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New material connections in a mother-of-pearl *Enconchado* from the Viceroyalty of New Spain

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Abstract

Adoration of the Magi (*ca.* 1695–1700)*,* an *enconchado* painting attributed to Miguel González, active in Mexico in the late seventeenth century, exemplifies the refinement of the arts produced in Spanish America as a response to the taste for Asian goods during the seventeenth and eighteenth centuries. The painting and its original mother-of-pearl inlaid frame were examined and analyzed using non-invasive and micro-sampling methods, an approach that permitted answering outstanding questions about the stratigraphy, pigments, and the use of shells throughout the painting and frame. The identification of the mother-of-pearl, determined to be from a *Pinctada* species, was a central focus of this study. In addition to the inlaid shells in the painting and frame, shell fragments were observed mixed with gypsum in the ground preparation of the painting by SEM–EDS. To our knowledge, this is a novel identification of marine shells in the ground of an easel painting. Traces of workmanship in the inlaid shells observed by SEM and optical microscopy are possibly connected to pre-Hispanic methodologies of mother-of-pearl refinement.

Keywords Enconchado, Viceregal paintings, Miguel González, Mother-of-pearl, Nacre, Pre-Hispanic shell processing, *Pinctada mazatlanica*, New Spain

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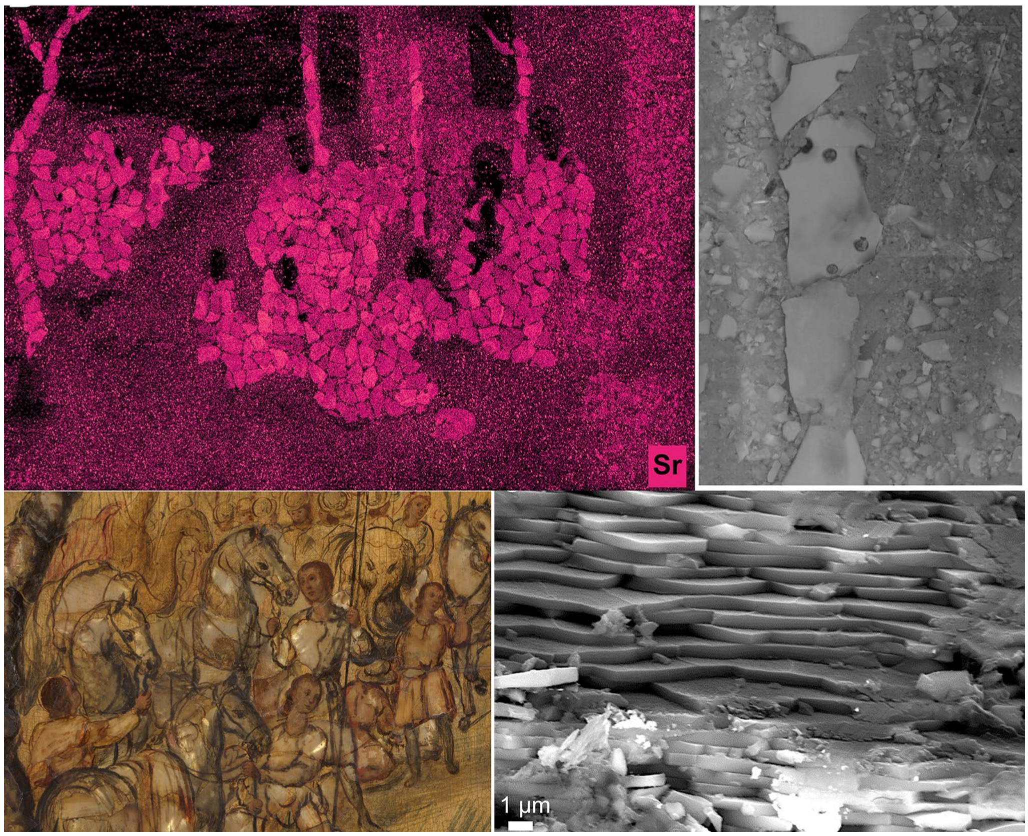
Graphical Abstract



Introduction

The painting

The *Adoration of the Magi* (*ca.* 1695–1700) is an unusually well-preserved *enconchado* painting recently acquired by The Metropolitan Museum of Art (The Met) (Fig. 1A). This mixed-media panel containing inlaid mother-of-pearl, pigments, glazes, and gilding is attributed to Miguel González (ca. 1664/66- after 1704), an artist active in Mexico City between 1692 and 1704 [1]. The painting was offered to the Museum as the work of an unknown 18th century Mexican artist however, based on signed and dated works by Miguel González and the subsequent finding of a well-documented provenance record, an attribution was possible [2]. The conservation treatment of the painting presented an opportunity for technical examination and investigation of the materials and techniques used by the artist. This study, one of few in-depth examinations of a single *enconchado* [3, 4] and its accompanying frame, involved microscopy, X-radiography, infrared reflectography (IRR), macro-XRF (MA-XRF) mapping, and the analysis of samples by Raman spectroscopy and scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM–EDS). The term *enconchado* has been used to refer to both paintings and furnishings [5]. Even though this investigation could help advance the understanding of furnishings with inlaid shells, these types of objects are beyond the scope of this article so, from now on, we will use the term *enconchado* to refer to paintings exclusively.

The composition shows the gift-bearing Magi giving their offerings to the Christ Child; Melchior, rapt in devotion, kneels beside Balthazar and Gaspar before the Virgin Mary and Joseph, who have taken refuge in a humble stable. The richness of the materials is reflected throughout the composition—gold and shells are carefully placed to achieve luminous effects. In this multi-figure scene, nacre is used as a pictorial element in the resplendent garments, crowns of the figures, and the horses, while smaller fragments are used as architectural ruffage in the stable and trees.

Surrounding the picture, a lush, polychrome original reverse *cassetta* frame parallels its embellishments.

Fig. 1 **A** Attributed to Miguel González (Mexico, active 1692–1704), *Adoration of the Magi*, ca. 1695–1700. Oil on canvas, 85 × 110 cm. Purchase, Louis V. Bell, Harris Brisbane Dick, Fletcher, and Rogers Funds and Joseph Pulitzer Bequest, Maria DeWitt Jesup Fund, and Museo Kaluz Gift, 2022. The Metropolitan Museum of Art, New York (MMA# 2022.408). **B** X-radiograph of **A**

Many extant *enconchados* have lost their original frames [6], which are an essential part of the character of these objects, as many were created as ensembles. Its motifs are common in *enconchados'* frames: flora, usually flowers and fruits, and birds, under which prismatic nacre is embedded, are interspersed with less common red *pastiglia* skeins that emulate coral formations [7–11].

Although *Adoration* is very well preserved, it has suffered from the expansion and contraction of the wooden panel and the subsequent mechanical stresses experienced by the ground and pictorial layers. There are fine cracks spanning the width of the panel along the grain of the wood and scattered losses of the translucent paint layers in areas where the shell meets the ground. The golden cast in *Adoration* has been observed in other *enconchados* [3, 6, 8, 12]. The nature of this warm tonal range is a major conservation and aesthetic concern that has yet to be adequately addressed. In addition to the coloration of the likely original surface of *Adoration*, there is evidence of selective past restorations in which some areas have been cursorily reinforced.

Approximately 300 *enconchados* are known to exist and many are currently found in Spain, where they were often sent as gifts from Mexico by colonial officials and *criollo* elites [8]. García Saiz's publication from the 1980's was the first to catalogue *enconchados* [11] while a more recent publication by Arisa provides an updated inventory including works in private collections [8]. Production of *enconchados* peaked between 1690 and 1730 [13]. Miguel González belonged to a prominent family of artists which included his father, Tomás [14], and his brother, Juan, who was a close collaborator [8, 13, 15–18]. Newly identified as part of a series depicting the life of the Virgin Mary var iously attributed to Juan and/or Miguel González [1, 13, 19], The Met's *enconchado* has been ascribed to the latter on stylistic grounds. Miguel and Juan were not the only ones practicing the *enconchado* technique; other artists included Nicolás Correa, Pedro López Calderón, and Antonio de Santander [13]. It stands to reason that the examination and analysis of paintings from different workshops within this period would likely show variability in technique and execution that will aid in the ongoing study of many currently decontextualized *enconchados.*

Mother-of-pearl inlaid paintings generally depict religious and historical subjects: mostly scenes from the lives of the Virgin, Jesus, and the saints as well as events from history like the conquest of Mexico [13]. Ronda Kasl, curator of Latin American Art at The Met, recognized *Adoration* as one of 12 panels from the series of the *Life of the Virgin* documented in the Spanish royal collection in 1700 and whose first owner was Carlos II of Spain [1]. Along with other *enconchados*, *Adoration* was shown in the Madrid Alcázar, in a gallery known as the Titian Vaults [2]. Like other such works, it would have been perceived as an avatar of the rich resources and artisanship in the Mexican territory [20]. In 1699, 14 *enconchados* also depicting the life of the Virgin were commissioned from Juan González and priced at 26 pesos [14], roughly equivalent to 26 oz of silver [21]. The price suggests the luxury status of these objects and the wealth of the patrons that commissioned them.

Enconchados embody the unique nature of the Viceroyalty of New Spain (1521–1821)—a territory where local Indigenous and Hispanic cultures were influenced by exchanges with Asia and Europe [22, 23]. These influences have been previously researched [6, 10, 24–26], but the nature of the materials used in these artworks and their pre-Hispanic connections remain to be investigated in-depth. European iconographical language as well as influences from Japanese export objects (*namban*), made specifically for the New Spanish and European markets, are found in *enconchados* [3, 25–31].

Tomás, the patriarch of the González workshop, was listed as a lacquerware artist. Scholars have made the connection between *maque*, a Mexican lacquerware technique originating in pre-Hispanic artisanship, and *maki-e*, a type of Japanese lacquerware, noting their aesthetic similarities and technical dissimilitude [6, 10, 26, 32, 33]. *Maki-e* involves the use of the *urushi* resin, gold dust, and black lacquer [34, 35] and was simplified for export objects, which used less coats of lacquer and were fashioned for Western tastes [26, 36]. Traditional Mexican lacquerware, often seen in *xical* or *jícara* (painted and lacquered gourds), used the fat extracted from the *Llaveia axin* insect (*aje*), chía oil, and *tepútzchuta,* a mineral composed of calcium carbonate, magnesium carbonate, silica and an iron oxide [35, 37, 38].

Analysis and identification of shells

Shell species used in *enconchado*s are yet to be identified scientifically, though there has been speculation based on geographical and historical knowledge [6, 12]. Mother-of-pearl is a common material in art objects, but deeper study beyond its nominal identification has only been conducted recently [39, 40]. This is partially due to the compromised integrity of shells in these objects caused by mechanical stresses and post-mortem desiccation of organic components in the nacreous layers, yielding vulnerable samples that are small and fragmented. However, recent integration of principles from biological sciences allows using the internal structure of nacre as an indication of its source [39].

Shells are predominantly composed of calcium carbonate ($CaCO_3$), water, and an organic matrix sometimes referred to as conchiolin [41]. Calcite and aragonite (calcium carbonate polymorphs) are arranged in various structural types generally unique to taxa of the same family or superfamily. There are two inorganic layers in nacreous shells: a prismatic layer (the white opaque shell layer) and nacre, in which aragonite crystals have different tablet arrangements (Fig. 2). The stratified structure of these aragonitic platelets gives the mother-of-pearl its distinctive iridescence [42] and strong resistance to external impact [43], but also confers weak shear strength that contributes to delamination [44]. By first identifying the binary aragonitic arrangement types in the nacre and then evaluating the size of the tablets, a distinctive microstructure emerges that enables the taxon to be identified [39]. For *enconchados*, *Pinctada* and *Pteria sterna* species have been suggested as potential candidates [6, 12]. In this study, we used the nacre tablet arrangement and size to identify the genus to which the shell in *Adoration* belongs.

