planking</td>
<td>48</td>
<td>15</td>
</tr>
<tr>
<td>Cathedral</td>
<td>Soulace</td>
<td>40</td>
<td>13</td>
</tr>
</tbody>
</table>

---

4.2. Construction elements analyzed

We studied different pieces from the restoration works of the wooden deck of the Mint Canal and of the wooden roof structure of the Cathedral in Segovia. With regard to the wooden deck, there is a greater number of elements than was analyzed in [14]: six beams, three planks and four support blocks (Fig. 2a and Table 1). In no case did these pieces show traces of bark, because they were treated for use in construction. Furthermore, the structural elements analyzed in the Cathedral roof involved 15 tiebeams, 3 raised aisles, 2 rafter braces, 2 common rafters and 3 roof battens (from different trusses), as well as 48 planks and 40 soulaces (Fig. 2b and Table 1). In relation to their structural functions and carving for use in construction, some of these pieces present rings very close to
In order to dendrodate archaeological or historical timber, the outermost ring is of maximum interest, since it constitutes the main indicator of the date when the wood was used. However, since the samples have often lost outer rings due to carving or biodegradation, the date assigned to the last ring is termed noncutting. Only in the case that the sample has bark can the date be assigned as a felling date = cutting date [34–36]. Both the cutting date and the noncutting date are after all dates post quem in historical and archaeological terminology, because the time elapsed since the tree was cut until its wood was used must be considered.

In dendroarchaeology the felling dates of each piece analyzed are usually estimated first [34] (see Hillam, 1998). In the present paper, for the dendrodating we alternatively dated first the series of indices of each architectural structure and, subsequently, we dated each one of the individual series. In some cases the individual series represent only internal or external portions of the trunk of the tree due to carving and construction, such as the planking and, therefore, the outer ring dating is more distant from the felling date. In other cases, the pieces are very complete and in a good state of preservation such as, for example some support blocks or beams from the Old Mint, or tiebeams, raised aisles and soulaces from the Cathedral. With all this information we evaluated and interpreted the dating of each construction element, as detailed in the results section.

4.5. Radiocarbon dating and calibration

To overcome problems with the dendrochronological dating it is convenient to increase the number of samples analyzed or to check this dating with the radiocarbon dating. In our case, given the difficulty involved in increasing the number of samples, which was already determined by the rehabilitation work conducted in both buildings, we radiocarbon dated wood samples: 1 sample from the Old Mint and the other 3 samples from different construction elements of the Cathedral roof. The radiocarbon dates were obtained from samples taken from the most inner rings. The sample from the Old Mint was dated in the CNA (National Accelerators Center, Seville, Spain, 13-06-2012) and the roof structure of the Cathedral in Beta (Beta Analytic Inc., Miami, Florida, 11-17-2015) and they were all calibrated by means of Radiocarbon Calibration Programs [37,38]. To compare the dendrochronological and the radiocarbon dates we used the approach proposed by [39], analyzing whether the dendrochronological date falls into the 95% probability interval of the calibrated 14C date.

5. Results

5.1. Dendrochronological dating

All the Old Mint tree-ring series involve noncutting dates, since the pieces do not present bark remains or the outer tree rings. Almost all the individual series of the different pieces analyzed synchronize with each other (Table 2) and were used to elaborate a mean series of indices after being standardized. When crossdating this average series with the reference chronology (the Guadarrama regional chronology), the 1552–1716 chronology proves to be the most reliable one (Table 3). Moreover, we studied the temporal range of the 12 individual tree-ring series according to this chronology. In the less carved and better preserved pieces (CM11, CM02 and CM04), the anatomical characteristics (curvature) of the outer rings indicate that they were very close to the bark; their dating is therefore close to the felling date. Taking into account the different dates of the pieces (Fig. 3), the construction elements have been grouped into two different sets, whose dating post quem are 1680 AD and 1716 AD, respectively. It is even possible that oldest outer rings, corresponding to CM12 and CM08 (Fig. 3), indicate other previous cutting and use dates.

