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Wood identification and acoustic analysis of three original Aztec teponaztli musical instruments

Identificación de la madera y análisis acústico de tres teponaztlis, instrumentos musicales aztecas originales

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Abstract

Teponaztlis exhibited in Mexico's Anthropology Museum are the most emblematic items among Aztec musical instruments. The purpose of this research was twofold: to correctly identify the wood used to manufacture three of the most important instruments of their kind and to perform an acoustic analysis to determine relevant acoustic and musical parameters of these instruments. Wood identification consisted in comparing some anatomical features of teponaztlis to those of known species from a wood collection and other sources. Multivariate analysis shows that species are separated by the percentage of uniseriate and partially biseriate rays at one hand and by fibre wall thickness at the other hand. The results show that the genus *Dalbergia* was used for these instruments, and the analysis suggests proximity of teponaztlis to *Dalbergia palo-escrito*, and to *D. granadillo*. The acoustic analysis was based on digital sound recordings of the instruments played with the under-side cavity closed or open. Results show that musical intervals between the two low and high pitch tones of the instruments are from slightly below a major third, to slightly above a fifth. Tones produced with the under-side cavity closed are slightly shorter in duration, and stronger, in comparison when it is open. Playing one of the two tones faintly produces sound from the other, and also from the sides of the instrument, especially with the under-side cavity open. The musical intervals that are observed in these instruments do not correspond exactly to conventional Western tunings.

KEYWORDS: *Dalbergia,* idiophones, México, musical pitch, ray parenchyma, tone duration

Resumen

Los teponaztlis del Museo de Antropología de México son los instrumentos musicales aztecas más emblemáticos. Por ello, los objetivos de esta investigación fueron identificar correctamente la madera usada para su manufactura y realizar el análisis acústico para determinar los parámetros relevantes. La identificación de la madera consistió en la comparación de los caracteres anatómicos de los instrumentos con los de las especies conocidas de una colección de maderas y de otras fuentes. El análisis multivariado muestra que, en un espacio discriminante, las especies se separan por el porcentaje de rayos uniseriados y parcialmente biseriados (primera forma) y por el grosor de la pared de la fibra (segunda). Los resultados muestran que estos instrumentos fueron elaborados con madera de *Dalbergia*, y el análisis sugiere proximidad de los teponaztlis con *Dalbergia palo-escrito* y con *D. granadillo*. El análisis acústico se realizó en registros digitales del sonido de los instrumentos tocados con la cavidad inferior cerrada o abierta. Se encontró que los intervalos musicales entre los dos tonos son desde ligeramente inferiores a una tercera mayor, hasta ligeramente superiores a una quinta. Los tonos producidos con la cavidad inferior cerrada fueron ligeramente más cortos en duración y más intensos que con la cavidad abierta. Se encontró que al tocar alguno de los dos tonos se produce débilmente sonido del otro tono, y también sonido de las partes laterales del instrumento, especialmente cuando la cavidad inferior está abierta. Los intervalos musicales observados no coinciden con los sistemas de afinación convencionales de la Música occidental.

PALABRAS CLAVE: *Dalbergia*; idiófonos; tono musical; parénquima radial; duración de tonos.

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Introduction

Teponaztlis are the most emblematic members among Mexican precolumbian musical instruments (Universidad Nacional Autónoma de México, 2012). They were portrayed in various historical documents such as the Florentine Codex (Sahagún, 1975), the Codex Mendoza (Cooper, 1938), the Mendoza Codex (Orozco y Berra, 1975), among others. In addition to their role as musical instruments, they belong to a ritual environment where the Aztecs considered them gods who lived in exile on Earth (Estrada, 1984). Nowadays they are still used in ethnographic contexts and are very important entities in the culture of several indigenous groups in the country, such as the Mixtec, Nahua, Teneek, Chontal, Maya, Mazahua and Otomi peoples (Ochoa, 2002). The teponaztli has been studied as an "active agent", an entity with a personality capable of inhabiting the universe of Nahua cosmogony, an idea related to the concept of a fluid person that moves through matter and space in a state of constant transformation (Estrada, 2010).

Teponaztlis are directly struck idiophones. They are built out of a single piece of a log or branch of a tree. The log is hollowed in the central part, while the ends remain solid, from which two opposing strips or tongues protrude on the longitudinal-dorsal face, one to the left and the other one to the right. The entrance to the resonance cavity is in the longitudinal-ventral face. The strips are the vibratory bars characteristically suspended over the soundboard in the direction of the wood wire. These instruments measure between 15 cm - 25 cm in diameter and 60 cm - 90 cm in length (Fig. 1). The outside of the piece could be carved with graphic characters depicting warriors, mythological animals or deities, although this is elective.

Three teponaztlis are exhibited In the Mexica Hall at the National Museum of Anthropology in Mexico City. These musical instruments were collected from different sites in central Mexico: Tlaxcala, Malinalco and Chalco. Castañeda and Mendoza (1991) include very detailed structural drawings and provide pitch and tuning values for each instrument. (1) The Tlaxcala-Teponaztli is an instrument whose carving represents one of the four great Calpulli chiefs and was part of war loot taken from Tlaxcala soldiers after a battle sustained against Hernán Cortés. These authors claim that this piece was built from walnut wood, producing a minor third interval with the actual notes G5 + ¼ tone and Bb 5 + ¼ tone. (2) The Cipactli Head Teponaztli exhibit the features of various fantastic animals such as a head of a crocodile, but could represent another animal. Its origin remains unknown. Regarding its manufacture, it is mentioned that it was built from sapodilla or chico zapote wood, producing a perfect fifth interval with the actual notes D5 + 1/8 tone and A5 + 1/8 tone. (3) The teponaztli from Malinalco may represent an ahuítzotl, i. e. a water dog (otter) (Castañeda & Mendoza, 1991) or a cuetlachtli, i.e. a wolf. It is thought to be a representation of an unidentified fantastic animal. These authors claim that it comes from Chalco, although according to the files of the National Museum of Anthropology its origins could be traced back to Malinalco. The use of sapodilla wood is reported here as well, as is the production of a perfect fifth interval with the actual notes A4 + ¼ tone and E5 + ¼ tone.

The percussion musical instruments that could be considered most akin to teponaztlis, due to their use of vibrating wooden bars struck with a mallet, are xylophones and marimbas. Existing literature on the characteristics of woods that determine good sound quality in this type of musical instruments, report some results on the relative importance of having low vibration damping, high wood density, and physical stability against changes in humidity. For instance, studies on the relationship of wood density and acoustic quality in 59 woody taxa (Mitsuko, Bailleres, Brancheriau, Kronland-Matinet, & Ystad, 2007), showed that instrument builders do not determine sound quality according to wood density, and observed that a high vibration damping is associated with poor acoustic quality. A review of studies on xylophones (Wegst, 2006), found that high wood density correlates with high values of the dynamic modulus, peak response, and sound radiation coefficient, but with a low damping coefficient. Also, that

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A

B

C

FIGURE 1. A. Tlaxcala-Teponaztli. B. Cipactli- Teponaztli. C. Malinalco- Teponaztli.