Origin and use of shells in New Spain

Initially regarded as a mere byproduct of pearl harvesting, nacre-yielding shells were a common and inexpensive commodity by the late seventeenth century in Mexico City [6, 45]. In 1695, two *huacales* (crates) filled with mother-of-pearl veneers to be used as *enconchado* inlays were documented in the estate of the late Doña Teresa de Reste, Marquise of San Jorge [46]. Shells could have been harvested in New Spain, but an alternative source may have been Asia, where trade was recorded on manifests from the annual Manila galleons to Acapulco [10]. It was noted by Giovanni Francesco Gemelli Careri while traveling in New Spain that mother-of-pearl was a coveted good from the New World [6]. It is likely that the González workshop used high quality domestic species, which were lower-priced and easier to obtain than imported ones [47]. However, morphological analysis of nacre does not allow the elimination of Asian shell species with similar sizes of aragonitic tablets,

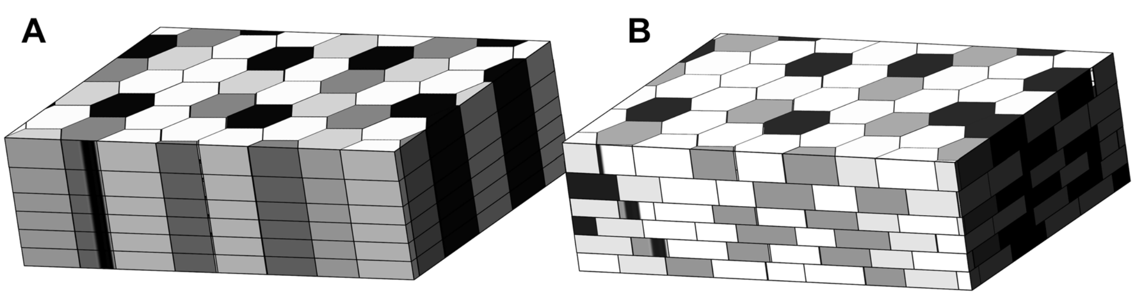


Fig. 2 Schematic of nacreous aragonitic tablets in **A** columnar and **B** sheet arrangements. Illustrated after [43]. Different colors are arbitrarily used for easier visualization

such as *Pinctada margaritifera*, from the Indo-Pacific tropical region [48], while other *Pinctada* species, such as *Pinctada fucata martensii* are ruled out due to their disparate coloration [49].

Shell waste, fragments, and dust were used as components in lime preparations in viceregal New Spain. Antonio de Ciudad Real's *ca.* 1551–1617 account of Fray Alonso Ponce's experiences in Acaponeta and Centipa near Mazatlán posits that "they take many *harrias* [bushels] loaded with them [oyster shells] to Mexico and other parts [...] very good white lime is made of these shells" [50]. The shells mentioned in de Ciudad Real's account have been proposed as *Pinctada mazatlanica* by Villaseñor Black, a plausible identification given the geographical proximity [12]. This species has been found in pre-Hispanic archaeological sites throughout modern-day Mexico in various stages of processing, ranging from intact shells and artifacts to particulate waste byproduct [51–53].

Due to the manual processing of the mother-of-pearl veneers used in *enconchados*, nacre pieces are of different thicknesses and sizes, but dimensions tend to be consistent within similar compositional elements, such as in garments or architectural features. It has been reported that larger pieces, approximately 3–3.5 cm in size, were irregularly fractured by impact and most likely obtained from the central planar part of the shell [27]. It is also common to find smaller, irregular pieces within the architectural elements—likely from recycled flakes, leftover from the refinement of the raw shell to mother-of-pearl [27].

Asian and pre-hispanic shell processing traditions

The existence of mother-of-pearl objects exported from Asia to Mexico during the seventeenth and eighteenth centuries motivates a comparison of nacre production methods among Korean, Japanese, Chinese, and pre-Hispanic traditions. While all share a general sequence—removing the nacre from the shell and then shaping to a desired form—the technology and species used differ. Chinese and Japanese methods begin by grinding the shell to the necessary thickness [34, 40]. In Korea, artisans before the mid-Joseon period (mid-1500's to mid-1600's) shaved away the layers manually but later began using a turning wheel to sand down the shell's outer- and middle-layers [54, 55]. An additional preliminary step in the Chinese method consisted in using white radish puree or boiling the shell in water to soften it prior to cutting [56].

A blunt instrument was often used in a percussive manner to crack the sheet of nacre to produce conchoidal pieces [36, 57, 58]. If more specific shapes were desired, tools such as chisels, knives, needles, awls, or wires were employed [34, 54–56, 58]. Fresh-water and marine Asian mollusks were used, including sea snails, abalone, pearl oysters, giant clams, and fresh-water pearl mussels [40, 54, 55].

Conversely, pre-Hispanic techniques used lithic and basalt tools [51] and shell species from the Pacific and Atlantic coasts of Mexico [52, 59–62]. Modern reconstructions using macro- and microscopic 'work trace study' methodologies [51, 52, 62] have replicated and analyzed conchological manufacture in objects from the Templo Mayor de Tenochtitlán and Hidalgo. Expanding upon ethno-archaeological research [53, 63], the following refinement process was proposed: surface abrasion with basalt stone tools to isolate the nacreous layer; cutting with obsidian tools to preform; edge abrasion with basalt tools; perforation with flint tools or thick reeds and an abrasive, such as shell dust or sand, and water; incision with obsidian tools; in some cases, openwork with obsidian and/or basalt tools followed by an abrasive, such as sand, quartz grains, shell powder, or seeds, and water; and burnishing and/or polishing with a soft material most similar to leather. Finally, *sgraffito*, fret working, and/or carving was sometimes done to complete the decoration of the object [51].

Traces of compounds used in the manufacture of *Pinctada mazatlanica* objects found in Tula, an archeological site northwest of Mexico City, were identified and characterized with optical microscopy and secondary electron signal SEM, which guided modern reconstructions [52, 62]. For these experiments, andesite (primarily SiO_2) was used to abrade the surface and regularize edges, obsidian was employed for incisions and cuts, and chert (quartz) burins and polishers to perforate and brighten the pieces [52, 64].

Shell processing was spread throughout Mesoamerica, where there were workshops that employed full-time artisans to produce nacre and manufacture carved utilitarian and ceremonial objects in both coastal and inland regions [51–53, 65]. Mother-of-pearl objects were imbued with meaning related to water, fecundity, and the stars [65, 66]. Relations to Aztec deities are recorded in the Codex Borbonicus from the sixteenth century [66]. *Ehecacoxcatl* (breastplates), *epcololli* (twisted shell earrings) and chokers made of *oliva sayana* shell evoking these gods have been found in various stages of production in the Templo Mayor de Tenochtitlán [51, 60, 66]. Nacreous beads have been uncovered in low-status residential groups in Mayan sites like Tikal and Chichén Itzá [60, 63, 67]. A clear understanding of the shell manufacturing processes in *enconchados* would shed light on the cultural influences at play in these fine artworks.

Previous technical investigations of *enconchados* used microscopy, X-radiography, and the examination and chemical analyses of microscopic samples primarily to survey materials and stratigraphy [3, 4, 9, 68–71], with most reports found in cultural institutions' internal files. To our knowledge, no non-invasive elemental imaging to characterize the artistic materials have been performed thus far. *Adoration*, with its sound provenance, exemplifies the refinement of the arts produced in Spanish America as a response to the taste for Asian goods during the seventeenth and eighteenth centuries. Therefore, the present study aims to further existing knowledge of the materiality of *Adoration* and *enconchado* paintings in general in the context of artistic practice in New Spain.

Materials and methods

Technical analysis relied mainly on in situ, non-invasive methods; the analysis of eight microscopic samples and of two shell samples assisted in the interpretation of the results from the non-invasive methods and helped answering further questions. Initial inspection of the *enconchado,* microscopic examination and documentation of the surface, X-radiography, and infrared reflectography (IRR) were done in The Met's Department of Painting Conservation. All scientific data was gathered in The Met's Department of Scientific Research, except for some SEM–EDS measurements which were performed at Columbia University in New York City.

Samples and cross section preparation

Samples were investigated to identify pigments, materials in the ground preparation, and the morphology of the shell(s). Sample cross-sections were prepared when stratigraphic information was necessary. Samples S1-3 and S5 were prepared by mounting them in Technovit® resin and polishing using Micromesh® cloths. Samples S6-10 were prepared by mounting them in Buehler EpoThin 2® Epoxy and polishing using Micromesh®. Sample S2B and a *Pinctada mazatlanica* reference sample were prepared by cutting the larger shell sample, mounting it on stiff carbon tape perpendicular to the puck, and embedding it within carbon-based black paint as it stiffened, to reveal the nacreous layered side. Sample S4 was analyzed without mounting.

Pinctada mazatlanica reference samples

Reference shells were purchased from Richard's Seashells (http://www.richardsseashells.com/), Lake Alfred, FL. The purchase of *Pinctada mazatlanica* is not restricted in the US to our knowledge.

Microscopy

For the examination of the wooden substrates of the frame and panel, canvas fibers, shells, and paint cross-sections, a Zeiss Axio Imager M2M, an Axiocam HRc digital camera, and AxioVision software were utilized. Samples were examined and photographed using polarized, visible and ultraviolet lights.

X-radiography

The X-ray source and controller are a TFI "Hotshot" portable industrial X-ray unit, consisting of 603 head and 805D Control, 120 V, 60 Hz (cat. no. 600 150; purchased from Associated X-ray Corporation, New Haven, CT, in 1983). The system has a range of 10 to 110 kV, with a 0.5 mm focal spot and a 96.5 cm radiation beam. Images are recorded onto Industrex Flex XL Blue 5537 plates and digitized with a Carestream HPX-1 scanner.

Infrared reflectography (IRR)

IRR images were acquired with an OSIRIS InGaAs near-infrared camera with a 6-element, 150 mm focal length, f/5.6—f/45 lens, and 900–1700 nm spectral response.

Point X-ray fluorescence (XRF)

Point XRF measurements were performed using a Bruker Artax® with unfiltered radiation from a Rh tube under ambient conditions. The X-ray generator was set to 50 kV and 700 µA. Spectra were acquired for a 480 s dwell time.

Macro-X-ray fluorescence (MA-XRF)

MA-XRF was carried out using a Bruker M6 Jetstream® instrument equipped with a 30 mm^2 XFlash® silicon drift detector (SDD) and an air-cooled micro-focus Rh-target X-ray tube operated at 50 kV and 0.5 mA. The full painting was mapped in two sections, each with a 580 µm spot size, a 650 µm step size, and a dwell time of 80 ms/pixel; an area of the frame was mapped with a 580 µm spot size, a 600 µm step size, and a dwell time of 80 ms/pixel. The scans of all areas were performed in ambient conditions, using unfiltered radiation. Calibration of the instrument is checked periodically using a set of NIST standards. The spectra were processed using the Bruker M6 Jetstream® software.

Raman spectroscopy

Raman spectroscopy measurements were performed using a Renishaw System 1000 coupled to a Leica DM LM microscope. Spectra were acquired using a 785 nm laser excitation and a 50 × objective lens with integration times between 5 and 10 s. A 1200 lines/mm grating was used in conjunction with a thermoelectrically cooled CCD detector. Powers at the sample were set between 0.5 and 5 mW using neutral density filters.

