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Hidden behind the mask: An authentication study on the Aztec mask of the Museum of Ethnography, Budapest, Hungary

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ABSTRACT

Turquoise covered mosaic objects – especially masks – were attractive components of treasures transported to Europe from Mexico after the fall of the Aztec Empire in the 1500s. According to our present knowledge, the mosaic masks were manufactured for ritual purpose. The main material of mosaics, the turquoise was a high-prestige semi-precious stone among Mexican native people. During the 20th century, such objects derived both from illegal treasure hunting and documented archaeological excavations. The aim of our research was the authentication of a turquoise covered Aztec wooden mask, which presumably originates from the Tehuacán Valley, Mexico and exchanged by the Museum of Ethnography, Budapest, in 1973. The detailed and complex analytical investigation of the mask is a curiosity. To reveal the origin of the object, UV photographs were taken, the wooden base was subjected to biological studies and C-14 dating, the organic glue fixing the tesserae and the inorganic mosaic tesserae were investigated by non-destructive chemical, FT-IR and Raman spectroscopic methods. Our investigations determined that the mask of the Museum of Ethnography was made of an alder species of tree and its age is AD 1492–1653. The light-coloured covering mosaic lamellae were identified as alabaster and claystone. Comparing the turquoise tesserae cover with reference materials, their chemical composition has been clearly differentiated from most of the well-known turquoise sources of the US Southwest. Based on our results, the Aztec mask of the Museum of Ethnography proved to be an original piece of art from the 15th-17th century.

1. Introduction

Turquoise (in nahuatl (Aztec language) *xihuitl)*, the 'stone from the sky', was one of the highest-prestige materials in the pre-Hispanic cultures, especially in the Aztec period (1325–1521 AD). It was attributed to the Sun, the fire, the meteors and the war. Its special appreciation in the Aztec culture is indicated by the turquoise-covered regalia (crown–*xiuhuitzoli*, nose ornament–*yacaxihuitl*) [1] connecting the Aztec rulers to the parent of all gods, Xiuhtecuhtli, the god of fire [2].

Compared to the jade which was popular since the Olmec culture (ca. 1500–400 BC), turquoise became widespread from 900 AD. Since turquoise is formed in tiny veins, its small-sized fragments were applied as tesserae fixed on wooden support by the Post-Classic artisans.

Various objects (e.g., masks, shields/discs) covered with turquoise tesserae were widespread used in the Aztec Empire in the time of European conquest (1519–1521). Thus, in the first half of the 16th century several mosaic objects reached Italian private collections and later on, European museums. The North American and European museums acquired another group of Mexican mosaic objects from the end of 19th century [3], especially in the 1960s and 1970s. Since neither of these objects were uncovered in scientific excavations, there is no information about their provenance and cultural contexts. Such a mask was exchanged by the Museum of Ethnography of Budapest, Hungary in 1973 with Everett Rassiga, an American art dealer (Fig. 1). The inventory book of the museum contains only the most basic information: the place of origin is

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Mexico, its material is wood, turquoise and shell. In order to shed light on the missing data, the age, the provenance, and cultural context of the object, museological and material studies were performed. Museological research revealed that between 1966 and 1978 E. Rassiga sold similar masks and other related finds (discs, ear spools and plaques covered by turquoise and shell, sandals, cotton textiles, clay pots, stone beads, baskets, mats, reed bundles, ropes, bark clothes and frameworks for bark clothes, corn cobs and shells) to the Nelson-Atkins Museum of Art in Kansas City, and The Textile Museum in Washington, which came to light from looted caves situated on the border area of the states of Oaxaca and Puebla, Mexico. In the same years, a very similar ensemble of finds from the same region was sold or exchanged by Émile Deletaille, another art dealer associated with E. Rassiga, to the Royal Museums of Art and History in Brussels, the Ethnologisches Museum in Berlin and the Musée International du Carnival et du Masque in Binche [4]. By analysing the findings in Brussels, Julia Montoya [5] showed that the objects formed sacrificial and/or mortuary bundles deposited in caves where masks were put on these bundles. Based on the composition of the ensemble of finds and their identical provenance region, it can be assumed that the mosaic mask of the Museum of Ethnography, Budapest (hereinafter abbreviated as the 'Budapest mask') may have been part of such a bundle.

In the next years several other mosaic masks and shields/discs came to light from the cave at Santa Ana (close to Teloxtoc, Puebla, Mexico) [6], the Cheve Cave at Teotitlán de Flores Magón (Oaxaca, Mexico) and from Cueva de Ejutla [7,8], but unfortunately none of them were excavated by archaeologists. Finally, archaeologists have been able to excavate and reconstruct such pieces in Tula [9] and the Templo Mayor in Mexico City [10] since the 1990s.

Based on the above information, it has museological importance to authenticate the 'Budapest mask' and to exclude the possibility of a modern fake. This was verified by scientific methods in the following steps: examination of (1) the age, (2) and materials composing the mask, and (3) getting information about the provenance of these materials.

As the most characteristic component of mosaic objects, turquoise deserves special attention. As such, it requires detailed knowledge on its mineralogy and chemistry. Turquoise is an opaque, blue-to-green mineral that is formed during the weathering of copper deposits having igneous (usually porphyric) (see in detail e.g. in [11] and references therein) or rarely sedimentary origin [12]. The chemical formula of turquoise is $CuAl_6(PO_4)_4(OH)_8{\cdot}4H_2O$. In its triclinic mineral, Cu often is substituted by Fe or Zn, while Al is substituted by Fe [13,14]. With such substitution, a variety of minerals, i.e. the 'chemical turquoise group' (for explanation see e.g. [15]), can be formed, such as aheylite: $(Fe,Zn)Al_6(PO_4)_4(OH)_8{\cdot}4H_2O$, chalcosiderite: $Cu(Fe,Al)_6(PO_4)_4(OH)_8{\cdot}4H_2O$, faustite: $(Zn,Cu)Al_6(PO_4)_4(OH)_8{\cdot}4H_2O$, planerite: $Al_6(PO_4)_2(OH)_8{\cdot}4H_2O$. As the ratio of the above minerals may vary from one quarry to another, Fe/Cu, Zn/Cu or Fe/Al mass ratios might be characteristic for the provenance of the turquoise. It is also known [16] that CuO is responsible for the blue colour, while Fe_2O_3 is responsible for green colour in turquoise. Furthermore, greenish blue and bluish green samples can be distinguished from each other on the basis of their Al_2O_3 and P_2O_5 contents. In addition, fading of turquoise might be due to the loss of colouring cations (Cu, Fe) and relative enrichment in Zn [10].

Despite the defined mineralogy and mineral chemistry of turquoise, numerous chemical elements can be present in this mineral deriving from the host rock during the formation process, thus varied chemistry is expected in specimens from the same mine at different depths [17,18]. Various studies (e.g. [11,17,19]) claimed the role of chemical composition in provenance determination of turquoises, especially regarding the so-called fingerprinting trace elements like rare-earth elements (e.g. [20–22]). Indeed, trace elements are sensitive indicators of the formation circumstances, e.g. chemistry of the supergene fluids present during the mineralization, or weathering [19]. According to [15,23,24], the concentrations of Cu, Fe, Zn, Al, As, Sr, and Ba might be used as fingerprinting elements characteristic for the provenance of turquoise.

On the American continent (Fig. 2), the Southwest United States, namely Arizona, California, Colorado, Nevada and New Mexico are the most significant source areas for turquoise [11,25,26]. Mexican sources exist in Baja California, Sonora, Chihuahua, Coahuila and Zacatecas [26–28] but our knowledge is limited on these localities. South American sources are not mentioned here being out of the scope of this study. All these sources – except for Zacatecas – are more than 2000 kms far from Central Mexico, thus no possible local or even regional turquoise sources are known in the territory of the Aztec Empire.