Fotos: Cultura-INAH-Canon, Sala Mexica.

the ratios of these parameters will determine the volume (loudness) and sound intensity. Studies of acoustic characteristics of *Pterocarpus erinaceus* wood from plantations in Sudan and Guinea (Traoré, Brancheriau, Perre, Stevanovic, & Diouf., 2010), revealed that the best specimens for xylophone construction in Mali are those characterized by low vibration damping, and low sensitivity to variations in humidity. Additionally, that vibration damping is inversely related to the extractive content and wood density. An analysis of the physical and anatomical properties of 58 tropical wood species correlated with the acoustic quality of xylophone-type percussion instruments (Brancheriau, Baillères, Détienne, Gril, & Kronland, 2006), found that wood density does not affect acoustic quality, and that softwoods have some technological drawbacks such as frailty, instability and lack of acoustic power.

Despite the importance of these instruments in Mexican culture, information on identification and acoustic characteristics of the wood relies exclusively in the work of Castañeda and Mendoza (1991), who make wood identification while they abstain from mentioning the methodology utilized in their findings. It is most likely that they relied only on color and density taken as identity diagnostic features.

Objectives

The purposes of this research were to correctly identify the wood species up to genus, with which these three original Aztec instruments were manufactured, through the study of some anatomical features of their woods, and approximately identify them by comparing with known species. Additionally, a separate acoustic analysis is also carried out in order to determine and document relevant acoustic and musical parameters: vibration frequencies, damping factors, tonal pitches, and tone duration.

Materials and Methods

The instruments studied here were taken out from the showcases that exhibit them in the Mexica Hall of the National Museum of Anthropology, to perform the sampling of the wood and the acoustic study.

To differentiate in a practical way each instrument, the names of the instruments with which they have been known for decades has been kept, although the meaning of the animals or characters that are represented in each instrument was not dealt with in depth, since it was not the purpose of this study.

Wood samples of *Dalbergia granadillo*, *D. palo-escrito* and *D. congestiflora* come from the collection kept by Lidia Guridi Gómez, who allowed access to the samples, (Universidad Michoacana de San Nicolás de Hidalgo) and wood samples of *Dalbergia retusa* and *D. stevensonii* come from the collection curated by Fernando Ortega, (Instituto de Ecología A.C., Xalapa), who identified the wood samples.

Anatomical Study

A small sample of wood 2 mm in length was obtained from the inside of the resonance box of each instrument. Each sample was hydrated in a carrier solution of polyethilenglycol 800 Baker® in other to soften it. A Leica cryostat Mod CM 1510-3 was used to obtain transverse, tangential and radial sections at 12 μm - 16 μm thick at -20 °C. The sections were dehydrated in ethyl-terbutyl alcoholic dehydration series, and then mounted on a glass slide using Entellan® resin. The remainder of the sample was prepared using Jeffrey's solution, which was then mounted on glycerinated gelatin (Johansen, 1940).One cube of 1 cm × 1 cm of each wood sample of *Dalbergia granadillo D. palo-escrito, D. retusa, D. stevensonii* and *D. congestiflora* was prepared in exactly the same way as the teponaztlis wood samples, in other to obtain permanent slides and compare wood structure between both groups.

The list of microscopic features by IAWA Committee (Wheeler, Baas, & Gasson 1989) and the Inside Wood database (NC State University, 2004) were used to confirm cell types and feature descriptions of genus *Dalbergia.* The following wood cell characteristics were measured in cross and tangential sections: tangential and radial vessel diameters, vessel wall thickness; ray cell number, height and width ray, as well as the total number of rays per mm, as well as diameter, wall thickness and length of fibres. Radial sections were used only to confirm presence of procumbent ray cells and of prismatic crystal in chambered axial parenchyma cells. Thirty to fifty data values were recorded of each measurable characteristic for each wood sample, these were obtained directly at the microscope with a calibrated 10x ocular 1 mm micrometer installed in a Zeiss Microscope Mod. K7. Additionally, the percentage of uniseriate, biseriate, triseriate and partially biseriate per mm was calculated. Microscopic photographs were taken using a Nikon D50 camera body installed in the microscope. Macroscopic cross surfaces were pictured with a Nikon D5000 camera and an AF Micro Nikkor 60 mm macro lens.

Univariate statistics was applied to the measurable features in order to obtain means, standard deviation and standard error. In order to detect significant differences between some anatomical features of constituent woods of each instrument and of the five known species of genus *Dalbergia*, and to determine affinities at genus level, a multivariate analysis was applied. For this, a Discriminant Multivariate Analysis (DMA) was performed on a matrix of 488 values, 8 samples and 5 anatomical variables. The criterion used to evaluate differences between groups was Wilks' Lambda (λ), which tends to take values close to zero when groups are well defined according to the variables considered, and towards one when groups are not well defined (Tatsuoka, 1970). The corresponding discriminant functions were extracted and the variables that contributed to group separation were identified. This analysis considered percentages of uniseriate, biseriate, triseriate, partially biseriate rays per mm and fibre wall thickness, since in our own preliminary analyses these were the only variables that showed significant differences to separate the groups. NCSS 2007 and JMP 7 software was used for all analyses (Hintze, 2009; SAS Institute Inc., 2007).

Acoustic Recording and Analysis.

Teponaztli tones played with medium soft mallets were produced repetitively by a professional musician, specialized in percussion instruments. Series of ten tones were recorded and analyzed for each of the two tones of the instruments, produced by playing on each of the two differently tuned vibrating cantilever beams, that extend horizontally in the upper part from both ends of the cylindrical body of the instruments.

Recording took place in the Mexica Hall, National Museum of Anthropology in Mexico City, on a Monday, when the museum is closed to the public, so background noise was at relatively low level, although the corresponding sound pressure level was not specifically measured (Fig. 2). Teponaztlis were placed over a table covered with a soft felt cloth. A mallet weighing 125 g was used to play the Cipactli and Malinalco instruments, while a mallet of 70 g was used to play the smaller Tlaxcala instrument. Two different ways to support the instruments were used: one with the instruments resting directly on the table, leaving the under-side cavity closed, and another in which soft plastic supports were used under the two ends, lifting the instruments about 10 cm above the table, leaving the under-side cavity open.

Sound was picked up at about 80 cm above the instruments by a MXL model V67G condenser microphone, connected to a Motu UltraLite Mk3 external audio interface, and this in turn to a MacBook Pro laptop portable computer running Adobe Audition CS6 sound recording software. Digital audio recordings had a sampling frequency of 48 000 samples per second, and 24 bits per sample. These were analyzed in the GNU Octave numerical processing software, using our own custom programming and graphical scripts, implementing standard signal processing and spectral analysis algorithms (Newland, 1989; Norton, 1989), where average time signals of the ten recordings for each tone were calculated, and FFT spectra of the ten recordings for each tone were squared in magnitude, and average frequency power spectra were obtained.

From the averaged frequency spectra, oscillation frequencies (f_0), spectral widths $(\Delta f_0)_{3\ \mathrm{dB}}$, damping ratios $D = \Delta f_0 / f_0$, and reverberation times $T_{60} = 13.8 / f_0 D$ of the single damped tonal component observed in each frequency spectrum were calculated in GNU Octave, using our own custom programming signal processing scripts. From these, in turn, tonal pitches relative to the standard equal temperament musical scale were calculated, along with micro-tonal deviations in cents, and the corresponding musical intervals in cents, and typical tone durations in seconds (Randall, 1987).