Scanning electron microscopy- energy dispersive X-ray spectrometry (SEM–EDS)

Samples S1 and S4-10 were carbon-coated up to 14 nm while samples S2A and S2B and the *Pinctada mazatlanica* reference samples were gold-sputtered to approximately 5–10 nm.

At The Met, SEM–EDS analyses were performed on the samples S1–S6 and S8–10 with a FE-SEM Zeiss Σigma HD, equipped with an Oxford Instrument X-MaxN 80 SDD detector using 20–25 keV beam energies. Backscattered electron (BSE) images, energy-dispersive spectrometry (EDS) analysis, and X-ray mapping were carried out with an accelerating voltage of 20–25 kV in high vacuum. Elemental compositions and atomic percentages were processed using AZTEC software.

At Columbia University, SEM–EDS measurements were performed on the cross-section S7 with a VP Zeiss Σigma HD using a beam energy of 15 kV. EDS was performed with a Bruker XFlash 6 | 30 attachment. Spectra were collected with a beam energy of 15 kV. Elemental compositions and atomic percentages were estimated by integrating under the characteristic spectrum peaks for each element using Bruker ESPRIT 2 software.

Results and discussion

Due to the complexity of *Adoration*'s construction, we have included a diagram of the stratigraphy (Additional file 1: Fig. S1) to facilitate the visualization of the results as these are discussed in a sequence that follows the structure of the painting from the bottom up. The samples are listed in Additional file 1: Table S1, and the locations where these samples were taken are indicated in Additional file 1: Fig. S2.

Support

Adoration was executed on a 12-mm thick wooden support made of four, horizontally butt-joined planks that are secured with two vertical dovetailed crossbeams at verso (Additional file 1: Fig. S3). Previous studies have discussed a variety of panel constructions that led to a grouping according to their function, though variations of plank alignment have been noted within the same series [4, 27, 70]. *Adoration*'s panel construction is akin to those of paintings from the same series at Museo de América [4, 27]. Although no in-depth technical analyses of the species/origin of the wood used have been undertaken, previous reports offer pine [19] and cypress [72] as possibilities. Optical microscopy of tangential and radial cross-sections of a sample of the wooden substrate used to construct the panel and frame suggests the same Cupressaceae family, possibly the *Cupressus lusitanica* species native to Mexico.

A layer of simple-weave canvas was adhered with glue to the face of the wooden panel. Similar to Italian panel paintings, the fabric serves as a bulwark against mechanical stresses. It has been reported that some *enconchado*s were found with no canvas support [11]. Analysis of weft and warp of canvas samples obtained from the painting's upper right corner indicated bast fibers. The support was then prepared with thick white ground layers.

X-radiography (Fig. 1B) provides visual insight into the complexity of this object and its condition, particularly its wooden support, different forms of shell pieces, and signs of aging. The shells were applied with an adhesive over the first ground layer and can be found mainly in three different sizes—large, conchoidal pieces in the figurative elements; medium triangular shapes on the molding of the frame; and minute shards in architectural features in the painting. The X-radiograph also shows a previously observed feature in many shells—relatively regular perforations [3, 4, 24, 27, 70] that will be discussed below. Finally, it shows cracks in the wood, minute paint losses, and detachment of a few shells—most likely products of mechanical stresses experienced by the support due to the expansion and contraction of wood orthogonal to the stasis of the mother-of-pearl. At some point in time, the cracks in the panels were reinforced at the verso as part of a restoration with six dovetails embedded against the grain of the support.

Ground preparation and underdrawing

When areas of paint loss were examined under a microscope, it was noted that the ground preparation applied over the canvas consists of several layers. The elemental distribution map of calcium (Ca) obtained by MA-XRF (Fig. 3A) showed the location of this element in the ground and the inlaid shells. In Sample S1 (Fig. 4), SEM analysis showed two layers in the ground preparation: a coarsely ground layer, which was not captured in its totality in this sample, and a finely ground one, approximately 100–120 um, on top (Additional file 1: Fig. S4).

Raman spectroscopy showed that both layers are mainly composed of gypsum ($CaSO_4·2H_2O$), by its characteristic peaks at *ca.* 414, 493, 619 and 1008 cm^{-1} [73]. Gypsum (or *chimaltizatl* in Nahuatl) was described as readily available by Toribio Benavente de Motolínia in Mexico in 1536 [74, 75]. This material has been previously identified

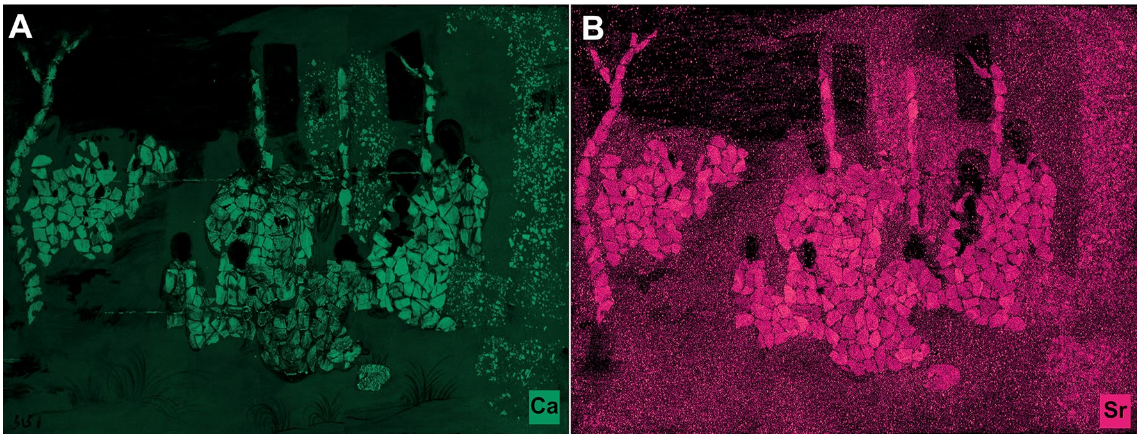


Fig. 3 Elemental distribution maps acquired via MA-XRF on *Adoration*: **A** Ca and **B** Sr

in the ground layer of several Mexican viceregal artworks such as *enconchados* [4], panel paintings [74], easel paintings [76, 77], and lacquerware objects [78]. A shard, primarily aragonite, a naturally occurring crystalline form of calcium carbonate with main peaks at *ca.* 206, 703, and 1086 cm^{-1}, was found in Sample S1 (Fig. 4B, F) [79]. The morphology of this shard, as observed by SEM, and its composition indicate that it is shell. This may be the first time that shell is reported in a ground preparation of a painting.

As mentioned above, the use of shell in lime for wall preparations in New Spain has been documented [50]. Substantial amounts of ground shell have been found in the context of pre-Hispanic mother-of-pearl manufacturing workshops [53]. In the ground of *Adoration*, shells may have been used as a bulking material that also contributed to the reflective properties of the gypsum. Coincidentally, evidence of oyster shells being used in paint has been found elsewhere: *Gofun*, a white pigment, was employed for its covering power and eggshell surface quality in the ground of Japanese lacquerware objects [34, 80]. Therefore, it is possible that these material properties motivated the use of shell in Mexican *enconchado* grounds.

In *enconchados*, the initial underdrawing guided the composition and the placement of the shells. Over the ground and underneath the translucent shell, optical microscopy allowed visualization of underdrawing as faint dark lines, for example underneath the Virgin's robe (Additional file 1: Fig. S5A). Infrared reflectography revealed a carbon-based medium in this underdrawing (Additional file 1: Fig. S5B, C). The distorted appearance of the underdrawing is most likely an optical effect produced by the translucent pearlescence of the shell. Even though the underdrawing appears fluid at times beneath the shell, some areas have a dry, reticulated appearance. This might be explained by the presence of an organic adhesive used to secure the shells on the ground, which pulled the underdrawing medium conferring it a granular surface.

Shell inlays

Details of conchoidal inlaid shell pieces are shown in Fig. 5A. We removed a 1.5 mm-sized fragment of shell from the right edge of the painting (Sample S2, Fig. 5B). Backscattering electron (BSE) imaging was performed on a fragment of Sample S2, labeled as Sample S2A. By orienting this unmounted and unpolished fractured shell sample perpendicular to an SEM aluminum (Al) puck, we characterized the layer height and fracture pattern (Fig. 5C). We identified the aragonitic layer as a sheet nacre with a random vertical arrangement of the tablets [39]. The remaining fragment from S2, Sample S2B, was embedded in resin and polished to obtain a clearer picture of the layer size (Fig. 5D). In both samples, the average aragonitic layer thickness is approximately 450 nm.

The hexagonal sheet morphology of the nacreous layer found in Samples S2A and S2B distinguishes the shell as a marine bivalve mollusk [39, 81] while its size is within the range reported for *Pinctada* species [39, 40, 82–85]. To correlate these results to a reference sample, *Pinctada mazatlanica* shells were sourced. The pristine shells were processed in a similar manner as in pre-Hispanic times [51, 52]: the outer layer was sanded off, and a fret saw (in lieu of an obsidian knife) was used to separate the nacre layer. BSE imaging of the reference sample revealed the same nacre type (sheet) and size, approximately 450 nm (Fig. 5E, F). Additional samples containing shell (Samples S1 and S3) showed the same nacre type and size (Additional file 1: Fig. S6).