2. Materials: description of the mask

Based on the macroscopic observations, the wood support of the 'Budapest mask' was carved from a single piece of a 0.8–2.2 cm thick softwood following the shape of the human face. Front side of the wood support is a convex, smooth surface appropriate for carrying the tesserae (Fig. 1a) while the back side is a concave, uneven surface with clear vertical traces of carving (Fig. 1b). Eye sockets are larger than necessary to look out of the mask, the edges of the holes are thinned. Similarly, the mouth is also larger compared to the ratios of a human face with a small and flat rectangular-shaped perforated part. The largest part of the front side is mostly covered with a

Fig. 1. Mosaic mask of the Museum of Ethnography (Budapest, Hungary) (inventory no. 74.2.9). (a) front view, (b) rear view (1–2: sampling point, 3: cleaned wooden surface).

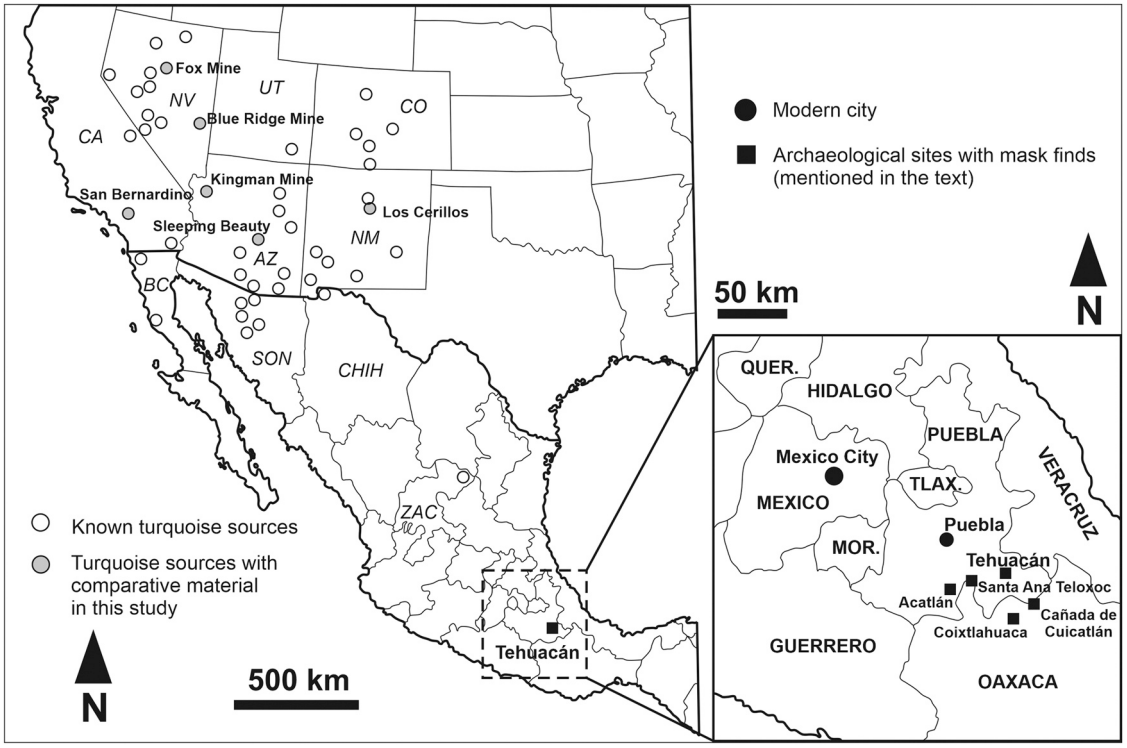


Fig. 2. Territory of Mexico and the USA Southwest with archaeological sites providing turquoise covered masks (in the inlay) and the turquoise sources related to this study and mentioned in the text (the map is compiled based on [11,25–28]).

brown, adhesive-like material which fixed the mosaic elements (tesserae, lamellae) to the surface. There are four regions of the front side which are not covered with mosaic: 2.7 cm diameter circles on the two temples, eyebrows, nostrils and around the mouth. The temples are the sole area having black-coloured surface, the other three regions are painted. There is black pigment on the eyebrows. The nostrils and the upper side of the mouth were painted in red.

There are two types of mosaic elements: (1) light-coloured lamellae framing the face, the mouth and the eyes, and covering the nose; and (2) grey, bluish green, greenish blue, blue tesserae filling in four regions (forehead, two cheeks, chin) among the light-coloured frames. Light-coloured lamellae are often cracked but well-fixed in the adhesive, except for some pieces on the edge of the mask where those are missing. Density of blue-green tesserae per cm^2 is 55–70 pieces. Those are missing in several places.

In its present state, the 'Budapest mask' is vertically broken into two pieces. After the break, the two parts could be deposited in separated places since the larger part has darkened wooden back while the smaller part preserved its original light wood colour (Fig. 1b). Darkening of the larger part can be easily removed by cleaning with distilled water (see Sample 3 in Fig. 1b). The broken pieces were stuck together with an imperfect fit which supports the idea of an ancient break and a modern repair. Despite the fact of breaking, the well-preserved wooden part of the objects raises the suspicion that the object was manufactured (1) by mounting mosaic elements deriving from archaeological context on a modern wood support; or (2) as a modern counterfeit.

During this study, altogether 50 points of the 'Budapest mask' were analysed by non-invasive and non-destructive methods, including the green or bluish-green tesserae, the light-coloured lamellae, as well as the wood support of the mask with different kinds of unidentified layers on it. Two wood samples and five pieces of the adhesive were removed from the object for analysis. In addition, five weakly adhered tesserae were removed for further analyses. The analysed tesserae on the mask are typically 1–2 mm and of a thickness of less than 1 mm. The analytical results have been compared with those obtained from comparative geological reference materials using the same methods. A limited set of comparative geological turquoise samples (10 pieces) deriving from some well-known sources in the USA Southwest were received from the Hungarian Natural History Museum (HNHM), the Natural History Museum at Eötvös Loránd University (ELTE) and the private collection of László Nádai (PC).

3. Methods

As most of the known Aztec period masks, the 'Budapest mask' is made of different materials and its analytical investigation required more techniques and knowledge on several scientific disciplines to shed light on its authenticity and origin. The macroscopic observations were supported by ultraviolet (UV) photography as a conventionally applied imaging technique in authentication and forensic studies. In the further analytical process apart from the absolute dating, expertise on biology of the wood support, composition of the organic compound (adhesive), and inorganic chemistry and mineralogy of the covering mosaic elements were necessary to reconstruct the history of this uniquely preserved object. For this reason, a complex analytical protocol was introduced. The analysed samples, as well as the applied methods and the laboratories, where the analysis have been performed are listed in Table 1. Spots selected for investigations on the mosaic mask are indicated in Appendix 1.

3.1. UV photography

A UV photography equipment at the National Centre of Conservation and Conservation Training, Hungarian National Museum has been applied. It was our aim to differentiate the mosaic materials and to verify the presence of resin types that were supposed to exhibit different fluorescence when illuminated with UV-radiation. The object was illuminated with a Philips TLD 18 W/8 UV-

Table 1
List of measurements done in this study on turquoise samples. Numbers indicate the measurement or sampling points on the mask. Abbreviations of research institutes: PRL, Poznan Radiocarbon Laboratory; TIF, Thünen-Institut für Holzforschung; TTK: Research Centre for Natural Sciences; EK, Centre for Energy Research; ATOMKI, Institute for Nuclear Research; ELTE, Eötvös Loránd University. Abbreviations of instruments: C-14 – 1.5 SDH-Pelletron Model "Compact Carbon AMS"; Mic – Olympus AX 70 microscope; IRS – Varian 2000 FT-IR spectrometer; DP HH XRF – InnovX Delta Premium handheld XRF; BT HH XRF – Bruker Tracer 5g handheld XRF; SEM – Jeol Scanning Electronmicroscope; 3D DMIC – Keyence 3D digital microscope; microXRF – Bruker M4 TORNADO micro-XRF; Raman MIC – Renishaw Raman-microscope; LabRam – Horiba LabRam HR800 UV–VIS–NIR Raman spectrometer equipped with Olympus BXFM microscope.