The intercorrelation between the tree-ring series of the different elements of the roof of the Segovia Cathedral was higher than 0.5 (Table 2). In addition, the mean Wooden Truss and the mean Planking tree-ring series crossdated very well (intercorrelation = 0.511 and CDI = 32). Conversely, no synchrony can be observed with the tree-ring series of the Soulaces. These data and others, from criteria related to the architectural context described in section 3, enable us to determine that the construction elements of the Cathedral roof structure constitute two sets of different chronologies. First, the trusses and planking, comprising 57 synchronized individual tree-ring series, and second the soulaces, made up of 40. The time span of the tree-ring series of the trusses and planking are different, depending on preservation state and carving; the dating of the outer ring varies by less than 6 decades, the planking tree-ring series being the furthest from the possible felling date (between 56 and 6 years). On the other hand, in the tree-ring series of the better preserved and less carved pieces (i.e., most of the tiebeams) we consider the dating of the outer rings to be very close to the felling date. The total mean tree-ring series of the Cathedral roof contains 156 width indices, and in relation with the reference regional chronology, 1496–1651 constitutes the most likely dating (Table 3).

As for the soulaces, we synchronized 40 individual tree-ring series. The soulaces are quite unelaborated wood pieces, and all the series ended in a 3-year range before the most recent outer ring, corresponding to a sample exhibiting remains of bark. We therefore conclude that the year after this last ring dating is when all the trees used for the soulaces were cut. The average sequence contains 92 tree-ring width indices and overlaps with the reference regional chronology in 1781–1871 and 1837–1927, constituting the two most probable chronologies, depending on the maximum values reached for the different statistical parameters considered (Table 3).

In addition we dated 6 internal scars (possibly caused by fires) in 1 tiebeam and in several soulaces, corresponding to 1579, 1801, 1818, 1846 and 1859.

5.2. Radiocarbon dating

We dated four samples by means of radiocarbon techniques: one beam of the Mint canal wooden deck and three pieces of the Cathedral wooden roof (one tiebeam, one raised aisle and one soulace, Table 4). In the dendrodated pieces the results obtained are coherent, since the dendrochronological date falls within the 95% probability interval of the calibrated 14C date and confirms the temporal range of the dendrodation. The D02 raised aisle was also radiocarbon dated, although its tree-ring series did not synchronize with the remaining ones, and dendrochronological dating therefore not being possible. As indicated in Table 4, for this piece two different time ranges are 95% probable: 1440/1520 and 1595/1620 cal AD. Both radiocarbon dates are very close to the tiebeam range, although the first is earlier by one decade. In any case, it could be

---

**Table 2**

<table>
<thead>
<tr>
<th>Site</th>
<th>Type</th>
<th>n</th>
<th>P (%)</th>
<th>Nm</th>
<th>Mt ± SD</th>
<th>IT</th>
<th>Nr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mint canal</td>
<td>Wooden deck</td>
<td>12</td>
<td>92</td>
<td>112.51 ± 0.85</td>
<td>0.497</td>
<td>166</td>
<td></td>
</tr>
<tr>
<td>Cathedral roof</td>
<td>Wooden truss</td>
<td>18</td>
<td>72</td>
<td>95</td>
<td>2.31 ± 1.20</td>
<td>0.522</td>
<td>149</td>
</tr>
<tr>
<td>Cathedral roof</td>
<td>Planking</td>
<td>39</td>
<td>81</td>
<td>86</td>
<td>1.74 ± 1.00</td>
<td>0.571</td>
<td>150</td>
</tr>
<tr>
<td>Cathedral roof</td>
<td>Soulaces</td>
<td>40</td>
<td>100</td>
<td>52</td>
<td>2.33 ± 0.80</td>
<td>0.577</td>
<td>92</td>
</tr>
</tbody>
</table>

n: number of mean individual series; P (%): percentage with respect to the total of analyzed series; Nm: average number of rings; Mt: mean tree ring width (mm); SD: standard deviation; IT: intercorrelation (Cofecha); Nr: total number of rings of the average tree-ring sequence.
5.3. The effects of natural disasters upon Segovia’s buildings

Génova et al. [14] had already considered the correlation between the years with documented floods in the Eresma river and the repairs recorded in the Old Mint canal [20]. In the present research, both the dendrochronological dating reviewed (1552–1716, Table 3) and the radiocarbon date (Table 4) confirm that the wooden deck of the Mint was indeed installed after the initial construction of the Herrera canal (1583–1585) and prior to construction of the Sabatini canal (1770–1771). In addition, it has been determined that not all the pieces analyzed have the same cutting age as shown by the outer ring date. These woods can therefore be grouped into at least two different post quem dates: 1680 and 1716, thus indicating that they were installed as replacements or repairs, most likely after floods that caused severe damage. These post quem dates could be related to the documented 1695 (and the subsequent repairs conducted in 1701) and 1733 floods, although in this case there was no available information on repairs after this date. In the 1733 flood some people and horses died and several bridges, mills and houses were destroyed; consequently, the situation was declared as catastrophic [14]. Lastly, some timbers are older, and were likely installed as a result of earlier repairs.