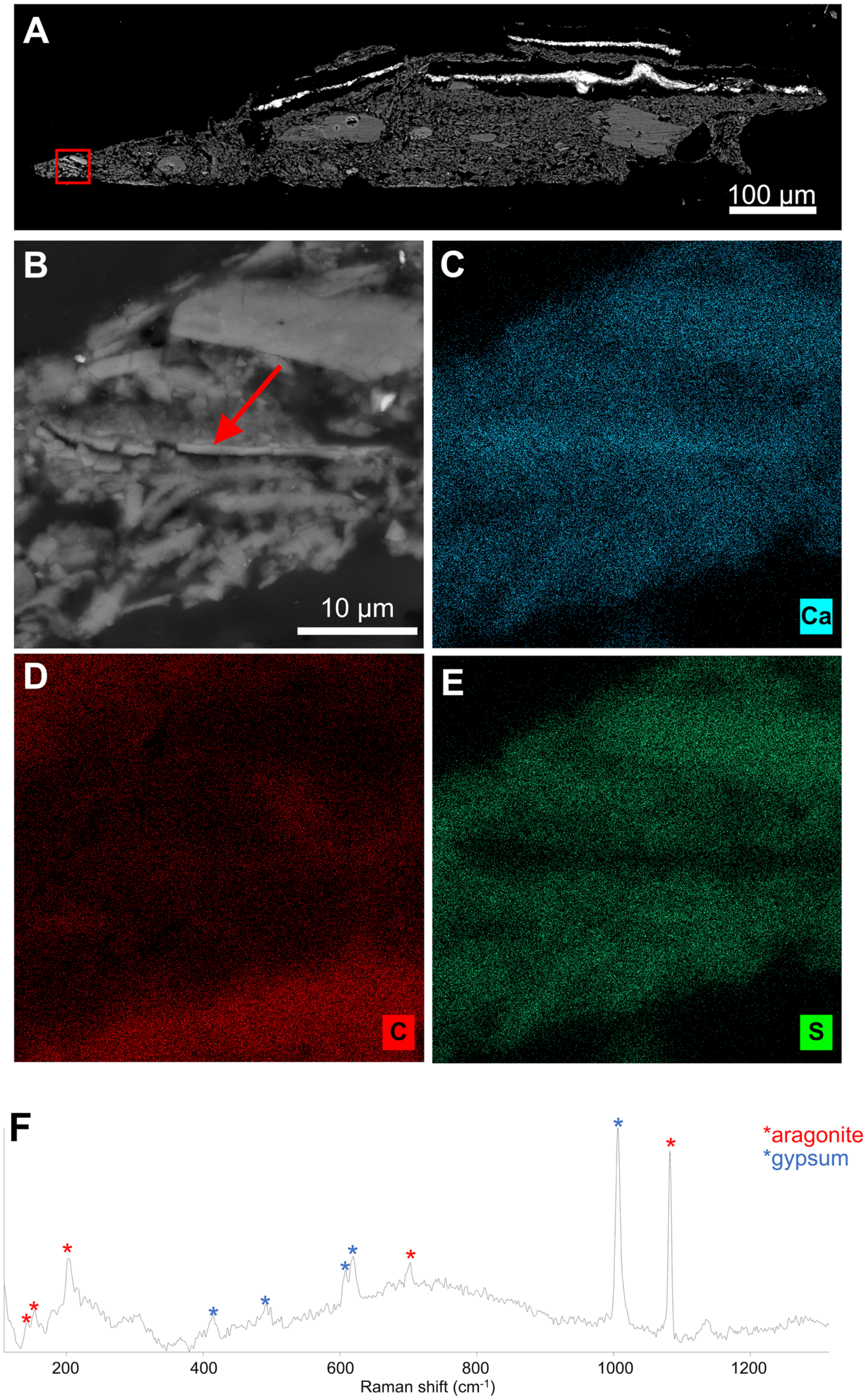


Fig. 4 **A** SEM-BSE image of Sample S1, 100x. The red square indicates the areas where images **B**–**E** were acquired. **B** detail of **A** with a red arrow pointing to a shell inclusion in the ground, 1360x. **C–E** EDS maps of Ca, C, and S, respectively. **F** Raman spectrum acquired from the shell inclusion showing an aragonitic phase in a gypsum matrix

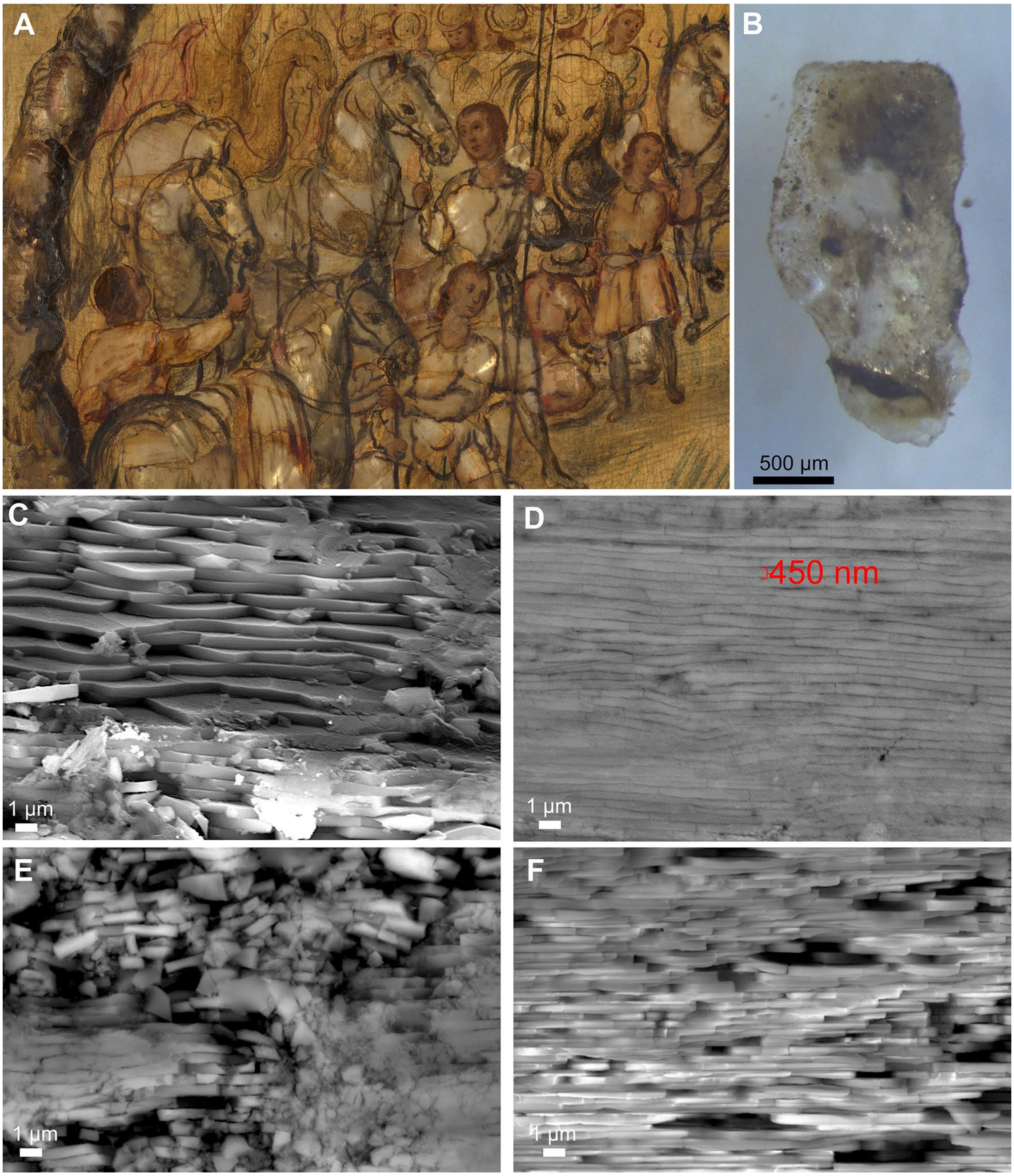


Fig. 5 **A** Detail of inlaid shells in the painting. **B** Intact shell Sample S2. **C** BSE image of Sample S2A showing the hexagonal fracture pattern of the unmounted and unpolished sample, 5000×. **D** BSE image of the mounted and polished Sample S2B showing the size of the nacreous layers, 5000×. Red brackets indicate one nacreous layer, approximately 450 nm thick. **E** Sample of *Pinctada mazatlanica* shell unpolished and unmounted, 5000× and **F** same sample, mounted and polished, showing analogous size and fracture pattern as Samples S2A and S2B in **C** and **D**, 5000×

Based on our SEM analysis along with historical and cultural contexts [6, 12, 52, 61, 86], we propose the following *Pinctada* species as possible candidates: *Pinctada mazatlanica*, from the Pacific Coast, *Pinctada imbricata* from the Caribbean Sea, and *Pinctada margaritifera*, from the Philippines [49]. In this case, we can discount other *Pinctada* species and *Pteria sterna* species due to the off-white color of mother-of-pearl observed in *Adoration,* which is the result of its *ca.* 450 nm nacreous layer refraction.

Additional characterization of the inlaid shell's calcite phase in Sample 2B by Raman spectroscopy showed characteristic peaks of aragonite at ca. 147, 208, 703, and 1086 cm^{-1}, similar to the Raman spectrum collected from the shell inclusion in the bottom layer of the ground preparation of Sample S1 (Fig. 4F). This aragonitic phase identification confirms that the inlaid shell was sourced from nacre.

MA-XRF revealed the distribution of Sr, present in the larger shell inlays and in smaller fragments and particles throughout the painting (Fig. 3B). Sr was also identified by point XRF in the inlaid shell Sample S2B (Additional file 1: Fig. S7). The intercalation of Sr from seawater in the shells' microstructure is a known phenomenon [85], has been observed in higher amounts in marine shells than in freshwater shells [49], and has been noted in *Pinctada* nacre [56].

SEM–EDS analysis of the shell inclusion in cross section Sample S1 confirmed the presence of Sr (Additional file 1: Fig. S8, Table S2). Therefore, the chemical and morphological characteristics of the shell inclusion in the bottom layer of the ground preparation in Sample S1, namely the presence of aragonitic sheet nacre with a tablet size of approximately 450 nm, prove that this is indeed shell, and likely from a *Pinctada* species.

While we can assign the presence of Sr to the larger inlaid shells and to the smaller shell fragments and inclusions, the source of the more finely divided Sr-containing material (Additional file 1: Fig. S9) could not be definitively identified. It could originate from shell dust or from another Sr-containing material associated with gypsum that will be discussed below in the Frame section. As mentioned before, shell dust has been noted in architectural ground preparations in New Spain and as a white pigment in Japanese artworks.

Perforations and abrasion marks in the inlaid mother-of-pearl

Further inspection of the X-radiograph (Fig. 1B) revealed an intriguing detail: a number of shells have perforations, with what visually appear to be consistent shapes and sizes (Fig. 6). Similar perforations have been reported in other *enconchados* in the collections of Museo del Prado and the Museo de América in Madrid, including *Ascension* from *The Life of the Virgin* series at the former [3, 27, 70].

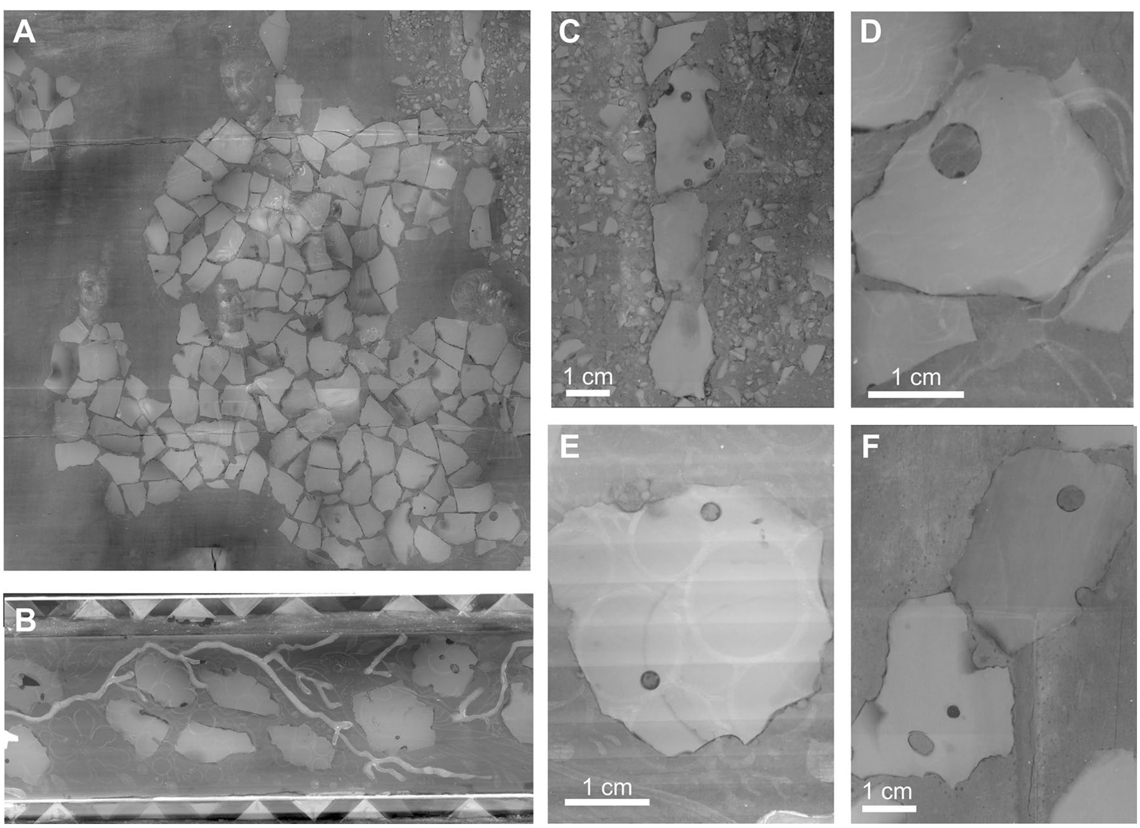


Fig. 6 Details of the X-radiograph showing **A** large conchoidal shell pieces in the figurative elements; **B** medium-sized triangular pieces in the inner and outer moldings of the frame; **C** minute shell shards surrounding the supporting beam of the thatched stable behind Joseph. **D–F** Conchoidal shells in the painting and frame, some with multiple perforations each

Numerous marine species can bore holes in shells, in some cases by a combination of physical and chemical means; these drill-holes may vary in morphology and size [87].