Laboratory / Institute:	PRL	TIF	TTK	EK	ATOMKI				ELTE
Device:	C-14 dating	Mic	IRS	DP HH XRF	SEM	3D DMIC	microXRF	Raman MIC	LabRaman
SAMPLES FROM THE 'BUDAPEST MASK'									
Wooden support	1	1							
Organic adhesive			5						
Various green and bluish green tesserae on the mask				9		2	2	3	
Green and bluish green tesserae, removed from the mask					5	5	5	5	5
White and yellowish white lamellae on the mask				13		6	6	8	
GEOLOGICAL SAMPLES									
New Mexico, USA / ELTE				11			1		
New Mexico, USA / HNHM Inv. Nr.: A59				4					
Los Cerrillos, New Mexico, USA / HNHM Inv. Nr.: A64				3					
California, USA / HNHM Inv. Nr.: A74				3					
Blue Ridge Mine, Nevada, USA / PC				8		1	3	1	
Fox Mine, Nevada, USA / PC				5		1	4	3	
Sleeping Beauty Mine, Arizona, USA / PC				4		1	4	4	
Kingman Mine, Arizona, USA / PC				6		1	3	3	
Arizona, USA / HNHM Inv. Nr.: A60, A63				7					

lamp both on its front and back sides. When taking photos, an upper UV and a double Y-1.4 yellow filter was applied.

3.2. C-14 dating

One wood sample (see Sample 2 in Fig. 1b) taken from the back side of the wood support was subjected to C-14 dating using the technique of accelerator mass spectrometry (AMS) at the Poznan Radiocarbon Laboratory. The AMS spectrometer was a 1.5 SDH-Pelletron Model "Compact Carbon AMS" produced by the National Electrostatics Corporation, Middleton, USA. The sample preparation and measurement procedure are described on the website of the laboratory [29]. Data calibration was made with the OxCal software (OxCal v4.4.2) [30], atmospheric data are from [31]. The raw sample (of wood) originally weighed 33.3 mg. After chemical processing 11.2 mg of alpha-cellulose was obtained and an aliquot of 2.8 mg (of cellulose) was taken for combustion, from which CO_2 bearing 1.3 mg of carbon was gained. For graphitization, an aliquot bearing 1 mg C was taken, and AMS C-14 measurement was made in the piece of solid carbon weighing 1 mg.

3.3. Optical microscopic identification of tree type

One wood piece was sampled from the back side of the mask (see Sample 1 in Fig. 1b) for microscopic wood identification at the Thünen Institute of Wood Research, Hamburg. From the air-dried sample, 20 µm thick transverse, radial and tangential sections were sequentially cut using a sliding microtome (Sartorius) and embedded in Euperal (Roth Art.-Nr. 7356.1). The wood anatomical structures of the specimens were microscopically investigated and directly compared with reference samples (vouchered material) of the scientific wood collection at the Thünen Institute. Terminology and descriptions of the wood structures were based on the IAWA List of microscopic features for hardwood identification [32]. Microscopic images were taken by an Olympus BX 41 microscope. The interpretation was also helped by András Gryneus.

3.4. FT-IR analyses of adhesives

Two adhesive samples (some micrograms) were separated from the edge and the left-side temple of the mask for infrared spectroscopic investigation (IRS). Further three adhesive samples were removed from the backside of three tesserae. It was important to compare the two types of samples if the brown-coloured material on the temples is a decoration by themselves or it is adhesive to fix some missing, decorative elements. IR measurements were performed by the means of a Varian 2000 FT-IR spectrometer (Varian Inc., US) equipped with a mercury-cadmium-telluride (MCT) detector and fitted with a 'Golden Gate' single reflection diamond attenuated total reflection (ATR) accessory (Specac Ltd., UK). The samples were placed on the diamond ATR crystal and pressed with a sapphire anvil to ensure a perfect contact with the ATR crystal. A nominal spectral resolution of 4 cm^{-1} and co-addition of 128 individual scans were used to collect the spectra.

3.5. On site and laboratory XRF and Raman measurements on the mask

It was explained in a recent study [24] that despite that non-invasive, surface-sensitive XRF results might be affected due to the contamination and weathering process, these can provide relevant information on the turquoises. To examine the possible variability in the concentration of the components, all samples were analysed at several points. It was also proved in earlier publications [23,24] that creating the binary plots for Fe/Cu and Zn/Cu peak intensity ratios is informative and discriminative in case of turquoises of different origin. In this research, two different XRF spectrometers were used, therefore the plot of Fe/Cu and Zn/Cu mass ratios was drawn for better comparability.

On-site X-ray fluorescence (XRF) measurements were carried out on the 'Budapest mask' to determine the chemical composition of the different inlays. To perform the analyses, an InnovX (now Olympus) Delta Premium handheld XRF spectrometer was used, equipped with Rh-tube and a Peltier cooled silicon drift detector (SDD). The maximum accelerating voltage is 40 kV with 200 µA current. The measurements were performed in air atmosphere, using the factory calibrated Mining Plus and Soil modes, with predefined filter settings. The spot size was 3 mm in diameter. Since no matrix-matched calibration was available, and due to the well-known limits of XRF being surface-sensitive method, these results are considered semi-quantitative.

In another measurement campaign, the mask was transported to the Institute for Nuclear Research (ATOMKI) to Debrecen, to perform additional measurements (micro-XRF, Raman microscope) and to take high resolution images (3D digital microscope, SEM). In

addition, separate tesserae removed from the mask were also subjected to these analyses. Micro-XRF investigations were carried out on a Bruker M4 TORNADO (Bruker, Billerica, Massachusetts, United States) with Rh-tube without any filter at 50 kV accelerating voltage and 200 µA current. The irradiation was performed in 20 mbar vacuum. The spot size was focused to 20 µm by the built-in polycapillary lens. Quantitative analysis was performed by the M4 TORNADO software.

Renishaw InVia Raman microscope (Renishaw, Wotton-under-Edge, United Kingdom) was used for the mineral characterization of the samples in the range 100–1325 Raman shift/cm^{-1}. The spectra were collected using 10x Leica objective. The laser used for the mapping was a 785 nm, 100 mW diode laser at 10% intensity with ~2 µm beam size excitation. The recorded rectangular map contained 320 acquisitions (10 s exposure time at each point, 1 accumulation) with 30 µm step size utilizing 1200 l/mm grating. Beam centering and Raman spectra calibration were performed daily before spectral acquisition using the inbuilt Si standard.

High resolution images of the mask surface were recorded by digital 3D microscope (Keyence VHX-6000, Keyence, Osaka, Japan). 20X-200X zoom lens was used at different magnifications with reflective illumination. Furthermore, imaging of the removed pieces was performed by JEOL JSM-IT500HR type Scanning electron microscope (JEOL, Tokyo, Japan). Image acquisition was carried out in low vacuum mode (50 Pa N2) with an accelerating voltage of 20 kV, probe current value Std. 50, working distance of 10 mm and counting time of 40 s

Finally, additional Raman microscopic investigations were done on the separate tesserae samples by a Horiba JobinYvon LabRam HR800 UV–VIS–NIR Raman spectrometer at the Research and Industrial Relations Center of the Faculty of Science, Eötvös Loránd University of Budapest. A frequency doubled Nd-YAG green laser with a 532 nm excitation wavelength, as well as a 633 nm (red) He-Ne laser were used displaying ~6 and 9 mW on the sample surface, respectively. An OLYMPUS × 100 (N.A. = 0.9) objective focused the laser. A 100 µm confocal hole, 600 l/mm optical grating, 120 s cumulated exposition time were applied.

4. Results and discussion

To authenticate the 'Budapest mask', firstly the complexity of the applied materials was studied by UV photography. On the first level of the instrumental investigation, the age and tree species of the wood support were studied. Then, the supposed organic glue was examined whether its material could be used in the pre-Hispanic Mexico or not. In case of a 'foreign' glue – even if all the other constituents of the mask were ancient or authentic – the complete artwork should be identified as a fake. On the third level, the mosaic elements were analysed whether those could be turquoise and could be available in the Aztec era. In addition, the possible origin of supposed turquoise tesserae was observed.