Results

Woods of *Dalbergia* spp (rosewood) were used to manufacture these three outstanding teponaztli instruments preserved in the Mexica Hall at National Museum of Anthropology. The instruments were built using the hardwood of big trunks. Wood color in the three teponaztli is very similar: dark brown, reddish brown and dark red. The woods show cross grain and median texture. The wood is diffuse-porous, semi-ring-porous; vessel elements with simple perforations plates, intervessel pits alternate, and gums present in lumina. The axial parenchyma is vasicentric, aliform, in narrow bands and diffuse-in-aggregates, formed by two fusiform parenchyma cells per strand. Rays are uni-, bi-, tri- and partially biseriate, in stratified pattern, all cells procumbent; prismatic crystals are present. Fibres are libriform with simple pits (Fig. 3). The wood of the five known species is thus found to present the same macroscopic characteristics as well as type and cell arrangements as previously described (Fig. 4 y 5). Measured features for teponaztlis and known species are given in tables 1 and 2.

FIGURE 2: Sound recording session. Tlaxcala-Teponaztli with the under-side cavity open.

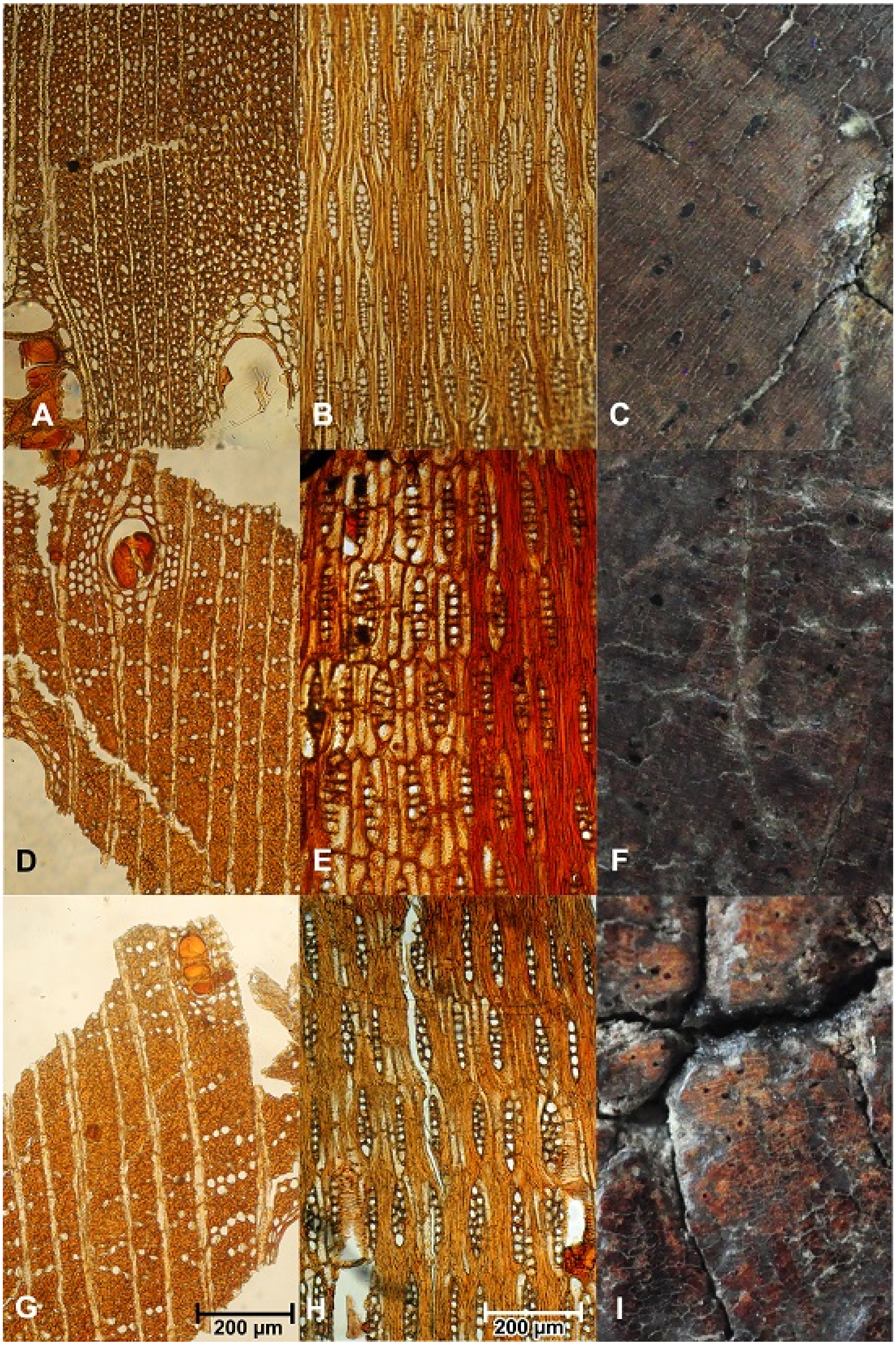

FIGURE 3. A-C Tlaxcala-Teponaztli. D-F. Cipactli-Teponaztli. G-I. Malinalco-Teponaztli. A, D, G. Cross section showing diffuse-agreggate axial parenchyma, vasicentric axial parenchyma. B, E, H. Tangential section showing stratified structure. C, F, I. Cross surfaces showing diffuse-porous and axial parenchyma at 4X magnification.