Holes have been recorded in manually processed shells found in caches in pre-Hispanic temples in Hidalgo [52] and Tenochtitlán [60], and Suárez Diez reports five distinct types of man-made perforations in about 1000 objects from the archaeological site at Presa Adolfo López Mateos: conical, cylindrical or tubular, biconic, lenticular, and irregular [88]. Many of the processed shell artifacts studied showed multiple perforations in one object, with various uses as earrings, beads, and pendants amongst others [51–53, 88].

The repurposing of pre-Hispanic objects in paintings is a known practice: for example, Murillo reused Mesoamerican unpainted obsidian "smoking mirrors" as a support [89], as did other European painters [90], and the same practice was followed by artists in New Spain [91]. However, in the case of *enconchados*, no material investigations to prove this have been conducted.

It has been proposed that perforations found in 15th-century mother-of-pearl veneers from the Templo Mayor de Tenochtitlán were used to secure them onto *mexica* garments [60]. Due to the organic and decaying nature of the cloth in these garments, the mother-of-pearl veneers are often all that remains. It is conceivable that *enconchado* artists working in the seventeenth century, such as those in the González workshop, would have encountered these pieces in such a state. It is hard to ascertain without full material and documentary evidence, but the use of mother-of-pearl in clothing may have a direct connection to its use in *enconchados*. In these paintings, the nacre is mainly, and sometimes exclusively, used to depict vestments.

Other functions for the presumed man-made holes in shells in *enconchados* have been put forward, such as to string them together for transportation or storage [70]. However, *Pinctada* species are quite resistant to mechanical stresses [83, 84] so the integrity of the shells during transportation or storage should not have been a major source of concern that would warrant the labor-intensive task of making a hole in each shell for protection. Moreover, many shells have more than one hole, with some of them close in proximity. These observations render the hypothesis of perforations for transportation or storage unlikely.

It is tenable that the veneers were obtained from both archaeological and contemporary sources. Further ethnographic and scientific research is necessary to determine if pre-Hispanic shells were repurposed in *enconchados* and, if so, establish whether their use was adaptive or was more symbolically and culturally significant. The possible contemporary sources of shells have not been studied in depth, but include such industries as mother-of-pearl button making, jewelry, marquetry, and household goods in seventeenth and eighteenth century Mexico.

In *Adoration*, the presence of silicon oxide and of abrasion marks on the surface of shell Sample S4 were identified and visualized (Fig. 7, Table 1); similar compounds and abrasion marks have been reported in objects found in the Tula archaeological site [52, 62]. This finding hints to a possible continuation of pre-Hispanic shell processing methods and refinement.

In keeping with analogous Japanese [34] and Korean [54, 58] practices, a gesso layer was applied up to the surface of the mother-of-pearl once it was secured in place [4], filling the perforations. Due to its smooth, compact appearance, it is likely that the surface was wet polished to bring the ground and shell surfaces to the same level. This finishing gesso layer has been reported in other *enconchados* [4, 34, 70]. SEM–EDS imaging of a sample including shell, gypsum, and pigment (Sample S3) showed that the shell is surrounded by gypsum (Additional File 1: Fig. S6), over which pigment was applied. Due to the filling and leveling of the perforation laden veneers, we were unable to determine the morphology, internal shape, and depth of these holes – and hence, how they were made.

Gilding and pictorial layers

The gilding in *enconchados* was applied to achieve a dynamic play of light between the metal and the mother-of-pearl. MA-XRF was used to visualize the distribution of gold (Au) throughout *Adoration* (Fig. 8A). The delicate shell gold decoration embellishes the robes as well as their linings, the Magi's crowns, and the halos of the Holy Family (Fig. 8B). It also adds dimensionality to the trees and ground shrubs (Fig. 8C). Examination of the surface shows that shell gold was applied with fine, articulated brushstrokes, often just the width of a few bristles, directly over the shell (Fig. 8D, E). The gold is not only found directly over the nacre, but sometimes interspersed amongst the paint layers.

Analysis of the shell gold in a paint cross-section obtained from Melchior's robe (Sample S5) showed relatively small amounts of silver (Ag, 1.11 wt%) and copper (Cu, 0.69 wt%) (Additional file 1: Fig. S10, Table S3). The morphology of the metallic lamellae seen here is consistent with that resulting from methods used to make shell gold, in which gold leaf is ground to a fine powder and dispersed in an organic binder to achieve a fluid medium [92], popular among New Spanish painters [93–95]. Optical microscopy showed the presence of another metallic paint layer

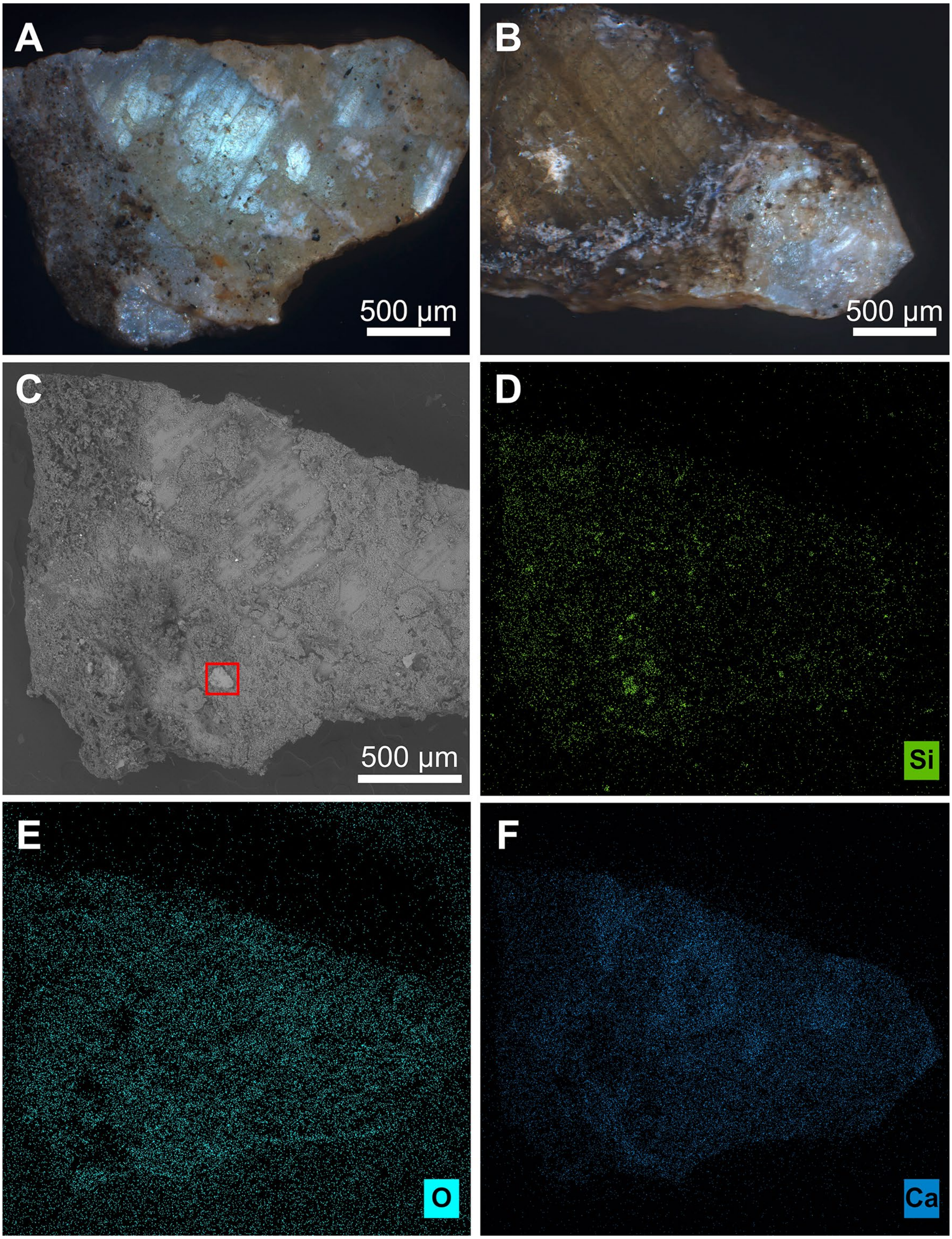


Fig. 7 Photomicrographs taken with visible illumination of **A** the front and **B** the back sides of the shell Sample S4, original magnification 50x. **C** SEM-BSE image of Sample S4 showing abrasion marks from the processing to separate the nacre layer. **D**–**F** EDS maps of Si, O, and Ca, respectively. The silicon-containing residues embedded on the surface are likely from the tool(s) used to abrade the shell. The elemental composition of the silica particles in the area indicated with a red square in **C** is included in Table 1

Table 1 Elemental composition of the particles in the area indicated with a red square in Fig. 7C

Element	Line type	Apparent concentration	k ratio	Wt%	Wt% sigma
Si	K series	8.84	0.07	27.95	2.29
S	K series	1.33	00115	4.97	1.46
Ca	K series	6.33	0.0565	19.87	2.26
O				47.21	
Total:				100	

above the original gilding with a much cooler tonality and dark reticulations. This is the result of a restoration campaign and will be discussed later.

The use of inorganic pigments in the pictorial layer was imaged in the elemental distribution maps for lead (Pb, mostly lead white, $2PbCO_3{\cdot}Pb(OH)_2$), mercury (Hg, vermilion HgS), iron (Fe, ochre/s) and manganese (Mn, umber) (Additional file 1: Fig. S11).

The sky was painted with brushy strokes of mostly Pb white-containing paint, leaving areas in reserve for architectural elements, vegetation, and the bodies of the figures (Additional file 1: Fig. S11A). The use of Pb white has been previously documented in other *enconchados*, which exhibit similarly brushy application [27]. Raman analysis of Sample S1 confirmed the presence of Pb white in the pigmented layer of the stratigraphy by its characteristic peak at ca. 1050 cm^{-1} [73]. In some areas, Pb and Hg distributions overlap where González painstakingly modulated the Pb white-containing paint with vermilion to achieve variable flesh tones (Additional file 1: Fig. S11B). Unmixed vermilion was used to paint the number "515" in the bottom left corner of the

Fig. 8 **A** Distribution map of Au acquired by MA-XRF. Details of shell gold applied to **B** the edges of garments and halos and **C** the greenery in the foreground. Detail of Melchior's pelted robe observed at **D** 100× and **E** 110× magnifications, respectively, with white arrows pointing to finely painted shell gold brushstrokes over the shell

painting [96]; this number corresponds with a 1747 inventory of the royal palace in Madrid [1, 2].