4.1. UV photography

By this method, we aimed to study both the organic glue and the inorganic mosaic elements of the mask (Fig. 3). The ultraviolet images were taken to verify the areas covered by resin. No fluorescent organic resin was possible to detect on the mosaic covered side of the mask this way. However, on the rear side of the mask, the UV-radiation has revealed the traces of fluorescent (probably protein-based) glue applied during the modern repair. Furthermore, the larger sized light-coloured lamellae of the mask seemed to be heterogeneous both by macroscopic and UV light inspection. The white (-light grey), smooth and pearlescent elements have dull blueish fluorescence. The eggshell-coloured and porous fragments show no fluorescence. The pale yellow and smooth lamellae emit clear white fluorescence. Thus, the colour differences of the light mosaic lamellae in UV radiation have confirmed their distinct compositions.

The UV photographic inspection revealed the use of multiple materials for the manufacturing the mask. It also indicated the need for detailed instrumental investigation of both the organic adhesive and the inorganic mosaic cover.

4.2. Dating the wood

According to the AMS measurement, the wood sample selected for the C-14 dating (No. Poz-129667) could be dated to 1492–1653 AD (Fig. 4). This means the tree providing the wood material for the mask was grown at the end of the pre-Hispanic era or at the first half of the colonial period. Since manufacturing mosaic objects was typical in the Post-Classic era (900–1521 AD) and ceased to the colonial period, it should be dated to the end of the Aztec period (1325–1521 AD).

4.3. Identification of the tree species

The wood anatomical structures of the mask support completely correspond to timber (species) of the genus *Alnus* sp. (alder tree), family *Betulaceae* (Fig. 5). Since alder is a common species distributed worldwide, the wood support of the mask could have derived from "anywhere". However, *Alnus acuminata* and *Alnus jorullensis* are native alder species in Mexico, regularly used and established as carving wood. In addition, it is a logic supposition that fakers creating a counterfeit would use a more noble tree type for an Aztec mosaic mask. Based on these facts and assumptions, it is probable that the 'Budapest mask' was manufactured from Mexican alder tree.

4.4. Adhesive

Adhesive samples removed from the backside of three different tesserae proved to be the same organic material by their very similar IR spectra (for discussion the best quality spectrum was chosen, see adhesive_1 in Fig. 6). The spectral features, namely the strong but not well-resolved methylene (CH2) stretching bands of alkyl chains (around 2929 and 2861 cm^{-1}), and the C=O (at 1713 cm^{-1}) and C–O vibrational bands (around 1251, 1173, 1029 cm^{-1}) of esters suggest that the adhesive might be of vegetal origin, mostly resin [34]. This conclusion is further affirmed by the reference spectra of tree resins [35], using dedicated spectrum library [36], for other compositions see [37]. Based on spectral similarities, the use of pine resin as adhesive material seems presumable.

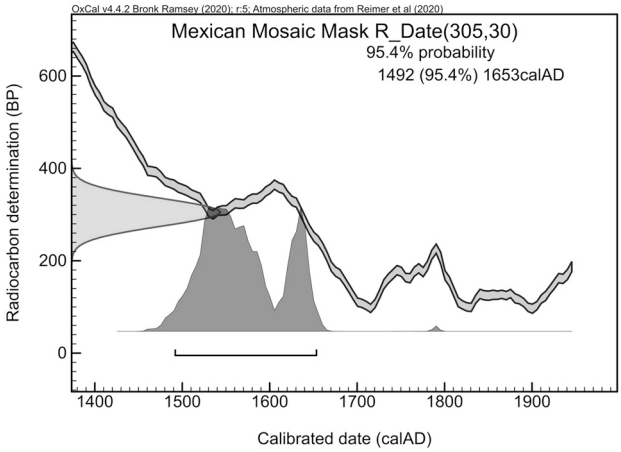
The spectra of sample removed from the black-coloured temple is identical with the adhesive on the tesserae (see black_1 and _2 spectra in Fig. 6). It is probable that additional decorative elements were fixed on the temples. The black discoloration on these parts might be caused by the superficial oxidation of the applied resin.

4.5. Blue-green tesserae

Turquoise is supposed to be the major greenish-blue material of the tesserae that was used as decorative mosaics on the mask surface. As a first step of the characterization, turquoise nature of the tesserae needed to be proved. For this purpose, not only the elemental composition but also the infrared spectra, characteristic for δ Al–OH and δ Cu–OH and δ Fe–OH bending vibrations [16] and Raman spectra of mineral phosphates [38–40] can be useful.

According to the chemical analyses (see in Appendix 2–4), all the investigated green or bluish green tesserae have showed the composition of turquoise, without doubt. Their major components have been identified by XRF as 2.6–16.1 m% P, 2.7–8.5 m% Al, 1.5–3.1 m% Cu and 0.4–0.9 m% Fe, and 0.1–0.3 m% Zn. The detected

Fig. 3. UV fluorescence photography of the 'Budapest mask'. Fluorescent glue on the rear side indicates protein-based adhesive used during the modern repair, while no fluorescent adhesive is detected under the mosaics. On the front side, lamellae from different materials can be clearly distinguished.



Code of sample	Poz-129667
Sample name	Mexican Mosaic Mask
Sample weight	33.3 mg
Conventional Radiocarbon Age (BP)	305 ± 30
Calibrated 68.3% probability	1521AD (52.6%) 1586AD 1623AD (15.7%) 1643AD
Calibrated 95.4% probability	1492AD (95.4%) 1653AD

Fig. 4. Result of radiocarbon dating on the wooden base of the 'Budapest mask'. Calibration and representation in KDE diagram is based on [33].

concentration values may deviate from the theoretical ones, because of the substitutions of Cu atoms by Fe and Zn atoms. Other detected minor elements are 0.6–2.1 m% Ca, < 1 m% Si and < 0.5 m% S, K, Ti and Mn as contaminants.

Raman spectrum of the tesserae were collected in the range between 100 and 1325 cm^{-1}. A typical Raman spectrum of a removed tesserae is depicted in Fig. 7. This spectrum shows the position of the bands and their relative intensities. The spectrum was identified as a natural turquoise by the built-in database of the Renishaw InVia Raman microscope (Spectral Databases, S.T. Japan-Europe GmbH, Köln, Germany) and the RRUFF mineral database (https://rruff.info/). The observed wavenumbers of the bands were deciphered based on the published data of Čejka and colleagues [39]. Raman bands between 136 and 277 cm^{-1} are assigned to the lattice vibrations, a band at 331 cm^{-1} is attributed to the stretching and bending vibrations of Cu–(O, OH, H_2O) or Al–(O, OH, H_2O) bonds, bands between 382 and 526 cm^{-1} can be connected with the ν_2 $(PO_4)^{3-}$ bending and/or the Cu–O stretching and bending vibrations, bands between 551 and 643 cm^{-1} are assigned to the ν_4 $(PO_4)^{3-}$ bending vibrations, however, these bands may partly overlap with band of Al–(O, OH) bending

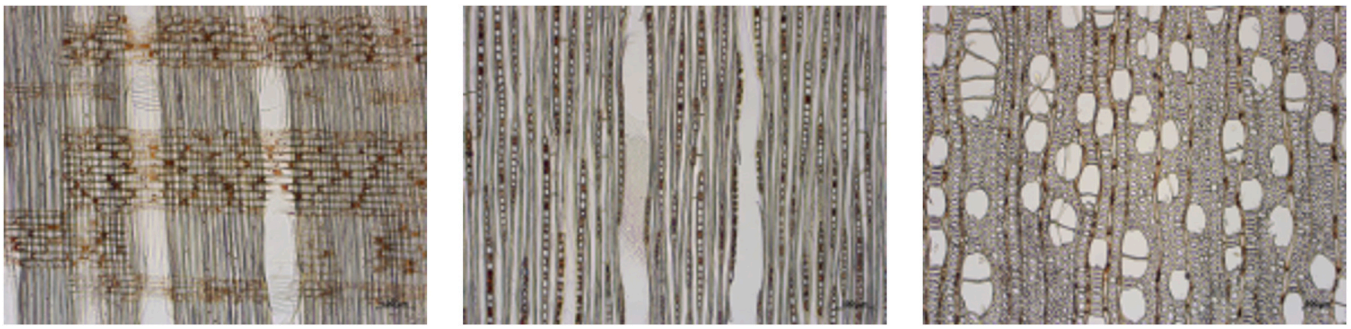


Fig. 5. Radial, tangential and transversal sections of the wooden base of the 'Budapest mask' (Thünen Institut for Wood Research, Hamburg, Germany). The wood anatomical features proves its derivation from an alder tree species which might be native in Mexico.