The chronology of the Cathedral roof (1496–1651, Table 3), confirmed by radiocarbon dating (Table 4), indicates that the cutting date of the trees used refers to the 1650s. This means that a new wooden roof structure was installed after the 1614 fire. As an exception, one of the radiocarbon dated tiebeams might not have been damaged by fire and was subsequently reused in the new roof (Table 3).

Moreover, we classified and measured the influence of EAEs in the Cathedral using the classification of [24]: penetrative fractures in masonry blocks in the main nave (N135° E) with lateral displacements towards N045° E; displaced masonry blocks (12 cm of displacement towards N010° E) and dropped key stones in the arches of the main nave (N135° E). The medium direction of ground movement for the main nave is N015° E, congruent with the location of the epicentral area of the 1755 Lisbon earthquake (SW of San Vicente Cape). All these EAEs were documented in historical chronicles, but there was no documentation on EAEs in the roof. We have, however, ascertained that the wooden structure of the roof was reinforced using soulaces because the trusses were tilted 7° towards N135° E (Fig. 4). The soulaces were all contemporaneous and were installed between the last quarter of the 19th and the start of the 20th centuries, although we cannot indicate a more accurate date by dendrochronological or radiocarbon dating (Table 3). Therefore, this research demonstrates that the inclination of the trusses and the subsequent installation of the soulaces resulted from the 1755 Lisbon earthquake.

### Table 3
Chronology characteristics of the Segovia buildings in relation to the Guadarrama master chronology (1462–2005).

<table>
<thead>
<tr>
<th>Type/Site</th>
<th>Chronologies</th>
<th>MC</th>
<th>TV</th>
<th>Glk</th>
<th>CDI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wooden deck/Mc</td>
<td>1552–1716 AD</td>
<td>–</td>
<td>3.2</td>
<td>65 ± 9</td>
<td>22</td>
</tr>
<tr>
<td>Wooden truss and planking/Cr</td>
<td>1496–1651 AD</td>
<td>–</td>
<td>4.7</td>
<td>63 ± 9</td>
<td>15</td>
</tr>
<tr>
<td>Soulaces/Cr</td>
<td>1781–1871 AD</td>
<td>1837–1927 AD</td>
<td>–0.34</td>
<td>--</td>
<td>64 ± 9</td>
</tr>
</tbody>
</table>

---

### Table 4
Contrasting dendrochronological and radiocarbon dating.

<table>
<thead>
<tr>
<th>ID</th>
<th>ID lab</th>
<th>Type/Site/n</th>
<th>Dendro Inner year</th>
<th>Conventional radiocarbon age</th>
<th>Calibrated radiocarbon age ranges (95% probability)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM02F</td>
<td>CNA1367</td>
<td>Beam/Mc/106</td>
<td>1611 AD</td>
<td>340 ± 40 BP</td>
<td>1463/1643 AD</td>
</tr>
<tr>
<td>TC26D</td>
<td>Beta-422245</td>
<td>Tiebeam/Cr/142</td>
<td>1506 AD</td>
<td>360 ± 30 BP</td>
<td>1450/1640 AD</td>
</tr>
<tr>
<td>D02</td>
<td>Beta-422244</td>
<td>Raised aisle/Cr/147</td>
<td>1590 ± 30 AD</td>
<td>400 ± 30 BP</td>
<td>1440/1520 AD</td>
</tr>
<tr>
<td>J18B</td>
<td>Beta-422243</td>
<td>Soulace/Cr/84</td>
<td>1787 AD 1843 AD</td>
<td>1550 ± 30 AD</td>
<td>1595/1620 AD</td>
</tr>
</tbody>
</table>

We indicate the most inner rings dated by dendrochronological methods because the radiocarbon datings were obtained from this part of the samples. For calibrated radiocarbon dating, the most probable ranges are indicated at 95% probability. It must be noted that there are two possible dendrochronological dates in the case of the soulace chronology and two possible radiocarbon dates in the case of the raised aisle (see results). Mc: Mint canal; Cr: Cathedral roof; n: number of tree-rings of the sample.