The Fe distribution map (Additional file 1: Fig. S11C) indicates the use of ochre(s) throughout the painting. In the figures, ochre was used in the eyes and hair of the figures, Balthazar's face and hands, in the wood and the thatched roof, the bull in the foreground, and the outlines of the figures and their robes. The Mn distribution map shows that umber is present in the darkest part of the shadows in the architectural features in the background and the bull in the lower right corner (Additional file 1: Fig. S11D).

There are at least two identifiable greens in *Adoration*. The first one was achieved through an optical effect by layering an organic blue and a yellow coating. The presence of indigo in the foreground's finely painted brushy vegetation was confirmed by Raman spectroscopy (Sample S6, Additional File 1: Fig. S12). No yellow pigment particles were observed mixed with indigo in Sample S6. This supports the idea that the original varnish had a warm tint at the time of application and was used to confer the painting a yellow cast overall. Optical green mixtures have been found in other *enconchados* [4, 9, 32, 71]. The second green, a copper-based pigment, can be visualized in garments where the elemental distribution map of Cu shows no other metals (Additional file 1: Fig. S13) [97]. The colored glazes in *Adoration* that cover the garments of the figures appear lighter when over the shells and darker when they rest upon the abutting ground preparation.

Two sets of brush-applied outlines, one brown and one black, were observed with the naked eye throughout the composition (Additional file 1: Fig. S14A), visualized by optical microscopy (Additional file 1: Fig. S14B), and identified as Fe-containing by MA-XRF (Additional file 1: Fig. S11C). The analysis by SEM–EDS and Raman spectroscopy of Sample S3 did not allow us to determine if an Fe-containing ink was used in these traces.

Previous restorations

Microscopic examination revealed the presence of metallic paint overlapping some of the original shell gold brushstrokes. Its application over the finished composition indicates that it is part of a restoration campaign to strengthen the original gilding. It is noticeably cooler, thicker, and less refined than the original gilding with slight reticulation. MA-XRF allowed visualization of this restoration, characterized by the presence of Cu and zinc (Zn), which mostly overlap Au, along with chromium (Cr) (Additional file 1: Fig. S15).

The Zn distribution overlaps with that of Cu (Additional file 1: Fig. S15A and B), although there are additional areas of a Cu-based green pigment as discussed before. Areas where the Cu–Zn-containing paint was not applied over the original Au gilding can be observed in the tree, background figures, cloaks, and shrubbery in the foreground (Additional file 1: Fig. S15C).

Micro sampling was undertaken where Cu and Zn distributions overlap (Sample S7). SEM–EDS analysis of this sample showed the presence of tin (Sn) within the Cu–Zn matrix. The SEM–EDS imaging of this sample is presented in Fig. 9, and a point quantification in the Additional file 1: Fig. S16, Table S4. The morphology of the metallic lamellae is consistent with that of 'bronze powder' paint [98]. Similar to the original shell gold used in the painting, pieces of the alloy were processed by grinding, which produced the folded over appearance, and mixing with an organic medium [92]. 'Bronze powder', which became commercially available in the 1840s following an industrial process invented by Bessemer in Nuremberg [92], was used as a cheaper alternative to shell gold [99].

A chrome-based pigment was observed by MA-XRF (Additional File 1: Fig. S15D), and visual examination showed it to be a dull green, indicating it is most likely a chrome oxide. Yellow and green chrome-based pigments were developed in the early nineteenth century [100].

Microscopic examination indicated that the applications of the 'bronze'- and chrome-containing paints belong to the same campaign. Based on the dates of production of these materials, this restoration cannot date earlier than the 1840's.

Frame

The panel is secured to a reverse profile *cassetta* frame with refined decorations suggesting that, most likely, it was made in the González workshop (Fig. 1A, details in Fig. 10). The reverse frame has four members assembled with shouldered half lap joints and inner and outer trapezoidal moldings separated by a sloping flat (Additional file 1: Fig. S3). The moldings are decorated with alternating triangular shell veneers and the inner molding creates a shelf for the rebate. Overall, the aesthetics of the frame reflects the Asian influence on Mexican lacquerware wooden objects [7, 29, 101]. As with the painting, shell gold and nacre were used in concert to elicit luster.

MA-XRF measurements undertaken in an area of the upper member of the frame showed the distribution of shell gold, which aligns with the outlines of the grape clusters, leaves, and birds (Au, MA-XRF Fig. 11B). As in the painting, the original gilding was enhanced by a superficial restoration campaign of 'bronze' paint, as seen in the overlap of Zn and Cu in the elemental distribution maps (Additional file 1: Fig. S17).

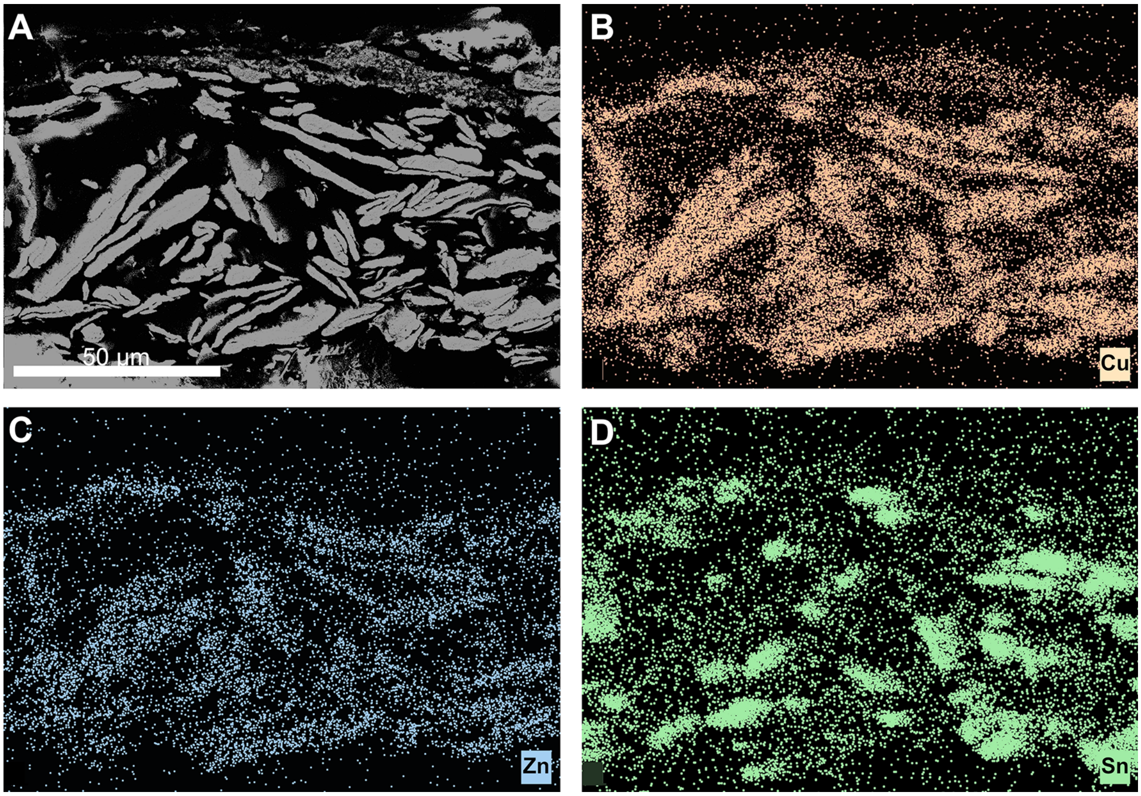


Fig. 9 Sample S7, taken from an area containing the 'bronze' paint restoration: **A** SEM image, 500×; and **B–D** EDS maps of Cu, Zn, and Sn, respectively

Discrete areas containing silver (Ag) were identified in the frame via MA-XRF (Fig. 11E). These correspond to areas of shell loss in the trapezoidal moldings, which indicates that this metal leaf is a later restoration, applied to mimic the reflective properties of the nacre.

SEM–EDS and Raman spectroscopy analyses were performed on two cross-sections, one taken from the dark paint in the outer trapezoidal upper molding (Sample S8) and another from the red paint in the richly decorated flat (Sample S9). On Sample S8, these analytical techniques revealed a ground preparation applied over the wooden support consisting of two layers composed of gypsum, a coarse one at the bottom and a fine one on top (layers 1 and 2 in Fig. 12A–C; EDS in Fig. 12D-E), followed by a thin layer mainly composed of a C-based black (layer 3 in Figs. 12A-C; EDS in Fig. 12F) and a layer that appears to be mainly organic in nature (layer 4 in Figs. 12A-C; EDS Fig. 12F). Over these original layers, there is a later campaign of preparation and paint. The preparation is composed mainly of $CaCO_3$ and contains relatively large particles of Pb white (layer 5 in Fig. 12A–C; EDS maps in Fig. 12D, G). Over this preparation, there is a thin layer composed of Zn white (Zn oxide; layer 6 in Fig. 12A–C; EDS Fig. 12H). A second black layer containing a C-based black (layer 7 in Figs. 12A–C; EDS in Fig. 12F) was then applied, followed by a C-containing layer, possibly organic in nature. All the layers above layer 4 (red line in Fig. 12A, B) can be assigned to a restoration campaign that attempted to level out the original painted molding, possibly to disguise existing losses in these protruding elements of the frame. The re-grounding and overpaint is unevenly concentrated in the moldings and not in the decorated flats and can be dated to no earlier than the middle of the nineteenth century because of the presence of Zn white, which became popular after the mid-1840's [102].

The gesso preparation throughout the frame is inlaid with shells, some of them perforated in a similar manner as shells in the painting, over which pigmented glazes were applied to accentuate their iridescence (Fig. 10A, B). The shells in the inner and outer edges of the frame differ from the painting's inlaid pieces due to their precise triangular shape (Fig. 6B) which contrast with the more organically shaped pieces. Not all the shells were formed mechanically. To embellish the flats, the artist cleverly used a C-based black over the shells to depict circular features, such as the volutes in the corners, birds, and grapes (Fig. 10C). This efficient use of paint creates