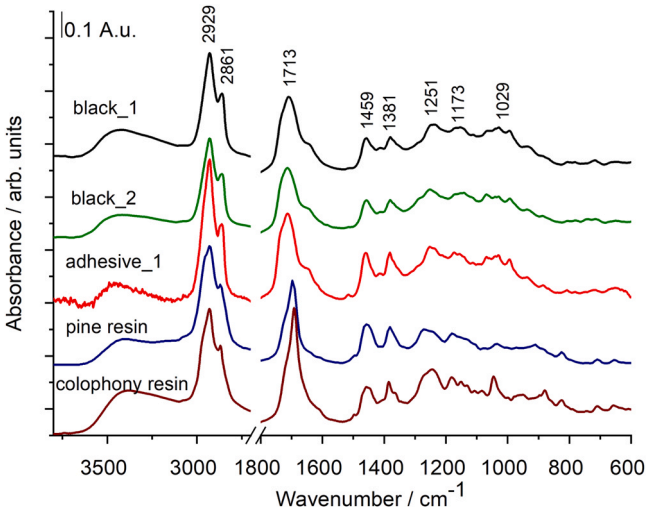


Fig. 6. ATR-IR spectra of adhesive material removed from tesserae (adhesive_1) and from black-coloured surfaces on the wood support (black_1 and _2). For comparison, the reference spectra of fresh pine resin and colophony resin are also included.

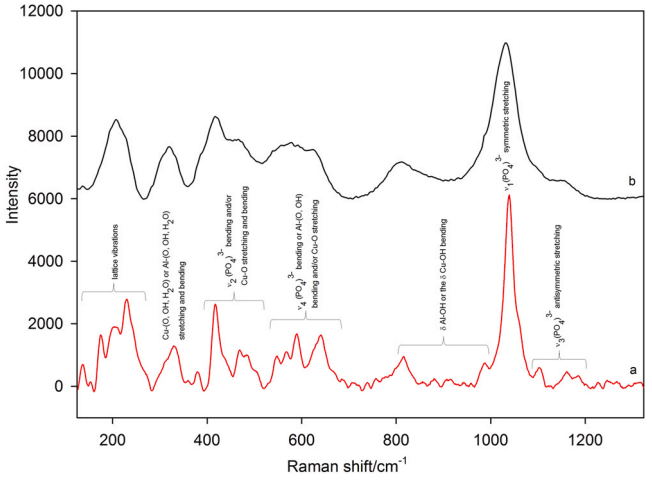


Fig. 7. (a) Raman spectrum of the removed tesserae from the 'Budapest mask' over the 100–1325 cm^{-1} spectral range. (b) Raman spectrum of the R050225 turquoise standard from the RRUFF mineral database (https://rruff.info/). The observed wavenumbers of the bands were deciphered based on the published data of Čejka and colleagues [39].

and/or Cu–O stretching. Bands at 812 and 978 cm^{-1} are attributed to the δ Al–OH or the δ Cu–OH bending vibrations. The most intense Raman band at 1040 cm^{-1} is related to the ν_1 $(PO_4)^{3-}$ symmetric stretching vibrations followed by two bands at 1100 and 1160 cm^{-1} which relate to the triply degenerate ν_3 $(PO_4)^{3-}$ antisymmetric stretching vibrations.

As a second step of the characterization, comparison to different turquoise sources was used to determine the provenance of the turquoise tesserae. Although, molecular spectroscopic methods are not capable to provide further detailed information on its origin, chemical composition of turquoise can hold important data. Based on the experiences from the literature [15,23,24], we have focused on the concentrations of Zn and Fe, compared to the Cu contents, determined by XRF methods. We suppose that concentrations of substituting minor elements (Fe, Zn) are more characteristic for the origin of copper ore source than for the formation conditions of turquoise. In addition, it was our observation that As and Sr concentrations are not distinctive for turquoise of various origin.

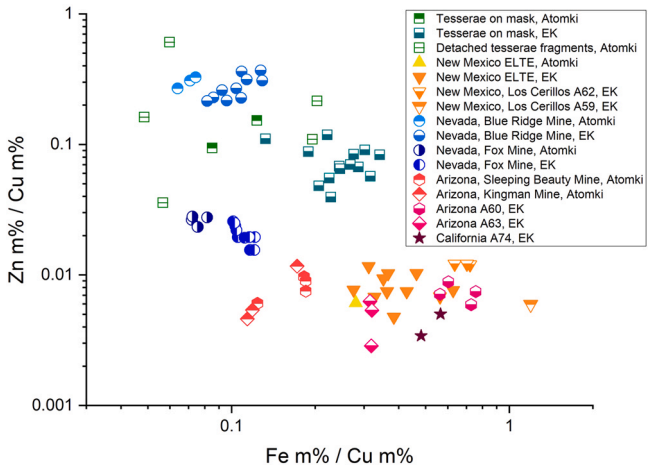


Fig. 8. Chemical discrimination diagram (Fe m% / Cu m% vs Zn m% / Cu m%) of turquoises after [23].

From Fig. 8, one can notice that the Fe and Zn contents show greater variance for the removed tesserae than for those, which are fixed to the mask. Similarly, the compositions for the faded, i.e. weathered turquoise tesserae show greater variance than those of the darker, i.e. the fresher ones. In accordance with [41], these phenomena draw our attention to the effect of weathering which may modify the original chemical composition of a sample in different degrees and may have an impact to our conclusion on the provenance. The presence of weathering also emphasizes the importance of the bulk analytical methods. In addition, the measured data could show higher variability in Fe and Zn content, probably due to the different range of co-measurement with the embedding environment or the hosting rock.

Despite the chemical variability of the turquoise tesserae on the 'Budapest mask' the measured data points still define a characteristic composition which is well comparable to the turquoise pieces revealed from three mosaic disks of the Aztec Templo Mayor, Tenochtitlan [23,42] due to their elevated Zn and moderate Fe content. In addition, turquoise tesserae on mosaic disks at Templo Mayor show similar wider distribution on Fe-Zn plots like our measurement data (Fig. 8), though those derived from three phases (in the 1440–1502 AD timespan) of the Aztec period. Based on their results, Laclavetine et al. [23] found an unspecified Mexican locality and Sleeping Beauty (USA Southwest, Arizona) as the most probable sources. It was also their conclusion that the expansion of the Aztec Empire might resulted in increasing demand for turquoise-covered objects (representing the power of the rulers) and involving new sources by time.