---

Fig. 3. Characteristics of the timber samples from the Mint canal (extended and revised in relation to Génova et al., 2011). The dashed line indicates insufficiently reliable (intercorrelation does not exceed the critical value of 0.32). The cells appear colored with different intensities depending on the outer ring dating, clearer in the older ones.

---

a piece from the original roof, which was not damaged by the fire and which was subsequently reused to make the new roof.
6. Discussion

6.1. Dating of the historical timber and its relationship with the effects of natural disasters

Diverse chronologies have been elaborated with historical wood of *P. sylvestris*, both from the wooden deck of the Mint canal and the roof structure of the Cathedral of Segovia. In addition, the dendrochronological dating has been supported with radiocarbon dating to overcome potential problems [40].

In Europe in the 16th and 17th centuries, dendroarchaeological studies of buildings rarely involved *Pinus* as the predominant wood, because whenever available, *Quercus* was the preferred material (especially *Q. robur* and *Q. petraea*), which is much more resistant and durable [40–43]. However, the use of wood from *Pinus* in the center and south of the Iberian peninsula has been very frequent, as...
indicated by several dendroarchaeological studies conducted over the last few decades [44–47]. Our research increases the number of Spanish buildings constructed with pine wood dated through dendroarchaeological methods. Moreover, it should be noted that the main temporal range of the timber determined in our research for the Segovian constructions (1496–1716) significantly enlarges the dendroarchaeological dataset known as far for the Iberian Peninsula in these two centuries [8].

But, in addition, our paper furthers a new line of study based upon the correlation between dendrochronological dating and analysis of the effects of natural disasters on historical buildings. With this objective, we expanded and revised the results obtained in [13,14], referring to the repairs carried out on the wooden deck of the Mint canal as a consequence of the floods, and we determined the unknown effects of a thunderbolt fire and an earthquake on the roof structure of the Cathedral of Segovia (Fig. 5).

In the Mint canal, the timber ages show the damages caused by the 1695 and 1733 floods (Fig. 6), confirming documented data (repairs in the canal in 1701) and supporting hypotheses regarding other undocumented data (possible repairs conducted between 1733 and 1742). Regarding the wooden roof structure (planking and trusses) of the Cathedral, the elaborated chronology (1496–1651), whose the outer ring dating is very close to the felling date, is much later than the construction dates of the original roof. According to European dendroarchaeological studies, the time lag between when the tree was felled and the wood was used to construct the roof is estimated to be between 1 and 3 years [9,42,48,49]. It is therefore highly likely that the definitive construction of the roof structure of the Cathedral was in the mid 1650s. Several decades passed between the fire of 1614 and this new and definitive installation of the roof (Fig. 6). The historical documentation has not provided precise information, but indicates that in 1656 the last chapel was built and that until 1680 construction of the new dome was not completed [21]; it also highlights the economic hardships existing in the city of Segovia in the first half of the 17th century, which prevented the use of resources to finalize construction of the Cathedral [50].

It has been shown by archaeoseismological methods that the earthquake of 1755 undoubtedly caused the roof frame tilting. It has also been shown that the support soulaces, employed to stabilize the tilted trusses, were installed much later than the roof frame and after this earthquake, as determined the dendrochronological and radiocarbon datings. The outermost tree-ring index of the soulace chronology is one year before the felling date, but we can only estimate a temporal range for this date, since the dendrochronological and radiocarbon datings are not absolutely conclusive. However, it can be pointed out that soulaces were installed between the last quarter of 19th and the beginning of the 20th centuries, at least more than 100 years after the earthquake (Fig. 6). There are two possible explanations for this delay: the earthquake damage in the roof was not known until that date, as it is not mentioned in the documentation on the damages caused, or the inclination of the trusses was progressive over time, until it was decided to install soulaces to redress it.

From the point of view of cultural heritage, the data provided by our paper are of great interest for the history of the reconstruction of the Old Mint and the Cathedral of Segovia and also with regard to evaluating the effects of the different natural disasters that affected them.