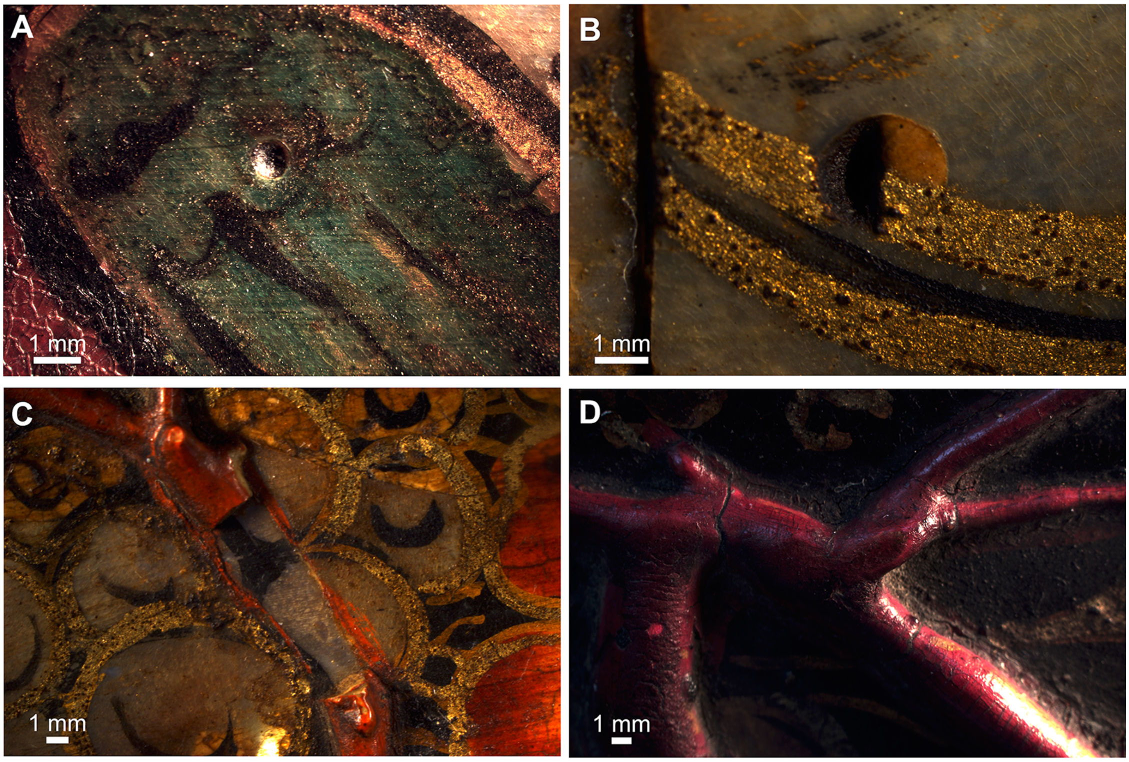


Fig. 10 Photomicrographs of areas in the frame showing **A, B** perforations running through the depth of the shell that have been partially filled with gesso, photographed at 150× and 170× magnifications, respectively. **C** Detail of a loss in the coral *pastiglia* exposing an area that shows the application of black paint over the shells to create marquetry-like contours, observed at 70× magnification. **D** The irregular thickness of the red *pastiglia* accentuated with raking light illumination, captured at 63× magnification

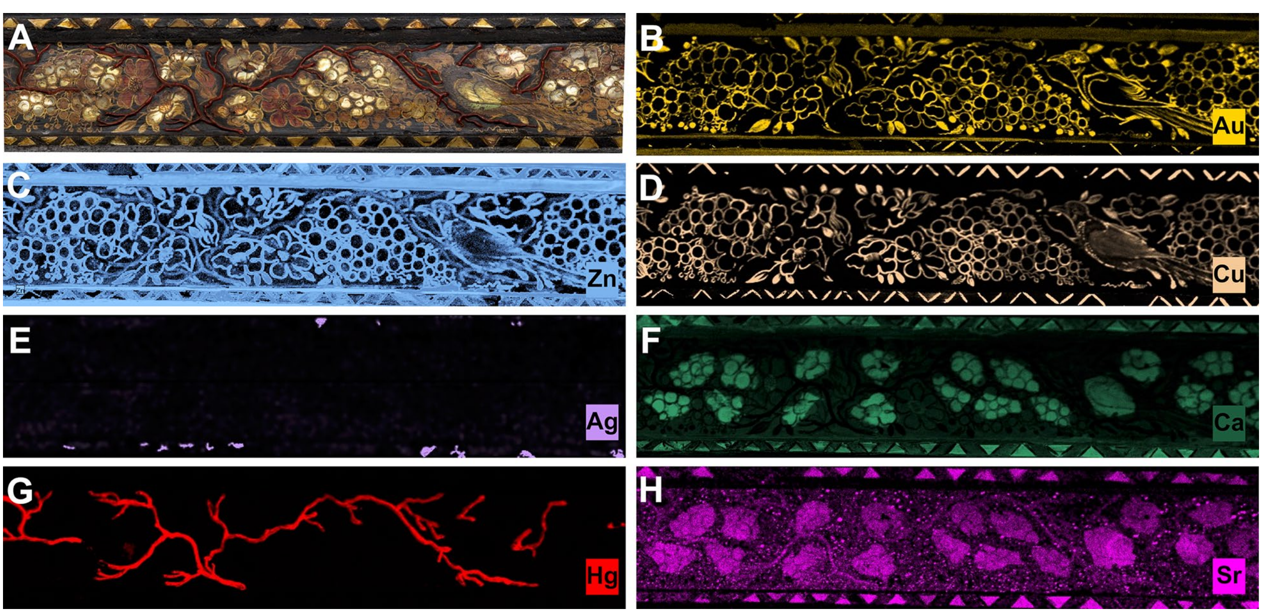


Fig. 11 Distribution maps acquired by MA-XRF in the area in the upper member of the frame shown in **A**. **B–H** Au, Zn, Cu, Ag, Ca, Hg, and Sr, respectively

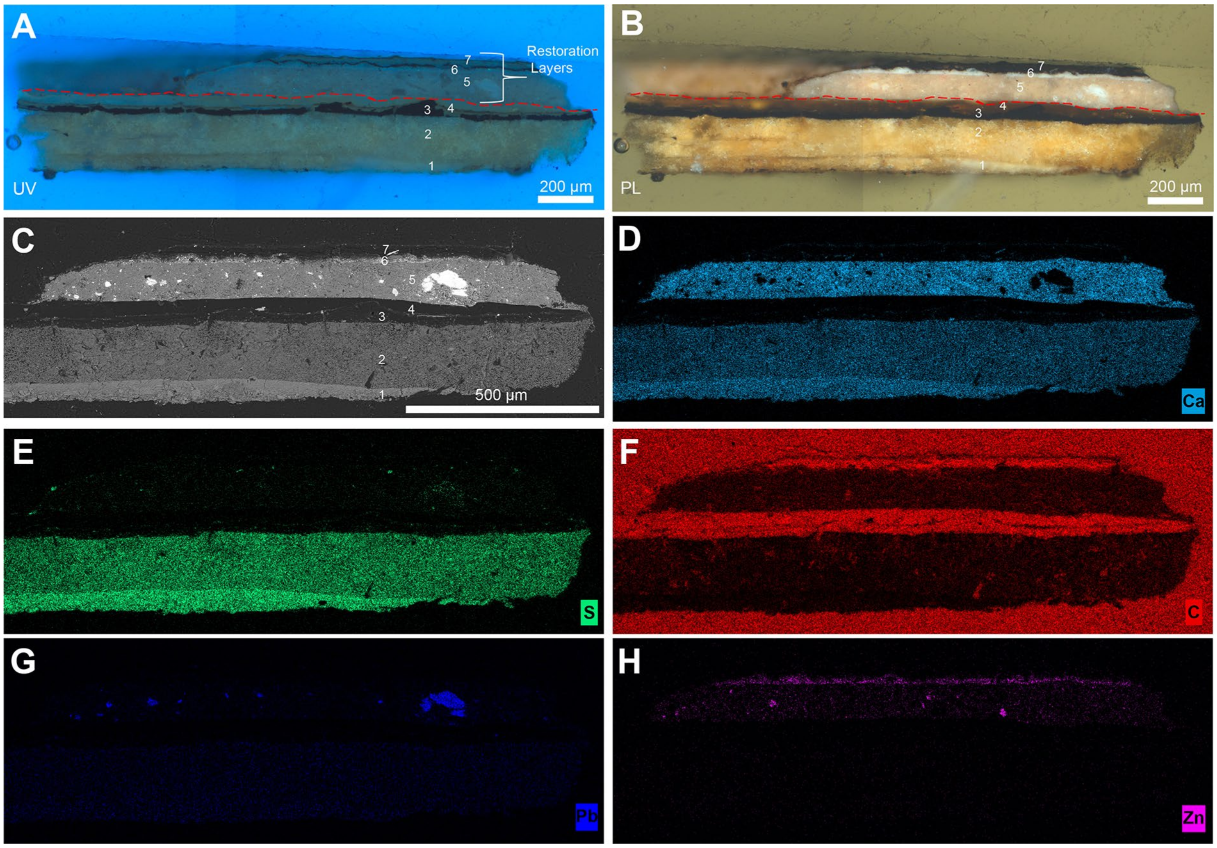


Fig. 12 Photomicrographs of Sample S8 taken **A** under UV illumination, original magnification 200×; and **B** under visible illumination, original magnification 200×. **C** SEM image, 68×. **D**–**H** EDS elemental maps of Ca, S, C, Pb, and Zn, respectively

a marquetry effect, which would have been otherwise extremely onerous to achieve.

The sculptural qualities of the frame contrast with the painting's smooth surface: *pastiglia* gesso was used to mimic coral (Fig. 10D). Sample S9 was taken from the flat in an area adjacent to the raised coral where the red paint extends onto the black paint (Additional file 1: Figs. S2 and S18A, B). In this sample, the pigmented top layer is primarily composed of vermilion (EDS in Additional file 1: Fig. S18C) with particles of Pb white (EDS in Additional file 1: S18E). Hg is present exclusively on the coral-like features (Fig. 11G). The *pastiglia* may have been created by extruding gesso from a fabric or animal tissue sleeve, given its irregular thickness (Fig. 10D).

SEM–EDS analysis of Sample S9 also revealed the presence of silicon, aluminum, chlorine, potassium, and magnesium in the ground preparation of the frame's flat (Additional file 1: Fig. S18G–J). This composition suggests the inclusion of a clay mineral. Clays such as albite, quartz, and anorthite were used in *maque* since pre-Hispanic times [103]. While the use of gypsum in traditional *maque* is unclear [75], similar clays/minerals have been found in the ground preparations of pre-Hispanic *jícaras* decorated with *maque* [103].

Similarly to the painting, MA-XRF showed that Ca and Sr co-locate with the larger shell inlays and smaller fragments; however, in the microscopic samples taken from the frame containing the full stratigraphy, no shell particles were observed in the ground preparation as they were in the painting. Sample S10, taken from the upper member of the frame (Additional file 1: Fig. S2), was not found to have the secondary $CaCO_3$ ground from the restoration campaign as Sample S8. Analysis by SEM–EDS of Sample S10 revealed the presence of a particle composed mainly of Sr, C, and S (Fig. 13) within the gypsum matrix of the ground layer. A similar Sr-rich particle was observed in Sample S9 obtained from the frame. No aragonitic $CaCO_3$ was identified in association with these particles. Therefore, we rule out that they originate from shell as it does in Samples S1 and S3. Celestite ($SrSO_4$) and strontianite ($SrCO_3$) are minerals found in gypsum deposits in northeastern Mexico, Southern Spain [104], and other locations [105, 106], while Sr is well known to be a minor component in