Regarding the provenance of turquoise tesserae of the 'Budapest mask', one can see from Fig. 8 that the composition (and particularly the Zn/Cu and Fe/Cu concentration ratios) of the mosaic elements show the highest similarity with the ones from Blue Ridge and Fox Mines in Nevada, although, because of the large variance of the data for the archaeological samples, the agreement is not entirely convincing. Nonetheless, the provenance from the other investigated sources, such as Arizona, California and New Mexico can be excluded with high confidence. Fox Mine turquoise (Nevada) can be characterized with elevated Cr content (0.06–0.09 m%, see in Appendix 2–4) which has no parallel neither among the 'Budapest mask' turquoises nor among the observed geological sources. Considering the above-mentioned compositional similarity of the studied turquoises with that of the objects of Templo Mayor (Tenochtitlan) the Mexican origin cannot be excluded. Based on these results, it is not yet

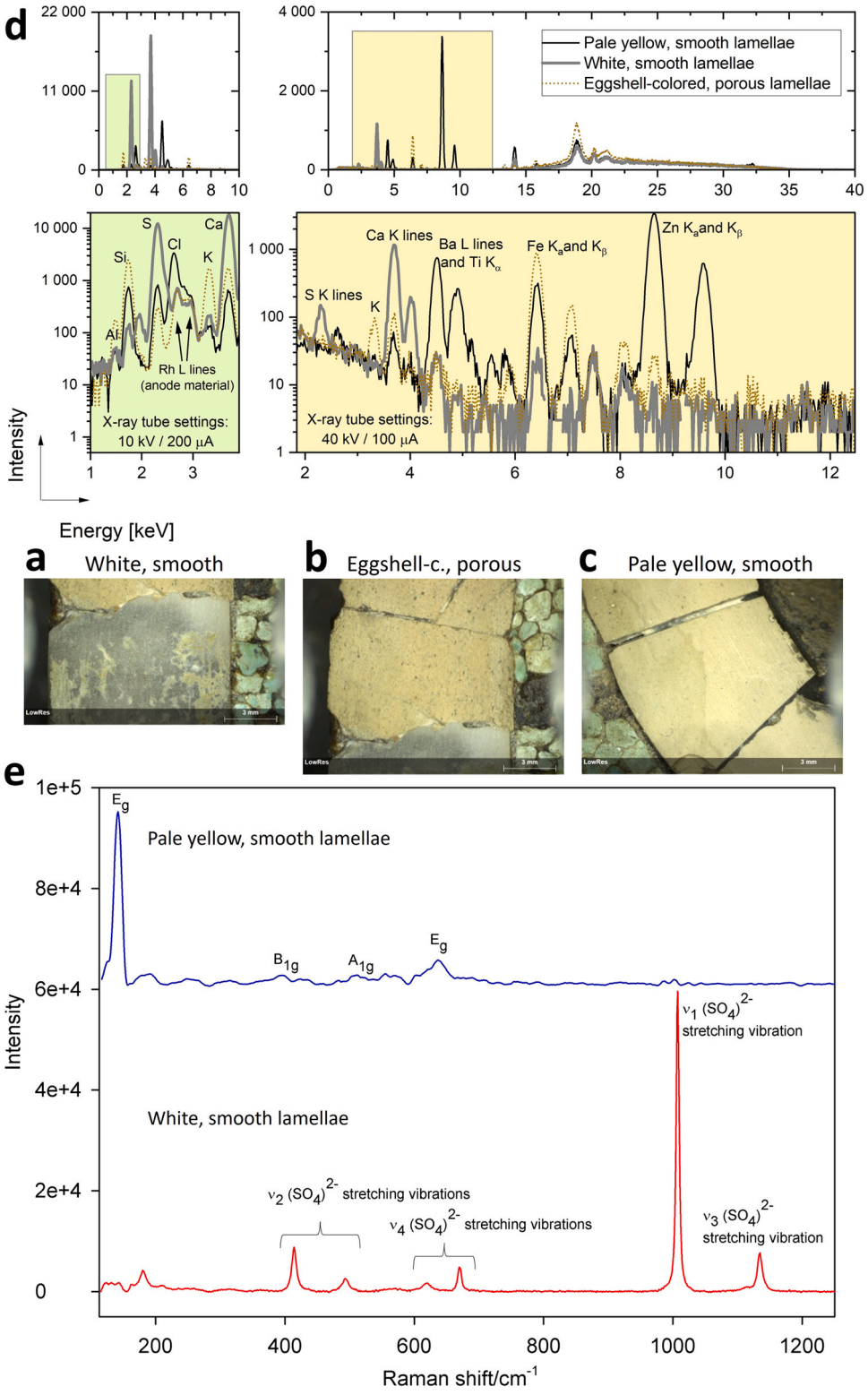


Fig. 9. Investigations on the light mosaic lamellae of the 'Budapest mask'. The three macroscopic types: (a) white, (b) eggshell, and (c) pale yellow. (d) Selected regions from XRF spectra. (e) Raman spectrum of the white smooth lamellae (red, band identifications based on the published data of [44]) and the pale yellow and smooth lamellae (blue, band identifications based on the article of [45]).

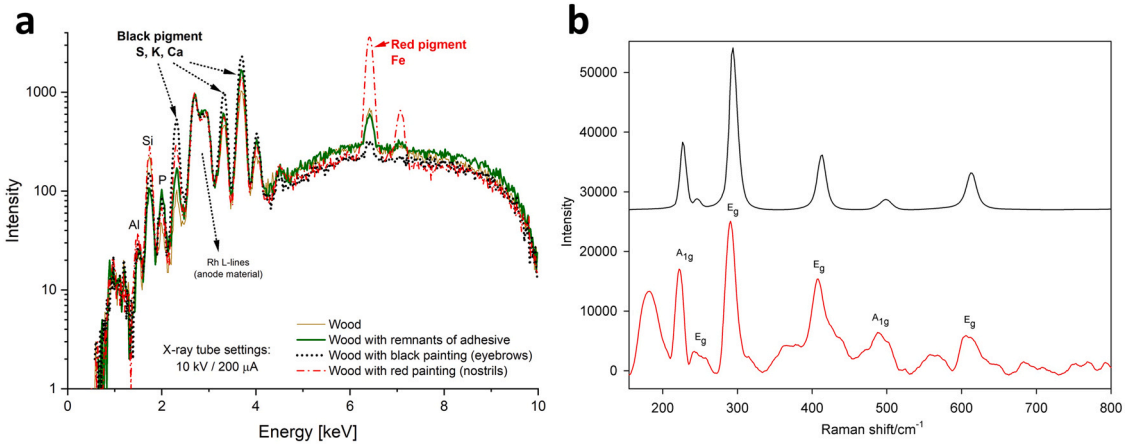


Fig. 10. Investigations on the painted wooden surfaces of the 'Budapest mask'. (a) Selected regions from XRF spectra of the wooden and painted wooden surfaces. (b) Raman spectra of the red-painted nostrils area (red) and a hematite standard (black, ID R110013) from the RRUFF mineral database (bands identified based on [46]).

possible to decide among the former popular proposition – that Mesoamerican societies (involving the Aztecs) acquired turquoise from the USA Southwest [22] – and the new conclusions based on radiogenic isotopic analyses [43] – that Mixtec and Aztec craftsmen used the much closer Mesoamerican turquoise sources to manufacture their emblematic objects – concerning the provenance of turquoise.

4.6. Light-coloured lamellae

The larger sized white or light-coloured lamellae of the mask seemed to be heterogeneous by macroscopic and UV light inspection: (1) white (-light grey), smooth and pearlescent (Figs. 9a), (2) eggshell-coloured and porous (Fig. 9b), and (3) pale yellow and smooth (Fig. 9c). The macroscopic differences were further proved by the chemical and molecular spectroscopic investigations (Appendix 5, Fig. 9d-e). The pearlescent white and smooth material is composed of mainly calcium and sulphur as shown by the qualitative XRF measurements. It has fibrous texture based on the 3D microscopic observations. Raman spectrum of the lamellae proved to be calcium sulphate dihydrate. According to these characteristics it was identified as fibrous gypsum, i.e. alabaster. The eggshell-coloured and porous material has an iron-poor aluminosilicate composition which might indicate a light claystone origin. We were unable to record Raman spectrum on this lamella. The pale yellow and smooth-surfaced material has ambiguous chemical composition with dominant chlorine content and indications of barium, titanium and zinc besides aluminium, silicon and magnesium which could not be interpreted properly. Its Raman spectrum depicts the presence of anatase which may occur in white clay-claystone (kaolin).