6.2. Tree-rings and management history of the Valsaín pine forest (Sierra de Guadarrama Mountains)

We investigated the relationships between the dendrochronological dating of the historical woods and the forest history of Valsaín. According to [51,52], exploitation of the pine forest of Valsaín was based on the need to guarantee the supply of timber for construction to the City of Segovia. Thus, as from the second half of the 13th century, this activity must have exerted intense pressure on the larger trees (since it was forbidden to carve pieces that had not reached a certain size), therefore placing particular stress upon the higher age classes.

The characteristics of the timber used in the construction of both these emblematic Segovian buildings also provide data about the former management of the Valsaín forests. Most of the pieces, dated from the 16th to the beginning of the 18th centuries, present a similar number of rings and crossdate very significantly, but vary with regard to mean tree-ring width. Most likely these timbers came from different forest stands, thus indicating a very specific forest management regime [52], in which trees were strictly selected according to different uses. This management system underwent big changes since it became property of the Crown in the mid-18th century [51,52]. The high degree of synchrony between the series of soulaces, which were used between the last quarter of the 19th and the beginning of the 20th centuries, indicates that they came from the same stand, and the tree-ring series provided evidence of intense forest exploitation (Fig. 7). Moreover, we provide some data on the fire history of the Valsaín pine forest.

7. Concluding remarks

For the first time, very different techniques of analysis are used to study the construction history of two buildings in the city of Segovia (Spain), declared as World Heritage sites. Both architectural as well as historical documentation techniques have been employed in the recognition of different wooden structures and in the pieces they comprise, in order to establish the different processes and the events they were subjected to throughout their construction. In addition, novel archaeoseismological analyses were performed to establish the causes of some damages. Lastly, numerous wood elements were dated by means of dendrochronological and radiocarbon techniques to use as a proxy for inferring the effects of certain natural disasters.

The studied structures involved a wooden canal in the Old Mint and the roof frame of the Cathedral. We verified the effects of three types of natural disasters upon their construction: floods, a thunderbolt fire and an earthquake, employing dendrochronological and radiocarbon dating of the woods used. We defined at least two floods that caused severe damage and subsequent timber replacement in the Mint canal. Furthermore, we displayed for the first time that the Cathedral roof frame was destroyed by the 1614 thunderbolt fire, and that the new one built in the mid-17th
century became tilted as a result of the 1755 earthquake. Moreover, we determined that there was a time span until the soulae supporting the trusses that were tilted by the earthquakes were installed and we propose some hypotheses in this regard. Additionally, we provide data about the Valsain pine forest management.

With this study, we extend the use of multidisciplinary techniques to promote the knowledge and preservation of Spanish historical heritage.

Acknowledgments

The authors would like to thank the Cabildo of the Cathedral, the managers of the Old Mint and Town Hall of Segovia, the technicians of the Junta de Castilla y León and the Company TRYCSA for their inestimable collaboration in the sampling and gathering of information. Eduardo Muñoz and Sira de la Fuente conducted preliminary analyses of the samples and Guadalupe De Marcello compiled a large amount of historical data. Some of the research and analyses for this article have been funded over the last decade by the Research Group Historia y Dinámica del Paisaje Vegetal of Madrid’s Universidad Politécnica and by the research projects Dendro-Avenidas (2008–2010), MAS Dendro-Avenidas (2011–2013) and MARCONI (CGL2013-42728-R; 2014–2017).

References

[19] G.S. Murray, El Real Ingenio de la Moneda de Segovia: Fábrica industrial más antigua, avanzada y completa que se conserva de la Humanidad. Razonamiento científico de la propuesta para su declaración como patrimonio de la humanidad, Cámara de Comercio e Industria de Segovia, Segovia (Spain), 2008.
[21] M.T. Cortoíz, La Construcción de La Catedral de Segovia (1525–1607), Caja de Ahorros y Monte de Piedad de Segovia, Segovia (Spain), 1997.


[50] M.A. Cillamnua, La construcción de la catedral de Segovia a través de sus cuentas: estudio patrimonial, financiero y contable de la edificación de la “Dama de las Catedrales”, Caja Segovia, Obra Social y Cultural, Segovia (Spain), 2009.