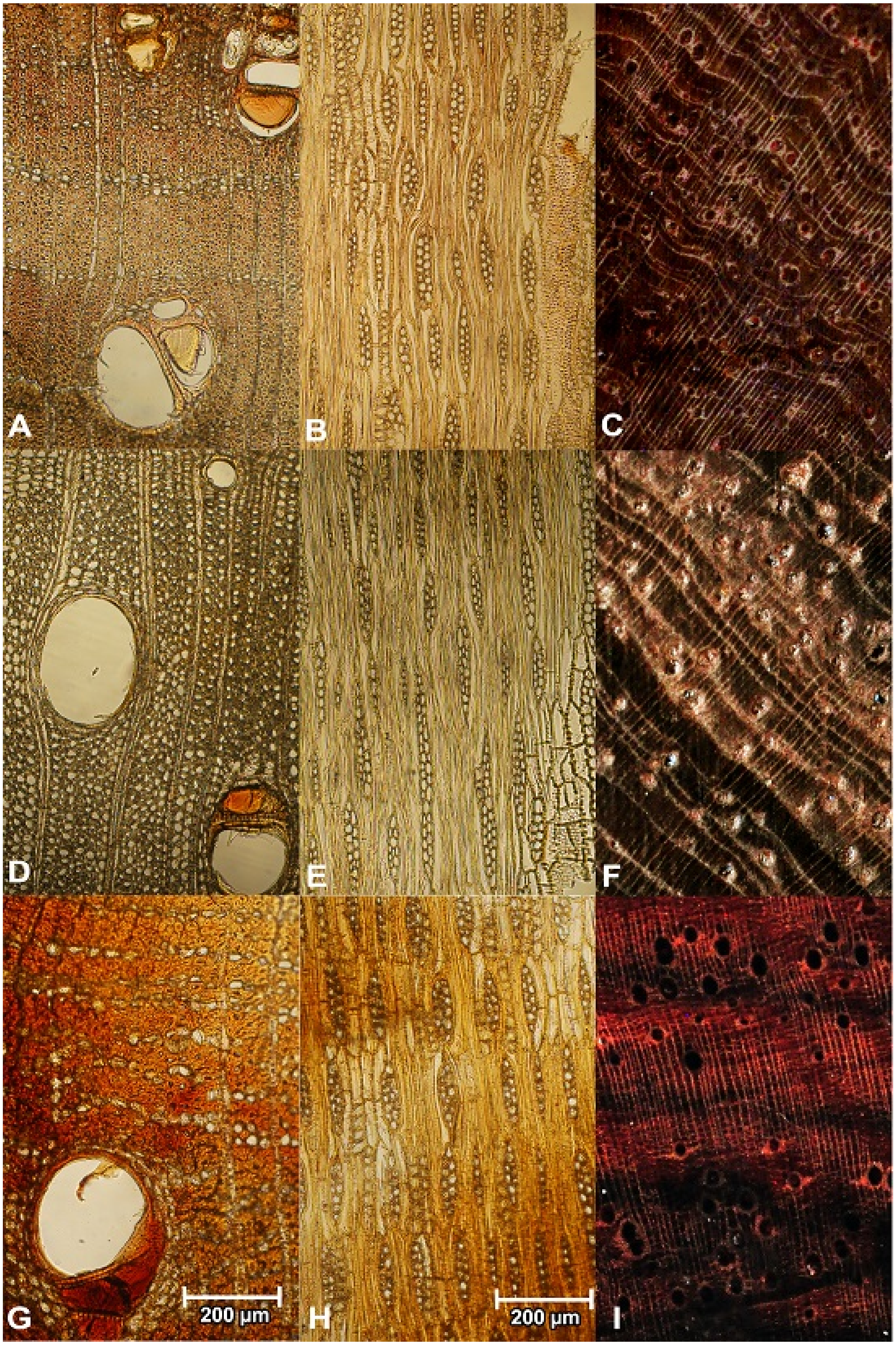

FIGURE 4. A-C *Dalbergia granadillo*. D-F. *Dalbergia palo-escrito*. G-I. *Dalbergia retusa*. A, D, G, Cross section showing marginal, diffuse-agreggate axial parenchyma, alliform confluent and vasicentric axial parenchyma. B, E, H. Tangential section showing stratified structure. C, F, I. Cross surfaces at 4X magnification showing diffuse-porous and semi-ring-porous in *D. retusa*.

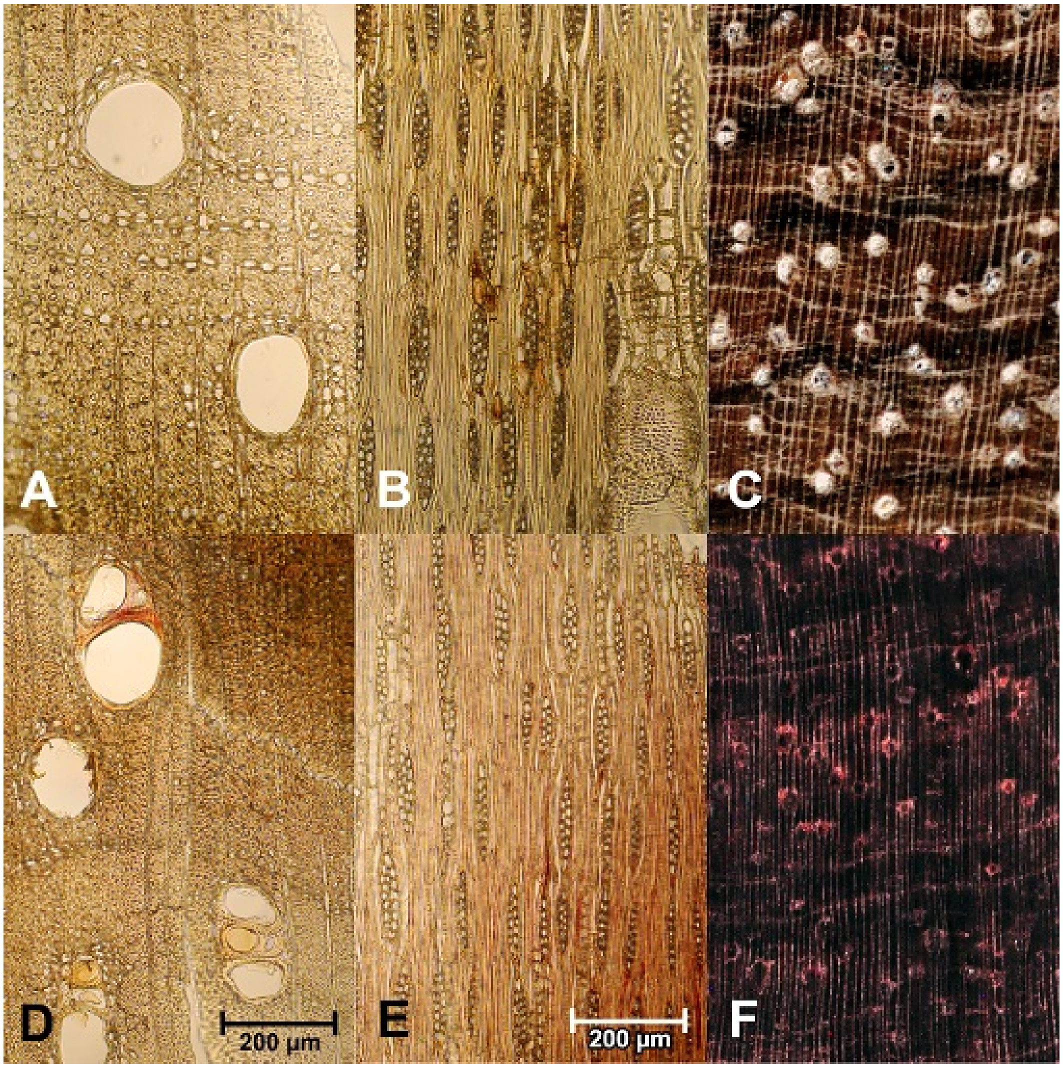

FIGURE 5. A-C *Dalbergia stevensonii*. D-F. *Dalbergia congestiflota*. A, D, Cross section showing diffuse-agreggate axial parenchyma. alliform and aliform confluent axial parenchyma. B, E. Tangential section showing stratified structure. C, F. Cross surfaces showing diffuse-porous at 4X magnification. Solid line = 200 µm

Tables 1 and 2 show that tangential vessel diameters are within features 42 and 43 of the IAWA Committee (Wheeler *et al.*, 1989). Fibre wall thickness in Malinalco-Teponaztli and *D. palo-escrito* fall within feature 68, and similarly for the others; fibre length fall within feature 72 and rays size in feature 97 in both groups (Wheeler *et al.*, 1989).