4.7. Painted wooden surfaces

Chemical composition of the painted surfaces of the mask were compared to the weathered or broken (thus relatively fresh) wooden material of the base (Appendix 5, Fig. 10a). Red-painted nostrils are characterized with significantly (sometimes 10 times) higher iron content than it is characteristic for the wood. The higher iron content is supposed to refer to the use of iron-rich earth pigments. Black-painted eyebrows are characterized with weakly elevated K, Ca and S content which can indicate the presence of ash- or charcoal-based colouring matter. Resin-covered areas on the temples show no chemical difference from the wood.

Raman spectrum of the red-painted nostril (Fig. 10b) revealed its hematite content. In the spectrum, seven peaks appeared: two A_{1g} modes (222 cm^{-1} and 488 cm^{-1}) and four E_g modes (243 cm^{-1}, 291 cm^{-1}, 408 cm^{-1} and 605 cm^{-1}). The positions of peaks are in a good agreement with a mineral standard from the RRUFF database (R110013) and the literature data [46].

5. Conclusions

The 'Budapest mask' became the property of the Museum of Ethnography, Budapest by exchange of objects and with uncertain inventory records. It was necessary to convince the authenticity (age) of the object, the application of contemporary (Aztec period) raw materials and as exact as possible provenance of them.

Based on the microscopic wood anatomical and the radiocarbon studies of the wood support, the mask was made between 1492 and 1653 using alder tree, which is native to Mexico. The analysis of the adhesive proved that this is an organic, probably pine resin which was known in the pre-Hispanic handicraft. Thus, the mask is considered to be authentic. The mosaic cover of the mask consisted of turquoise tesserae, as well as alabaster and possibly white claystone lamellae. The black- and red-coloured wooden surfaces are probably painted with ash-based colouring matter and red (iron-rich) earth pigment. The turquoise applied might be originated from an unknown Mexican source or a far locality (Blue Ridge Mine) in Nevada but not from closer and well-known American South-western turquoise sources.

It was a completely new result that gypsum alabaster was applied as white mosaic lamellae on an Aztec mosaic object. It is our assumption that by further characterization of alabaster it could be connected to a specific source of which there is not many in the observed region. Similarly to the case of turquoise, known gypsum alabaster localities are in the USA Southwest (e.g. Texas, New Mexico, Arizona, California) calling our attention to possible north directed raw material supplying system of the Aztecs.

Investigating the provenance of mosaic elements on masks having cultural relationship with the 'Budapest mask', e.g. that of the Nelson-Atkins Museum of Art (Kansas City) and The Textile Museum (Washington), would give new data. It might have been possible to connect these objects by independent analytical methods and also help to understand the raw material procurement in the Aztec Empire.

CRediT authorship contribution statement

János Gyarmati: Writing – original draft, Visualization, Supervision. **Boglárka Maróti:** Investigation, Validation, Formal analysis, Visualization, Writing – review & editing. **Zsolt Kasztovszky:** Writing – original draft, Writing – review & editing.

Boglárka Döncző: Investigation, Validation, Formal analysis, Writing – review & editing. **Zita Szikszai:** Investigation, Validation, Formal analysis, Writing – review & editing. **László Aradi:** Investigation, Validation, Formal analysis, Writing – review & editing. **Judith Mihály:** Investigation, Validation, Formal analysis, Writing – review & editing. **Gerald Koch:** Investigation. **Veronika Szilágyi:** Conceptualization, Investigation, Visualization, Writing – original draft.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.forsciint.2022.111236.