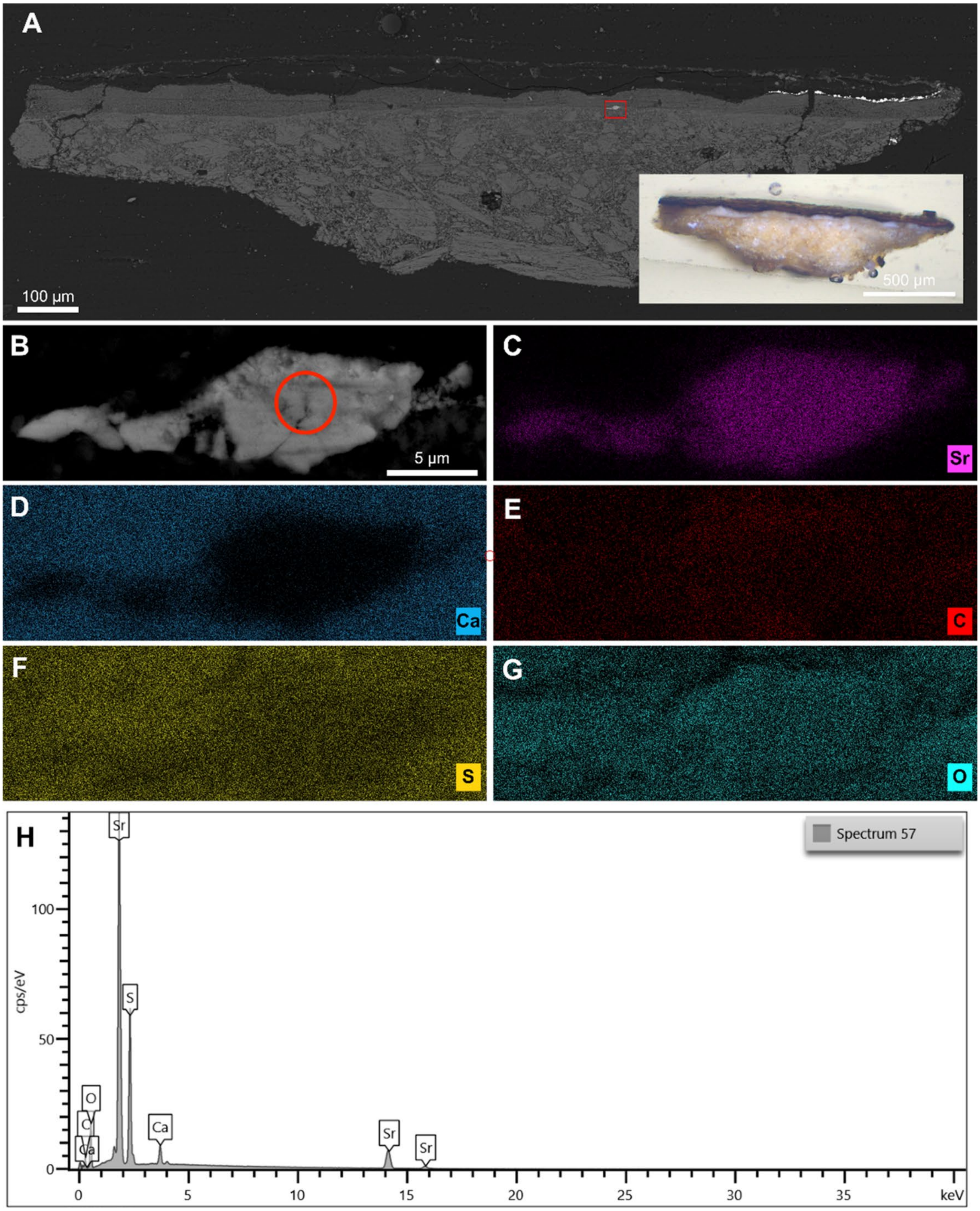


Fig. 13 **A** SEM-BSE image of Sample S10, 69x; the insert shows a photomicrograph of the sample taken with visible illumination, original magnification 200x. **B** SEM-BSE image of the Sr-containing inclusion, acquired in the area indicated with a red square in **A**, 2840x. **C**–**G** EDS maps of Sr, Ca, C, S, and O, respectively. **H** EDS spectrum taken at the location marked by the red circle in **B**

materials used in works of art from various origins [107, 108].

This finding makes us question the source of the finest Sr-containing particles observed by MA-XRF in both the painting and the frame (Fig. 3B and Fig. 11H, Additional file 1: Fig. S9). We observed Sr-rich particles independent of shell origin only in samples from the frame, but we cannot rule out that they may also be present in areas of the painting not subjected to sampling in addition to the Sr associated with shell fragments as found in the ground of Sample S1. A significant number of *enconchados* and their frames need to be analyzed to fully characterize the composition of the gypsum ore source with associated Sr and the significance of its presence for tracing the geographical origin of the materials.

Conclusions

The materiality of an *enconchado* attributed to Miguel González, *Adoration of the Magi* (ca.1695–1700), and that of its original frame were studied in-depth using a combination of non-invasive and micro-sampling methods that gave information with a level of detail not previously reported for other *enconchados*. This analytical approach allowed answering questions about the stratigraphy, pigments used, inclusion of shells throughout the painting and frame, and the origin of the mother-of-pearl itself.

The shells used in the inlays were identified by the hexagonal sheet morphology of the nacreous layer and its sheet size, determined by BSE imaging, as belonging to a *Pinctada* species, with *Pinctada mazatlanica* as the most likely candidate. SEM–EDS showed the presence of aragonitic shell particles in the ground preparation of the painting. To our knowledge, this is the first time in which shell has been identified in the preparation of an easel painting.

The co-location of Ca and Sr in the elemental distribution maps revealed the overall use of shell in *Adoration.* Sr is present in higher concentrations in marine shells than in freshwater shells and has been specifically reported in *Pinctada* nacre. Other Sr-containing particles not associated with shell (as indicated by the absence of aragonitic $CaCO_3$) were identified in the ground preparation of the frame and are attributed to Sr-containing compounds associated with gypsum deposits. This finding invites the possibility of tracing the Sr content in ground preparations to determine the geographical origin of the materials.

Optical and SEM microscopy of an intact inlaid shell sample from *Adoration* revealed abrasions like those found in archaeological objects from pre-Hispanic sites where *Pinctada mazatlanica* shells were found in great numbers, suggesting a connection between the workmanship in the inlaid *enconchado* shells and pre-Hispanic methodologies of mother-of-pearl refinement.

X-radiography of the painting and the frame and the in situ microscopic observation of the frame showed that some of the larger shell pieces have one or more holes comparable to the human-made perforations widely reported in pre-Hispanic shell objects. While it is known that holes in shells with different morphologies may be made by boring marine organisms, we propose the potential reuse of pre-Hispanic nacre objects in some *enconchados*. The repurposing of these objects may have had the advantage of doing away with the lengthy and work-intensive process involved in creating a translucent veneer. As *enconchados* in collections around the world are investigated, perhaps the discovery of inlaid shells with recognizable manufactured shapes and/or the in-depth study of the morphology of the holes will resolve this issue.

Technical studies of *enconchados* in other collections will reveal if the inclusion of shell particulate and/or dust in the ground preparations was an established practice, and shed light on the possible access to pre-worked ancient shell veneers by New Spanish artists. It is likely that the sourcing of materials was as creative and practical as the artists developing the innovative *enconchado* technique.

Abbreviations

IRR	Infrared reflectography, infrared reflectogram
MA-XRF	Macro-X-ray fluorescence or XRF mapping
PL	Polarized light
UV	Ultraviolet
SEM–EDS	Scanning electron microscopy–energy dispersive X-ray spectrometry
SI	Supplementary information
BSE image	Backscattered electron image
SEI	Secondary electron image

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40494-024-01187-4.

Additional file 1. Table S1. Stratigraphy and materials identified in cross-sections from Adoration of the Magi and its frame. **Fig. S1.** Schematic of Adoration's stratigraphy. From the bottom up: (1) wood support; (2) canvas support; (3) two-layer ground preparation; (4) underdrawing; (5) shells and leveling gypsum layer; and (6) gilding, paint, and pigmented glazes. **Fig. S2.** Diagram indicating the sample locations. **Fig. S3.** Overall image of the panel verso photographed in normal light. **Fig. S4.** (A) SEM-BSE image of Sample S1, 100x. (B) SEM-BSE image acquired in the location indicated by a red rectangle in (A), 417x, showing a coarse ground layer (layer 1, not complete), and a finer ground layer (layer 2). **Fig. S5.** (A) Photomicrograph where the underdrawing visible through the translucent inlaid mother-of-pearl is indicated with a red arrow. (B) Infrared reflectogram (IRR) of Adoration. (C) Detail of the IRR in the area indicated by a rectangle in (B), where the carbon-based underdrawing is indicated by a red arrow. **Fig. S6.** SEM-BSE images of (A) Sample S3 with shell areas outlined in red, 1130x. (B-D) EDS maps of S, Ca, and Fe, respectively. (E-F) SEM-BSE details of Sample S3 with additional enhancements by 2.6x and 3.9x, respectively, showing shell tablet morphology. **Fig. S7.** Point XRF spectrum taken from the inlaid shell Sample S2B showing the presence of Sr and Ca. **Fig. S8.** (A) EDS spectrum taken of the shell inclusion in Sample S1 with (B) etail of the higher energy Sr peaks centered at 14.1 keV. **Table S2** shows the elemental composition of the shell with Sr concentration, as determined by EDS, highlighted in yellow. **Fig. S9.** Sr distribution map acquired by MA-XRF in Adoration. The white arrow indicates a larger inlaid shell, the yellow arrow shows a smaller shell fragment, and the blue arrow points to more finely divided Sr-containing particles. **Fig. S10.** SEM-BSE image of Sample S5, 350x. The red arrow indicates the location of the shell gold layer. **Table S3** shows the elemental composition of the shell gold as determined by EDS analysis. **Fig. S11.** Elemental distribution maps acquired by MA-XRF on Adoration: (A) Pb, (B) Hg, (C) Fe, and (D) Mn. **Fig. S12.** Raman spectrum acquired in Sample S6: (A) from 200 to 1300 cm-1 and (B) from 1100 to 1900 cm-1; λ0= 785 nm. Black asterisks indicate the peaks attributed to the indigo pigment (L. Burgio and R. J. H. Clark, 'Library of FT-Raman spectra of pigments, minerals, pigment media and varnishes, and supplement to existing library of Raman spectra of pigments with visible excitation,' Spectrochim Acta Part A Mol Biomol Spectrosc 2001 Vol. 57. DOI: 10.1016/s1386-1425(00)00495-9). **Fig. S13.** (A) MA-XRF map of Cu showing only the areas corresponding to the distribution of Cu-based pigment, likely a verdigris (areas corresponding to the 'bronze' paint have been subtracted). (B) Photomicrograph taken in Melchior's robe, showing the green pigment particles. **Fig. S14.** (A) Detail of the brush-applied outlines as seen in the bull, in the bottom right of Adoration. (B) Photomicrograph taken with visible illumination in the area indicated by the red arrow in (A), in which the overlap of the different-colored outlines is seen. : Fig. S6 Additional File 1: Fig. S6. **Fig. S15.** Elemental distribution maps acquired by MA-XRF on Adoration: (A) Cu, (B) Zn, (C) Overlay of Cu-Zn (green) and Au (yellow), and (D) Distribution of materials from the old restoration campaign: Cu-Zn (green) and Cr-based pigment, possibly a chrome-oxide (orange). **Fig. S16.** (A) SEM-BSE image of Sample S7, showing a detail of the 'bronze' paint restoration, 988x. The red box indicates the location where the elemental composition shown in Table S4 was acquired by EDS. **Fig. S17.** Elemental distribution maps acquired by MA-XRF in an area of the upper member of the frame: (A) Cu-Zn overlap and (B) Cu-Zn overlap in green with Au distribution in yellow. **Fig. S18.** (A) Photomicrograph of Sample S9 taken under visible illumination, original magnification 200x and (B) SEM-BSE image of the sample shown in (A), 141x. (C-J) EDS maps of Hg, S, Pb, Ca, Si, Al, Cl, and K, respectively.

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Author contributions
JL provided the conservation perspective and insights into González's technique, determined sample sites, took the samples, and carried out their examination by optical microscopy. AD prepared the samples, performed the SEM–EDS analyses, acquired the Raman spectral data, interpreted the results from these techniques, and contributed to the examination by optical microscopy. AD and SAC acquired and interpreted the MA-XRF data. JL, AD, and SAC placed the data in the context of the painting's technique. All authors wrote and edited the manuscript and approved the final version.

Availability of data and materials
The datasets acquired at The Met are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare no competing interests.

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