Similarity between teponaztlis and known species of *Dalbergia*

Discriminant analysis shows that the percentage of uniseriate rays and the percentage of partially biseriate rays constitute the variables that conform the first discriminant function that have the highest values in the eigenvectors, meanwhile the second function is formed by the fibre wall thickness (Table 3). This explains 84% of the variability observed noting that both functions are significant ($p <$ 0,00001) (Fig. 6). The Wilk's Lambda for the first two eigenfunctions (or canons) is low (0,011541) and significant ($p <$ 0,0001).

The purpose of the analysis was to find the affinity between the woods used to manufacture the teponaztlis from the Mexica Hall and of the five known species of genus *Dalbergia*. The analysis shows that the selected

TABLE 1. Mean values and standard deviation of measured features from woods of the three teponaztlis.

Feature			*Tlaxcala*	*Cipactli*	*Malinalco*
Vessel elements (µm)	Radial diameter		172 ± 59	318 ± 60	186 ± 23
	Tangential diameter		142 ± 33	223 ± 39	141 ± 22
	Wall thickness		7,39 ± 3,38	8,82 ± 2,01	6,20 ± 1,58
Fibres (µm)	Diameter		27,1 ± 7	21 ± 3	18 ± 2
	Wall thickness		4 ± 0,4 thin	7 ± 1,1 thin to thick	7,1 ± 1,3 thin to thick
	Length		1264,27 ± 183,82	924,8 ± 167,15	1072 ± 122,68
Rays	Height (µm)	uniseriate	95 ± 18	138,4 ± 17	135 ± 11
		biseriate	123 ± 17	158 ± 14	159 ± 18
		triseriate	125 ± 15	149 ± 27	157 ± 13
		partially biseriate	126 ± 12	162 ± 13	142 ± 20
	Width (µm)		26,4 ± 9,03	26,67 ± 9,4	24,53 ± 9,78
	Cell number		7,2 ± 2,89	8,6 ± 2,44	9,4 ± 2,75
	% Uniseriate (mm^{-1})		25	46	36,1
	% Biseriate (mm^{-1})		43	24	51,2
	% Triseriates (mm^{-1})		8,4	8,6	9,4
	% Partially biseriate (mm^{-1})		22	20	3,1
	Total number (mm^{-1})		13 ± 1,8	10 ± 1,46	11 ± 1,36

TABLE 2. Mean values and standard deviation of measured features from known species of *Dalbergia* (*n* = 30 - 50).

Feature			D. granadillo	D. palo-escrito	D. retusa	D. stevensonii	D. congestiflora
Vessel elements (µm)	Radial diameter		184 ± 30	265 ± 40	261,7 ± 30	223,7 ± 30	171 ± 30
	Tangential diameter		163 ± 25	210 ± 36	237 ± 25	200 ± 30	161,2 ± 28
	Wall thickness		10 ± 1,2	8,5 ± 2	9,6 ± 2,5	8,3 ± 1	10 ± 1,2
Fibres (µm)	Diameter		34,5 ± 4,8	14,8 ± 2,34	18,4 ± 3,6	14 ± 1,2	12,8 ± 1,7
	Wall thickness		11,6 ± 1,2 thin to thick	3,2 ± 0,78 thin	6 ± 1 thin to thick	4,9 ± 1 thin to thick	4,4 ± 0,6 thin to thick
	Length		955,9 ± 60	937 ± 60	1062 ± 57	1155 ± 40	1036 ± 109
Rays	Height (µm)	uniseriate	100,9 ± 15	100,2 ± 29	142 ± 20	120 ± 10	133,8 ± 10
		biseriate	141,6 ± 13	167 ± 4,5	139 ± 3	153 ± 16	145 ± 16
		triseriate	138,9 ± 15	181 ± 25	144 ± 15	160 ± 16	157 ± 7
		partially biseriate	117,6 ± 20	125 ± 8,9	133 ± 15	143 ± 17	145 ± 13
	Width (µm)		19,5 ± 2,5	24 ± 3	22 ± 3	19 ± 2,5	19,5 ± 2,7
	Cell number		7 ± 1	6 ± 1	7 ± 1	7 ± 1	7 ± 1
	% Uniseriate (mm^{-1})		19	17,4	11,7	2	10,5
	% Biseriate (mm^{-1})		65	63,1	54	31	73,6
	% Triseriates (mm^{-1})		12	14,5	31	67	14,03
	% Partially biseriate (mm^{-1})		2,6	4,8	2,6	1	1,7
	Total (mm^{-1})		11 ± 1,1	10 ± 1,1	9 ± 0,89	9 ± 1	11 ± 1,4

TABLE 3. Structure matrix of the DMA with the eigenfunctions that explain the separation of the groups. The values represent the correlation between the variables and the discriminant functions extracted. The values of the variables that contribute most to the separation between groups for each discriminant function are shown in bold (r = 0,86).

Variable	*Canon 1*	*Canon 2*
Percentage of uniseriate rays	**-0,951772**	-0,073235
Percentage of biseriate rays	-0,835247	-0,121341
Percentage of triseriate rays	-0,829081	-0,097489
Percentage of parcially biseriate rays	**-0,913672**	-0,095538
Fibre wall thickness	0,455877	**2,221607**

anatomical wood characters of the Tlaxcala-Teponaztli overlaps those of *Dalbergia-palo escrito*, while those of the Malinalco-Teponaztli extend over the values of *D. granadillo*. It is noteworthy that the values of the Cipactli are close to those of the Malinalco instrument.

Acoustics

The average time signals of ten recordings of the two tones of the Teponaztli-Tlaxcala, played with the under-side cavity closed, are shown in figures 7 A-B, while the frequency power spectra, each of them an average of ten squared magnitude FFT spectra, are shown in figure 7B. Time signals and frequency power spectra for the Teponaztli-Tlaxcala, played with the under-side cavity open, are shown in figures 7 C-D. Oscillation frequencies, spectral widths, damping ratios, and reverberation times of the single damped tonal component observed in each frequency spectrum are shown in table 4 and table 5 for the teponaztlis with the underside cavity closed and open, respectively. Tonal pitches relative to the standard equal temperament musical scale, micro-tonal deviations in cents, the corresponding musical intervals in cents, and typical tone durations in seconds are shown in table 6.

Discussion

Identifying the wood used for the manufacturing of the teponaztlis of this study is relevant because it demonstrates a historical preference in the selection of the genus *Dalbergia* as material and because it was used for the representation of important deities or characters that illustrate the visual environment of Mexican culture.

It is clear that the use of this wood before and during the sixteenth century bridges the Mexican manufacturing tradition of the construction of ancient and modern musical instruments, exemplified nowadays in the use of pegs, fingerboards and guitar sound boxes of high quality sound and aesthetics, as well as in the manufacturing of selected xylophone bars (D. Guzmán, personal communication, 2017, August 14). In this sense a profound knowledge is made evident of the aesthetic and physical properties of this particular timber taxon.

The wood of this genus has qualities such as workability, density and resistance to deterioration on one hand, and macroscopic characteristics such as color, texture and grain, on the other, that provide high values of strength and aesthetics that make it appreciated and, unfortunately, over-exploited, which have even led some species such as *D. congestiflora*, *D. stevensonii*, *D. retusa* or *D. palo-escrito* endangered, to the brink or risk of extinction in Mexico and Central America (Comisión Nacional para el Conocimiento y Uso de la Biodiversidad [Conabio], 2015; Cervantes-Maldonado, 2016).