References

[1] K.A. Taube, The symbolism of turquoise in ancient Mesoamerica, in: J.C.H. King, M. Carocci, C. Cartwright, C. McEwan, R. Stacey (Eds.), Turquoise in Mexico and North America: science, conservation, culture and collections, Archetype Publications – The British Museum, London, 2012, pp. 117–134.
[2] G. Olivier, L. López Luján, Images of Moctezuma and his symbols of power', in: C. McEwan, L. López Luján (Eds.), Moctezuma: Aztec Ruler, British Museum Press, London, 2009, pp. 78–91.
[3] M. Saville, Turquois Mosaic Art in Mexico, Museum of the American Indian, Heye Foundation, New York, 1922.
[4] M.E. Berger, 'From a Cave near Tehuacán'. An attempt to reassemble post-classic mesoamerican ritual deposits that were separated by the art market, in: C.G. Tremain, D. Yates (Eds.), The Market for Mesoamerica: Reflections on the Sale of Pre-Columbian Antiquities, University Press of Florida, Gainesville, 2019, pp. 112–135.
[5] J. Montoya, Textiles y otros materiales arqueológicos del Valle de Tehuacán, México, en los Museos Reales de Arte e Historia (MRAH), Bruselas, in: L. Bjerregaard, A. Peters (Eds.), PreColumbian Textile Conference VII / Jornadas de Textiles PreColombinos VII, Zea Books, (Lincoln, NE, 2017: pp. 104–131.
[6] E. Vargas, Las máscaras de la cueva de Santa Ana Teloxtoc. UNAM México, 1989.
[7] M. Izeki, Conceptualization of 'Xihuitl' History, Environment, and Cultural Dynamics in Postclassic Mexica Cognition. Ph.D. Dissertation, Institute of Archaeology University College London, London, 2007.
[8] C.L. Moser, Cueva de Ejutla: Una Cueva Funerarie Posclásica? Bol. Del. INAH 14 (1975) 25–37.
[9] P. Meehan, V. Magar, 'Conservation of a turquoise mosaic disk from Tula. Mexico', in: J.C.H. King, M. Carocci, C. Cartwright, C. McEwan, R. Stacey (Eds.), Turquoise in Mexico and North America: science, conservation, culture and collections, Archetype Publications – The British Museum, London, 2012, pp. 41–54.
[10] A. Velázquez Castro, M.E. Marín Benito, E.R. Melgar Tísoc, R.B. Solís Ciriaco, J.L. Ruvalcaba Sil, The turquoise disk from Offering 99 at the Templo Mayor in Tenochtitlan, in: J.C.H. King, M. Carocci, C. Cartwright, C. McEwan, R. Stacey (Eds.), Turquoise in Mexico and North America: science, conservation, culture and collections, Archetype Publications – The British Museum, London, 2012, pp. 75–87.
[11] A.M. Thibodeau, D.J. Killick, S.L. Hedquist, J.T. Chesley, J. Ruiz, Isotopic evidence for the provenance of turquoise in the southwestern United States, Geol. Soc. Am. Bull. 127 (2015) 1617–1631.
[12] V.W. Lueth, Two diverse origins of turquoise at the Orogrande mining district: New Mexico, Geology 20 (2) (1998) 64–65.
[13] E.E. Foord, J.E.Jr Taggart, A reexamination of turquoise group: the mineral aheleyte, planerite (redefined), turquoise and coeruleolactite, Mineral. Mag. 62 (1998) 93–111.
[14] Y.A. Abdu, S.K. Hull, M. Fayek, F.C. Hawthorne, The turquoise-chalcosiderite Cu(Al,Fe^{3+})6(PO4)4(OH)8*4H2O solid-solution series: A Mössbauer spectroscopy, XRD, EMPA, and FTIR study, Am. Mineral. 96 (10) (2011) 1433–1442, https://doi.org/10.2138/am.2011.3658
[15] J. Kim, A.W. Simon, V. Ripoche, J.W. Mayer, B. Wilkens, Proton-induced x-ray emission analysis of turquoise artefacts from Salado Platform Mound sites in the Tonto Basin of central Arizona, Meas. Sci. Technol. 14 (2003) 1579–1589.
[16] H. Sabbaghi, A combinative technique to recognise and discriminate turquoise stone, Vib. Spectrosc. 99 (2018) 93–99.
[17] H. Ruppert, Zur verbreitung und herkunft von Tiirkis und Sodalith in prako-lumbischen Kulturen der Kordilleren, Baessler-Arch. 30 (1982) 69–124.
[18] A.M.C. Sigleo, 'Trace-element geochemistry of Southwestern turquoise', MA thesis, University of New Mexico (unpublished), 1970.
[19] S.K. Hull, M. Fayek, Cracking the code of pre-Columbian turquoise trade networks and procurement strategies, in: J.C.H. King, M. Carocci, C. Cartwright, C. McEwan, R. Stacey (Eds.), Turquoise in Mexico and North America: science, conservation, culture and collections, Archetype Publications – The British Museum, London, 2012, pp. 29–40.
[20] A.R. Ronzio, M.L. Salmon, 'Relation between source and composition of turquoise', J. Colo. -Wyo. Acad. Sci. 5 (1967) 30–31.
[21] F.J. Mathien, B. Olinger, 'An experiment with x-ray fluorescence to determine trace element variability in turquoise composition', in: M.S. Duran, D.T. Kirpatrick (Eds.), Archaeology, Art, and Anthropology: Papers in Honor of J.J. Brody, The Archaeological Society of New Mexico, Albuquerque, 1992, pp. 123–134.
[22] G. Harbottle, P.C. Weigand, 'Turquoise in pre-Columbian America', Sci. Am. 266 (2) (1992) 78–85.
[23] K. Laclavetine, J.L. Ruvalcaba-Sil, E.R. Melgar Tísoc, Caracterización no destructiva in situ de turquesas del Templo Mayor de México-Tenochtitlan mediante XRF, in: R. Esparza López (Ed.), Nuevos aportes de las técnicas de Arqueometría en el estudio y caracterización del Patrimonio Cultural de Latinoamérica, El Colegio de Michoacán, México, 2015, pp. 1–16.
[24] F. Carò, D. Schorsch, L. Smieska, B. Santarelli, Non-invasive XRF analysis of ancient Egyptian and near Eastern turquoise: A pilot study, J. Archaeol. Sci.: Rep. 36 (2021) 102893.
[25] J.E. Pogue, The Turquois, 3rd Memoir, Memoirs of the National Academy of Science 12 Rio Grande Press,, Glorieta, New Mexico, 1915.
[26] F.J. Mathien, The organization of turquoise production and consumption by the prehistoric Chacoans, Am, Antiquity 66 (2001) 103–118.
[27] W.D. Panczner, Minerals of Mexico, Van Nostrand Reinhold,, New York, 1987.
[28] F. Berdan, Mexican turquoise mosaics in Vienna, in: J.C.H. King, M. Carocci, C. Cartwright, C. McEwan, R. Stacey (Eds.), Turquoise in Mexico and North America: science, conservation, culture and collections, Archetype Publications – The British Museum, London, 2012, pp. 91–102.
[29] Poznan Radiocarbon Laboratory, Description of Procedures, 2021. ⟨https://radiocarbon.pl/en/description-of-procedures/⟩ (accessed 28 October 2021).
[30] C. Bronk Ramsey, Bayesian analysis of radiocarbon dates, Radiocarbon 51 (1) (2009) 337–360.
[31] P. Reimer, W. Austin, E. Bard, A. Bayliss, P. Blackwell, C. Bronk Ramsey, M. Butzin, H. Cheng, R. Edwards, M. Friedrich, P. Grootes, T. Guilderson, I. Hajdas, T. Heaton, A. Hogg, K. Hughen, B. Kromer, S. Manning, R. Muscheler, J. Palmer, C. Pearson, J. van der Plicht, R. Reimer, D. Richards, E. Scott, J. Southon, C. Turney, L. Wacker, F. Adolphi, U. Büntgen, M. Capano, S. Fahrni, A. Fogtmann-Schulz, R. Friedrich, P. Köhler, S. Kudsk, F. Miyake, J. Olsen, F. Reinig, M. Sakamoto, A. Sookdeo, A. Talamo, The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP), Radiocarbon 62 (2020).
[32] E.A. Wheeler, P. Baas, P.E. Gasson, List of microscopic features for hardwood identification, IAWA Bull. 10 (3) (1989) 219–332.
[33] C. Bronk Ramsey, Methods for summarizing radiocarbon datasets, Radiocarbon 59 (2) (2017) 1809–1833.
[34] F. Berdan, The Technology of Ancient Mesoamerican Mosaics: An Experimental Investigation of Alternative Super Glues, Unpublished manuscript, FAMSI (2007).
[35] S. Vahur, A. Kriiska, I. Leito, Investigation of the adhesive residue on the flint insert and the adhesive lump found from the Pulli Early Mesolithic settlement site (Estonia) by micro-ATR-FT-IR spectroscopy, Est. J. Archaeol. 15 (2011) 3.
[36] Database of ATR-FT-IR spectra of various materials, ATR-FT-IR spectra of conservation-related materials in the MID-IR and FAR-IR region, Binders, 2021. http://lisa.chem.ut.ee/IR_spectra/paint/binders (accessed 28 October 2021).
[37] S. Chen, S. Vahur, A. Teearu, T. Juus, M. Zhilin, S. Savchenko, S. Oshibkina, V. Asheichyk, A. Vashanau, E. Lychagina, E. Kashina, K. German, E. Dubovtseva, A. Kriiska, I. Leito, E. Oras, Classification of archaeological adhesives from Eastern Europe and Urals by ATR-FT-IR spectroscopy and chemometric analysis, Archaeometry (2021) 12686 (arcm).
[38] R.L. Frost, B.J. Reddy, W.N. Martens, M. Weier, The molecular structure of the phosphate mineral turquoise – a Raman spectroscopic study, J. Mol. Struct. 788 (2006) 224–231.
[39] J. Čejka, J. Sejkora, I. Macek, R. Malíková, L. Wang, R. Scholz, Y. Xi, R.L. Frost, Raman and infrared spectroscopic study of turquoise minerals, Spectrochim. Acta Part A: Mol. Biomol. Spectrosc. 149 (2015) 173–182.
[40] N. D'Elboux Bernardino, C.M.S. Izumi, D.L.A. de Faria, Fake turquoises investigated by Raman microscopy, Forensic Sci. Int. 262 (2016) 196–200.
[41] C.A. Spier, A. Kumar, A.P.L. Nunes, Mineralogy and genesis of rare Al-phosphate minerals in weathered itabirite and iron ore from the Quadrilátero Ferrífero, Minas Gerais, Brazil, Ore Geol. Rev. 118 (2020) 103359.
[42] K. Laclavetine, J.L. Ruvalcaba-Sil, C. Duverger, E.R. Melgar Tísoc, Les "turquoise culturelles" et la caractérisation par fluorescence de rayos X (XRF) in situ du disque de mosaïque de l'offrande 99 Templo Mayor de México-Tenochtitlán, ArcheoSciences 38 (2014), https://doi.org/10.4000/archeosciences.4269 ⟨http://journals.openedition.org/archeosciences/4269⟩.
[43] A.M. Thibodeau, L. López Luján, D.J. Killick, F.F. Berdan, J. Ruiz, Was Aztec and Mixtec turquoise mined in the American Southwest? Sci. Adv. 4 (2018) eaas9370.

[44] Z. Tomić, P. Makreski, B. Gajić, Identification and spectra–structure determination of soil minerals: Raman study supported by IR spectroscopy and X-ray powder diffraction, J. Raman Spectrosc. 41 (2010) 582–586.
[45] S. Challagulla, K. Tarafder, R. Ganesan, S. Roy, Structure sensitive photocatalytic reduction of nitroarenes over TiO_2, Sci. Rep. 7 (2017) 8783.
[46] T. Szatkowski, M. Wysokowski, G. Lota, D. Pęziak, V.V. Bazhenov, G. Nowaczyk, J. Walter, S.L. Molodtsov, H. Stöcker, C. Himcinschi, I. Petrenko, A.L. Stelling, S. Jurga, T. Jesionowski, H. Ehrlich, Novel nanostructured hematite–spongin composite developed using an extreme biomimetic approach, RSC Adv. 5 (2015) 79031–79040.