Regarding species identification for this genus, it is a subject that causes much conflict since its aesthetic characteristics are tremendously similar and according to Zobel and Buijneten, (1989) color can be determined by the type of soil or region where it has grown or aged (Hoadley, 1990). Espinoza, Wiemann, Barajas–Morales, Chavarria, and McClure (2015) found that by performing a Kernel Discriminant Analysis of variables such as phenol type and wood chemistry they were able to find differences between known species of this genus. However, in this case, this type of analysis could not be used because of the required sample size.

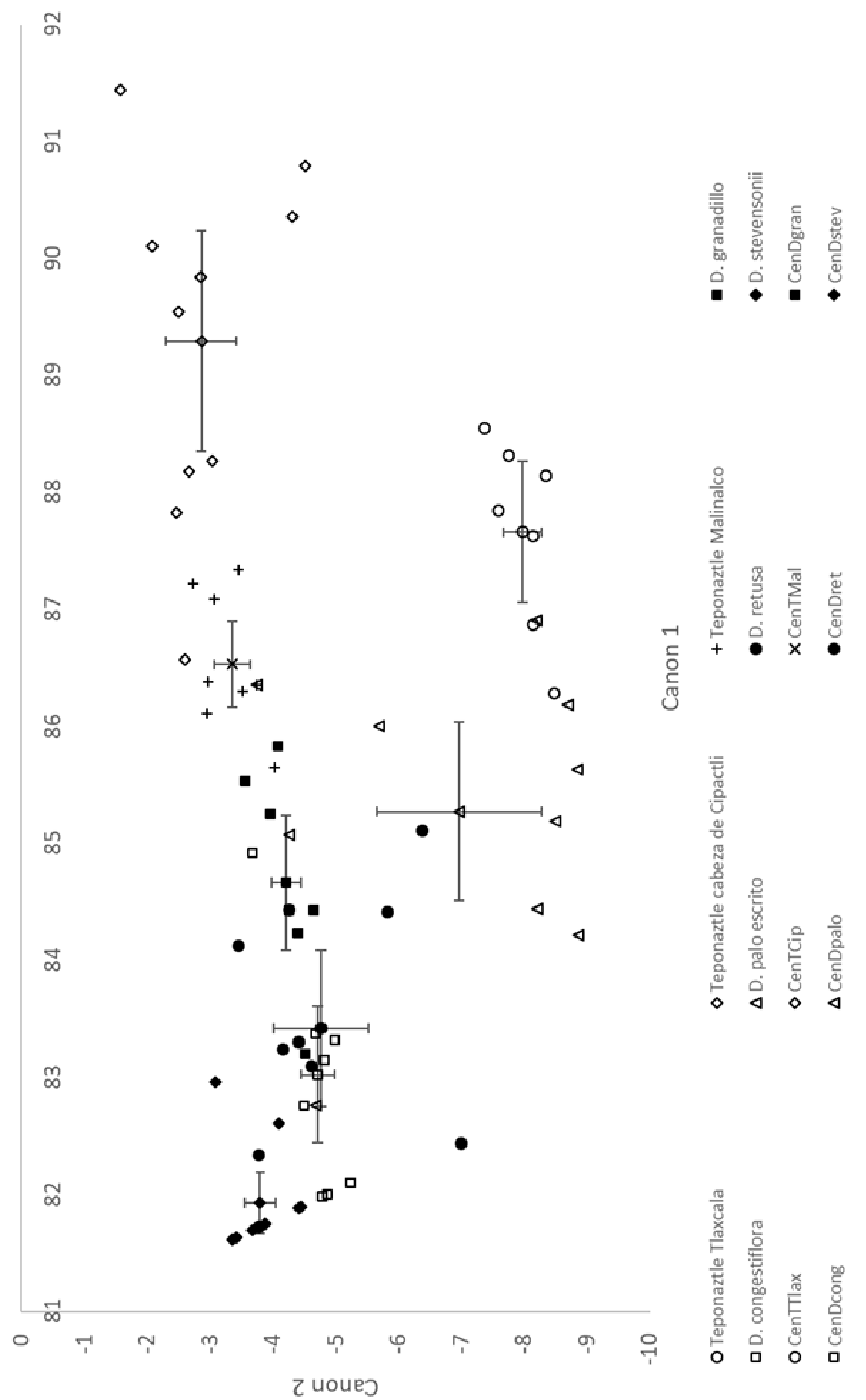

FIGURE 6. Dispersion diagram obtained from the 488 values from 8 samples and 5 variables in a discriminant space defined by the first two functions of the DMA that explain 84% of the matrix variability. Canon 1 (58%) and Canon 2 (26%).

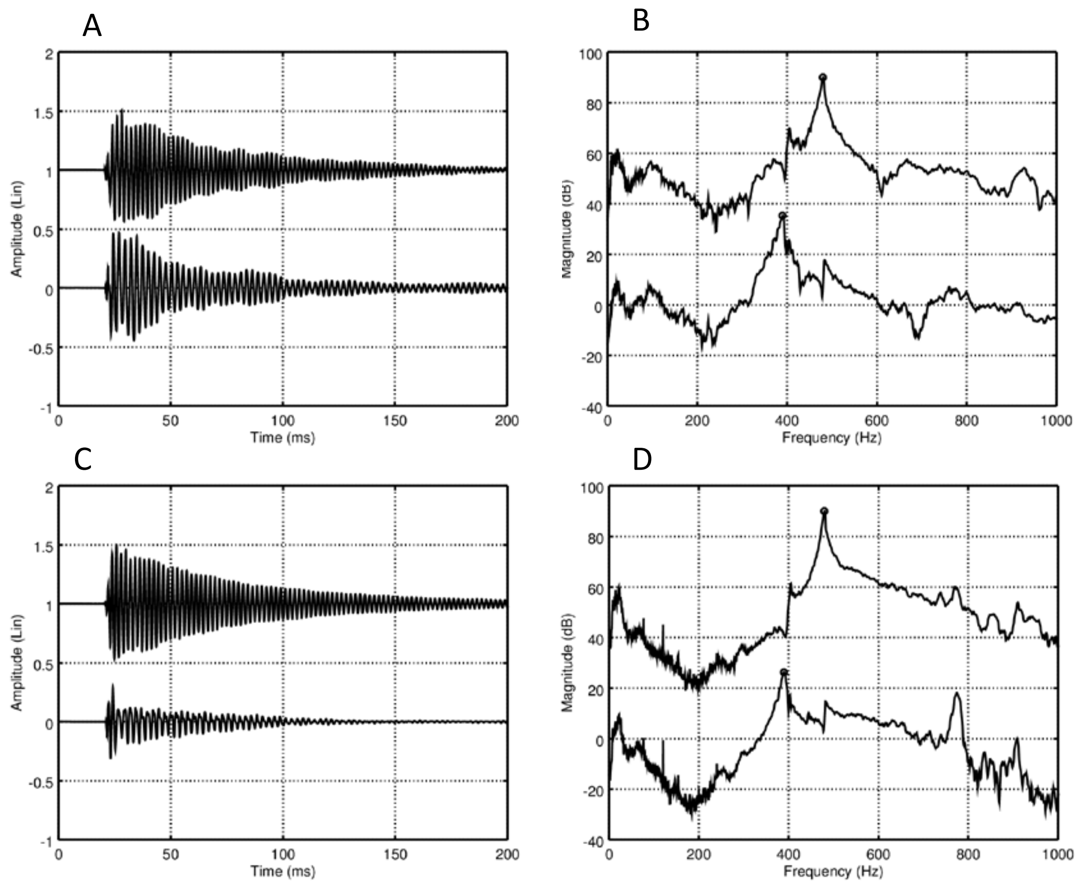

FIGURE 7. Tlaxcala- Teponaztli. A, B. Under-side closed. C, D. Under-side open. A, C. Time signals: high tone (above), low tone (below). B, D. Frequency spectra: high tone (above), low tone (below).

TABLE 4: Mean values and standard deviations of the acoustic parameters for the low and high pitch teponaztli tones, with under-side closed.

Teponaztli	*Pitch*	*f_0 [Hz]*	*Δf_0 [Hz]*	*$\Delta f_0/f_0$ [%]*	*T_{60} [s]*
Cipactli	Low	142,41 ± 0,15	5,95 ± 0,39	4,17 ± 0,28	0,739 ± 0,049
	High	222,22 ± 0,08	3,04 ± 0,05	1,37 ± 0,02	1,443 ± 0,026
Malinalco	Low	109,92 ± 0,07	2,67 ± 0,22	2,43 ± 0,20	1,644 ± 0,133
	High	167,00 ± 0,02	2,89 ± 0,02	1,73 ± 0,01	1,517 ± 0,011
Tlaxcala	Low	389,62 ± 0,37	11,24 ± 0,76	2,89 ± 0,20	0,391 ± 0,026
	High	479,58 ± 0,32	6,65 ± 0,51	1,39 ± 0,11	0,660 ± 0,050

TABLE 5. Mean values and standard deviations of the acoustic parameters for the low and high pitch teponaztli tones, with under-side open.

Teponaztli	*Pitch*	*f_0 [Hz]*	*Δf_0 [Hz]*	*$\Delta f_0/f_0$ [%]*	*T_{60} [s]*
Cipactli	Low	141,84 ± 0,17	5,54 ± 0,43	3,91 ± 0,31	0,793 ± 0,062
	High	221,59 ± 0,06	2,23 ± 0,07	1,01 ± 0,03	1,971 ± 0,059
Malinalco	Low	110,18 ± 0,04	2,19 ± 0,09	1,98 ± 0,08	2,009 ± 0,079
	High	167,20 ± 0,30	2,52 ± 1,33	1,51 ± 0,80	1,743 ± 0,917
Tlaxcala	Low	389,55 ± 0,17	9,21 ± 0,27	2,36 ± 0,07	0,477 ± 0,014
	High	479,41 ± 0,28	6,49 ± 1,16	1,35 ± 0,24	0,677 ± 0,121

TABLE 6. Tonal pitches with deviations in cents, intervals in cents, and tone durations in seconds, with the under-sides of the teponaztlis closed and open, respectively.

Teponaztli	*Condition*	*Low pitch*	*Duration [s]*	*High pitch*	*Duration [s]*	*Interval*
Cipactli	Closed	$C\#_3$ + 40	0,739	A_3 + 12	1,443	+ 772
	Open	$C\#_3$ + 47	0,793	A_3 + 17	1,971	+ 770
Malinalco	Closed	A_2 + 03	1,644	E_3 + 25	1,517	+ 722
	Open	A_2 - 01	2,009	E_3 + 23	1,743	+ 724
Tlaxcala	Closed	G_4 - 11	0,391	$A\#_4$ + 49	0,660	+ 359
	Open	G_4 - 11	0,477	$A\#_4$ + 49	0,677	+ 360

Although Espinoza, *et al.* (2015) indicate that it is fairly difficult to separate species of *Dalbergia* using only anatomical characteristics, we considered that by reviewing ray width and calculating the percentage of each uni. bi, tri and partially biseriate rays, it was possible to find differences between teponaztlis and known species. These authors show a statistical analysis where *D. retusa* and *D. granadillo* form a group and *D. stevensonii* another one. Our Multivariate Analysis shows that values of *D. retusa* and *D. congestiflora* overlap forming a group, though near to the *D. granadillo* centroid, yet significantly different from this last one. In our analysis *D. stevensonii* is separated similar to the work of Espinoza, *et al.* (2015).

The tendency of the analyses of Tlaxcala-Teponaztli shows a proximity to *D. palo-escrito*, and also similar trends in Malinalco-Teponaztli to the group *D. retusa-D. congestiflora*. We consider that although the Cipactli–Teponaztli centroid is significantly different to that of Teponaztli-Malinalco, a proximity can be appreciated between them. As an exploratory experience, using Multivariate Analysis it was possible to separate the three instruments, which probably highlights the variability among these wood species but does not solve with certainty whether they are distinct species even though there is an evident proximity. The sample size used to analyze wood anatomy of teponaztlis entails a discussion about the importance of identifying the constituent materials of historical cultural assets, in the sense that restoration-sampling criteria limit the size and number of samples.

On the other hand it is known that species of rosewood are considered heavy woods, since it has been reported that *Dalbergia nigra* has a specific gravity of 0,84 (Meier, s/f) and up to 1,2 – 1,25 for *Dalbergia melanoxylon* (Seely, 2017). Density values have been recently reported for *D. congestiflora* around 0,9 g/cm^3 – 1,19 g/cm^3 and for *D. granadillo* 1 g/cm^3 – 1,1 g/cm^3, which can be both considered as heavy (Morales, 2016). It is being pointed out that density could be a factor that influences acoustic features such as the radiation coeficient, the dynamic modulus and the damping value in xylophones (Wegst, 2006). This last feature is inversely related to the extractive content and wood density (Traoré *et al.*, 2010), which could possibly have been recognized as criteria of selection by 16th century Aztec luthiers. Although these instruments cannot be considered strictly as a xylophone but as an idiophone which had to endure the struck of the mallets on the keys, the intensity of the blow and its continuous use for years had to prove the acoustic and mechanical quality of the selected woods. In this sense, these wood species have lasted to be recognized as appropriate for the production of blow instruments to this day.

The acoustic analyses revealed that musical intervals between the low and high pitch tones of the three instruments were found between slightly under a major third (four semitones, or 400 cents), and slightly over a fifth (seven semitones, or 700 cents). They differ to some degree from those reported by Castañeda and Mendoza (1991). The musical intervals that were found in the present study do not exactly correspond to a particular tuning scheme (harmonic or natural), neither to equal temperament, or to other conventional Western musical scales. Teponaztli tones are of slightly shorter duration, and of higher sound intensity, when the under-side is closed than when the under-side is open. Tonal pitches are virtually not affected by whether the under-side is closed or open. When one of the tones is played, sound spectra show that, alongside the strong damped sound produced by that tone, some faint sound is also produced by the other (un-played) tone. There is some additional faint sound produced by the (also un-played) lateral parts of the body, something that is more evident when the under-side is open, as shown in figure 7 in the frequency region from 700 Hz to 1000 Hz.

It is interesting here to note that a previous study by Castañeda and Mendoza (1991) carried out on these very same instruments, indicates the musical intervals as a minor third (300 cents) for the Tlaxcala instrument, and a fifth (700 cents) for the other two instruments. These authors also report tonal pitches that are one or two octaves higher than those found in the present study. However, apart from these differences, which are understandable given that Castañeda and Mendoza (1991) probably estimated the tonal pitches by ear, and that they give no indication of their tuning reference, the present study matches theirs in broad terms.

Conclusions

The teponaztlis were made using the beautiful tropical rosewood (*Dalbergia* spp.). Percentages of ray seriation and fibre wall thickness were used as variables with which teponaztlis and known species of *Dalbergia* formed separate groups in a discriminant space. The wood features of the Tlaxcala-Teponaztli extended over *D. palo-escrito* and the Malinalco-Teponaztlis over *D.granadillo*. Values of Cipatlli-Teponaztli shows adjacency to the Malinalco instrument. The results showed that these instruments may have been built with both species of *Dalbergia*, which is striking, given that it is known that the wood of these species has been used for decades in the development of handicrafts, acoustic instruments, keys for xylophones and other accessories which is one of the reasons they are currently facing extinction in Mesoamerica.

In the acoustic analysis, musical intervals between the low and high pitch tones of the three instruments were found between slightly under a major third (four semitones), and slightly over a fifth (seven semitones). These intervals do not correspond exactly to conventional Western tunings. Teponaztli tones are of slightly shorter duration, and of higher sound intensity, when the under-side cavity is closed than when it is open; while tonal pitches remain virtually unaffected. Sound spectra obtained when one of the tones is played, also show some faint sound produced by the other (un-played) tone. There is also some faint sound produced by the lateral portions of the body, especially when the under-side cavity is open.

This study reveals that Castañeda and Mendoza reported incorrect wood identification and some inaccurate acoustical characteristics for the three teponaztlis. These new results contribute an important update to the previously documented information of these instruments, that we consider relevant for future historical and anthropological studies of these artifacts.

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References

Brancheriau, L., Baillères, H., Détienne, P., Gril, J., & Kronland R. (2006). Key signal and wood anatomy parameters related to the acoustic quality of wood for xylophone-type percussion instruments. *Journal of Wood Science*, *52*(3), 270-274. doi: 10.1007/s10086-005-0755-2

Castañeda, D. V., & T. Mendoza. (1991). *Instrumental precortesiano: instrumentos de percusión, Tomo I*. México: Universidad Nacional Autónoma de México.

Cervantes-Maldonado, A. (2016). La conservación del granadillo en México, una carrera contra el tiempo. Conabio. *Biodiversitas*, *128*, 6-11.

Comisión Nacional para el Conocimiento y Uso de la Biodiversidad [Conabio] (2015). *Taller para la evaluación del riesgo de extinción de las Dalbergias maderables de México en el marco de la NOM-059-SEMARNAT-2010*. Retrieved of http://conabioweb.conabio.gob.mx/webservice/dalbergias/Dalbergia_granadillo.pdf

Cooper Clark, J. (Ed. and trans.). (1938). *Codex Mendoza. The Mexican manuscript known as the "Collection of Mendoza" and preserved in the Bodleian Library*. London: Waterlow & Sons Ltd.

Orozco y Berra, M. (1975). *Códice Ramírez: Manuscrito del siglo XVI intitulado "Relación del origen de los indios que habitan esta Nueva España, según sus historias"* (2a ed.). Ciudad de México: Porrua.

Universidad Nacional Autónoma de México (2012). *Gran Diccionario Náhuatl*. Retrieved of http://www.gdn.unam.mx. Consulted on November 2017.

Estrada, J. (1984). *La música de México I Historia 4. Periodo Nacionalista*. México: Universidad Nacional Autónoma de México.

Estrada O., A. C. (2010). Dialogismo y entidades en el mundo nahua. *Estudios Mesoamericanos. Nueva época*, *9*, 17-34. Retrieved of http://www.iifilologicas.unam.mx/estmesoam/uploads/Volúmenes/Volumen 9/estrada-dialoguismo-entidades-nahua.pdf

Espinoza, E. O., Wiemann, M. C., Barajas–Morales, J., Chavarria, G. D., & McClure, P. J. (2015). Forensic analysis of CITES-protected *Dalbergia* timber from Americas. *IAWA Journal*, *36*(3), 311-325.

Hintze, J. (2009). NCSS (version 2007) [Software]. Kaysville, Utah: NCSS, LLC.

Hoadley, B. (1990). *Identifying Wood. Accurate results with simple tools*. USA: The Taunton Press.

NC State University (2004). *Inside Wood database*. Retrieved of http://insidewood.lib.ncsu.edu/

Wheeler, Baas, & Gasson (Eds.) (1989). IAWA list of microscopic features for hardwood identification. *IAWA Bulletin n.s.*, *10*(3), 219–332.

Johansen, D. A. (1940). *Plant michrotechnique*. Nueva York: McGraw-Hill.

Meier, E. (s/f). *The Wood Data Base*. Retrieved of http://www.wood-database.com/brazilian-rosewood/

Mitsuko, A., Bailleres, H., Brancheriau, L., Kronland-Matinet, R., & Ystad. S. (2007). Sound quality assesment of wood for xylophone bars. *The Journal of the Acoustical Society of America*, *121*(4), 2407-2420.

Morales H., F. (2016). Estudio anatómico y botánico de: *Dalbergia congestiflora* Pittier, *D. granadillo* Pittier y *D. calcyna* Benth. Tesis de Licenciatura. Morelia, Michoacán: Universidad Michoacana de San Nicolás de Hidalgo.

Newland, D. E. (1989). *Mechanical vibration analysis and computation*. Essex, England: Longman Scientific and Technical.

Norton, M. P. (1989). *Fundamentals of noise and vibration analysis for engineers*. Cambridge, England: Cambridge University Press.

Ochoa, J. (2002). *Catálogo de instrumentos musicales y objetos sonoros del México indígena*. México: Fondo Nacional para la Cultura y las Artes.

Randall, R. B. (1987). *Frequency analysis* (3a ed.). Denmark: Brüel & Kjaer.

Sahagún, F. B. de. (1975). *Historia general de las cosas de Nueva España*. México: Porrúa.

SAS Institute Inc. (2007). JMP ® (version 7.0) [Programa de cómputo]. SAS Institute Inc.

Seely, O. (2017). *Physical properties of common woods*. Retrieved of http://www5.csudh.edu/oliver/chemdata/woods.htm

Tatsuoka, M. M. (1970). *Discriminant analysis. The study of group differences*. USA: IPAT.

Traoré, B., Brancheriau, L., Perre, P., Stevanovic, T. & Diouf, P. (2010). Acoustic quality of vène wood (*Pterocarpus erinaceus* Poir.) for xylophone instrument manufacture in Mali. *Annals of Forest Science*, *67*(8), 815-822. doi: 10.1051/forest/20100

Wegst, U. G. K. (2006). Wood for sound. *American Journal of Botany*, *93*(10), 1439–1448. doi: 10.3732/ajb.93.10.1439

Zobel, B. & Van Buijtenen, B. (1989). *Wood variation: its causes and control*. New York, USA: Springer Verlag.

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